CHAPTER TWO

2.1 **(a)** $$\begin{array}{c|c|c|c|c} 3\text{ wk} & 7\text{ d} & 24\text{ h} & 3600\text{ s} & 1000\text{ ms} \\ \hline & 1\text{ wk} & 1\text{ d} & 1\text{ h} & 1\text{ s} \end{array} = \underline{\underline{1.8144\times 10^{9}\text{ ms}}}$$

(b) $$\begin{array}{c|c|c} 38.1\text{ ft / s} & 0.0006214\text{ mi} & 3600\text{ s} \\ \hline & 3.2808\text{ ft} & 1\text{ h} \end{array} = 25.98\text{ mi / h} \Rightarrow \underline{\underline{26.0\text{ mi / h}}}$$

(c) $$\begin{array}{c|c|c|c|c} 554\text{ m}^4 & 1\text{ d} & 1\text{ h} & 1\text{ kg} & 10^8\text{ cm}^4 \\ \hline \text{d}\cdot\text{kg} & 24\text{ h} & 60\text{ min} & 1000\text{ g} & 1\text{ m}^4 \end{array} = \underline{\underline{3.85\times 10^{4}\text{ cm}^4\text{ / min}\cdot\text{g}}}$$

2.2 **(a)** $$\begin{array}{c|c|c} 760\text{ mi} & 1\text{ m} & 1\text{ h} \\ \hline \text{h} & 0.0006214\text{ mi} & 3600\text{ s} \end{array} = \underline{\underline{340\text{ m / s}}}$$

(b) $$\begin{array}{c|c|c} 921\text{ kg} & 2.20462\text{ lb}_\text{m} & 1\text{ m}^3 \\ \hline \text{m}^3 & 1\text{ kg} & 35.3145\text{ ft}^3 \end{array} = \underline{\underline{57.5\text{ lb}_\text{m}\text{ / ft}^3}}$$

(c) $$\begin{array}{c|c|c|c} 5.37\times 10^{3}\text{ kJ} & 1\text{ min} & 1000\text{ J} & 1.34\times 10^{-3}\text{ hp} \\ \hline \text{min} & 60\text{ s} & 1\text{ kJ} & 1\text{ J / s} \end{array} = 119.93\text{ hp} \Rightarrow \underline{\underline{120\text{ hp}}}$$

2.3 Assume that a golf ball occupies the space equivalent to a $2\text{ in }\times 2\text{ in }\times 2\text{ in}$ cube. For a classroom with dimensions $40\text{ ft}\times 40\text{ ft}\times 15\text{ ft}$:

$$n_\text{balls} = \begin{array}{c|c|c} 40\times 40\times 15\text{ ft}^3 & (12)^3\text{ in}^3 & 1\text{ ball} \\ \hline & \text{ft}^3 & 2^3\text{ in}^3 \end{array} = 5.18\times 10^{6} \approx \underline{\underline{5\text{ million balls}}}$$

The estimate could vary by an order of magnitude or more, depending on the assumptions made.

2.4 $$\begin{array}{c|c|c|c|c|c|c} 4.3\text{ light yr} & 365\text{ d} & 24\text{ h} & 3600\text{ s} & 1.86\times 10^{5}\text{ mi} & 3.2808\text{ ft} & 1\text{ step} \\ \hline & 1\text{ yr} & 1\text{ d} & 1\text{ h} & 1\text{ s} & 0.0006214\text{ mi} & 2\text{ ft} \end{array} = \underline{\underline{7\times 10^{16}\text{ steps}}}$$

2.5 Distance from the earth to the moon = 238857 miles

$$\begin{array}{c|c|c} 238857\text{ mi} & 1\text{ m} & 1\text{ report} \\ \hline & 0.0006214\text{ mi} & 0.001\text{ m} \end{array} = \underline{\underline{4\times 10^{11}\text{ reports}}}$$

2.6

$$\begin{array}{c|c|c|c} 19\text{ km} & 1000\text{ m} & 0.0006214\text{ mi} & 1000\text{ L} \\ \hline 1\text{ L} & 1\text{ km} & 1\text{ m} & 264.17\text{ gal} \end{array} = 44.7\text{ mi / gal}$$

Calculate the total cost to travel *x* miles.

$$\text{Total Cost}_\text{American} = \$14{,}500 + \begin{array}{c|c|c} \$1.25 & 1\text{ gal} & x\text{ (mi)} \\ \hline \text{gal} & 28\text{ mi} & \end{array} = 14{,}500 + 0.04464x$$

$$\text{Total Cost}_\text{European} = \$21{,}700 + \begin{array}{c|c|c} \$1.25 & 1\text{ gal} & x\text{ (mi)} \\ \hline \text{gal} & 44.7\text{ mi} & \end{array} = 21{,}700 + 0.02796x$$

Equate the two costs $\Rightarrow x = \underline{\underline{4.3\times 10^{5}\text{ miles}}}$

2.7

$$\begin{array}{r|c|c|c|c|c|c} 5320\ \text{imp. gal} & 14\ \text{h} & 365\ \text{d} & 10^6\ \text{cm}^3 & 0.965\ \text{g} & 1\ \text{kg} & 1\ \text{tonne} \\ \hline \text{plane}\cdot\text{h} & 1\ \text{d} & 1\ \text{yr} & 220.83\ \text{imp. gal} & 1\ \text{cm}^3 & 1000\ \text{g} & 1000\ \text{kg} \end{array}$$

$$=1.188\times10^5\ \frac{\text{tonne kerosene}}{\text{plane}\cdot\text{yr}}$$

$$\begin{array}{r|c|c} 4.02\times10^9\ \text{tonne crude oil} & 1\ \text{tonne kerosene} & \text{plane}\cdot\text{yr} \\ \hline \text{yr} & 7\ \text{tonne crude oil} & 1.188\times10^5\ \text{tonne kerosene} \end{array}$$

$$= 4834\ \text{planes} \Rightarrow \underline{\underline{5000\ \text{planes}}}$$

2.8 (a)

$$\begin{array}{l|l|c} 25.0\ \text{lb}_\text{m} & 32.1714\ \text{ft}/\text{s}^2 & 1\ \ \ \text{lb}_\text{f} \\ \hline & & 32.1714\ \text{lb}_\text{m}\cdot\text{ft}/\text{s}^2 \end{array} = \underline{\underline{25.0\ \text{lb}_\text{f}}}$$

(b)

$$\begin{array}{l|c|c} 25\ \text{N} & 1 & 1\ \text{kg}\cdot\text{m/s}^2 \\ \hline & 9.8066\ \text{m/s}^2 & 1\ \text{N} \end{array} = 2.5493\ \text{kg} \Rightarrow \underline{\underline{2.5\ \text{kg}}}$$

(c)

$$\begin{array}{l|c|c|c|c} 10\ \text{ton} & 1\ \text{lb}_\text{m} & 1000\ \text{g} & 980.66\ \text{cm}/\text{s}^2 & 1\ \text{dyne} \\ \hline & 5\times10^{-4}\ \text{ton} & 2.20462\ \text{lb}_\text{m} & & 1\ \text{g}\cdot\text{cm}/\text{s}^2 \end{array} = \underline{\underline{9\times10^9\ \text{dynes}}}$$

2.9

$$\begin{array}{l|c|c|c|c} 50\times15\times2\ \text{m}^3 & 35.3145\ \text{ft}^3 & 85.3\ \text{lb}_\text{m} & 32.174\ \text{ft} & 1\ \text{lb}_\text{f} \\ \hline & 1\ \ \ \text{m}^3 & 1\ \ \text{ft}^3 & 1\ \ \ \text{s}^2 & 32.174\ \text{lb}_\text{m}/\text{ft}\cdot\text{s}^2 \end{array} = \underline{\underline{4.5\times10^6\ \text{lb}_\text{f}}}$$

2.10

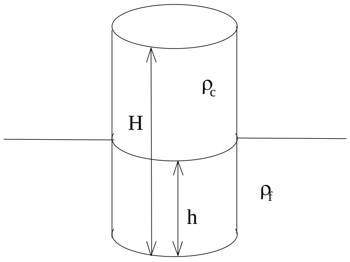
$$\begin{array}{l|c|c} 500\ \text{lb}_\text{m} & 1\ \ \ \text{kg} & 1\ \ \text{m}^3 \\ \hline & 2.20462\ \text{lb}_\text{m} & 11.5\ \text{kg} \end{array} \approx 5\times10^2\left(\frac{1}{2}\right)\left(\frac{1}{10}\right) \approx \underline{\underline{25\ \text{m}^3}}$$

2.11 **(a)**

$$m_{\text{displaced fluid}} = m_{\text{cylinder}} \Rightarrow \rho_f V_f = \rho_c V_c \Rightarrow \rho_f h\pi r^2 = \rho_c H\pi r^2$$

$$\rho_c = \frac{\rho_f h}{H} = \frac{(30\ \text{cm} - 14.1\ \text{cm})(1.00\ \text{g}/\text{cm}^3)}{30\ \text{cm}} = \underline{\underline{0.53\ \text{g}/\text{cm}^3}}$$

(b) $$\rho_f = \frac{\rho_c H}{h} = \frac{(30\ \text{cm})(0.53\ \text{g}/\text{cm}^3)}{(30\ \text{cm - }20.7\ \text{cm})} = \underline{\underline{1.71\ \text{g}/\text{cm}^3}}$$



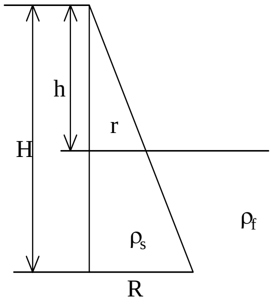
2.12

$$V_s = \frac{\pi R^2 H}{3};\ \ V_f = \frac{\pi R^2 H}{3} - \frac{\pi r^2 h}{3}\ ;\ \ \frac{R}{H} = \frac{r}{h} \Rightarrow r = \frac{R}{H}h$$

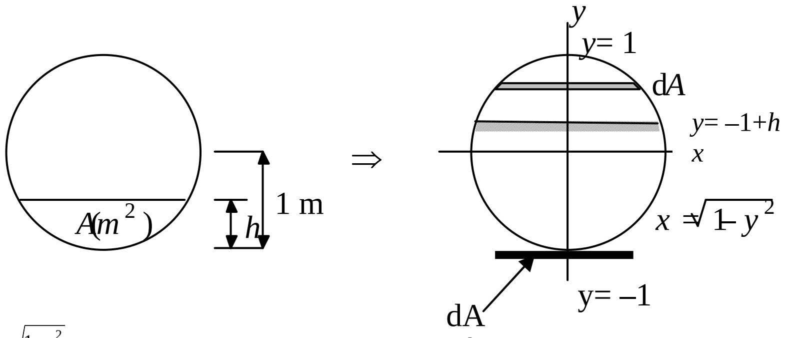
$$\Rightarrow\ V_f = \frac{\pi R^2 H}{3} - \frac{\pi h}{3}\left(\frac{Rh}{H}\right)^2 = \frac{\pi R^2}{3}\left(H - \frac{h^3}{H^2}\right)$$

$$\rho_f V_f = \rho_s V_s \Rightarrow \rho_f\ \frac{\pi R^2}{3}\left(H - \frac{h^3}{H^2}\right) = \rho_s\ \frac{\pi R^2 H}{3}$$

$$\Rightarrow \rho_f = \rho_s\ \frac{H}{H - \dfrac{h^3}{H^2}} = \rho_s\ \frac{H^3}{H^3 - h^3} = \underline{\underline{\rho_s\ \frac{1}{1 - \left(\dfrac{h}{H}\right)^3}}}$$



2.13 Say $h(m) =$ depth of liquid



$$dA = dy\cdot\int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} dx = 2\sqrt{1-y^2}\,dy \Rightarrow A\left(m^2\right) = 2\int_{-1}^{-1+h}\sqrt{1-y^2}\,dy$$

⇓ Table of integrals or trigonometric substitution

$$A\left(\mathrm{m}^2\right) = y\sqrt{1-y^2} + \sin^{-1} y\Big]_{-1}^{h-1} = (h-1)\sqrt{1-(h-1)^2} + \sin^{-1}(h-1) + \frac{\pi}{2}$$

$$W(N) = \begin{array}{c|c|c|c|c} 4\text{ m}\times A(\mathrm{m}^2) & 0.879\text{ g} & 10^6\text{ cm}^2 & 1\text{ kg} & 9.81\text{ N} \\ \hline & \mathrm{cm}^3 & 1\text{ m}^3 & 10^3\text{ g} & \underbrace{\mathrm{kg}}_{g/g_0} \end{array} = 3.45\times 10^4 A$$

⇓ Substitute for A

$$\underline{\underline{W(\mathrm{N}) = 3.45\times 10^4\left[(h-1)\sqrt{1-(h-1)^2} + \sin^{-1}(h-1) + \frac{\pi}{2}\right]}}$$

2.14 $1\text{ lb}_\mathrm{f} = 1\text{ slug}\cdot\text{ft}/\text{s}^2 = 32.174\text{ lb}_\mathrm{m}\cdot\text{ft}/\text{s}^2 \Rightarrow 1\text{ slug} = 32.174\text{ lb}_\mathrm{m}$

$1\text{ poundal} = 1\text{ lb}_\mathrm{m}\cdot\text{ft}/\text{s}^2 = \dfrac{1}{32.174}\text{ lb}_\mathrm{f}$

(a) (i) On the earth:

$$M = \begin{array}{c|c} 175\text{ lb}_\mathrm{m} & 1\text{ slug} \\ \hline & 32.174\text{ lb}_\mathrm{m} \end{array} = \underline{\underline{5.44\text{ slugs}}}$$

$$W = \begin{array}{c|c|c} 175\text{ lb}_\mathrm{m} & 32.174\text{ ft} & 1\text{ poundal} \\ \hline & \mathrm{s}^2 & 1\text{ lb}_\mathrm{m}\cdot\text{ft}/\text{s}^2 \end{array} = \underline{\underline{5.63\times 10^3\text{ poundals}}}$$

(ii) On the moon

$$M = \begin{array}{c|c} 175\text{ lb}_\mathrm{m} & 1\text{ slug} \\ \hline & 32.174\text{ lb}_\mathrm{m} \end{array} = \underline{\underline{5.44\text{ slugs}}}$$

$$W = \begin{array}{c|c|c} 175\text{ lb}_\mathrm{m} & 32.174\text{ ft} & 1\text{ poundal} \\ \hline & 6\quad\ \mathrm{s}^2 & 1\text{ lb}_\mathrm{m}\cdot\text{ft}/\text{s}^2 \end{array} = \underline{\underline{938\text{ poundals}}}$$

(b) $F = ma \Rightarrow a = F/m = \begin{array}{c|c|c|c} 355\text{ poundals} & 1\text{ lb}_\mathrm{m}\cdot\text{ft}/\text{s}^2 & 1\quad\text{slug} & 1\text{ m} \\ \hline 25.0\text{ slugs} & 1\text{ poundal} & 32.174\text{ lb}_\mathrm{m} & 3.2808\text{ ft} \end{array}$

$= \underline{\underline{0.135\text{ m}/\text{s}^2}}$

2.15 (a) $F = ma \Rightarrow 1\text{ fern} = (1\text{ bung})(32.174\text{ ft / s}^2)\left(\frac{1}{6}\right) = \underline{\underline{5.3623\text{ bung}\cdot\text{ft / s}^2}}$

$$\Rightarrow \underline{\underline{\frac{1\text{ fern}}{5.3623\text{ bung}\cdot\text{ft / s}^2}}}$$

(b) On the moon: $W = \frac{3\text{ bung}}{} \left| \frac{32.174\text{ ft}}{6\quad\text{s}^2} \right| \frac{1\text{ fern}}{5.3623\text{ bung}\cdot\text{ft / s}^2} = \underline{\underline{3\text{ fern}}}$

On the earth: $W = (3)(32.174)/5.3623 = \underline{\underline{18\text{ fern}}}$

2.16 (a) $\approx (3)(9) = \underline{\underline{27}}$

$(2.7)(8.632) = \underline{\underline{23}}$

(b) $\approx \frac{4.0\times10^{-4}}{40} \approx \underline{\underline{1\times10^{-5}}}$

$(3.600\times10^{-4})/45 = \underline{\underline{8.0\times10^{-6}}}$

(c) $\approx 2 + 125 = \underline{\underline{127}}$

$2.365 + 125.2 = \underline{\underline{127.5}}$

(d) $\approx 50\times10^3 - 1\times10^3 \approx 49\times10^3 \approx \underline{\underline{5\times10^4}}$

$4.753\times10^4 - 9\times10^2 = \underline{\underline{5\times10^4}}$

2.17 $R \approx \frac{(7\times10^{-1})(3\times10^5)(6)(5\times10^4)}{(3)(5\times10^6)} \approx 42\times10^2 \approx \underline{\underline{4\times10^3}}$ (Any digit in range 2-6 is acceptable)

$R_{exact} = 3812.5 \Rightarrow \underline{\underline{3810}} \Rightarrow \underline{\underline{3.81\times10^3}}$

2.18 (a)

A: $R = 73.1 - 72.4 = \underline{\underline{0.7^\circ\text{C}}}$

$$\bar{X} = \frac{72.4 + 73.1 + 72.6 + 72.8 + 73.0}{5} = \underline{\underline{72.8^\circ\text{C}}}$$

$$s = \sqrt{\frac{(72.4-72.8)^2 + (73.1-72.8)^2 + (72.6-72.8)^2 + (72.8-72.8)^2 + (73.0-72.8)^2}{5-1}}$$

$$= \underline{\underline{0.3^\circ\text{C}}}$$

B: $R = 103.1 - 97.3 = \underline{\underline{5.8^\circ\text{C}}}$

$$\bar{X} = \frac{97.3 + 101.4 + 98.7 + 103.1 + 100.4}{5} = \underline{\underline{100.2^\circ\text{C}}}$$

$$s = \sqrt{\frac{(97.3-100.2)^2 + (101.4-100.2)^2 + (98.7-100.2)^2 + (103.1-100.2)^2 + (100.4-100.2)^2}{5-1}}$$

$$= \underline{\underline{2.3^\circ\text{C}}}$$

(b) Thermocouple B exhibits a higher degree of scatter and is also more accurate.

2.19 (a)

$$\overline{X} = \frac{\sum_{i=1}^{12} X_i}{12} = 73.5 \qquad s = \sqrt{\frac{\sum_{i=1}^{12} (X - 73.5)^2}{12-1}} = 1.2$$

$$\text{C}_{\text{min}=} = \overline{X} - 2s = 73.5 - 2(1.2) = \underline{\underline{71.1}}$$

$$\text{C}_{\text{max}=} = \overline{X} + 2s = 73.5 + 2(1.2) = \underline{\underline{75.9}}$$

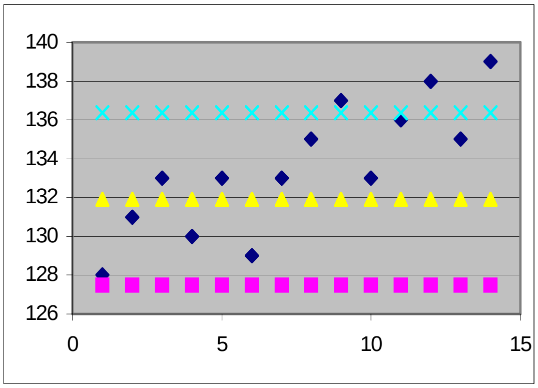
(b) Joanne is more likely to be the statistician, because she wants to make the control limits stricter.

(c) Inadequate cleaning between batches, impurities in raw materials, variations in reactor temperature (failure of reactor control system), problems with the color measurement system, operator carelessness

2.20 (a), (b)

(a) Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
X	134	131	129	133	135	131	134	130	131	136	129	130	133	130	133
Mean(X)	131.9														
Stdev(X)	2.2														
Min	127.5														
Max	136.4														

(b) Run	X	Min	Mean	Max
1	128	127.5	131.9	136.4
2	131	127.5	131.9	136.4
3	133	127.5	131.9	136.4
4	130	127.5	131.9	136.4
5	133	127.5	131.9	136.4
6	129	127.5	131.9	136.4
7	133	127.5	131.9	136.4
8	135	127.5	131.9	136.4
9	137	127.5	131.9	136.4
10	133	127.5	131.9	136.4
11	136	127.5	131.9	136.4
12	138	127.5	131.9	136.4
13	135	127.5	131.9	136.4
14	139	127.5	131.9	136.4



(c) Beginning with Run 11, the process has been near or well over the upper quality assurance limit. An overhaul would have been reasonable after Run 12.

2.21 (a)

$$Q' = \begin{array}{r|r|r|r} 2.36\times10^{-4}\ \text{kg}\cdot\text{m}^2 & 2.20462\ \text{lb} & 3.2808^2\ \text{ft}^2 & 1\quad \text{h} \\ \hline \text{h} & \text{kg} & \text{m}^2 & 3600\ \text{s} \end{array}$$

(b) $$Q'_{\text{approximate}} \approx \frac{(2\times10^{-4})(2)(9)}{3\times10^3} \approx 12\times10^{(-4-3)} \approx \underline{\underline{1.2\times10^{-6}\ \text{lb}\cdot\text{ft}^2/\text{s}}}$$

$$Q'_{\text{exact}} = \underline{\underline{1.56\times10^{-6}\ \text{lb}\cdot\text{ft}^2/\text{s}}} = \underline{\underline{\ 0.00000156\ \text{lb}\cdot\text{ft}^2/\text{s}}}$$

2.22 $$N_{\text{Pr}} = \frac{C_p\mu}{k} = \begin{array}{c|c|c|c|c} 0.583\ \text{J / g}\cdot{}^{o}\,C & 1936\ \text{lb}_{\text{m}} & 1\ \ \text{h} & 3.2808\ \text{ft} & 1000\ \text{g} \\ \hline 0.286\ \text{W / m}\cdot{}^{o}\,C & \text{ft}\cdot\text{h} & 3600\ \text{s} & \text{m} & 2.20462\ \text{lb}_{\text{m}} \end{array}$$

$$N_{\text{Pr}} \approx \frac{(6\times10^{-1})(2\times10^{3})(3\times10^{3})}{(3\times10^{-1})(4\times10^{3})(2)} \approx \frac{3\times10^{3}}{2} \approx \underline{\underline{1.5\times10^{3}}}.\ \text{ The calculator solution is } \underline{\underline{1.63\times10^{3}}}$$

2.23

$$\text{Re} = \frac{Du\rho}{\mu} = \begin{array}{r|c|c|c|c|c|c} 0.48\ \text{ft} & 1\ \ \ \text{m} & 2.067\ \text{in} & 1\ \ \text{m} & 0.805\ \text{g} & 1\ \ \text{kg} & 10^{6}\ \text{cm}^{3} \\ \hline \text{s} & 3.2808\ \text{ft} & 0.43\times10^{-3}\ \text{kg / m}\cdot\text{s} & 39.37\ \text{in} & \text{cm}^{3} & 1000\ \text{g} & 1\ \ \ \text{m}^{3} \end{array}$$

$$\text{Re} \approx \frac{(5\times10^{-1})(2)(8\times10^{-1})(10^{6})}{(3)(4\times10)(10^{3})(4\times10^{-4})} \approx \frac{5\times10^{1-(-3)}}{3} \approx 2\times10^{4} \Rightarrow\ \underline{\underline{\text{the flow is turbulent}}}$$

2.24 (a) $$\frac{\boldsymbol{k_g d_p y}}{\boldsymbol{D}} = 2.00 + 0.600\left(\frac{\mu}{\rho\boldsymbol{D}}\right)^{1/3}\left(\frac{\boldsymbol{d_p u}\rho}{\mu}\right)^{1/2}$$

$$= 2.00 + 0.600\left[\frac{1.00\times10^{-5}\ \text{N}\cdot\text{s/m}^{2}}{(1.00\ \text{kg/m}^{3})(1.00\times10^{-5}\ \text{m}^{2}\,/\,\text{s})}\right]^{1/3}\left[\frac{(0.00500\ \text{m})(10.0\ \text{m/s})(1.00\ \text{kg/m}^{3})}{(1.00\times10^{-5}\ \text{N}\cdot\text{s/m}^{2})}\right]^{1/2}$$

$$= 44.426 \Rightarrow \frac{\boldsymbol{k_g}(0.00500\ \text{m})(0.100)}{1.00\times10^{-5}\ \text{m}^{2}\,/\,\text{s}} = 44.426 \Rightarrow \boldsymbol{k_g} = \underline{\underline{0.888\ \text{m}\,/\,\text{s}}}$$

(b) The diameter of the particles is not uniform, the conditions of the system used to model the equation may differ significantly from the conditions in the reactor (out of the range of empirical data), all of the other variables are subject to measurement or estimation error.

(c)

d_p (m)	y	D (m^2/s)	μ (N-s/m^2)	ρ (kg/m^3)	u (m/s)	k_g
0.005	0.1	1.00E-05	1.00E-05	1	10	0.889
0.010	0.1	1.00E-05	1.00E-05	1	10	0.620
0.005	0.1	2.00E-05	1.00E-05	1	10	1.427
0.005	0.1	1.00E-05	2.00E-05	1	10	0.796
0.005	0.1	1.00E-05	1.00E-05	1	20	1.240

2.25 (a) $\underline{\underline{200\ \text{crystals / min}\cdot\text{mm};}}\ \ \underline{\underline{10\ \text{crystals / min}\cdot\text{mm}^{2}}}$

(b) $$r = \begin{array}{c|c|c} 200\ \text{crystals} & 0.050\ \text{in} & 25.4\ \text{mm} \\ \hline \text{min}\cdot\text{mm} & & \text{in} \end{array} - \begin{array}{c|c|c} 10\ \text{crystals} & 0.050^{2}\ \text{in}^{2} & (25.4)^{2}\ \text{mm}^{2} \\ \hline \text{min}\cdot\text{mm}^{2} & & \text{in}^{2} \end{array}$$

$$= 238\ \text{crystals / min} \Rightarrow \begin{array}{c|c} 238\ \text{crystals} & 1\ \text{min} \\ \hline \text{min} & 60\ \text{s} \end{array} = \underline{\underline{4.0\ \text{crystals / s}}}$$

(c) $$D(\text{mm}) = \begin{array}{c|c} D'(\text{in}) & 25.4\ \text{mm} \\ \hline & 1\ \text{in} \end{array} = 25.4D'\ ;\ r\left(\frac{\text{crystals}}{\text{min}}\right) = r'\begin{array}{c|c} \text{crystals} & 60\ \text{s} \\ \hline \text{s} & 1\ \text{min} \end{array} = 60r'$$

$$\Rightarrow 60r' = 200(25.4D') - 10(25.4D')^{2} \Rightarrow \underline{\underline{r' = 84.7D' - 108(D')^{2}}}$$

2.26 (a) $\underline{\underline{70.5\ \text{lb}_\text{m}\ /\ \text{ft}^3}}$; $\underline{\underline{8.27 \times 10^{-7}\ \text{in}^2\ /\ \text{lb}_\text{f}}}$

(b) $$\rho = (70.5\ \text{lb}_\text{m}/\text{ft}^3)\exp\left[\begin{array}{r|r|r} 8.27\times10^{-7}\ \text{in}^2 & 9\times10^6\ \text{N} & 14.696\ \text{lb}_\text{f}/\text{in}^2 \\ \hline \text{lb}_\text{f} & \text{m}^2 & 1.01325\times10^5\ \text{N/m}^2 \end{array}\right]$$

$$= \begin{array}{r|r|r|r} 70.57\ \text{lb}_\text{m} & 35.3145\ \text{ft}^3 & 1\quad \text{m}^3 & 1000\ \text{g} \\ \hline \text{ft}^3 & \text{m}^3 & 10^6\ \text{cm}^3 & 2.20462\ \text{lb}_\text{m} \end{array} = \underline{\underline{1.13\ \text{g/cm}^3}}$$

(c) $$\rho\left(\frac{\text{lb}_\text{m}}{\text{ft}^3}\right) = \rho' \begin{array}{r|r|r} \text{g} & 1\ \text{lb}_\text{m} & 28{,}317\ \text{cm}^3 \\ \hline \text{cm}^3 & 453.593\ \text{g} & 1\ \text{ft}^3 \end{array} = 62.43\rho'$$

$$P\left(\frac{\text{lb}_\text{f}}{\text{in}^2}\right) = P' \begin{array}{r|r|r} \text{N} & 0.2248\ \text{lb}_\text{f} & 1^2\quad \text{m}^2 \\ \hline \text{m}^2 & 1\ \text{N} & 39.37^2\ \text{in}^2 \end{array} = 1.45\times10^{-4}P'$$

$$\Rightarrow 62.43\rho' = 70.5\exp\left[\left(8.27\times10^{-7}\right)\left(1.45\times10^{-4}P'\right)\right] \Rightarrow \underline{\underline{\rho' = 1.13\exp\left(1.20\times10^{-10}P'\right)}}$$

$$P' = 9.00\times10^6\ \text{N}/\text{m}^2 \Rightarrow \rho' = 1.13\exp[(1.20\times10^{-10})(9.00\times10^6)] = \underline{\underline{1.13\ \text{g}/\text{cm}^3}}$$

2.27 (a) $$V\left(\text{cm}^3\right) = \begin{array}{c|r} V'\left(\text{in}^3\right) & 28{,}317\ \text{cm}^3 \\ \hline & 1728\ \text{in}^3 \end{array} = 16.39V'\ ;\ t(\text{s}) = 3600t'(\text{hr})$$

$$\Rightarrow 16.39V' = \exp\left(3600t'\right) \Rightarrow \underline{\underline{V' = 0.06102\exp\left(3600t'\right)}}$$

(b) The t in the exponent has a coefficient of s^{-1}.

2.28 (a) $\underline{\underline{3.00\ \text{mol / L}}}$, $\underline{\underline{2.00\ \text{min}^{-1}}}$

(b) $t = 0 \Rightarrow C = 3.00\ \exp[(-2.00)(0)] = 3.00\ \text{mol / L}$

$\text{t} = 1 \Rightarrow\ C = 3.00\ \exp[(-2.00)(1)] = 0.406\ \text{mol / L}$

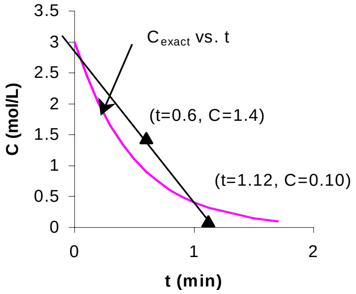
For t=0.6 min: $$C_\text{int} = \frac{0.406 - 3.00}{1 - 0}(0.6 - 0) + 3.00 = \underline{\underline{1.4\ \text{mol / L}}}$$

$$C_\text{exact} = 3.00\ \exp[(-2.00)(0.6)] = \underline{\underline{0.9\ \text{mol / L}}}$$

For C=0.10 mol/L: $$t_\text{int} = \frac{1 - 0}{0.406 - 3}(0.10 - 3.00) + 0 = \underline{\underline{1.12\ \text{min}}}$$

$$t_\text{exact} = -\frac{1}{2.00}\ln\frac{\text{C}}{3.00} = -\frac{1}{2}\ln\frac{0.10}{3.00} = \underline{\underline{1.70\ \text{min}}}$$

(c)



2.29 (a) $$p^* = \frac{60-20}{199.8-166.2}(185-166.2)+20 = \underline{\underline{42\text{ mm Hg}}}$$

(b)

```
    c     MAIN PROGRAM FOR PROBLEM 2.29
          IMPLICIT REAL*4(A–H, 0–Z)
          DIMENSION TD(6), PD(6)
          DO 1 I = 1, 6
                READ (5, *) TD(I), PD(I)
    1     CONTINUE
          WRITE (5, 902)
  902     FORMAT (‘0’, 5X, ‘TEMPERATURE     VAPOR PRESSURE’/6X,
    *                  ‘        (C)                   (MM HG)’/)
          DO 2 I = 0, 115, 5
          T = 100 + I
          CALL VAP (T, P, TD, PD)
          WRITE (6, 903)   T, P
  903     FORMAT (10X, F5.1, 10X, F5.1)
    2     CONTINUE
          END
          SUBROUTINE VAP (T, P, TD, PD)
          DIMENSION TD(6), PD(6)
          I = 1
    1     IF (TD(I).LE.T.AND.T.LT.TD(I + 1)) GO TO 2
          I = I + 1
          IF (I.EQ.6) STOP
          GO TO 1
    2     P = PD(I) + (T – TD(I))/(TD(I + 1) – TD(I)) * (PD(I + 1) – PD(I))
          RETURN
          END
```

```
DATA                        OUTPUT
  98.5      1.0               TEMPERATURE      VAPOR PRESSURE
 131.8      5.0                   (C)             (MM HG)
   ⋮         ⋮                   100.0               1.2
 215.5    100.0                  105.0               1.8
                                   ⋮                  ⋮
                                 215.0               98.7
```

2.30 (b) $\ln y = \ln a + bx \Rightarrow y = ae^{bx}$

$$b = (\ln y_2 - \ln y_1)/(x_2 - x_1) = (\ln 2 - \ln 1)/(1-2) = -0.693$$

$$\ln a = \ln y - bx = \ln 2 + 0.63(1) \Rightarrow a = 4.00 \Rightarrow \underline{\underline{y = 4.00e^{-0.693x}}}$$

(c) $\ln y = \ln a + b\ln x \Rightarrow y = ax^b$

$$b = (\ln y_2 - \ln y_1)/(\ln x_2 - \ln x_1) = (\ln 2 - \ln 1)/(\ln 1 - \ln 2) = -1$$

$$\ln a = \ln y - b\ln x = \ln 2 - (-1)\ln(1) \Rightarrow a = 2 \Rightarrow \underline{\underline{y = 2/x}}$$

(d) $\ln(xy) = \ln a + b(y/x) \Rightarrow xy = ae^{by/x} \Rightarrow y = (a/x)e^{by/x}$ [can't get $y = f(x)$]

$$b = [\ln(xy)_2 - \ln(xy)_1]/[(y/x)_2 - (y/x)_1] = (\ln 807.0 - \ln 40.2)/(2.0-1.0) = 3$$

$$\ln a = \ln(xy) - b(y/x) = \ln 807.0 - 3\ln(2.0) \Rightarrow a = 2 \Rightarrow \underline{\underline{xy = 2e^{3y/x}}}$$

[can't solve explicitly for $y(x)$]

2.30 (cont'd)

(e) $\ln(y^2/x) = \ln a + b\ln(x-2) \Rightarrow y^2/x = a(x-2)^b \Rightarrow y = [ax(x-2)^b]^{1/2}$

$$b = [\ln(y^2/x)_2 - \ln(y^2/x)_1]/[\ln(x-2)_2 - \ln(x-2)_1]$$

$$= (\ln 807.0 - \ln 40.2)/(\ln 2.0 - \ln 1.0) = 4.33$$

$$\ln a = \ln(y^2/x) - b(x-2) = \ln 807.0 - 4.33\ln(2.0) \Rightarrow a = 40.2$$

$$\Rightarrow y^2/x = 40.2(x-2)^{4.33} \Rightarrow \underline{\underline{y = 6.34x^{1/2}(x-2)^{2.165}}}$$

2.31 **(b)** $\underline{\underline{\text{Plot } y^2 \text{ vs. } x^3 \text{ on rectangular axes. Slope} = m, \text{Intcpt} = -n}}$

(c) $\dfrac{1}{\ln(y-3)} = \dfrac{1}{b} + \dfrac{a}{b}\sqrt{x} \Rightarrow \underline{\underline{\text{Plot } \dfrac{1}{\ln(y-3)} \text{ vs. } \sqrt{x} \text{ [rect. axes], slope} = \dfrac{\text{a}}{\text{b}}, \text{ intercept} = \dfrac{1}{\text{b}}}}$

(d)

$\dfrac{1}{(y+1)^2} = a(x-3)^3 \Rightarrow \underline{\underline{\text{Plot } \dfrac{1}{(y+1)^2} \text{ vs. } (x-3)^3 \text{ [rect. axes], slope} = a, \text{ intercept} = 0}}$

OR

$$2\ln(y+1) = -\ln a - 3\ln(x-3)$$

$\underline{\underline{\text{Plot } \ln(y+1) \text{ vs. } \ln(x-3) \text{ [rect.] or (y+1) vs. (x - 3) [log]}}}$

$\underline{\underline{\Rightarrow \text{slope} = -\dfrac{3}{2}, \text{ intercept} = -\dfrac{\ln a}{2}}}$

(e) $\ln y = a\sqrt{x} + b$

$\underline{\underline{\text{Plot } \ln y \text{ vs. } \sqrt{x} \text{ [rect.] or } y \text{ vs. } \sqrt{x} \text{ [semilog], slope = a, intercept = b}}}$

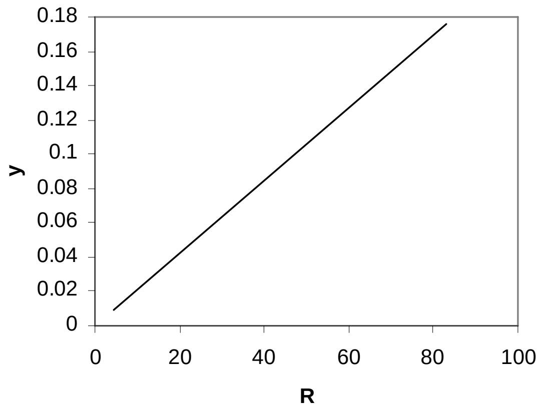
(f) $\log_{10}(xy) = a(x^2 + y^2) + b$

$\underline{\underline{\text{Plot } \log_{10}(xy) \text{ vs. } (x^2 + y^2) \text{ [rect.]} \Rightarrow \text{slope = a, intercept = b}}}$

(g) $\dfrac{1}{y} = ax + \dfrac{b}{x} \Rightarrow \dfrac{x}{y} = ax^2 + b \Rightarrow \underline{\underline{\text{Plot } \dfrac{x}{y} \text{ vs. } x^2 \text{ [rect.], slope} = a, \text{ intercept} = b}}$

OR $\dfrac{1}{y} = ax + \dfrac{b}{x} \Rightarrow \dfrac{1}{xy} = a + \dfrac{\text{b}}{x^2} \Rightarrow \underline{\underline{\text{Plot } \dfrac{1}{xy} \text{ vs. } \dfrac{1}{x^2} \text{ [rect.], slope} = b, \text{ intercept} = a}}$

2.32 **(a)** A plot of y vs. R is a line through ($R = 5$, $y = 0.011$) and ($R = 80$, $y = 0.169$).



$$y = aR + b \qquad \left.\begin{array}{l} a = \dfrac{0.169 - 0.011}{80 - 5} = 2.11 \times 10^{-3} \\ b = 0.011 - \left(2.11 \times 10^{-3}\right)(5) = 4.50 \times 10^{-4} \end{array}\right\} \Rightarrow \underline{\underline{y = 2.11 \times 10^{-3} R + 4.50 \times 10^{-4}}}$$

(b) $R = 43 \Rightarrow y = \left(2.11 \times 10^{-3}\right)(43) + 4.50 \times 10^{-4} = 0.092 \text{ kg } \mathrm{H_2O/kg}$

$$(1200 \text{ kg/h})(0.092 \text{ kg } \mathrm{H_2O/kg}) = \underline{\underline{110 \text{ kg } \mathrm{H_2O/h}}}$$

2.33 (a) $\ln T = \ln a + b \ln\phi \Rightarrow T = a\phi^b$

$$b = (\ln T_2 - \ln T_1) / (\ln\phi_2 - \ln\phi_1) = (\ln 120 - \ln 210) / (\ln 40 - \ln 25) = -1.19$$

$$\ln a = \ln T - b\ln\phi = \ln 210 - (-1.19)\ln(25) \Rightarrow a = 9677.6 \Rightarrow \underline{\underline{T = 9677.6\phi^{-1.19}}}$$

(b) $T = 9677.6\phi^{-1.19} \Rightarrow \phi = \left(9677.6 / T\right)^{0.8403}$

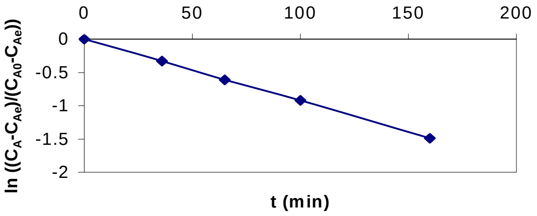
$T = 85^{\circ} C \Rightarrow \phi = \left(9677.6 / 85\right)^{0.8403} = \underline{\underline{53.5 \text{ L / s}}}$

$T = 175^{\circ} C \Rightarrow \phi = \left(9677.6 / 175\right)^{0.8403} = \underline{\underline{29.1 \text{ L / s}}}$

$T = 290^{\circ} C \Rightarrow \phi = \left(9677.6 / 290\right)^{0.8403} = \underline{\underline{19.0 \text{ L / s}}}$

(c) The estimate for *T*=175°C is probably closest to the real value, because the value of temperature is in the range of the data originally taken to fit the line. The value of *T*=290°C is probably the least likely to be correct, because it is farthest away from the date range.

2.34 (a) Yes, because when $\ln[(C_A - C_{Ae})/(C_{A0} - C_{Ae})]$ is plotted vs. *t* in rectangular coordinates, the plot is a straight line.



$$\text{Slope} = \text{-}0.0093 \Rightarrow \underline{\underline{k = 9.3\times 10^{-3}\ \text{min}^{-1}}}$$

(b) $\ln[(\boldsymbol{C_A} - \boldsymbol{C_{Ae}})/(\boldsymbol{C_{A0}} - \boldsymbol{C_{Ae}})] = -\boldsymbol{kt} \Rightarrow \boldsymbol{C_A} = (\boldsymbol{C_{A0}} - \boldsymbol{C_{Ae}})\boldsymbol{e}^{-\boldsymbol{kt}} + \boldsymbol{C_{Ae}}$

$$\boldsymbol{C_A} = (0.1823 - 0.0495)\boldsymbol{e}^{-(9.3\times 10^{-3})(120)} + 0.0495 = 9.300\times 10^{-2}\ \text{g/L}$$

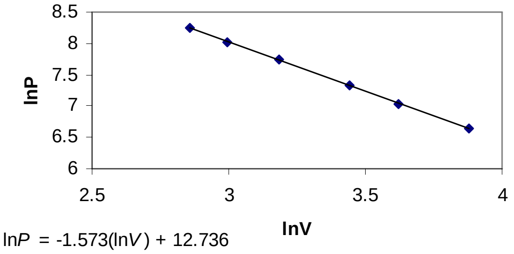
$$\boldsymbol{C}=\boldsymbol{m}/\boldsymbol{V} \Rightarrow \boldsymbol{m}=\boldsymbol{CV} = \frac{9.300\times 10^{-2}\ \text{g}}{\text{L}}\left|\frac{30.5\ \text{gal}}{}\right|\frac{28.317\ \text{L}}{7.4805\ \text{gal}} = \underline{\underline{10.7\ \text{g}}}$$

2.35 (a) ft^3 and h^{-2}, respectively

(b) $\ln(V)$ vs. t^2 in rectangular coordinates, slope=2 and intercept= $\ln(3.53\times 10^{-2})$; or V(logarithmic axis) vs. t^2 in semilog coordinates, slope=2, intercept= 3.53×10^{-2}

(c) $\underline{\underline{V(\text{m}^3) = 1.00\times 10^{-3}\exp(1.5\times 10^{-7}\,\text{t}^2)}}$

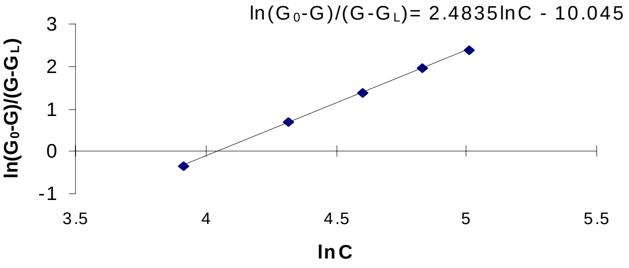
2.36 $PV^k = C \Rightarrow P = C/V^k \Rightarrow \ln P = \ln C - k\ln V$



$$k = -\text{slope} = -(-1.573) = \underline{\underline{1.573}}\ \text{(dimensionless)}$$

$$\text{Intercept} = \ln C = 12.736 \Rightarrow C = e^{12.736} = \underline{\underline{3.40\times 10^5\ \text{mm Hg}\cdot\text{cm}^{4.719}}}$$

2.37 (a) $\dfrac{G - G_L}{G_0 - G} = \dfrac{1}{K_L C^m} \Rightarrow \dfrac{G_0 - G}{G - G_L} = K_L C^m \Rightarrow \ln\dfrac{G_0 - G}{G - G_L} = \ln K_L + m\ln C$



2.37 (cont'd)

$$m = \text{slope} = \underline{\underline{2.483}}\ \text{(dimensionless)}$$

$$\text{Intercept} = \ln K_L = -10.045 \Rightarrow K_L = \underline{\underline{4.340\times10^{-5}\ \text{ppm}^{-2.483}}}$$

(b) $C = 475 \Rightarrow \dfrac{G - 1.80\times10^{-3}}{3.00\times10^{-3} - G} = 4.340\times10^{-5}(475)^{2.483} \Rightarrow G = \underline{\underline{1.806\times10^{-3}}}$

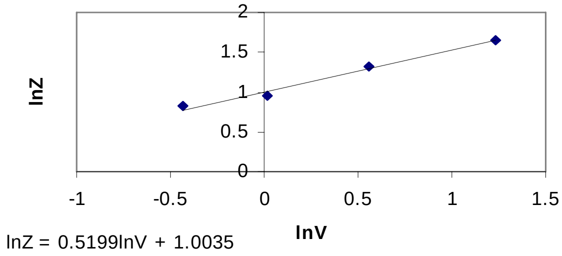
C=475 ppm is well beyond the range of the data.

2.38 (a) For runs 2, 3 and 4:

$$Z = a\dot{V}^b p^c \Rightarrow \ln Z = \ln a + b\ln\dot{V} + c\ln p$$

$$\left.\begin{array}{l}\ln(3.5) = \ln a + b\ln(1.02) + c\ln(9.1)\\ \ln(2.58) = \ln a + b\ln(1.02) + c\ln(11.2)\\ \ln(3.72) = \ln a + b\ln(1.75) + c\ln(11.2)\end{array}\right\} \Rightarrow \begin{array}{l} b = \underline{\underline{0.68}}\\ c = \underline{\underline{-1.46}}\\ \text{a} = \underline{\underline{86.7\ \text{volts}\cdot\text{kPa}^{1.46}/(\text{L/s})^{0.678}}}\end{array}$$

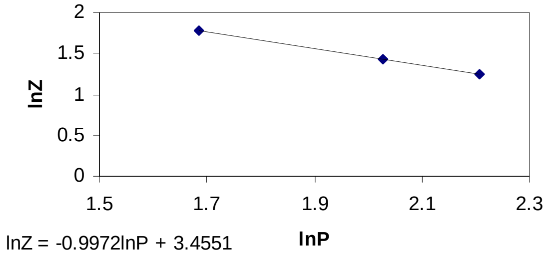
(b) When P is constant (runs 1 to 4), plot $\ln Z$ vs. $\ln\dot{\text{V}}$. Slope=b, Intercept= $\ln a + c\ln p$



$$b = \text{slope} = \underline{\underline{0.52}}$$

$$\text{Intercept} = \ln a + c\ln P = 1.0035$$

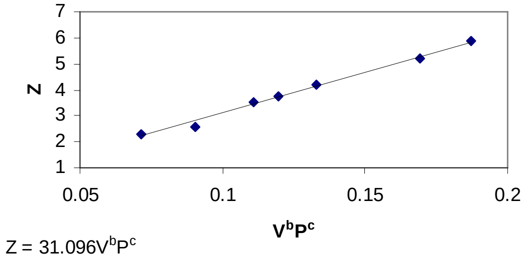
When $\dot{V}$ is constant (runs 5 to 7), plot ln*Z* vs. ln*P*. Slope=c, Intercept= $\ln a + c\ln\dot{V}$



$$c = slope = -0.997 \Rightarrow \underline{\underline{1.0}}$$

$$\text{Intercept} = \ln a + b\ln\dot{V} = 3.4551$$

Plot Z vs $\dot{V}^b P^c$. Slope=a (no intercept)



$$a = slope = \underline{\underline{31.1\ \text{volt}\cdot\text{kPa}/(\text{L/s})^{.52}}}$$

The results in part (b) are more reliable, because more data were used to obtain them.

2.39 (a)

$$s_{xy}=\frac{1}{n}\sum_{i=1}^{n}x_i y_i=[(0.4)(0.3)+(2.1)(1.9)+(3.1)(3.2)]/3=4.677$$

$$s_{xx}=\frac{1}{n}\sum_{i=1}^{n}x_i^2=(0.3^2+1.9^2+3.2^2)/3=4.647$$

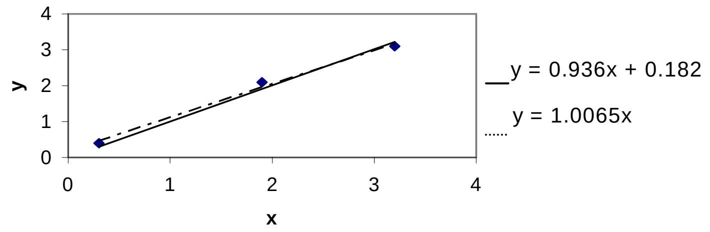
$$s_x=\frac{1}{n}\sum_{i=1}^{n}x_i=(0.3+1.9+3.2)/3=1.8;\quad s_y=\frac{1}{n}\sum_{i=1}^{n}y_i=(0.4+2.1+3.1)/3=1.867$$

$$a=\frac{s_{xy}-s_x s_y}{s_{xx}-(s_x)^2}=\frac{4.677-(1.8)(1.867)}{4.647-(1.8)^2}=0.936$$

$$b=\frac{s_{xx}s_y-s_{xy}s_x}{s_{xx}-(s_x)^2}=\frac{(4.647)(1.867)-(4.677)(1.8)}{4.647-(1.8)^2}=0.182$$

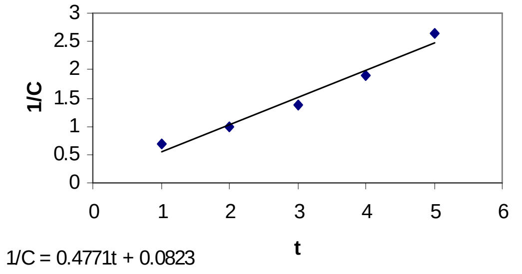
$$\underline{\underline{y=0.936x+0.182}}$$

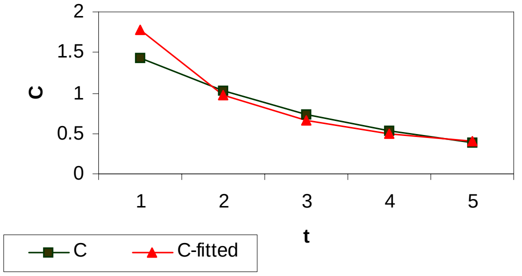
(b) $a=\frac{s_{xy}}{s_{xx}}=\frac{4.677}{4.647}=1.0065\Rightarrow \underline{\underline{y=1.0065x}}$



2.40 (a) 1/C vs. t. Slope= b, intercept=a

(b) $b=\text{slope}=\underline{\underline{0.477\ \text{L/g}\cdot\text{h}}};\qquad a=\text{Intercept}=\underline{\underline{0.082\ \text{L/g}}}$





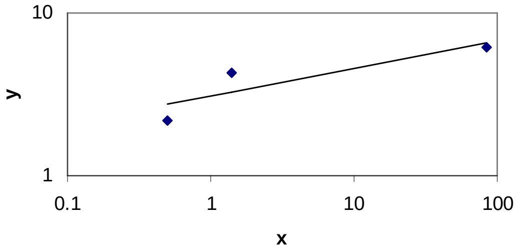
(c) $C=1/(a+bt)\Rightarrow 1/[0.082+0.477(0)]=\underline{\underline{12.2\ \text{g/L}}}$

$$t=(1/C-a)/b=(1/0.01-0.082)/0.477=\underline{\underline{209.5\ \text{h}}}$$

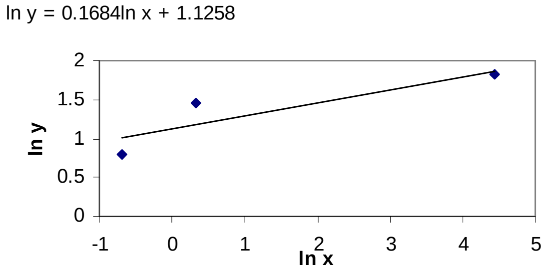
(d) t=0 and C=0.01 are out of the range of the experimental data.

(e) The concentration of the hazardous substance could be enough to cause damage to the biotic resources in the river; the treatment requires an extremely large period of time; some of the hazardous substances might remain in the tank instead of being converted; the decomposition products might not be harmless.

2.41 (a) and (c)



(b) $y = ax^b \Rightarrow \ln y = \ln a + b \ln x$; Slope = b, Intercept = ln a

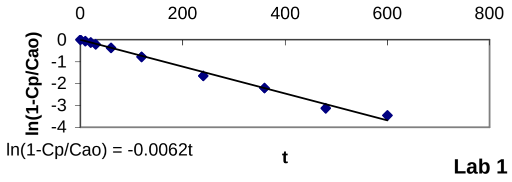


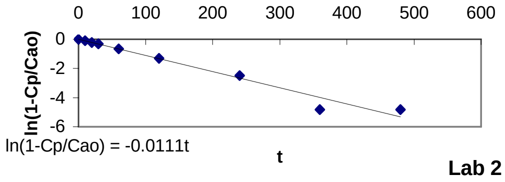
$b = \text{slope} = \underline{\underline{0.168}}$

$\text{Intercept} = \ln a = 1.1258 \Rightarrow a = \underline{\underline{3.08}}$

2.42 (a) ln(1-C_p/C_{A0}) vs. t in rectangular coordinates. Slope=-k, intercept=0

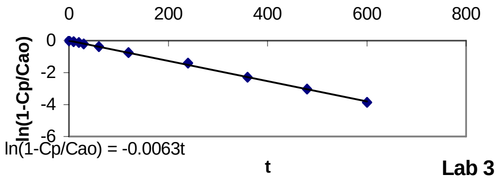
(b)

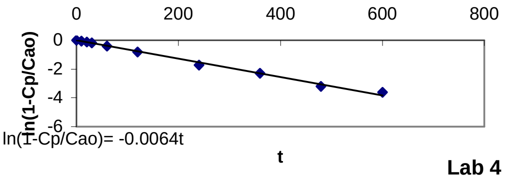




$k = \underline{\underline{0.0062 \text{ s}^{-1}}}$

$k = \underline{\underline{0.0111 \text{ s}^{-1}}}$





$k = \underline{\underline{0.0063 \text{ s}^{-1}}}$

$k = \underline{\underline{0.0064 \text{ s}^{-1}}}$

(c) Disregarding the value of k that is very different from the other three, k is estimated with the average of the calculated k's. $k = \underline{\underline{0.0063 \text{ s}^{-1}}}$

(d) Errors in measurement of concentration, poor temperature control, errors in time measurements, delays in taking the samples, impure reactants, impurities acting as catalysts, inadequate mixing, poor sample handling, clerical errors in the reports, dirty reactor.

2.43 $y_i = ax_i \Rightarrow \phi(a) = \sum_{i=1}^{n} d_i^2 = \sum_{i=1}^{n} \left(y_i - ax_i\right)^2 \Rightarrow \frac{d\phi}{da} = 0 = \sum_{i=1}^{n} 2\left(y_i - ax_i\right)x_i \Rightarrow \sum_{i=1}^{n} y_i x_i - a\sum_{i=1}^{n} x_i^2 = 0$

$$\Rightarrow \underline{\underline{a = \sum_{i=1}^{n} y_i x_i \Big/ \sum_{i=1}^{n} x_i^2}}$$

2.44

```
          DIMENSION X(100), Y(100)
          READ (5, 1) N
C         N = NUMBER OF DATA POINTS
         1FORMAT (I10)
          READ (5, 2) (X(J), Y(J), J = 1, N
         2FORMAT (8F 10.2)
          SX = 0.0
          SY = 0.0
          SXX = 0.0
          SXY = 0.0
          DO 100J = 1, N
          SX = SX + X(J)
          SY = SY + Y(J)
          SXX = SXX + X(J) ** 2
       100SXY = SXY + X(J) * Y(J)
          AN = N
          SX = SX/AN
          SY = SY/AN
          SXX = SXX/AN
          SXY = SXY/AN
          CALCULATE SLOPE AND INTERCEPT
          A = (SXY - SX * SY)/(SXX - SX ** 2)
          B = SY - A * SX
          WRITE (6, 3)
         3FORMAT (1H1, 20X 'PROBLEM 2-39'/)
          WRITE (6, 4) A, B
         4FORMAT (1H0, 'SLOPEb -- bAb =', F6.3, 3X 'INTERCEPTb -- b8b =', F7.3/)
C         CALCULATE FITTED VALUES OF Y, AND SUM OF SQUARES OF
                RESIDUALS
          SSQ = 0.0
          DO 200J = 1, N
          YC = A * X(J) + B
          RES = Y(J) - YC
          WRITE (6, 5) X(J), Y(J), YC, RES
         5FORMAT (3X 'Xb =', F5.2, 5X /Yb =', F7.2, 5X 'Y(FITTED)b =', F7.2, 5X
         *    'RESIDUALb =', F6.3)
       200SSQ = SSQ + RES ** 2
          WRITE (6, 6) SSQ
         6FORMAT (IH0, 'SUM OF SQUARES OF RESIDUALSb =', E10.3)
          STOP
          END
      $DATA
            5
      1.0   2.35    1.5     5.53    2.0     8.92    2.5     12.15
      3.0   15.38
```

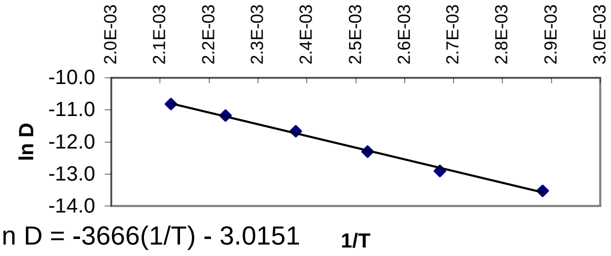
SOLUTION: $\underline{\underline{a = 6.536, b = -4.206}}$

2.45 (a) E(cal/mol), D_0 (cm^2/s)

(b) ln D vs. 1/T, Slope=-E/R, intercept=ln D_0.

(c) $\text{Intercept} = \ln D_0 = \text{-3.0151} \Rightarrow D_0 = \underline{\underline{0.05\ \text{cm}^2\ /\ \text{s}}}$.

$\text{Slope} = -E\ /\ R = \text{-3666 K} \Rightarrow E = (3666\ \text{K})(1.987\ \text{cal / mol} \cdot \text{K}) = \underline{\underline{7284\ \text{cal / mol}}}$



(d) Spreadsheet

T	D	1/T	lnD	(1/T)*(lnD)	(1/T)**2
347	1.34E-06	2.88E-03	-13.5	-0.03897	8.31E-06
374.2	2.50E-06	2.67E-03	-12.9	-0.03447	7.14E-06
396.2	4.55E-06	2.52E-03	-12.3	-0.03105	6.37E-06
420.7	8.52E-06	2.38E-03	-11.7	-0.02775	5.65E-06
447.7	1.41E-05	2.23E-03	-11.2	-0.02495	4.99E-06
471.2	2.00E-05	2.12E-03	-10.8	-0.02296	4.50E-06

Sx	2.47E-03
Sy	-12.1
Syx	-3.00E-02
Sxx	6.16E-06
-E/R	-3666
ln D_0	-3.0151
D_0	7284
E	0.05

CHAPTER THREE

3.1 **(a)** $$m=\begin{array}{c|c} 16\times 6\times 2\ \text{m}^3 & 1000\ \text{kg} \\ \hline & \text{m}^3 \end{array}\approx(2\times10)(5)(2)\left(10^3\right)\approx\underline{\underline{2\times10^5\ \text{kg}}}$$

(b) $$\dot{m}=\begin{array}{c|c|c|c} 8\ \text{oz} & 1\ \text{qt} & 10^6\ \text{cm}^3 & 1\ \text{g} \\ \hline 2\ \text{s} & 32\ \text{oz} & 1056.68\ \text{qt} & \text{cm}^3 \end{array}\approx\frac{4\times10^6}{(3\times10)\left(10^3\right)}\approx\underline{\underline{1\times10^2\ \text{g}/\text{s}}}$$

(c) Weight of a boxer $\approx$ 220 lb_m

$$W_{\max}\geq\begin{array}{c|c} 12\times220\ \text{lb}_\text{m} & 1\ \text{stone} \\ \hline & 14\ \text{lb}_\text{m} \end{array}\approx\underline{\underline{220\ \text{stones}}}$$

(d)

$$V=\frac{\pi D^2 L}{4}=\begin{array}{c|c|c|c|c|c} \frac{3.14}{4} & 4.5^2\ \text{ft}^2 & 800\ \text{miles} & 5880\ \text{ft} & 7.4805\ \text{gal} & 1\ \text{barrel} \\ \hline & & & 1\ \text{mile} & 1\ \text{ft}^3 & 42\ \text{gal} \end{array}\ \longleftarrow\ \text{dictionary}$$

$$\approx\frac{3\times4\times5\times\left(8\times10^2\right)\times\left(5\times10^3\right)\times7}{4\times4\times10}\approx\underline{\underline{1\times10^7\ \text{barrels}}}$$

(e) $$(i)V\approx\begin{array}{c|c} 6\ \text{ft}\times1\ \text{ft}\times0.5\ \text{ft} & 28{,}317\ \text{cm}^3 \\ \hline & 1\ \text{ft}^3 \end{array}\approx3\times3\times10^4\approx\underline{\underline{1\times10^5\text{cm}^3}}$$

$$(ii)V\approx\begin{array}{c|c|c} 150\ \text{lb}_\text{m} & 1\ \text{ft}^3 & 28{,}317\ \text{cm}^3 \\ \hline & 62.4\ \text{lb}_\text{m} & 1\ \text{ft}^3 \end{array}\approx\frac{150\times3\times10^4}{60}\approx\underline{\underline{1\times10^5\ \text{cm}^3}}$$

(f) $\underline{\underline{SG\approx1.05}}$

3.2 **(a)** $$\text{(i)}\ \begin{array}{c|c|c} 995\ \text{kg} & 1\ \text{lb}_\text{m} & 0.028317\ \text{m}^3 \\ \hline \text{m}^3 & 0.45359\ \text{kg} & 1\ \text{ft}^3 \end{array}=\underline{\underline{62.12\ \text{lb}_\text{m}/\text{ft}^3}}$$

$$\text{(ii)}\ \begin{array}{c|c} 995\ \text{kg}/\text{m}^3 & 62.43\ \text{lb}_\text{m}/\text{ft}^3 \\ \hline & 1000\ \text{kg}/\text{m}^3 \end{array}=\underline{\underline{62.12\ \text{lb}_\text{m}/\text{ft}^3}}$$

(b) $\rho=\rho_{H_2O}\times SG=62.43\ \text{lb}_\text{m}/\text{ft}^3\times5.7=\underline{\underline{360\ \text{lb}_\text{m}/\text{ft}^3}}$

3.3 **(a)** $$\begin{array}{c|c|c} 50\ \text{L} & 0.70\times10^3\ \text{kg} & 1\ \text{m}^3 \\ \hline & \text{m}^3 & 10^3\ \text{L} \end{array}=\underline{\underline{35\ \text{kg}}}$$

(b) $$\begin{array}{c|c|c|c} 1150\ \text{kg} & \text{m}^3 & 1000\ \text{L} & 1\ \text{min} \\ \hline \text{min} & 0.7\times1000\ \text{kg} & 1\ \text{m}^3 & 60\ \text{s} \end{array}=\underline{\underline{27\ \text{L/s}}}$$

(c) $$\begin{array}{c|c|c} 10\ \text{gal} & 1\ \text{ft}^3 & 0.70\times62.43\ \text{lb}_\text{m} \\ \hline 2\ \text{min} & 7.481\ \text{gal} & 1\ \text{ft}^3 \end{array}\cong\underline{\underline{29\ \text{lb}_\text{m}/\text{min}}}$$

3.3 (cont'd)

(d) Assuming that 1 cm^3 kerosene was mixed with V_g (cm^3) gasoline

$$V_g\left(\text{cm}^3\text{gasoline}\right) \Rightarrow 0.70V_g\left(\text{g gasoline}\right)$$

$$1\left(\text{cm}^3\ \text{kerosene}\right) \Rightarrow 0.82\left(\text{g kerosene}\right)$$

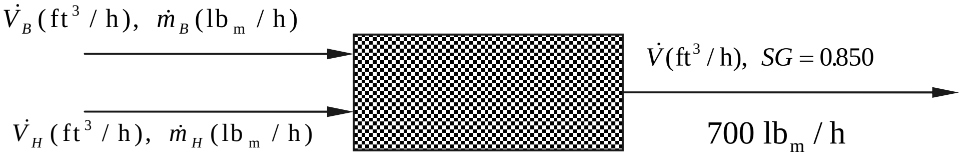
$$SG = \frac{\left(0.70V_g + 0.82\right)\left(\text{g blend}\right)}{V_g + 1\left(\text{cm}^3\ \text{blend}\right)} = 0.78 \ \Rightarrow\ V_g = \frac{0.82 - 0.78}{0.78 - 0.70} = 0.50\ \text{cm}^3$$

$$\underline{\text{Volumetric ratio}} = \frac{V_{\text{gasoline}}}{V_{\text{kerosene}}} = \frac{0.50\ \text{cm}^3}{1\ \text{cm}^3} = \underline{\underline{0.50\ \text{cm}^3\ \text{gasoline / cm}^3\ \text{kerosene}}}$$

3.4 In France: $$\begin{array}{c|c|c|c} 50.0\ \text{kg} & \text{L} & 5\ \text{Fr} & \$1 \\ \hline & 0.7 \times 1.0\ \text{kg} & 1\text{L} & 5.22\ \text{Fr} \end{array} = \underline{\underline{\$68.42}}$$

In U.S.: $$\begin{array}{c|c|c|c} 50.0\ \text{kg} & \text{L} & 1\ \text{gal} & \$1.20 \\ \hline & 0.70 \times 1.0\ \text{kg} & 3.7854\ \text{L} & 1\ \text{gal} \end{array} = \underline{\underline{\$22.64}}$$

3.5



(a) $$\dot{V} = \begin{array}{c|c} 700\ \text{lb}_\text{m} & \text{ft}^3 \\ \hline \text{h} & 0.850 \times 62.43\ \text{lb}_\text{m} \end{array} = 13.19\ \text{ft}^3/\text{h}$$

$$\dot{m}_B = \begin{array}{c|c} \dot{V}_B\left(\text{ft}^3\right) & 0.879 \times 62.43\ \text{lb}_\text{m} \\ \hline (\text{h}) & \text{ft}^3 \end{array} = 54.88\dot{\text{V}}_\text{B}\ \left(\text{kg/h}\right)$$

$$\dot{m}_H = \left(\dot{V}_H\right)\left(0.659 \times 62.43\right) = 41.14\dot{V}_H\ \left(\text{kg/h}\right)$$

$$\dot{V}_B + \dot{V}_H = 13.19\ \text{ft}^3/\text{h}$$

$$\dot{m}_B + \dot{m}_H = 54.88\dot{V}_B + 41.14\dot{V}_H = 700\ \text{lb}_\text{m}$$

$$\Rightarrow\quad \dot{V}_B = \underline{\underline{11.4\ \text{ft}^3/\text{h}}} \Rightarrow \dot{m}_B = \underline{\underline{628\ \text{lb}_\text{m}/\text{h benzene}}}$$

$$\dot{V}_H = \underline{\underline{1.74\ \text{ft}^3/\text{h}}} \Rightarrow \dot{m}_H = \underline{\underline{71.6\ \text{lb}_\text{m}/\text{h hexane}}}$$

(b) – No buildup of mass in unit.
– ρ_B and ρ_H at inlet stream conditions are equal to their tabulated values (which are strictly valid at 20°C and 1 atm.)
– Volumes of benzene and hexane are additive.
– Densitometer gives correct reading.

3.6 **(a)** $$V = \begin{array}{c|c|c} 195.5\text{ kg H}_2\text{SO}_4 & 1\text{ kg solution} & \text{L} \\ \hline & 0.35\text{kg H}_2\text{SO}_4 & 1.2563\times 1.000\text{ kg} \end{array} = \underline{\underline{445\text{ L}}}$$

(b)

$$V_{\text{ideal}} = \begin{array}{c|c} 195.5\text{ kg H}_2\text{SO}_4 & \text{L} \\ \hline & 1.8255\times 1.00\text{ kg} \end{array}$$

$$+ \begin{array}{c|c|c} 195.5\text{ kg H}_2\text{SO}_4 & 0.65\text{ kg H}_2\text{O} & \text{L} \\ \hline & 0.35\text{ kg H}_2\text{SO}_4 & 1.000\text{ kg} \end{array} = 470\text{ L}$$

$$\underline{\%\text{ error}} = \frac{470-445}{445}\times 100\% = \underline{\underline{5.6\%}}$$

3.7 Buoyant force $(\text{up}) = \text{Weight of block }(\text{down})$

$$\Downarrow$$

Mass of oil displaced + Mass of water displaced = Mass of block

$$\rho_{\text{oil}}\,(0.542)V + \rho_{\text{H}_2\text{O}}\,(1-0.542)V = \rho_{\text{c}}\,V$$

From Table B.1: $\rho_c = 2.26\text{ g/cm}^3$, $\rho_w = 1.00\text{ g/cm}^3 \;\Rightarrow\; \rho_{oil} = 3.325\text{ g/cm}^3$

$$m_{\text{oil}} = \rho_{\text{oil}}\times V = 3.325\text{ g/cm}^3\times 35.3\text{ cm}^3 = 117.4\text{ g}$$

$$m_{\text{oil + flask}} = 117.4\text{ g} + 124.8\text{ g} = \underline{\underline{242\text{ g}}}$$

3.8 Buoyant force $(\text{up}) = \text{Weight of block }(\text{down})$

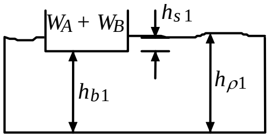
$$\Rightarrow W_{\text{displaced liquid}} = W_{\text{block}} \Rightarrow (\rho V g)_{\text{disp. Liq}} = (\rho V g)_{\text{block}}$$

Expt. 1: $\rho_w(1.5A)g = \rho_B(2A)g \Rightarrow \rho_B = \rho_w\times\dfrac{1.5}{2}$

$$\xrightarrow{\rho_w=1.00\text{ g/cm}^3} \rho_B = 0.75\text{ g/cm}^3 \Rightarrow \underline{\underline{(SG)_B = 0.75}}$$

Expt. 2: $\rho_{\text{soln}}(A)g = \rho_B(2A)g \Rightarrow \rho_{\text{soln}} = 2\rho_B = 1.5\text{ g/cm}^3 \Rightarrow \underline{\underline{(SG)_{\text{soln}} = 1.5}}$

3.9



Before object is jettisoned

Let $\rho_w =$ density of water. Note: $\underline{\rho_A > \rho_w}$ (object sinks)

Volume displaced: $V_{d1} = A_b h_{si} = A_b\left(h_{p1} - h_{b1}\right)$ (1)

Archimedes $\Rightarrow$ $\underbrace{\rho_w V_{d1} g}_{\text{weight of displaced water}} = W_A + W_B$

Subst. (1) for V_{d1}, solve for $\left(h_{p1} - h_{b1}\right)$

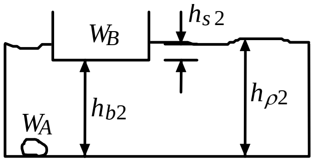
$$h_{p1} - h_{b1} = \frac{W_A + W_B}{p_w g A_b} \qquad (2)$$

Volume of pond water: $V_w = A_p h_{p1} - V_{d1} \overset{(i)}{\Rightarrow} V_w = A_p h_{p1} - A_b\left(h_{p1} - h_{b1}\right)$

$$\xrightarrow[\text{for } b_{p1}-h_{b1}]{\text{subst. (2)}} V_w = A_p h_{p1} - \frac{W_A + W_B}{p_w g} \Rightarrow h_{p1} = \frac{V_w}{A_p} + \frac{W_A + W_B}{p_w g A_p} \qquad (3)$$

$$\xrightarrow[\text{(2), solve for } h_{b1}]{\text{subst. (3)for } h_{p1}\text{ in}} h_{b1} = \frac{V_w}{A_p} + \frac{\left(W_A + W_B\right)}{p_w g}\left[\frac{1}{A_p} - \frac{1}{A_b}\right] \qquad (4)$$

3.9 (cont'd)



After object is jettisoned

Let $V_A =$ volume of jettisoned object $= \dfrac{W_A}{\rho_A g}$ (5)

<u>Volume displaced by boat</u>: $V_{d2} = A_b\left(h_{p2} - h_{b2}\right)$ (6)

<u>Archimedes</u> $\Rightarrow \rho_W V_{d2} g \underset{\Downarrow}{=} W_B$

Subst. for V_{d2}, solve for $\left(h_{p2} - h_{b2}\right)$

$$h_{p2} - h_{b2} = \frac{W_B}{p_w g A_b} \qquad (7)$$

<u>Volume of pond water</u>: $V_w = A_p h_{p2} - V_{d2} - V_A \xRightarrow{(5),\,(6)\,\&\,(7)} V_w = A_p h_{p2} - \dfrac{W_B}{p_w g} - \dfrac{W_A}{p_A g}$

$$\underset{h_{p2}}{\overset{\text{solve for}}{\Rightarrow}} h_{p2} = \frac{V_w}{A_p} + \frac{W_B}{p_w g A_p} + \frac{W_A}{p_A g A_p} \qquad (8)$$

$$\underset{\text{for } h_{p2} \text{ in } (7)\text{, solve for } h_{b2}}{\overset{\text{subst. } (8)}{\Rightarrow}} h_{b2} = \frac{V_w}{A_p} + \frac{W_B}{p_w g A_p} + \frac{W_A}{p_A g A_p} - \frac{W_B}{p_w g A_b} \qquad (9)$$

(a) <u>Change in pond level</u>

$$h_{p2} - h_{p1} \overset{(8)-(3)}{=} \frac{W_A}{A_p g}\left[\frac{1}{p_A} - \frac{1}{p_W}\right] = \frac{W_A\left(p_W - p_A\right)}{p_A p_W g A_p} \xrightarrow{\rho_W < \rho_A} < 0$$

$\Rightarrow$ <u>the pond level falls</u>

(b) <u>Change in boat level</u>

$$h_{p2} - h_{p1} \overset{(9)-(4)}{=} \frac{W_A}{A_p g}\left[\frac{1}{p_A A_p} - \frac{1}{p_W A_p} + \frac{1}{p_W A_b}\right] \overset{(5)}{=} \overbrace{\left(\frac{V_A}{A_p}\right)}^{>0}\left[1 + \overbrace{\left(\frac{p_A}{p_W}\left(\frac{A_p}{A_b} - 1\right)\right)}^{>0}\right] > 0$$

$\Rightarrow$ <u>the boat rises</u>

3.10 (a) $\rho_{\text{bulk}} = \dfrac{2.93 \text{ kg CaCO}_3}{\text{L CaCO}_3} \left| \dfrac{0.70 \text{ L CaCO}_3}{\text{L total}} \right. = \underline{\underline{2.05 \text{ kg / L}}}$

(b) $W_{bag} = \rho_{bulk} V g = \dfrac{2.05 \text{ kg}}{\text{L}} \left| \dfrac{50 \text{ L}}{} \right| \dfrac{9.807 \text{ m / s}^2}{} \left| \dfrac{1 \text{ N}}{1 \text{ kg} \cdot \text{m / s}^2} \right. = \underline{\underline{1.00 \times 10^3 \text{ N}}}$

<u>Neglected the weight of the bag itself and of the air in the filled bag.</u>

(c) The limestone would fall short of filling three bags, because
– the powder would pack tighter than the original particles.
– you could never recover 100% of what you fed to the mill.

3.11 **(a)** $$W_b = m_b g = \frac{122.5 \text{ kg}}{} \left| \frac{9.807 \text{ m/s}^2}{} \right| \frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2} = \underline{\underline{1202 \text{ N}}}$$

$$V_b = \frac{W_b - W_I}{\rho_w g} = \frac{(1202 \text{ N - } 44.0 \text{ N})}{0.996 \text{ kg/L} \times 9.807 \text{ m/s}^2} \left| \frac{1 \text{ kg}\cdot\text{m/s}^2}{1 \text{ N}} \right. = \underline{\underline{119 \text{ L}}}$$

$$\rho_b = \frac{m_b}{V_b} = \frac{122.5 \text{ kg}}{119 \text{ L}} = \underline{\underline{1.03 \text{ kg/L}}}$$

(b)
$$m_f + m_{nf} = m_b \qquad (1)$$

$$x_f = \frac{m_f}{m_b} \Rightarrow m_f = m_b x_f \qquad (2)$$

$$(1),(2) \Rightarrow m_{nf} = m_b(1 - x_f) \qquad (3)$$

$$V_f + V_{nf} = V_b \Rightarrow \frac{m_f}{\rho_f} + \frac{m_{nf}}{\rho_{nf}} = \frac{m_b}{\rho_b}$$

$$\overset{(2),(3)}{\Rightarrow} m_b\left(\frac{x_f}{\rho_f} + \frac{1 - x_f}{\rho_{nf}}\right) = \frac{m_b}{\rho_b} \Rightarrow x_f\left(\frac{1}{\rho_f} - \frac{1}{\rho_{nf}}\right) = \frac{1}{\rho_b} - \frac{1}{\rho_{nf}} \quad \Rightarrow x_f = \underline{\underline{\frac{1/\rho_b - 1/\rho_{nf}}{1/\rho_f - 1/\rho_{nf}}}}$$

(c) $$x_f = \frac{1/\rho_b - 1/\rho_{nf}}{1/\rho_f - 1/\rho_{nf}} = \frac{1/1.03 - 1/1.1}{1/0.9 - 1/1.1} = \underline{\underline{0.31}}$$

(d) $$V_f + V_{nf} + V_{lungs} + V_{other} = V_b$$

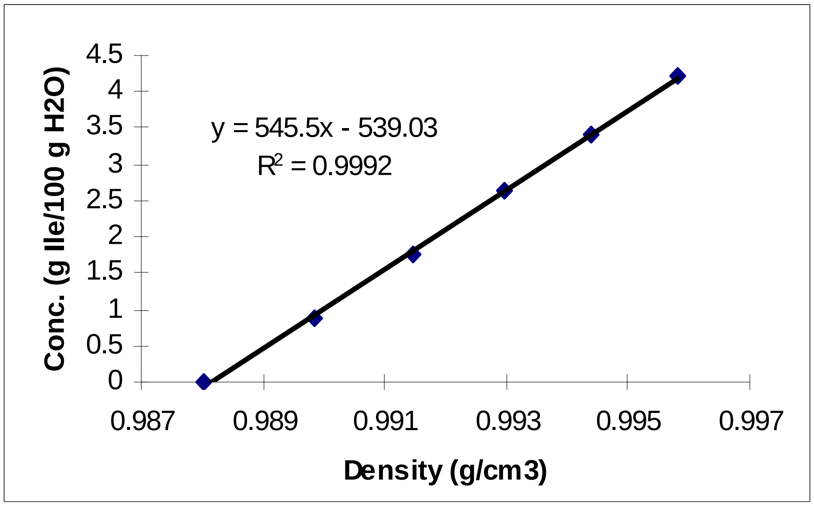
$$\frac{m_f}{\rho_f} + \frac{m_{nf}}{\rho_{nf}} + V_{lungs} + V_{other} = \frac{m_b}{\rho_b}$$

$$\xrightarrow[m_{nf} = m_b(1 - x_f)]{m_f = m_b x_f} m_b\left(\frac{x_f}{\rho_f} - \frac{1 - x_f}{\rho_{nf}}\right) + (V_{lungs} + V_{other}) = m_b\left(\frac{1}{\rho_b} - \frac{1}{\rho_{nf}}\right)$$

$$\Rightarrow x_f\left(\frac{1}{\rho_f} - \frac{1}{\rho_{nf}}\right) = \frac{1}{\rho_b} - \frac{1}{\rho_{nf}} - \frac{V_{lungs} + V_{other}}{m_b}$$

$$\Rightarrow x_f = \frac{\left(\frac{1}{\rho_b} - \frac{1}{\rho_{nf}}\right) - \left(\frac{V_{lungs} + V_{other}}{m_b}\right)}{\left(\frac{1}{\rho_f} - \frac{1}{\rho_{nf}}\right)} = \frac{\left(\frac{1}{1.03} - \frac{1}{1.1}\right) - \left(\frac{1.2 + 0.1}{122.5}\right)}{\left(\frac{1}{0.9} - \frac{1}{1.1}\right)} = \underline{\underline{0.25}}$$

3.12 (a)



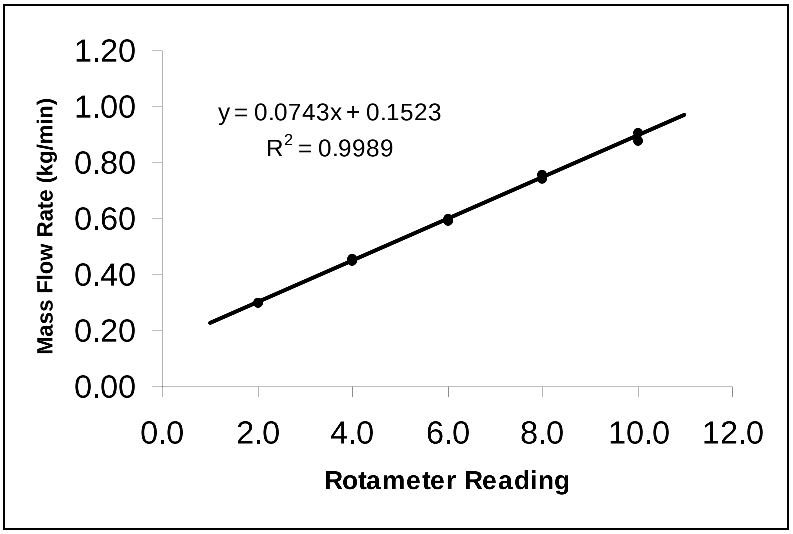
From the plot above, $r = 545.5\rho - 539.03$

(b) For $\rho = 0.9940\ \text{g}/\text{cm}^3$, $r = 3.197\ \text{g Ile}/100\text{g H}_2\text{O}$

$$\dot{m}_{Ile} = \begin{array}{r|r|r|r|r} 150\ \text{L} & 0.994\ \text{g} & 1000\ \text{cm}^3 & 3.197\ \text{g Ile} & 1\ \text{kg} \\ \hline \text{h} & \text{cm}^3 & \text{L} & 103.197\ \text{g sol} & 1000\ \text{g} \end{array} = \underline{\underline{4.6\ \text{kg Ile}/\text{h}}}$$

(c) The measured solution density is 0.9940 g ILE/cm^3 solution *at 50^{o}C*. For the calculation of Part (b) to be correct, the density would have to be changed to its equivalent at 47^{o}C. Presuming that the dependence of solution density on *T* is the same as that of pure water, the solution density at 47^{o}C would be higher than 0.9940 g ILE/cm^3. The ILE mass flow rate calculated in Part (b) is therefore $\underline{\underline{\text{too low}}}$.

3.13 (a)



3.13 (cont'd)

From the plot, $R = 5.3 \Rightarrow \dot{m} = 0.0743\,(5.3) + 0.1523 = \underline{\underline{0.55\ \text{kg / min}}}$

(b)

Rotameter Reading	Collection Time (min)	Collected Volume (cm3)	Mass Flow Rate (kg/min)	Difference Duplicate (D_i)	Mean D_i
2	1	297	0.297		0.0104
2	1	301	0.301	0.004	
4	1	454	0.454		
4	1	448	0.448	0.006	
6	0.5	300	0.600		
6	0.5	298	0.596	0.004	
8	0.5	371	0.742		
8	0.5	377	0.754	0.012	
10	0.5	440	0.880		
10	0.5	453	0.906	0.026	

$$\overline{D_i} = \frac{1}{5}\left(0.004 + 0.006 + 0.004 + 0.012 + 0.026\right) = \underline{\underline{0.0104\ \text{kg / min}}}$$

<u>95% confidence limits</u>: $(0.610 \pm 1.74\overline{D_i})$ kg / min $= \underline{\underline{0.610 \pm 0.018\ \text{kg / min}}}$

There is roughly a 95% probability that the true flow rate is between 0.592 kg / min and 0.628 kg / min.

3.14 **(a)** $\dfrac{15.0\ \text{kmol C}_6\text{H}_6 \mid 78.114\ \text{kg C}_6\text{H}_6}{\mid \text{kmol C}_6\text{H}_6} = \underline{\underline{1.17 \times 10^3\ \text{kg C}_6\text{H}_6}}$

(b) $\dfrac{15.0\ \text{kmol C}_6\text{H}_6 \mid 1000\ \text{mol}}{\mid \text{kmol}} = \underline{\underline{1.5 \times 10^4\ \text{mol C}_6\text{H}_6}}$

(c) $\dfrac{15{,}000\ \text{mol C}_6\text{H}_6 \mid \text{lb-mole}}{\mid 453.6\ \text{mol}} = \underline{\underline{33.07\ \text{lb-mole C}_6\text{H}_6}}$

(d) $\dfrac{15{,}000\ \text{mol C}_6\text{H}_6 \mid 6\ \text{mol C}}{\mid 1\ \text{mol C}_6\text{H}_6} = \underline{\underline{90{,}000\ \text{mol C}}}$

(e) $\dfrac{15{,}000\ \text{mol C}_6\text{H}_6 \mid 6\ \text{mol H}}{\mid 1\ \text{mol C}_6\text{H}_6} = \underline{\underline{90{,}000\ \text{mol H}}}$

(f) $\dfrac{90{,}000\ \text{mol C} \mid 12.011\ \text{g C}}{\mid \text{mol C}} = \underline{\underline{1.08 \times 10^6\ \text{g C}}}$

(g) $\dfrac{90{,}000\ \text{mol H} \mid 1.008\ \text{g H}}{\mid \text{mol H}} = \underline{\underline{9.07 \times 10^4\ \text{g H}}}$

(h) $\dfrac{15{,}000\ \text{mol C}_6\text{H}_6 \mid 6.022 \times 10^{23}}{\mid \text{mol}} = \underline{\underline{9.03 \times 10^{27}\ \text{molecules of C}_6\text{H}_6}}$

3.15 (a) $$\dot{m}=\begin{array}{c|c|c|c} 175\text{ m}^3 & 1000\text{ L} & 0.866\text{ kg} & 1\text{ h} \\ \hline \text{h} & \text{m}^3 & \text{L} & 60\text{ min}\end{array}=\underline{\underline{2526\text{ kg / min}}}$$

(b) $$\dot{n}=\begin{array}{c|c|c} 2526\text{ kg} & 1000\text{ mol} & 1\text{ min} \\ \hline \text{min} & 92.13\text{ kg} & 60\text{ s}\end{array}=\underline{\underline{457\text{ mol / s}}}$$

(c) Assumed density (SG) at T, P of stream is the same as the density at 20°C and 1 atm

3.16 (a) $$\begin{array}{c|c|c|c} 200.0\text{ kg mix} & 0.150\text{ kg CH}_3\text{OH} & \text{kmol CH}_3\text{OH} & 1000\text{ mol} \\ \hline & \text{kg mix} & 32.04\text{ kg CH}_3\text{OH} & 1\text{ kmol}\end{array}=\underline{\underline{936\text{ mol CH}_3\text{OH}}}$$

(b) $$\dot{m}_{mix}=\begin{array}{c|c|c} 100.0\text{ lb-mole MA} & 74.08\text{ lb}_\text{m}\text{ MA} & 1\text{ lb}_\text{m}\text{ mix} \\ \hline \text{h} & 1\text{ lb-mole MA} & 0.850\text{ lb}_\text{m}\text{ MA}\end{array}=\underline{\underline{8715\text{ lb}_\text{m}\text{ / h}}}$$

3.17 $$\overline{M}=\begin{array}{c|c} 0.25\text{ mol N}_2 & 28.02\text{ g N}_2 \\ \hline & \text{mol N}_2\end{array}+\begin{array}{c|c} 0.75\text{ mol H}_2 & 2.02\text{ g H}_2 \\ \hline & \text{mol H}_2\end{array}=8.52\text{ g/mol}$$

$$\dot{m}_{N_2}=\begin{array}{c|c|c|c} 3000\text{ kg} & \text{kmol} & 0.25\text{ kmol N}_2 & 28.02\text{ kg N}_2 \\ \hline \text{h} & 8.52\text{ kg} & \text{kmol feed} & \text{kmol N}_2\end{array}=\underline{\underline{2470\text{ kg N}_2\text{/h}}}$$

3.18 $M_\text{suspension}=565\text{ g}-65\text{ g}=500\text{ g}$, $M_{\text{CaCO}_3}=215\text{ g}-65\text{ g}=150\text{ g}$

(a) $\dot{V}=\underline{\underline{455\text{ mL/min}}}$, $\dot{m}=\underline{\underline{500\text{ g/min}}}$

(b) $\rho=\dot{m}/\dot{V}=500\text{ g / }455\text{ mL}=\underline{\underline{1.10\text{ g/mL}}}$

(c) $150\text{ g CaCO}_3\text{ / }500\text{ g suspension}=\underline{\underline{0.300\text{ g CaCO}_3\text{/g suspension}}}$

3.19 Assume 100 mol mix.

$$m_{\text{C}_2\text{H}_5\text{OH}}=\begin{array}{c|c} 10.0\text{ mol C}_2\text{H}_5\text{OH} & 46.07\text{ g C}_2\text{H}_5\text{OH} \\ \hline & \text{mol C}_2\text{H}_5\text{OH}\end{array}=461\text{ g C}_2\text{H}_5\text{OH}$$

$$m_{\text{C}_4\text{H}_8\text{O}_2}=\begin{array}{c|c} 75.0\text{ mol C}_4\text{H}_8\text{O}_2 & 88.1\text{ g C}_4\text{H}_8\text{O}_2 \\ \hline & \text{mol C}_4\text{H}_8\text{O}_2\end{array}=6608\text{ g C}_4\text{H}_8\text{O}_2$$

$$m_{\text{CH}_3\text{COOH}}=\begin{array}{c|c} 15.0\text{ mol CH}_3\text{COOH} & 60.05\text{ g CH}_3\text{COOH} \\ \hline & \text{mol CH}_3\text{COOH}\end{array}=901\text{ g CH}_3\text{COOH}$$

$$x_{\text{C}_2\text{H}_5\text{OH}}=\frac{461\text{ g}}{461\text{ g}+6608\text{ g}+901\text{ g}}=\underline{\underline{0.0578\text{ g C}_2\text{H}_5\text{OH / g mix}}}$$

$$x_{\text{C}_4\text{H}_8\text{O}_2}=\frac{6608\text{ g}}{461\text{ g}+6608\text{ g}+901\text{ g}}=\underline{\underline{0.8291\text{ g C}_4\text{H}_8\text{O}_2\text{ / g mix}}}$$

$$x_{\text{CH}_3\text{COOH}}=\frac{901\text{ g}}{461\text{ g}+6608\text{ g}+901\text{ g}}=\underline{\underline{0.113\text{ g CH}_3\text{COOH / g mix}}}$$

$$\overline{MW}=\frac{461\text{ g}+6608\text{ g}+901\text{ g}}{100\text{ mol}}=\underline{\underline{79.7\text{ g / mol}}}$$

$$m=\begin{array}{c|c|c} 25\text{ kmol EA} & 100\text{ kmol mix} & 79.7\text{ kg mix} \\ \hline & 75\text{ kmol EA} & 1\text{ kmol mix}\end{array}=\underline{\underline{2660\text{ kg mix}}}$$

3.20 (a)

Unit	*Function*
Crystallizer	Form solid gypsum particles from a solution
Filter	Separate particles from solution
Dryer	Remove water from filter cake

(b) $m_{\text{gypsum}} = \begin{array}{c|c} 1\text{ L slurry} & 0.35\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O} \\ \hline & \text{L slurry} \end{array} = \underline{\underline{0.35\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O}}}$

$V_{\text{gypsum}} = \begin{array}{c|c} 0.35\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O} & \text{L CaSO}_4\cdot 2\text{H}_2\text{O} \\ \hline & 2.32\text{ kg CaSO}_4\cdot 2\text{H}_2\text{O} \end{array} = \underline{\underline{0.151\text{ L CaSO}_4\cdot 2\text{H}_2\text{O}}}$

CaSO_4 in gypsum: $m = \begin{array}{c|c} 0.35\text{ kg } gypsum & 136.15\text{ kg CaSO}_4 \\ \hline & 172.18\text{ kg } gypsum \end{array} = \underline{\underline{0.277\text{ kg CaSO}_4}}$

CaSO_4 in soln.: $m = \begin{array}{c|c|c} (1-0.151)\text{ L sol} & 1.05\text{ kg} & 0.209\text{ kg CaSO}_4 \\ \hline & \text{L} & 100.209\text{ kg sol} \end{array} = \underline{\underline{0.00186\text{ kg CaSO}_4}}$

(c) $m = \begin{array}{c|c|c} 0.35\text{ kg gypsum} & 0.05\text{ kg sol} & 0.209\text{ g CaSO}_4 \\ \hline & 0.95\text{ kg gypsum} & 100.209\text{ g sol} \end{array} = 3.84\times 10^{-5}\text{ kg CaSO}_4$

$\underline{\%\,\text{recovery}} = \dfrac{0.277\text{ g} + 3.84\times 10^{-5}\text{ g}}{0.277\text{ g} + 0.00186\text{ g}}\times 100\% = \underline{\underline{99.3\%}}$

3.21

$$\left.\begin{array}{l} \underline{\text{CSA}}: \begin{array}{c|c|c} 45.8\text{ L} & 0.90\text{ kg} & \text{kmol} \\ \hline \text{min} & \text{L} & 75\text{ kg} \end{array} = 0.5496\ \dfrac{\text{kmol}}{\text{min}} \\ \underline{\text{FB}}: \begin{array}{c|c|c} 55.2\text{ L} & 0.75\text{ kg} & \text{kmol} \\ \hline \text{min} & \text{L} & 90\text{ kg} \end{array} = 0.4600\ \dfrac{\text{kmol}}{\text{min}} \end{array}\right\} \Rightarrow \dfrac{0.5496}{0.4600} = \underline{\underline{1.2\ \dfrac{\text{mol CSA}}{\text{mol FB}}}}$$

<u>She was wrong.</u>

<u>The mixer would come to a grinding halt and the motor would overheat.</u>

3.22 (a) $\begin{array}{c|c} 150\text{ mol EtOH} & 46.07\text{ g EtOH} \\ \hline & \text{mol EtOH} \end{array} = 6910\text{ g EtOH}$

$\begin{array}{c|c} 6910\text{ g EtOH} & 0.600\text{ g H}_2\text{O} \\ \hline & 0.400\text{ g EtOH} \end{array} = 10365\text{ g H}_2\text{O}$

$V = \begin{array}{c|c} 6910\text{ g EtOH} & \text{L} \\ \hline & 789\text{ g EtOH} \end{array} + \begin{array}{c|c} 10365\text{ g H}_2\text{O} & \text{L} \\ \hline & 1000\text{ g H}_2\text{O} \end{array} = 19.123\text{ L} \Rightarrow \underline{\underline{19.1\text{ L}}}$

$SG = \begin{array}{c|c} (6910+10365)\text{ g} & \text{L} \\ \hline 19.1\text{ L} & 1000\text{ g} \end{array} = \underline{\underline{0.903}}$

(b) $V' = \begin{array}{c|c} (6910+10365)\text{ g mix} & \text{L} \\ \hline & 935.18\text{ g} \end{array} = 18.472\text{ L} \Rightarrow \underline{\underline{18.5\text{ L}}}$

$\underline{\%\,\text{error}} = \dfrac{(19.123-18.472)\text{ L}}{18.472\text{ L}}\times 100\% = \underline{\underline{3.5\%}}$

3.23 $$\overline{M}=\begin{array}{c|c} 0.09\text{ mol CH}_4 & 16.04\text{ g} \\ \hline & \text{mol}\end{array} + \begin{array}{c|c} 0.91\text{ mol Air} & 29.0\text{ g Air} \\ \hline & \text{mol}\end{array} = 27.83\ \text{g/mol}$$

$$\begin{array}{c|c|c} 700\text{ kg} & \text{kmol} & 0.090\text{ kmol CH}_4 \\ \hline \text{h} & 27.83\text{ kg} & 1.00\text{ kmol mix}\end{array} = 2.264\text{ kmol CH}_4/\text{h}$$

$$\begin{array}{c|c} 2.264\text{ kmol CH}_4 & 0.91\text{ kmol air} \\ \hline \text{h} & 0.09\text{ kmol CH}_4\end{array} = 22.89\text{ kmol air/h}$$

$$\underline{5\%\ \text{CH}_4} \Rightarrow \begin{array}{c|c} 2.264\text{ kmol CH}_4 & 0.95\text{ kmol air} \\ \hline \text{h} & 0.05\text{ kmol CH}_4\end{array} = 43.01\text{ kmol air/h}$$

<u>Dilution air required</u>: $$\begin{array}{c|c} (43.01-22.89)\text{ kmol air} & 1000\text{ mol} \\ \hline \text{h} & 1\text{ kmol}\end{array} = \underline{\underline{20200\text{ mol air/h}}}$$

<u>Product gas</u>: $$\frac{700\text{ kg}}{\text{h}} + \begin{array}{c|c} 20.20\text{ kmol Air} & 29\text{ kg Air} \\ \hline \text{h} & \text{kmol Air}\end{array} = 1286\ \text{kg/h}$$

$$\begin{array}{c|c|c|c} 43.01\text{ kmol Air} & 0.21\text{ kmol O}_2 & 32.00\text{ kg O}_2 & \text{h} \\ \hline \text{h} & 1.00\text{ kmol Air} & 1\text{ kmol O}_2 & 1286\text{ kg total}\end{array} = \underline{\underline{0.225\frac{\text{kg O}_2}{\text{kg}}}}$$

3.24 $$x_i=\frac{m_i}{M}\ ,\ \rho_i=\frac{m_i}{V_i}\ ,\ \overline{\rho}=\frac{\text{M}}{\text{V}}$$

$$A:\ \sum x_i\rho_i=\sum\frac{m_i}{M}\frac{m_i}{V_i}=\frac{1}{M}\sum\frac{m_i^2}{V_i}\neq\overline{\rho}$$ Not helpful.

$$B:\ \sum\frac{x_i}{\rho_i}=\sum\frac{m_i}{M}\frac{V_i}{m_i}=\frac{1}{M}\sum V_i=\frac{V}{M}=\frac{1}{\overline{\rho}}$$ Correct.

$$\frac{1}{\overline{\rho}}=\sum\frac{x_i}{\rho_i}=\frac{0.60}{0.791}+\frac{0.25}{1.049}+\frac{0.15}{1.595}=1.091\quad\Rightarrow\ \overline{\rho}=\underline{\underline{0.917\ \text{g}/\text{cm}^3}}$$

3.25 (a) $$\text{Basis: }100\text{ mol N}_2\Rightarrow 20\text{ mol CH}_4\Rightarrow\begin{cases}20\times\dfrac{80}{25}=64\text{ mol CO}_2\\ 20\times\dfrac{40}{25}=32\text{ mol CO}\end{cases}$$

$$N_{total}=100+20+64+32=216\text{ mol}$$

$$x_{\text{CO}}=\frac{32}{216}=\underline{\underline{0.15\text{ mol CO}/\text{mol}}}\ ,\ x_{\text{CO}_2}=\frac{64}{216}=\underline{\underline{0.30\text{ mol CO}_2/\text{mol}}}$$

$$x_{\text{CH}_4}=\frac{20}{216}=\underline{\underline{0.09\text{ mol CH}_4/\text{mol}}}\ ,\ x_{\text{N}_2}=\frac{100}{216}=\underline{\underline{0.46\text{ mol N}_2/\text{mol}}}$$

(b) $$\overline{M}=\sum y_iM_i=0.15\times28+0.30\times44+0.09\times16+0.46\times28=\underline{\underline{32\ \text{g}/\text{mol}}}$$

3.26 (a)

Samples	Species	MW	k	Peak Area	Mole Fraction	Mass Fraction	moles	mass
1	CH4	16.04	0.150	3.6	0.156	0.062	0.540	8.662
	C2H6	30.07	0.287	2.8	0.233	0.173	0.804	24.164
	C3H8	44.09	0.467	2.4	0.324	0.353	1.121	49.416
	C4H10	58.12	0.583	1.7	0.287	0.412	0.991	57.603
2	CH4	16.04	0.150	7.8	0.249	0.111	1.170	18.767
	C2H6	30.07	0.287	2.4	0.146	0.123	0.689	20.712
	C3H8	44.09	0.467	5.6	0.556	0.685	2.615	115.304
	C4H10	58.12	0.583	0.4	0.050	0.081	0.233	13.554
3	CH4	16.04	0.150	3.4	0.146	0.064	0.510	8.180
	C2H6	30.07	0.287	4.5	0.371	0.304	1.292	38.835
	C3H8	44.09	0.467	2.6	0.349	0.419	1.214	53.534
	C4H10	58.12	0.583	0.8	0.134	0.212	0.466	27.107
4	CH4	16.04	0.150	4.8	0.333	0.173	0.720	11.549
	C2H6	30.07	0.287	2.5	0.332	0.324	0.718	21.575
	C3H8	44.09	0.467	1.3	0.281	0.401	0.607	26.767
	C4H10	58.12	0.583	0.2	0.054	0.102	0.117	6.777
5	CH4	16.04	0.150	6.4	0.141	0.059	0.960	15.398
	C2H6	30.07	0.287	7.9	0.333	0.262	2.267	68.178
	C3H8	44.09	0.467	4.8	0.329	0.380	2.242	98.832
	C4H10	58.12	0.583	2.3	0.197	0.299	1.341	77.933

(b)

```
REAL A(10), MW(10), K(10), MOL(10), MASS(10), MOLT, MASST
INTEGER N, ND, ID, J
READ (5, *) N
CN-NUMBER OF SPECIES
READ (5, *) (MW(J), K(J), J = 1, N)
READ (5, *) ND
DO 20 ID = 1, ND
    READ (5, *)(A(J), J = 1, N)
    MOLT = 0.0
    MASST = 0.0
    DO 10 J = 1, N
      MOL(J) =
      MASS(J) = MOL(J) * MW(J)
      MOLT = MOLT + MOL(J)
      MASST = MASST + MASS(J)
    10          CONTINUE
    DO 15 J = 1, N
      MOL(J) = MOL(J)/MOLT
      MASS(J) = MASS(J)/MASST
    15          CONTINUE
    WRITE (6, 1) ID, (J, MOL(J), MASS (J), J = 1, N)
20  CONTINUE
1   FORMAT (' SAMPLE:  `, I3, /,
    * ' SPECIES MOLE FR. MASS FR.', /,
```

3.26 (cont'd)

```
* 10(3X, I3, 2(5X, F5.3), /), /)
END
$DATA
*
   4
16.04   0.150
30.07   0.287
44.09   0.467
58.12   0.583
   5
3.6   2.8   2.4   1.7
7.8   2.4   5.6   0.4
3.4   4.5   2.6   0.8
4.8   2.5   1.3   0.2
6.4   7.9   4.8   2.3
[OUTPUT]
SAMPLE:        1
 SPECIES    MOLE FR    MASS FR
      1          0.156         0.062
      2          0.233         0.173
      3          0.324         0.353
      4          0.287         0.412
SAMPLE: 2
(ETC.)
```

3.27 (a)

$$\frac{(8.7\times10^{6}\times0.40)\text{ kg C}}{}\left|\frac{44\text{ kg CO}_2}{12\text{ kg C}}\right.=1.28\times10^{7}\text{ kg CO}_2\Rightarrow 2.9\times10^{5}\text{ kmol CO}_2$$

$$\frac{(1.1\times10^{6}\times0.26)\text{ kg C}}{}\left|\frac{28\text{ kg CO}}{12\text{ kg C}}\right.=6.67\times10^{5}\text{ kg CO}\Rightarrow 2.38\times10^{4}\text{ kmol CO}$$

$$\frac{(3.8\times10^{5}\times0.10)\text{ kg C}}{}\left|\frac{16\text{ kg CH}_4}{12\text{ kg C}}\right.=5.07\times10^{4}\text{ kg CH}_4\Rightarrow 3.17\times10^{3}\text{ kmol CH}_4$$

$$m=\frac{(1.28\times10^{7}+6.67\times10^{5}+5.07\times10^{4})\text{ kg}}{}\left|\frac{1\text{ metric ton}}{1000\text{ kg}}\right.=\underline{\underline{13{,}500\ \frac{\text{metric tons}}{\text{yr}}}}$$

$$\overline{M}=\sum y_i M_i=0.915\times44+0.075\times28+0.01\times16=\underline{\underline{42.5\text{ g / mol}}}$$

3.28 (a) Basis: 1 liter of solution

$$\frac{1000\text{ mL}}{}\left|\frac{1.03\text{ g}}{\text{mL}}\right|\frac{5\text{ g H}_2\text{SO}_4}{100\text{ g}}\left|\frac{\text{mol H}_2\text{SO}_4}{98.08\text{ g H}_2\text{SO}_4}\right.=0.525\text{ mol / L}\Rightarrow\underline{\underline{0.525\text{ molar solution}}}$$

3.28 (cont'd)

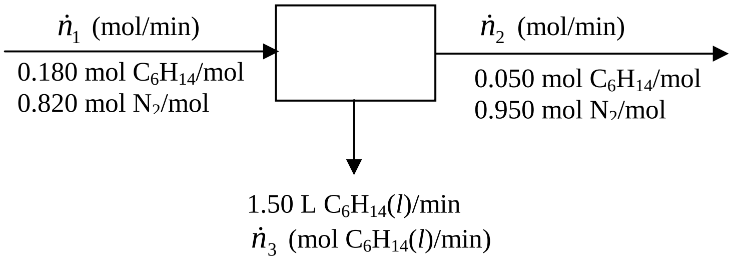
(b) $t = \dfrac{V}{\dot{V}} = \dfrac{55\ \text{gal} \mid 3.7854\ \text{L} \mid \text{min} \mid 60\ \text{s}}{\mid \text{gal} \mid 87\ \text{L} \mid \text{min}} = \underline{\underline{144\ \text{s}}}$

$$\frac{55\ \text{gal} \mid 3.7854\ \text{L} \mid 10^3\ \text{mL} \mid 1.03\ \text{g} \mid 0.0500\ \text{g H}_2\text{SO}_4 \mid 1\ \text{lbm}}{\mid \text{gal} \mid 1\ \text{L} \mid \text{mL} \mid \text{g} \mid 453.59\ \text{g}} = \underline{\underline{23.6\ \text{lb}_\text{m}\ \text{H}_2\text{SO}_4}}$$

(c) $u = \dfrac{\dot{V}}{A} = \dfrac{87\ \text{L} \mid \text{m}^3 \mid 1\ \text{min} \mid}{\text{min} \mid 1000\ \text{L} \mid 60\ \text{s} \mid (\pi \times 0.06^2\ /\ 4)\ \text{m}^2} = 0.513\ \text{m/s}$

$t = \dfrac{L}{u} = \dfrac{45\ \text{m}}{0.513\ \text{m/s}} = \underline{\underline{88\ \text{s}}}$

3.29 (a)



$$\dot{n}_3 = \frac{1.50\ \text{L} \mid 0.659\ \text{kg} \mid 1000\ \text{mol}}{\text{min} \mid \text{L} \mid 86.17\ \text{kg}} = 11.47\ \text{mol/min}$$

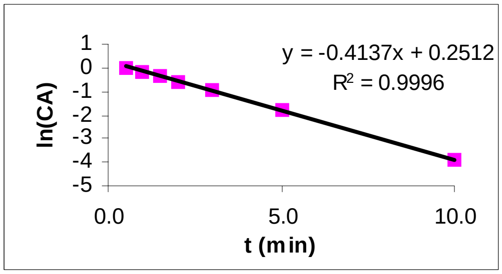
$$\left.\begin{array}{l} \underline{\text{Hexane balan}}\text{ce: } 0.180\dot{n}_1 = 0.050\dot{n}_2 + 11.47\ (\text{mol C}_6\text{H}_{14}\ /\ \text{min}) \\ \underline{\text{Nitrogen balance}}\text{: } 0.820\dot{n}_1 = 0.950\dot{n}_2\ (\text{mol N}_2\ /\ \text{min}) \end{array}\right\} \overset{\text{solve}}{\Rightarrow} \left\{\begin{array}{l} \dot{n}_1 = 83.8\ \text{mol/min} \\ \underline{\underline{\dot{n}_2 = 72.3\ \text{mol/min}}} \end{array}\right.$$

(b) $\underline{\text{Hexane recovery}} = \dfrac{\dot{n}_3}{\dot{n}_1} \times 100\% = \dfrac{11.47}{0.180(83.8)} \times 100\% = \underline{\underline{76\%}}$

3.30 $\dfrac{30\ \text{mL} \mid 1\ \text{L} \mid 0.030\ \text{mol} \mid 172\ \text{g}}{\mid 10^3\ \text{mL} \mid 1\ \text{L} \mid 1\ \text{mol}} = \underline{\underline{0.155\ \text{g Nauseum}}}$

3.31 **(a)** kt is dimensionless $\Rightarrow k\ (\text{min}^{-1})$

(b) A semilog plot of C_A vs. t is a straight line $\Rightarrow \ln C_{\text{A}} = \ln C_{\text{AO}} - kt$



$$\underline{\underline{k = 0.414\ \text{min}^{-1}}}$$

$$\ln C_{\text{AO}} = 0.2512 \Rightarrow \underline{\underline{C_{\text{AO}} = 1.286\ \text{lb-moles}/\text{ft}^3}}$$

(c) $$C_A\left(\frac{\text{1b-moles}}{\text{ft}^3}\right) = C_A' \begin{array}{c|c|c} \text{mol} & 28.317\ \text{liter} & 2.26462\ \text{lb-moles} \\ \hline \text{liter} & 1\ \text{ft}^3 & 1000\ \text{mol} \end{array} = 0.06243 C_A'$$

$$t(\text{min}) = \begin{array}{c|c} t'(s) & 1\ \text{min} \\ \hline & 60\ \text{s} \end{array} = t'/60$$

$$\Big\Downarrow\ C_A = C_{A0}\exp(-kt)$$

$$0.06243 C_A' = 1.334\exp(-0.419t'/60) \overset{\text{drop primes}}{\Rightarrow} \underline{\underline{C_A(\text{mol / L}) = 21.4\exp(-0.00693t)}}$$

$$t = 200\ \text{s} \Rightarrow C_A = \underline{\underline{5.30\ \text{mol / L}}}$$

3.32 **(a)** $$\begin{array}{c|c} 2600\ \text{mm Hg} & 14.696\ \text{psi} \\ \hline & 760\ \text{mm Hg} \end{array} = \underline{\underline{50.3\ \text{psi}}}$$

(b) $$\begin{array}{c|c} 275\ \text{ft H}_2\text{O} & 101.325\ \text{kPa} \\ \hline & 33.9\ \text{ft H}_2\text{O} \end{array} = \underline{\underline{822.0\ \text{kPa}}}$$

(c) $$\begin{array}{c|c|c} 3.00\ \text{atm} & 1.01325\times10^5\ \text{N}/\text{m}^2 & 1^2\ \text{m}^2 \\ \hline & 1\ \text{atm} & 100^2\ \text{cm}^2 \end{array} = \underline{\underline{30.4\ \text{N}/\text{cm}^2}}$$

(d) $$\begin{array}{c|c|c|c} 280\ \text{cm Hg} & 10\ \text{mm} & 1.01325\times10^6\ \text{dynes}/\text{cm}^2 & 100^2\ \text{cm}^2 \\ \hline & 1\ \text{cm} & 760\ \text{mm Hg} & 1^2\ \text{m}^2 \end{array} = \underline{\underline{3.733\times10^{10}\ \frac{\text{dynes}}{\text{m}^2}}}$$

(e) $$1\ \text{atm} - \begin{array}{c|c|c} 20\ \text{cm Hg} & 10\ \text{mm} & 1\ \text{atm} \\ \hline & 1\ \text{cm} & 760\ \text{mm Hg} \end{array} = 0.737\ \text{atm}$$

3.32 (cont'd)

(f) $$\begin{array}{c|c} 25.0\text{ psig} & 760\text{ mm Hg}\left(\text{gauge}\right) \\ \hline & 14.696\text{ psig} \end{array} = \underline{\underline{1293\text{ mm Hg}\left(\text{gauge}\right)}}$$

(g) $$\begin{array}{c|c} \left(25.0+14.696\right)\text{psi} & 760\text{ mm Hg} \\ \hline & 14.696\text{ psi} \end{array} = \underline{\underline{2053\text{ mm Hg}\left(\text{abs}\right)}}$$

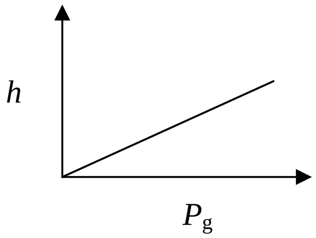
(h) $325\text{ mm Hg} - 760\text{ mm Hg} = \underline{\underline{-435\text{ mm Hg}\left(\text{gauge}\right)}}$

(i) $$\text{Eq. (3.4-2)} \Rightarrow h = \frac{P}{\rho g} = \begin{array}{c|c|c|c|c|c} 35.0\text{ lb}_\text{f} & 144\text{ in}^2 & \text{ft}^3 & \text{s}^2 & 32.174\text{ lb}_\text{m}\cdot\text{ft} & 100\text{ cm} \\ \hline \text{in}^2 & 1\text{ ft}^2 & 1.595\text{x}62.43\text{ lb}_\text{m} & 32.174\text{ ft} & \text{s}^2\cdot\text{lb}_\text{f} & 3.2808\text{ ft} \end{array}$$

$$= \underline{\underline{1540\text{ cm CCl}_4}}$$

3.33 (a) $$P_g = \rho g h = \begin{array}{c|c|c|c|c} 0.92\times1000\text{ kg} & 9.81\text{ m/s}^2 & h\text{ (m)} & 1\text{ N} & 1\text{ kPa} \\ \hline \text{m}^3 & & & 1\text{ kg}\cdot\text{m/s}^2 & 10^3\text{ N/m}^2 \end{array}$$

$$\Rightarrow h\text{ (m)} = 0.111 P_g\text{ (kPa)}$$



$$P_g = 68\text{ kPa} \Rightarrow h = 0.111\times68 = \underline{\underline{7.55\text{ m}}}$$

$$m_{oil} = \rho V = \left(0.92\times1000\ \frac{\text{kg}}{\text{m}^3}\right)\times\left(7.55\times\pi\times\frac{16^2}{4}\ \text{m}^3\right) = \underline{\underline{1.4\times10^6\text{ kg}}}$$

(b) $$P_g + P_{atm} = P_{top} + \rho g h$$

$$\Downarrow$$

$$68+101 = 115+\left[\left(0.92\times1000\right)\times\left(9.81\right)/10^3\right]h \Rightarrow h = \underline{\underline{5.98\text{ m}}}$$

3.34 (a) Weight of block = Sum of weights of displaced liquids

$$(h_1+h_2)A\rho_b g = h_1 A\rho_1 g + h_2 A\rho_2 g \Rightarrow \rho_b = \frac{\rho_1 h_1 + \rho_2 h_2}{h_1+h_2}$$

(b)

$$P_\text{top} = P_\text{atm} + \rho_1 g h_0\text{ , } P_\text{bottom} = P_\text{atm} + \rho_1 g(h_0+h_1) + \rho_2 g h_2\text{ , } W_\text{b} = \rho_b(h_1+h_2)A$$

$$\Rightarrow F_\text{down} = (P_\text{atm} + \rho_1 g h_0)A + \rho_b(h_1+h_2)A,\ F_\text{up} = [P_\text{atm} + \rho_1 g(h_0+h_1) + \rho_2 g h_2]A$$

$$F_\text{down} = F_\text{up} \Rightarrow \rho_b(h_1+h_2)A = \rho_1 g h_1 A + \rho_2 g h_2 A \Rightarrow W_\text{block} = W_\text{liquid displaced}$$

3.35 $\Delta P = \left(P_{\text{atm}} + \rho g h\right) - P_{\text{inside}}$

$$= 1\text{ atm} - 1\text{ atm} + \begin{array}{c|c|c|c|c} (1.05)1000\text{ kg} & 9.8066\text{ m} & 150\text{ m} & 1^2\text{ m}^2 & 1\text{ N} \\ \hline \text{m}^3 & \text{s}^2 & & 100^2\text{ cm}^2 & 1\text{ kg}\cdot\text{m/s}^2 \end{array}$$

$$F = \begin{array}{c|c} 154\text{ N} & 65\text{ cm}^2 \\ \hline \text{cm}^2 & \end{array} = \underline{\underline{1.00\times 10^4\text{ N}}} \times \left(\frac{0.22481\text{ lb}_\text{f}}{1\text{ N}}\right) = \underline{\underline{2250\text{ lb}_\text{f}}}$$

3.36 $m = \rho V = \begin{array}{c|c|c} 1.4\times 62.43\text{ lb}_\text{m} & 1\text{ ft}^3 & 2.3\times 10^6\text{ gal} \\ \hline \text{ft}^3 & 7.481\text{ gal} & \end{array} = \underline{\underline{2.69\times 10^7\text{ lb}_\text{m}}}$

$P = P_0 + \rho g h$

$$= 14.7\frac{\text{lb}_\text{f}}{\text{in}^2} + \begin{array}{c|c|c|c|c} 1.4\times 62.43\text{ lb}_\text{m} & 32.174\text{ ft} & 30\text{ ft} & 1\text{ lb}_\text{f} & 1^2\text{ ft}^2 \\ \hline \text{ft}^3 & \text{s}^2 & & 32.174\text{ lb}_\text{m}\cdot\text{ft/s}^2 & 12^2\text{ in}^2 \end{array}$$

$= \underline{\underline{32.9\text{ psi}}}$

— Structural flaw in the tank.
— Tank strength inadequate for that much force.
— Molasses corroded tank wall

3.37 (a) $m_{\text{head}} = \begin{array}{c|c|c} \dfrac{\pi\times 24^2\times 3\text{ in}^3}{4} & \dfrac{1\text{ ft}^3}{12^3\text{ in}^3} & \dfrac{8.0\times 62.43\text{ lb}_\text{m}}{\text{ft}^3} \end{array} = 392\text{ lb}_\text{m}$

$W = m_{\text{head}}\, g = \begin{array}{c|c|c} 392\text{ lb}_\text{m} & 32.174\text{ ft}/s^2 & 1\text{ lb}_\text{f} \\ \hline & & 32.174\text{ lb}_\text{m}\cdot\text{ft/s}^2 \end{array} = 392\text{ lb}_\text{f}$

$$F_{\text{net}} = F_{\text{gas}} - F_{\text{atm}} - W = \begin{array}{c|c} \left[(30+14.7)\right]\text{lb}_\text{f} & \pi\times 20^2\text{ in}^2 \\ \hline \text{in}^2 & 4 \end{array}$$

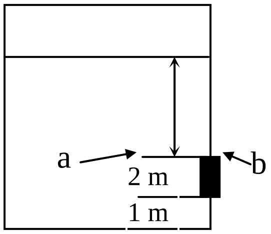
$$- \begin{array}{c|c} 14.7\text{ lb}_\text{f} & \pi\times 24^2\text{ in}^2 \\ \hline \text{in}^2 & 4 \end{array} - 392\text{ lb}_\text{f} = \underline{\underline{7.00\times 10^3\text{ lb}_\text{f}}}$$

The head would blow off.

Initial acceleration: $a = \dfrac{F_{\text{net}}}{m_{\text{head}}} = \begin{array}{c|c} 7.000\times 10^3\text{ lb}_\text{f} & 32.174\text{ lb}_\text{m}\cdot\text{ft/s}^2 \\ \hline 392\text{ lb}_\text{m} & 1\text{ lb}_\text{f} \end{array} = \underline{\underline{576\text{ ft/s}^2}}$

(b) Vent the reactor through a valve to the outside or a hood before removing the head.

3.38 (a)



$P_a = \rho gh + P_{atm} \quad , \quad P_b = P_{atm}$

If the inside pressure on the door equaled P_a, the force on the door would be $F = A_{door}(P_a - P_b) = \rho ghA_{door}$

Since the pressure at every point on the door is greater than P_a, Since the pressure at every point on the door is greater than P_a, $F > \rho ghA_{\text{door}}$

(b) Assume an average bathtub 5 ft long, 2.5 ft wide, and 2 ft high takes about 10 min to fill.

$$\dot{V}_{tub} = \frac{V}{t} \approx \frac{5\times2.5\times2\ \text{ft}^3}{10\ \text{min}} = 2.5\ \text{ft}^3/\text{min} \Rightarrow \dot{V} = 5\times2.5 = 12.5\ \text{ft}^3/\text{min}$$

(i) For a full room, $h = 7$ m

$$\Rightarrow F > \begin{array}{r|r|c|c|c} 1000\ \text{kg} & 9.81\ \text{m} & 1\ \text{N} & 7\ \text{m} & 2\ \text{m}^2 \\ \hline \text{m}^3 & \text{s}^2 & 1\ \text{kg}\cdot\text{m/s}^2 & & \end{array} \Rightarrow \underline{\underline{F > 1.4\times10^5\ \text{N}}}$$

<u>The door will break before the room fills</u>

(ii) If the door holds, it will take

$$t_{\text{fill}} = \frac{V_{\text{room}}}{\dot{V}} = \begin{array}{c|c|c|c} (5\times15\times10)\ \text{m}^3 & & 35.3145\ \text{ft}^3 & 1\ \text{h} \\ \hline & 12.5\ \text{ft}^3/\text{min} & 1\ \text{m}^3 & 60\ \text{min} \end{array} = \underline{\underline{31\ \text{h}}}$$

<u>He will not have enough time.</u>

3.39 (a) $$\left(P_g\right)_{tap} = \begin{array}{c|c} 25\ \text{m H}_2\text{O} & 101.3\ \text{kPa} \\ \hline & 10.33\ \text{m H}_2\text{O} \end{array} = \underline{\underline{245\ \text{kPa}}}$$

$$\left(P_g\right)_{junction} = \begin{array}{c|c} (25+5)\ \text{m H}_2\text{O} & 101.3\ \text{kPa} \\ \hline & 10.33\ \text{m H}_2\text{O} \end{array} = \underline{\underline{294\ \text{kPa}}}$$

(b) <u>Air in the line. (lowers average density of the water.)</u>

(c) <u>The line could be clogged, or there could be a leak between the junction and the tap.</u>

3.40 $P_{abs} = \underline{\underline{800\ \text{mm Hg}}}$

$P_{gauge} = \underline{\underline{25\ \text{mm Hg}}}$

$P_{atm} = 800 - 25 = \underline{\underline{775\ \text{mm Hg}}}$

3.41 **(a)** $P_1 + \rho_A g(h_1 + h_2) = P_2 + \rho_B g h_1 + \rho_C g h_2$

$$\Rightarrow \underline{\underline{P_1 - P_2 = (\rho_B - \rho_A) g h_1 + (\rho_C - \rho_A) g h_2}}$$

(b) $$P_1 = 121 \text{ kPa} + \left[\frac{(1.0 - 0.792)\text{ g}}{\text{cm}^3} \left| \frac{981 \text{ cm}}{\text{s}^2} \right| \frac{30.0 \text{ cm}}{} + \frac{(1.37 - 0.792)\text{ g}}{\text{cm}^3} \left| \frac{981 \text{ cm}}{\text{s}^2} \right| \frac{24.0 \text{ cm}}{} \right]$$

$$\times \left(\frac{1 \text{ dyne}}{1 \text{ g} \cdot \text{cm/s}^2} \right) \left(\frac{101.325 \text{ kPa}}{1.01325 \times 10^6 \text{ dynes/cm}^2} \right) = \underline{\underline{123.0 \text{ kPa}}}$$

3.42 **(a)** Say ρ_t (g/cm^3) = density of toluene, ρ_m (g/cm^3) = density of manometer fluid

$$\rho_t g(500 - h + R) = \rho_m g R \Rightarrow R = \frac{500 - h}{\dfrac{\rho_m}{\rho_t} - 1}$$

(i) Hg: $\rho_t = 0.866,\ \rho_m = 13.6,\ h = 150 \text{ cm} \Rightarrow R = \underline{\underline{23.8 \text{ cm}}}$

(ii) H_2O: $\rho_t = 0.866,\ \rho_m = 1.00,\ h = 150 \text{ cm} \Rightarrow R = \underline{\underline{2260 \text{ cm}}}$

Use mercury, because the water manometer would have to be too tall.

(b) If the manometer were simply filled with toluene, the level in the glass tube would be at the level in the tank.

Advantages of using mercury: smaller manometer; less evaporation.

(c) The nitrogen blanket is used to avoid contact between toluene and atmospheric oxygen, minimizing the risk of combustion.

3.43 $$P_{\text{atm}} = \rho_f g(7.23 \text{ m}) \ \Rightarrow\ \rho_f = \frac{P_{\text{atm}}}{7.23 \text{ g}}$$

$$P_a - P_b = (\rho_f - \rho_w) g(26 \text{ cm}) = \left(\frac{P_{\text{atm}}}{7.23 \text{ m}} - \rho_w g \right)(26 \text{ cm})$$

$$= \left(\frac{756 \text{ mmHg}}{7.23 \text{ m}} \left| \frac{1 \text{ m}}{100 \text{ cm}} \right. - \frac{1000 \text{ kg}}{\text{m}^3} \left| \frac{9.81 \text{ m/s}^2}{} \right| \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \left| \frac{760 \text{ mmHg}}{1.01325 \times 10^5 \text{ N/m}^2} \right| \frac{1 \text{ m}}{100 \text{ cm}} \right)(26 \text{ cm})$$

$$\Rightarrow P_a - P_b = \underline{\underline{8.1 \text{ mm Hg}}}$$

3.44 **(a)** $$\Delta h = 900 - h_1 = \frac{7.5 \text{ psi}}{} \left| \frac{760 \text{ mm Hg}}{14.696 \text{ psi}} \right. = 388 \text{ mm Hg} \Rightarrow h_1 = 900 - 388 = \underline{\underline{512 \text{ mm}}}$$

(b) $$\Delta h = 388 - 25 \times 2 = 338 \text{ mm} \Rightarrow P_g = \frac{338 \text{ mm Hg}}{} \left| \frac{14.696 \text{ psi}}{760 \text{ mm Hg}} \right. = \underline{\underline{6.54 \text{ psig}}}$$

3.45 **(a)** $h = L \sin \theta$

(b) $h = (8.7\ \text{cm})\sin(15°) = 2.3\ \text{cm H}_2\text{O} = \underline{\underline{23\ \text{mm H}_2\text{O}}}$

3.46 **(a)** $P = P_{atm} - P_{oil} - P_{Hg}$

$$= 765 - 365 - \begin{array}{c|c|c|c|c} 920\ \text{kg} & 9.81\ \text{m/s}^2 & 0.10\ \text{m} & 1\ \text{N} & 760\ \text{mm Hg} \\ \hline \text{m}^3 & & & 1\ \text{kg}\cdot\text{m/s}^2 & 1.01325\times10^5\ \text{N/m}^2 \end{array}$$

$$= \underline{\underline{393\ \text{mm Hg}}}$$

(b) — Nonreactive with the vapor in the apparatus.
— Lighter than and immiscible with mercury.
— Low rate of evaporation (low volatility).

3.47 **(a)** Let ρ_f = manometer fluid density $(1.10\ \text{g/cm}^3)$, ρ_{ac} = acetone density $(0.791\ \text{g/cm}^3)$

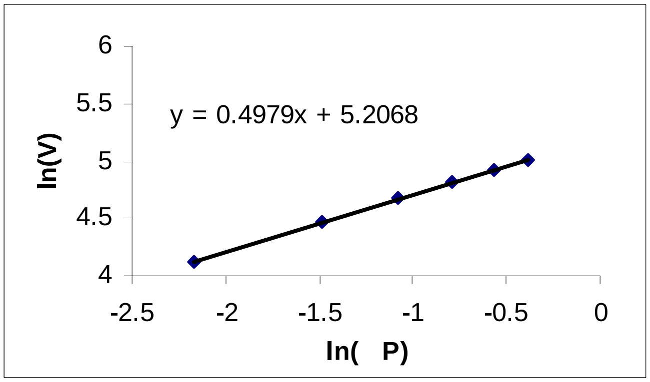
Differential manometer formula: $\Delta P = (\rho_f - \rho_{ac})gh$

$$\Delta P\,(\text{mm Hg}) = \begin{array}{c|c|c|c|c|c} (1.10-0.791)\text{g} & 981\ \text{cm} & \text{h (mm)} & 1\ \text{cm} & 1\ \text{dyne} & 760\ \text{mm Hg} \\ \hline \text{cm}^3 & \text{s}^2 & & 10\ \text{mm} & 1\ \text{g}\cdot\text{cm/s}^2 & 1.01325\times10^6\ \text{dyne/cm}^2 \end{array}$$

$$= 0.02274\ \text{h(mm)}$$

$\dot{V}$(mL/s)	62	87	107	123	138	151
h(mm)	5	10	15	20	25	30
$\underline{\underline{\Delta P(\text{mm Hg})}}$	$\underline{\underline{0.114}}$	$\underline{\underline{0.227}}$	$\underline{\underline{0.341}}$	$\underline{\underline{0.455}}$	$\underline{\underline{0.568}}$	$\underline{\underline{0.682}}$

(b) $\ln \dot{V} = n \ln(\Delta P) + \ln K$



From the plot above, $\ln \dot{V} = 0.4979\ \ln(\Delta P) + 5.2068$

$\Rightarrow \underline{\underline{n = 0.4979 \approx 0.5}}$, $\ln K = 5.2068 \Rightarrow \underline{\underline{K = 183 \dfrac{\text{ml/s}}{(\text{mm Hg})^{0.5}}}}$

3.47 (cont'd)

(c) $h = 23 \Rightarrow \Delta P = (0.02274)(23) = 0.523 \text{ mm Hg} \Rightarrow \dot{V} = 183(0.523)^{0.5} = \underline{\underline{132\ \text{mL/s}}}$

$$\begin{array}{c|c} 132\text{ mL} & 0.791\text{ g} \\ \hline \text{s} & \text{mL} \end{array} = \underline{\underline{104\ \text{g/s}}} \qquad \begin{array}{c|c} 104\text{ g} & 1\text{ mol} \\ \hline \text{s} & 58.08\text{ g} \end{array} = \underline{\underline{1.80\ \text{mol/s}}}$$

3.48 **(a)** $T = 85°\text{F} + 459.7 = \underline{\underline{544°\text{R}}} / 1.8 = \underline{\underline{303\text{ K}}} - 273 = \underline{\underline{30°\text{C}}}$

(b) $T = -10°\text{C} + 273 = \underline{\underline{263\text{ K}}} \times 1.8 = \underline{\underline{474°\text{R}}} - 460 = \underline{\underline{14°\text{F}}}$

(c) $\Delta T = \begin{array}{c|c} 85°\text{C} & 1.0°\text{K} \\ \hline & 1.0°\text{C} \end{array} = \underline{\underline{85°\text{K}}};\quad \begin{array}{c|c} 85°\text{C} & 1.8°\text{F} \\ \hline & 1°\text{C} \end{array} = \underline{\underline{153°\text{F}}};\quad \begin{array}{c|c} 85°\text{C} & 1.8°\text{R} \\ \hline & 1.0°\text{C} \end{array} = \underline{\underline{153°\text{R}}}$

(d) $\begin{array}{c|c} 150°\text{R} & 1°\text{F} \\ \hline & 1°\text{R} \end{array} = \underline{\underline{150°\text{F}}};\quad \begin{array}{c|c} 150°\text{R} & 1.0°\text{K} \\ \hline & 1.8°\text{R} \end{array} = \underline{\underline{83.3°\text{K}}};\quad \begin{array}{c|c} 150°\text{R} & 1.0°\text{C} \\ \hline & 1.8°\text{R} \end{array} = \underline{\underline{83.3°\text{C}}}$

3.49 **(a)** $T = 0.0940 \times 1000°\text{FB} + 4.00 = 98.0°\text{C} \Rightarrow \text{T} = 98.0 \times 1.8 + 32 = \underline{\underline{208°\text{F}}}$

(b) $\Delta T\ (°\text{C}) = 0.0940\Delta T\ (°\text{FB}) = \underline{\underline{0.94°\text{C}}} \Rightarrow \Delta T\ (\text{K}) = \underline{\underline{0.94\text{ K}}}$

$$\Delta T\ (°\text{F}) = \begin{array}{c|c} 0.94°\text{C} & 1.8°\text{F} \\ \hline & 1.0°\text{C} \end{array} = \underline{\underline{1.69°\text{F}}} \Rightarrow \Delta T\ (°\text{R}) = \underline{\underline{1.69°\text{R}}}$$

(c) $T_1 = 15°\text{C} \Rightarrow 100°\text{L}\ ;\quad T_2 = 43°\text{C} \Rightarrow 1000°\text{L}$

$$T\ (°\text{C}) = aT\ (°\text{L}) + b$$

$$a = \frac{(43-15)°\text{C}}{(1000\text{ - }100)°\text{L}} = 0.0311\left(\frac{°\text{C}}{°\text{L}}\right); \qquad b = 15 - 0.0311 \times 100 = 11.9°\text{C}$$

$$\Rightarrow \begin{array}{l} \underline{\underline{T\ (°\text{C}) = 0.0311T\ (°\text{L}) + 11.9}} \quad \text{and} \\ T\ (°\text{L}) = \dfrac{1}{0.0311}\Big[0.0940T(°\text{FB}) + 4.00\text{-}11.9\Big] = \underline{\underline{3.023T(°\text{FB})\text{-}254}} \end{array}$$

(d) $T_{bp} = -88.6°\text{C} \Rightarrow \underline{\underline{184.6\text{ K}}} \Rightarrow \underline{\underline{332.3°\text{R}}} \Rightarrow \underline{\underline{\text{-}127.4°\text{F}}} \Rightarrow \underline{\underline{-985.1°\text{FB}}} \Rightarrow \underline{\underline{-3232°\text{L}}}$

(e) $\Delta T = 50.0°\text{L} \Rightarrow \underline{\underline{1.56°\text{C}}} \Rightarrow \underline{\underline{16.6°\text{FB}}} \Rightarrow \underline{\underline{1.56\text{ K}}} \Rightarrow \underline{\underline{2.8°\text{F}}} \Rightarrow \underline{\underline{2.8°\text{R}}}$

3.50 $(T_b)_{\mathrm{H_2O}} = 100°\mathrm{C} \quad (T_m)_{\mathrm{AgCl}} = 455°\mathrm{C}$

(a) $V(\mathrm{mV}) = aT(°\mathrm{C}) + b$

$$\begin{array}{l} 5.27 = 100a + b \\ 24.88 = 455a + b \end{array} \Rightarrow \begin{array}{l} a = 0.05524 \ \ \mathrm{mV}/°\mathrm{C} \\ b = -0.2539 \ \mathrm{mV} \end{array}$$

$$\underline{\underline{V(\mathrm{mV}) = 0.05524T(°\mathrm{C}) - 0.2539}}$$

$$\Downarrow$$

$$\underline{\underline{T(°\mathrm{C}) = 18.10V(\mathrm{mV}) + 4.596}}$$

(b) $10.0\ \mathrm{mV} \to 13.6\ \mathrm{mV} \Rightarrow 185.6°\mathrm{C} \to 250.8°\mathrm{C} \ \Rightarrow \ \dfrac{dT}{dt} = \dfrac{(250.8 - 185.6)°\mathrm{C}}{20\ \mathrm{s}} = \underline{\underline{3.26\ °\mathrm{C/s}}}$

3.51 **(a)** $\ln T = \ln K + n \ln R \quad \left[T = KR^n\right]$

$$n = \frac{\ln(250.0/110.0)}{\ln(40.0/20.0)} = 1.184$$

$$\ln K = \ln\ 110.0 - 1.184(\ln 20.0) = 1.154 \Rightarrow K = 3.169 \Rightarrow \underline{\underline{T = 3.169R^{1.184}}}$$

(b) $R = \left(\dfrac{320}{3.169}\right)^{1/1.184} = \underline{\underline{49.3}}$

(c) Extrapolation error, thermocouple reading wrong.

3.52 **(a)** $PV = 0.08206nT$

$$P(\mathrm{atm}) = \frac{P'(\mathrm{psig}) + 14.696}{14.696} \quad , \quad \mathrm{V(L)} = V'(\mathrm{ft}^3) \times \frac{28.317\ \mathrm{ft}^3}{\mathrm{L}}$$

$$n(\mathrm{mol}) = n'(\mathrm{lb\text{-}moles}) \times \frac{453.59\ \mathrm{mol}}{\mathrm{lb-moles}} \quad , \quad \mathrm{T(°K)} = \frac{T'(°\mathrm{F}) - 32}{1.8} + 273.15$$

$$\Rightarrow \frac{(P' + 14.696)}{14.696} \times V' \times 28.317 = 0.08206 \times n' \times \frac{453.59}{1} \times \left[\frac{(T' - 32)}{1.8} + 273.15\right]$$

$$\Rightarrow (P' + 14.696) \times V' = \frac{0.08206 \times 14.696 \times 453.59}{28.317 \times 1.8} \times n' \times (T' + 459.7)$$

$$\Rightarrow \underline{\underline{(P' + 14.696)V' = 10.73n'(T' + 459.7)}}$$

3.52 (cont'd)

(b) $n'_{tot}=\dfrac{(500+14.696)\times 3.5}{10.73\times(85+459.7)}=\underline{\underline{0.308\text{ lb-mole}}}$

$$m_{CO}=\left.\frac{0.308\text{ lb-mole}}{}\right|\left.\frac{0.30\text{ lb-mole CO}}{\text{lb-mole}}\right|\frac{28\text{ lb}_\text{m}\text{ CO}}{\text{lb-mole CO}}=\underline{\underline{2.6\text{ lb}_\text{m}\text{ CO}}}$$

(c) $T'=\dfrac{(3000+14.696)\times 3.5}{10.73\times 0.308}-459.7=\underline{\underline{2733^\circ\text{F}}}$

3.53 **(a)** $T(^\circ\text{C})=a\times r(\text{ohms})+b$

$$\left.\begin{aligned}0&=23.624a+b\\100&=33.028a+b\end{aligned}\right\}\Rightarrow\begin{aligned}a&=10.634\\b&=-251.22\end{aligned}\Rightarrow\underline{\underline{T(^\circ\text{C})=10.634r(\text{ohms})-251.22}}$$

(b) $\dot{n}\left(\dfrac{\text{kmol}}{\text{s}}\right)=\left.\dfrac{\dot{n}'\text{ (kmol)}}{\text{min}}\right|\dfrac{1\text{ min}}{60\text{ s}}=\dfrac{\dot{n}'}{60}$

$$P(\text{atm})=\left.\frac{P'(\text{mm Hg})}{}\right|\frac{1\text{ atm}}{760\text{ mm Hg}}=\frac{P'}{760}\quad,\quad T(\text{K})=T'(^\circ\text{C})+273.16$$

$$\dot{V}\left(\frac{\text{m}^3}{\text{s}}\right)=\dot{V}'\left.\frac{\text{m}^3}{\text{min}}\right|\frac{1\text{ min}}{60\text{ s}}=\frac{\dot{V}'}{60}$$

$$\frac{\dot{n}'}{60}=\left.\frac{12.186}{}\right|\left.\frac{P'}{760}\right|\left.\frac{}{T'+273.16}\right|\frac{\dot{V}'}{60}\Rightarrow\underline{\underline{\dot{n}'=\frac{0.016034P'(\text{mm Hg})\dot{V}'(\text{m}^3/\text{min})}{T'(^\circ\text{C})+273.16}}}$$

(c) $T=10.634r-251.22$

$$\Rightarrow\begin{aligned}r_1&=26.159\Rightarrow\underline{\underline{T_1=26.95^\circ\text{C}}}\\r_2&=26.157\Rightarrow\underline{\underline{T_2=26.93^\circ\text{C}}}\\r_3&=44.789\Rightarrow\underline{\underline{T_3=225.1^\circ\text{C}}}\end{aligned}$$

$$P\text{ (mm Hg)}=h+P_\text{atm}=h+(29.76\text{ in Hg})\left(\frac{760\text{ mm Hg}}{29.92\text{ in Hg}}\right)=h+755.9$$

$$\Rightarrow\begin{aligned}h_1&=232\text{ mm}\Rightarrow\underline{\underline{P_1=987.9\text{ mm Hg}}}\\h_2&=156\text{ mm}\Rightarrow\underline{\underline{P_2=911.9\text{ mm Hg}}}\\h_3&=74\text{ mm}\Rightarrow\underline{\underline{P_3=829.9\text{ mm Hg}}}\end{aligned}$$

3.53 (cont'd)

(d) $$\dot{n}_1 = \frac{(0.016034)(987.9)(947/60)}{26.95+273.16} = 0.8331 \text{ kmol CH}_4/\text{min}$$

$$\dot{n}_2 = \frac{(0.016034)(911.9)(195)}{26.93+273.16} = 9.501 \text{ kmol air}/\text{min}$$

$$\dot{n}_3 = \dot{n}_1 + \dot{n}_2 = \underline{\underline{10.33 \text{ kmol}/\text{min}}}$$

(e) $$V_3 = \frac{\dot{n}_3(T_2+273.16)}{0.016034\, P_3} = \frac{(10.33)(225.1+273.16)}{(0.016034)(829.9)} = \underline{\underline{387 \text{ m}^3/\text{min}}}$$

(f) $$\frac{0.8331 \text{ kmol CH}_4}{\text{min}} \left| \frac{16.04 \text{ kg CH}_4}{\text{kmol}} \right. = 13.36 \frac{\text{kg CH}_4}{\text{min}}$$

$$\frac{0.21 \times 9.501 \text{ kmol O}_2}{\text{min}} \left| \frac{32.0 \text{ kg O}_2}{\text{kmol O}_2} \right. + \frac{0.79 \times 9.501 \text{ kmol N}_2}{\text{min}} \left| \frac{28.0 \text{ kg N}_2}{\text{kmol N}_2} \right. = 274 \ \frac{\text{kg air}}{\text{min}}$$

$$x_{CH_4} = \frac{13.36 \text{ kg CH}_4/\text{min}}{(13.36+274) \text{ kg / min}} = \underline{\underline{0.0465 \text{ kg CH}_4/\text{kg}}}$$

3.54

```
      REAL, MW, T, SLOPE, INTCPT, KO, E
      REAL TIME (100), CA (100), TK (100), X (100), Y(100)
      INTEGER IT, N, NT, J
      READ (5,*) MW, NT
      DO 10 IT=1, NT
         READ (5,*) TC, N
         TK(IT) = TC + 273.15
         READ (5,*) (TIME (J), CA (J), J = 1, N)
         DO 1 J=1, N
           CA(J) = CA(J) / MW
           X(J) = TIME(J)
           Y(J) = 1./CA(J)
1        CONTINUE
         CALL LS (X, Y, N, SLOPE, INTCPT)
         K(IT) = SLOPE
         WRITE (E, 2) TK (IT), (TIME (J), CA (J), J = 1, N)
         WRITE (6, 3) K (IT)
10    CONTINUE
      DO 4 J=1, NT
         X(J) = 1./TK(J)
         Y(J) = LOG(K(J))
```

3.54 (cont’d)

```
4   CONTINUE
    CALL LS (X, Y, NT, SLOPE, INTCPT)
    KO = EXP(INTCPT)
    E = –8.314 = SLOPE
    WRITE (6, 5) KO, E
2   FORMAT (' TEMPERATURE (K):  ', F6.2, /
        *  '  TIME  CA', /,
        *  ' (MIN)  (MOLES)', /
        *  100 (IX, F5.2, 3X, F7.4, /))
3   FORMAT (' K (L/MOL – MIN):  ', F5.3, //)
5   FORMAT (/, ' KO (L/MOL – MIN) :  ', E 12.4, /, ' E (J/MOL):  ', E 12.4)
    END
    SUBROUTINE LS (X, Y, N, SLOPE, INTCPT)
    REAL X(100), Y(100), SLOPE, INTCPT, SX, SY, SXX, SXY, AN
    INTEGER N, J
    SX=0
    SY=0
    SXX=0
    SXY=0
    DO 10 J=1,N
        SX = SX + X(J)
        SY = SY + Y(J)
        SXX = SXX + X(J)**2
        SXY = SXY + X(J)*Y(J)
10  CONTINUE
    AN = N
    SX = SX/AN
    SY = SY/AN
    SXX = SXX/AN
    SXY = SXY/AN
    SLOPE = (SXY – SX*SY)/(SXX – SX**2)
    INTCPT = SY – SLOPE*SX
    RETURN
    END

    $ DATA                         [OUTPUT]
    65.0      4                    TEMPERATURE (K):  367.15
    94.0      6                    TIME  CA
    10.0      8.1                  (MIN)  (MOLS/L)
    20.0      4.3                  10.00   0.1246
    30.0      3.0                  20.00   0.0662
    40.0      2.2                  30.00   0.0462
    50.0      1.8                  40.00   0.0338
```

3.54 (cont'd)

```
60.0        1.5                 50.00   0.0277
                                60.00   0.0231

                                K(L / MOL · MIN):  0.707    (at 94° C)

110.        6
10.0        3.5
20.0        1.8                 TEMPERATURE (K):  383.15
30.0        1.2                 ⋮
40.0        0.92                K(L / MOL · MIN):  1.758
50.0        0.73
60.0        0.61                ⋮

127.        6
  ⋮                             K0(L / MOL – MIN):  0.2329E + 10
  ⋮ ETC                         E (J / MOL):  0.6690E + 05
```

CHAPTER FOUR

4.1 **a.** Continuous, Transient

b. Input – Output = Accumulation
No reactions ⇒ Generation = 0, Consumption = 0

$$6.00\frac{\text{kg}}{\text{s}} - 3.00\frac{\text{kg}}{\text{s}} = \frac{dn}{dt} \Rightarrow \underline{\underline{\frac{dn}{dt} = 3.00\frac{\text{kg}}{\text{s}}}}$$

c.

$$t = \frac{1.00\,\text{m}^3}{}\left|\frac{1000\,\text{kg}}{1\,\text{m}^3}\right|\frac{1\,\text{s}}{3.00\,\text{kg}} = \underline{\underline{333\text{ s}}}$$

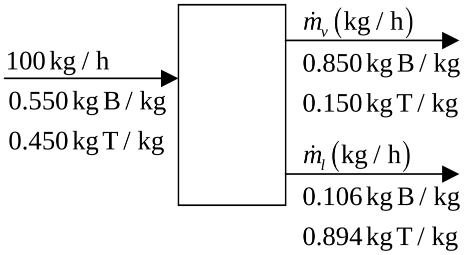
4.2 **a.** Continuous, Steady State

b. $k = 0 \Rightarrow \underline{\underline{\mathrm{C_A} = \mathrm{C_{A0}}}}$ $\qquad k = \infty \Rightarrow \underline{\underline{\mathrm{C_A} = 0}}$

c. Input – Output – Consumption = 0
Steady state ⇒ Accumulation = 0
A is a reactant ⇒ Generation = 0

$$\dot{V}\left(\frac{\text{m}^3}{\text{s}}\right)C_{A0}\left(\frac{\text{mol}}{\text{m}^3}\right) = \dot{V}\left(\frac{\text{m}^3}{\text{s}}\right)C_A\left(\frac{\text{mol}}{\text{m}^3}\right) + kVC_A\left(\frac{\text{mol}}{\text{s}}\right) \Rightarrow \underline{\underline{C_A = \frac{C_{A0}}{1+\frac{kV}{\dot{V}}}}}$$

4.3 **a.**



Input – Output = 0
Steady state ⇒ Accumulation = 0
No reaction ⇒ Generation = 0, Consumption = 0

(1) Total Mass Balance: $100.0\text{ kg / h} = \dot{m}_v + \dot{m}_l$

(2) Benzene Balance: $[0.550 \times 100.0]\text{ kg B / h} = 0.850\dot{m}_v + 0.106\dot{m}_l$

Solve (1) & (2) simultaneously ⇒ $\underline{\underline{\dot{m}_v = 59.7\text{ kg/h},\ \dot{m}_l = 40.3\text{ kg/h}}}$

b. The flow chart is identical to that of (a), except that mass flow rates (kg/h) are replaced by masses (kg). The balance equations are also identical (initial input = final output).

c. Possible explanations ⇒ a chemical reaction is taking place, the process is not at steady state, the feed composition is incorrect, the flow rates are not what they are supposed to be, other species are in the feed stream, measurement errors.

4.4 **b.**

$$\xrightarrow{\quad n\,(\text{mol})\quad}$$

$0.500\text{ mol N}_2/\text{mol}$

$0.500\text{ mol CH}_4/\text{mol}$

$$\frac{0.500n\,(\text{mol N}_2)}{}\left|\frac{28\text{ g N}_2}{\text{mol N}_2}\right|\frac{1\text{ kg}}{1000\text{ g}} = \underline{\underline{0.014n\,(\text{kg N}_2)}}$$

c.

$$\xrightarrow{\quad 100.0\text{ g/s}\quad}$$

$x_E\,(\text{g C}_2\text{H}_6/\text{g})$

$x_P\,(\text{g C}_3\text{H}_8/\text{g})$

$x_B\,(\text{g C}_4\text{H}_{10}/\text{g})$

$$\dot{n}_E = \frac{100x_E\,(\text{g C}_2\text{H}_6)}{\text{s}}\left|\frac{1\text{ lb}_\text{m}}{453.593\text{ g}}\right|\frac{\text{lb-mole C}_2\text{H}_6}{30\text{ lb}_\text{m}\text{ C}_2\text{H}_6}\left|\frac{3600\text{ s}}{\text{h}}\right.$$

$$= \underline{\underline{26.45x_E\,(\text{lb-mole C}_2\text{H}_6/\text{h})}}$$

d.

$$\xrightarrow{\quad \dot{n}_1\,(\text{lb-mole H}_2\text{O/s})\quad}$$

$$\left\{\begin{array}{l}\dot{n}_2\,(\text{lb-mole DA/s})\\ \quad 0.21\text{ lb-mole O}_2/\text{lb-mole DA}\\ \quad 0.79\text{ lb-mole N}_2/\text{lb-mole DA}\end{array}\right\}$$

$$\dot{n}_{\text{O}_2} = \underline{\underline{0.21\dot{n}_2\,(\text{lb-mole O}_2/\text{s})}}$$

$$x_{\text{H}_2\text{O}} = \underline{\underline{\frac{\dot{n}_1}{\dot{n}_1+\dot{n}_2}\left(\frac{\text{lb-mole H}_2\text{O}}{\text{lb-mole}}\right)}}$$

$$x_{\text{O}_2} = \underline{\underline{\frac{0.21\dot{n}_2}{\dot{n}_1+\dot{n}_2}\left(\frac{\text{lb-mole O}_2}{\text{lb-mole}}\right)}}$$

e.

$$\xrightarrow{\quad n\,(\text{mol})\quad}$$

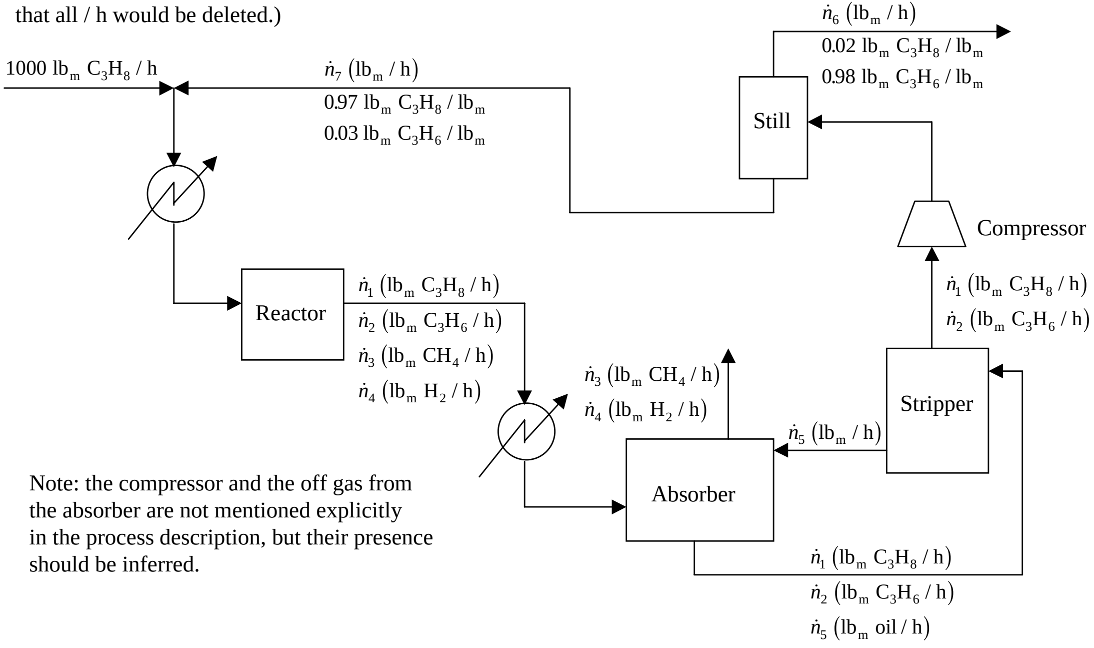
0.400 mol NO/mol

$y_{\text{NO}_2}\,(\text{mol NO}_2/\text{mol})$

$0.600 - y_{\text{NO}_2}\,(\text{mol N}_2\text{O}_4/\text{mol})$

$$n_{\text{N}_2\text{O}_4} = n\left[0.600 - y_{\text{NO}_2}\right](\text{mol N}_2\text{O}_4)$$

4.5 **a.** Basis: 1000 $\text{lb}_\text{m}\text{ C}_3\text{H}_8$ / h fresh feed
(Could also take 1 h operation as basis -
flow chart would be as below except
that all / h would be deleted.)



Note: the compressor and the off gas from
the absorber are not mentioned explicitly
in the process description, but their presence
should be inferred.

4.5 (cont'd)

b. Overall objective: To produce C_3H_6 from C_3H_8.
Preheater function: Raise temperature of the reactants to raise the reaction rate.
Reactor function: Convert C_3H_8 to C_3H_6.
Absorption tower function: Separate the C_3H_8 and C_3H_6 in the reactor effluent from the other components.
Stripping tower function: Recover the C_3H_8 and C_3H_6 from the solvent.
Distillation column function: Separate the C_3H_5 from the C_3H_8.

4.6 **a.** $\underline{\underline{\text{3 independent balances}}}$ (one for each species)

b. 7 unknowns ($\dot m_1, \dot m_3, \dot m_5, x_2, y_2, y_4, z_4$)
– 3 balances
– 2 mole fraction summations
2 unknowns must be specified

c. $\underline{\underline{y_2}} = 1 - x_2$

A Balance: $$5300x_2\left(\frac{\text{kg A}}{\text{h}}\right) = \left[\underline{\underline{\dot m_3}} + (1200)(0.70)\right]\left(\frac{\text{kg A}}{\text{h}}\right)$$

Overall Balance: $$\left[\dot m_1 + 5300\right]\left(\frac{\text{kg}}{\text{h}}\right) = \left[\dot m_3 + 1200 + \underline{\underline{\dot m_5}}\right]\left(\frac{\text{kg}}{\text{h}}\right)$$

B Balance: $$\left[0.03\dot m_1 + 5300x_2\right]\left(\frac{\text{kg B}}{\text{h}}\right) = \left[1200\underline{\underline{y_4}} + 0.60\dot m_5\right]\left(\frac{\text{kg B}}{\text{h}}\right)$$

$\underline{\underline{z_4}} = 1 - 0.70 - y_4$

4.7 **a.** $\underline{\underline{\text{3 independent balances}}}$ (one for each species)

b. Water Balance: $$\frac{400\,g}{\text{min}}\left|\frac{0.885\,\text{g H}_2\text{O}}{\text{g}}\right. = \frac{\underline{\underline{\dot m_R}}\,(g)}{(\text{min})}\left|\frac{0.995\,\text{g H}_2\text{O}}{\text{g}}\right. \Rightarrow \underline{\underline{\dot m_R = 356\,\text{g/min}}}$$

Acetic Acid Balance: $$\left[(400)(0.115)\right]\left(\frac{\text{g CH}_3\text{OOH}}{\text{min}}\right) = \left[0.005\dot m_R + 0.096\underline{\underline{\dot m_E}}\right]\left(\frac{\text{g CH}_3\text{OOH}}{\text{min}}\right)$$

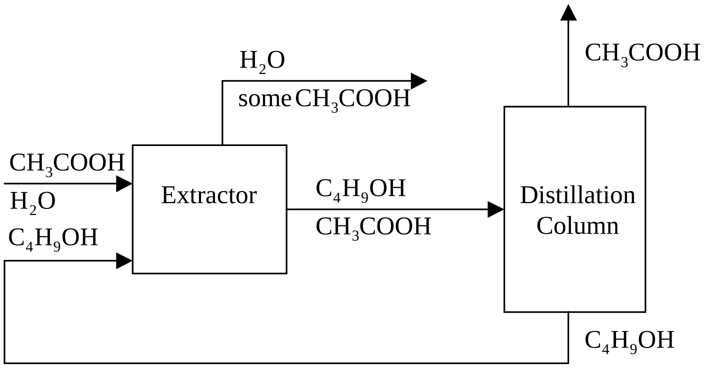
$$\Rightarrow \underline{\underline{\dot m_E = 461\,\text{g/min}}}$$

Overall Balance: $$\left[\underline{\underline{\dot m_C}} + 400\right]\left(\frac{\text{g}}{\text{min}}\right) = \left[\dot m_R + \dot m_E\right]\left(\frac{\text{g}}{\text{min}}\right) \Rightarrow \underline{\underline{\dot m_C = 417\,\text{g/min}}}$$

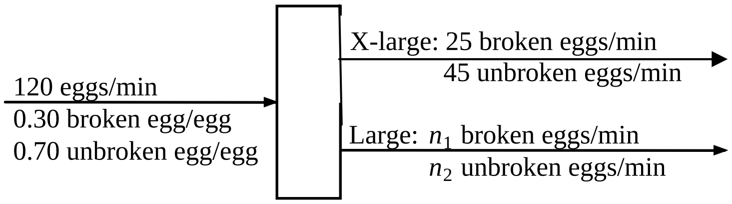
c. $$\left[(0.115)(400) - (0.005)(356)\right]\left(\frac{\text{g}}{\text{min}}\right) = \left[(0.096)(461)\right]\left(\frac{\text{g}}{\text{min}}\right) \Rightarrow \underline{\underline{44\,\text{g/min} = 44\,\text{g/min}}}$$

4.7 (cont'd)

d.



4.8 **a.**



b. $120 = 25 + 45 + n_1 + n_2 \quad (\text{eggs/min}) \Rightarrow \underline{\underline{n_1 + n_2 = 50}}$

$\underline{\underline{(0.30)(120) = 25 + n_1}}$

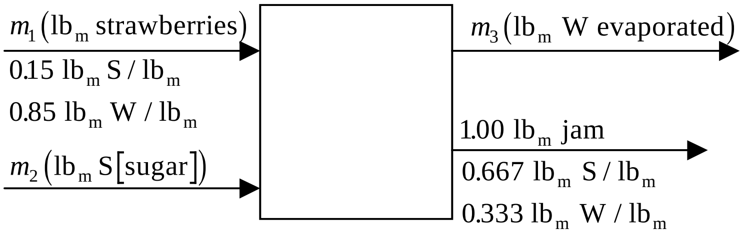
$\Rightarrow \underline{\underline{n_1 = 11}}$, $\underline{\underline{n_2 = 39}}$

c. $n_1 + n_2 = \underline{\underline{50 \text{ large eggs/min}}}$

n_1 large eggs broken/50 large eggs $= (11/50) = \underline{\underline{0.22}}$

d. 22% of the large eggs (right hand) and $(25/70) \Rightarrow 36\%$ of the extra-large eggs (left hand) are broken. Since it does not require much strength to break an egg, the left hand is probably poorly controlled (rather than strong) relative to the right. Therefore, Fred is right-handed.

4.9 **a.**



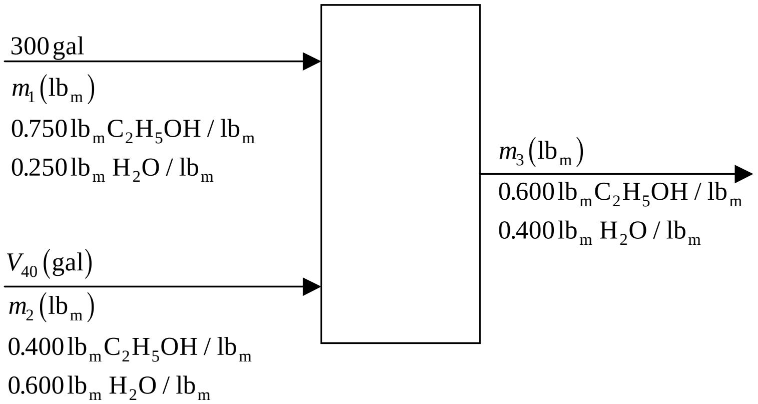
b.
3 unknowns (m_1, m_2, m_3)
– 2 balances
– 1 feed ratio
0 DF

c. Feed ratio: $m_1 / m_2 = 45/55$ (1)

S balance: $0.15m_1 + m_2 = 0.667$ (2)

Solve simultaneously $\Rightarrow$ $m_1 = \underline{\underline{0.49 \text{ lb}_\text{m} \text{ strawberries}}}$, $m_2 = 0.59 \text{ lb}_\text{m}$ sugar

4.10 **a.**



4 unknowns (m_1, m_2, V_{40}, m_3)
– 2 balances
<u>– 2 specific gravities</u>
0 DF

b.

$$m_1 = \frac{300\,\text{gal}}{} \left| \frac{1\,\text{ft}^3}{7.4805\,\text{gal}} \right| \frac{0.877\times 62.4\,\text{lb}_\text{m}}{\text{ft}^3} = 2195\,\text{lb}_\text{m}$$

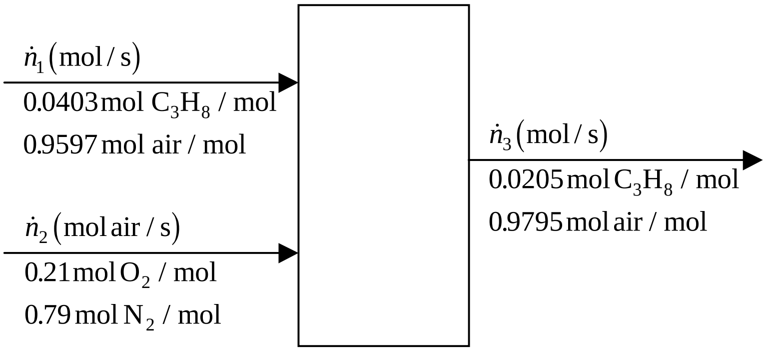
<u>Overall balance</u>: $m_1 + m_2 = m_3$ (1)

<u>C$_2$H$_5$OH balance</u>: $0.750m_1 + 0.400m_2 = 0.600m_3$ (2)

Solve (1) & (2) simultaneously $\Rightarrow m_2 = 1646\,\text{lb}_{\text{m},}, m_3 = 3841\,\text{lb}_\text{m}$

$$V_{40} = \frac{1646\,\text{lb}_\text{m}}{} \left| \frac{\text{ft}^3}{0.952\times 62.4\,\text{lb}_\text{m}} \right| \frac{7.4805\,\text{gal}}{1\,\text{ft}^3} = \underline{\underline{207\,\text{gal}}}$$

4.11 **a.**



3 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_3$)
<u>– 2 balances</u>
1 DF

b.

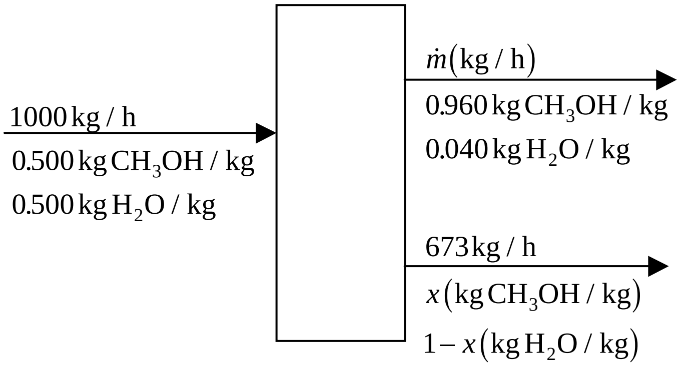
<u>Propane feed rate</u>: $0.0403\dot{n}_1 = 150 \Rightarrow \dot{n}_1 = 3722(\text{mol/s})$

<u>Propane balance</u>: $0.0403\dot{n}_1 = 0.0205\dot{n}_3 \Rightarrow \dot{n}_3 = 7317(\text{mol/s})$

<u>Overall balance</u>: $3722 + \dot{n}_2 = 7317 \Rightarrow \underline{\underline{\dot{n}_2 = 3600(\text{mol/s})}}$

c. $\geq$. The dilution rate should be greater than the value calculated to ensure that ignition is not possible even if the fuel feed rate increases slightly.

4.12 **a.**



2 unknowns ($\dot{m}, x$)
<u>– 2 balances</u>
0 DF

b. <u>Overall balance</u>: $1000=\dot{m}+673 \Rightarrow \dot{m}=327\ \text{kg/h}$

<u>Methanol balance</u>: $0.500(1000)=0.960(327)+x(673) \Rightarrow \underline{\underline{x=0.276\ \text{kg}\ CH_3OH/\text{kg}}}$

<u>Molar flow rates of methanol and water</u>:

$$\frac{673\ \text{kg}}{\text{h}}\left|\frac{0.276\ \text{kg}\ CH_3OH}{\text{kg}}\right|\frac{1000\ \text{g}}{\text{kg}}\left|\frac{\text{mol}\ CH_3OH}{32.0\ \text{g}\ CH_3OH}\right.=\underline{\underline{5.80\times10^3\ \text{mol}\ CH_3OH/\text{h}}}$$

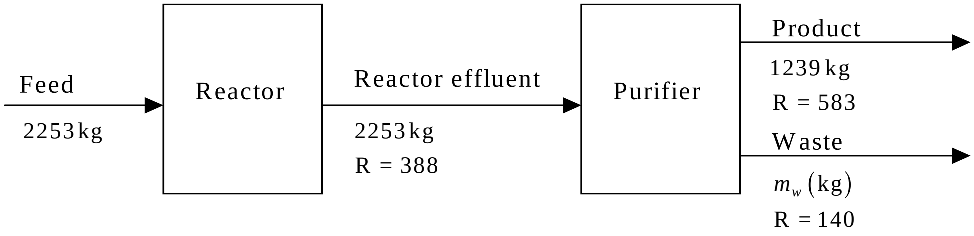
$$\frac{673\ \text{kg}}{\text{h}}\left|\frac{0.724\ \text{kg}\ H_2O}{\text{kg}}\right|\frac{1000\ \text{g}}{\text{kg}}\left|\frac{\text{mol}\ H_2O}{18\ \text{g}\ H_2O}\right.=\underline{\underline{2.71\times10^4\ \text{mol}\ H_2O/\text{h}}}$$

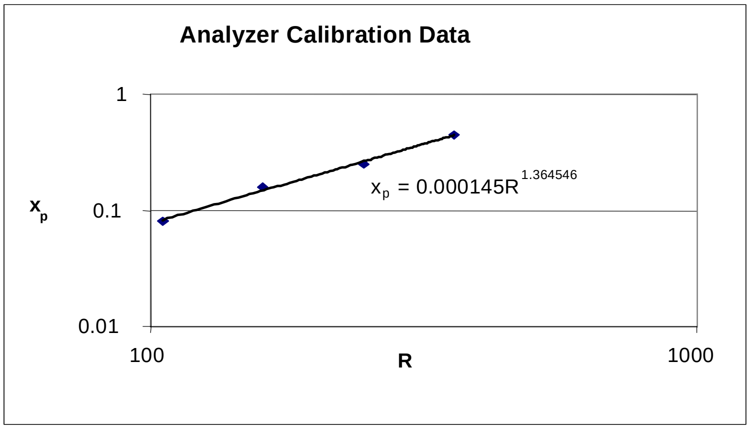
<u>Mole fraction of Methanol</u>:

$$\frac{5.80\times10^3}{5.80\times10^3+2.71\times10^4}=\underline{\underline{0.176\ \text{mol}\ CH_3OH/\text{mol}}}$$

c. Analyzer is wrong, flow rates are wrong, impurities in the feed, a reaction is taking place, the system is not at steady state.

4.13 **a.**





4.13 (cont'd)

b. Effluent: $x_p = 0.000145(388)^{1.3645} = \underline{\underline{0.494\,\text{kg P / kg}}}$

Product: $x_p = 0.000145(583)^{1.3645} = \underline{\underline{0.861\,\text{kg P / kg}}}$

Waste: $x_p = 0.000145(140)^{1.3645} = \underline{\underline{0.123\,\text{kg P / kg}}}$

$$\underline{\text{Efficiency}} = \frac{0.861(1239)}{0.494(2253)} \times 100\% = \underline{\underline{95.8\%}}$$

c. Mass balance on purifier: $2253 = 1239 + m_w \Rightarrow m_w = 1014\,\text{kg}$

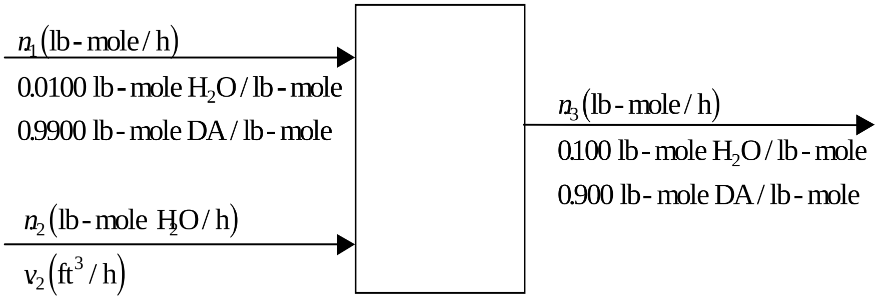
P balance on purifier:

Input: $(0.494\text{ kg P / kg})(2253\text{ kg}) = 1113\text{ kg P}$

Output: $(0.861\text{ kg P / kg})(1239\text{ kg}) + (0.123\text{ kg P / kg})(1014\text{ kg}) = 1192\text{ kg P}$

The P balance does not close. Analyzer readings are wrong; impure feed; extrapolation beyond analyzer calibration data is risky -- recalibrate; get data for R > 583; not at steady state; additional reaction occurs in purifier; normal data scatter.

4.14 a.



4 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{v}$) – 2 balances – 1 density – 1 meter reading = 0 DF

Assume linear relationship: $\dot{v} = aR + b$

Slope: $a = \dfrac{\dot{v}_2 - \dot{v}_1}{R_2 - R_1} = \dfrac{96.9 - 40.0}{50 - 15} = 1.626$

Intercept: $b = \dot{v}_a - aR_1 = 40.0 - 1.626(15) = 15.61$

$\dot{v}_2 = 1.626(95) + 15.61 = 170\,(\text{ft}^3/\text{h})$

$$\dot{n}_2 = \frac{170\,\text{ft}^3}{\text{h}}\left|\frac{62.4\,\text{lb}_\text{m}}{\text{ft}^3}\right|\frac{\text{lb-mol}}{18.0\,\text{lb}_\text{m}} = 589\,(\text{lb-moles}\,H_2O/\text{h})$$

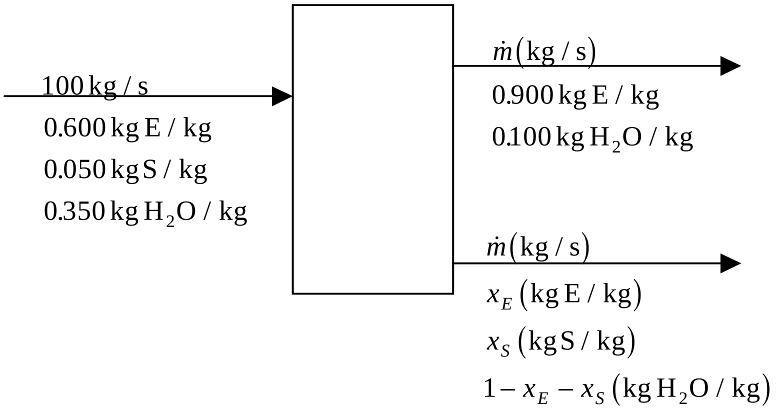
DA balance: $0.9900\dot{n}_1 = 0.900\dot{n}_3$ (1)

Overall balance: $\dot{n}_1 + \dot{n}_2 = \dot{n}_3$ (2)

Solve (1) & (2) simultaneously $\Rightarrow \dot{n}_1 = 5890$ lb-moles/h, $\underline{\underline{\dot{n}_3 = 6480\text{ lb-moles/h}}}$

b. Bad calibration data, not at steady state, leaks, 7% value is wrong, $\dot{v}$ – R relationship is not linear, extrapolation of analyzer correlation leads to error.

4.15 **a.**



3 unknowns ($\dot{m}, x_E, x_S$)
<u>– 3 balances</u>
0 DF

b. <u>Overall balance</u>: $100 = 2\dot{m} \Rightarrow \dot{m} = 50.0(\text{kg/s})$

<u>S balance</u>: $0.050(100) = x_S(50) \Rightarrow \underline{\underline{x_S = 0.100(\text{kg S/kg})}}$

<u>E balance</u>: $0.600(100) = 0.900(50) + x_E(50) \Rightarrow x_E = 0.300\ \text{kg E/kg}$

$$\frac{\text{kg E in bottom stream}}{\text{kg E in feed}} = \frac{0.300(50)}{0.600(100)} = \underline{\underline{0.25\frac{\text{kg E in bottom stream}}{\text{kg E in feed}}}}$$

c. $x = aR^b \Rightarrow \ln(x) = \ln(a) + b\ln(R)$

$$b = \frac{\ln(x_2/x_1)}{\ln(R_2/R_1)} = \frac{\ln(0.400/0.100)}{\ln(38/15)} = 1.491$$

$$\ln(a) = \ln(x_1) - b\ln(R_1) = \ln(0.100) - 1.491\ln(15) = -6.340 \Rightarrow a = 1.764\times10^{-3}$$

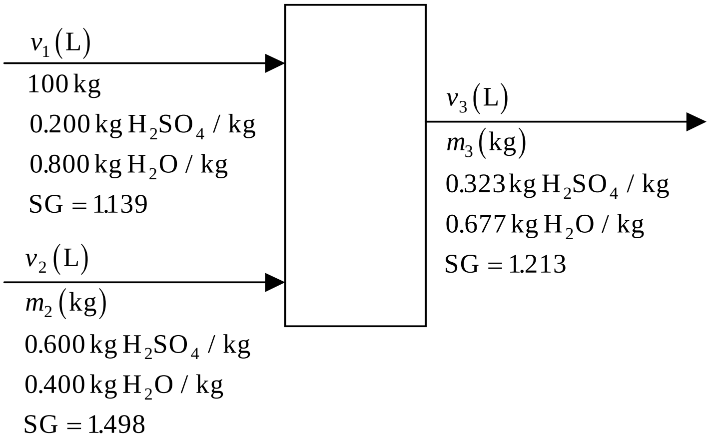
$$\underline{\underline{x = 1.764\times10^{-3}R^{1.491}}}$$

$$R = \left(\frac{x}{a}\right)^{\frac{1}{b}} = \left(\frac{0.900}{1.764\times10^{-3}}\right)^{\frac{1}{1.491}} = \underline{\underline{65.5}}$$

d. Device not calibrated – recalibrate. Calibration curve deviates from linearity at high mass fractions – measure against known standard. Impurities in the stream – analyze a sample. Mixture is not all liquid – check sample. Calibration data are temperature dependent – check calibration at various temperatures. System is not at steady state – take more measurements. Scatter in data – take more measurements.

4.16 **a.** $$\frac{4.00\,\text{mol}\,H_2SO_4}{\text{L of solution}}\left|\frac{0.098\,\text{kg}\,H_2SO_4}{\text{mol}\,H_2SO_4}\right|\frac{\text{L of solution}}{1.213\,\text{kg solution}} = \underline{\underline{0.323\left(\text{kg}\,H_2SO_4\,/\,\text{kg solution}\right)}}$$

b.



5 unknowns (v_1, v_2, v_3, m_2, m_3)
– 2 balances
<u>– 3 specific gravities</u>
0 DF

<u>Overall mass balance</u>: $100 + m_2 = m_3$
<u>Water balance</u>: $0.800(100) + 0.400m_2 = 0.677m_3$

$$\left.\begin{array}{l} 100 + m_2 = m_3 \\ 0.800(100) + 0.400m_2 = 0.677m_3 \end{array}\right\} \Rightarrow \begin{array}{l} m_2 = 44.4\,\text{kg} \\ m_3 = 144\,\text{kg} \end{array}$$

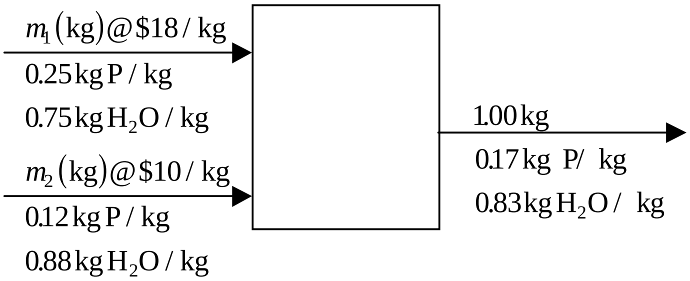
$$v_1 = \frac{100\,\text{kg}}{}\left|\frac{\text{L}}{1.139\,\text{kg}}\right. = 87.80\,\text{L 20\% solution}$$

$$v_2 = \frac{44.4\,\text{kg}}{}\left|\frac{\text{L}}{1.498\,\text{kg}}\right. = 29.64\,\text{L 60\% solution}$$

$$\frac{v_1}{v_2} = \frac{87.80}{29.64} = \underline{\underline{2.96\frac{\text{L 20\% solution}}{\text{L 60\% solution}}}}$$

c. $$\frac{1250\,\text{kg P}}{\text{h}}\left|\frac{44.4\,\text{kg 60\% solution}}{144\,\text{kg P}}\right|\frac{\text{L}}{1.498\,\text{kg solution}} = \underline{\underline{257\,\text{L/h}}}$$

4.17



<u>Overall balance</u>: $m_1 + m_2 = 1.00$ (1)

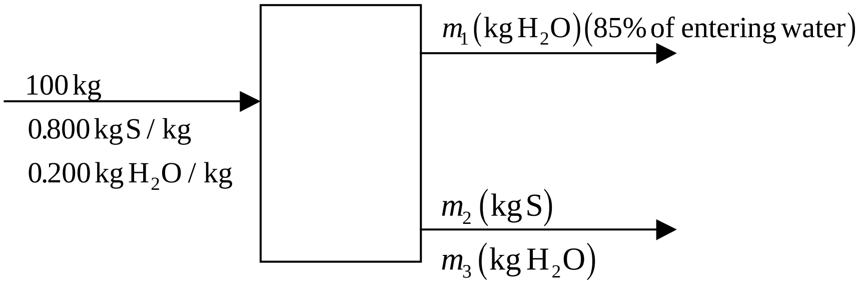
<u>Pigment balance</u>: $0.25m_1 + 0.12m_2 = 0.17(1.00)$ (2)

Solve (1) and (2) simultaneously $\Rightarrow m_1 = 0.385\,\text{kg 25\% paint}, m_2 = 0.615\,\text{kg 12\% paint}$

<u>Cost of blend</u>: $0.385(\$18.00) + 0.615(\$10.00) = \$13.08$ per kg

<u>Selling price</u>: $1.10(\$13.08) = \underline{\underline{\$14.39\text{ per kg}}}$

4.18 **a.**



<u>85% drying</u>: $m_1 = 0.850(0.200)(100) = 17.0\ \text{kg H}_2\text{O}$

<u>Sugar balance</u>: $m_2 = 0.800(100) = 80.0\ \text{kg S}$

<u>Overall balance</u>: $100 = 17 + 80 + m_3 \Rightarrow m_3 = 3\ \text{kg H}_2\text{O}$

$$x_w = \frac{3\ \text{kg H}_2\text{O}}{(3+80)\ \text{kg}} = \underline{\underline{0.0361\ \text{kg H}_2\text{O / kg}}}$$

$$\frac{m_1}{m_2+m_3} = \frac{17\ \text{kg H}_2\text{O}}{(80+3)\ \text{kg}} = \underline{\underline{0.205\ \text{kg H}_2\text{O / kg wet sugar}}}$$

b.

$$\frac{1000\ \text{tons wet sugar}}{\text{day}}\left|\frac{3\ \text{tons H}_2\text{O}}{100\ \text{tons wet sugar}}\right. = \underline{\underline{30\ \text{tons H}_2\text{O / day}}}$$

$$\frac{1000\ \text{tons WS}}{\text{day}}\left|\frac{0.800\ \text{tons DS}}{\text{ton WS}}\right|\frac{2000\ \text{lb}_\text{m}}{\text{ton}}\left|\frac{\$0.15}{\text{lb}_\text{m}}\right|\frac{365\ \text{days}}{\text{year}} = \underline{\underline{\$8.8\times10^7\ \text{per year}}}$$

c.

$$\bar{x}_w = \frac{1}{10}(x_{w1} + x_{w2} + \ldots + x_{w10}) = 0.0504\ \text{kg H}_2\text{O / kg}$$

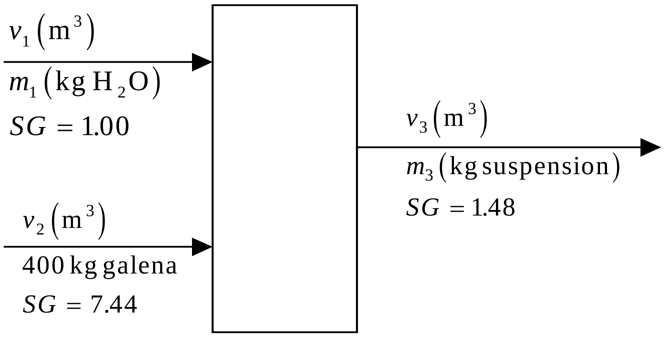
$$\text{SD} = \sqrt{\frac{1}{9}\left[(x_{w1} - \bar{x}_w)^2 + \ldots + (x_{w10} - \bar{x}_w)^2\right]} = 0.00181\ \text{kg H}_2\text{O / kg}$$

$$\text{Endpoints} = 0.0504 \pm 3(0.00181)$$

$$\underline{\underline{\text{Lower limit} = 0.0450}},\ \underline{\underline{\text{Upper limit} = 0.0558}}$$

d. The evaporator is probably not working according to design specifications since $x_w = 0.0361 < 0.0450$.

4.19 **a.**



5 unknowns (v_1, v_2, v_3, m_1, m_3)
– 1 mass balance
– 1 volume balance
<u>– 3 specific gravities</u>
0 DF

<u>Total mass balance</u>: $m_1 + 400 = m_3$ (1)

4.19 (cont'd)

Assume volume additivity: $\dfrac{m_1(\text{kg})}{}\left|\dfrac{\text{m}^3}{1000\,\text{kg}}\right. + \dfrac{400\,\text{kg}}{}\left|\dfrac{\text{m}^3}{7440\,\text{kg}}\right. = \dfrac{m_3(\text{kg})}{}\left|\dfrac{\text{m}^3}{1480\,\text{kg}}\right.$ (2)

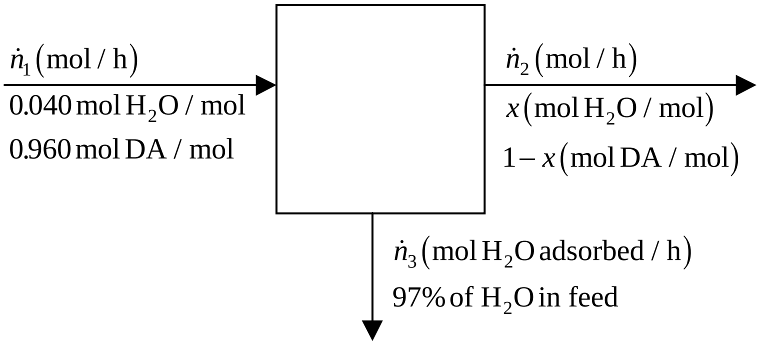
Solve (1) and (2) simultaneously $\Rightarrow m_1 = 668\,\text{kg H}_2\text{O}, m_3 = 1068\,\text{kg suspension}$

$$v_1 = \frac{668\,\text{kg}}{}\left|\frac{\text{m}^3}{1000\,\text{kg}}\right. = \underline{\underline{0.668\,\text{m}^3\text{ water fed to tank}}}$$

b. Specific gravity of coal < 1.48 < Specific gravity of slate

c. The suspension begins to settle. Stir the suspension. 1.00 < Specific gravity of coal < 1.48

4.20 a.



Adsorption rate: $\dot{n}_3 = \dfrac{(3.54-3.40)\,\text{kg}}{5\text{ h}}\left|\dfrac{\text{mol H}_2\text{O}}{0.0180\,\text{kg H}_2\text{O}}\right. = 1.556\,\text{mol H}_2\text{O/h}$

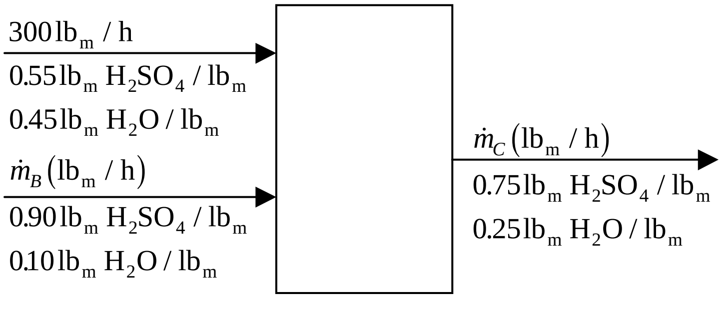
97% adsorbed: $1.56 = 0.97(0.04\dot{n}_1) \Rightarrow \dot{n}_1 = \underline{\underline{40.1\,\text{mol/h}}}$

Total mole balance: $\dot{n}_1 = \dot{n}_2 + \dot{n}_3 \Rightarrow \dot{n}_2 = 40.1 - 1.556 = 38.54\,\text{mol/h}$

Water balance: $0.040(40.1) = 1.556 + x(38.54) \Rightarrow x = \underline{\underline{1.2\times10^{-3}\,(\text{mol H}_2\text{O/mol})}}$

b. The calcium chloride pellets have reached their saturation limit. Eventually the mole fraction will reach that of the inlet stream, i.e. 4%.

4.21 a.



Overall balance: $300 + \dot{m}_B = \dot{m}_C$ (1)

H_2SO_4 balance: $0.55(300) + 0.90\dot{m}_B = 0.75\dot{m}_C$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{m}_B = \underline{\underline{400\,\text{lb}_\text{m}/\text{h}}}, \dot{m}_C = \underline{\underline{700\,\text{lb}_\text{m}/\text{h}}}$

4.21 (cont'd)

b.

$$\dot{m}_A - 150 = \frac{500-150}{70-25}(R_A - 25) \Rightarrow \underline{\underline{\dot{m}_A = 7.78R_A - 44.4}}$$

$$\dot{m}_B - 200 = \frac{800-200}{60-20}(R_B - 20) \Rightarrow \underline{\underline{\dot{m}_B = 15.0R_B - 100}}$$

$$\ln x - \ln 20 = \frac{\ln 100 - \ln 20}{10-4}(R_x - 4) \Rightarrow \ln x = 0.2682R_x + 1.923 \Rightarrow \underline{\underline{x = 6.841e^{0.2682R_x}}}$$

$$m_A = 300 \Rightarrow R_A = \frac{300+44.4}{7.78} = \underline{\underline{44.3}}, m_B = 400 \Rightarrow R_B = \frac{400+100}{15.0} = \underline{\underline{33.3}},$$

$$x = 55\% \Rightarrow R_x = \frac{1}{0.268}\ln\left(\frac{55}{6.841}\right) = \underline{\underline{7.78}}$$

c. <u>Overall balance</u>: $\dot{m}_A + \dot{m}_B = \dot{m}_C$

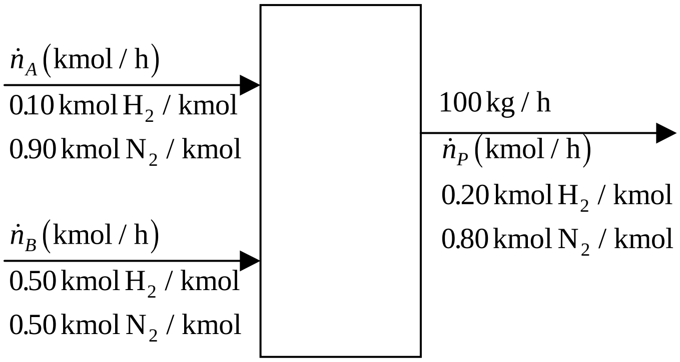
<u>H_2SO_4 balance</u>: $0.01x\dot{m}_A + 0.90\dot{m}_B = 0.75\dot{m}_C = 0.75(\dot{m}_A + \dot{m}_B) \Rightarrow \dot{m}_B = \dfrac{(0.75-0.01x)\dot{m}_A}{0.15}$

$$\Rightarrow 15.0R_B - 100 = \frac{\left[0.75 - 0.01\left(6.841e^{0.2682R_x}\right)\right](7.78R_A - 44.4)}{0.15}$$

$$\Rightarrow \underline{\underline{R_B = \left(2.59 - 0.236e^{0.2682R_x}\right)R_A + 1.35e^{0.2682R_x} - 8.13}}$$

<u>Check</u>: $R_A = 44.3, R_x = 7.78 \Rightarrow R_B = \left(2.59 - 0.236e^{0.2682(7.78)}\right)44.3 + 1.35e^{0.2682(7.78)} - 8.13 = 33.3$

4.22 a.



$$\overline{MW} = 0.20(2.016) + 0.80(28.012) = 22.813 \text{ kg / kmol}$$

$$\Rightarrow \dot{n}_P = \frac{100 \text{ kg}}{\text{h}}\bigg|\frac{\text{kmol}}{22.813 \text{ kg}} = 4.38 \text{ kmol / h}$$

<u>Overall balance</u>: $\dot{n}_A + \dot{n}_B = 4.38$ (1)

<u>H_2 balance</u>: $0.10\dot{n}_A + 0.50\dot{n}_B = 0.20(4.38)$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{n}_A = \underline{\underline{3.29 \text{ kmol / h}}},\ \dot{n}_B = \underline{\underline{1.10 \text{ kmol / h}}}$

4.22 (cont'd)

b. $\dot{n}_P = \dfrac{\dot{m}_P}{22.813}$

Overall balance: $\dot{n}_A + \dot{n}_B = \dfrac{\dot{m}_P}{22.813}$

H_2 balance: $x_A\dot{n}_A + x_B\dot{n}_B = \dfrac{x_P\dot{m}_P}{22.813}$

$$\Rightarrow \quad \underline{\underline{\dot{n}_A = \frac{\dot{m}_P}{22.813}\frac{(x_B - x_P)}{(x_B - x_A)}}} \qquad \underline{\underline{\dot{n}_B = \frac{\dot{m}_P}{22.813}\frac{(x_P - x_A)}{(x_B - x_A)}}}$$

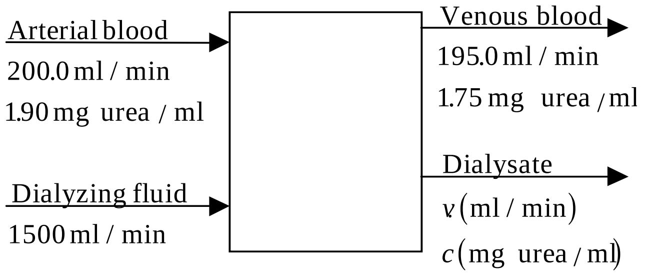
c.

Trial	X_A	X_B	X_P	m_P	n_A	n_B
1	0.10	0.50	0.10	100	4.38	0.00
2	0.10	0.50	0.20	100	3.29	1.10
3	0.10	0.50	0.30	100	2.19	2.19
4	0.10	0.50	0.40	100	1.10	3.29
5	0.10	0.50	0.50	100	0.00	4.38
6	**0.10**	**0.50**	**0.60**	**100**	**-1.10**	**5.48**
7	0.10	0.50	0.10	250	10.96	0.00
8	0.10	0.50	0.20	250	8.22	2.74
9	0.10	0.50	0.30	250	5.48	5.48
10	0.10	0.50	0.40	250	2.74	8.22
11	0.10	0.50	0.50	250	0.00	10.96
12	**0.10**	**0.50**	**0.60**	**250**	**-2.74**	**13.70**

The results of trials 6 and 12 are impossible since the flow rates are negative. You cannot blend a 10% H_2 mixture with a 50% H_2 mixture and obtain a 60% H_2 mixture.

d. Results are the same as in part c.

4.23



a. Water removal rate: $200.0 - 195.0 = \underline{\underline{5.0 \text{ ml / min}}}$

Urea removal rate: $1.90(200.0) - 1.75(195.0) = \underline{\underline{38.8 \text{ mg urea / min}}}$

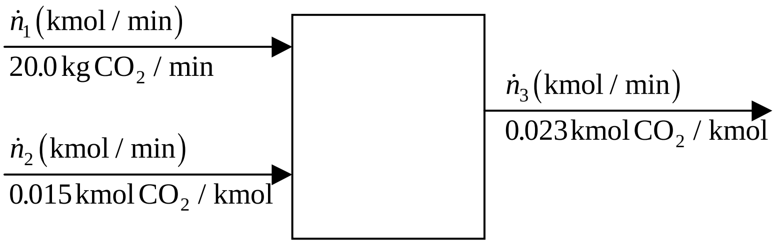
b. $\dot{v} = 1500 + 5.0 = 1505 \text{ ml / min}$

$$c = \frac{38.8 \text{ mg urea/min}}{1505 \text{ ml/min}} = \underline{\underline{0.0258 \text{ mg urea/ml}}}$$

c.

$$\frac{(2.7 - 1.1)\text{ mg removed}}{\text{ml}}\left|\frac{1 \text{ min}}{38.8 \text{ mg removed}}\right|\frac{10^3 \text{ ml}}{1 \text{ L}}\left|\frac{5.0 \text{ L}}{}\right. = \underline{\underline{206 \text{ min}}}\ (3.4 \text{ h})$$

4.24 **a.**



$$\dot{n}_1 = \frac{20.0\,\text{kg}\,CO_2}{\text{min}}\left|\frac{\text{kmol}}{44.0\,\text{kg}\,CO_2}\right. = 0.455\ \text{kmol}\,CO_2\ /\ \text{min}$$

<u>Overall balance</u>: $0.455 + \dot{n}_2 = \dot{n}_3$ (1)

<u>CO_2 balance</u>: $0.455 + 0.015\dot{n}_2 = 0.023\dot{n}_3$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{n}_2 = \underline{\underline{55.6\ \text{kmol / min}}}, \dot{n}_3 = 56.1\ \text{kmol / min}$

b.

$$u = \frac{150\,\text{m}}{18\,\text{s}} = \underline{\underline{8.33\ \text{m / s}}}$$

$$A = \frac{1}{4}\pi D^2 = \frac{56.1\,\text{kmol}}{\text{min}}\left|\frac{\text{m}^3}{0.123\,\text{kmol}}\right|\frac{1\,\text{min}}{60\,\text{s}}\left|\frac{\text{s}}{8.33\,\text{m}}\right. \Rightarrow D = \underline{\underline{1.08\ \text{m}}}$$

4.25

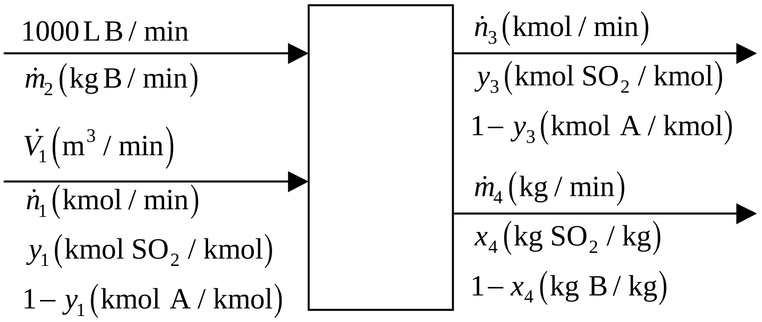
<u>Spectrophotometer calibration</u>: $C = kA \underset{C=3}{\overset{}{\underset{A=0.9}{=\!=\!=\!=\!>}}} C\ (\mu\text{g / L}) = 3.333A$

<u>Dye concentration</u>: $A = 0.18 \Rightarrow C = (3.333)(0.18) = 0.600\ \mu\text{g / L}$

<u>Dye injected</u> $= \dfrac{0.60\ \text{cm}^3}{}\left|\dfrac{1\ \text{L}}{10^3\ \text{cm}^3}\right|\dfrac{5.0\ \text{mg}}{1\ \text{L}}\left|\dfrac{10^3\ \mu\text{g}}{1\ \text{mg}}\right. = 3.0\ \mu\text{g}$

$\Rightarrow (3.0\ \mu\text{g}) / V(\text{L}) = 0.600\ \mu\text{g / L} \Rightarrow \underline{\underline{V = 5.0\ \text{L}}}$

4.26 **a.**



4.26 (cont'd)

8 unknowns ($\dot{n}_1, \dot{n}_3, \dot{v}_1, \dot{m}_2, \dot{m}_4, x_4, y_1, y_3$)
– 3 material balances
– 2 analyzer readings
– 1 meter reading
– 1 gas density formula
– 1 specific gravity
0 DF

b. Orifice meter calibration:

A log plot of $\dot{V}$ vs. h is a line through the points $\left(h_1 = 100, \dot{V}_1 = 142\right)$ and $\left(h_2 = 400, \dot{V}_2 = 290\right)$.

$$\ln \dot{V} = b \ln h + \ln a \Rightarrow \dot{V} = a h^b$$

$$b = \frac{\ln\left(\dot{V}_2/\dot{V}_1\right)}{\ln\left(h_2/h_1\right)} = \frac{\ln(290/142)}{\ln(400/100)} = 0.515$$

$$\ln a = \ln \dot{V}_1 - b \ln h_1 = \ln(142) - 0.515 \ln 100 = 2.58 \Rightarrow a = e^{2.58} = 13.2 \Rightarrow \underline{\underline{\dot{V} = 13.2 h^{0.515}}}$$

Analyzer calibration:

$$\ln y = bR + \ln a \Rightarrow y = a e^{bR}$$

$$\left.\begin{array}{l} b = \dfrac{\ln\left(y_2/y_1\right)}{R_2 - R_1} = \dfrac{\ln(0.1107/0.00166)}{90 - 20} = 0.0600 \\ \ln a = \ln y_1 - bR_1 = \ln(0.00166) - 0.0600(20) = -7.60 \\ \qquad \Downarrow \\ a = 5.00 \times 10^{-4} \end{array}\right\} \Rightarrow \underline{\underline{y = 5.00 \times 10^{-4} e^{0.0600R}}}$$

c.

$$h_1 = 210 \text{ mm} \Rightarrow \dot{V}_1 = 13.2(210)^{0.515} = 207.3 \ \text{m}^3/\text{min}$$

$$\rho_{\text{feed gas}} = \frac{(12.2)\left[(150 + 14.7)/14.7\right](\text{atm})}{\left[(75 + 460)/1.8\right](\text{K})} = 0.460 \text{ mol / L} \ = \ 0.460 \text{ kmol / m}^3$$

$$\Downarrow$$

$$\dot{n}_1 = \frac{207.3 \text{ m}^3}{\text{min}}\left|\frac{0.460 \text{ kmol}}{\text{m}^3}\right. = 95.34 \ \text{kmol/min}$$

$$R_1 = 82.4 \Rightarrow y_1 = 5.00 \times 10^{-4} \exp(0.0600 \times 82.4) = 0.0702 \text{ kmol SO}_2/\text{kmol}$$

$$R_3 = 11.6 \Rightarrow y_3 = 5.00 \times 10^{-4} \exp(0.0600 \times 11.6) = 0.00100 \text{ kmol SO}_2/\text{kmol}$$

$$\dot{m}_2 = \frac{1000 \text{ L B}}{\text{min}}\left|\frac{1.30 \text{ kg}}{\text{L B}}\right. = 1300 \text{ kg / min}$$

4.26 (cont'd)

A balance: $(1-0.0702)(95.34)=(1-0.00100)n_3 \Rightarrow n_3 = 88.7$ kmol/min

SO$_2$ balance: $(0.0702)(95.34)(64.0\text{ kg/kmol}) = (0.00100)(88.7)(64) + \dot{m}_4 x_4$ (1)

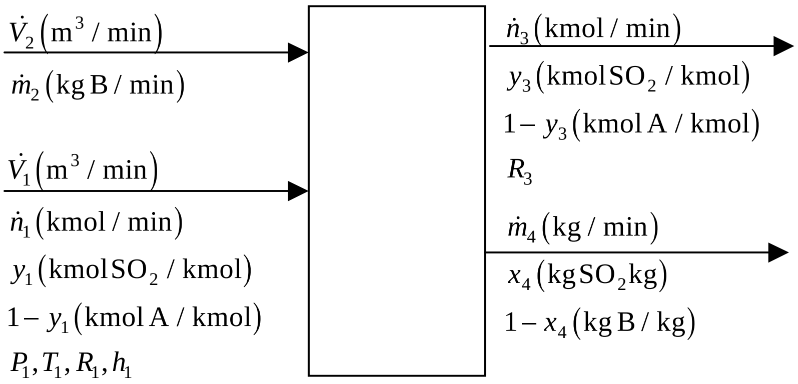
B balance: $1300 = \dot{m}_4(1-x_4)$ (2)

Solve (1) and (2) simultaneously $\Rightarrow \dot{m}_4 = 1723$ kg/min, $x_4 = \underline{\underline{0.245\text{ kg SO}_2\text{ absorbed/kg}}}$

SO$_2$ removed $= \dot{m}_4 x_4 = \underline{\underline{422\text{ kg SO}_2/\text{min}}}$

d. Decreasing the bubble size increases the bubble surface-to-volume ratio, which results in a higher rate of transfer of SO$_2$ from the gas to the liquid phase.

4.27 **a.**



b. 14 unknowns ($\dot{n}_1, \dot{V}_1, y_1, P_1, T_1, R_1, h_1, \dot{V}_2, \dot{m}_2, \dot{n}_3, y_3, R_3, \dot{m}_4, x_4$)
– 3 material balances
– 3 analyzer and orifice meter readings
– 1 gas density formula (relates $\dot{n}_1$ and $\dot{V}_1$)
– 1 specific gravity (relates $\dot{m}_2$ and $\dot{V}_2$)
6 DF

A balance: $(1-y_1)\dot{n}_1 = (1-y_3)\dot{n}_3$ (1)

SO$_2$ balance: $y_1\dot{n}_1 = y_3\dot{n}_3 + \dfrac{x_4\dot{m}_4}{64\text{ kg SO}_2/\text{kmol}}$ (2)

B balance: $\dot{m}_2 = (1-x_4)\dot{m}_4$ (3)

Calibration formulas: $y_1 = 5.00\times10^{-4}e^{0.060R_1}$ (4)

$y_3 = 5.00\times10^{-4}e^{0.060R_3}$ (5)

$\dot{V}_1 = 13.2h_1^{0.515}$ (6)

Gas density formula: $\dot{n}_1 = \dfrac{12.2\left[(P_1+14.7)/14.7\right]}{\left[(T_1+460)/1.8\right]}\dot{V}_1$ (7)

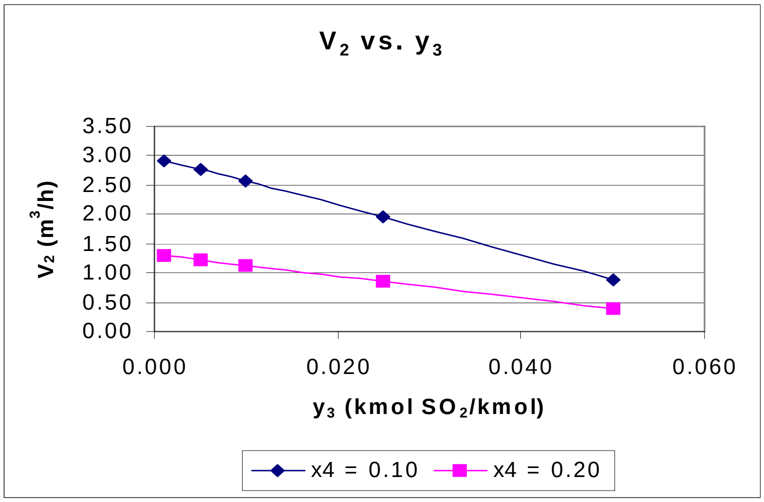
Liquid specific gravity: $SG = 1.30 \Rightarrow \dot{V}_2 = \dfrac{\dot{m}_2(\text{kg})}{\text{h}}\left|\dfrac{\text{m}^3}{1300\text{ kg}}\right.$ (8)

4.27 (cont'd)

c.

T_1	75	°F	y_1	0.07	kmol SO_2/kmol
P_1	150	psig	V_1	207	m3/h
h_1	210	torr	n_1	95.26	kmol/h
R_1	82.4				

Trial	x_4 (kg SO_2/kg)	y_3 (kmol SO_2/kmol)	V_2 (m_3/h)	n_3 (kmol/h)	m_4 (kg/h)	m_2 (kg/h)
1	0.10	0.050	0.89	93.25	1283.45	1155.11
2	0.10	0.025	1.95	90.86	2813.72	2532.35
3	0.10	0.010	2.56	89.48	3694.78	3325.31
4	0.10	0.005	2.76	89.03	3982.57	3584.31
5	0.10	0.001	2.92	88.68	4210.72	3789.65
6	0.20	0.050	0.39	93.25	641.73	513.38
7	0.20	0.025	0.87	90.86	1406.86	1125.49
8	0.20	0.010	1.14	89.48	1847.39	1477.91
9	0.20	0.005	1.23	89.03	1991.28	1593.03
10	0.20	0.001	1.30	88.68	2105.36	1684.29



For a given SO_2 feed rate removing more SO_2 (lower y_3) requires a higher solvent feed rate ($\dot{V}_2$).

For a given SO_2 removal rate (y_3), a higher solvent feed rate ($\dot{V}_2$) tends to a more dilute SO_2 solution at the outlet (lower x_4).

d. Answers are the same as in part c.

4.28 Maximum balances: Overall - 3, Unit 1 - 2; Unit 2 - 3; Mixing point - 3

Overall mass balance $\Rightarrow \dot{m}_3$

Mass balance - Unit 1 $\Rightarrow \dot{m}_1$

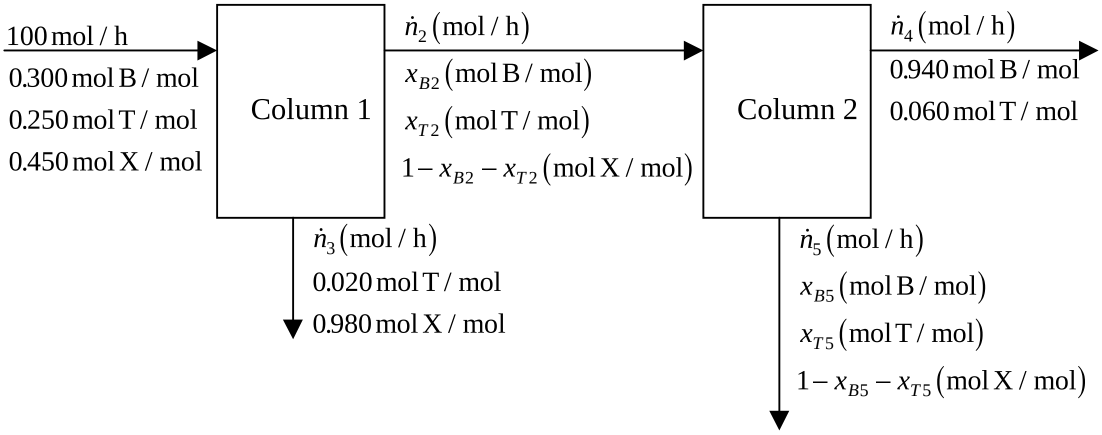
A balance - Unit 1 $\Rightarrow x_1$

Mass balance - mixing point $\Rightarrow \dot{m}_2$

A balance - mixing point $\Rightarrow x_2$

C balance - mixing point $\Rightarrow y_2$

4.29 **a.**



<u>Column 1</u>
4 unknowns ($\dot{n}_2, \dot{n}_3, x_{B2}, x_{T2}$)
–3 balances
<u>– 1 recovery of X in bot. (96%)</u>
0 DF

<u>Column 2</u>:
4 unknowns ($\dot{n}_3, \dot{n}_4, \dot{n}_5, y_x$)
– 3 balances
<u>– 1 recovery of B in top (97%)</u>
0 DF

<u>Column 1</u>

<u>96% X recovery</u>: $0.96(0.450)(100) = 0.98\underline{\underline{\dot{n}_3}}$ (1)

<u>Total mole balance</u>: $100 = \underline{\underline{\dot{n}_2}} + \dot{n}_3$ (2)

<u>B balance</u>: $0.300(100) = \underline{\underline{x_{B2}}}\dot{n}_2$ (3)

<u>T balance</u>: $0.250(100) = \underline{\underline{x_{T2}}}\dot{n}_2 + 0.020\dot{n}_3$ (4)

<u>Column 2</u>

<u>97% B recovery</u>: $0.97x_{B2}\dot{n}_2 = 0.940\underline{\underline{\dot{n}_4}}$ (5)

<u>Total mole balance</u>: $\dot{n}_2 = \dot{n}_4 + \underline{\underline{\dot{n}_5}}$ (6)

<u>B balance</u>: $x_{B2}\dot{n}_2 = 0.940\dot{n}_4 + \underline{\underline{x_{B5}}}\dot{n}_5$ (7)

<u>T balance</u>: $x_{T2}\dot{n}_2 = 0.060\dot{n}_4 + \underline{\underline{x_{T5}}}\dot{n}_5$ (8)

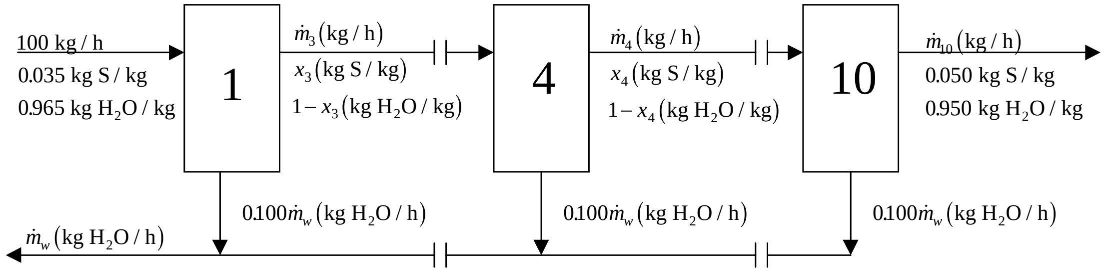
b.

$(1) \Rightarrow \dot{n}_3 = 44.1\ \text{mol/h}$ $\quad (2) \Rightarrow \dot{n}_2 = 55.9\ \text{mol/h}$
$(3) \Rightarrow x_{B2} = 0.536\ \text{mol B/mol}$ $\quad (4) \Rightarrow x_{T2} = 0.431\ \text{mol T/mol}$
$(5) \Rightarrow \dot{n}_4 = 30.95\ \text{mol/h}$ $\quad (6) \Rightarrow \dot{n}_5 = 24.96\ \text{mol/h}$
$(7) \Rightarrow x_{B5} = 0.036\ \text{mol B/mol}$ $\quad (8) \Rightarrow x_{T5} = 0.892\ \text{mol T/mol}$

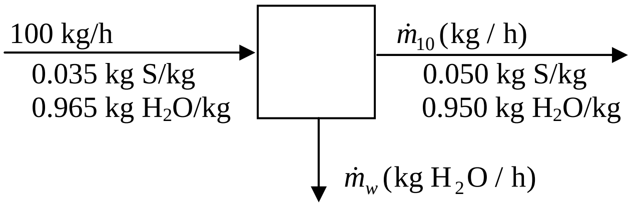
Overall benzene recovery: $\dfrac{0.940(30.95)}{0.300(100)} \times 100\% = \underline{\underline{97\%}}$

Overall toluene recovery: $\dfrac{0.892(24.96)}{0.250(100)} \times 100 = \underline{\underline{89\%}}$

4.30 **a.**



b. Overall process

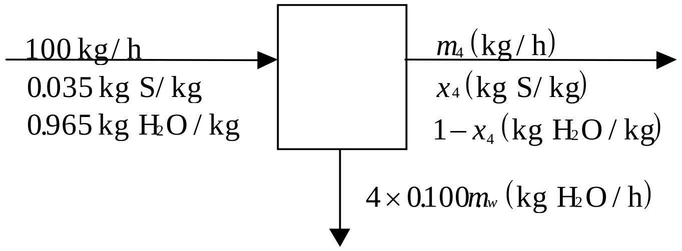


Salt balance: $0.035(100) = 0.050\underline{\underline{\dot{m}_{10}}}$

Overall balance: $100 = \underline{\underline{\dot{m}_w}} + \dot{m}_{10}$

H₂O yield: $\underline{\underline{Y_w}} = \dfrac{\dot{m}_w \left(\text{kg H}_2\text{O recovered}\right)}{96.5\left(\text{kg H}_2\text{O in fresh feed}\right)}$

First 4 evaporators



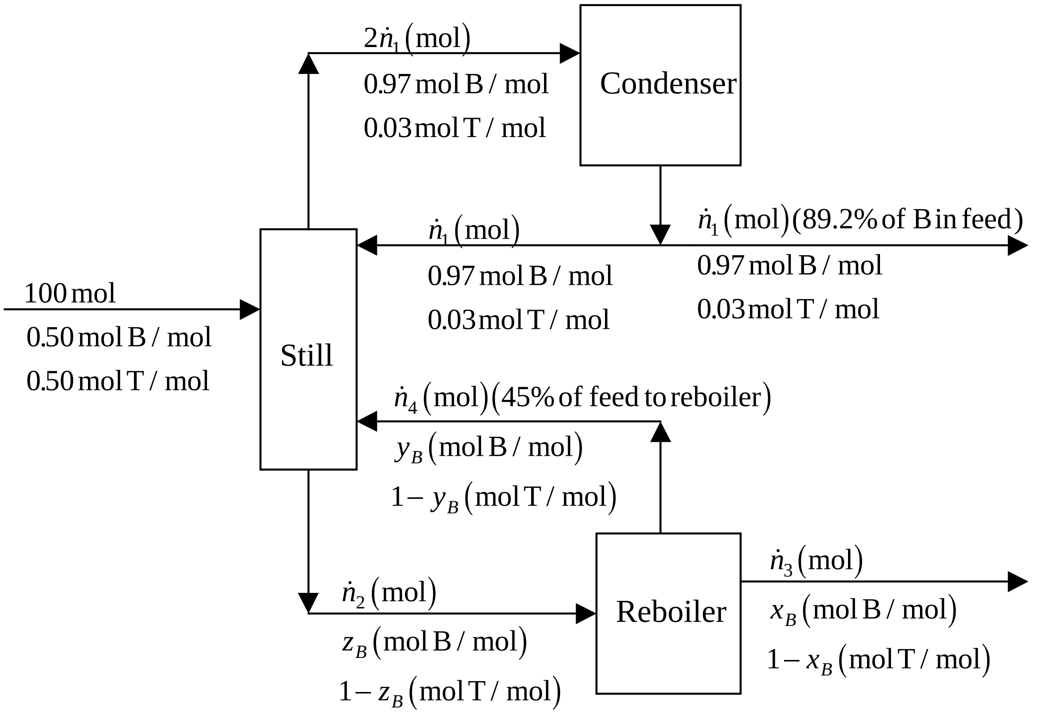
Overall balance: $100 = 4(0.100)\dot{m}_w + \underline{\underline{\dot{m}_4}}$

Salt balance: $0.035(100) = \underline{\underline{x_4}}\dot{m}_4$

c. $\underline{\underline{Y_w = 0.31}}$

$\underline{\underline{x_4 = 0.0398}}$

4.31 a.



Overall process: 3 unknowns ($\dot{n}_1, \dot{n}_3, x_B$)
– 2 balances
– 1 relationship (89.2% recovery)
0 DF

Still: 5 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_4, y_B, z_B$)
– 2 balances
3 DF

Condenser: 1 unknown ($\dot{n}_1$)
– 0 balances
1 DF

Reboiler: 6 unknowns ($\dot{n}_2, \dot{n}_3, \dot{n}_4, x_B, y_B, z_B$)
– 2 balances
– 2 relationships (2.25 ratio & 45% vapor)
3 DF

Begin with overall process.

b. Overall process

89.2% recovery: $0.892(0.50)(100) = 0.97\underline{\underline{\dot{n}_1}}$

Overall balance: $100 = \dot{n}_1 + \underline{\underline{\dot{n}_3}}$

B balance: $0.50(100) = 0.97\dot{n}_1 + \underline{\underline{x_B}}\dot{n}_3$

Reboiler

Composition relationship: $\dfrac{\underline{\underline{y_B}}/\left(1-\underline{\underline{y_B}}\right)}{x_B/\left(1-x_B\right)} = 2.25$

Percent vaporized: $\underline{\underline{\dot{n}_4}} = 0.45\underline{\underline{\dot{n}_2}}$ (1)

Mole balance: $\underline{\underline{\dot{n}_2}} = \dot{n}_3 + \underline{\underline{\dot{n}_4}}$ (2)

(Solve (1) and (2) simultaneously.)

B balance: $\underline{\underline{z_B}}\dot{n}_2 = x_B\dot{n}_3 + y_B\dot{n}_4$

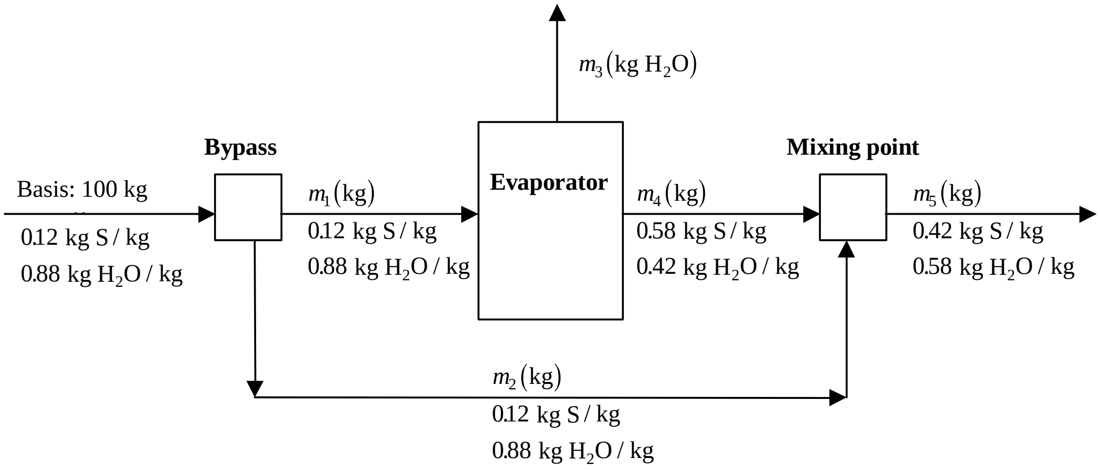
4.31 (cont'd)

c. B fraction in bottoms: $x_B = \underline{\underline{0.100\ \text{mol B/mol}}}$

Moles of overhead: $\dot{n}_1 = \underline{\underline{46.0\ \text{mol}}}$ Moles of bottoms: $\dot{n}_3 = \underline{\underline{54.0\ \text{mol}}}$

Recovery of toluene: $\dfrac{(1-x_B)\dot{n}_3}{0.50(100)} \times 100\% = \dfrac{(1-0.10)(54.02)}{0.50(100)} \times 100\% = \underline{\underline{97\%}}$

4.32 a.



Overall process: 2 unknowns (m_3, m_5)
– 2 balances
0 DF

Bypass: 2 unknowns (m_1, m_2)
– 1 independent balance
1 DF

Evaporator: 3 unknowns (m_1, m_3, m_4)
– 2 balances
1 DF

Mixing point: 3 unknowns (m_2, m_4, m_5)
– 2 balances
1 DF

Overall S balance: $0.12(100) = 0.42\underline{\underline{m_5}}$

Overall mass balance: $100 = \underline{\underline{m_3}} + m_5$

Mixing point mass balance: $\underline{\underline{m_4}} + \underline{\underline{m_2}} = m_5$ (1)

Mixing point S balance: $0.58\underline{\underline{m_4}} + 0.12\underline{\underline{m_2}} = 0.42m_5$ (2)

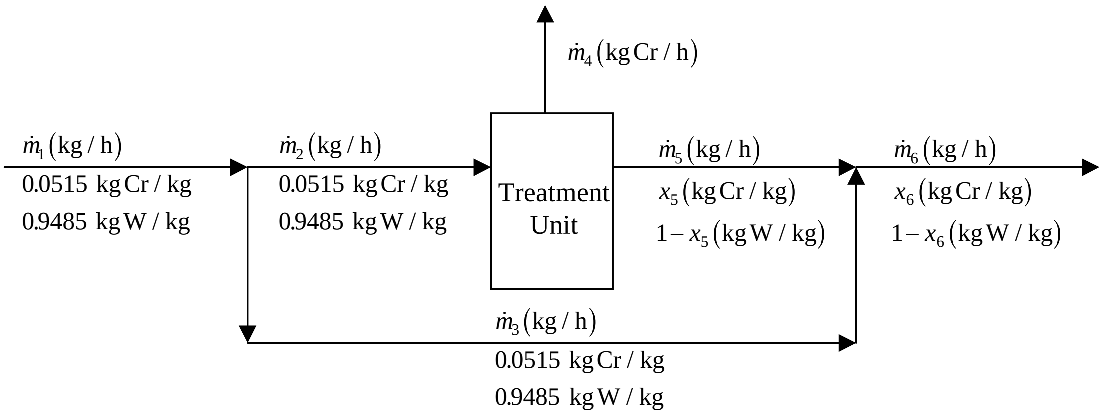
Solve (1) and (2) simultaneously
Bypass mass balance: $100 = \underline{\underline{m_1}} + m_2$

b. $m_1 = 90.05$ kg, $m_2 = 9.95$ kg, $m_3 = 71.4$ kg, $m_4 = 18.65$ kg, $m_5 = \underline{\underline{28.6\ \text{kg product}}}$

Bypass fraction: $\dfrac{m_2}{100} = \underline{\underline{0.095}}$

c. Over-evaporating could degrade the juice; additional evaporation could be uneconomical; a stream consisting of 90% solids could be hard to transport.

4.33 **a.**



b. $\dot{m}_1 = 6000 \text{ kg / h} \Rightarrow \dot{m}_2 = 4500 \text{ kg / h}$ (maximum allowed value)

Bypass point mass balance: $\dot{m}_3 = 6000 - 4500 = 1500 \text{ kg / h}$

95% Cr removal: $\dot{m}_4 = 0.95(0.0515)(4500) = 220.2 \text{ kg Cr / h}$

Mass balance on treatment unit: $\dot{m}_5 = 4500 - 220.2 = 4279.8 \text{ kg / h}$

Cr balance on treatment unit: $x_5 = \dfrac{0.0515(4500) - 220.2}{4779.8} = 0.002707 \text{ kg Cr / kg}$

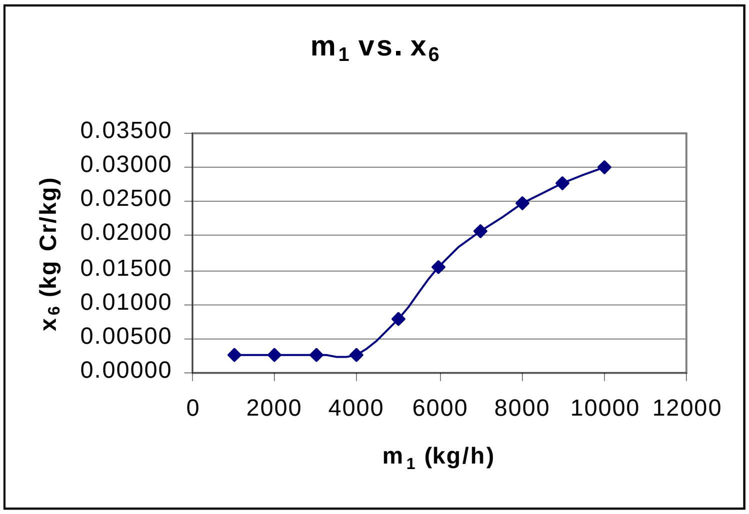
Mixing point mass balance: $\dot{m}_6 = 1500 + 4279.8 = \underline{\underline{5779.8 \text{ kg / h}}}$

Mixing point Cr balance: $x_6 = \dfrac{0.0515(1500) + 0.0002707(4279.8)}{5779.8} = \underline{\underline{0.0154 \text{ kg Cr / kg}}}$

c.

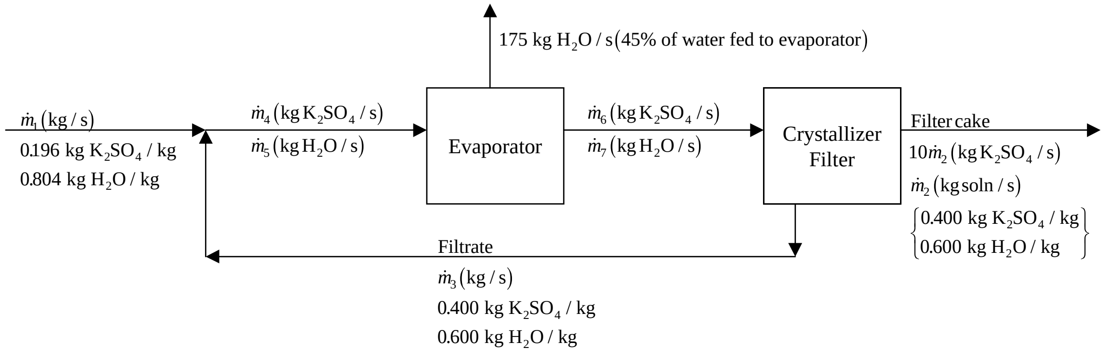
m_1 (kg/h)	m_2 (kg/h)	m_3 (kg/h)	m_4 (kg/h)	m_5 (kg/h)	x_5	m_6 (kg/h)	x_6
1000	1000	0	48.9	951	0.00271	951	0.00271
2000	2000	0	97.9	1902	0.00271	1902	0.00271
3000	3000	0	147	2853	0.00271	2853	0.00271
4000	4000	0	196	3804	0.00271	3804	0.00271
5000	4500	500	220	4280	0.00271	4780	0.00781
6000	4500	1500	220	4280	0.00271	5780	0.0154
7000	4500	2500	220	4280	0.00271	6780	0.0207
8000	4500	3500	220	4280	0.00271	7780	0.0247
9000	4500	4500	220	4280	0.00271	8780	0.0277
10000	4500	5500	220	4280	0.00271	9780	0.0301

4.33 (cont'd)



d. Cost of additional capacity – installation and maintenance, revenue from additional recovered Cr, anticipated wastewater production in coming years, capacity of waste lagoon, regulatory limits on Cr emissions.

4.34 **a.**



Let K = K_2SO_4, W = H_2 Basis: 175 kg W evaporated/s

Overall process: 2 unknowns ($\dot{m}_1, \dot{m}_2$)
- 2 balances
0 DF

Mixing point: 4 unknowns ($\dot{m}_1, \dot{m}_3, \dot{m}_4, \dot{m}_5$)
- 2 balances
2 DF

Evaporator: 4 unknowns ($\dot{m}_4, \dot{m}_5, \dot{m}_6, \dot{m}_7$)
– 2 balances
– 1 percent evaporation
1 DF

Crystallizer: 4 unknowns ($\dot{m}_2, \dot{m}_3, \dot{m}_6, \dot{m}_7$)
– 2 balances
2 DF

Strategy: Overall balances $\Rightarrow \dot{m}_1, \dot{m}_2$
% evaporation $\Rightarrow \dot{m}_5$
Balances around mixing point $\Rightarrow \dot{m}_3, \dot{m}_4$
Balances around evaporator $\Rightarrow \dot{m}_6, \dot{m}_7$

} verify that each chosen subsystem involves no more than two unknown variables

4.34 (cont'd)

$$\left.\begin{aligned}
&\underline{\text{Overall mass balance:}} && \underline{\underline{\dot{m}_1}} = 175 + 10\underline{\underline{\dot{m}_2}} + \underline{\underline{\dot{m}_2}} \\
&\underline{\text{Overall K balance:}} && 0.196\underline{\underline{\dot{m}_1}} = 10\underline{\underline{\dot{m}_2}} + 0.400\underline{\underline{\dot{m}_2}}
\end{aligned}\right\}$$

$$\underline{\text{Production rate of crystals}} = \underline{\underline{10\dot{m}_2}}$$

$\underline{\text{45\% evaporation:}}$ 175 kg evaporated/min $= 0.450\underline{\underline{\dot{m}_5}}$

$\underline{\text{W balance around mixing point:}}$ $0.804\dot{m}_1 + 0.600\underline{\underline{\dot{m}_3}} = \dot{m}_5$

$\underline{\text{Mass balance around mixing point:}}$ $\dot{m}_1 + \dot{m}_3 = \underline{\underline{\dot{m}_4}} + \dot{m}_5$

$\underline{\text{K balance around evaporator:}}$ $\underline{\underline{\dot{m}_6}} = \dot{m}_4$

$\underline{\text{W balance around evaporator:}}$ $\dot{m}_5 = 175 + \underline{\underline{\dot{m}_7}}$

$$\underline{\text{Mole fraction of K in stream entering evaporator}} = \underline{\underline{\frac{\dot{m}_4}{\dot{m}_4 + \dot{m}_5}}}$$

b. $\underline{\text{Fresh feed rate}}$: $\dot{m}_1 = \underline{\underline{221\ \text{kg/s}}}$

$$\underline{\text{Production rate of crystals}} = 10\dot{m}_2 = \underline{\underline{41.6\ \text{kg K(s)/s}}}$$

$$\underline{\text{Recycle ratio:}}\ \frac{\dot{m}_3(\text{kg recycle/s})}{\dot{m}_1(\text{kg fresh feed/s})} = \frac{352.3}{220.8} = \underline{\underline{1.60\frac{\text{kg recycle}}{\text{kg fresh feed}}}}$$

c. Scale to 75% of capacity.
$\underline{\text{Flow rate of stream entering evaporator}} = 0.75(398\ \text{kg/s}) = \underline{\underline{299\ \text{kg/s}}}$

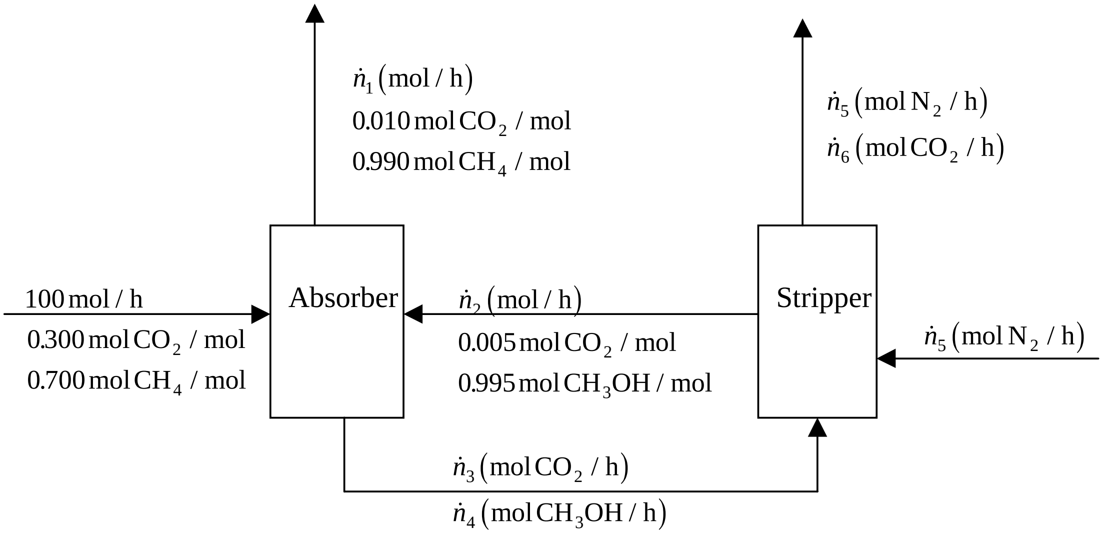
$$\underline{\underline{46.3\%\ \text{K},\ 53.7\%\ \text{W}}}$$

d. $\underline{\underline{\text{Drying}}}$. Principal costs are likely to be the heating cost for the evaporator and the dryer and the cooling cost for the crystallizer.

4.35 **a.** Overall objective: Separate components of a CH_4-CO_2 mixture, recover CH_4, and discharge CO_2 to the atmosphere.
Absorber function: Separates CO_2 from CH_4.
Stripper function: Removes dissolved CO_2 from CH_3OH so that the latter can be reused.

b. The top streams are liquids while the bottom streams are gases. The liquids are heavier than the gases so the liquids fall through the columns and the gases rise.

c.



Overall: 3 unknowns ($\dot{n}_1, \dot{n}_5, \dot{n}_6$)
– 2 balances
1 DF

Absorber: 4 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{n}_4$)
– 3 balances
1 DF

Stripper: 4 unknowns ($\dot{n}_2, \dot{n}_3, \dot{n}_4, \dot{n}_5$)
– 2 balances
– 1 percent removal (90%)
1 DF

Overall CH_4 balance: $\left[(0.700)(100)\right](\text{mol CH}_4/\text{h}) = 0.990\underline{\underline{\dot{n}_1}}$

Overall mole balance: $100(\text{mol/h}) = \dot{n}_1 + \underline{\underline{\dot{n}_6}}$

Percent CO_2 stripped: $0.90\underline{\underline{\dot{n}_3}} = \dot{n}_6$

Stripper CO_2 balance: $\dot{n}_3 = \dot{n}_6 + 0.005\underline{\underline{\dot{n}_2}}$

Stripper CH_3OH balance: $\underline{\underline{\dot{n}_4}} = 0.995\dot{n}_2$

d. $\dot{n}_1 = 70.71\text{ mol/h}, \dot{n}_2 = 651.0\text{ mol/h}, \dot{n}_3 = 32.55\text{ mol CO}_2/\text{h}, \dot{n}_4 = 647.7\text{ mol CH}_3\text{OH/h},$
$\dot{n}_6 = 29.29\text{ mol CO}_2/\text{h}$

Fractional CO_2 absorption: $f_{CO_2} = \dfrac{30.0 - 0.010\dot{n}_1}{30.0} = \underline{\underline{0.976\text{ mol CO}_2\text{ absorbed / mol fed}}}$

4.35 (cont'd)

Total molar flow rate of liquid feed to stripper and mole fraction of CO_2:

$$\dot{n}_3+\dot{n}_4=\underline{\underline{680\,\text{mol}/\text{h}}},\ x_3=\frac{\dot{n}_3}{\dot{n}_3+\dot{n}_4}=\underline{\underline{0.0478\,\text{mol}\,CO_2/\text{mol}}}$$

e. Scale up to 1000 kg/h (=10^6 g/h) of product gas:

$$\overline{\text{MW}}_1=0.01(44\text{ g }CO_2\text{ / mol})+0.99(16\text{ g }CH_4\text{ / mol})=16.28\text{ g / mol}$$

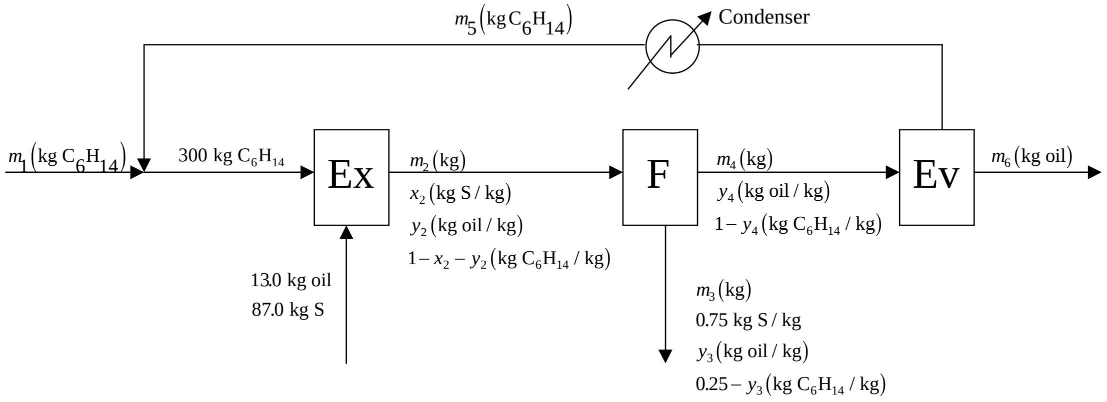
$$(\dot{n}_1)_{new}=(1.0\times10^6\text{ g / h})(16.28\text{ g / mol})=6.142\times10^4\text{ mol / h}$$

$$(\dot{n}_{\text{feed}})_{new}=(100\text{ mol / h})\left[(6.142\times10^4\text{ mol / h})/(70.71\text{ mol / h})\right]=\underline{\underline{8.69\times10^4\text{ mol / h}}}$$

f. $T_a<T_s$ The higher temperature in the stripper will help drive off the gas.
$P_a>P_s$ The higher pressure in the absorber will help dissolve the gas in the liquid.

g. The methanol must have a high solubility for CO_2, a low solubility for CH_4, and a low volatility at the stripper temperature.

4.36 **a.** Basis: 100 kg beans fed



Overall: 4 unknowns (m_1,m_3,m_6,y_3)
– 3 balances
1 DF

Extractor: 3 unknowns (m_2,x_2,y_2)
– 3 balances
0 DF

Mixing Pt: 2 unknowns (m_1,m_5)
– 1 balance
1 DF

Evaporator: 4 unknowns (m_4,m_5,m_6,y_4)
– 2 balances
2 DF

Filter: 7 unknowns ($m_2,m_3,m_4,x_2,y_2,y_3,y_4$)
– 3 balances
– 1 oil/hexane ratio
3 DF

Start with extractor (0 degrees of freedom)

Extractor mass balance: $[300+87.0+13.0]\text{ kg}=\underline{\underline{m_2}}$

4.36 (cont'd)

<u>Extractor S balance</u>: $87.0 \text{ kg S} = \underline{\underline{x_2}} m_2$

<u>Extractor oil balance</u>: $13.0 \text{ kg oil} = \underline{\underline{y_2}} m_2$

<u>Filter S balance</u>: $87.0 \text{ kg S} = 0.75\underline{\underline{m_3}}$

<u>Filter mass balance</u>: $m_2(\text{kg}) = m_3 + \underline{\underline{m_4}}$ <u>Oil / hexane ratio in filter cake</u>:

$$\frac{\underline{\underline{y_3}}}{0.25 - \underline{\underline{y_3}}} = \frac{y_2}{1 - x_2 - y_2}$$

<u>Filter oil balance</u>: $13.0 \text{ kg oil} = y_3 m_3 + \underline{\underline{y_4}} m_4$

<u>Evaporator hexane balance</u>: $(1 - y_4) m_4 = \underline{\underline{m_5}}$

<u>Mixing pt. Hexane balance</u>: $\underline{\underline{m_1}} + m_5 = 300 \text{ kg } C_6H_{14}$

<u>Evaporator oil balance</u>: $y_4 m_4 = \underline{\underline{m_6}}$

b.

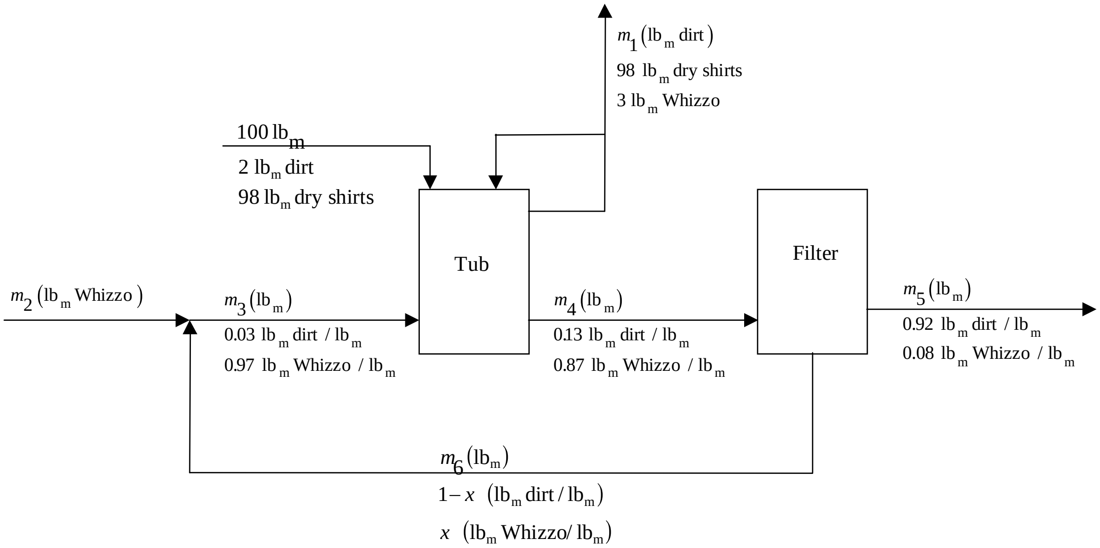
$$\underline{\text{Yield}} = \frac{m_6}{100} = \frac{11.8 \text{ kg oil}}{100 \text{ kg beans fed}} = \underline{\underline{0.118(\text{kg oil / kg beans fed})}}$$

$$\underline{\text{Fresh hexane feed}} = \frac{m_1}{100} = \frac{28 \text{ kg } C_6H_{14}}{100 \text{ kg beans fed}} = \underline{\underline{0.28(\text{kg } C_6H_{14} \text{ / kg beans fed})}}$$

$$\text{Recycle ratio} = \frac{m_5}{m_1} = \frac{272 \text{ kg } C_6H_{14} \text{ recycled}}{28 \text{ kg } C_6H_{14} \text{ fed}} = \underline{\underline{9.71(\text{kg } C_6H_{14} \text{ recycled / kg } C_6H_{14} \text{ fed})}}$$

c. Lower heating cost for the evaporator and lower cooling cost for the condenser.

4.37



<u>Strategy</u>

95% dirt removal $\Rightarrow m_1$ $(= 5\%$ of the dirt entering)

Overall balances: 2 allowed (we have implicitly used a clean shirt balance in labeling the chart) $\Rightarrow m_2, m_5$ (solves Part (a))

4.37 (cont'd)

Balances around the mixing point involve 3 unknowns (m_3, m_6, x), as do balances around the filter (m_4, m_6, x), but the tub only involves $2(m_3, m_4)$ and 2 balances are allowed for each subsystem. Balances around tub $\Rightarrow m_3, m_4$

Balances around mixing point $\Rightarrow m_6, x$ (solves Part (b))

a. <u>95% dirt removal</u>: $m_1 = (0.05)(2.0) = 0.10\ \text{lb}_\text{m}$ dirt

<u>Overall dirt balance</u>: $2.0 = 0.10 + (0.92)m_5 \Rightarrow m_5 = 2.065\ \text{lb}_\text{m}$ dirt

<u>Overall Whizzo balance</u>: $m_2 = [3 + (0.08)(2.065)](\text{lb}_\text{m}\ \text{Whizzo}) = \underline{\underline{3.17\ \text{lb}_\text{m}\ \text{Whizzo}}}$

b. <u>Tub dirt balance</u>: $2 + 0.03m_3 = 0.10 + 0.13m_4$ (1)

<u>Tub Whizzo balance</u>: $0.97m_3 = 3 + 0.87m_4$ (2)

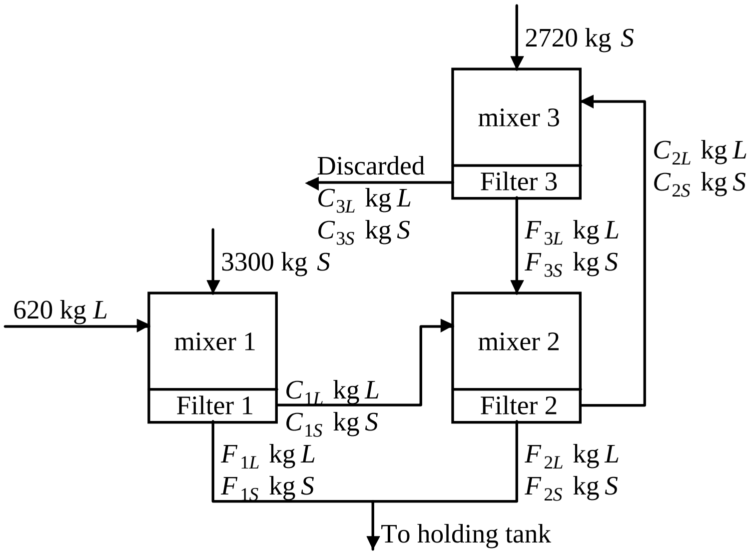
Solve (1) & (2) simultaneously $\Rightarrow m_3 = 20.4\ \text{lb}_\text{m}, m_4 = 19.3\ \text{lb}_\text{m}$

<u>Mixing pt. mass balance</u>: $3.17 + m_6 = 20.4\ \text{lb}_\text{m} \Rightarrow m_6 = 17.3\ \text{lb}_\text{m}$

<u>Mixing pt. Whizzo balance</u>:

$$3.17 + x(17.3) = (0.97)(20.4) \Rightarrow x = 0.961\ \text{lb}_\text{m}\ \text{Whizzo/lb}_\text{m} \Rightarrow \underline{\underline{96\%\ \text{Whizzo, 4\% dirt}}}$$

4.38 a.



$$\begin{array}{rrcr}
\text{mixer/filter 1:} & 0.01(620) = F_{1L} & \Rightarrow & F_{1L} = 6.2\ \text{kg L} \\
\text{balance:} & 620 = 6.2 + C_{1L} & \Rightarrow & C_{1L} = 613.8\ \text{kg L} \\
\text{mixer/filter 2:} & 0.01(613.8 + F_{3L}) = F_{2L} & \left.\right\} & F_{2L} = 6.2\ \text{kg L} \\
\text{balance:} & 613.8 + F_{3L} = F_{2L} + C_{3L} & \Rightarrow & C_{2L} = 613.7\ \text{kg L} \\
\text{mixer/filter 3:} & 0.01C_{2L} = F_{3L} & & F_{3L} = 6.1\ \text{kg L} \\
\text{balance:} & 613.7 = 6.1 + \text{C}_{3L} & \Rightarrow & C_{3L} = 607.6\ \text{kg L}
\end{array}$$

4.38 (cont'd)

Solvent

$$\begin{array}{rll}
\text{m/f 1:} & 0.15(3300) = C_{1S} \Rightarrow & C_{1S} = 495\text{ kg S} \\
\text{balance:} & 3300 = 495 + F_{1S} \Rightarrow & F_{1S} = 2805\text{ kg S}
\end{array}$$

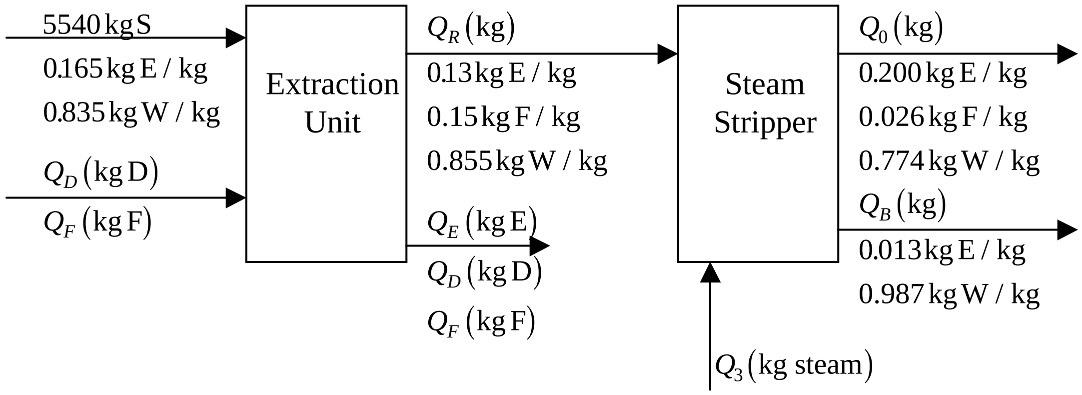
$$\left.\begin{array}{rl}
\text{m/f 2:} & 0.15(495 + F_{3S}) = C_{2S} \\
\text{balance:} & 495 + F_{3S} = C_{2S} + F_{2S} \\
\text{m/f 3:} & 0.15(2720 + C_{2S}) = C_{3S} \\
\text{balance:} & 2720 + \mathrm{C}_{2S} = F_{3S} + C_{3S}
\end{array}\right\}\Rightarrow
\begin{array}{l}
C_{2S} = 482.6\text{ kg S} \\
F_{2S} = 2734.6\text{ kg S} \\
C_{3S} = 480.4\text{ kg S} \\
F_{3S} = 2722.2\text{ kg S}
\end{array}$$

Holding Tank Contents

$6.2 + 6.2 = \underline{\underline{12.4\text{ kg leaf}}}$

$2805 + 2734.6 = \underline{\underline{5540\text{ kg solvent}}}$

b.



Mass of D in Product: $\dfrac{1\text{ kg D}}{1000\text{ kg leaf}}\bigg|\dfrac{620\text{ kg leaf}}{} = \underline{\underline{0.62\text{ kg D} = Q_D}}$

Water balance around extraction unit: $0.835(5540) = 0.855Q_R \Rightarrow Q_R = 5410\text{ kg}$

Ethanol balance around extraction unit:

$0.165(5540) = 0.13(5410) + Q_E \Rightarrow \underline{\underline{Q_E = 211\text{ kg}}}$ (ethanol in extract)

c. F balance around stripper

$0.015(5410) = 0.026Q_0 \Rightarrow \underline{\underline{Q_0 = 3121\text{ kg}}}$ (mass of stripper overhead product)

E balance around stripper

$0.13(5410) = 0.200(3121) + 0.013Q_B \Rightarrow \underline{\underline{Q_B = 6085\text{ kg}}}$ (mass of stripper bottom product)

W balance around stripper

$0.855(5410) + Q_S = 0.774(3121) + 0.987(6085) \Rightarrow \underline{\underline{Q_S = 3796\text{ kg steam fed to stripper}}}$

4.39 a. $\mathrm{C_2H_2 + 2\,H_2 \rightarrow C_2H_6}$

$\underline{\underline{2\text{ mol } \mathrm{H_2}\text{ react / mol } \mathrm{C_2H_2}\text{ react}}}$

$\underline{\underline{0.5\text{ kmol } \mathrm{C_2H_6}\text{ formed / kmol } \mathrm{H_2}\text{ react}}}$

4.39 (cont'd)

b. $$\frac{n_{\mathrm{H_2}}}{n_{\mathrm{C_2H_2}}} = 1.5 < 2.0 \Rightarrow \underline{\underline{\mathrm{H_2}\text{ is limiting reactant}}}$$

$$1.5\text{ mol H}_2\text{ fed} \Rightarrow 1.0\text{ mol C}_2\text{H}_2\text{ fed} \Rightarrow 0.75\text{ mol C}_2\text{H}_2\text{ required (theoretical)}$$

$$\%\text{ excess C}_2\text{H}_2 = \frac{1.0\text{ mol fed} - 0.75\text{ mol required}}{0.75\text{ mol required}} \times 100\% = \underline{\underline{33.3\%}}$$

c. $$\frac{4\times10^6\text{ tonnes C}_2\text{H}_6}{\text{yr}}\bigg|\frac{1\text{ yr}}{300\text{ days}}\bigg|\frac{1\text{ day}}{24\text{ h}}\bigg|\frac{1\text{ h}}{3600\text{ s}}\bigg|\frac{1000\text{ kg}}{\text{tonne}}\bigg|\frac{1\text{ kmol C}_2\text{H}_6}{30.0\text{ kg C}_2\text{H}_6}\bigg|\frac{2\text{ kmol H}_2}{1\text{ kmol C}_2\text{H}_6}\bigg|\frac{2.00\text{ kg H}_2}{1\text{ kmol H}_2}$$
$$= 20.6\text{ kg H}_2/\text{s}$$

d. The extra cost will be involved in separating the product from the excess reactant.

4.40 **a.** $$4\,\mathrm{NH_3} + 5\,\mathrm{O_2} \rightarrow 4\,\mathrm{NO} + 6\,\mathrm{H_2O}$$

$$\frac{5\text{ lb-mole O}_2\text{ react}}{4\text{ lb-mole NO formed}} = \underline{\underline{1.25\text{ lb-mole O}_2\text{ react / lb-mole NO formed}}}$$

b. $$\left(n_{\mathrm{O_2}}\right)_{\text{theoretical}} = \frac{100\text{ kmol NH}_3}{\text{h}}\bigg|\frac{5\text{ kmol O}_2}{4\text{ kmol NH}_3} = 125\text{ kmol O}_2$$

$$40\%\text{ excess O}_2 \Rightarrow \left(n_{\mathrm{O_2}}\right)_{\text{fed}} = 1.40(125\text{ kmol O}_2) = \underline{\underline{175\text{ kmol O}_2}}$$

c. $$(50.0\text{ kg NH}_3)(1\text{ kmol NH}_3/17\text{ kg NH}_3) = 2.94\text{ kmol NH}_3$$
$$(100.0\text{ kg O}_2)(1\text{ kmol O}_2/32\text{ kg O}_2) = 3.125\text{ kmol O}_2$$
$$\left(\frac{n_{\mathrm{O_2}}}{n_{\mathrm{NH_3}}}\right)_{\text{fed}} = \frac{3.125}{2.94} = 1.06 < \left(\frac{n_{\mathrm{O_2}}}{n_{\mathrm{NH_3}}}\right)_{\text{stoich}} = \frac{5}{4} = 1.25$$
$$\Rightarrow \underline{\underline{\mathrm{O_2}\text{ is the limiting reactant}}}$$

Required NH_3: $$\frac{3.125\text{ kmol O}_2}{}\bigg|\frac{4\text{ kmol NH}_3}{5\text{ kmol O}_2} = 2.50\text{ kmol NH}_3$$

$$\underline{\%\text{ excess NH}_3} = \frac{2.94-2.50}{2.50}\times100\% = \underline{\underline{17.6\%\text{ excess NH}_3}}$$

Extent of reaction: $$n_{\mathrm{O_2}} = \left(n_{\mathrm{O_2}}\right)_0 - \nu_{\mathrm{O_2}}\xi \Rightarrow 0 = 3.125 - (-5)\xi \Rightarrow \xi = 0.625\text{ kmol} = \underline{\underline{625\text{ mol}}}$$

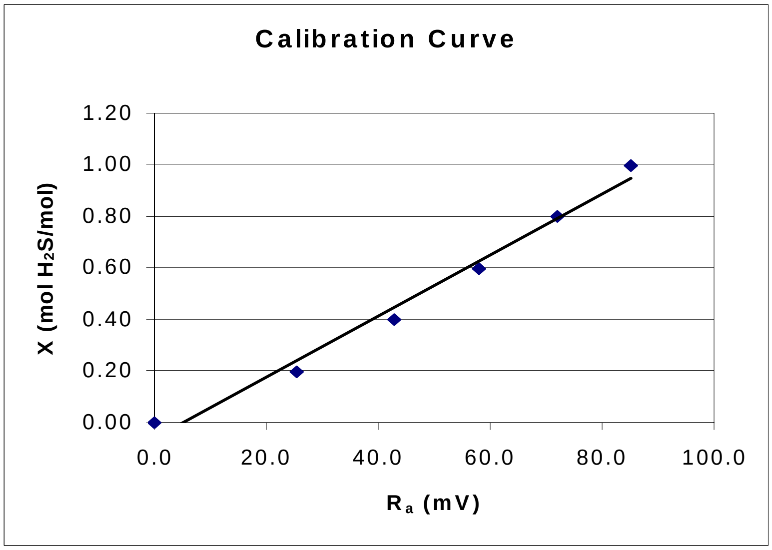
Mass of NO: $$\frac{3.125\text{ kmol O}_2}{}\bigg|\frac{4\text{ kmol NO}}{5\text{ kmol O}_2}\bigg|\frac{30.0\text{ kg NO}}{1\text{ kmol NO}} = \underline{\underline{75.0\text{ kg NO}}}$$

4.41 **a.** By adding the feeds in stoichometric proportion, all of the H_2S and SO_2 would be consumed. Automation provides for faster and more accurate response to fluctuations in the feed stream, reducing the risk of release of H_2S and SO_2. It also may reduce labor costs.

4.41 (cont'd)

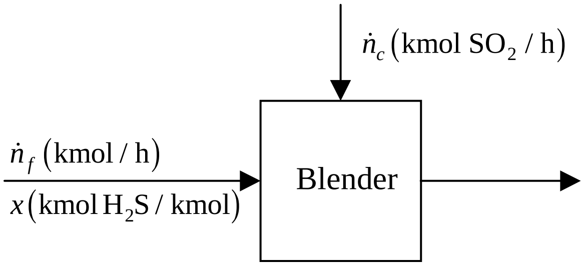
b. $$\dot{n}_c = \frac{3.00\times 10^2\ \text{kmol}}{\text{h}}\left|\frac{0.85\ \text{kmol}\ \text{H}_2\text{S}}{\text{kmol}}\right|\frac{1\ \text{kmol}\ \text{SO}_2}{2\ \text{kmol}\ \text{H}_2\text{S}} = \underline{\underline{127.5\,\text{kmol}\,\text{SO}_2\ /\ \text{h}}}$$

c.



$$\underline{\underline{X = 0.0199R_a - 0.0605}}$$

d.



Flowmeter calibration: $$\left.\begin{matrix}\dot{n}_f = aR_f \\ \dot{n}_f = 100\,\text{kmol / h}, R_f = 15\,\text{mV}\end{matrix}\right\}\dot{n}_f = \frac{20}{3}R_f$$

Control valve calibration: $$\left.\begin{matrix}\dot{n}_c = 25.0\,\text{kmol / h}, \text{R}_\text{c} = 10.0\,\text{mV} \\ \dot{n}_c = 60.0\,\text{kmol / h}, R_c = 25.0\,\text{mV}\end{matrix}\right\}\dot{n}_c = \frac{7}{3}R_c + \frac{5}{3}$$

Stoichiometric feed: $$\dot{n}_c = \frac{1}{2}\dot{n}_f x \Rightarrow \frac{7}{3}R_c + \frac{5}{3} = \frac{1}{2}\left(\frac{20}{3}R_f\right)(0.0119R_a - 0.0605)$$

$$\Rightarrow \underline{\underline{R_c = \frac{10}{7}R_f(0.0119R_a - 0.0605) - \frac{5}{7}}}$$

$$\dot{n}_f = 3.00\times 10^2\ \text{kmol / h} \Rightarrow R_f = \frac{3}{20}\dot{n}_f = 45\,\text{mV}$$

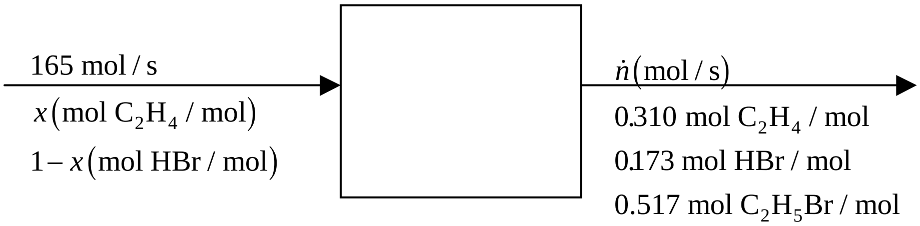
4.41 (cont'd)

$$R_c = \frac{10}{7}(45)\left[(0.0119)(76.5) - 0.0605\right] - \frac{5}{7} = 53.9\,\text{mV}$$

$$\Rightarrow \dot{n}_c = \frac{7}{3}(53.9) + \frac{5}{3} = 127.4\,\text{kmol / h}$$

e. Faulty sensors, computer problems, analyzer calibration not linear, extrapolation beyond range of calibration data, system had not reached steady state yet.

4.42



$$C_2H_4 + HBr \rightarrow C_2H_5Br$$

<u>C balance</u>: $\dfrac{165\,\text{mol}}{\text{s}}\left|\dfrac{x(\text{mol}\,C_2H_4)}{\text{mol}}\right|\dfrac{2\,\text{mol}\,C}{\text{mol}\,C_2H_4} = \dot{n}(0.310)(2) + \dot{n}(0.517)(2)$ (1)

<u>Br balance</u>: $165(1-x)(1) = \dot{n}(0.173)(1) + \dot{n}(0.517)(1)$ (2)

(Note: An atomic H balance can be obtained as 2*(Eq. 2) + (Eq. 1) and so is not independent)

Solve (1) and (2) simultaneously $\Rightarrow \dot{n} = 108.77\,\text{mol / s},\ x = 0.545\,\text{mol}\,C_2H_4\,/\,\text{mol}$

$\Rightarrow (1-x) = 0.455\,\text{mol HBr / mol}$

Since the C_2H_4/HBr feed ratio (0.545/0.455) is greater than the stoichiometric ration (=1), <u>HBr is the limiting reactant</u>.

$$(\dot{n}_{\text{HBr}})_{\text{fed}} = (165\,\text{mol / s})(0.455\,\text{mol HBr / mol}) = 75.08\,\text{mol HBr}$$

<u>Fractional conversion of HBr</u> $= \dfrac{75.08 - (0.173)(108.8)}{75.08} = \underline{\underline{0.749\ \text{mol HBr react/mol fed}}}$

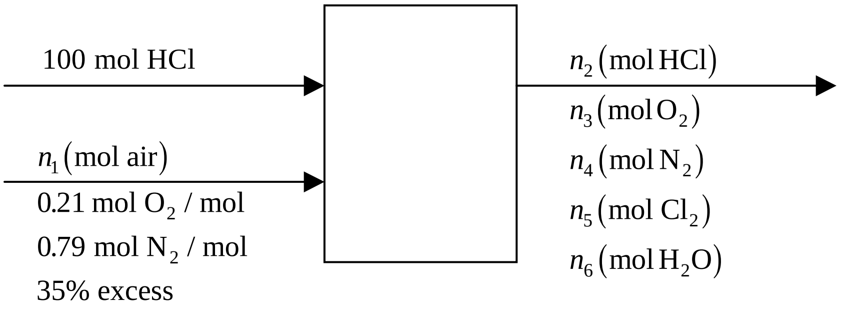
$$(\dot{n}_{C_2H_4})_{\text{stoich}} = 75.08\,\text{mol}\,C_2H_4$$

$$(\dot{n}_{C_2H_4})_{\text{fed}} = (165\,\text{mol/s})(0.545\,\text{mol}\,C_2H_4/\text{mol}) = 89.93\,\text{mol}\,C_2H_4$$

<u>% excess of C_2H_4</u> $= \dfrac{89.93 - 75.08}{75.08} = \underline{\underline{19.8\%}}$

<u>Extent of reaction</u>: $\dot{n}_{C_2H_5Br} = (\dot{n}_{C_2H_5Br})_0 + \nu_{C_2H_5Br}\xi \Rightarrow (108.8)(0.517) = 0 + (1)\xi \Rightarrow \underline{\underline{\xi = 56.2\,\text{mol/s}}}$

4.43 **a.** $2\text{HCl}+\frac{1}{2}\text{O}_2 \rightarrow \text{Cl}_2+\text{H}_2\text{O}$ <u>Basis</u>: 100 mol HCl fed to reactor



$$(\text{O}_2)_{\text{stoic}} = \frac{100\text{ mol HCl} \;\big|\; 0.5\text{ mol O}_2}{\big|\; 2\text{ mol HCl}} = 25\text{ mol O}_2$$

<u>35% excess air:</u> $0.21n_1(\text{mol O}_2\text{ fed}) = 1.35\times 25 \Rightarrow n_1 = 160.7\text{ mol air fed}$

<u>85% conversion</u> $\Rightarrow$ 85 mol HCl react $\Rightarrow n_2 = 15\text{ mol HCl}$

$$n_5 = \frac{85\text{ mol HCl react} \;\big|\; 1\text{ mol Cl}_2}{\big|\; 2\text{ mol HCl}} = 42.5\text{ mol Cl}_2$$

$$n_6 = (85)(1/2) = 42.5\text{ mol H}_2\text{O}$$

<u>N_2 balance:</u> $(160.7)(0.79) = n_4 \Rightarrow n_4 = 127\text{ mol N}_2$

<u>O balance:</u>

$$\frac{(160.7)(0.21)\text{ mol O}_2 \;\big|\; 2\text{ mol O}}{\big|\; 1\text{ mol O}_2} = 2n_3 + \frac{42.5\text{ mol H}_2\text{O} \;\big|\; 1\text{ mol O}}{\big|\; 1\text{ mol H}_2\text{O}} \Rightarrow n_3 = 12.5\text{ mol O}_2$$

<u>Total moles:</u>

$$\sum_{j=2}^{5} n_j = 239.5\text{ mol} \Rightarrow \frac{15\text{ mol HCl}}{239.5\text{ mol}} = \underline{\underline{0.063\ \frac{\text{mol HCl}}{\text{mol}}}},\ \underline{\underline{0.052\ \frac{\text{mol O}_2}{\text{mol}}}},\ \underline{\underline{0.530\ \frac{\text{mol N}_2}{\text{mol}}}},$$

$$\underline{\underline{0.177\ \frac{\text{mol Cl}_2}{\text{mol}}}},\ \underline{\underline{0.177\ \frac{\text{mol H}_2\text{O}}{\text{mol}}}}$$

b. As before, $n_1 = 160.7$ mol air fed, $n_2 = \underline{\underline{15\text{ mol HCl}}}$

$$2\text{HCl}+\frac{1}{2}\text{O}_2 \rightarrow \text{Cl}_2+\text{H}_2\text{O}$$

$$n_i = (n_i)_0 + \nu_i\xi$$

$$\Downarrow$$

<u>HCl</u>: $15 = 100 - 2\xi \Rightarrow \xi = 42.5\text{ mol}$

4.43 (cont'd)

$$\underline{O_2}:\quad n_3 = 0.21(160.7) - \frac{1}{2}\xi = \underline{\underline{12.5 \text{ mol } O_2}}$$

$$\underline{N_2}:\quad n_4 = 0.79(160.7) = \underline{\underline{127 \text{ mol } N_2}}$$

$$\underline{Cl_2}:\quad n_5 = \xi = \underline{\underline{42.5 \text{ mol } Cl_2}}$$

$$\underline{H_2O}:\quad n_6 = \xi = \underline{\underline{42.5 \text{ mol } H_2O}}$$

These molar quantities are the same as in part (a), so the mole fractions would also be the same.

c. Use of pure O_2 would eliminate the need for an extra process to remove the N_2 from the product gas, but O_2 costs much more than air. The cheaper process will be the process of choice.

4.44

$$FeTiO_3 + 2H_2SO_4 \rightarrow (TiO)SO_4 + FeSO_4 + 2H_2O$$

$$Fe_2O_3 + 3H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 3H_2O$$

$$(TiO)SO_4 + 2H_2O \rightarrow H_2TiO_3(s) + H_2SO_4$$

$$H_2TiO_3(s) \rightarrow TiO_2(s) + H_2O$$

<u>Basis</u>: 1000 kg TiO_2 produced

$$\frac{1000 \text{ kg } TiO_2}{} \left| \frac{\text{kmol } TiO_2}{79.90 \text{ kg } TiO_2} \right| \frac{1 \text{ kmol } FeTiO_3}{1 \text{ kmol } TiO_2} = 12.52 \text{ kmol } FeTiO_3 \text{ decomposes}$$

$$\frac{12.52 \text{ kmol } FeTiO_3 \text{ dec.}}{} \left| \frac{1 \text{ kmol } FeTiO_3 \text{ feed}}{0.89 \text{ kmol } FeTiO_3 \text{ dec.}} \right. = 14.06 \text{ kmol } FeTiO_3 \text{ fed}$$

$$\frac{14.06 \text{ kmol } FeTiO_3}{} \left| \frac{1 \text{ kmol Ti}}{1 \text{ kmol } FeTiO_3} \right| \frac{47.90 \text{ kg Ti}}{\text{kmol Ti}} = 673.5 \text{ kg Ti fed}$$

$$673.5 \text{ kg Ti} \,/\, M(\text{kg ore}) = 0.243 \Rightarrow M = \underline{\underline{2772 \text{ kg ore fed}}}$$

Ore is made up entirely of 14.06 kmol $FeTiO_3$ + $n(\text{kmol } Fe_2O_3)$ (<u>Assumption!</u>)

$$n = 2772 \text{ kg ore} - \frac{14.06 \text{ kmol } FeTiO_3}{} \left| \frac{151.74 \text{ kg } FeTiO_3}{\text{kmol } FeTiO_3} \right. = 638.1 \text{ kg } Fe_2O_3$$

$$\frac{638.1 \text{ kg } Fe_2O_3}{} \left| \frac{\text{kmol } Fe_2O_3}{159.69 \text{ kg } Fe_2O_3} \right. = 4.00 \text{ kmol } Fe_2O_3$$

$$\frac{14.06 \text{ kmol } FeTiO_3}{} \left| \frac{2 \text{ kmol } H_2SO_4}{1 \text{ kmol } FeTiO_3} \right. + \frac{4.00 \text{ kmol } FeTiO_3}{} \left| \frac{3 \text{ kmol } H_2SO_4}{1 \text{ kmol } Fe_2O_3} \right. = 40.12 \text{ kmol } H_2SO_4$$

<u>50% excess</u>: $1.5(40.12 \text{ kmol } H_2SO_4) = 60.18 \text{ kmol } H_2SO_4$ fed

<u>Mass of 80% solution</u>: $\frac{60.18 \text{ kmol } H_2SO_4}{} \left| \frac{98.08 \text{ kg } H_2SO_4}{1 \text{ kmol } H_2SO_4} \right. = 5902.4 \text{ kg } H_2SO_4$

$$5902.4 \text{ kg } H_2SO_4 \,/\, M_a(\text{kg soln}) = 0.80 \Rightarrow M_a = \underline{\underline{7380 \text{ kg } 80\% \; H_2SO_4 \text{ feed}}}$$

4.45 **a.** Plot C (log scale) vs. R (linear scale) on semilog paper, get straight line through

$$\left(R_1 = 10,\ C_1 = 0.30\ \text{g/m}^3\right) \text{ and } \left(R_2 = 48,\ C_2 = 2.67\ \text{g/m}^3\right)$$

$$\ln C = bR + \ln a \Leftrightarrow C = ae^{br}$$

$$b = \frac{\ln(2.67/0.30)}{48-10} = 0.0575\,,\ \ \ln a = \ln(2.67) - 0.0575(48) = -1.78 \Rightarrow a = e^{-1.78} = 0.169$$

$$\Rightarrow\ C = 0.169e^{0.0575R}$$

$$C\left(\text{g/m}^3\right) = \frac{C'(\ \text{lb}_\text{m})}{\text{ft}^3}\left|\frac{453.6\ \text{g}}{1\ \text{lb}_\text{m}}\right|\frac{35.31\ \text{ft}^3}{1\ \text{m}^3} = 16{,}020C'$$

$$\Downarrow$$

$$16{,}020C' = 0.169e^{0.0575R} \Rightarrow \underline{\underline{C'\left(\text{lb}_\text{m}\ \text{SO}_2/\text{ft}^3\right) = 1.055\times 10^{-5}e^{0.0575R}}}$$

b. $$\frac{\left(2867\ \text{ft}^3/\text{s}\right)(60\ \text{s/min})}{1250\ \text{lb}_\text{m}/\text{min}} = \underline{\underline{138\ \text{ft}^3/\text{lb}_\text{m}\ \text{coal}}}$$

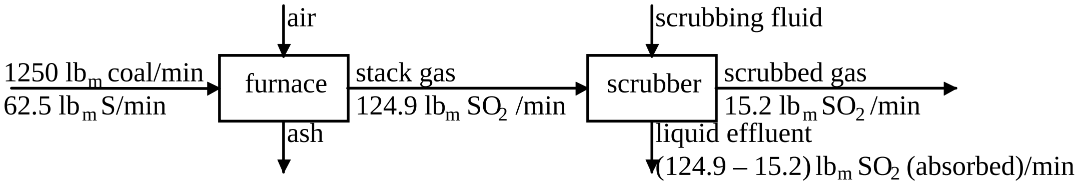
$$R = 37 \Rightarrow C'\left(\text{lb}_\text{m}\ \text{SO}_2/\text{ft}^3\right) = 1.055\times 10^{-5}e^{(0.0575)(37)} = 8.86\times 10^{-5}\ \ \text{lb}_\text{m}\ \text{SO}_2/\text{ft}^3$$

$$\frac{8.86\times 10^{-5}\ \text{lb}_\text{m}\ \text{SO}_2}{\text{ft}^3}\left|\frac{138\ \text{ft}^3}{1\ \text{lb}_\text{m}\ \text{coal}}\right. = 0.012 < 0.018\frac{\text{lb}_\text{m}\ \text{SO}_2}{\text{lb}_\text{m}\ \text{coal}}\ \ \underline{\underline{\text{compliance achieved}}}$$

c. $\text{S} + \text{O}_2 \rightarrow \text{SO}_2$

$$\frac{1250\ \text{lb}_\text{m}\ \text{coal}}{\text{min}}\left|\frac{0.05\ \text{lb}_\text{m}\ \text{S}}{1\ \text{lb}_\text{m}\ \text{coal}}\right|\frac{64.06\ \text{lb}_\text{m}\ \text{SO}_2}{32.06\ \text{lb}_\text{m}\ \text{S}} = 124.9\ \text{lb}_\text{m}\ \text{SO}_2\ \text{generated/min}$$

$$\frac{2867\ \text{ft}^3}{\text{s}}\left|\frac{60\ \text{s}}{1\ \text{min}}\right|\frac{8.86\times 10^{-5}\ \text{lb}_\text{m}\ \text{SO}_2}{\text{ft}^3} = 15.2\ \text{lb}_\text{m}\ \text{SO}_2/\text{min in scrubbed gas}$$



$$\underline{\%\ \text{removal}} = \frac{(124.9 - 15.2)\ \text{lb}_\text{m}\ \text{SO}_2\ \text{scrubbed/min}}{124.9\ \text{lb}_\text{m}\ \text{SO}_2\ \text{fed to scrubber/min}}\times 100\% = \underline{\underline{88\%}}$$

d. The regulation was avoided by diluting the stack gas with fresh air before it exited from the stack. The new regulation prevents this since the mass of SO_2 emitted per mass of coal burned is independent of the flow rate of air in the stack.

4.46 **a.** $A + B \rightleftharpoons C + D$

$$\left.\begin{array}{l} n_A = n_{A_0} - \xi \\ n_B = n_{B_0} - \xi \\ n_C = n_{C_0} + \xi \\ n_D = n_{D_0} + \xi \\ \underline{\quad n_I = n_{I_0}} \\ \text{Total } n_T = \sum n_i \end{array}\right\} \Longrightarrow \begin{array}{l} y_A = \left(n_{A_0} - \xi\right)/n_T \\ y_B = \left(n_{B_0} - \xi\right)/n_T \\ y_C = \left(n_{C_0} + \xi\right)/n_T \\ y_D = \left(n_{D_0} + \xi\right)/n_T \end{array}$$

At equilibrium: $\dfrac{y_C y_D}{y_A y_B} = \dfrac{(n_{C0} + \xi_c)(n_{D0} + \xi_c)}{(n_{A0} - \xi_c)(n_{B0} - \xi_c)} = 4.87$ (n_T's cancel)

$$3.87\xi_c^2 - \left(n_{C0} + n_{D0} + 4.87(n_{A0} + n_{B0})\right)\xi_c - \left(n_{C0}n_{D0} - 4.87n_{A0}n_{B0}\right) = 0$$

$$[a\xi_c^2 + b\xi_c + c = 0]$$

$$\therefore \xi_c = \frac{1}{2a}\left(-b \pm \sqrt{b^2 - 4ac}\right) \text{ where } \begin{array}{l} a = 3.87 \\ b = -\left[n_{C0} + n_{D0} + 4.87(n_{A0} + n_{B0})\right] \\ c = -\left[n_{C0}n_{D0} - 4.87n_{A0}n_{B0}\right] \end{array}$$

b. Basis: 1 mol A feed $\quad n_{A0} = 1 \quad n_{B0} = 1 \quad n_{C0} = n_{D0} = n_{I0} = 0$

Constants: $a = 3.87 \quad b = -9.74 \quad c = 4.87$

$$\xi_e = \frac{1}{2(3.87)}\left(9.74 \pm \sqrt{(9.74)^2 - 4(3.87)(4.87)}\right) \Rightarrow \xi_{e1} = 0.688$$

$\left(\xi_{e2} = 1.83 \text{ is also a solution but leads to a negative conversion}\right)$

Fractional conversion: $X_A\left(= X_B\right) = \dfrac{n_{A0} - n_A}{n_{A0}} = \dfrac{\xi_{e1}}{n_{A0}} = \underline{\underline{0.688}}$

c. $n_{B0} = 80, n_{C0} = n_{D0} = n_{J0} = 0$

$$n_C = 70 = n_{C0} + \xi_c \xrightarrow{n_{C0} = 0} \xi_c = 70 \text{ mol}$$

$$n_A = n_{A0} - \xi_c = n_{A0} - 70 \text{ mol}$$

$$n_B = n_{B0} - \xi_c = 80 - 70 = 10 \text{ mol}$$

$$n_C = n_{C0} + \xi_c = 70 \text{ mol}$$

$$n_D = n_{D0} + \xi_c = 70 \text{ mol}$$

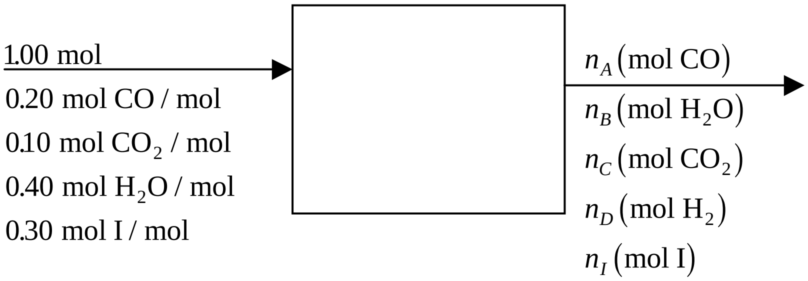
$$4.87 = \frac{y_C y_D}{y_A y_B} = \frac{n_C n_D}{n_A n_B} \Rightarrow \frac{(70)(70)}{(n_{A0} - 70)(10)} = 4.87 \Rightarrow \underline{\underline{n_{A0} = 170.6 \text{ mol methanol fed}}}$$

4.46 (cont'd)

$$\underline{\text{Product gas}}\quad \left.\begin{array}{l} n_A = 170.6 - 70 = 100.6\text{ mol} \\ n_B = 10\text{ mol} \\ n_C = 70\text{ mol} \\ n_D = 70\text{ mol} \\ \hline n_{total} = 250.6\text{ mol} \end{array}\right\} \Rightarrow \begin{array}{l} \underline{\underline{y_A = 0.401\text{ mol CH}_3\text{OH/mol}}} \\ \underline{\underline{y_B = 0.040\text{ mol CH}_3\text{COOH/mol}}} \\ \underline{\underline{y_C = 0.279\text{ mol CH}_3\text{COOCH}_3\text{/mol}}} \\ \underline{\underline{y_D = 0.279\text{ mol H}_2\text{O/mol}}} \end{array}$$

d. Cost of reactants, selling price for product, market for product, rate of reaction, need for heating or cooling, and many other items.

4.47 a. $\underset{\text{(A)}}{\text{CO}} + \underset{\text{(B)}}{\text{H}_2\text{O}} \longleftrightarrow \underset{\text{(C)}}{\text{CO}_2} + \underset{\text{(D)}}{\text{H}_2}$



<u>Degree of freedom analysis</u>: 6 unknowns ($n_A, n_B, n_C, n_D, n_I, \xi$)
– 4 expressions for $n_i(\xi)$
– 1 balance on I
<u>– 1 equilibrium relationship</u>
0 DF

b. Since two moles are prodcued for every two moles that react,

$$(n_{\text{total}})_{\text{out}} = (n_{\text{total}})_{\text{in}} = \underline{\underline{1.00(\text{mol})}}$$

$$n_A = 0.20 - \xi \tag{1}$$
$$n_B = 0.40 - \xi \tag{2}$$
$$n_C = 0.10 + \xi \tag{3}$$
$$n_D = \xi \tag{4}$$
$$\underline{n_I = 0.30} \tag{5}$$
$$n_{tot} = 1.00\text{ mol}$$

At equilibrium: $\dfrac{y_C y_D}{y_A y_B} = \dfrac{n_C n_D}{n_A n_B} = \dfrac{(0.10+\xi)(\xi)}{(0.20-\xi)(0.40-\xi)} = 0.0247\exp\left(\dfrac{4020}{1123}\right) \Rightarrow \xi = 0.110\text{ mol}$

$$y_D = n_D = \xi = \underline{\underline{0.110(\text{mol H}_2\text{ / mol})}}$$

c. The reaction has not reached equilibrium yet.

4.47 (cont'd)

d.

T (K)	x (CO)	x (H_2O)	x (CO_2)	Keq	Keq (Goal Seek)	Extent of Reaction	y (H_2)
1223	0.5	0.5	0	0.6610	0.6610	0.2242	0.224
1123	0.5	0.5	0	0.8858	0.8856	0.2424	0.242
1023	0.5	0.5	0	1.2569	1.2569	0.2643	0.264
923	0.5	0.5	0	1.9240	1.9242	0.2905	0.291
823	0.5	0.5	0	3.2662	3.2661	0.3219	0.322
723	0.5	0.5	0	6.4187	6.4188	0.3585	0.358
623	0.5	0.5	0	15.6692	15.6692	0.3992	0.399
673	0.5	0.5	0	9.7017	9.7011	0.3785	0.378
698	0.5	0.5	0	7.8331	7.8331	0.3684	0.368
688	0.5	0.5	0	8.5171	8.5177	0.3724	0.372
1123	0.2	0.4	0.1	0.8858	0.8863	0.1101	0.110
1123	0.4	0.2	0.1	0.8858	0.8857	0.1100	0.110
1123	0.3	0.3	0	0.8858	0.8856	0.1454	0.145
1123	0.5	0.4	0	0.8858	0.8867	0.2156	0.216

The lower the temperature, the higher the extent of reaction. An equimolar feed ratio of carbon monoxide and water also maximizes the extent of reaction.

4.48 a. $\mathrm{A}+2\mathrm{B}\rightarrow\mathrm{C}$

$$\ln K_e=\ln A_0+E/T(K)$$

$$E=\frac{\ln(K_{e1}/K_{e2})}{1/T_1-1/T_2}=\frac{\ln\left(10.5/2.316\times10^{-4}\right)}{1/373-1/573}=11458$$

$$\ln A_0=\ln K_{e1}-11458/T_1=\ln 10.5-11458/373=-28.37\Rightarrow A_0=4.79\times10^{-13}$$

$$K_e=\underline{\underline{4.79\times10^{-13}\exp\left(11458/T(K)\right)\ \mathrm{atm}^{-2}}}\Rightarrow\underline{\underline{K_e(450K)=0.0548\ \mathrm{atm}^{-1}}}$$

b.

$$\left.\begin{aligned}n_A&=n_{A0}-\xi\\ n_B&=n_{B0}-2\xi\\ \underline{n_C}&\underline{=n_{C0}+\xi}\\ n_T&=n_{T0}-2\xi\end{aligned}\right\}\Rightarrow\begin{aligned}y_A&=(n_{A0}-\xi)/(n_{T0}-2\xi)\\ y_B&=(n_{B0}-2\xi)/(n_{T0}-2\xi)\\ \underline{y_C}&\underline{=(n_{C0}+\xi)/(n_{T0}-2\xi)}\\ (n_{T0}&=n_{A0}+n_{B0}+n_{C0})\end{aligned}$$

At equilibrium,

$$\frac{y_C}{y_Ay_B^2}\frac{1}{P^2}=\underline{\underline{\frac{(n_{C0}+\xi_e)(n_{T0}-2\xi_e)^2}{(n_{A0}-\xi_e)(n_{B0}-2\xi_e)^2}\frac{1}{P^2}}}=K_e(T)\ \text{(substitute for } K_e(T)\text{ from Part a.)}$$

c. Basis: 1 mol A (CO)

$$n_{A0}=1\quad n_{B0}=1\quad n_{C0}=0\Rightarrow n_{T0}=2,\ P=2\ \mathrm{atm},\ T=423\mathrm{K}$$

$$\frac{\xi_e(2-2\xi_e)^2}{(1-\xi_e)(1-2\xi_e)^2}\frac{1}{4\ \mathrm{atm}^2}=K_e(423)=0.278\ \mathrm{atm}^{-2}\Rightarrow\xi_e^2-\xi_e+0.1317=0$$

4.48 (cont'd)

(For this particular set of initial conditions, we get a quadratic equation. In general, the equation will be cubic.)

$\xi_e = 0.156$, ~~0.844~~ Reject the second solution, since it leads to a negative n_B.

$y_A = (1 - 0.156)/(2 - 2(0.156)) \Rightarrow \underline{\underline{y_A = 0.500}}$

$y_B = (1 - 2(0.156))/(2 - 2(0.156)) \Rightarrow \underline{\underline{y_B = 0.408}}$

$y_C = (0 + 0.156)/(2 - 2(0.156)) \Rightarrow \underline{\underline{y_C = 0.092}}$

Fractional Conversion of CO $(A) = \dfrac{n_{A0} - n_A}{n_{A0}} = \dfrac{\xi}{n_{A0}} = \underline{\underline{0.156 \text{ mol } A \text{ reacted / mol } A \text{ feed}}}$

d. Use the equations from part b.

i) Fractional conversion decreases with increasing fraction of CO.
ii) Fractional conversion decreases with increasing fraction of CH_3OH.
iii) Fractional conversion decreases with increasing temperature.
iv) Fractional conversion increases with increasing pressure.

```
      REAL TRU, A, E, YA0, YC0, T, P, KE, P2KE, C0, C1, C2, C3, EK, EKPI,
     *      FN, FDN, NT, CON, YA, YB, YC
      INTEGER NIT, INMAX
      TAU = 0.0001
      INMAX = 10
      A = 4.79E–13
      E = 11458.
      READ (5, *) YA0, YB0, YC0, T, P
      KE = A * EXP(E/T)
      P2KE = P*P*KE
      C0 = YC0 – P2KE * YA0 * YB0 * YB0
      C1 = 1. – 4. * YC0 + P2KE * YB0 * (YB0 + 4. * YA0)
      C2 = 4. * (YC0 –1. – P2KE * (YA0 + YB0))
      C3 = 4. * (1. + P2KE)
      EK = 0.0        (Assume an initial value ξe = 0.0)
      NIT = 0
 1    FN = C0 + EK * (C1 + EK * (C2 + EK * C3))   FDN = C1 + EK * (2. * C2 +
      EK * 3. * C3)   EKPI = EK - FN/FDN   NIT = NIT + 1   IF (NIT.EQ.INMAX)
      GOTO 4   IF (ABS((EKPI – EK)/EKPI).LT.TAU) GOTO 2   EK =
      EKPI   GOTO 1
  2   NT = 1. – 2. * EKPI
      YA = (YA0 – EKPI)/NT
      YB = (YB0 – 2. + EKPI)/NT
      YC = (YC0 + EKPI)/NT
```

4.48 (cont'd)

```
        CON = EKPI/YA0   WRITE (6, 3) YA, YB, YC, CON   STOP
4       WRITE (6, 5) INMAX, EKPI
3       FORMAT ('  YA    YB    YC    CON', 1, 4(F6.3, 1X))   FORMAT ('DID NOT
        CONVERGE IN', I3, 'ITERATIONS',/,
*                     'CURRENT VALUE = ', F6.3)   END
$       DATA   0.5      0.5       0.0       423.      2.
```

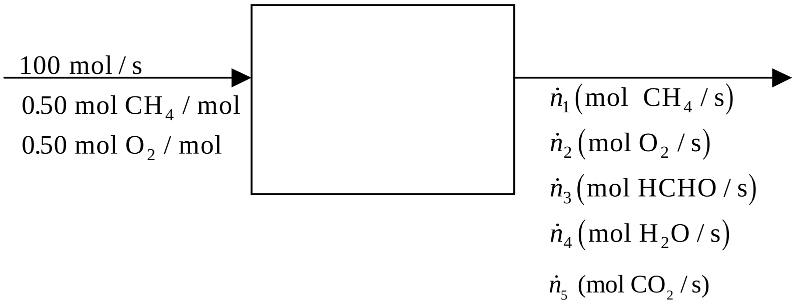
RESULTS: YA = 0.500, YB = 0.408, YC = 0.092, CON = 0.156

Note: This will only find one root — there are two others that can only be found by choosing different initial values of ξ_a

4.49 **a.**

$$CH_4 + O_2 \longrightarrow HCHO + H_2O \qquad (1)$$

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \qquad (2)$$



7 unknowns ($\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{n}_4, \dot{n}_5, \dot{\xi}_1, \dot{\xi}_2$)

−5 equations for $\dot{n}_i\left(\dot{\xi}_1, \dot{\xi}_2\right)$

2 DF

b.

$$\dot{n}_1 = 50 - \dot{\xi}_1 - \dot{\xi}_2 \qquad (1)$$

$$\dot{n}_2 = 50 - \dot{\xi}_1 - 2\dot{\xi}_2 \qquad (2)$$

$$\dot{n}_3 = \dot{\xi}_1 \qquad (3)$$

$$\dot{n}_4 = \dot{\xi}_1 + 2\dot{\xi}_2 \qquad (4)$$

$$\dot{n}_5 = \dot{\xi}_2 \qquad (5)$$

c.

Fractional conversion: $\frac{(50 - \dot{n}_1)}{50} = 0.900 \Rightarrow \dot{n}_1 = 5.00 \text{ mol } CH_4 / s$

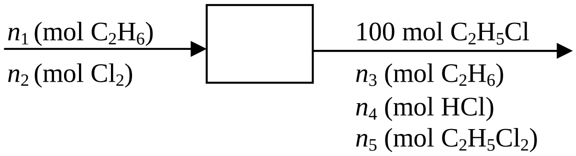
Fractional yield: $\frac{\dot{n}_3}{50} = 0.855 \Rightarrow \dot{n}_3 = 42.75 \text{ mol HCHO / s}$

$$\left.\begin{aligned} &\text{Equation } 3 \Rightarrow \xi_1 = 42.75 \\ &\text{Equation } 1 \Rightarrow \xi_2 = 2.25 \\ &\text{Equation } 2 \Rightarrow \dot{n}_2 = 2.75 \\ &\text{Equation } 4 \Rightarrow \dot{n}_4 = 47.25 \\ &\text{Equation } 5 \Rightarrow \dot{n}_5 = 2.25 \end{aligned}\right\} \Rightarrow \begin{aligned} y_{CH_4} &= \underline{\underline{0.0500 \text{ mol } CH_4 / \text{mol}}} \\ y_{O_2} &= \underline{\underline{0.0275 \text{ mol } O_2 / \text{mol}}} \\ y_{HCHO} &= \underline{\underline{0.4275 \text{ mol HCHO / mol}}} \\ y_{H_2O} &= \underline{\underline{0.4725 \text{ mol } H_2O / \text{mol}}} \\ y_{CO_2} &= \underline{\underline{0.0225 \text{ mol } CO_2 / \text{mol}}} \end{aligned}$$

Selectivity: [(42.75 mol HCHO/s)/(2.25 mol CO_2/s) = $\underline{\underline{19.0 \text{ mol HCHO/mol } CO_2}}$

4.50 **a.** <u>Design for low conversion and feed ethane in excess.</u> Low conversion and excess ethane make the second reaction unlikely.

b. $C_2H_6 + Cl_2 \rightarrow C_2H_5Cl + HCl$, $C_2H_5Cl + Cl_2 \rightarrow C_2H_4Cl_2 + HCl$
<u>Basis</u>: 100 mol C_2H_5Cl produced



5 unknowns
<u>–3 atomic balances</u>
2 D.F.

c. <u>Selectivity:</u> $100 \text{ mol } C_2H_5Cl = 14n_5 \text{ (mol } C_2H_4Cl_2) \Rightarrow n_5 = 7.143 \text{ mol } C_2H_4Cl_2$

$$\left.\begin{array}{ll}\underline{\text{15\% conversion:}} & (1-0.15)n_1 = n_3 \\ \underline{\text{C balance:}} & 2n_1 = 2(100) + 2n_3 + 2(7.143)\end{array}\right\} \Rightarrow \begin{array}{l} n_1 = 714.3 \text{ mol } C_2H_6 \text{ in} \\ n_3 = 114.3 \text{ mol } C_2H_6 \text{ out}\end{array}$$

<u>H balance</u>: $6(714.3) = 5(100) + 6(114.3) + n_4 + 4(7.143) \Rightarrow n_4 = 607.1 \text{ mol HCl}$

<u>Cl balance:</u> $2n_2 = 100 + 607.1 + 2(7.143) \Rightarrow n_2 = 114.3 \text{ mol } Cl_2$

<u>Feed Ratio</u>: $114.3 \text{ mol } Cl_2 \,/\, 714.3 \text{ mol } C_2H_6 = \underline{\underline{0.16 \text{ mol } Cl_2 \,/\, \text{mol } C_2H_6}}$

<u>Maximum possible amount of C_2H_5Cl</u>:

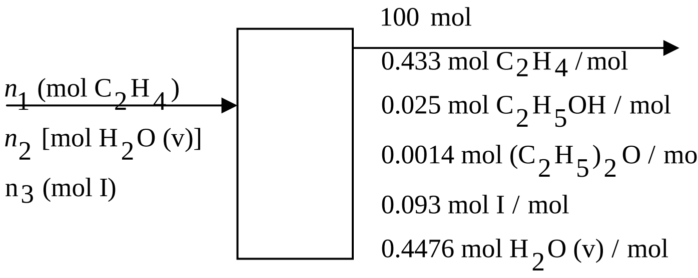
$$n_{\max} = \frac{114.3 \text{ mol } Cl_2}{} \left| \frac{1 \text{ mol } C_2H_5Cl}{1 \text{ mol } Cl_2} \right. = 114.3 \text{ mol } C_2H_5Cl$$

<u>Fractional yield of C_2H_5Cl</u>: $\dfrac{n_{C_2H_5Cl}}{n_{\max}} = \dfrac{100 \text{ mol}}{114.3 \text{ mol}} = 0.875$

d. Some of the $C_2H_4Cl_2$ is further chlorinated in an undesired side reaction:
$C_2H_5Cl_2 + Cl_2 \rightarrow C_2H_4Cl_3 + HCl$

4.51 **a.** $C_2H_4 + H_2O \rightarrow C_2H_5OH$, $2\ C_2H_5OH \rightarrow (C_2H_5)_2O + H_2O$

<u>Basis</u>: 100 mol effluent gas



3 unknowns
-2 independent atomic balances
<u>-1 I balance</u>
$\underline{\underline{\text{0 D.F.}}}$

(1) C balance: $2n_1 = 100(2*0.433 + 2*0.025 + 4*0.0014)$

(2) H balance: $4n_1 + 2n_2 = 100(4*0.433 + 6*0.025 + 10*0.0014 + 2*0.4476)$

(3) O balance: $n_2 = 100(0.025 + 0.0014 + 0.4476)$

Note; *Eq.* (1)*2 + Eq. (3)*2 = Eq. (2) ⇒2 independent atomic balances

(4) I balance: $n_3 = 9.3$

4.51 (cont'd)

b.

$$\left.\begin{array}{r} (1) \Rightarrow n_1 = 46.08 \text{ mol } C_2H_6 \\ (3) \Rightarrow n_2 = 47.4 \text{ mol } H_2O \\ (4) \Rightarrow n_3 = 9.3 \text{ mol I} \end{array}\right\} \Rightarrow \underline{\underline{\text{Reactor feed contains } 44.8\%\ C_2H_6,\ 46.1\%\ H_2O,\ 9.1\%\ I}}$$

<u>% conversion of C_2H_4</u>: $\dfrac{46.08 - 43.3}{46.08} \times 100\% = \underline{\underline{6.0\%}}$

If all C_2H_4 were converted and the second reaction did not occur, $\left(n_{C_2H_5OH}\right)_{\max} = 46.08$ mol

$\Rightarrow$ <u>Fractional Yield of C_2H_5OH</u>: $n_{C_2H_5OH} \,/\, \left(n_{C_2H_5OH}\right)_{\max} = (2.5/46.08) = \underline{\underline{0.054}}$

<u>Selectivity of C_2H_5OH to $(C_2H_5)_2O$</u>:

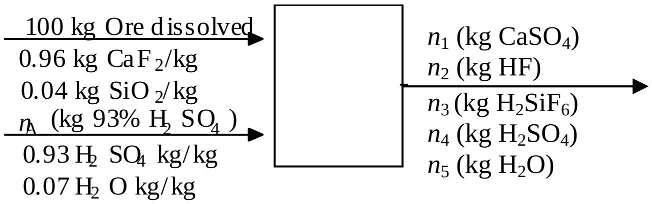
$$\frac{2.5 \text{ mol } C_2H_5OH}{0.14 \text{ mol } (C_2H_5)_2O} = \underline{\underline{17.9 \text{ mol } C_2H_5OH / \text{ mol } (C_2H_5)_2O}}$$

c. Keep conversion low to prevent C_2H_5OH from being in reactor long enough to form significant amounts of $(C_2H_5)_2O$. Separate and recycle unreacted C_2H_4.

4.52 $CaF_2(s) + H_2SO_4(l) \rightarrow CaSO_4(s) + 2HF(g)$

$$\frac{1 \text{ metric ton acid}}{} \left| \frac{1000 \text{ kg acid}}{1 \text{ metric ton acid}} \right| \frac{0.60 \text{ kg HF}}{1 \text{ kg acid}} = 600 \text{ kg HF}$$

<u>Basis: 100 kg Ore dissolved (not fed)</u>



<u>Atomic balance - Si:</u>

$$\frac{0.04(100) \text{ kg } SiO_2}{} \left| \frac{28.1 \text{ kg Si}}{60.1 \text{ kg } SiO_2} \right. = \frac{n_3 \text{ (kg } H_2SiF_6)}{} \left| \frac{28.1 \text{ kg Si}}{144.1 \text{ kg } H_2SiF_6} \right. \Rightarrow n_3 = 9.59 \text{ kg } H_2SiF_6$$

<u>Atomic balance - F:</u>

$$\frac{0.96(100) \text{ kg } CaF_2}{} \left| \frac{38.0 \text{ kg F}}{78.1 \text{ kg } CaF_2} \right. = \frac{n_2 \text{ (kg HF)}}{} \left| \frac{19.0 \text{ kg F}}{20.0 \text{ kg HF}} \right.$$

$$+ \frac{9.59 \text{ kg } H_2SiF_6}{} \left| \frac{114.0 \text{ kg F}}{144.1 \text{ kg } H_2SiF_6} \right. \Rightarrow n_2 = 41.2 \text{ kg HF}$$

$$\frac{600 \text{ kg HF}}{} \left| \frac{100 \text{ kg ore diss.}}{41.2 \text{ kg HF}} \right| \frac{1 \text{ kg ore feed}}{0.95 \text{ kg ore diss.}} = \underline{\underline{1533 \text{ kg ore}}}$$

4.53 **a.** $C_6H_6 + Cl_2 \rightarrow C_6H_5Cl + HCl$

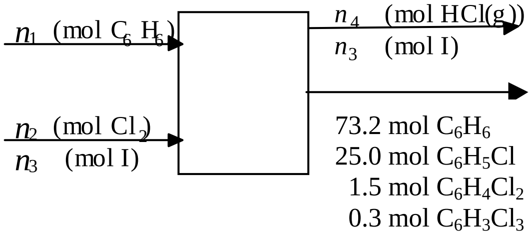
$C_6H_5Cl + Cl_2 \rightarrow C_6H_4Cl_2 + HCl$

$C_6H_4Cl_2 + Cl_2 \rightarrow C_6H_3Cl_3 + HCl$

Convert output wt% to mol%: Basis 100 g output

species	g	Mol. Wt.	mol	mol %
C_6H_6	65.0	78.11	0.832	73.2
C_6H_5Cl	32.0	112.56	0.284	25.0
$C_6H_4Cl_2$	2.5	147.01	0.017	1.5
$C_6H_3Cl_3$	0.5	181.46	0.003	0.3
		total	1.136	

<u>Basis: 100 mol output</u>



4 unknowns
-3 atomic balances
<u>-1 wt% Cl_2 in feed</u>
0 D.F.

b. <u>C balance:</u> $6n_1 = 6(73.2+25.0+1.5+0.3) \Rightarrow n_1 = 100 \text{ mol } C_6H_6$

<u>H balance:</u> $6(100) = 6(73.2)+5(25.0)+4(1.5)+3(0.3)+n_4 \Rightarrow n_4 = 28.9 \text{ mol HCl}$

<u>Cl balance:</u> $2n_2 = 28.9+25.0+2(1.5)+3(0.3) \Rightarrow n_2 = 28.9 \text{ mol } Cl_2$

<u>Theoretical C_6H_6</u> $= 28.9 \text{ mol } Cl_2 (1 \text{ mol } C_6H_6 / 1 \text{ mol } Cl_2) = 28.9 \text{ mol } C_6H_6$

<u>Excess C_6H_6:</u> $(100-28.9)/28.9 \times 100\% = \underline{\underline{246\% \text{ excess } C_6H_6}}$

<u>Fractional Conversion:</u> $(100-73.2)/100 = \underline{\underline{0.268 \text{ mol } C_6H_6 \text{ react/mol fed}}}$

<u>Yield:</u> $(25.0 \text{ mol } C_6H_5Cl)/(28.9 \text{ mol } C_6H_5Cl \text{ maximum}) = \underline{\underline{0.865}}$

$$\left.\begin{array}{l} \underline{\text{Gas feed:}} \quad \dfrac{28.9 \text{ mol } Cl_2}{} \left| \dfrac{70.91 \text{ g } Cl_2}{\text{mole } Cl_2} \right| \dfrac{1 \text{ g gas}}{0.98 \text{ g } Cl_2} = 2091 \text{ g gas} \\ \underline{\text{Liquid feed:}} \quad (100 \text{ mol } C_6H_6)\left(\dfrac{78.11 \text{ g } C_6H_6}{\text{mol } C_6H_6}\right) = 7811 \text{ g liquid} \end{array}\right\} \Rightarrow 0.268 \frac{\text{g gas}}{\text{g liquid}}$$

c. Low conversion ⇒ low residence time in reactor ⇒ lower chance of 2nd and 3rd reactions occurring. Large excess of $C_6H_6 \Rightarrow Cl_2$ much more likely to encounter C_6H_6 than substituted $C_6H_6 \Rightarrow$ higher selectivity.

d. Dissolve in water to produce hydrochloric acid.

e. Reagent grade costs <u>much</u> more. Use only if impurities in technical grade mixture affect the reaction rate or desired product yield.

4.54 **a.** $2CO_2 \Leftrightarrow 2CO + O_2$ $\qquad$ $2A \Leftrightarrow 2B + C$

$O_2 + N_2 \Leftrightarrow 2NO$ $\qquad$ $C + D \Leftrightarrow 2E$

$$\begin{array}{lll} n_A = n_{A0} - 2\xi_{e1} & & y_A = \left(n_{A0} - 2\xi_{e1}\right)/\left(n_{T0} + \xi_{e1}\right) \\ n_B = n_{B0} + 2\xi_{e2} & & y_B = \left(n_{B0} + 2\xi_{e1}\right)/\left(n_{T0} + \xi_{e1}\right) \\ n_C = n_{C0} + \xi_{e1} - \xi_{e2} & \Rightarrow & y_C = \left(n_{C0} + \xi_{e1} - \xi_{e2}\right)/\left(n_{T0} + \xi_{e1}\right) \\ n_D = n_{D0} - \xi_{e2} & & y_D = \left(n_{D0} - 1\xi_{e2}\right)/\left(n_{T0} + \xi_{e1}\right) \\ \underline{n_E = n_{E0} + 2\xi_{e2}} & & y_E = \left(n_{E0} + 2\xi_{e2}\right)/\left(n_{T0} + \xi_{e1}\right) \end{array}$$

$n_{\text{total}} = n_{T0} + \xi_{e1}$ $\qquad$ $\left(n_{T0} = n_{A0} + n_{B0} + n_{C0} + n_{D0} + n_{E0}\right)$

<u>Equilibrium at 3000K and 1 atm</u>

$$\frac{y_B^2 y_C}{y_A^2} = \frac{\left(n_{B0} + 2\xi_{e1}\right)^2 \left(n_{C0} + \xi_{e1} - \xi_{e2}\right)}{\left(n_{A0} - 2\xi_{e1}\right)^2 \left(n_{T0} + \xi_{e1}\right)} = 0.1071$$

$$\frac{y_E^2}{y_C y_D} = \frac{\left(n_{E0} + 2\xi_{e2}\right)^2}{\left(n_{A0} + \xi_{e1} - \xi_{e2}\right)\left(n_{D0} - \xi_{e2}\right)} = 0.01493$$

$\Downarrow$

$$\left.\begin{array}{c} \underline{\underline{f_1 = 0.1071\left(n_{A0} - 2\xi_{e1}\right)^2 \left(n_{T0} + \xi_{e1}\right) - \left(n_{B0} + 2\xi_{e1}\right)^2 \left(n_{C0} + \xi_{e1} - \xi_{e2}\right) = 0}} \\ \underline{\underline{f_2 = 0.01493\left(n_{C0} + \xi_{e1} - \xi_{e2}\right)\left(n_{D0} - \xi_{e2}\right) - \left(n_{E0} + 2\xi_{e2}\right)^2 = 0}} \end{array}\right\} \begin{array}{c} \text{Defines functions} \\ f_1(\xi_1, \xi_2) \text{ and} \\ f_2(\xi_1, \xi_2) \end{array}$$

b. Given all n_{io}'s, solve above equations for ξ_{e1} and $\xi_{e2} \Rightarrow n_A, n_B, n_C, n_D, n_E \Rightarrow y_A, y_B, y_C, y_D, y_E$

c. $n_{A0} = n_{C0} = n_{D0} = 0.333$, $n_{B0} = n_{E0} = 0 \Rightarrow \xi_{e1} = 0.0593$, $\xi_{e2} = 0.0208$

$\Rightarrow \underline{\underline{y_A = 0.2027}}$, $\underline{\underline{y_B = 0.1120}}$, $\underline{\underline{y_C = 0.3510}}$, $\underline{\underline{y_D = 0.2950}}$, $\underline{\underline{y_E = 0.0393}}$

d.

$$\begin{array}{ll} a_{11}d_1 + a_{12}d_2 = -f_1 & \qquad a_{21}d_1 + a_{22}d_2 = -f_2 \\ d_1 = \dfrac{a_{12}f_2 - a_{22}f_1}{a_{11}a_{22} - a_{12}a_{21}} & \qquad d_2 = \dfrac{a_{21}f_1 - a_{11}f_2}{a_{11}a_{22} - a_{12}a_{21}} \\ \left(\xi_{e1}\right)_{\text{new}} = \xi_{e1} + d_1 & \qquad \left(\xi_{e2}\right)_{\text{new}} = \xi_{e1} + d_2 \end{array}$$

(Solution given following program listing.)

```
      IMPLICIT REAL * 4(N)
      WRITE (6, 1)
  1   FORMAT('1', 30X, 'SOLUTION TO PROBLEM 4.57'///)
 30   READ (5, *) NA0, NB0, NC0, ND0, NE0
      IF (NA0.LT.0.0)STOP
      WRITE (6, 2) NA0, NB0, NC0, ND0, NE0
```

4.54 (cont’d)

```
  2     FORMAT('0', 15X, 'NA0, NB0, NC0, ND0, NE0 *', 5F6.2/)
        NTO = NA0 + NB0 + NC0 + ND0 + NE0
        NMAX = 10
        X1 = 0.1
        X2 = 0.1
        DO 100 J = 1, NMAX
        NA = NA0 – X1 – X1
        NB = NB0 + X1 + X1
        NC = NC0 + X1 – X2
        ND = ND0 – X2
        NE = NE0 + X2 + X2
        NAS = NA ** 2
        NBS = NB ** 2
        NES = NE ** 2
        NT = NT0 + X1
        F1 = 0.1071 * NAS * NT – NBS * NC
        F2 = 0.01493 * NC * ND – NES
        A11 = –0.4284 * NA * NT * 0.1071 * NAS – 4.0 * NB * NC – NBS
        A12 = NBS
        A21 = 0.01493 * ND
         A22 = –0.01493 * (NC + ND) – 4.0 * NE
        DEN = A11 * A22 – A12 * A21
        D1 = (A12 * F2 – A22 * F1)/DEN
        D2 = (A21 * F1 – A11 * F2)/DEN
        X1C = X1 + D1
        X2C = X2 + D2
        WRITE (6, 3) J, X1, X2, X1C, X2C
  3     FORMAT(20X, 'ITER *', I3, 3X, 'X1A, X2A =', 2F10.5, 6X, 'X1C, X2C =', * 2F10.5)
        IF (ABS(D1/X1C).LT.1.0E–5.AND.ABS(D2/X2C).LT.1.0E–5) GOTO 120
        X1 = X1C
        X2 = X2C
100     CONTINUE
        WRITE (6, 4) NMAX
  4     FORMAT('0', 10X, 'PROGRAM DID NOT CONVERGE IN', I2, 'ITERATIONS'/)
        STOP
120     YA = NA/NT
        YB = NB/NT
        YC = NC/NT
        YD = ND/NT
        YE = NE/NT
        WRITE (6, 5) YA, YB, YC, YD, YE
      5 FORMAT ('0', 15X, 'YA, YB, YC, YD, YE =', 1P5E14.4///)
        GOTO 30
        END
        $DATA
        0.3333   0.00   0.3333   0.3333   0.0
        0.50     0.0    0.0      0.50     0.0
        0.20     0.20   0.20     0.20     0.20
```

```
SOLUTION TO PROBLEM 4.54

NA0, NB0, NC0, ND0, NE0 = 0.33   0.00    0.33    0.33    0.00
ITER = 1   X1A, X2A = 0.10000    0.10000         X1C, X2C = 0.06418      0.05181
ITER = 2   X1A, X2A = 0.06418    0.05181         X1C, X2C = 0.05969      0.02986
ITER = 3   X1A, X2A = 0.05969    0.02486         X1C, X2C = 0.05937      0.02213
```

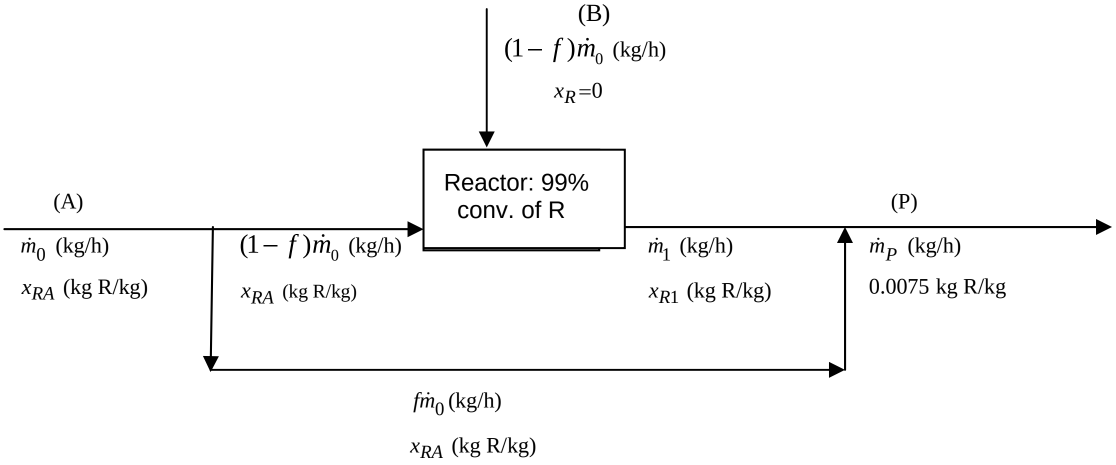
4.54 (cont'd)

```
ITER = 4   X1A, X2A = 0.05437    0.02213           X1C, X2C = 0.05931       0.02086
ITER = 5   X1A, X2A = 0.05931    0.02086           X1C, X2C = 0.05930       0.02083
ITER = 6   X1A, X2A = 0.05930    0.02083           X1C, X2C = 0.05930       0.02083
YA, YB, YC, YD, YE =          2.0270E – 01    1.1197E – 01     3.5100E – 01
                              2.9501E – 01    3.9319E – 02
```

```
NA0, NB0, NC0, ND0, NE0 = 0.20    0.20     0.20     0.20      0.20
ITER = 1   X1A, X2A = 0.10000                       0.10000   X1C, X2C = 0.00012        0.00037
  ↓
ITER = 7   X1A, X2A = –0.02244                      –0.08339  X1C, X2C = –0.02244       –0.08339

YA, YB, YC, YD, YE=          2.5051E – 01   1.5868E – 01   2.6693E – 01
                             2.8989E – 01   3.3991E – 02
```

4.55 **a.**



<u>Mass balance on reactor</u>: $2(1-f)\dot{m}_0 = \dot{m}_1$ (1)

<u>99% conversion of R</u>: $\dot{m}_1 x_{R1} = 0.01(1-f)\dot{m}_0 x_{RA}$ (2)

<u>Mass balance on mixing point</u>: $\dot{m}_1 + f\dot{m}_0 = \dot{m}_P$ (3)

<u>R balance on mixing point</u>: $\dot{m}_1 x_{R1} + f\dot{m}_0 x_{RA} = 0.0075\dot{m}_P$ (4)

The system has 6 unknowns $(\dot{m}_0, x_{RA}, f, \dot{m}_1, x_{R1}, \dot{m}_P)$ and four independent equations relating them, so there must be two degrees of freedom.

b.

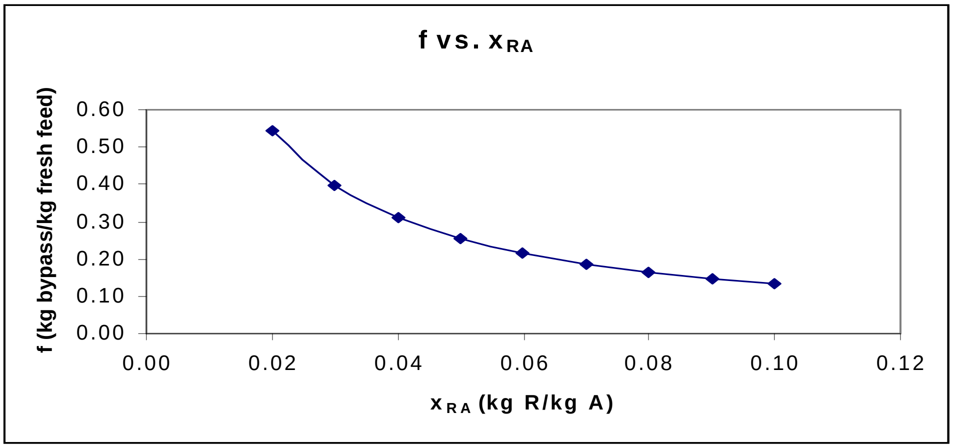
$$\left.\begin{aligned}
&2(1-f)\dot{m}_0 = \dot{m}_1 \\
&\dot{m}_1 x_{R1} = 0.01(1-f)\dot{m}_0 x_{RA} \\
&\dot{m}_1 + f\dot{m}_0 = \dot{m}_P \\
&\dot{m}_1 x_{R1} + f\dot{m}_0 x_{RA} = 0.0075\dot{m}_P \\
&\dot{m}_P = 4850 \\
&x_{RA} = 0.0500
\end{aligned}\right\}\xrightarrow{\text{E-Z Solve}}
\begin{aligned}
&\dot{m}_0 = 2780 \text{ kg/h} \\
&f = 0.254 \text{ kg bypassed/kg fresh feed}
\end{aligned}$$

4.55 (cont'd)

c.

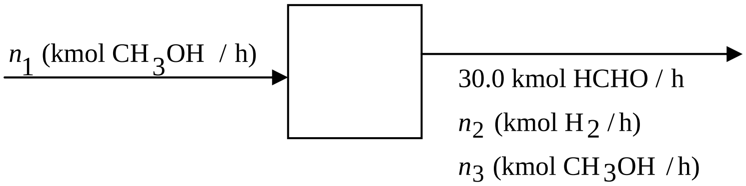
m_P	x_{RA}	m_{A0}	m_{B0}	f
4850	0.02	3327	1523	0.54
4850	0.03	3022	1828	0.40
4850	0.04	2870	1980	0.31
4850	0.05	2778	2072	0.25
4850	0.06	2717	2133	0.21
4850	0.07	2674	2176	0.19
4850	0.08	2641	2209	0.16
4850	0.09	2616	2234	0.15
4850	0.10	2596	2254	0.13

m_P	x_{RA}	m_{A0}	m_{B0}	f
2450	0.02	1663	762	0.54
2450	0.03	1511	914	0.40
2450	0.04	1435	990	0.31
2450	0.05	1389	1036	0.25
2450	0.06	1359	1066	0.22
2450	0.07	1337	1088	0.19
2450	0.08	1321	1104	0.16
2450	0.09	1308	1117	0.15
2450	0.10	1298	1127	0.13



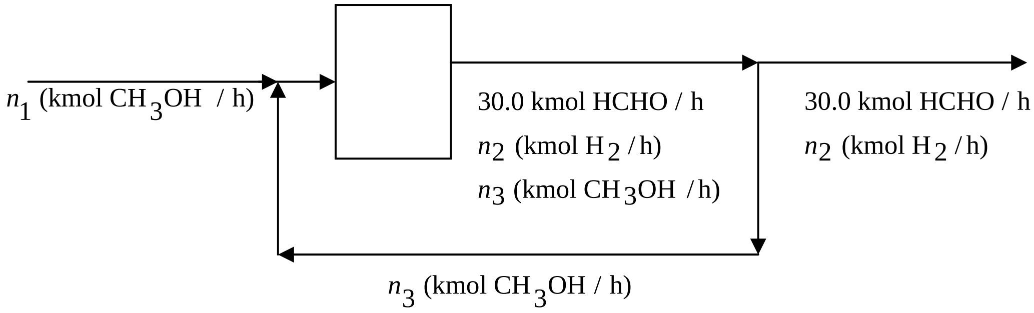
4.56 **a.**

$$\frac{900\text{ kg HCHO}}{h}\left|\frac{1\text{ kmol HCHO}}{30.03\text{ kg HCHO}}\right.=30.0\text{ kmol HCHO / h}$$



<u>% conversion</u>: $\frac{30.0}{n_1}=0.60\Rightarrow \underline{\underline{n_1=50.0\text{ kmol }CH_3OH\text{ / h}}}$

b.



<u>Overall C balance</u>: n_1 (1) = 30.0 (1) ⇒ n_1 = 30.0 kmol CH_3OH/h (fresh feed)

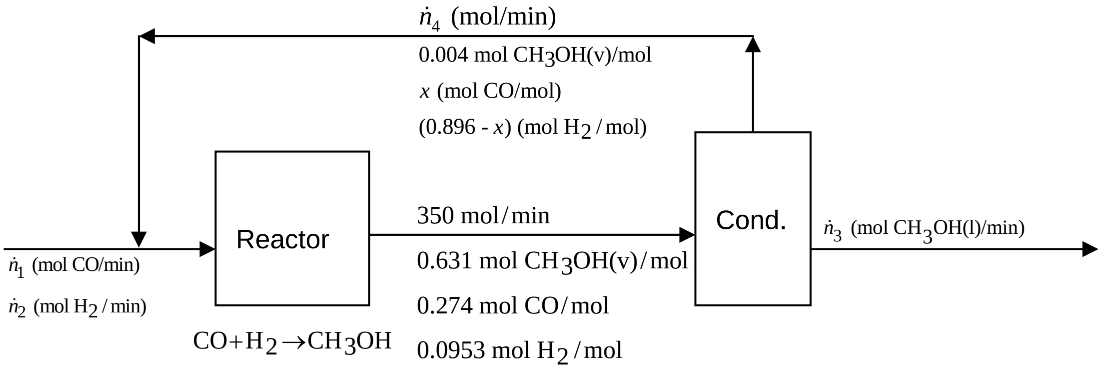
<u>Single pass conversion</u>: $\frac{30.0}{n_1+n_3}=0.60\Rightarrow \underline{\underline{n_3=20.0\text{ kmol }CH_3OH\text{ / h}}}$

n_1+n_3 = <u>50.0 kmol CH_3OH fed to reactor/h</u>

c. Increased x_{sp} will (1) require a larger reactor and so will increase the cost of the reactor and (2) lower the quantities of unreacted methanol and so will decrease the cost of the separation. The plot would resemble a concave upward parabola with a minimum around x_{sp} = 60%.

4.57 **a.** <u>Convert effluent composition to molar basis</u>. <u>Basis</u>: 100 g effluent:

$$\left.\begin{aligned}&\frac{10.6\text{ g }H_2}{}\left|\frac{1\text{ mol }H_2}{2.01\text{ g }H_2}\right.=5.25\text{ mol }H_2\\&\frac{64.0\text{ g CO}}{}\left|\frac{1\text{ mol CO}}{28.01\text{ g CO}}\right.=2.28\text{ mol CO}\\&\frac{25.4\text{ g }CH_3OH}{}\left|\frac{1\text{ mol }CH_3OH}{32.04\text{ g }CH_3OH}\right.\\&=0.793\text{ mol }CH_3OH\end{aligned}\right\}\Rightarrow\begin{aligned}H_2&:\ 0.631\text{ mol }H_2\text{ / mol}\\CO&:\ 0.274\text{ mol CO / mol}\\CH_3OH&:\ 0.0953\text{ mol }CH_3OH\text{ / mol}\end{aligned}$$



Condenser	Overall process
3 unknowns $(\dot{n}_3, \dot{n}_4, x)$	2 unknowns $(\dot{n}_1, \dot{n}_2)$
–3 balances	–2 independent atomic balances
0 degrees of freedom	0 degrees of freedom

Balances around condenser

$$\left.\begin{aligned} \text{CO: } 350*0.274 &= \dot{n}_4 * x \\ H_2: \; 350*0.631 &= \dot{n}_4*(0.996-x) \\ CH_3OH: \; 350*0.0953 &= \dot{n}_3 + 0.004*\dot{n}_4 \end{aligned}\right\} \Rightarrow \begin{aligned} &\underline{\underline{\dot{n}_3 = 32.1 \text{ mol } CH_3OH(l)\text{/min}}} \\ &\dot{n}_4 = 318.7 \text{ mol recycle/min} \\ &x = .301 \text{ molCO/mol} \end{aligned}$$

Overall balances

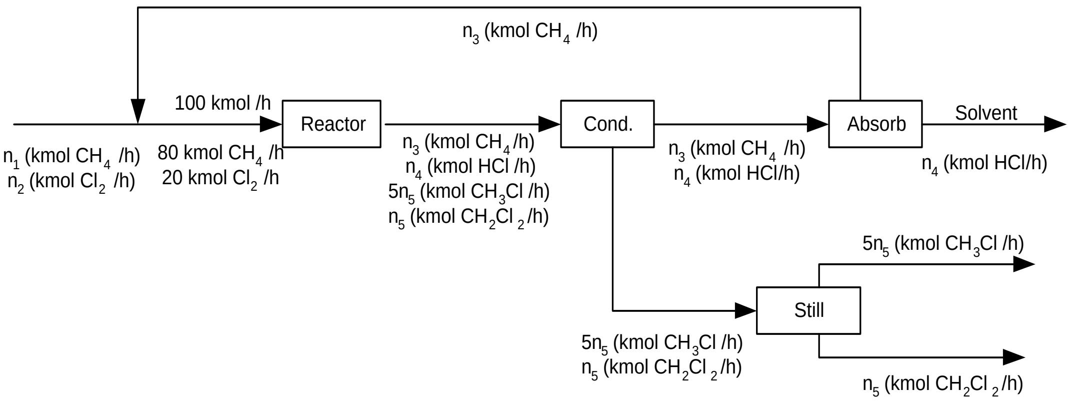
$$\left.\begin{aligned} C: \; \dot{n}_1 &= \dot{n}_3 \\ H: \; 2\dot{n}_2 &= 4\dot{n}_3 \end{aligned}\right\} \Rightarrow \begin{aligned} &\underline{\underline{\dot{n}_1 = 32.08 \text{ mol/min CO in feed}}} \\ &\underline{\underline{\dot{n}_2 = 64.16 \text{ mol/min } H_2 \text{ in feed}}} \end{aligned}$$

Single pass conversion of CO: $\dfrac{(32.08+318.72*0.3009)-350*0.274}{(32.08+318.72*0.3009)} \times 100\% = \underline{\underline{25.07\%}}$

Overall conversion of CO: $\dfrac{32.08-0}{32.08} \times 100\% = \underline{\underline{100\%}}$

b.
- – Reactor conditions or feed rates drifting. (Recalibrate measurement instruments.)
- – Impurities in feed. (Re-analyze feed.)
- – Leak in methanol outlet pipe before flowmeter. (Check for it.)

4.58 **a.** Basis: 100 kmol reactor feed/hr



Overall process: 4 unknowns (n_1, n_2, n_4, n_5) -3 balances = 1 D.F.
Mixing Point: 3 unknowns (n_1, n_2, n_3) -2 balances = 1 D.F.
Reactor: 3 unknowns (n_3, n_4, n_5) -3 balances = 0 D.F.
Condenser: 3 unknowns (n_3, n_4, n_5) -0 balances = 3 D.F.
Absorption column: 2 unknowns (n_3, n_4) -0 balances = 2 D.F.
Distillation Column: 2 unknowns (n_4, n_5) -0 balances = 2 D.F.
Atomic balances around reactor:

$$\left.\begin{array}{l}1)\ \text{C balance: } 80 = n_3 + 5n_5 + n_5 \\ 2)\ \text{H balance: } 320 = 4n_3 + n_4 + 15n_5 + 2n_5 \\ 3)\ \text{Cl balance: } 40 = n_4 + 5n_5 + 2n_5\end{array}\right\} \Rightarrow \text{Solve for } n_3, n_4, n_5$$

CH_4 balance around mixing point: $n_1 = (80 - n_3)$ Solve for n_1

Cl_2 balance: $n_2 = 20$

b. For a basis of 100 kmol/h into reactor

n_1 = 17.1 kmol CH_4/h
n_2 = 20.0 kmol Cl_2/h
n_3 = 62.9 kmol CH_4/h
n_4 = 20.0 kmol HCl/h
$5n_5$ = 14.5 kmol CH_3Cl/h

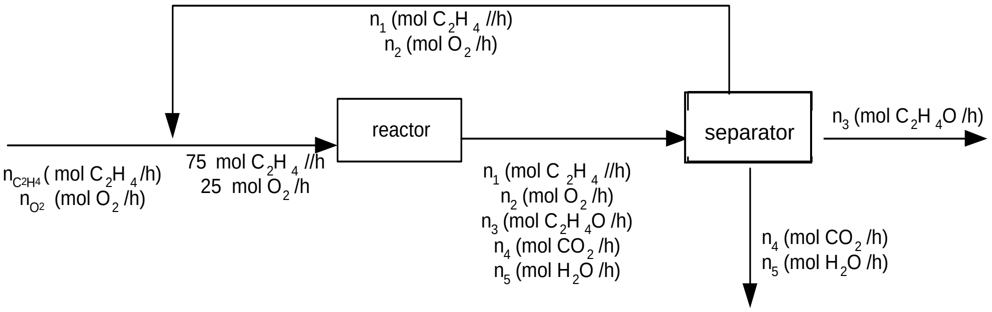
c. (1000 kg CH_3Cl/h)(1 kmol/50.49 kg) = 19.81 kmol CH_3Cl/h

$$\text{Scale factor} = \frac{19.81\ \text{kmol CH}_3\text{Cl/h}}{14.5\ \text{kmol CH}_3\text{Cl/h}} = 1.366$$

$$\text{Fresh feed: } \left.\begin{array}{l} n_1 = (17.1)(1.366) = 23.3\ \text{kmol CH}_4/\text{h} \\ n_2 = (20.0)(1.366) = 27.3\ \text{kmol Cl}_2/\text{h}\end{array}\right\} \Rightarrow \begin{array}{c} n_{tot} = 50.6\ \text{kmol/h} \\ 46.0\ \text{mol\% CH}_4,\ 54.0\ \text{mole\% Cl}_2\end{array}$$

Recycle: n_3 = (62.9)(1.366) = 85.9 kmol CH_4 recycled/h

4.59 **a.** Basis: 100 mol fed to reactor/h ⇒ 25 mol O_2/h, 75 mol C_2H_4/h



Reactor

5 unknowns (n_1 - n_5)
-3 atomic balances
-1 - % yield
-1 - % conversion
0 D.F.

Strategy: 1. Solve balances around reactor to find n_1- n_5
2. Solve balances around mixing point to find n_{O2}, n_{C2H4}

(1) % Conversion ⇒ $n_1 = .800 * 75$

(2) % yield: $(.200)(75)\,\text{mol}\,C_2H_4 \times \dfrac{90\,\text{mol}\,C_2H_4O}{100\,\text{mol}\,C_2H_4} = n_3$ (production rate of C_2H_4O)

(3) C balance (reactor): $150 = 2\,n_1 + 2\,n_3 + n_4$

(4) H balance (reactor): $300 = 4\,n_1 + 4\,n_3 + 2\,n_5$

(5) O balance (reactor): $50 = 2\,n_2 + n_3 + 2\,n_4 + n_5$

(6) O_2 balance (mix pt): $n_{O2} = 25 - n_2$

(7) C_2H_4 balance (mix pt): $n_{C2H4} = 75 - n_1$

Overall conversion of C_2H_4: 100%

b.

$n_1 = 60.0$ mol C_2H_4/h
$n_2 = 13.75$ mol O_2 /h
$n_3 = 13.5$ mol C_2H_4O/h
$n_4 = 3.00$ mol CO_2/h
$n_5 = 3.00$ mol H_2O/h
$n_{O2} = 11.25$ mol O_2/h
$n_{C2H4} = 15.0$ mol C_2H_4/h
100% conversion of C_2H_4

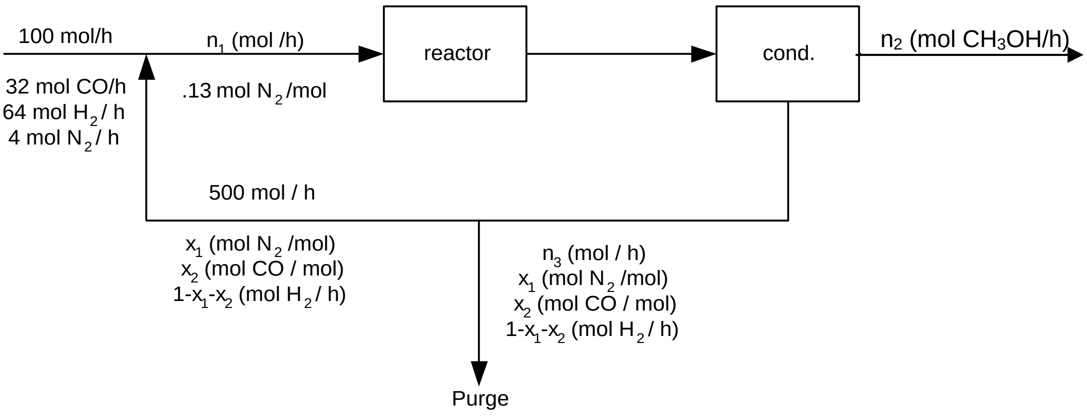
c.

$$\text{Scale factor} = \frac{2000\,\text{lbm}\,C_2H_4O}{\text{h}}\bigg|\frac{1\,\text{lb-mole}\,C_2H_4O}{44.05\,\text{lbm}\,C_2H_4O}\bigg|\frac{\text{h}}{13.5\,\text{mol}\,C_2H_4O} = 3.363\,\frac{\text{lb}-\text{mol/h}}{\text{mol/h}}$$

$n_{C2H4} = (3.363)(15.0) = 50.4$ lb-mol C_2H_4/h

$n_{O2} = (3.363)(11.25) = 37.8$ lb-mol O_2/h

4.60 **a.** Basis: 100 mol feed/h. Put dots above all *n*'s in flow chart.



Mixing point balances:

total: (100) + 500 = $\dot{n}_1 \Rightarrow \dot{n}_1$ = 600 mol/h

N_2: 4 + x_1 * 500 = .13 * 600 $\Rightarrow$ x_1 = 0.148 mol N_2/mol

Overall system balances:

N_2: 4 = .148 * $\dot{n}_3 \Rightarrow \dot{n}_3$ = 27 mol/h

$$\left.\begin{array}{l}\text{Atomic C: } 32 = \dot{n}_2 + x_2 * 27 \\ \text{Atomic H: } 2 * 64 = 4 * 24.3 + 2 * (1-0.148-x_2) * 27\end{array}\right\} \Rightarrow \begin{array}{l}\dot{n}_2 = \underline{24.3 \text{ mol CH}_3\text{OH/h}} \\ x_2 = \underline{0.284 \text{ mol CO/mol}}\end{array}$$

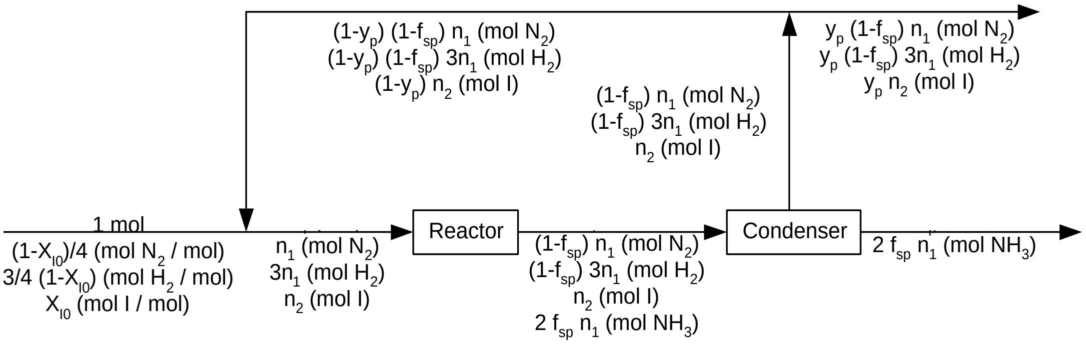
Overall CO conversion: 100*[32-0.284(27)]/32 = 76%

Single pass CO conversion: 24.3/ (32+.284*500) = 14%

b. Recycle: To recover unconsumed CO and H_2 and get a better overall conversion.

Purge: to prevent buildup of N_2.

4.61 **a.** $N_2 + 3H_2 \rightarrow 2NH_3$



4.61 (cont'd)

At mixing point:

N_2: $(1-X_{I0})/4 + (1-y_p)(1-f_{sp})\, n_1 = n_1$

I: $X_{I0} + (1-y_p)\, n_2 = n_2$

Total moles fed to reactor: $\underline{\underline{n_r = 4n_1 + n_2}}$

Moles of NH_3 produced: $\underline{\underline{n_p = 2f_{sp}n_1}}$

Overall N_2 conversion: $\underline{\underline{\dfrac{(1-X_{I0})/4 - y_p(1-f_{sp})n_1}{(1-X_{I0})/4}\times 100\%}}$

b. $X_{I0} = 0.01$ $f_{sp} = 0.20$ $y_p = 0.10$

$n_1 = 0.884$ mol N_2

$n_2 = 0.1$ mol I

$n_r = \underline{\underline{3.636 \text{ mol fed}}}$

$n_p = \underline{\underline{0.3536 \text{ mol } NH_3 \text{ produced}}}$

N_2 conversion = $\underline{\underline{71.4\%}}$

c. Recycle: recover and reuse unconsumed reactants.

Purge: avoid accumulation of I in the system.

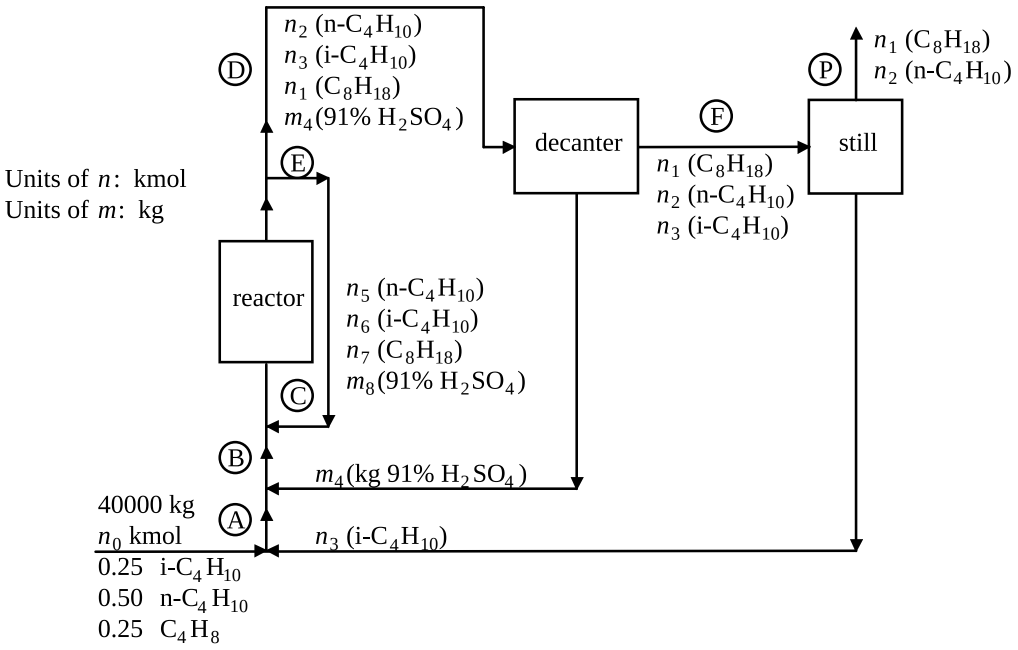
d. Increasing X_{I0} results in increasing n_r, decreasing n_p, and has no effect on f_{ov}. Increasing f_{sp} results in decreasing n_r, increasing n_p, and increasing f_{ov}.

Increasing y_p results in decreasing n_r, decreasing n_p, and decreasing f_{ov}.

Optimal values would result in a low value of n_r and f_{sp}, and a high value of n_p, this would give the highest profit.

X_{I0}	f_{sp}	y_p	n_r	n_p	f_{ov}
0.01	0.20	0.10	3.636	0.354	71.4%
0.05	0.20	0.10	3.893	0.339	71.4%
0.10	0.20	0.10	4.214	0.321	71.4%
0.01	0.30	0.10	2.776	0.401	81.1%
0.01	0.40	0.10	2.252	0.430	87.0%
0.01	0.50	0.10	1.900	0.450	90.9%
0.10	0.20	0.20	3.000	0.250	55.6%
0.10	0.20	0.30	2.379	0.205	45.5%
0.10	0.20	0.40	1.981	0.173	38.5%

4.62 **a.** $i\text{-}C_4H_{10} + C_4H_8 = C_8H_{18}$ <u>Basis</u>: 1-hour operation



<u>Calculate moles of feed</u>

$$\overline{M} = 0.25M_{\text{L}-C_4H_{10}} + 0.50M_{\text{n}-C_4H_{10}} + 0.25M_{C_4H_8} = (0.75)(58.12) + (0.25)(56.10)$$
$$= 57.6 \text{ kg/kmol}$$
$$n_0 = (40000 \text{ kg})(1 \text{ kmol}/57.6 \text{ kg}) = 694 \text{ kmol}$$

<u>Overall n-C_4H_{10} balance:</u> $n_2 = (0.50)(694) = \underline{\underline{347 \text{ kmol n-}C_4H_{10} \text{ in product}}}$

<u>C_8H_{18} balance:</u>

$$n_1 = \frac{(0.25)(694) \text{ kmol } C_4H_8 \text{ react}}{} \left| \frac{1 \text{ mol } C_8H_{18}}{1 \text{ mol } C_4H_8} \right. = \underline{\underline{173.5 \text{ kmol } C_8H_8 \text{ in product}}}$$

<u>At (A)</u>, 5 mol $i\text{-}C_4H_{10}/1 \text{ mole } C_4H_8 \Rightarrow \text{n}(\text{mol } i\text{-}C_4H_{10})_A = \underbrace{(5)(0.25)(694)}_{\substack{\text{moles } C_4H_8 \text{ at} \\ \text{A=173.5}}} = \underbrace{867.5 \text{ kmol}}_{\substack{i\text{-}C_4H_{10} \text{ at} \\ \text{(A) and (B)}}}$

Note: $\text{n}(\text{mol } C_4H_8) = 173.5$ at (A), (B) and (C) and in feed

<u>$i\text{-}C_4H_{10}$ balance around first mixing point</u> $\Rightarrow (0.25)(694) + n_3 = 867.5$

$$\Rightarrow n_3 = \underline{\underline{694 \text{ kmol } i\text{-}C_4H_{10} \text{ recycled from still}}}$$

At C, $200 \text{ mol } i\text{-}C_4H_{10}/\text{mol } C_4H_8$

$$\Rightarrow \text{n}(\text{mol } i\text{-}C_4H_{10})_C = (200)(173.5) = 34{,}700 \text{ kmol } i\text{-}C_4H_{10}$$

4.62 (cont'd)

$\underline{i\text{-}C_4H_{10}\text{ balance around second mixing point}} \Rightarrow 867.5 + n_6 = 34{,}700$

$$\Rightarrow n_6 = \underline{\underline{33{,}800\text{ kmol }C_4H_{10}\text{ in recycle E}}}$$

Recycle E: Since Streams (D) and (E) have the same composition,

$$\frac{n_5\ (\text{moles n-}C_4H_{10})_E}{n_2\ (\text{moles n-}C_4H_{10})_D} = \frac{n_6\ (\text{moles }i\text{-}C_4H_{10})_E}{n_3\ (\text{moles }i\text{-}C_4H_{10})_D} \Rightarrow n_5 = \underline{\underline{16{,}900\text{ kmol n-}C_4H_{10}}}$$

$$\frac{n_7\ (\text{moles }C_8H_{18})_E}{n_1\ (\text{moles }C_8H_{18})_D} = \frac{n_6}{n_3} \Rightarrow n_7 = \underline{\underline{8460\text{ kmol }C_4H_{18}}}$$

Hydrocarbons entering reactor:

$$\left[(347+16900)(\text{kmol n-}C_4H_{10})\right]\left(58.12\ \frac{\text{kg}}{\text{kmol}}\right)$$
$$+\left[(867.5+33800)(\text{kmol }i\text{-}C_4H_{10})\right]\left(58.12\ \frac{\text{kg}}{\text{kmol}}\right) + \left[173.5\text{ kmol }C_4H_8\right]\left(56.10\ \frac{\text{kg}}{\text{kmol}}\right)$$
$$+\left[8460\text{ kmol }C_8H_{18}\right]\left(114.22\ \frac{\text{kg}}{\text{kmol}}\right) = 4.00\times10^6\text{ kg .}$$

$$\frac{\underline{H_2SO_4\text{ solution entering reactor}}}{\underline{(\text{and leaving reactor})}} = \frac{4.00\times10^6\text{ kg HC}}{} \left| \frac{2\text{ kg }H_2SO_4(aq)}{1\text{ kg HC}}\right.$$

$$= 8.00\times10^6\text{ kg }H_2SO_4(aq)$$

$$\frac{m_8(H_2SO_4\text{ in recycle})}{8.00\times10^6(H_2SO_4\text{ leaving reactor})} = \frac{n_5(\text{n-}C_4H_{10}\text{ in recycle})}{n_2+n_5(\text{n-}C_4H_{10}\text{ leaving reactor})}$$

$$\Rightarrow m_8 = 7.84\times10^6\text{ kg }H_2SO_4(aq)\text{ in recycle E}$$

$m_4 = H_2SO_4\text{ entering reactor} - H_2SO_4\text{ in E}$

$= 1.6\times10^5\text{ kg }H_2SO_4(aq)\text{ recycled from decanter}$

$\Rightarrow \left[(1.6\times10^5)(0.91)\text{kg }H_2SO_4\right](1\text{ kmol}/98.08\text{ kg}) = 1480\text{ kmol }H_2SO_4\text{ in recycle}$

$\left[(1.6\times10^5)(0.09)\text{kg }H_2O\right](1\text{ kmol}/18.02\text{ kg}) = 799\text{ kmol }H_2O\text{ from decanter}$

Summary: (Change amounts to flow rates)

$\underline{\underline{\text{Product: }173.5\text{ kmol }C_8H_{18}/\text{h},\ 347\text{ kmol }n\text{-}C_4H_{10}/\text{h}}}$

$\underline{\underline{\text{Recycle from still: }694\text{ kmol }i\text{-}C_4H_{10}/\text{h}}}$

$\underline{\underline{\text{Acid recycle: }1480\text{ kmol }H_2SO_4/\text{h},\ 799\text{ kmol }H_2O/\text{h}}}$

$\underline{\underline{\text{Recycle E: }16{,}900\text{ kmol n-}C_4H_{10}/\text{h},\ 33{,}800\text{ kmol L-}C_4H_{10}/\text{h},\ 8460\text{ kmol }C_8H_{18}/\text{h},}}$

$\underline{\underline{7.84\times10^6\text{ kg/h }91\%\ H_2SO_4 \Rightarrow 72{,}740\text{ kmol }H_2SO_4/\text{h},\ 39{,}150\text{ kmol }H_2O/\text{h}}}$

4.63 **a.** <u>A balance on *i*th tank</u> (input = output + consumption)

$$\dot{v}(\text{L/min})C_{A,\,i-1}(\text{mol/L}) = \dot{v}C_{Ai} + kC_{Ai}C_{Bi}(\text{mol/liter}\cdot\text{min})V(\text{L})$$

$$\Downarrow \div \dot{v},\ \text{note } V\,/\,\dot{v} = \tau$$

$$\underline{\underline{C_{A,\,i-1} = C_{Ai} + k\tau\, C_{Ai}C_{Bi}}}$$

<u>B balance</u>. By analogy, $C_{B,\,i-1} = C_{Bi} + k\tau\, C_{Ai}C_{Bi}$

Subtract equations $\Rightarrow C_{Bi} - C_{Ai} = C_{B,\,i-1} - C_{A,\,i-1} \underset{\substack{\uparrow\\ \text{from balances on}\\ (i-1)^{\text{st}}\ \text{tank}}}{=} C_{B,\,i-2} - C_{A,\,i-2} = \ldots = C_{B0} - C_{A0}$

b. $C_{Bi} - C_{Ai} = C_{B0} - C_{A0} \Rightarrow C_{Bi} = C_{Ai} + C_{B0} - C_{A0}$. Substitute in A balance from part (a).

$C_{A,\,i-1} = C_{Ai} + k\tau\, C_{Ai}\left[C_{Ai} + (C_{B0} - C_{A0})\right]$. Collect terms in C_{Ai}^2, C_{Ai}^1, C_{Ai}^0.

$$C_{Ai}^2[k\tau] + C_{AL}\left[1 + k\tau(C_{B0} - C_{A0})\right] - C_{A,\,i-1} = 0$$

$$\Rightarrow \alpha C_{AL}^2 + \beta C_{AL} + \gamma = 0 \text{ where } \alpha = k\tau,\ \beta = 1 + k\tau(C_{B0} - C_{A0}),\ \gamma = -C_{A,\,i-1}$$

<u>Solution</u>: $C_{Ai} = \dfrac{-\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}$ (Only + rather than ±: since αγ is negative and the negative solution would yield a negative concentration.)

c.

k =	36.2
v =	5000
V =	2000
CA0 =	0.0567
CB0 =	0.1000
alpha =	14.48
beta =	1.6270

N	gamma	CA(N)	xA(N)
1	-5.670E-02	2.791E-02	0.5077
2	-2.791E-02	1.512E-02	0.7333
3	-1.512E-02	8.631E-03	0.8478
4	-8.631E-03	5.076E-03	0.9105
5	-5.076E-03	3.038E-03	0.9464
6	-3.038E-03	1.837E-03	0.9676
7	-1.837E-03	1.118E-03	0.9803
8	-1.118E-03	6.830E-04	0.9880
9	-6.830E-04	4.182E-04	0.9926
10	-4.182E-04	2.565E-04	0.9955
11	-2.565E-04	1.574E-04	0.9972
12	-1.574E-04	9.667E-05	0.9983
13	-9.667E-05	5.939E-05	0.9990
14	-5.939E-05	3.649E-05	0.9994

($x_{\min} = 0.50$, $N = 1$), ($x_{\min} = 0.80$, $N = 3$), ($x_{\min} = 0.90$, $N = 4$), ($x_{\min} = 0.95$, $N = 6$), ($x_{\min} = 0.99$, $N = 9$), ($x_{\min} = 0.999$, $N = 13$).

As $x_{\min} \to 1$, the required number of tanks and hence the process cost becomes infinite.

d. (i) *k* increases ⇒ *N* decreases (faster reaction ⇒ fewer tanks)

(ii) $\dot{v}$ increases ⇒ *N* increases (faster throughput ⇒ less time spent in reactor ⇒ lower conversion per reactor)

(iii) *V* increases ⇒ *N* decreases (larger reactor ⇒ more time spent in reactor ⇒ higher conversion per reactor)

4.64 **a.** Basis: 1000 g gas

Species	m (g)	MW	n (mol)	**mole % (wet)**	**mole % (dry)**
C_3H_8	800	44.09	18.145	**77.2%**	**87.5%**
C_4H_{10}	150	58.12	2.581	**11.0%**	**12.5%**
H_2O	50	18.02	2.775	**11.8%**	
Total	1000		23.501	**100%**	**100%**

Total moles = 23.50 mol, Total moles (dry) = 20.74 mol

Ratio: $2.775 / 20.726 = \underline{\underline{0.134 \text{ mol } H_2O \ / \ \text{mol dry gas}}}$

b. $C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$, $C_4H_{10} + 13/2\ O_2 \rightarrow 4\ CO_2 + 5\ H_2O$

Theoretical O_2:

$$\underline{C_3H_8}: \ \frac{100 \text{ kg gas}}{\text{h}} \bigg| \frac{80 \text{ kg } C_3H_8}{100 \text{ kg gas}} \bigg| \frac{1 \text{ kmol } C_3H_8}{44.09 \text{ kg } C_3H_8} \bigg\| \frac{5 \text{ kmol } O_2}{1 \text{ kmol } C_3H_8} = 9.07 \text{ kmol } O_2 \ / \text{ h}$$

$$\underline{C_4H_{10}}: \ \frac{100 \text{ kg gas}}{\text{h}} \bigg| \frac{15 \text{ kg } C_4H_{10}}{100 \text{ kg gas}} \bigg| \frac{1 \text{ kmol } C_4H_{10}}{58.12 \text{ kg } C_4H_{10}} \bigg| \frac{6.5 \text{ kmol } O_2}{1 \text{ kmol } C_4H_{10}} = 1.68 \text{ kmol } O_2 \ / \text{ h}$$

Total: $(9.07 + 1.68)$ kmol O_2/h = 10.75 kmol O_2/h

$$\underline{\text{Air feed rate}}: \ \frac{10.75 \text{ kmol } O_2}{\text{h}} \bigg| \frac{1 \text{ kmol Air}}{.21 \text{ kmol } O_2} \bigg| \frac{1.3 \text{ kmol air fed}}{1 \text{ kmol air required}} = \underline{\underline{66.5 \text{ kmol air / h}}}$$

<u>The answer does not change for incomplete combustion</u>

4.65

$$\frac{5 \text{ L } C_6H_{14}}{} \bigg| \frac{0.659 \text{ kg } C_6H_{14}}{\text{L } C_6H_{14}} \bigg| \frac{1000 \text{ mol } C_6H_{14}}{86 \text{ kg } C_6H_{14}} = 38.3 \text{ mol } C_6H_{14}$$

$$\frac{4 \text{ L } C_7H_{16}}{} \bigg| \frac{0.684 \text{ kg } C_7H_{16}}{\text{L } C_7H_{16}} \bigg| \frac{1000 \text{ mol } C_7H_{16}}{100 \text{ kg } C_7H_{16}} = 27.36 \text{ mol } C_7H_{16}$$

$C_6H_{14} + 19/2\ O_2 \rightarrow 6\ CO_2 + 7\ H_2O$ $\quad$ $C_6H_{14} + 13/2\ O_2 \rightarrow 6\ CO + 7\ H_2O$

$C_7H_{16} + 11\ O_2 \rightarrow 7\ CO_2 + 8\ H_2O$ $\quad$ $C_7H_{16} + 15/2\ O_2 \rightarrow 7\ CO + 8\ H_2O$

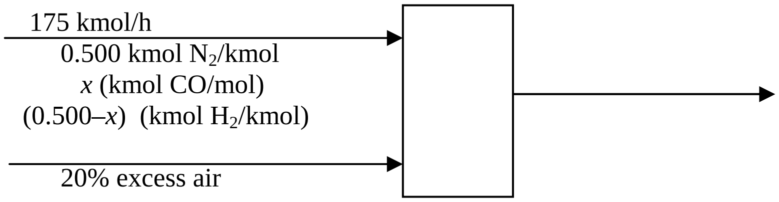
Theoretical oxygen:

$$\frac{38.3 \text{ mol } C_6H_{14}}{} \bigg| \frac{9.5 \text{ mol } O_2}{\text{mol } C_6H_{14}} + \frac{27.36 \text{ mol } C_7H_{16}}{} \bigg| \frac{11 \text{ mol } O_2}{\text{mol } C_7H_{16}} = 665 \text{ mol } O_2 \text{ required}$$

$\underline{O_2 \text{ fed}}$: (4000 mol air)(.21 mol O_2 / mol air) = 840 mol O_2 fed

$$\underline{\text{Percent excess air}}: \ \frac{840 - 665}{665} \times 100\% = \underline{\underline{26.3\% \text{ excess air}}}$$

4.66 $$CO+\frac{1}{2}O_2\rightarrow CO_2 \qquad H_2+\frac{1}{2}O_2\rightarrow H_2O$$



Note: Since CO and H_2 each require 0.5 mol O_2 / mol fuel for complete combustion, we can calculate the air feed rate without determining x_{CO}. We include its calculation for illustrative purposes.

A plot of x vs. R on log paper is a straight line through the points $(R_1=10.0, x_1=0.05)$ and $(R_2=99.7, x_2=1.0)$.

$$\begin{array}{ll} \ln x=b\ln R+\ln a & b=\ln(1.0/0.05)/\ln(99.7/10.0)=1.303 \\ \Updownarrow & \ln a=\ln(1.0)-1.303\ln(99.7)=-6.00 \quad \Rightarrow \underline{\underline{x=2.49\times10^{-3}R^{1.303}}} \\ x=a\,R^b & a=\exp(-6.00)=2.49\times10^{-3} \end{array}$$

$$R=38.3\Rightarrow x=0.288\frac{\text{moles CO}}{\text{mol}}$$

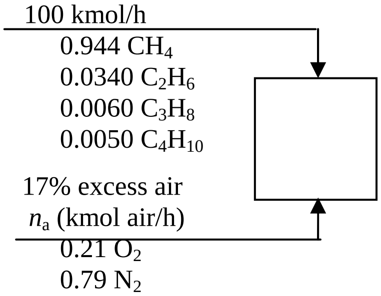
$$\underline{\text{Theoretical } O_2}:\ \begin{array}{c|c|c} 175\text{ kmol} & 0.288\text{ kmol CO} & 0.5\text{ kmol } O_2 \\ \hline \text{h} & \text{kmol} & \text{kmol CO} \end{array}$$

$$+\begin{array}{c|c|c} 175\text{ kmol} & 0.212\text{ kmol } H_2 & 0.5\text{ kmol } O_2 \\ \hline \text{h} & \text{kmol} & \text{kmol } H_2 \end{array}=43.75\frac{\text{kmol } O_2}{\text{h}}$$

$$\underline{\text{Air fed:}}\ \begin{array}{c|c|c} 43.75\text{ kmol } O_2\text{ required} & 1\text{ kmol air} & 1.2\text{ kmol air fed} \\ \hline \text{h} & 0.21\text{ kmol } O_2 & 1\text{ kmol air required} \end{array}=\underline{\underline{250\frac{\text{kmol air}}{\text{h}}}}$$

4.67 **a.**

$$CH_4+2O_2\rightarrow CO_2+2H_2O$$
$$C_2H_6+\frac{7}{2}O_2\rightarrow 2CO_2+3H_2O$$
$$C_3H_8+5O_2\rightarrow 3CO_2+4H_2O$$
$$C_4H_{10}+\frac{13}{2}O_2\rightarrow 4CO_2+5H_2O$$



$$\underline{\text{Theoretical } O_2}:\begin{array}{c|c} 0.944(100)\text{kmol } CH_4 & 2\text{ kmol } O_2 \\ \hline \text{h} & 1\text{ kmol } CH_4 \end{array}+\begin{array}{c|c} 0.0340(100)\text{kmol } C_2H_6 & 3.5\text{ kmol } O_2 \\ \hline \text{h} & 1\text{ kmol } C_2H_6 \end{array}$$

$$+\begin{array}{c|c} 0.0060(100)\text{kmol } C_3H_8 & 5\text{ kmol } O_2 \\ \hline \text{h} & 1\text{ kmol } C_3H_3 \end{array}+\begin{array}{c|c} 0.0050(100)\text{kmol } C_4H_{10} & 6.5\text{ kmol } O_2 \\ \hline \text{h} & 1\text{ kmol } C_4H_{10} \end{array}$$

$$=207.0\ \text{kmol } O_2/\text{h}$$

4.67 (cont'd)

Air feed rate: $n_f = \dfrac{207.0 \text{ kmol O}_2}{\text{h}} \left| \dfrac{1 \text{ kmol air}}{0.21 \text{ kmol O}_2} \right| \dfrac{1.17 \text{ kmol air fed}}{\text{kmol air req.}} = \underline{\underline{1153 \text{ kmol air/h}}}$

b. $\underline{\underline{n_a = n_f\,(2x_1 + 3.5x_2 + 5x_3 + 6.5x_4)(1 + P_{xs}/100)(1/0.21)}}$

c. $\dot{n}_f = aR_f$, $(\dot{n}_f = 75.0 \text{ kmol / h}, R_f = 60) \Rightarrow \dot{n}_f = 1.25R_f$

$\dot{n}_a = bR_a$, $(\dot{n}_a = 550 \text{ kmol / h}, R_a = 25) \Rightarrow \dot{n}_a = 22.0R_a$

$$x_i = kA_i \Rightarrow \sum_{\text{i}} x_i = k\sum_{\text{i}} A_i = 1 \Rightarrow k = \frac{1}{\sum_{\text{i}} A_i}$$

$$\Rightarrow x_i = \frac{A_i}{\sum_{\text{i}} A_i}, \; i = \text{CH}_4, \text{C}_2\text{H}_4, \text{C}_3\text{H}_8, \text{C}_4\text{H}_{10}$$

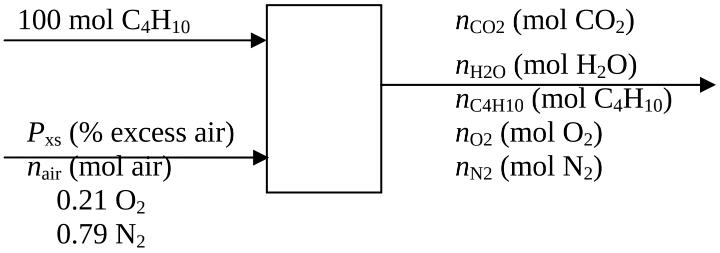
Run	P_{xs}	R_f	A_1	A_2	A_3	A_4
1	15%	62	248.7	19.74	6.35	1.48
2	15%	83	305.3	14.57	2.56	0.70
3	15%	108	294.2	16.61	4.78	2.11

Run	n_f	x_1	x_2	x_3	x_4	n_a	R_a
1	77.5	0.900	0.0715	0.0230	0.0054	934	42.4
2	103.8	0.945	0.0451	0.0079	0.0022	1194	54.3
3	135.0	0.926	0.0523	0.0150	0.0066	1592	72.4

d. Either of the flowmeters could be in error, the fuel gas analyzer could be in error, the flowmeter calibration formulas might not be linear, or the stack gas analysis could be incorrect.

4.68 **a.** $C_4H_{10} + 13/2\ O_2 \rightarrow 4\ CO_2 + 5\ H_2O$

Basis:



D.F. analysis

6 unknowns (n, n_1, n_2, n_3, n_4, n_5)

-3 atomic balances (C, H, O)

-1 N_2 balance

-1 % excess air

-1 % conversion

0 D.F.

4.68 (cont'd)

b. i) <u>Theoretical oxygen</u> = (100 mol C_4H_{10})(6.5 mol O_2/mol C_4H_{10}) = 650 mol O_2

$n_{air} = (650 \text{ mol } O_2)(1 \text{ mol air} / 0.21 \text{ mol } O_2) = 3095 \text{ mol air}$

<u>100% conversion</u> $\Rightarrow\ n_{C4H10} = 0,\ n_{O_2} = 0$

$$\left.\begin{array}{l} n_{N2} = (0.79)(3095 \text{ mol}) = 2445 \text{ mol} \\ n_{CO2} = (100 \text{ mol } C_4H_{10} \text{ react})(4 \text{ mol } CO_2/\text{mol } C_4H_{10}) = 400 \text{ mol } CO_2 \\ n_{H2O} = (100 \text{ mol } C_4H_{10} \text{ react})(5 \text{ mol } H_2O/\text{mol } C_4H_{10}) = 500 \text{ mol } H_2O \end{array}\right\} \begin{array}{l} 73.1\%\ N_2 \\ 12.0\%\ CO_2 \\ \underline{\underline{14.9\%\ H_2O}} \end{array}$$

ii) <u>100% conversion</u> $\Rightarrow n_{C4H10} = 0$

<u>20% excess</u> $\Rightarrow$ n_{air} = 1.2(3095) = 3714 mol (780 mol O_2, 2934 mol N_2)

<u>Exit gas</u>:

$$\left.\begin{array}{l} 400 \text{ mol } CO_2 \\ 500 \text{ mol } H_2O \\ 130 \text{ mol } O_2 \\ 2934 \text{ mol } N_2 \end{array}\right\} \begin{array}{l} 10.1\%\ CO_2 \\ 12.6\%\ H_2O \\ 3.3\%\ O_2 \\ \underline{\underline{74.0\%\ N_2}} \end{array}$$

iii) <u>90% conversion</u> $\Rightarrow n_{C4H10}$ = 10 mol C_4H_{10} (90 mol C_4H_{10} react, 585 mol O_2 consumed)

<u>20% excess</u>: n_{air} = 1.2(3095) = 3714 mol (780 mol O_2, 2483 mol N_2)

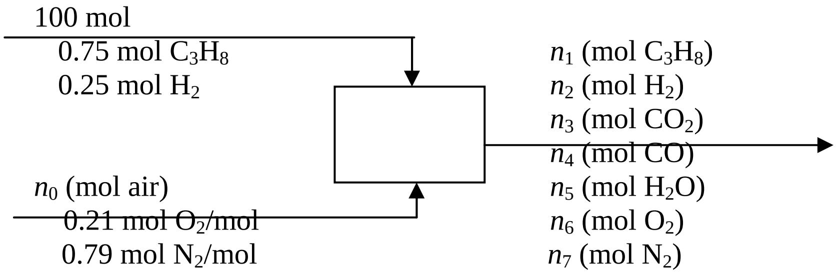
<u>Exit gas</u>:

$$\left.\begin{array}{l} 10 \text{ mol } C_4H_{10} \\ 360 \text{ mol } CO_2 \\ 450 \text{ mol } H_2O \text{ (v)} \\ 195 \text{ mol } O_2 \\ 2934 \text{ mol } N_2 \end{array}\right\} \begin{array}{l} 0.3\%\ C_4H_{10} \\ 9.1\%\ CO_2 \\ 11.4\%\ H_2O \\ 4.9\%\ O_2 \\ \underline{\underline{74.3\%\ N_2}} \end{array}$$

4.69 **a.** $C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$ $H_2 + 1/2\ O_2 \rightarrow H_2O$

$C_3H_8 + 7/2\ O_2 \rightarrow 3\ CO + 4\ H_2O$

<u>Basis:</u> 100 mol feed gas



<u>Theoretical oxygen</u>: $\dfrac{75 \text{ mol } C_3H_8}{} \left| \dfrac{5 \text{ mol } O_2}{\text{mol } C_3H_8} \right. + \dfrac{25 \text{ mol } H_2}{} \left| \dfrac{0.50 \text{ mol } O_2}{\text{mol } H_2} \right. = 387.5 \text{ mol } O_2$

4.69 (cont'd)

Air feed rate: $n_0 = \dfrac{387.5 \text{ mol } O_2}{\text{h}}\left|\dfrac{1 \text{ kmol air}}{0.21 \text{ kmol } O_2}\right|\dfrac{1.25 \text{ kmol air fed}}{1 \text{ kmol air req'd.}} = 2306.5 \text{ mol air}$

90% propane conversion $\Rightarrow n_1 = 0.100(75 \text{ mol } C_3H_8) = 7.5 \text{ mol } C_3H_8$

$(67.5 \text{ mol } C_3H_8 \text{ reacts})$

85% hydrogen conversion $\Rightarrow n_2 = 0.150(25 \text{ mol } C_3H_8) = 3.75 \text{ mol } H_2$

95% CO_2 selectivity $\Rightarrow n_3 = \dfrac{0.95(67.5 \text{ mol } C_3H_8 \text{ react})}{}\left|\dfrac{3 \text{ mol } CO_2 \text{ generated}}{\text{mol } C_3H_8 \text{ react}}\right.$

$= 192.4 \text{ mol } CO_2$

5% CO selectivity $\Rightarrow n_3 = \dfrac{0.05(67.5 \text{ mol } C_3H_8 \text{ react})}{}\left|\dfrac{3 \text{ mol CO generated}}{\text{mol } C_3H_8 \text{ react}}\right. = 10.1 \text{ mol CO}$

H balance: $(75 \text{ mol } C_3H_8)\left(8 \dfrac{\text{mol H}}{\text{mol } C_3H_8}\right) + (25 \text{ mol } H_2)(2)$

$= (7.5 \text{ mol } C_3H_8)(8) + (3.75 \text{ mol } H_2)(2) + n_5(\text{mol } H_2O)(2) \Rightarrow n_5 = 291.2 \text{ mol } H_2O$

O balance: $(0.21 \times 2306.5 \text{ mol } O_2)(2 \dfrac{\text{mol O}}{\text{mol } O_2}) = (192.4 \text{ mol } CO_2)(2)$

$+ (10.1 \text{ mol CO})(1) + (291.2 \text{ mol } H_2O)(1) + 2n_6(\text{mol } O_2) \Rightarrow n_6 = 141.3 \text{ mol } O_2$

N_2 balance: $n_7 = 0.79(2306.5) \text{ mol } N_2 = 1822 \text{ mol } N_2$

Total moles of exit gas = (7.5 + 3.75 + 192.4 + 10.1 + 291.2 + 141.3 + 1822) mol

= 2468 mol

CO concentration in exit gas = $\dfrac{10.1 \text{ mol CO}}{2468 \text{ mol}} \times 10^6 = \underline{\underline{4090 \text{ ppm}}}$

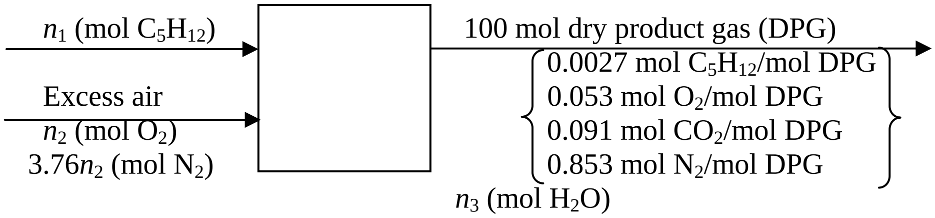
b. If more air is fed to the furnace,

(i) more gas must be compressed (pumped), leading to a higher cost (possibly a larger pump, and greater utility costs)

(ii) The heat released by the combustion is absorbed by a greater quantity of gas, and so the product gas temperature decreases and less steam is produced.

4.70 **a.** $C_5H_{12} + 8\ O_2 \rightarrow 5\ CO_2 + 6\ H_2O$

Basis: 100 moles dry product gas



3 unknowns (n_1, n_2, n_3)

-3 atomic balances (O, C, H)

<u>-1 N2 balance</u>

-1 D.F. ⇒ Problem is overspecified

b. N$_2$ balance: $3.76\ n_2 = 0.8533\ (100) \Rightarrow n_2 = 22.69$ mol O_2

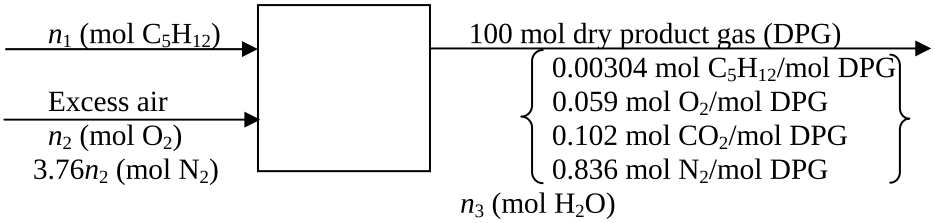
C balance: $5\ n_1 = 5(0.0027)(100) + (0.091)(100) \Rightarrow n_1 = 2.09$ mol C_5H_{12}

H balance: $12\ n_1 = 12(0.0027)(100) + 2n_3 \Rightarrow n_3 = 10.92$ mol H_2O

O balance: $2n_2 = 100[(0.053)(2) + (0.091)(2)] + n_3 \Rightarrow 45.38$ mol O = 39.72 mol O

Since the 4th balance does not close, the given data cannot be correct.

c.



N$_2$ balance: $3.76\ n_2 = 0.836\ (100) \Rightarrow n_2 = 22.2$ mol O_2

C balance: $5\ n_1 = 100\ (5*0.00304 + 0.102) \Rightarrow n_1 = 2.34$ mol C_5H_{12}

H balance: $12\ n_1 = 12(0.00304)(100) + 2n_3 \Rightarrow n_3 = 12.2$ mol H_2O

O balance: $2n_2 = 100[(0.0590)(2) + (0.102)(2)] + n_3 \Rightarrow 44.4$ mol O = 44.4 mol O √

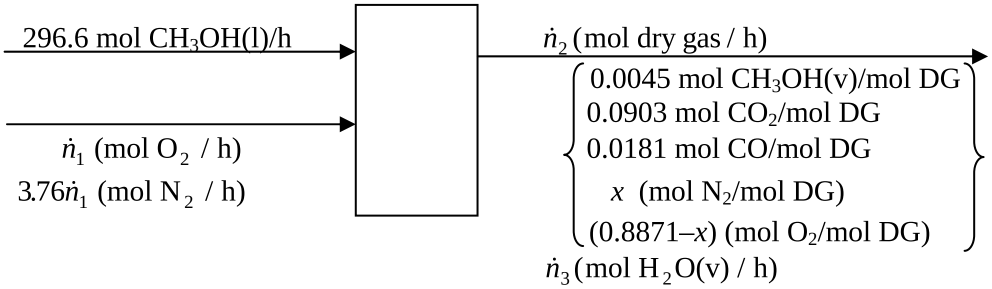
Fractional conversion of C_5H_{12}: $\dfrac{2.344 - 100 \times 0.00304}{2.344} = \underline{\underline{0.870\ \text{mol react/mol fed}}}$

Theoretical O$_2$ required: 2.344 mol C_5H_{12} (8 mol O_2/mol C_5H_{12}) = 18.75 mol O_2

% excess air: $\dfrac{22.23\ \text{mol}\ O_2\ \text{fed} - 18.75\ \text{mol}\ O_2\ \text{required}}{18.75\ \text{mol}\ O_2\ \text{required}} \times 100\% = \underline{\underline{18.6\%\ \text{excess air}}}$

4.71 **a.** $$\frac{12\text{ L CH}_3\text{OH}}{\text{h}}\left|\frac{1000\text{ ml}}{\text{L}}\right|\frac{0.792\text{ g}}{\text{ml}}\left|\frac{\text{mol}}{32.04\text{ g}}\right.=296.6\text{ mol CH}_3\text{OH / h}$$

$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2\ H_2O$, $CH_3OH + O_2 \rightarrow CO + 2\ H_2O$



4 unknowns $(\dot{n}_1, \dot{n}_2, \dot{n}_3, x)$ – 4 balances (C, H, O, N_2) = 0 D.F.

b. Theoretical O_2: 296.6 (1.5) = 444.9 mol O_2 / h

C balance: $296.6 = \dot{n}_2 (0.0045 + 0.0903 + 0.0181) \Rightarrow \dot{n}_2 = 2627$ mol/h

H balance: $4 (296.6) = \dot{n}_2 (4*0.0045) + 2\ \dot{n}_3 \Rightarrow \dot{n}_3 = 569.6$ mol H_2O / h

O balance: $296.6 + 2n_1 = 2627[0.0045 + 2(0.0903) + 0.0181 + 2(0.8871 - x)] + 569.6$

N_2 balance: $3.76\ \dot{n}_1 = x\ (2627)$

Solving simultaneously $\Rightarrow$ $\dot{n}_1 = 574.3$ mol O_2 / h, x = 0.822 mol N_2 / mol DG

Fractional conversion: $$\frac{296.6 - 2627(0.0045)}{296.6} = \underline{\underline{0.960\text{ mol CH}_3\text{OH react/mol fed}}}$$

% excess air: $$\frac{574.3 - 444.9}{444.9} \times 100\% = \underline{\underline{29.1\%}}$$

Mole fraction of water: $$\frac{569.6\text{ mol H}_2\text{O}}{(2627 + 569.6)\text{ mol}} = \underline{\underline{0.178\text{ mol H}_2\text{O/mol}}}$$

c. Fire, CO toxicity. Vent gas to outside, install CO or hydrocarbon detector in room, trigger alarm if concentrations are too high

4.72 **a.** G.C. Say n_s mols fuel gas constitute the sample injected into the G.C. If x_{CH_4} and $x_{C_2H_6}$ are the mole fractions of methane and ethane in the fuel, then

$$\frac{n_s(\text{mol})x_{C_2H_6}(\text{mol C}_2\text{H}_2/\text{mol})(2\text{ mol C}/1\text{ mol C}_2\text{H}_6)}{n_s(\text{mol})x_{CH_4}(\text{mol CH}_4/\text{mol})(1\text{ mol C}/1\text{ mol CH}_4)} = \frac{20}{85}$$

$$\Downarrow$$

$$\frac{x_{C_2H_6}(\text{mol C}_2\text{H}_6/\text{mol fuel})}{x_{CH_4}(\text{mol CH}_4/\text{mol fuel})} = 0.1176\text{ mole C}_2\text{H}_6/\text{mole CH}_4\text{ in fuel gas}$$

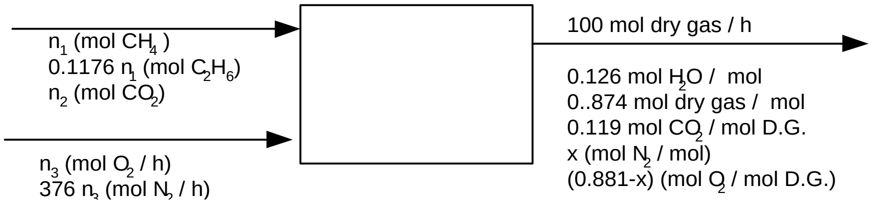
4.72 (cont'd)

Condensation measurement: $$\frac{(1.134\text{ g H}_2\text{O})(1\text{ mol}/18.02\text{ g})}{0.50\text{ mol product gas}} = 0.126\frac{\text{mole H}_2\text{O}}{\text{mole product gas}}$$

Basis: 100 mol product gas. Since we have the most information about the product stream composition, we choose this basis now, and would subsequently scale to the given fuel and air flow rates if it were necessary (which it is not).

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$$

$$\text{C}_2\text{H}_6 + \frac{7}{2}\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O}$$



Strategy: H balance $\Rightarrow n_1$; C balance $\Rightarrow n_2$; $\left.\begin{array}{c}\text{N}_2\text{ balance}\\ \text{O balance}\end{array}\right\} \Rightarrow n_3, x$

H balance: $4n_1 + (6)(0.1176n_1) = (100)(0.126)(2) \Rightarrow n_1 = 5.356\text{ mol CH}_4\text{ in fuel}$

$\Rightarrow 0.1176(5.356) = 0.630\text{ mol C}_2\text{H}_6$ in fuel

C balance: $5.356 + (2)(0.630) + n_2 = (100)(0.874)(0.119) \Rightarrow n_2 = 3.784\text{ mol CO}_2\text{ in fuel}$

Composition of fuel: $5.356\text{ mol CH}_4,\ 0.630\text{ mol C}_2\text{H}_6,\ 3.784\text{ mols CO}_2$

$\Rightarrow \underline{\underline{0.548\text{ CH}_4,\ 0.064\text{ C}_2\text{H}_6,\ 0.388\text{ CO}_2}}$

N$_2$ balance: $3.76n_3 = (100)(0.874)x$

O balance: $(2)(3.784) + 2n_3 = (100)(0.126) + (100)(0.874)(2)[0.119 + (0.881 - x)]$

Solve simultaneously: $n_3 = 18.86$ mols O$_2$ fed, $x = 0.813$

Theoretical O$_2$: $$\frac{5.356\text{ mol CH}_4}{} \left| \frac{2\text{ mol O}_2}{1\text{ mol CH}_4} \right. + \frac{0.630\text{ mol C}_2\text{H}_6}{} \left| \frac{3.5\text{ mol O}_2}{1\text{ mol CH}_4} \right.$$

$= 12.92\text{ mol O}_2$ required

Desired O$_2$ fed: $$\frac{(5.356 + 0.630 + 3.784)\text{ mol fuel}}{} \left| \frac{7\text{ mol air}}{1\text{ mol fuel}} \right| \frac{0.21\text{ mol O}_2}{\text{mol air}} = \underline{\underline{14.36\text{ mol O}_2}}$$

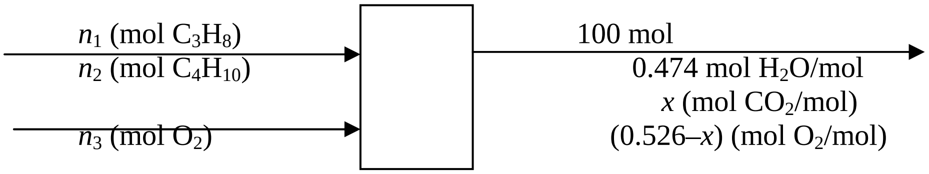
Desired % excess air: $$\frac{14.36 - 12.92}{12.92} \times 100\% = \underline{\underline{11\%}}$$

b. Actual % excess air: $$\frac{18.86 - 12.92}{12.92} \times 100\% = \underline{\underline{46\%}}$$

Actual molar feed ratio of air to fuel: $$\frac{(18.86/0.21)\text{ mol air}}{9.77\text{ mol feed}} = \underline{\underline{9:1}}$$

4.73 **a.** $C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$, $C_4H_{10} + 13/2\ O_2 \rightarrow 4\ CO_2 + 5\ H_2O$

<u>Basis 100</u>: mol product gas



<u>Dry product gas contains 69.4% CO_2</u> $\Rightarrow \dfrac{x}{0.526-x} = \dfrac{69.4}{30.6} \Rightarrow x = 0.365\ \text{mol}\ CO_2/\text{mol}$

3 unknowns (n_1, n_2, n_3) – 3 balances (C, H, O) = 0 D.F.

<u>O balance</u>: $2\ n_3 = 152.6 \Rightarrow n_3 = 76.3$ mol O_2

$$\left.\begin{array}{l}\underline{\text{C balance}}: 3\,n_1 + 4\,n_2 = 36.5\\ \underline{\text{H balance}}: 8\,n_1 + 10\,n_2 = 94.8\end{array}\right\} \Rightarrow \begin{array}{l} n_1 = 7.1\ \text{mol}\ C_3H_8\\ n_2 = 3.8\ \text{mol}\ C_4H_{10}\end{array} \Rightarrow \underline{\underline{65.1\%\ C_3H_8,\ 34.9\%\ C_4H_{10}}}$$

b. n_c=100 mol (0.365 mol CO_2/mol)(1mol C/mol CO_2) = 365 mol C

n_h = 100 mol (0.474 mol H_2O/mol)(2mol H/mol H_2O)=94.8 mol H

$\Rightarrow$ $\underline{\underline{27.8\%\text{C},\ 72.2\%\ \text{H}}}$

From a:

$$\frac{\dfrac{7.10\ \text{mol}\ C_3H_8}{}\Big|\dfrac{3\ \text{mol C}}{\text{mol}\ C_3H_8} + \dfrac{3.80\ \text{mol}\ C_4H_{10}}{}\Big|\dfrac{4\ \text{mol C}}{\text{mol}\ C_4H_{10}}}{\dfrac{7.10\ \text{mol}\ C_3H_8}{}\Big|\dfrac{11\ \text{mol (C + H)}}{\text{mol}\ C_3H_8} + \dfrac{3.80\ \text{mol}\ C_4H_{10}}{}\Big|\dfrac{14\ \text{mol (C + H)}}{\text{mol}\ C_4H_{10}}} \times 100\% = \underline{\underline{27.8\%\ \text{C}}}$$

4.74 <u>Basis:</u> 100 kg fuel oil

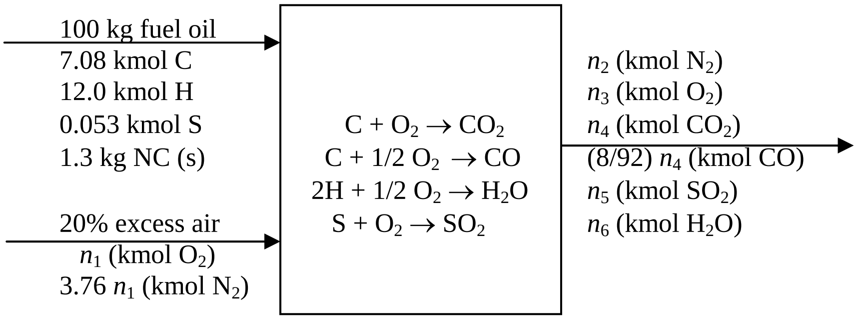
<u>Moles of C in fuel:</u> $\dfrac{100\ \text{kg}}{}\Big|\dfrac{0.85\ \text{kg C}}{\text{kg}}\Big|\dfrac{1\ \text{kmol C}}{12.01\ \text{kg C}} = 7.08\ \text{kmol C}$

<u>Moles of H in fuel:</u> $\dfrac{100\ \text{kg}}{}\Big|\dfrac{0.12\ \text{kg H}}{\text{kg}}\Big|\dfrac{1\ \text{kmol H}}{1\ \text{kg H}} = 12.0\ \text{kmol H}$

<u>Moles of S in fuel:</u> $\dfrac{100\ \text{kg}}{}\Big|\dfrac{0.017\ \text{kg S}}{\text{kg}}\Big|\dfrac{1\ \text{kmol S}}{32.064\ \text{kg S}} = 0.053\ \text{kmol S}$

1.3 kg non-combustible materials (NC)

4.74 (cont'd)



Theoretical O_2:

$$\frac{7.08\,\text{kmol C}}{}\left|\frac{1\,\text{kmol O}_2}{1\,\text{kmol C}}\right. + \frac{12\,\text{kmol H}}{}\left|\frac{.5\,\text{kmol O}_2}{2\,\text{kmol H}}\right. + \frac{0.053\,\text{kmol S}}{}\left|\frac{1\,\text{kmol O}_2}{1\,\text{kmol S}}\right. = 10.133\,\text{kmol O}_2$$

20 % excess air: $n_1 = 1.2(10.133) = 12.16$ kmol O_2 fed

O balance: $2\ (12.16) = 2\ (6.5136) + 0.5664 + 2\ (0.053) + 6 + 2\ n_3 \Rightarrow n_3 = 2.3102$ kmol O_2

C balance: $7.08 = n_4 + 8n_4/92 \Rightarrow n_4 = 6.514$ mol CO_2

$\Rightarrow 8\ (6.514)/92 = 0.566$ mol CO

S balance: $n_5 = 0.53$ kmol SO_2

H balance: $12 = 2n_6 \Rightarrow n_6 = 6.00$ kmol H_2O

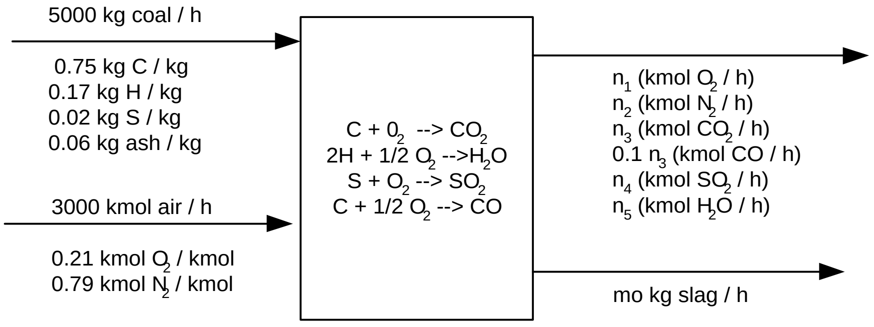
N_2 balance: n2 = 3.76(12.16) = 45.72 kmol N_2

Total moles of stack gas = (6.514 + 0.566 + 0.053 + 6.00 + 2.310 + 45.72) kmol

= 61.16 kmol

$$\Rightarrow \underline{\underline{10.7\%\ \text{CO},\ 0.92\%\ \text{CO},\ 0.087\%\ \text{SO}_2,\ 9.8\%\ \text{H}_2\text{O},\ 3.8\%\ \text{O}_2,\ 74.8\%\ \text{N}_2}}$$

4.75 **a.** Basis: 5000 kg coal/h; $50\ \text{kmol air/min} = 3000\ \text{kmol air/h}$



Theoretical O_2:

C: $$\frac{0.75(5000)\ \text{kg C}}{\text{h}}\left|\frac{1\ \text{kmol C}}{12.01\ \text{kg C}}\right|\frac{1\ \text{kmol O}_2}{1\ \text{kmol C}} = 312.2\ \text{kmol O}_2/\text{h}$$

4.75 (cont'd)

H: $$\begin{array}{c|c|c|c} 0.17(5000)\text{ kg H} & 1\text{ kmol H} & 1\text{ kmol H}_2\text{O} & 1\text{ kmol O}_2 \\ \hline \text{h} & 1.01\text{ kg H} & 2\text{ kmol H} & 2\text{ kmol H}_2\text{O} \end{array} = 210.4\text{ kmol O}_2/\text{h}$$

S: $$\begin{array}{c|c|c} 0.02(5000)\text{ kg S} & 1\text{ kmol S} & 1\text{ kmol O}_2 \\ \hline \text{h} & 32.06\text{ kg S} & 1\text{ kmol S} \end{array} = 3.1\text{ kmol O}_2/\text{h}$$

Total = (312.2+210.4 + 3.1) kmol O_2/h = 525.7 kmol O_2/h

O_2 fed = $0.21(3000) = 630\text{ kmol O}_2/\text{h}$

Excess air: $$\frac{630-525.7}{525.7}\times 100\% = \underline{\underline{19.8\%\text{ excess air}}}$$

b. Balances:

C: $$\begin{array}{c|c} (0.94)(0.75)(5000)\text{ kg C react} & 1\text{ kmol C} \\ \hline \text{h} & 12.01\text{ kg C} \end{array} = \dot{n}_3 + 0.1\dot{n}_3$$

$$\Rightarrow \dot{n}_3 = 266.8\text{ kmol CO}_2/\text{h},\ 0.1\dot{n}_3 = 26.7\text{ kmol CO/h}$$

H: $$\begin{array}{c|c|c} (0.17)(5000)\text{ kg H} & 1\text{ kmol H} & 1\text{ kmol H}_2\text{O} \\ \hline \text{h} & 1.01\text{ kg H} & 2\text{ kmol H} \end{array} = n_5 \Rightarrow n_5 = 420.8\text{ kmol H}_2\text{O/h}$$

S: (from part a) $$\begin{array}{c|c} 3.1\text{ kmol O}_2\ (\text{for SO}_2) & 1\text{ kmol SO}_2 \\ \hline \text{h} & 1\text{ kmol O}_2 \end{array} = \dot{n}_4 \Rightarrow \dot{n}_4 = 3.1\text{ kmol SO}_2/\text{h}$$

N_2: $(0.79)(3000)\text{ kmol N}_2/\text{h} = \dot{n}_2 \Rightarrow \dot{n}_2 = 2370\text{ kmol N}_2/\text{h}$

O: $(0.21)(3000)(2) = 2\dot{n}_1 + 2(266.8) + 1(26.68) + 2(3.1) + (1)(420.8)$

$\Rightarrow \dot{n}_1 = 136.4\text{ kmol O}_2\ /\ \text{h}$

Stack gas total = 3223 kmol/h

Mole fractions:

$$x_{\text{CO}} = 26.7/3224 = \underline{\underline{8.3\times 10^{-3}\text{ mol CO/mol}}}$$

$$x_{\text{SO}_2} = 3.1/3224 = \underline{\underline{9.6\times 10^{-4}\text{ mol SO}_2/\text{mol}}}$$

c. $SO_2 + \frac{1}{2}O_2 \rightarrow SO_3$

$SO_3 + H_2O \rightarrow H_2SO_4$

$$\begin{array}{c|c|c|c} 3.1\text{ kmol SO}_2 & 1\text{ kmol SO}_3 & 1\text{ kmol H}_2\text{SO}_4 & 98.08\text{ kg H}_2\text{SO}_4 \\ \hline \text{h} & 1\text{ kmol SO}_2 & 1\text{ kmol SO}_3 & \text{kmol H}_2\text{SO}_4 \end{array} = \underline{\underline{304\text{ kg H}_2\text{SO}_4/\text{h}}}$$

4.76 a. Basis: 100 g coal as received (c.a.r.). Let a.d.c. denote air-dried coal; v.m. denote volatile matter

$$\begin{array}{c|c} 100 \text{ g c.a.r.} & 1.147 \text{ g a.d.c.} \\ \hline & 1.207 \text{ g c.a.r.} \end{array} = 95.03 \text{ g air - dried coal; } 4.97 \text{ g } H_2O \text{ lost by air drying}$$

$$\begin{array}{c|c} 95.03 \text{ g a.d.c} & (1.234 - 1.204) \text{ g } H_2O \\ \hline & 1.234 \text{ g a.d.c.} \end{array} = 2.31 \text{ g } H_2O \text{ lost in second drying step}$$

$$\text{Total } H_2O = 4.97 \text{ g} + 2.31 \text{ g} = \underline{7.28 \text{ g moisture}}$$

$$\begin{array}{c|c} 95.03 \text{ g a.d.c} & (1.347 - 0.811) \text{ g } (\text{v.m.} + H_2O) \\ \hline & 1.347 \text{ g a.d.c.} \end{array} - 2.31 \text{ g } H_2O = \underline{35.50 \text{ g volatile matter}}$$

$$\begin{array}{c|c} 95.03 \text{ g a.d.c} & 0.111 \text{ g ash} \\ \hline & 1.175 \text{ g a.d.c.} \end{array} = \underline{8.98 \text{ g ash}}$$

$$\text{Fixed carbon } = (100 - 7.28 - 35.50 - 8.98)\text{g} = \underline{48.24 \text{ g fixed carbon}}$$

$$\begin{array}{l} 7.28 \text{ g moisture} \\ 48.24 \text{ g fixed carbon} \\ 35.50 \text{ g volatile matter} \\ \underline{8.98 \text{ g ash}} \\ 100 \text{ g coal as received} \end{array} \Rightarrow \begin{array}{l} \underline{\underline{7.3\% \text{ moisture}}} \\ \underline{\underline{48.2\% \text{ fixed carbon}}} \\ \underline{\underline{35.5\% \text{ volatile matter}}} \\ \underline{\underline{9.0\% \text{ ash}}} \end{array}$$

b. Assume volatile matter is all carbon and hydrogen.

$$C + CO_2 \to CO_2 : \begin{array}{c|c|c|c} 1 \text{ mol } O_2 & 1 \text{ mol C} & 10^3 \text{ g} & 1 \text{ mol air} \\ \hline 1 \text{ mol C} & 12.01 \text{ g C} & 1 \text{ kg} & 0.21 \text{ mol } O_2 \end{array} = 396.5 \text{ mol air/kg C}$$

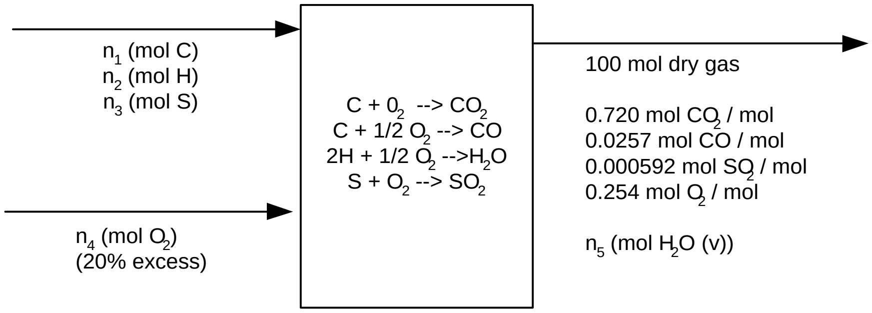
$$2H + \frac{1}{2}O_2 \to H_2O : \begin{array}{c|c|c|c} 0.5 \text{ mol } O_2 & 1 \text{ mol H} & 10^3 \text{ g} & 1 \text{ mol air} \\ \hline 2 \text{ mol H} & 1.01 \text{ g H} & 1 \text{ kg} & 0.21 \text{ mol } O_2 \end{array} = 1179 \text{ mol air/kg H}$$

$$\underline{\text{Air required:}} \quad \begin{array}{c|c|c} 1000 \text{ kg coal} & 0.482 \text{ kg C} & 396.5 \text{ mol air} \\ \hline & \text{kg coal} & \text{kg C} \end{array}$$

$$+ \begin{array}{c|c|c|c} 1000 \text{ kg} & 0.355 \text{ kg v.m.} & 6 \text{ kg C} & 396.5 \text{ mol air} \\ \hline & \text{kg} & 7 \text{ kg v.m.} & \text{kg C} \end{array}$$

$$+ \begin{array}{c|c|c|c} 1000 \text{ kg} & 0.355 \text{ kg v.m.} & 1 \text{ kg H} & 1179 \text{ mol air} \\ \hline & \text{kg} & 7 \text{ kg v.m.} & \text{kg H} \end{array} = \underline{\underline{3.72 \times 10^5 \text{ mol air}}}$$

4.77 **a.** Basis 100 mol dry fuel gas. <u>Assume no solid or liquid products!</u>

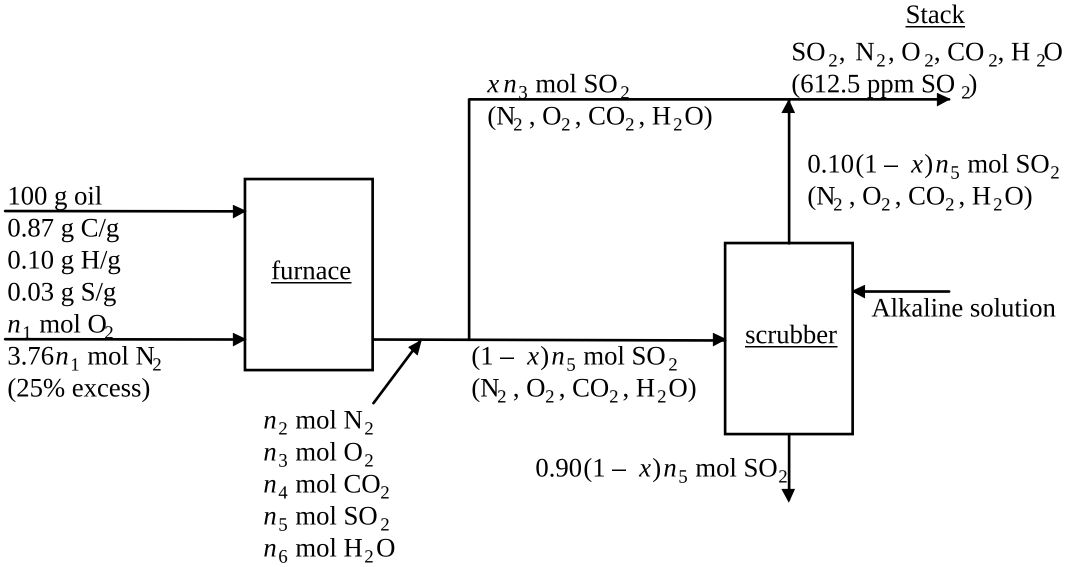


$$\left.\begin{aligned}
&\underline{\text{H balance}}:\ n_2 = 2\,n_5\\
&\underline{\text{O balance}}:\ 2\,n_4 = 100[\,2(0.720) + 0.0257 + 2\,(0.000592) + 2\,(0.254)] + n_5\\
&\underline{20\,\%\ \text{excess}\ O_2}:\ (1.20)\,(74.57 + 0.0592 + 0.25\,n_2] = n_4
\end{aligned}\right\}$$

$\Rightarrow$ n_2 = 183.6 mol H, n_4 = 144.6 mol O_2, n_5 = 91.8 mol H_2O

Total moles in feed: 258.4 mol (C+H+S) $\Rightarrow$ <u>28.9% C, 71.1% H, 0.023% S</u>

4.78 <u>Basis: 100 g oil</u>



$$\underline{CO_2}:\ \frac{0.87(100)\text{g C}}{}\left|\frac{1\text{ mol C}}{12.01\text{ g C}}\right|\frac{1\text{ mol }CO_2}{1\text{ mol C}} \Rightarrow n_4 = 7.244\text{ mol }CO_2\left(\begin{array}{l}7.244\text{ mol }O_2\\ \text{consumed}\end{array}\right)$$

$$\underline{H_2O}:\ \frac{0.10(100)\text{g H}}{}\left|\frac{1\text{ mol H}}{1.01\text{ g H}}\right|\frac{1\text{ mol }H_2O}{2\text{ mol H}} \Rightarrow n_6 = 4.95\text{ mol }H_2O\left(\begin{array}{l}2.475\text{ mol }O_2\\ \text{consumed}\end{array}\right)$$

4.78 (cont'd)

$$\underline{SO_2}:\ \frac{0.03(100)\text{g S}}{}\left|\frac{1\text{ mol S}}{32.06\text{ g S}}\right|\frac{1\text{ mol SO}_2}{1\text{ mol S}}\Rightarrow n_5=0.0936\text{ mol SO}_2\left(\begin{array}{l}0.0956\text{ mol O}_2\\ \text{consumed}\end{array}\right)$$

$$\underline{25\%\text{ excess O}_2}:\quad n_1=1.25(7.244+2.475+0.0936)\Rightarrow 12.27\text{ mol O}_2$$

$$\underline{\text{O}_2\text{ balance}}:\ n_3=12.27\text{ mol O}_2\text{ fed}-(7.244+2.475+0.0936)\text{ mol O}_2\text{ consumed}$$

$$=2.46\text{ mol O}_2$$

$$\underline{\text{N}_2\text{ balance}}:\quad n_2=3.76(12.27\text{ mol})=46.14\text{ mol N}_2$$

$\underline{\text{SO}_2\text{ in stack }(\text{SO}_2\text{ balance around mixing point}):}$

$$x\big(\underset{n_5}{0.0936}\big)+0.10(1-x)(0.0936)=0.00936+0.0842x(\text{mol SO}_2)$$

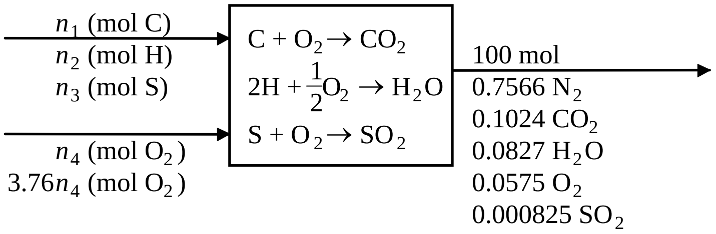
Total dry gas in stack (Assume no CO_2, O_2, or N_2 is absorbed in the scrubber)

$$\underset{(\text{CO}_2)}{7.244}+\underset{(\text{O}_2)}{2.46}+\underset{(\text{N}_2)}{46.14}+\underset{(\text{SO}_2)}{(0.00936+0.0842x)}=55.85+0.0842x(\text{mol dry gas})$$

$\underline{612.5\text{ ppm SO}_2(\text{dry basis})\text{ in stack gas}}$

$$\frac{0.00936+0.0842x}{55.85+0.0842x}=\frac{612.5}{1.0\times10^6}\Rightarrow x=0.295\Rightarrow\underline{\underline{30\%\text{ bypassed}}}$$

4.79 Basis: 100 mol stack gas



a.

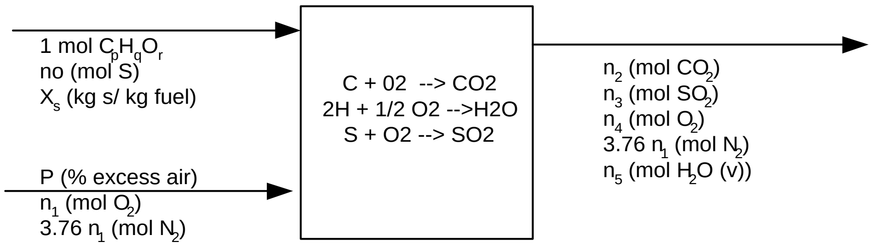
$$\left.\begin{array}{l}\underline{\text{C balance}}:\quad n_1=(100)(0.1024)=10.24\text{ mol C}\\ \underline{\text{H balance}}:\quad n_2=(100)(0.0827)(2)=16.54\text{ mol H}\end{array}\right\}\Rightarrow\frac{10.24\text{ mol C}}{16.54\text{ mol H}}=\underline{\underline{0.62\ \frac{\text{mol C}}{\text{mol H}}}}$$

The C/H mole ratio of CH_4 is 0.25, and that of C_2H_6 is 0.333; no mixture of the two could have a C/H ratio of 0.62, so the fuel could not be the natural gas.

b. $\underline{\text{S balance}}:\quad n_3=(100)(0.000825)=0.0825\text{ mol S}$

$$\left.\begin{array}{r}(10.24\text{ mol C})(12.0\text{ g/1 mol})=122.88\text{ g C}\\ (16.54\text{ mol H})(1.01\text{ g/1 mol})=16.71\text{ g H}\\ (0.0825\text{ mol S})(32.07\text{ g/1 mol})=2.65\text{ g S}\end{array}\right\}\Rightarrow\begin{array}{l}\dfrac{122.88}{16.71}=\underline{\underline{7.35\text{ g C/g H}}}\\ \dfrac{2.65}{142.24}\times100\%=\underline{\underline{1.9\%\text{ S}}}\end{array}\Rightarrow\underline{\underline{\text{No. 4 fuel oil}}}$$

4.80 **a.** Basis: 1 mol $C_pH_qO_r$



Hydrocarbon mass:
$$\left.\begin{array}{l} p\text{ (mol C) (12 g / mol) = 12 p (g C)} \\ q\text{ (mol H) (1 g / mol) = } \quad q\text{ (g H)} \\ r\text{ (mol O) (16 g / mol) = 16 r (g O)} \end{array}\right\} \Rightarrow (12\,p + q + 16\,r)\text{ g fuel}$$

S in feed:

$$n_o = \frac{(12\,p + q + 16r)\text{ g fuel}}{}\left|\frac{X_s\ (\text{g S})}{(1 - X_s)\ (\text{g fuel})}\right|\frac{1\,\text{mol S}}{32.07\text{ g S}} = \frac{X_s(12\,p + q + 16\,r)}{32.07(1 - X_s)}(\text{mol S}) \quad (1)$$

Theoretical O_2:
$$\frac{p\ (\text{mol C})}{}\left|\frac{1\,\text{mol}\ O_2}{1\,\text{mol C}}\right. + \frac{q\ (\text{mol H})}{}\left|\frac{0.5\ \text{mol}\ O_2}{2\ \text{mol H}}\right. - \frac{(r\ \text{mol O})}{}\left|\frac{1\,\text{mol}\ O_2}{2\ \text{mol O}}\right.$$

$$= (p + 1/4\,q - 1/2\,r)\ \text{mol}\ O_2$$

% excess $\Rightarrow n_1 = (1 + P/100)\ (p + 1/4\ q - ½\ r)$ mol O_2 fed (2)

C balance: $n_2 = p$ (3)

H balance: $n_5 = q/2$ (4)

S balance: $n_3 = n_0$ (5)

O balance: $r + 2n_1 = 2n_2 + 2n_3 + 2n_4 + n_5 \Rightarrow n_4 = ½\ (r+2n_1-2n_2-2n_3-n_5)$ (6)

Given: $p = 0.71$, $q= 1.1$, $r = 0.003$, $X_s = 0.02$ $P = 18\%$ excess air

(1) $\Rightarrow n_0 = 0.00616$ mol S (5) $\Rightarrow n_3 = 0.00616$ mol SO_2

(2) $\Rightarrow n_1 = 1.16$ mol O_2 fed (6) $\Rightarrow n_4 = 0.170$ mol O_2

(3) $\Rightarrow n_2 = 0.71$ mol CO_2 (4) $\Rightarrow n_5 = 0.55$ mol H_2O

(3.76*1.16) mol N_2 = 4.36 mol N_2

Total moles of dry product gas = $n_2 + n_3 + n_4 + 3.76\ n_1$=5.246 mol dry product gas

Dry basis composition

y_{CO2} = (0.710 mol CO_2/ 5.246 mol dry gas) * 100% = 13.5% CO_2

y_{O2} = (0.170 / 5.246) * 100% = 3.2% O_2

y_{N2} = (4.36 / 5.246) * 100% = 83.1% N_2

y_{SO2} = (0.00616 / 5.246) * 10^6 = 1174 ppm SO_2

CHAPTER FIVE

5.1 Assume volume additivity

Av. density (Eq. 5.1-1): $$\frac{1}{\bar{\rho}} = \frac{0.400}{\underset{\substack{\uparrow \\ \rho_O}}{0.703\ \text{kg/L}}} + \frac{0.600}{\underset{\substack{\uparrow \\ \rho_D}}{0.730\ \text{kg/L}}} \Rightarrow \bar{\rho} = 0.719\ \text{kg/L}$$

a. $$\underset{\substack{\uparrow \\ \text{mass of tank} \\ \text{at time } t}}{m} = \dot{m}t + \underset{\substack{\uparrow \\ \text{mass of} \\ \text{empty tank}}}{m_0} \Rightarrow \dot{m} = \frac{(250-150)\text{kg}}{(10-3)\text{min}} = 14.28\ \text{kg/min} \quad (\dot{m} = \text{mass flow rate of liquid})$$

$$\Rightarrow \dot{V}(\text{L/min}) = \frac{\dot{m}(\text{kg/min})}{\bar{\rho}(\text{kg/L})} \;\Rightarrow\; \dot{V} = \frac{14.28\ \text{kg}}{\text{min}}\left|\frac{1\ \text{L}}{0.719\ \text{kg}}\right. = \underline{\underline{19.9\ \text{L/min}}}$$

b. $$m_0 = m(t) - \dot{m}t = 150 - 14.28(3) = \underline{\underline{107\ \text{kg}}}$$

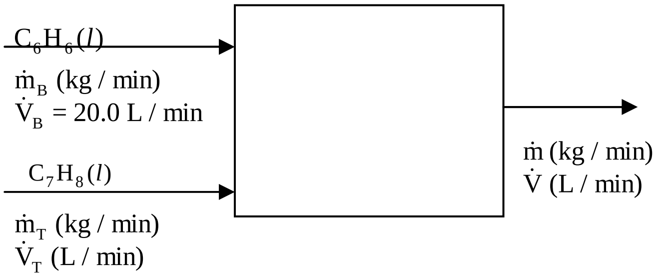
5.2 void volume of bed: $100\ \text{cm}^3 - (233.5 - 184)\text{cm}^3 = 50.5\ \text{cm}^3$

porosity: $50.5\ \text{cm}^3\ \text{void}/184\ \text{cm}^3\ \text{total} = \underline{\underline{0.274\ \text{cm}^3\ \text{void}/\text{cm}^3\ \text{total}}}$

bulk density: $600\ \text{g}/184\ \text{cm}^3 = \underline{\underline{3.26\ \text{g/cm}^3}}$

absolute density: $600\ \text{g}/(184 - 50.5)\text{cm}^3 = \underline{\underline{4.49\ \text{g/cm}^3}}$

5.3



$$\dot{V} = \frac{\Delta V}{\Delta t} = \frac{\pi D^2}{4}\frac{\Delta h}{\Delta t} = \frac{\pi (5.5\ \text{m})^2}{4}\left|\frac{0.15\ \text{m}}{60\ \text{min}}\right. = 0.0594\ \text{m}^3/\text{min}$$

Assume additive volumes

$$\dot{V}_T = \dot{V} - \dot{V}_B = (59.4 - 20.0)\ \text{L/min} = \underline{\underline{39.4\ \text{L/min}}}$$

$$\dot{m} = \rho_B \cdot \dot{V}_B + \rho_T \cdot \dot{V}_T = \frac{0.879\ \text{kg}}{\text{L}}\left|\frac{20.0\ \text{L}}{\text{min}}\right. + \frac{0.866\ \text{kg}}{\text{L}}\left|\frac{39.4\ \text{L}}{\text{min}}\right. = 51.7\ \text{kg/min}$$

$$x_B = \frac{\dot{m}_B}{\dot{m}} = \frac{(0.879\ \text{kg/L})(20.0\ \text{L/min})}{(51.7\ \text{kg/min})} = \underline{\underline{0.34\ \text{kg B/kg}}}$$

5.4 **a.**
$$\left.\begin{array}{l} P_1 = P_0 + \rho_{sl} g h_1 \\ P_2 = P_0 + \rho_{sl} g h_2 \\ h = h_1 - h_2 \end{array}\right\} \Rightarrow \Delta P = P_1 - P_2 = \rho_{sl}\left(\tfrac{kg}{m^3}\right) g\left(\tfrac{m}{s^2}\right) h(m) \left(\frac{1\ N}{1\frac{kg\cdot m}{s^2}}\right)\left(\frac{1\ Pa}{1\frac{N}{m^2}}\right) = \underline{\underline{\rho_{sl} g h}}$$

b.
$$\frac{1}{\rho_{sl}} = \frac{x_c}{\rho_c} + \frac{(1-x_c)}{\rho_l} \Rightarrow \text{check units!}$$

$$\frac{1}{\text{kg slurry / L slurry}} = \frac{\text{kg crystals / kg slurry}}{\text{kg crystals / L crystals}} + \frac{\text{kg liquid / kg slurry}}{\text{kg liquid / L liquid}}$$

$$\frac{\text{L slurry}}{\text{kg slurry}} = \frac{\text{L crystals}}{\text{kg slurry}} + \frac{\text{L liquid}}{\text{kg slurry}} = \frac{\text{L slurry}}{\text{kg slurry}}$$

c. **i.)**
$$\rho_{sl} = \frac{\Delta P}{gh} = \frac{2775}{(9.8066)(0.200)} = \underline{\underline{1415\ \text{kg}/\text{m}^3}}$$

ii.)
$$\frac{1}{\rho_{sl}} = \frac{x_c}{\rho_c} + \frac{(1\text{-}x_c)}{\rho_l} \Rightarrow x_c\left(\frac{1}{\rho_c} - \frac{1}{\rho_l}\right) = \left(\frac{1}{\rho_{sl}} - \frac{1}{\rho_l}\right)$$

$$x_c = \frac{\left(\dfrac{1}{1415\ \text{kg}/\text{m}^3} - \dfrac{1}{1.2\left(1000\ \text{kg}/\text{m}^3\right)}\right)}{\left(\dfrac{1}{2.3\left(1000\ \text{kg}/\text{m}^3\right)} - \dfrac{1}{1.2\left(1000\ \text{kg}/\text{m}^3\right)}\right)} = \underline{\underline{0.316\ \text{kg crystals / kg slurry}}}$$

iii.)
$$V_{sl} = \frac{m_{sl}}{\rho_{sl}} = \frac{175\ \text{kg}}{1415\ \text{kg}/\text{m}^3}\left|\frac{1000\ \text{L}}{\text{m}^3}\right. = \underline{\underline{123.8\ \text{L}}}$$

iv.)
$$m_c = x_c m_{sl} = (0.316\ \text{kg crystals / kg slurry})(175\ \text{kg slurry}) = \underline{\underline{55.3\ \text{kg crystals}}}$$

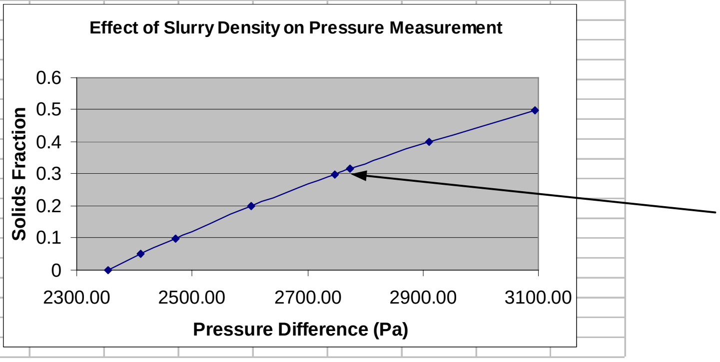
v.)
$$m_{CuSO_4} = \frac{55.3\ \text{kg}\ CuSO_4\cdot 5H_2O}{}\left|\frac{1\ \text{kmol}}{249\ \text{kg}}\right|\frac{1\ \text{kmol}\ CuSO_4}{1\ \text{kmol}\ CuSO_4\cdot 5H_2O}\left|\frac{159.6\ \text{kg}}{1\ \text{kmol}}\right. = \underline{\underline{35.4\ \text{kg}\ CuSO_4}}$$

vi.)
$$m_l = (1-x_c)m_{sl} = (0.684\ \text{kg liquid / kg slurry})(175\ \text{kg slurry}) = \underline{\underline{120\ \text{kg liquid solution}}}$$

vii.)
$$V_l = \frac{m_l}{\rho_l} = \frac{120\ \text{kg}}{(1.2)\left(1000\ \text{kg}/\text{m}^3\right)}\left|\frac{1000\ \text{L}}{\text{m}^3}\right. = \underline{\underline{100\ \text{L}}}$$

d.

h(m)	0.2							
ρl(kg/m^3)	1200							
ρc(kg/m^3)	2300							
ΔP(Pa)	2353.58	2411.24	2471.80	2602.52	2747.84	2772.61	2910.35	3093.28
xc	0	0.05	0.1	0.2	0.3	0.316	0.4	0.5
ρsl(kg/m^3)	1200.00	1229.40	1260.27	1326.92	1401.02	1413.64	1483.87	1577.14



ΔP = 2775, ρ = 0.316

5.4 (cont'd)

e. Basis: $1\text{ kg slurry} \Rightarrow x_c(\text{kg crystals}),\ V_c\left(\text{m}^3\text{ crystals}\right) = \dfrac{x_c(\text{kg crystals})}{\rho_c\left(\text{kg / m}^3\right)}$

$$(1-x_c)(\text{kg liquid}),\ V_l\left(\text{m}^3\text{ liquid}\right) = \frac{(1-x_c)(\text{kg liquid})}{\rho_l\left(\text{kg / m}^3\right)}$$

$$\underline{\underline{\rho_{sl} = \frac{1\text{ kg}}{(V_c+V_l)\left(\text{m}^3\right)} = \frac{1}{\dfrac{x_c}{\rho_c} + \dfrac{(1-x_c)}{\rho_l}}}}$$

5.5 Assume $P_{atm} = 1\text{ atm}$

$$P\hat{V} = RT \Rightarrow \hat{V} = \begin{array}{c|c|c} 0.08206\text{ m}^3\cdot\text{atm} & 313.2\text{ K} & 1\text{ kmol} \\ \hline \text{kmol}\cdot\text{K} & 4.0\text{ atm} & 10^3\text{ mol} \end{array} = \underline{\underline{0.0064\ \text{m}^3/\text{mol}}}$$

$$\rho = \begin{array}{c|c|c} 1\text{ mol} & 29.0\text{ g} & 1\text{ kg} \\ \hline 0.0064\text{ m}^3\text{ air} & \text{mol} & 10^3\text{ g} \end{array} = \underline{\underline{4.5\ \text{kg}/\text{m}^3}}$$

5.6 **a.** $V = \dfrac{nRT}{P} = \begin{array}{c|c|c} 1.00\text{ mol} & 0.08206\text{ L}\cdot\text{atm} & 373.2\text{ K} \\ \hline & \text{mol}\cdot\text{K} & 10\text{ atm} \end{array} = \underline{\underline{3.06\text{ L}}}$

b. $\%\text{ error} = \dfrac{(3.06\text{L} - 2.8\text{L})}{2.8\text{L}} \times 100\% = \underline{\underline{9.3\%}}$

5.7 Assume $P_{atm} = 1.013\text{ bar}$

a.

$$PV = nRT \Rightarrow n = \begin{array}{c|c|c|c} (10+1.013)\text{bar} & 20.0\text{ m}^3 & \text{kmol}\cdot\text{K} & 28.02\text{ kg N}_2 \\ \hline & (25+273.2)\text{K} & 0.08314\text{ m}^3\cdot\text{bar} & \text{kmol} \end{array} = \underline{\underline{249\text{ kg N}_2}}$$

b. $\dfrac{PV}{P_sV_s} = \dfrac{nRT}{n_sRT_s} \Rightarrow n = V\cdot\dfrac{T_s}{T}\cdot\dfrac{P}{P_s}\cdot\dfrac{n_s}{V_s}$

$$n = \begin{array}{c|c|c|c|c} 20.0\text{ m}^3 & 273\text{K} & (10+1.013)\text{bar} & 1\text{ kmol} & 28.02\text{ kg N}_2 \\ \hline & 298.2\text{K} & 1.013\text{ bar} & 22.415\text{ m}^3(\text{STP}) & \text{kmol} \end{array} = \underline{\underline{249\text{ kg N}_2}}$$

5.8 **a.** $R = \dfrac{P_sV_s}{n_sT_s} = \begin{array}{c|c} 1\text{ atm} & 22.415\text{ m}^3 \\ \hline 1\text{ kmol} & 273\text{ K} \end{array} = \underline{\underline{8.21\times10^{-2}\ \dfrac{\text{atm}\cdot\text{m}^3}{\text{kmol}\cdot\text{K}}}}$

b. $R = \dfrac{P_sV_s}{n_sT_s} = \begin{array}{c|c|c} 1\text{ atm} & 760\text{ torr} & 359.05\text{ ft}^3 \\ \hline 1\text{ lb-mole} & 1\text{ atm} & 492\ ^\circ\text{R} \end{array} = \underline{\underline{555\ \dfrac{\text{torr}\cdot\text{ft}^3}{\text{lb-mole}\cdot{}^\circ\text{R}}}}$

5.9 $P = 1\text{ atm} + \dfrac{10\text{ cm H}_2\text{O}}{}\Bigg|\dfrac{1\text{ m}}{10^2\text{ cm}}\Bigg|\dfrac{1\text{ atm}}{10.333\text{ m H}_2\text{O}} = 1.01\text{ atm}$

$T = 25^\circ\text{C} = 298.2\text{ K}\,,\quad \dot{V} = \dfrac{2.0\text{ m}^3}{5\text{ min}} = 0.40\ \text{m}^3/\text{min} = 400\ \text{L/min}$

$\dot{m} = \dot{n}(\text{mol/min})\cdot \text{MW}(\text{g/mol})$

a. $\dot{m} = \dfrac{P\dot{V}}{RT}\cdot \text{MW} = \dfrac{1.01\text{ atm}}{0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\Bigg|\dfrac{400\ \frac{\text{L}}{\text{min}}}{298.2\text{ K}}\Bigg|\dfrac{28.02\ \frac{\text{g}}{\text{mol}}}{} = \underline{\underline{458\ \text{g/min}}}$

b. $\dot{m} = \dfrac{400\ \frac{\text{L}}{\text{min}}}{}\Bigg|\dfrac{273\text{ K}}{298.2\text{ K}}\Bigg|\dfrac{1\text{ mol}}{22.4\text{ L(STP)}}\Bigg|\dfrac{28.02\ \frac{\text{g}}{\text{mol}}}{} = \underline{\underline{458\ \text{g/min}}}$

5.10 Assume ideal gas behavior: $u\left(\dfrac{\text{m}}{\text{s}}\right) = \dfrac{\dot{V}(\text{m}^3/\text{s})}{A(\text{m}^2)} = \dfrac{\dot{n}RT/P}{\pi D^2/4} \Rightarrow \dfrac{u_2}{u_1} = \dfrac{\dot{n}R}{\dot{n}R}\cdot\dfrac{T_2}{T_1}\cdot\dfrac{P_1}{P_2}\cdot\dfrac{D_1^2}{D_2^2}$

$$u_2 = u_1\frac{T_2P_1D_1^2}{T_1P_2D_2^2} = \frac{60.0\text{ m}}{\text{sec}}\Bigg|\frac{333.2\text{K}}{300.2\text{K}}\Bigg|\frac{(1.80+1.013)\text{bar}}{(1.53+1.013)\text{bar}}\Bigg|\frac{(7.50\text{ cm})^2}{(5.00\text{ cm})^2} = \underline{\underline{165\ \text{m/sec}}}$$

5.11 Assume ideal gas behavior: $n = \dfrac{PV}{RT} = \dfrac{(1.00+1.00)\text{ atm}}{0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\Bigg|\dfrac{5\text{ L}}{300\text{ K}} = 0.406\text{ mol}$

$\text{MW} = 13.0\text{ g}/0.406\text{ mol} = 32.0\ \text{g/mol} \Rightarrow \underline{\underline{\text{Oxygen}}}$

5.12 Assume ideal gas behavior: Say m_t = mass of tank, n_g = mol of gas in tank

$$\left.\begin{array}{ll}\text{N}_2: & 37.289\text{ g} = m_t + n_g(28.02\text{ g/mol})\\ \text{CO}_2: & 37.440\text{ g} = m_t + n_g(44.1\text{ g/mol})\end{array}\right\}\Rightarrow \begin{array}{l} n_g = 0.009391\text{ mol}\\ m_t = 37.0256\text{ g}\end{array}$$

unknown: $\text{MW} = \dfrac{(37.062 - 37.0256)\text{g}}{0.009391\text{ mol}} = \underline{\underline{3.9\ \text{g/mol}}} \Rightarrow \text{Helium}$

5.13 **a.** $\dot{V}_{\text{std}}\left[\text{cm}^3(\text{STP})/\text{min}\right] = \dfrac{\Delta V\text{ liters}}{\Delta t\text{ min}}\Bigg|\dfrac{273\text{K}}{296.2\text{K}}\Bigg|\dfrac{763\text{ mm Hg}}{760\text{ mm Hg}}\Bigg|\dfrac{10^3\text{cm}^3}{1\text{ L}} = 925.3\dfrac{\Delta V}{\Delta t}$

ϕ	$\dot{V}_{\text{std}}\left[\text{cm}^3(\text{STP})/\text{min}\right]$
5.0	139
9.0	268
12.0	370

straight line plot

⇓

$\underline{\underline{\phi = 0.031\dot{V}_{\text{std}} + 0.93}}$

b. $\dot{V}_{\text{std}} = \dfrac{0.010\text{ mol N}_2}{\text{min}}\Bigg|\dfrac{22.4\text{ liters(STP)}}{1\text{ mole}}\Bigg|\dfrac{10^3\text{ cm}^3}{1\text{ L}} = 224\text{ cm}^3/\text{min}$

$\phi = 0.031(224\text{ cm}^3/\text{min}) + 0.93 = \underline{\underline{7.9}}$

5.14 Assume ideal gas behavior $\rho(\text{kg/L}) = \dfrac{n(\text{kmol})M(\text{kg / kmol})}{V(\text{L})} \xRightarrow{\frac{n}{V}=\frac{P}{RT}} \dfrac{PM}{RT}$

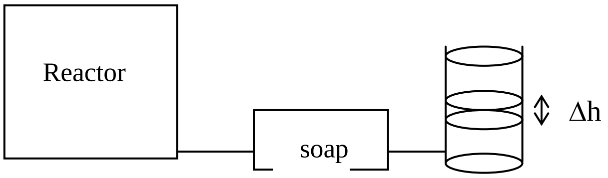
$$V_2(\text{cm}^3/\text{s}) = V_1(\text{cm}^3/\text{s}) \cdot \left(\frac{\rho_1}{\rho_2}\right)^{1/2} = V_1\left[P_1M_1T_2/P_2M_2T_1\right]^{1/2}$$

a. $V_{H_2} = 350\dfrac{\text{cm}^3}{\text{s}}\left[\dfrac{758 \text{ mm Hg}}{1800 \text{ mm Hg}}\bigg|\dfrac{28.02 \text{ g/mol}}{2.02 \text{ g/mol}}\bigg|\dfrac{323.2\text{K}}{298.2\text{K}}\right]^{1/2} = \underline{\underline{881 \text{ cm}^3/\text{s}}}$

b. $\overline{M} = 0.25M_{CH_4} + 0.75M_{C_3H_8} = (0.25)(16.05) + (0.75)(44.11) = 37.10 \text{ g/mol}$

$$V_g = 350\frac{\text{cm}^3}{\text{s}}\left[\frac{(758)(28.02)(323.2)}{(1800)(37.10)(298.2)}\right]^{1/2} = \underline{\underline{205 \text{ cm}^3/\text{s}}}$$

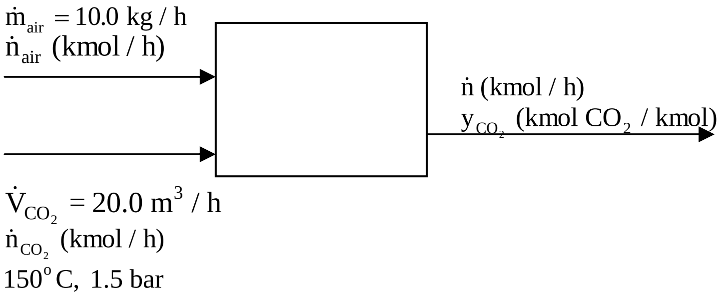
5.15 a.



b. $\dot{n}_{CO_2} = \dfrac{P\dot{V}}{RT} \Rightarrow \dot{V} = \dfrac{\pi R^2 \Delta h}{\Delta t} = \dfrac{\pi}{4}\dfrac{(0.012 \text{ m}^2)^2}{}\bigg|\dfrac{1.2 \text{ m}}{7.4 \text{ s}}\bigg|\dfrac{60 \text{ s}}{\text{min}} = 1.1\times10^{-3} \text{ m}^3 / \text{min}$

$$\dot{n}_{CO_2} = \frac{755 \text{ mm Hg}}{0.08206 \frac{\text{m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}}\bigg|\frac{1 \text{ atm}}{760 \text{ mm Hg}}\bigg|\frac{1.1\times10^{-3} \text{ m}^3/\text{min}}{300 \text{ K}}\bigg|\frac{1000 \text{ mol}}{1 \text{ kmol}} = \underline{\underline{0.044 \text{ mol/min}}}$$

5.16



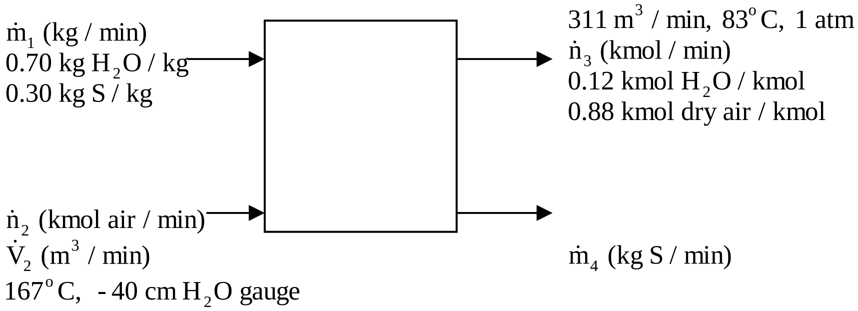
Assume ideal gas behavior

$$\dot{n}_{air} = \frac{10.0 \text{ kg}}{\text{h}}\bigg|\frac{1 \text{ kmol}}{29.0 \text{ kg air}} = 0.345 \text{ kmol air / h}$$

$$\dot{n}_{CO_2} = \frac{P\dot{V}}{RT} = \frac{1.5 \text{ bar}}{8.314 \frac{\text{m}^3\cdot\text{kPa}}{\text{kmol}\cdot\text{K}}}\bigg|\frac{100 \text{ kPa}}{1 \text{ bar}}\bigg|\frac{20.0 \text{ m}^3 / \text{h}}{423.2 \text{ K}} = 0.853 \text{ kmol } CO_2 / \text{h}$$

$$y_{CO_2} \times 100\% = \frac{0.853 \text{ kmol } CO_2 / \text{h}}{(0.853 \text{ kmol } CO_2 / \text{h} + 0.345 \text{ kmol air / h})} \times 100\% = \underline{\underline{71.2\%}}$$

5.17 Basis: Given flow rates of outlet gas. Assume ideal gas behavior



a. $$\dot{n}_3 = \frac{1\text{ atm}}{356.2\text{K}}\bigg|\frac{311\text{ m}^3}{\text{min}}\bigg|\frac{\text{kmol}\cdot\text{K}}{0.08206\text{ m}^3\cdot\text{atm}} = 10.64\ \text{kmol/min}$$

$$\underline{H_2O\text{ balance}}:\quad 0.70\,\dot{m}_1 = \frac{10.64\text{ kmol}}{\text{min}}\bigg|\frac{0.12\text{ kmol }H_2O}{\text{kmol}}\bigg|\frac{18.02\text{ kg}}{\text{kmol}}$$

$$\Rightarrow \dot{m}_1 = 32.9\ \text{kg/min milk}$$

$$\underline{\text{S(olids) balance}}:\ 0.30(32.2\ \text{kg/min}) = \dot{m}_4 \Rightarrow \underline{\underline{\dot{m}_4 = 9.6\ \text{kg S/min}}}$$

$$\underline{\text{Dry air balance}}:\ \dot{n}_2 = 0.88(10.64\ \text{kmol/min}) \Rightarrow \dot{n}_2 = 9.36\ \text{kmol/min air}$$

$$\dot{V}_2 = \frac{9.36\text{ kmol}}{\text{min}}\bigg|\frac{0.08206\text{ m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\bigg|\frac{440\text{K}}{(1033-40)\text{cm }H_2O}\bigg|\frac{1033\text{ cm }H_2O}{1\text{ atm}}$$

$$= \underline{\underline{352\ \text{m}^3\ \text{air/min}}}$$

$$u_{\text{air}}(\text{m/min}) = \frac{\dot{V}_{\text{air}}\ (\text{m}^3/\text{s})}{A\ (\text{m}^2)} = \frac{352\text{ m}^3}{\text{min}}\bigg|\frac{1\text{ min}}{60\text{ s}}\bigg|\frac{}{\frac{\pi}{4}\cdot(6\text{ m})^2} = \underline{\underline{0.21\text{ m/s}}}$$

b. If the velocity of the air is too high, the powdered milk would be blown out of the reactor by the air instead of falling to the conveyor belt.

5.18 $$SG_{CO_2} = \frac{\rho_{CO_2}}{\rho_{\text{air}}} = \frac{\frac{PM_{CO_2}}{RT}}{\frac{PM_{\text{air}}}{RT}} = \frac{M_{CO_2}}{M_{\text{air}}} = \frac{44\text{ kg / kmol}}{29\text{ kg / kmol}} = \underline{\underline{1.52}}$$

5.19 **a.** $x_{CO_2} = 0.75 \quad x_{\text{air}} = 1 - 0.75 = 0.25$

Since air is 21% O_2, $x_{O_2} = (0.25)(0.21) = 0.0525 = \underline{\underline{5.25\text{ mole\% }O_2}}$

b. $$m_{CO_2} = n\cdot x_{CO_2}\cdot M_{CO_2} = \frac{1\text{ atm}}{0.08206\ \frac{\text{m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}}\bigg|\frac{(2\times1.5\times3)\text{m}^3}{298.2\text{ K}}\bigg|\frac{0.75\text{ kmol }CO_2}{\text{kmol}}\bigg|\frac{44.01\text{ kg }CO_2}{\text{kmol }CO_2} = \underline{\underline{12\text{ kg}}}$$

More needs to escape from the cylinder since the room is not sealed.

5.19 (cont'd)

c. With the room closed off all weekend and the valve to the liquid cylinder leaking, if a person entered the room and closed the door, over a period of time the person could die of asphyxiation. Measures that would reduce hazards are:

1. Change the lock so the door can always be opened from the inside without a key.
2. Provide ventilation that keeps air flowing through the room.
3. Install a gas monitor that sets off an alarm once the mole% reaches a certain amount.
4. Install safety valves on the cylinder in case of leaks.

5.20 $$n_{CO_2} = \begin{array}{c|c} 15.7\text{ kg} & 1\text{ kmol} \\ \hline & 44.01\text{ kg} \end{array} = 0.357\text{ kmol CO}_2$$

$\underline{\text{Assume ideal gas behavior, negligible temperature change}}\ \left(T = 19°\text{C} = 292.2\text{K}\right)$

a. $$\frac{P_1V}{P_2V} = \frac{n_1RT}{(n_1+0.357)RT} \Rightarrow \frac{n_1}{n_1+0.357} = \frac{P_1}{P_2} = \frac{102\text{kPa}}{3.27\times10^3\text{kPa}}$$

$$\Rightarrow n_1 = \underline{\underline{0.0115\text{ kmol air in tank}}}$$

b. $$V_{\text{tank}} = \frac{n_1RT}{P_1} = \begin{array}{c|c|c|c} 0.0115\text{ kmol} & 292.2\text{ K} & 8.314\text{ m}^3\cdot\text{kPa} & 10^3\text{L} \\ \hline & 102\text{kPa} & \text{kmol}\cdot\text{K} & \text{m}^3 \end{array} = 274\text{ L}$$

$$\rho_f = \frac{15700\text{ g CO}_2 + 11.5\text{ mol air}\cdot(29.0\text{ g air / mol})}{274\text{ L}} = \underline{\underline{58.5\text{ g / L}}}$$

c. CO_2 sublimates ⇒ large volume change due to phase change ⇒ rapid pressure rise. Sublimation causes temperature drop; afterwards, T gradually rises back to room temperature, increase in T at constant V ⇒ slow pressure rise.

5.21 At point of entry, $P_1 = (10\text{ ft H}_2\text{O})(29.9\text{ in. Hg}/33.9\text{ ft H}_2\text{O}) + 28.3\text{ in. Hg} = 37.1\text{ in. Hg}$.

At surface, $P_2 = 28.3\text{ in. Hg},\ V_2 = \text{bubble volume at entry}$

$\underline{\text{Mean Slurry Density:}}$ $$\frac{1}{\rho_{sl}} = \frac{x_{\text{solid}}}{\rho_{\text{solid}}} + \frac{x_{\text{solution}}}{\rho_{\text{solution}}} = \frac{0.20}{(1.2)(1.00\text{ g / cm}^3)} + \frac{0.80}{(1.00\text{ g / cm}^3)}$$

$$= 0.967\ \frac{\text{cm}^3}{\text{g}} \Rightarrow \rho_{sl} = \begin{array}{c|c|c|c} 1.03\text{ g} & 2.20\text{ lb} & 5\times10^{-4}\text{ ton} & 10^6\text{ cm}^3 \\ \hline \text{cm}^3 & 1000\text{ g} & 1\text{ lb} & 264.17\text{ gal} \end{array} = 4.3\times10^{-3}\text{ ton / gal}$$

a. $$\begin{array}{c|c|c|c|c} 300\text{ ton} & \text{gal} & 40.0\text{ ft}^3\text{(STP)} & 534.7°\text{R} & 29.9\text{ in Hg} \\ \hline \text{hr} & 4.3\times10^{-3}\text{ ton} & 1000\text{ gal} & 492°\text{R} & 37.1\text{ in Hg} \end{array} = \underline{\underline{2440\text{ ft}^3\text{ / hr}}}$$

b. $$\frac{P_2V_2}{P_1V_1} = \frac{nRT}{nRT} \Rightarrow \frac{V_2}{V_1} = \frac{P_1}{P_2} \Rightarrow \frac{\frac{4}{3}\pi\left(\frac{D_2}{2}\right)^3}{\frac{4}{3}\pi\left(\frac{D_1}{2}\right)^3} = \frac{37.1}{28.3} \Rightarrow D_2^3 = 1.31D_1^3 \xRightarrow{D_1=2\text{ mm}} D_2 = 2.2\text{ mm}$$

$$\%\text{ change} = \frac{(2.2-2.0)\text{ mm}}{2.0\text{ mm}}\times100 = \underline{\underline{10\%}}$$

5.22 Let B = benzene

n_1, n_2, n_3 = moles in the container when the sample is collected, after the helium is added, and after the gas is fed to the GC.

n_{inj} = moles of gas injected

n_B, n_{air}, n_{He} = moles of benzene and air in the container and moles of helium added

n_{BGC}, m_{BGC} = moles, g of benzene in the GC

y_B = mole fraction of benzene in room air

a. $P_1V_1 = n_1RT_1$ ($1 \equiv$ condition when sample was taken): $P_1 = 99$ kPa, $T_1 = 306\text{K}$

$$n_1 = \frac{99\text{ kPa}}{101.3\frac{\text{kPa}}{\text{atm}}}\left|\frac{2\text{ L}}{306\text{ K}}\right|\frac{\text{mol}\cdot\text{K}}{.08206\text{ L}\cdot\text{atm}} = 0.078\text{ mol} = n_{air} + n_B$$

$P_2V_2 = n_2RT_2$ ($2 \equiv$ condition when charged with He): $P_2 = 500$ kPa, $T_2 = 306\text{K}$

$$n_2 = \frac{500\text{ kPa}}{101.3\frac{\text{kPa}}{\text{atm}}}\left|\frac{2\text{ L}}{306\text{ K}}\right|\frac{\text{mol}\cdot\text{K}}{.08206\text{ L}\cdot\text{atm}} = 0.393\text{ mol} = n_{air} + n_B + n_{He}$$

$P_3V_3 = n_3RT_3$ ($3 \equiv$ final condition in lab): $P_3 = 400$ kPa, $T_3 = 296\text{K}$

$$n_3 = \frac{400\text{ kPa}}{101.3\frac{\text{kPa}}{\text{atm}}}\left|\frac{2\text{ L}}{296\text{ K}}\right|\frac{\text{mol}\cdot\text{K}}{.08206\text{ L}\cdot\text{atm}} = 0.325\text{ mol} = (n_{air} + n_B + n_{He}) - n_{inj}$$

$$n_{inj} = n_2 - n_3 = 0.068\text{ mol}$$

$$n_B = n_{BGC} \times \frac{n_2}{n_{inj}} = \frac{0.393\text{ mol}}{0.068\text{ mol}}\left|\frac{m_{BGC}(\text{g B})}{}\right|\frac{1\text{ mol}}{78.0\text{ g}} = 0.0741\cdot m_{BGC}$$

$$y_B(\text{ppm}) = \frac{n_B}{n_1}\times 10^6 = \frac{0.0741\cdot m_{BGC}}{0.078}\times 10^6 = 0.950\times 10^6\cdot m_{BGC}$$

$$\left.\begin{array}{l} \text{9 am:}\quad y_B = (0.950\times 10^6)(0.656\times 10^{-6}) = \underline{\underline{0.623\text{ ppm}}} \\ \text{1 pm:}\quad y_B = (0.950\times 10^6)(0.788\times 10^{-6}) = \underline{\underline{0.749\text{ ppm}}} \\ \text{5 pm:}\quad y_B = (0.950\times 10^6)(0.910\times 10^{-6}) = \underline{\underline{0.864\text{ ppm}}} \end{array}\right\}\text{The avg. is below the PEL}$$

b. Helium is used as a carrier gas for the gas chromatograph, and to pressurize the container so gas will flow into the GC sample chamber. Waiting a day allows the gases to mix sufficiently and to reach thermal equilibrium.

c. (*i*) It is very difficult to have a completely evacuated sample cylinder; the sample may be dilute to begin with. (*ii*) The sample was taken on Monday after 2 days of inactivity at the plant. A reading should be taken on Friday. (*iii*) Helium used for the carrier gas is less dense than the benzene and air; therefore, the sample injected in the GC may be He-rich depending on where the sample was taken from the cylinder. (*iv*) The benzene may not be uniformly distributed in the laboratory. In some areas the benzene concentration could be well above the PEL.

5.23 Volume of balloon $= \frac{4}{3}\pi(10\ \text{m})^3 = 4189\ \text{m}^3$

Moles of gas in balloon

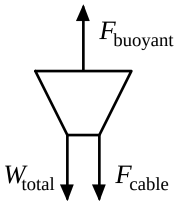
$$n(\text{kmol}) = \begin{array}{c|c|c|c} 4189\ \text{m}^3 & 492^\circ\text{R} & 3\ \text{atm} & 1\ \text{kmol} \\ \hline & 535^\circ\text{R} & 1\ \text{atm} & 22.4\ \text{m}^3(\text{STP}) \end{array} = 515.9\ \text{kmol}$$

a. He in balloon:

$$m = (515.9\ \text{kmol})\cdot(4.003\ \text{kg/kmol}) = \underline{\underline{2065\ \text{kg He}}}$$

$$m_g = \begin{array}{c|c|c} 2065\ \text{kg} & 9.807\ \text{m} & 1\ \text{N} \\ \hline & \text{s}^2 & 1\ \text{kg}\cdot\text{m/s}^2 \end{array} = \underline{\underline{20{,}250\ \text{N}}}$$

b. $$\begin{matrix} (P_{\text{gas in balloon}})V = n_{\text{gas}}RT \\ (P_{\text{air displaced}})V = n_{\text{air}}RT \end{matrix} \Rightarrow n_{\text{air}} = \frac{P_{\text{air}}}{P_{\text{gas}}}\cdot n_{\text{gas}} = \frac{1\ \text{atm}}{3\ \text{atm}}\cdot 515.9\ \text{kmol} = 172.0\ \text{kmol}$$



$$F_{\text{buoyant}} = W_{\text{air displaced}} = \begin{array}{c|c|c|c} 172.0\ \text{kmol} & 29.0\ \text{kg} & 9.807\ \text{m} & 1\ \text{N} \\ \hline & 1\ \text{kmol} & \text{s}^2 & 1\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2} \end{array} = 48{,}920\ \text{N}$$

Since balloon is stationary, $\sum F_1 = 0$

$$F_{\text{cable}} = F_{\text{buoyant}} - W_{\text{total}} = 48920\ \text{N} - \begin{array}{c|c|c} (2065+150)\text{kg} & 9.807\ \text{m} & 1\ \text{N} \\ \hline & \text{s}^2 & 1\ \frac{\text{kg}\cdot\text{m}}{\text{s}^2} \end{array} = \underline{\underline{27{,}20}}$$

c. When cable is released, $F_{\text{net}}(\uparrow) = 27200\ \text{N} = M_{\text{tot}}a$

$$\Rightarrow a = \begin{array}{c|c} 27200\ \text{N} & 1\ \text{kg}\cdot\text{m/s}^2 \\ \hline (2065+150)\text{kg} & \text{N} \end{array} = \underline{\underline{12.3\ \text{m/s}^2}}$$

d. When mass of displaced air equals mass of balloon + helium the balloon stops rising. Need to know how density of air varies with altitude.

e. The balloon expands, displacing more air ⇒ buoyant force increases ⇒ balloon rises until decrease in air density at higher altitudes compensates for added volume.

5.24 Assume ideal gas behavior, $P_{\text{atm}} = 1\ \text{atm}$

a. $$P_N V_N = P_c V_c \Rightarrow V_c = \frac{P_N V_N}{P_c} = \begin{array}{c|c} 5.7\ \text{atm} & 400\ \text{m}^3/\text{h} \\ \hline 9.5\ \text{atm} & \end{array} = \underline{\underline{240\ \text{m}^3/\text{h}}}$$

b. Mass flow rate before diversion:

$$\begin{array}{c|c|c|c|c} 400\ \text{m}^3 & 273\ \text{K} & 5.7\ \text{atm} & 1\ \text{kmol} & 44.09\ \text{kg} \\ \hline \text{h} & 303\ \text{K} & 1\ \text{atm} & 22.4\ \text{m}^3(\text{STP}) & \text{kmol} \end{array} = 4043\frac{\text{kg C}_3\text{H}_6}{\text{h}}$$

5.24 (cont'd)

Monthly revenue:

$$(4043\ \text{kg/h})(24\ \text{h/day})(30\ \text{days/month})(\$0.60/\text{kg}) = \underline{\underline{\$1,747,000/\text{month}}}$$

c. Mass flow rate at Noxious plant after diversion:

$$\left.\frac{400\ \text{m}^3}{\text{hr}}\right|\left.\frac{273\ \text{K}}{303\ \text{K}}\right|\left.\frac{2.8\ \text{atm}}{1\ \text{atm}}\right|\left.\frac{1\ \text{kmol}}{22.4\ \text{m}^3}\right|\frac{44.09\ \text{kg}}{\text{kmol}} = 1986\ \text{kg/hr}$$

Propane diverted $= (4043 - 1986)\,\text{kg/h} = \underline{\underline{2057\ \text{kg/h}}}$

5.25 a. $P_{He} = y_{He} \cdot P = 0.35 \cdot (2.00\ \text{atm}) = \underline{\underline{0.70\ \text{atm}}}$

$P_{CH_4} = y_{CH_4} \cdot P = 0.20 \cdot (2.00\ \text{atm}) = \underline{\underline{0.40\ \text{atm}}}$

$P_{N_2} = y_{N_2} \cdot P = 0.45 \cdot (2.00\ \text{atm}) = \underline{\underline{0.90\ \text{atm}}}$

b. Assume 1.00 mole gas

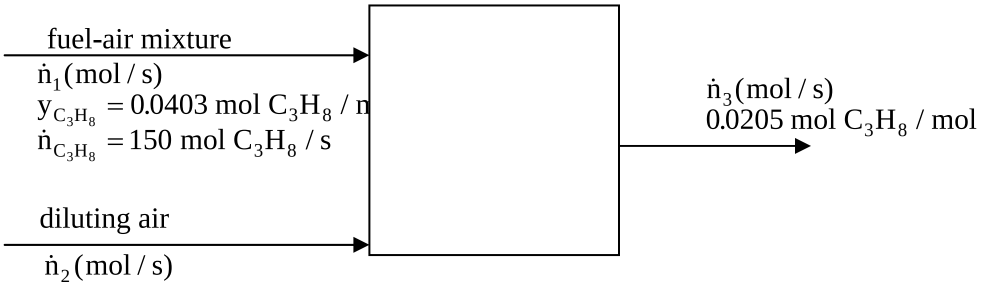
$$\left.\begin{array}{l} 0.35\ \text{mol He}\left(\dfrac{4.004\ \text{g}}{\text{mol}}\right) = 1.40\ \text{g He} \\ 0.20\ \text{mol CH}_4\left(\dfrac{16.05\ \text{g}}{\text{mol}}\right) = 3.21\ \text{g CH}_4 \\ 0.45\ \text{mol N}_2\left(\dfrac{28.02\ \text{g}}{\text{mol}}\right) = 12.61\ \text{g N}_2 \end{array}\right\} 17.22\ \text{g} \Rightarrow \text{mass fraction CH}_4 = \frac{3.21\ \text{g}}{17.22\ \text{g}} = \underline{\underline{0.186}}$$

c. $\overline{MW} = \dfrac{\text{g of gas}}{\text{mol}} = \underline{\underline{17.2\ \text{g / mol}}}$

d. $\rho_{gas} = \dfrac{m}{V} = \dfrac{n(\overline{MW})}{V} = \dfrac{P(\overline{MW})}{RT} = \dfrac{(2.00\ \text{atm})(17.2\ \text{kg / kmol})}{\left(0.08206\ \frac{\text{m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\right)(363.2\ \text{K})} = \underline{\underline{1.15\ \text{kg / m}^3}}$

5.26 a. It is safer to release a mixture that is too lean to ignite.
If a mixture that is rich is released in the atmosphere, it can diffuse in the air and the C_3H_8 mole fraction can drop below the UFL, thereby producing a fire hazard.

b.



$$\dot{n}_1 = \left.\frac{150\ \text{mol C}_3\text{H}_8}{\text{s}}\right|\frac{\text{mol}}{0.0403\ \text{mol C}_3\text{H}_8} = 3722\ \text{mol / s}$$

Propane balance: $150 = 0.0205 \cdot \dot{n}_3 \Rightarrow \dot{n}_3 = 7317\ \text{mol / s}$

5.26 (cont'd)

Total mole balance: $\dot{n}_1 + \dot{n}_2 = \dot{n}_3 \Rightarrow \dot{n}_2 = 7317 - 3722 = 3595 \text{ mol air / s}$

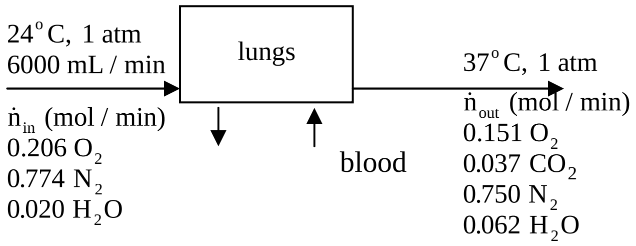
c. $\dot{n}_2 = 1.3(\dot{n}_2)_{\min} = 4674 \text{ mol / s}$

$$\left.\begin{array}{l} \dot{V}_2 = \dfrac{4674 \text{ mol / s}}{} \left| \dfrac{8.314 \text{ m}^3 \cdot \text{Pa}}{\text{mol} \cdot \text{K}} \right| \dfrac{398.2 \text{ K}}{131{,}000 \text{ Pa}} = 118 \text{ m}^3\text{ / s} \\[2ex] \dot{V}_1 = \dfrac{3722 \text{ mol}}{\text{s}} \left| \dfrac{8.314 \text{ m}^3 \cdot \text{Pa}}{\text{mol} \cdot \text{K}} \right| \dfrac{298.2 \text{ K}}{110000 \text{ Pa}} = 83.9 \text{ m}^3\text{ / s} \end{array} \right\} \frac{\dot{V}_2}{\dot{V}_1} = \underline{\underline{1.41 \frac{\text{m}^3 \text{ diluting air}}{\text{m}^3 \text{ fuel gas}}}}$$

$$y_2 = \frac{150 \text{ mol / s}}{\dot{n}_1 + \dot{n}_2} = \frac{150 \text{ mol / s}}{(3722 \text{ mol / s} + 4674 \text{ mol / s})} \times 100\% = \underline{\underline{1.8\%}}$$

d. The incoming propane mixture could be higher than 4.03%.
If $\dot{n}_2 = (\dot{n}_2)_{\min}$, fluctuations in the air flow rate would lead to temporary explosive conditions.

5.27 Basis: $(12 \text{ breaths/min})(500 \text{ mL air inhaled/breath}) = 6000 \text{ mL inhaled/min}$



a. $$\dot{n}_{in} = \frac{6000 \text{ mL}}{\text{min}} \left| \frac{1 \text{ L}}{10^3 \text{ mL}} \right| \frac{273\text{K}}{297\text{K}} \left| \frac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right. = 0.246 \text{ mol/min}$$

$\underline{N_2 \text{ balance:}}$ $(0.774)(0.246) = 0.750\dot{n}_{out} \Rightarrow \dot{n}_{out} = 0.254 \text{ mol exhaled/min}$

$\underline{O_2 \text{ transferred to blood:}}$ $[(0.246)(0.206) - (0.254)(0.151)](\text{mol } O_2/\text{min})[32.0 \text{ g/mol}]$
$= \underline{\underline{0.394 \text{ g } O_2/\text{min}}}$

$\underline{CO_2 \text{ transferred from blood:}}$ $[(0.254)(0.037)](\text{mol } CO_2/\text{min})[44.01 \text{ g/mol}]$
$= \underline{\underline{0.414 \text{ g } CO_2/\text{min}}}$

$\underline{H_2O \text{ transferred from blood:}}$

$[(0.254)(0.062) - (0.246)(0.020)](\text{mol } H_2O/\text{min})[18.02 \text{ g/mol}]$
$= \underline{\underline{0.195 \text{ g } H_2O/\text{min}}}$

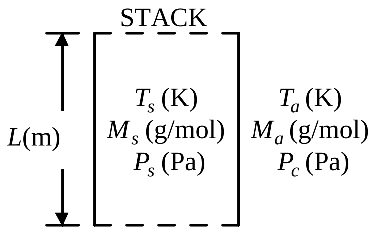
5.27 (cont'd)

$$\frac{PV_{in}}{PV_{out}}=\frac{n_{in}RT_{in}}{n_{out}RT_{out}}$$

$$\Rightarrow \frac{V_{out}}{V_{in}}=\left(\frac{n_{out}}{n_{in}}\right)\left(\frac{T_{out}}{T_{in}}\right)=\left(\frac{0.254\ \text{mol/min}}{0.246\ \text{mol/min}}\right)\left(\frac{310\text{K}}{297\text{K}}\right)=\underline{\underline{1.078\ \text{mL exhaled/ml inhaled}}}$$

b. $(0.414\ \text{g CO}_2\ \text{lost/min})+(0.195\ \text{g H}_2\text{O lost/min})-(0.394\ \text{g O}_2\ \text{gained/min})=\underline{\underline{0.215\ \text{g/min}}}$

5.28



<u>Ideal gas:</u> $\rho=\dfrac{PM}{RT}$

a. $D=(\rho gL)_{\text{combust.}}-(\rho gL)_{\text{stack}}=\dfrac{P_aM_a}{RT_a}gL-\dfrac{P_aM_s}{RT_s}gL=\dfrac{P_agL}{R}\left[\dfrac{M_a}{T_a}-\dfrac{M_a}{T_s}\right]$

b. $M_s=(0.18)(44.1)+(0.02)(32.0)+(0.80)(28.0)=31.0\ \text{g/mol}$, $T_s=655\text{K}$, $P_a=755\ \text{mm Hg}$

$M_a=29.0\ \text{g/mol}$, $T_a=294\text{K}$, $L=53\ \text{m}$

$$D=\begin{array}{c|c|c|c|c}755\ \text{mm Hg} & 1\ \text{atm} & 53.0\ \text{m} & 9.807\ \text{m} & \text{kmol-K}\\\hline & 760\ \text{mm Hg} & & \text{s}^2 & 0.08206\ \text{m}^3-\text{atm}\end{array}$$

$$\times\left[\frac{29.0\ \text{kg/kmol}}{294\text{K}}-\frac{31.0\ \text{kg/kmol}}{655\text{K}}\right]\times\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)=\begin{array}{c|c}323\ \text{N} & 1033\ \text{cm H}_2\text{O}\\\hline \text{m}^2 & 1.013\times10^5\ \text{N/m}^2\end{array}$$

$$=\underline{\underline{3.3\ \text{cm H}_2\text{O}}}$$

5.29 **a.** $\rho=\dfrac{P(MW)}{RT}\xRightarrow{MW_{CCl_2O}=98.91\ \text{g/mol}}\dfrac{\rho_{CCl_2O}}{\rho_{air}}=\dfrac{98.91}{29.0}=3.41$

Phosgene, which is 3.41 times more dense than air, will displace air near the ground.

b. $V_{tube}=\dfrac{\pi(D_{in})^2L}{4}=\dfrac{\pi}{4}\left[0.635\ \text{cm}-2(0.0559\ \text{cm})\right]^2(15.0\ \text{cm})=3.22\ \text{cm}^3$

$$m_{CCl_2O}=V_{tube}\cdot\rho_{CCl_2O}=\begin{array}{c|c|c|c}3.22\ \text{cm}^3 & 1\ \text{L} & 1\ \text{atm} & 98.91\ \text{g/mol}\\\hline & 10^3\ \text{cm}^3 & 0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} & 296.2\ \text{K}\end{array}=\underline{\underline{0.0131\ \text{g}}}$$

c. $$n_{CCl_2O(l)}=\begin{array}{c|c|c}3.22\ \text{cm}^3 & 1.37\times1.000\ \text{g} & \text{mol}\\\hline & \text{cm}^3 & 98.91\ \text{g}\end{array}=0.0446\ \text{mol CCl}_2\text{O}$$

5.29 (cont'd)

$$n_{air} = \frac{PV}{RT} = \frac{1\text{ atm}}{} \left| \frac{2200\text{ ft}^3}{296.2\text{K}} \right| \frac{28.317\text{ L}}{\text{ft}^3} \left| \frac{\text{mol}\cdot\text{K}}{.08206\text{ L}\cdot\text{atm}} \right. = 2563\text{ mol air}$$

$$\frac{n_{CCl_2O}}{n_{air}} = \frac{0.0446}{2563} = \underline{\underline{17.4\times 10^{-6}}} = \underline{\underline{17.4\text{ ppm}}}$$

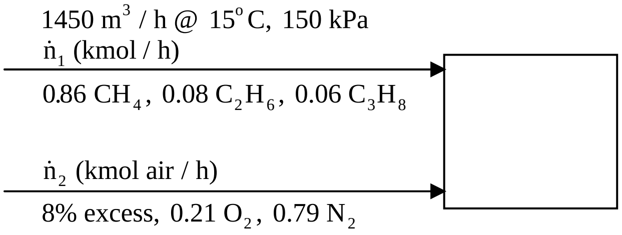
The level of phosgene in the room exceeded the safe level by a factor of more than 100. Even if the phosgene were below the safe level, there would be an unsafe level near the floor since phosgene is denser than air, and the concentration would be much higher in the vicinity of the leak.

d. Pete's biggest mistake was working with a highly toxic substance with no supervision or guidance from an experienced safety officer. He also should have been working under a hood and should have worn a gas mask.

5.30 $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$



$$\dot{n}_1 = \frac{1450\text{ m}^3}{\text{h}} \left| \frac{273.2\text{K}}{288.2\text{K}} \right| \frac{(101.3+150)\text{kPa}}{101.3\text{ kPa}} \left| \frac{1\text{ kmol}}{22.4\text{ m}^3(\text{STP})} \right. = 152\ \text{kmol/h}$$

Theoretical O_2:

$$\frac{152\text{kmol}}{\text{h}}\left[0.86\left(\frac{2\text{ kmol }O_2}{\text{kmol }CH_4}\right) + 0.08\left(\frac{3.5\text{ kmol }O_2}{\text{kmol }C_2H_6}\right) + 0.06\left(\frac{5\text{ kmol }O_2}{\text{kmol }C_3H_8}\right)\right] = 349.6\ \text{kmol/h }O_2$$

Air flow: $$\dot{V}_{air} = \frac{1.08(349.6)\text{ kmol }O_2}{\text{h}} \left| \frac{1\text{ kmol Air}}{0.21\text{ kmol }O_2} \right| \frac{22.4\text{ m}^3(\text{STP})}{\text{kmol}} = \underline{\underline{4.0\times 10^4\ \text{m}^3(\text{STP})/\text{h}}}$$

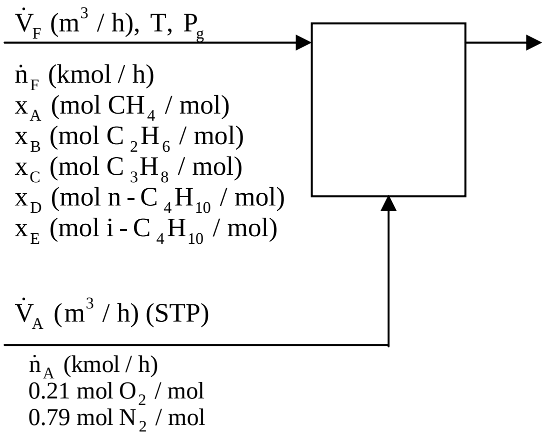
5.31 Calibration formulas

$$(T = 25.0;\ R_T = 14),\ (T = 35.0,\ R_T = 27) \Rightarrow T(^\circ C) = 0.77R_T + 14.2$$

$$(P_g = 0;\ R_p = 0),\ (P_g = 20.0,\ R_r = 6) \Rightarrow P_{gauge}(kPa) = 3.33R_p$$

$$(\dot{V}_F = 0;\ R_p = 0),\ (\dot{V}_F = 2.0\times 10^3,\ R_F = 10) \Rightarrow \dot{V}_F(m^3/h) = 200R_F$$

$$(\dot{V}_A = 0;\ R_A = 0),\ (\dot{V}_A = 1.0\times 10^5,\ R_A = 25) \Rightarrow \dot{V}_A(m^3/h) = 4000R_A$$



$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

$$C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O$$

$$\dot{n}_F = \frac{\dot{V}_F(m^3/h)}{} \left| \frac{273.2K}{(T+273.2)K} \right| \frac{(P_g + 101.3)kPa}{101.3\ kPa} \left| \frac{1\ kmol}{22.4\ m^3(STP)} \right.$$

$$= \frac{0.12031\dot{V}_F(P_g + 101.3)}{(T+273)}\left(\frac{kmol}{h}\right)$$

Theoretical O_2:

$$(\dot{n}_{o_2})_{Th} = \dot{n}_F(2x_A + 3.5x_B + 5x_C + 6.5(x_D + x_E))\text{kmol } O_2 \text{ req.}/h$$

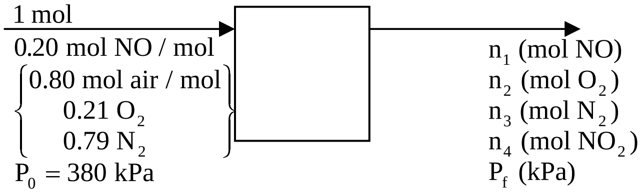
Air feed: $$\dot{n}_A = \frac{(\dot{n}_{o_2})_{Th}\ \text{kmol } O_2 \text{ req.}}{h} \left| \frac{1\ \text{kmol air}}{0.21\ \text{kmol } O_2} \right| \frac{(1 + P_x/100)\text{kmol feed}}{1\ \text{kmol req.}}$$

$$= 4.762\left(1 + \frac{P_x}{100}\right)(n_{o_2})_{Th}$$

$$\dot{V}_A = [\dot{n}_a\ (\text{kmol air}/h)](22.4\ m^3(STP)/\text{kmol}) = 22.4\dot{n}_A[m^3(STP)/h]$$

RT	T(C)	Rp	Pg (kPa)	Rf	xa	xb	xc	xd	xe	PX (%)	nF	nO2, th	nA	Vf (m3/h)	Va (m3/h)	Ra
23.1	32.0	7.5	25.0	7.25	0.81	0.08	0.05	0.04	0.02	15	72.2	183.47	1004.74	1450	22506.2	5.63
7.5	20.0	19.3	64.3	5.8	0.58	0.31	0.06	0.05	0.00	23	78.9	226.4	1325.8	1160	29697.8	7.42
46.5	50.0	15.8	52.6	2.45	0.00	0.00	0.65	0.25	0.10	33	28.1	155.2	983.1	490	22022.3	5.51
21	30.4	3	10.0	6	0.02	0.4	0.35	0.1	0.13	15	53.0	248.1	1358.9	1200	30439.2	7.6
23	31.9	4	13.3	7	0.45	0.12	0.23	0.16	0.04	15	63.3	238.7	1307.3	1400	29283.4	7.3
25	33.5	5	16.7	9	0.5	0.3	0.1	0.04	0.06	15	83.4	266.7	1460.8	1800	32721.2	8.2
27	35.0	6	20.0	10	0.5	0.3	0.1	0.04	0.06	15	94.8	303.2	1660.6	2000	37196.7	9.3

5.32 $NO + \frac{1}{2}O_2 \Leftrightarrow NO_2$



a. Basis: 1.0 mol feed

90% NO conversion: $n_1 = 0.10(0.20) = 0.020 \text{ mol NO} \Rightarrow \text{NO reacted} = 0.18 \text{ mol}$

$$\underline{O_2 \text{ balance:}}\; n_2 = 0.80(0.21) - \frac{0.18 \text{ mol NO}}{}\bigg|\frac{0.5 \text{ mol } O_2}{\text{mol NO}} = 0.0780 \text{ mol } O_2$$

$$\underline{N_2 \text{ balance:}}\; n_3 = 0.80(0.79) = 0.632 \text{ mol } N_2$$

$$n_4 = \frac{0.18 \text{ mol NO}}{}\bigg|\frac{1 \text{ mol } NO_2}{1 \text{ mol NO}} = 0.18 \text{ mol } NO_2 \Rightarrow n_f = n_1 + n_2 + n_3 + n_4 = 0.91 \text{ mol}$$

$$y_{NO} = \frac{0.020 \text{ mol NO}}{0.91 \text{ mol}} = \underline{\underline{0.022 \frac{\text{mol NO}}{\text{mol}}}}$$

$$y_{O_2} = \underline{\underline{0.086 \frac{\text{mol } O_2}{\text{mol}}}} \quad y_{N_2} = \underline{\underline{0.695 \frac{\text{mol } N_2}{\text{mol}}}} \quad y_{NO_2} = \underline{\underline{0.198 \frac{\text{mol } NO_2}{\text{mol}}}}$$

$$\frac{P_f V}{P_0 V} = \frac{n_f RT}{n_0 RT} \Rightarrow P_f = P_0 \frac{n_f}{n_0} = 380 \text{ kPa}\left(\frac{0.91 \text{ mol}}{1 \text{ mol}}\right) = \underline{\underline{346 \text{ kPa}}}$$

b. $n_f = n_0 \frac{P_f}{P_0} = (1 \text{ mol})\frac{360 \text{ kPa}}{380 \text{ kPa}} = 0.95 \text{ mol}$

$$n_i = n_{i0} + \upsilon_i \xi$$

$$\Downarrow$$

$n_1 \text{ (mol NO)} = 0.20 - \xi$

$n_2 (\text{mol } O_2) = (0.21)(0.80) - 0.5\xi$

$n_3 \text{ (mol } N_2) = (0.79)(0.80)$

$\underline{n_4 \text{ (mol } NO_2) = \xi}$

$n_f = 1 - 0.5\xi = 0.95 \;\Rightarrow \xi = \underline{\underline{0.10}}$

$\Rightarrow n_1 = 0.10 \text{ mol NO},\; n_2 = 0.118 \text{ mol } O_2,\; n_3 = 0.632 \text{ mol } N_2,$

$n_4 = 0.10 \text{ mol } NO_2 \Rightarrow y_{NO} = 0.105,\; y_{O_2} = 0.124,\; y_{N_2} = 0.665,\; y_{NO_2} = 0.105$

$$\underline{\text{NO conversion}} = \frac{(0.20 - n_1)}{0.20} \times 100\% = \underline{\underline{50\%}}$$

$$P \text{ (atm)} = \frac{360 \text{ kPa}}{101.3 \frac{\text{kPa}}{\text{atm}}} = 3.55 \text{ atm}$$

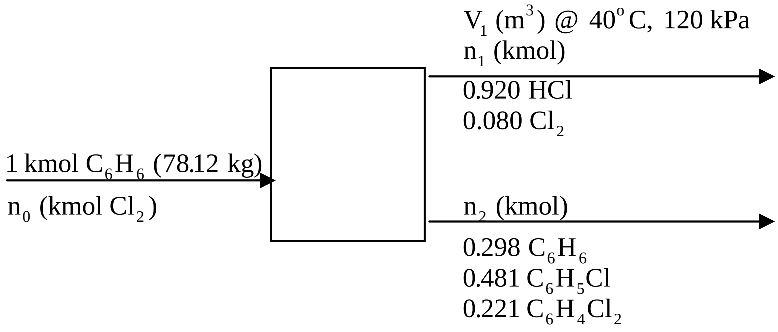
$$K_p = \frac{(y_{NO_2} P)}{(y_{NO} P)(y_{O_2} P)^{0.5}} = \frac{(y_{NO_2})}{(y_{NO})(y_{O_2})^{0.5} P^{0.5}} = \frac{0.105}{(0.105)(0.124)^{0.5}(3.55)^{0.5}} = \underline{\underline{1.51 \text{ atm}^{\frac{1}{2}}}}$$

5.33

Liquid composition:

$$\left.\begin{array}{l} 100 \text{ kg liquid} \Rightarrow \dfrac{49.2 \text{ kg M}}{}\left|\dfrac{1 \text{ kmol}}{112.6 \text{ kg}}\right. = 0.437 \text{ kmol M} \\ \dfrac{29.6 \text{ kg D}}{}\left|\dfrac{1 \text{ kmol}}{147.0 \text{ kg}}\right. = 0.201 \text{ kmol D} \\ \dfrac{21.2 \text{ kg B}}{}\left|\dfrac{1 \text{ kmol}}{78.12 \text{ kg}}\right. = 0.271 \text{ kmol B} \\ \hline \quad 0.909 \text{ kmol} \end{array}\right\} \Rightarrow \begin{array}{l} 0.481 \text{ kmol M / kmol} \\ 0.221 \text{ kmol D / kmol} \\ 0.298 \text{ kmol B / kmol} \end{array}$$

a. Basis: 1 kmol C_6H_6 fed



$$C_6H_6 + Cl_2 \rightarrow C_6H_5Cl + HCl \qquad C_6H_5Cl + Cl_2 \rightarrow C_6H_5Cl_2 + HCl$$

C balance: $\dfrac{1 \text{ kmol } C_6H_6}{}\left|\dfrac{6 \text{ kmol C}}{1 \text{ kmol } C_6H_6}\right. = n_2[0.298 \times 6 + 0.481 \times 6 + 0.221 \times 6]$

$$\Rightarrow n_2 = 1.00 \text{ kmol}$$

H balance: $\dfrac{1 \text{ kmol } C_6H_6}{}\left|\dfrac{6 \text{ kmol H}}{1 \text{ kmol } C_6H_6}\right. = n_1(0.920)(1)$

$$+ n_2[0.298 \times 6 + 0.481 \times 5 + 0.221 \times 4] \Rightarrow n_1 = 1.00 \text{ kmol}$$

$$V_1 = \frac{n_1RT}{P} = \frac{1.00 \text{ kmol}}{120 \text{ kPa}}\left|\frac{101.3 \text{ kPa}}{1 \text{ atm}}\right|\frac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}}\left|\frac{313.2\text{K}}{}\right. = 21.7 \text{ m}^3$$

$$\Rightarrow \frac{V_1}{m_B} = \frac{21.7 \text{ m}^3}{78.12 \text{ kg B}} = \underline{\underline{0.278 \text{ m}^3 / \text{kg B}}}$$

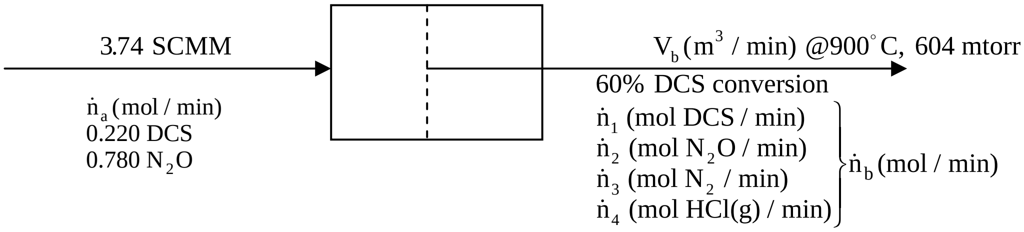
b. $\dot{V}_{gas}(m^3/s) = u(m/s) \cdot A(m^2) = u \cdot \dfrac{\pi d^2}{4} \Rightarrow d^2 = \dfrac{4 \cdot \dot{V}_{gas}}{\pi \cdot u}$

$$d^2 = \frac{4\dot{m}_{B0}(\text{kg B})}{\text{min}}\left|\frac{0.278 \text{ m}^3}{\text{kg B}}\right|\frac{\text{s}}{\pi(10)\text{m}}\left|\frac{1 \text{ min}}{60 \text{ s}}\right|\frac{10^4 \text{ cm}^2}{\text{m}^2} = 5.90\dot{m}_{B0} \text{ (cm}^2)$$

$$\Rightarrow d(\text{cm}) = \underline{\underline{2.43 \cdot (\dot{m}_{B0})^{\frac{1}{2}}}}$$

c. Decreased use of chlorinated products, especially solvents.

5.34



$$SiH_2Cl_{2(g)} + 2N_2O_{(g)} \rightarrow SiO_{2(s)} + 2N_{2(g)} + 2HCl_{(g)}$$

a. $\dot{n}_a = \dfrac{3.74\ m^3\ (STP)}{min}\left|\dfrac{10^3\ mol}{22.4\ m^3\ (STP)}\right. = 167\ mol/min$

60% conversion: $\dot{n}_1 = (1 - 0.60)\left(\dfrac{0.220\ mol\ DCS}{mol}\right)(167\ mol/min) = 14.7\ mol\ DCS/min$

<u>DCS reacted:</u> $(0.60)(0.220)(167)\dfrac{mol\ DCS}{min} = 22.04\ mol\ DCS\ reacted/min$

<u>N_2O balance:</u> $\dot{n}_2 = 0.780(167)\dfrac{mol\ N_2O}{min} - \dfrac{22.04\ mol\ DCS}{min}\left|\dfrac{2\ mol\ N_2O}{mol\ DCS}\right. = 86.18\ mol\ N_2O/min$

<u>N_2 balance:</u> $\dot{n}_3 = \dfrac{22.04\ mol\ DCS}{min}\left|\dfrac{2\ mol\ N_2}{mol\ DCS}\right. = 44.08\ mol\ N_2/min$

<u>HCl balance:</u> $\dot{n}_4 = \dfrac{22.04\ mol\ DCS}{min}\left|\dfrac{2\ mol\ HCl}{mol\ DCS}\right. = 44.08\ mol\ HCl/min$

$\dot{n}_B = \dot{n}_1 + \dot{n}_2 + \dot{n}_3 + \dot{n}_4 = 189\ mol/min$

$\Rightarrow \dot{V}_B = \dfrac{\dot{n}_B RT}{P} = \dfrac{189\ mol}{min}\left|\dfrac{62.36\ L \cdot torr}{mol \cdot K}\right|\dfrac{0.001\ m^3}{L}\left|\dfrac{1173\ K}{0.604\ torr}\right. = \underline{\underline{2.29 \times 10^4\ m^3/min}}$

b. $p_{DCS} = x_{DCS} \cdot P = \dfrac{\dot{n}_1}{\dot{n}_B}P = \dfrac{14.7\ mol\ DCS/min}{189\ mol/min} \cdot 604\ mtorr = 47.0\ mtorr$

$p_{N_2O} = x_{N_2O} \cdot P = \dfrac{\dot{n}_2}{\dot{n}_B}P = \dfrac{86.2\ mol\ N_2O/min}{189\ mol/min} \cdot 604\ mtorr = 275.5\ mtorr$

$r = 3.16 \times 10^{-8} \cdot p_{DCS} \cdot p_{N_2O}{}^{0.65} = 3.16 \times 10^{-8}(47.0)(275.5)^{0.65} = \underline{\underline{5.7 \times 10^{-5}\ \dfrac{mol\ SiO_2}{m^2 \cdot s}}}$

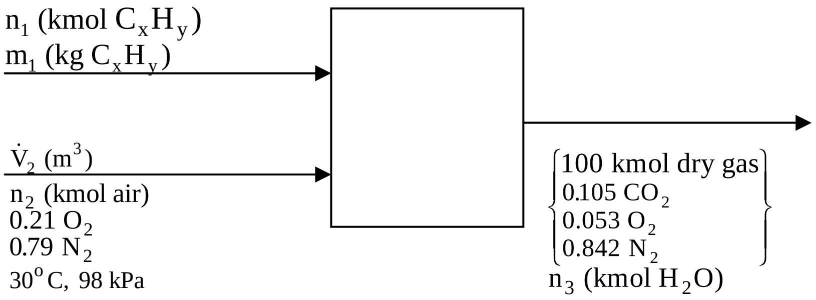
c. $h(\dot{A}) = r \cdot t \cdot \dfrac{MW}{\rho_{SiO_2}} = \dfrac{5.7 \times 10^{-5}\ mol\ SiO_2}{m^2 \cdot s}\left|\dfrac{60\ s}{min}\right|\dfrac{120\ min}{}\left|\dfrac{60.09\ g/mol}{\underset{\text{(Table B.1)}}{2.25 \times 10^6\ g/m^3}}\right|\dfrac{10^{10}\ \dot{A}}{1\ m}$

$= \underline{\underline{1.1 \times 10^5 \dot{A}}}$

The films will be thicker closer to the entrance where the lower conversion yields higher p_{DCS} and p_{N_2O} values, which in turn yields a higher deposition rate.

5.35

Basis: 100 kmol dry product gas



a. $\underline{N_2 \text{ balance:}}$ $0.79n_2 = 0.842(100) \Rightarrow n_2 = 106.6$ kmol air

$\underline{\text{O balance:}}$ $2(0.21n_2) = 100[2(0.105) + 2(0.053)] + n_3 \Rightarrow n_3 = 13.17$ kmol H_2O

$$\underline{\text{C balance:}}\quad \left.\frac{n_1\ (\text{kmol } C_xH_y)}{}\right|\frac{x\ (\text{kmol C})}{(\text{kmol } C_xH_y)} = 100(0.105) \Rightarrow n_1x = 10.5 \qquad (1)$$

$$\underline{\text{H balance:}}\quad n_1y = 2n_3 \xRightarrow{n_3=13.17} n_1y = 26.34 \qquad (2)$$

$$\text{Divide (2) by (1)} \Rightarrow \frac{y}{x} = \frac{26.34}{10.5} = \underline{\underline{2.51 \text{ mol H / mol C}}}$$

$\underline{O_2 \text{ fed:}}$ $0.21(106.6 \text{ kmol air}) = 22.4$ kmol

$\underline{O_2 \text{ in excess}} = 5.3 \text{ kmol} \Rightarrow \underline{\text{Theoretical } O_2} = (22.4 - 5.3)$ kmol $= 17.1$ kmol

$$\underline{\%\text{ excess}} = \frac{5.3 \text{ kmol } O_2}{17.1 \text{ kmol } O_2} \times 100\% = \underline{\underline{31\% \text{ excess air}}}$$

b.
$$V_2 = \left.\frac{106.6 \text{ kmol } N_2}{}\right|\left.\frac{22.4 \text{ m}^3 \text{ (STP)}}{\text{kmol}}\right|\left.\frac{101.3 \text{ kPa}}{98 \text{ kPa}}\right|\frac{303 \text{ K}}{273 \text{ K}} = 2740 \text{ m}^3$$

$$m_1 = \left.\frac{n_1x\ (\text{kmol C})}{}\right|\frac{12.0 \text{ kg}}{\text{kmol}} + \left.\frac{n_1y\ (\text{kmol H})}{}\right|\frac{1.01 \text{ kg}}{\text{kmol}} \xRightarrow[n_1y=26.34]{n_1x=10.5} m_1 = 152.6 \text{ kg}$$

$$\frac{V_2}{m_1} = \frac{2740 \text{ m}^3 \text{ air}}{152.6 \text{ kg fuel}} = \underline{\underline{18.0\ \frac{\text{m}^3 \text{ air}}{\text{kg fuel}}}}$$

5.36 $3N_2H_4 \rightarrow 6xH_2 + (1+2x)N_2 + (4-4x)NH_3$

a. $\underline{\underline{0 \le x \le 1}}$

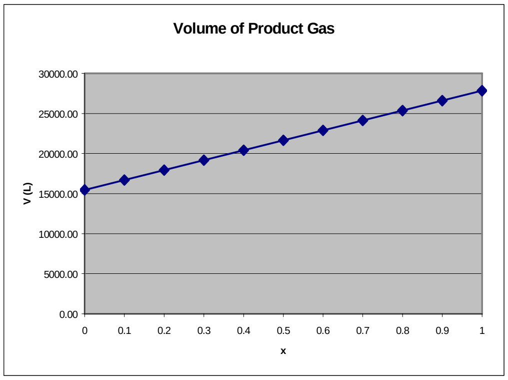
b.
$$n_{N_2H_4} = \left.\frac{50 \text{ L}}{}\right|\left.\frac{0.82 \text{ kg}}{\text{L}}\right|\frac{1 \text{ kmol}}{32.06 \text{ kg}} = 1.28 \text{ kmol}$$

$$n_{\text{product}} = 1.28 \text{ kmol } N_2H_4\left[\frac{6x \text{ kmol } H_2}{3 \text{ kmol } N_2H_4} + \frac{(1+2x) \text{ kmol } N_2}{3 \text{ kmol } N_2H_4} + \frac{(4-4x) \text{ kmol } NH_3}{3 \text{ kmol } N_2H_4}\right]$$

$$= \frac{1.28}{3}(6x + 1 + 2x + 4 - 4x) = 1.707x + 2.13 \text{ kmol}$$

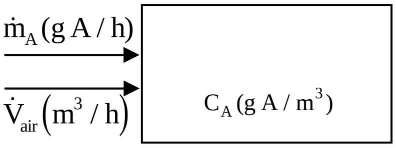
5.36 (cont'd)

~~x~~	~~nproduct~~	~~Vp (L)~~
0	2.13	15447.92
0.1	2.30	16685.93
0.2	2.47	17923.94
0.3	2.64	19161.95
0.4	2.81	20399.96
0.5	2.98	21637.97
0.6	3.15	22875.98
0.7	3.32	24113.99
0.8	3.50	25352.00
0.9	3.67	26590.01
1	3.84	27828.02



c. Hydrazine is a good propellant because as it decomposes generates a large number of moles and hence a large volume of gas.

5.37



a. (i) Cap left off container of liquid A and it evaporates into room, (ii) valve leak in cylinder with A in it, (iii) pill of liquid A which evaporates into room, (iv) waste containing A poured into sink, A used as cleaning solvent.

b. $$\dot m_A\left(\frac{\text{kg A}}{\text{h}}\right)_{\text{in}} = \dot m_A\left(\frac{\text{kg A}}{\text{h}}\right)_{\text{out}} = \underline{\underline{\dot V_{\text{air}}\left(\frac{\text{m}^3}{\text{h}}\right) C_A\left(\frac{\text{kg A}}{\text{m}^3}\right)}}$$

c. $$y_A = \frac{\text{mol A}}{\text{mol air}} = \frac{C_A\left(\frac{\text{g A}}{\text{m}^3}\right)\cdot V}{M_A\left(\frac{\text{g A}}{\text{mol}}\right)\cdot n_{\text{air}}} \xrightarrow[C_A=\frac{\dot m_A}{k\cdot \dot V_{\text{air}}};\ n_{\text{air}}=\frac{PV}{RT}]{} y_A = \underline{\underline{\frac{\dot m_A}{k\cdot \dot V_{\text{air}}}\,\frac{RT}{M_A P}}}$$

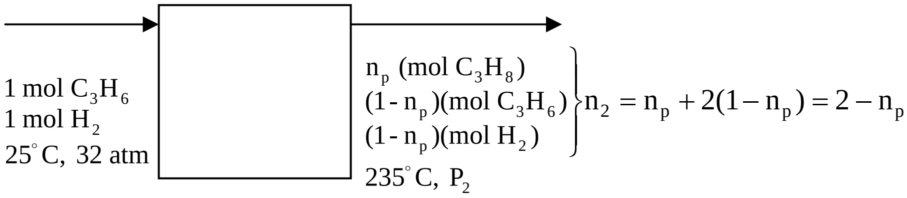
d. $y_A = 50\times10^{-6}$ $\qquad \dot m_A = 9.0\ \text{g/h}$

$$\left(\dot V_{\text{air}}\right)_{\min} = \frac{\dot m_A}{k y_A}\,\frac{RT}{M_A P} = \frac{9.0\ \text{g/h}}{0.5\left(50\times10^{-6}\right)}\left|\frac{8.314\,\frac{\text{m}^3\cdot\text{Pa}}{\text{mol}\cdot\text{K}}}{101.3\times10^3\ \text{Pa}}\right|\frac{293\ \text{K}}{104.14\ \text{g/mol}} = \underline{\underline{83\ \text{m}^3/\text{h}}}$$

Concentration of styrene could be higher in some areas due to incomplete mixing (high concentrations of A near source); 9.0 g/h may be an underestimate; some individuals might be sensitive to concentrations < PEL.

e. Increase in the room temperature could increase the volatility of A and hence the rate of evaporation from the tank. T in the numerator of expression for $\dot V_{\text{air}}$: At higher T, need a greater air volume throughput for y to be < PEL.

5.38 Basis: 2 mol feed gas $C_3H_6 + H_2 \Leftrightarrow C_3H_8$



a. At completion, $n_p = 1$ mol, $n_2 = 2 - 1 = 1$ mol

$$\frac{P_2 V}{P_1 V} = \frac{n_2 R T_2}{n_1 R T_1} \Rightarrow P_2 = \frac{n_2}{n_1}\frac{T_2}{T_1}P_1 = \frac{1\text{ mol}\,\big|\,508\text{K}\,\big|\,32.0\text{ atm}}{2\text{ mol}\,\big|\,298\text{K}\,\big|\,} = 27.3\text{ atm}$$

b. $P_2 = 35.1$ atm

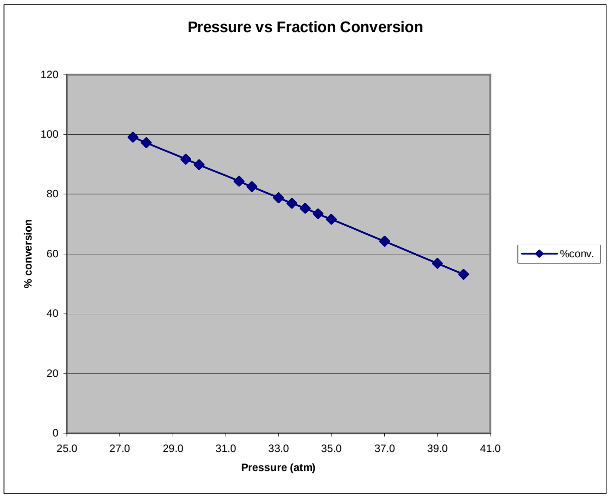
$$n_2 = \frac{P_2}{P_1}\frac{T_1}{T_2}n_1 = \frac{35.1\text{ atm}\,\big|\,298\text{K}\,\big|\,2\text{ mol}}{32.0\text{ atm}\,\big|\,508\text{K}\,\big|\,} = 1.29\text{ mol}$$

$1.29 = 2 - n_p \Rightarrow n_p = 0.71$ mol C_3H_8 produced

$\Rightarrow (1-0.71) = 0.29$ mol C_3H_6 unreacted $\Rightarrow$ 71% conversion of propylene

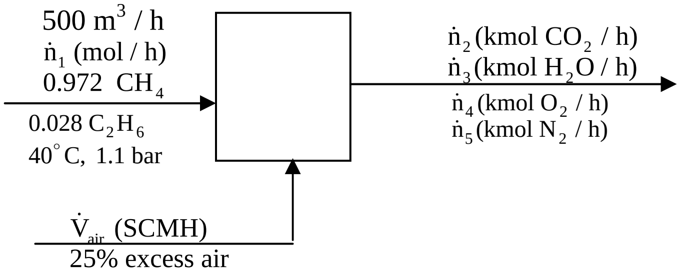
c.

P2 (atm)	n2	C3H8 prod.	%conv.
27.5	1.009	0.99075	99.075
28.0	1.028	0.9724	97.24
29.5	1.083	0.91735	91.735
30.0	1.101	0.899	89.9
31.5	1.156	0.84395	84.395
32.0	1.174	0.8256	82.56
33.0	1.211	0.7889	78.89
33.5	1.229	0.77055	77.055
34.0	1.248	0.7522	75.22
34.5	1.266	0.73385	73.385
35.0	1.285	0.7155	71.55
37.0	1.358	0.6421	64.21
39.0	1.431	0.5687	56.87
40.0	1.468	0.532	53.2



5.39 Convert fuel composition to molar basis

$$\underline{\text{Basis: 100 g}} \Rightarrow \left.\begin{matrix} 95\text{ g CH}_4(1\text{ mol}/16.04\text{ g}) = 5.92\text{ mol CH}_4 \\ 5\text{ g C}_2\text{H}_6(1\text{ mol}/30.07\text{ g}) = 0.17\text{ mol C}_2\text{H}_6 \end{matrix}\right\} \Rightarrow \begin{matrix} 97.2\text{ mol \% CH}_4 \\ 2.8\text{ mol \% C}_2\text{H}_6 \end{matrix}$$



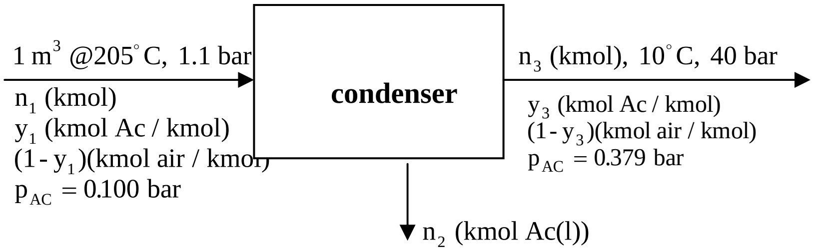
$$\dot{n}_1 = \frac{P_1\dot{V}_1}{RT_1} = \frac{1.1\text{ bar}}{313\text{K}}\,\Bigg|\,\frac{500\text{ m}^3}{\text{h}}\,\Bigg|\,\frac{\text{kmol}\cdot\text{K}}{0.08314\text{ m}^3\cdot\text{bar}} = 21.1\text{ kmol/h}$$

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \qquad \text{C}_2\text{H}_6 + \frac{7}{2}\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O}$$

$$\underline{\text{Theoretical O}_2} = \frac{21.1\text{ kmol}}{\text{h}}\left[\frac{0.972\text{ kmol CH}_4}{\text{kmol}}\,\Bigg|\,\frac{2\text{ kmol O}_2}{1\text{ kmol CH}_4} + \frac{0.028\text{ kmol C}_2\text{H}_6}{\text{kmol}}\,\Bigg|\,\frac{3.5\text{ kmol O}_2}{1\text{ kmol C}_2\text{H}_6}\right] = 43.1\frac{\text{kmol O}_2}{\text{h}}$$

$$\underline{\text{Air Feed:}}\quad \frac{1.25(43.1\text{ kmol O}_2)}{\text{h}}\,\Bigg|\,\frac{1\text{ kmol Air}}{0.21\text{ kmol O}_2}\,\Bigg|\,\frac{22.4\text{ m}^3(\text{STP})}{1\text{ kmol}} = \underline{\underline{5700\text{ SCMH}}}$$

5.40 $\underline{\text{Basis: 1 m}^3\text{ gas fed @ 205°C, 1.1 bars}}$ $\quad$ Ac = acetone



a. $$n_1 = \frac{1.00\text{ m}^3}{}\,\Bigg|\,\frac{273\text{K}}{478\text{K}}\,\Bigg|\,\frac{1.10\text{ bars}}{1.0132\text{ bars}}\,\Bigg|\,\frac{1\text{ kmol}}{22.4\text{ m}^3(\text{STP})} = 0.0277\text{ kmol}$$

$$y_1 = \frac{0.100\text{ bar}}{1.1\text{ bars}} = 0.0909\text{ kmol Ac/kmol}, \quad y_3 = \frac{0.379\text{ bar}}{40.0\text{ bars}} = 9.47\times10^{-3}\text{ kmol Ac/kmol}$$

Air balance: $(0.0277)(0.910) = (1 - 9.47\times10^{-3})n_3 \Rightarrow n_3 = 0.0254$ kmol

Mole balance: $0.0277 = 0.0254 + n_2 \Rightarrow n_2 = 0.0023$ kmol Ac condensed

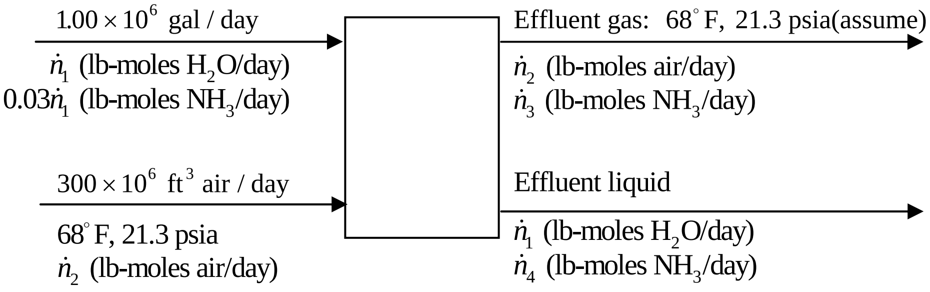
$$\underline{\text{Acetone condensed}} = \frac{0.0023\text{ kmol Ac}}{}\,\Bigg|\,\frac{58.08\text{ kg Ac}}{1\text{ kmol Ac}} = \underline{\underline{0.133\text{ kg acetone condensed}}}$$

5.40 (cont'd)

$$\underline{\text{Product gas volume}} = \frac{0.0254\text{ kmol}}{} \left| \frac{22.4\text{ m}^3(\text{STP})}{} \right| \frac{283\text{K}}{273\text{K}} \left| \frac{1.0132\text{ bars}}{40.0\text{ bars}} \right. = \underline{\underline{0.0149\text{ m}^3}}$$

b. $$\frac{20.0\text{ m}^3\text{ effluent}}{\text{h}} \left| \frac{0.0277\text{ kmol feed}}{0.0149\text{ m}^3\text{ effluent}} \right| \frac{0.0909\text{ kmol Ac}}{\text{kmol feed}} \left| \frac{58.08\text{ kg Ac}}{\text{kmol Ac}} \right. = \underline{\underline{196\text{ kg Ac/h}}}$$

5.41 Basis: 1.00×10^6 gal. wastewater/day. Neglect evaporation of water.



a. Density of wastewater: Assume $\rho = 62.4\ \text{lb}_\text{m}/\text{ft}^3$

$$\left[\frac{\dot{n}_1\text{ lb-moles H}_2\text{O}}{\text{day}} \left| \frac{18.02\text{ lb}_\text{m}}{1\text{ lb-mole}} \right. + \frac{0.03\dot{n}_1\text{ lb}_\text{m}\text{ NH}_3}{\text{day}} \left| \frac{17.03\text{ lb}_\text{m}}{1\text{ lb-mole}} \right.\right] \times \frac{1\text{ ft}^3}{62.4\text{ lb}_\text{m}} \left| \frac{7.4805\text{ gal}}{1\text{ ft}^3} \right.$$

$$= 1.00\times10^6\ \frac{\text{gal}}{\text{day}}$$

$$\Rightarrow \dot{n}_1 = 4.50\times10^5\text{ lb-moles H}_2\text{O fed/day},\ 0.03\dot{n}_1 = 1.35\times10^4\text{ lb-moles NH}_3\text{ fed/day}$$

$$\dot{n}_2 = \frac{300\times10^6\text{ ft}^3}{\text{day}} \left| \frac{492^\circ\text{R}}{527.7^\circ\text{R}} \right| \frac{21.3\text{ psi}}{14.7\text{ psi}} \left| \frac{1\text{ lb-mole}}{359\text{ ft}^3(\text{STP})} \right. = \underline{\underline{1.13\times10^6\text{ lb-moles air/day}}}$$

93% stripping: $\dot{n}_3 = 0.93\times13500\text{ lb-moles NH}_3\text{ fed/day} = 12555\text{ lb-moles NH}_3/\text{day}$

Volumetric flow rate of effluent gas

$$\frac{P\dot{V}_\text{out}}{P\dot{V}_\text{in}} = \frac{\dot{n}_\text{out}RT}{\dot{n}_\text{in}RT} \Rightarrow \dot{V}_\text{out} = \dot{V}_\text{in}\frac{\dot{n}_\text{out}}{\dot{n}_\text{in}} = \frac{300\times10^6\text{ ft}^3}{\text{day}} \left| \frac{(1.13\times10^6+12555)\text{ lb-moles/day}}{1.13\times10^6\text{ lb-moles/day}} \right.$$

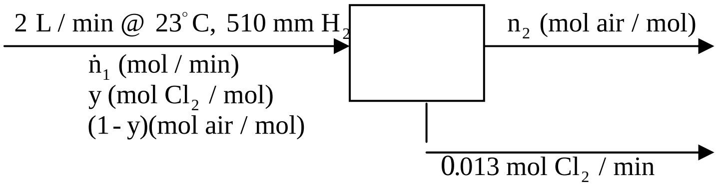
$$= \underline{\underline{303\times10^6\text{ ft}^3/\text{day}}}$$

$$\underline{\text{Partial pressure of NH}_3} = y_{\text{NH}_3}P = \frac{12555\text{ lb-moles NH}_3/\text{day}}{(1.129\times10^6+12555)\text{lb-moles/day}}\times 21.3\text{ psi}$$

$$= \underline{\underline{0.234\text{ psi}}}$$

5.42 <u>Basis: 2 liters fed / min</u>

$$\text{Cl ads.}=\frac{2.0\ \text{L soln}}{60\ \text{min}}\bigg|\frac{1130\ \text{g}}{\text{L}}\bigg|\frac{0.12\ \text{g NaOH}}{\text{g soln}}\bigg|\frac{1\ \text{mol}}{40.0\ \text{g}}\bigg|\frac{0.23\ \text{NaOH ads.}}{\text{mol NaOH}}\bigg|\frac{1\ \text{mol Cl}_2}{2\ \text{mol NaOH}}=0.013\ \frac{\text{mol}}{\text{min}}$$

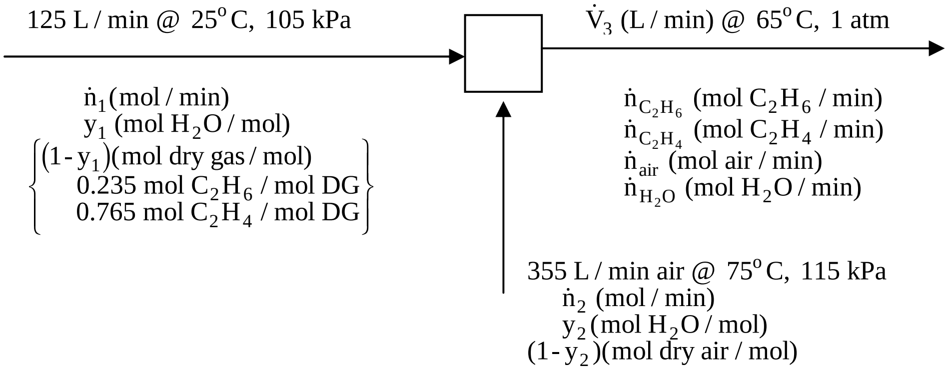


<u>Assume $P_{\text{atm}}=10.33\ \text{m H}_2\text{O}$</u> $\Rightarrow (P_{\text{abs}})_{\text{in}}=(10.33+0.510)\ \text{m H}_2\text{O}=10.84\ \text{m H}_2\text{O}$

$$\dot{n}_1=\frac{2\ \text{L}}{\text{min}}\bigg|\frac{273\text{K}}{296\text{K}}\bigg|\frac{10.84\ \text{m H}_2\text{O}}{10.33\ \text{m H}_2\text{O}}\bigg|\frac{1\ \text{mol}}{22.4\ \text{L(STP)}}=0.0864\ \text{mol/min}$$

<u>Cl balance</u>: $0.0864y=0.013\Rightarrow \underline{\underline{y=0.150\dfrac{\text{mol Cl}_2}{\text{mol}},\therefore\ \text{specification is wrong}}}$

5.43



a. <u>Hygrometer Calibration</u> $\ln y=bR+\ln a\quad (y=ae^{bR})$

$$b=\frac{\ln(y_1/y_2)}{R_2-R_1}=\frac{\ln(0.2/10^{-4})}{90-5}=0.08942$$

$$\ln a=\ln y_1-bR_1=\ln 10^{-4}-0.08942(5)\Rightarrow a=6.395\times10^{-5}\Rightarrow \underline{\underline{y=6.395\times10^{-5}e^{0.08942R}}}$$

b. $$\dot{n}_1=\frac{125\ \text{L}}{\text{min}}\bigg|\frac{273\text{K}}{298\text{K}}\bigg|\frac{105\ \text{kPa}}{101\ \text{kPa}}\bigg|\frac{1\ \text{mol}}{22.4\ \text{L (STP)}}=5.315\ \text{mol/min wet gas}$$

$$\dot{n}_2=\frac{355\ \text{L}}{\text{min}}\bigg|\frac{273\text{K}}{348\text{K}}\bigg|\frac{115\ \text{kPa}}{101\ \text{kPa}}\bigg|\frac{1\ \text{mol}}{22.4\ \text{L (STP)}}=14.156\ \text{mol/min wet air}$$

$$R_1=86.0\rightarrow y_1=0.140,\ R_2=12.8\rightarrow y_2=2.00\times10^{-4}\ \text{mol H}_2\text{O/mol}$$

5.43 (cont'd)

$$\text{C}_2\text{H}_6 \text{ balance: } \dot{n}_{\text{C}_2\text{H}_6} = (5.315 \text{ mol/min})\left((1-0.140)\frac{\text{mol DG}}{\text{mol}}\right)\left(0.235\frac{\text{mol C}_2\text{H}_6}{\text{mol DG}}\right)$$

$$= 1.07 \text{ mol C}_2\text{H}_6/\text{min}$$

$$\text{C}_2\text{H}_4 \text{ balance: } \dot{n}_{\text{C}_2\text{H}_4} = (5.315)(0.860)(0.765) = 3.50 \text{ mol C}_2\text{H}_4/\text{min}$$

$$\text{Dry air balance: } \dot{n}_{\text{air}} = (14.156)\left(1-2.00\times10^{-4}\right) = 14.15 \text{ mol DA/min}$$

$$\text{Water balance: } \dot{n}_{\text{H}_2\text{O}} = (5.315)(0.140) + (14.156)\left(1.00\times10^{-4}\right) = 0.746 \text{ mol H}_2\text{O/min}$$

$$\dot{n}_{\text{dry product gas}} = (1.07+3.50+14.15) \text{ mol/min} = 18.72 \text{ mol/min},$$

$$\dot{n}_{\text{total}} = (18.72+0.746) = 19.47 \text{ mol/min}$$

$$\dot{V}_3 = \begin{array}{c|c|c} 19.47 \text{ mol/min} & 22.4 \text{ L (STP)} & 338\text{K} \\ \hline & \text{mol} & 273\text{K} \end{array} = \underline{\underline{540 \text{ liters/min}}}$$

$$\text{Dry basis composition: } \left(\frac{1.07}{18.72}\right)\times100\% = \underline{\underline{5.7\%\ \text{C}_2\text{H}_6,\ 18.7\%\ \text{C}_2\text{H}_4,\ 75\% \text{ dry air}}}$$

c. $$p_{\text{H}_2\text{O}} = y_{\text{H}_2\text{O}_1}\cdot P = \frac{0.746 \text{ mol H}_2\text{O}}{19.47 \text{ mol}}\times 1 \text{ atm} = \underline{\underline{0.03832 \text{ atm}}}$$

$$y_{\text{H}_2\text{O}} = 0.03832 \Rightarrow R = \frac{1}{0.08942}\ln\left(\frac{0.03832}{6.395\times10^{-5}}\right) = \underline{\underline{71.5}}$$

5.44 $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$

$$\dot{n}_{\text{CO}_2} = \begin{array}{c|c|c} 1350 \text{ m}^3 & 273\text{K} & 1 \text{ kmol} \\ \hline \text{h} & 1273\text{K} & 22.4 \text{ m}^3\text{(STP)} \end{array} = 12.92 \text{ kmol CO}_2/\text{h}$$

$$\begin{array}{c|c|c|c} 12.92 \text{ kmol CO}_2 & 1 \text{ kmol CaCO}_3 & 100.09 \text{ kg CaCO}_3 & 1 \text{ kg limestone} \\ \hline \text{h} & 1 \text{ kmol CO}_2 & 1 \text{ kmol CaCO}_3 & 0.95 \text{ kg CaCO}_3 \end{array} = \underline{\underline{1362 \text{ kg limestone/h}}}$$

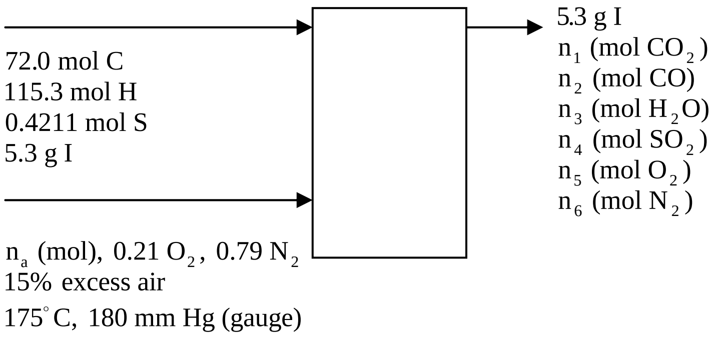
$$\begin{array}{c|c} 1362 \text{ kg limestone} & 0.17 \text{ kg clay} \\ \hline \text{h} & 0.83 \text{ kg limestone} \end{array} = \underline{\underline{279 \text{ kg clay/h}}}$$

Weight % Fe_2O_3

$$\frac{279\ \overset{\text{kg Fe}_2\text{O}_3/\text{kg clay}}{(0.07)}}{\underset{\text{kg limestone}}{1362} + \underset{\text{kg clay}}{279} - \underbrace{12.92(44.1)}_{\text{kg CO}_2 \text{ evolved}}}\times100\% = \underline{\underline{1.8\%\ \text{Fe}_2\text{O}_3}}$$

5.45

$$\underline{\text{Basis: } 1\text{ kg Oil}} \Rightarrow \begin{cases} 864.7\text{ g C }(1\text{ mol}/12.01\text{ g}) = 72.0\text{ mol C} \\ 116.5\text{ g H }(1\text{ mol}/1.01\text{ g}) = 115.3\text{ mol H} \\ 13.5\text{ g S }(1\text{ mol}/32.06\text{ g}) = 0.4211\text{ mol S} \\ 5.3\text{ g I} \end{cases}$$



$$C + O_2 \rightarrow CO_2$$

$$C + \frac{1}{2}O_2 \rightarrow CO$$

$$S + O_2 \rightarrow SO_2$$

$$2H + \frac{1}{2}O_2 \rightarrow H_2O$$

a. Theoretical O_2:

$$\frac{72.0\text{ mol C}}{}\left|\frac{1\text{ mol }O_2}{1\text{ mol C}}\right. + \frac{115.3\text{ mol H}}{}\left|\frac{0.25\text{ mol }O_2}{1\text{ mol H}}\right.$$

$$+\frac{0.4211\text{ mol S}}{}\left|\frac{1\text{ mol }O_2}{1\text{ mol S}}\right. = 101.2\text{ mol }O_2$$

$$\underline{\text{Air Fed}}: \frac{1.15\left(101.2\text{ mol }O_2\right)}{}\left|\frac{1\text{ mol Air}}{0.21\text{ mol }O_2}\right. = 554\text{ mol Air} = n_a$$

$$\frac{554\text{ mol Air}}{1\text{ kg oil}}\left|\frac{22.4\text{ liter}(\text{STP})}{\text{mol}}\right|\frac{1\text{ m}^3}{10^3\text{ liter}}\left|\frac{448\text{K}}{273\text{K}}\right|\frac{760\text{ mm Hg}}{940\text{ mm Hg}} = \underline{\underline{16.5\text{ m}^3\text{ air/kg oil}}}$$

b. $\underline{\text{S balance}}$: $n_4 = 0.4211\text{ mol }SO_2$

$\underline{\text{H balance}}$: $115.3 = 2n_3 \Rightarrow n_3 = 57.6\text{ mol }H_2O$

$\underline{\text{C balance}}$: $0.95(72.0) = n_1 \Rightarrow n_1 = 68.4\text{ mol }CO_2 \;\Rightarrow 0.05(72.0) = n_2 = 3.6\text{ mol CO}$

$\underline{N_2\text{ balance}}$: $0.79(554) = n_6 \Rightarrow n_6 = 437.7\text{ mol }N_2$

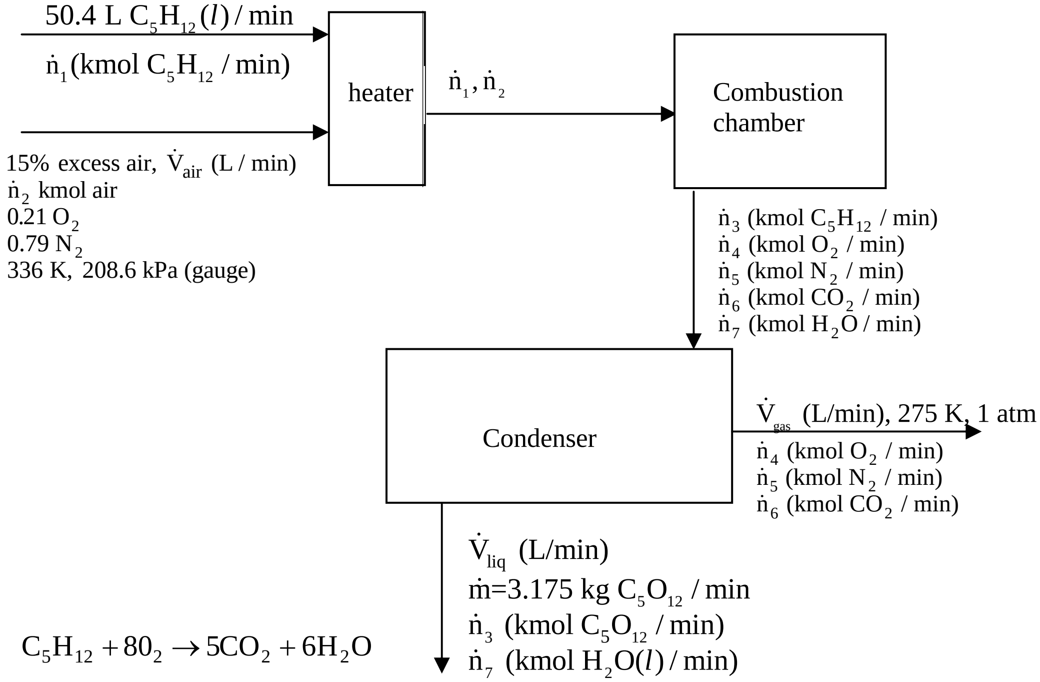
$\underline{\text{O balance}}$: $0.21(554)2 = 57.6 + 3.6 + 2(68.4) + 2(0.4211) + 2n_5 \Rightarrow n_5 = 16.9\text{ mol }O_2$

$\underline{\text{Total moles (excluding inerts)}}$ wet: 585 mols dry: 527 mols

$$\underline{\text{dry basis:}}\text{-}\frac{3.6\text{ mol CO}}{527\text{ mol}} = \underline{\underline{6.8\times10^{-3}\ \frac{\text{mol CO}}{\text{mol}}}}\ ,\ \frac{0.4211\text{ mol }SO_2}{527\text{ mol}} = \underline{\underline{7.2\times10^{-4}\ \frac{\text{mol }SO_2}{\text{mol}}}}$$

$$\underline{\text{wet basis:}}\ \frac{3.6\text{ mol CO}}{585\text{ mol}}\times10^6 = \underline{\underline{6150\text{ ppm CO}}}\ ,\ \frac{0.4211\text{ mol }SO_2}{585\text{ mol}}\times10^6 = \underline{\underline{720\text{ ppm }SO_2}}$$

5.46 Basis: 50.4 liters $C_5H_{12}\,(l)/\text{min}$



$$C_5H_{12} + 80_2 \rightarrow 5CO_2 + 6H_2O$$

a.
$$\dot{n}_1 = \frac{50.4\text{ L}}{\text{min}}\bigg|\frac{0.630\text{ kg}}{\text{L}}\bigg|\frac{1\text{ kmol}}{72.15\text{ kg}} = 0.440\ \text{kmol/min}$$

$$\dot{n}_3 = \frac{3.175\text{ kg}}{\text{min}}\bigg|\frac{1\text{ kmol}}{72.15\text{ kg}} = 0.044\text{ kmol / min}$$

$$\text{frac. convert} = \frac{0.440 - 0.044\text{ kmol}}{0.440}\times 100 = \underline{\underline{90\%\ C_5H_{12}\text{ converted}}}$$

$$\dot{n}_2 = \frac{0.440\text{ kmol } C_5H_{12}}{\text{min}}\bigg|\frac{1.15(8\text{ kmol } O_2)}{\text{kmol } C_5H_{12}}\bigg|\frac{1\text{ mol air}}{0.21\text{ mol } O_2} = 19.28\ \text{kmol air/min}$$

$$\dot{V}_{air} = \frac{19.28\text{ kmol}}{\text{min}}\bigg|\frac{22.4\text{ L(STP)}}{\text{mol}}\bigg|\frac{336\text{K}}{273\text{K}}\bigg|\frac{101\text{ kPa}}{309.6\text{ kPa}}\bigg|\frac{1000\text{ mol}}{\text{kmol}} = \underline{\underline{173000\ \text{L/min}}}$$

$$\dot{n}_4 = [(0.21)(19.28) - (0.90)(0.440)(8)]\frac{\text{kmol } O_2}{\text{min}} = \underline{\underline{0.882\text{ kmol } O_2}}/\text{min}$$

$$\dot{n}_5 = \frac{19.28\text{ kmol air}}{\text{min}}\bigg|\frac{0.79\text{ kmol } N_2}{\text{kmol air}} = 15.23\text{ kmol } N_2/\text{min}$$

$$\dot{n}_6 = \frac{0.90(0.440\text{ kmol } C_5H_{12})}{\text{min}}\bigg|\frac{5\text{ kmol } CO_2}{\text{kmol } C_5H_{12}} = 1.98\text{ kmol } CO_2\text{ / min}$$

$$\dot{V}_{gas} = \frac{0.882\text{+}15.23\text{+}1.98\text{ kmol}}{\text{min}}\bigg|\frac{22.4\text{ L(STP)}}{\text{mol}}\bigg|\frac{275\text{ K}}{273\text{ K}}\bigg|\frac{1000\text{ mol}}{\text{kmol}} = \underline{\underline{4.08\times 10^5\ \text{L/min}}}$$

5.46 (cont'd)

$$\dot{n}_7 = \frac{0.9(0.440 \text{ kmol } C_5H_{12})}{\text{min}}\left|\frac{6 \text{ kmol } H_2O}{\text{kmol } C_5H_{12}}\right. = 2.38 \text{ kmol } H_2O(l) / \text{min}$$

<u>Condensate:</u>

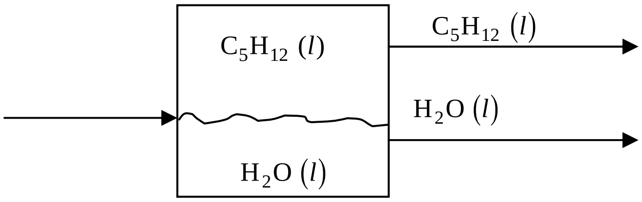
$$\dot{V}_{C_5H_{12}} = \frac{0.044 \text{ kmol}}{\text{min}}\left|\frac{72.15 \text{ kg}}{\text{kmol}}\right|\frac{\text{L}}{0.630 \text{ kg}} = 5.04 \text{ L/min}$$

$$\dot{V}_{H_2O} = \frac{2.38 \text{ kmol}}{\text{min}}\left|\frac{18.02 \text{ kg}}{\text{kmol}}\right|\frac{\text{L}}{1 \text{ kg}} = 42.89 \text{ L/min}$$

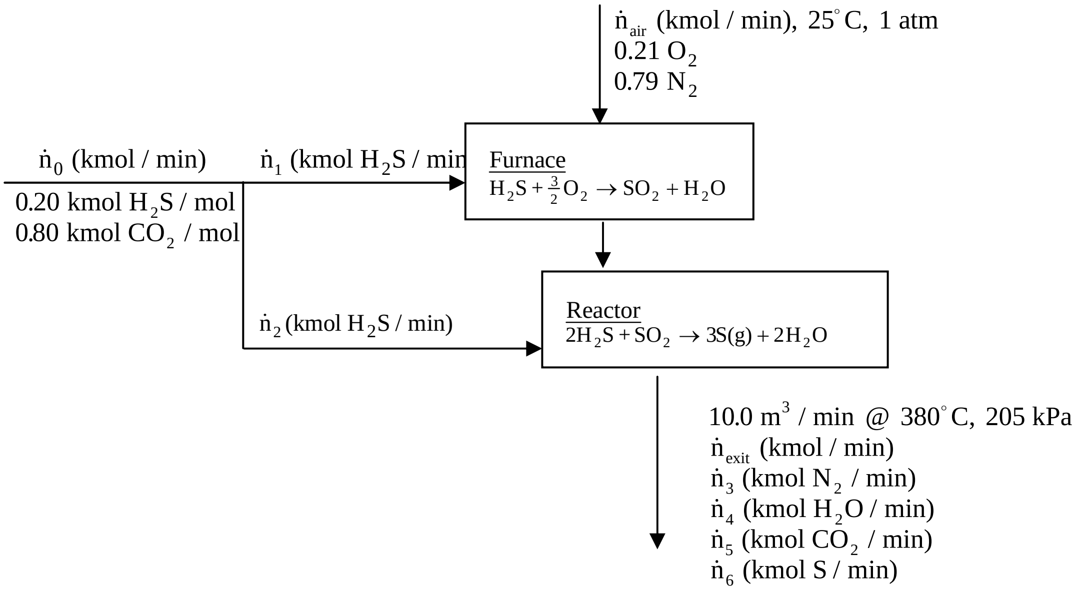
Assume volume additivity (liquids are immiscible)

$$\dot{V}_{\text{liq}} = 5.04 + 42.89 = \underline{\underline{47.9 \text{ L/min}}}$$

b.



5.47



$$\dot{n}_{\text{exit}} = \frac{P\dot{V}}{RT} = \frac{205 \text{ kPa}}{8.314 \frac{\text{m}^3\cdot\text{kPa}}{\text{kmol}\cdot\text{K}}}\left|\frac{10.0 \text{ m}^3/\text{min}}{653 \text{ K}}\right. = 0.377 \text{ kmol/min}$$

$$\dot{n}_1 = (0.20)\dot{n}_0 / 3 = 0.0667\dot{n}_0; \quad \dot{n}_2 = 2\dot{n}_1 = 0.133\dot{n}_0$$

5.47 (cont'd)

Air feed to furnace: $$\dot{n}_{\text{air}} = \frac{0.0667\dot{n}_0\ (\text{kmol H}_2\text{S fed})}{(\text{min})}\bigg|\frac{1.5\ \text{kmol O}_2}{1\ \text{kmol H}_2\text{S}}\bigg|\frac{1\ \text{kmol air}}{0.21\ \text{kmol O}_2}$$

$$= 0.4764\dot{n}_0\ \text{kmol air / min}$$

Overall N_2 balance: $$\dot{n}_3 = \frac{0.4764\dot{n}_0\ (\text{kmol air})}{(\text{min})}\bigg|\frac{0.79\ \text{kmol N}_2}{\text{min}} = 0.3764\dot{n}_0(\text{kmol N}_2\ /\ \text{min})$$

Overall S balance: $$\dot{n}_6 = \frac{0.200\dot{n}_0\ (\text{kmol H}_2\text{S})}{(\text{min})}\bigg|\frac{1\ \text{kmol S}}{1\ \text{kmol H}_2\text{S}} = 0.200\dot{n}_0\ (\text{kmol S / min})$$

Overall CO_2 balance: $\dot{n}_5 = 0.800\dot{n}_0\ (\text{kmol CO}_2\ /\ \text{min})$

Overall H balance: $$\frac{0.200\dot{n}_0\ (\text{kmol H}_2\text{S})}{(\text{min})}\bigg|\frac{2\ \text{kmol H}}{1\ \text{kmol H}_2\text{S}} = \frac{\dot{n}_4\ \text{kmol H}_2\text{O}}{\text{min}}\bigg|\frac{2\ \text{kmol H}}{1\ \text{kmol H}_2\text{O}}$$

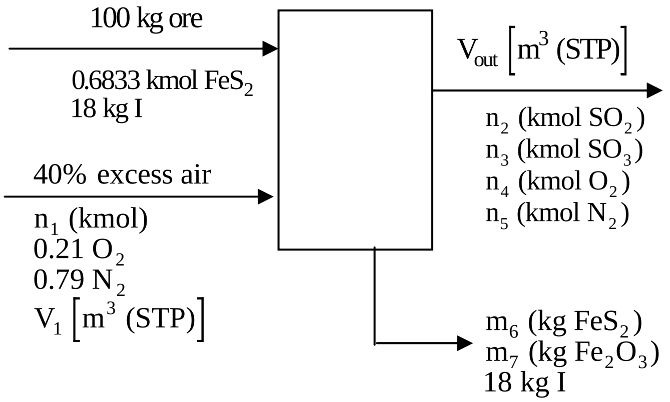
$$\Rightarrow \dot{n}_4 = 0.200\dot{n}_0\ (\text{kmol H}_2\text{O / min})$$

$$\dot{n}_{\text{exit}} = \dot{n}_0(0.376 + 0.200 + 0.200 + 0.800) = 0.377\ \text{kmol / min} \Rightarrow \dot{n}_0 = \underline{\underline{0.24\ \text{kmol / min}}}$$

$$\dot{n}_{\text{air}} = 0.4764(0.24\ \text{kmol air / min}) = \underline{\underline{0.114\ \text{kmol air / min}}}$$

5.48 Basis: 100 kg ore fed $\Rightarrow$ 82.0 kg $FeS_2(s)$, 18.0 kg I.

$$n_{\text{FeS}_2}\ \text{fed} = (82.0\ \text{kg FeS}_2)(1\ \text{kmol}/120.0\ \text{kg}) = 0.6833\ \text{kmol FeS}_2$$



$$2\text{FeS}_{2(s)} + \tfrac{11}{2}\text{O}_{2(g)} \rightarrow \text{Fe}_2\text{O}_{3(s)} + 4\text{SO}_{2(g)}$$

$$2\text{FeS}_{2(s)} + \tfrac{15}{2}\text{O}_{2(g)} \rightarrow \text{Fe}_2\text{O}_{3(s)} + 4\text{SO}_{3(g)}$$

a. $$n_1 = \frac{0.6833\ \text{kmol FeS}_2}{}\bigg|\frac{7.5\ \text{kmol O}_2}{2\ \text{kmol FeS}_2}\bigg|\frac{1\ \text{kmol air req'd}}{0.21\ \text{kmol O}_2}\bigg|\frac{1.40\ \text{kmol air fed}}{\text{kmol air req'd}} = 17.08\ \text{kmol air}$$

$$V_1 = (17.08\ \text{kmol})(22.4\ \text{SCM / kmol}) = \underline{\underline{382\ \text{SCM}/100\ \text{kg ore}}}$$

$$n_2 = \frac{(0.85)(0.40)0.6833\ \text{kmol FeS}_2}{}\bigg|\frac{4\ \text{kmol SO}_2}{2\ \text{kmol FeS}_2} = 0.4646\ \text{kmol SO}_2$$

5.48 (cont'd)

$$n_3 = \frac{(0.85)(0.60)0.6833 \text{ kmol FeS}_2}{} \left| \frac{4 \text{ kmol SO}_2}{2 \text{ kmol FeS}_2} \right. = 0.6970 \text{ kmol SO}_3$$

$$n_4 = (0.21 \times 17.08) \text{kmol O}_2 \text{ fed} - \frac{.4646 \text{ kmol SO}_2}{} \left| \frac{5.5 \text{ kmol O}_2}{4 \text{ kmol SO}_2} \right.$$

$$- \frac{.697 \text{ kmol SO}_3}{} \left| \frac{7.5 \text{ kmol O}_2}{4 \text{ kmol SO}_3} \right. = 1.641 \text{ kmol O}_2$$

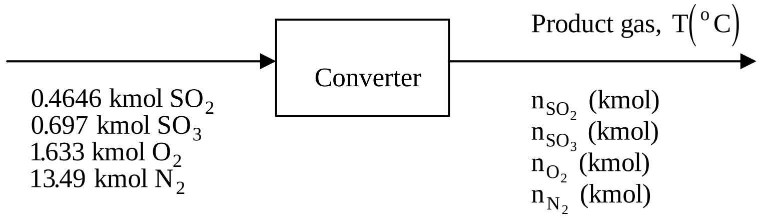
$$n_5 = (0.79 \times 17.08) \text{ kmol N}_2 = 13.49 \text{ kmol N}_2$$

$$V_{out} = \left[(0.4646 + 0.6970 + 1.641 + 13.49) \text{ kmol} \right] \left[22.4 \text{ SCM (STP)/kmol} \right]$$

$$= \underline{\underline{365 \text{ SCM/100 kg ore fed}}}$$

$$y_{SO_2} = \frac{0.4646 \text{ kmol SO}_2}{16.285 \text{ kmol}} \times 100\% = \underline{\underline{2.9\%}}; \quad y_{SO_3} = \underline{\underline{4.3\%}}; \quad y_{O_2} = \underline{\underline{10.1\%}}; \quad y_{N_2} = \underline{\underline{82.8\%}}$$

b.



Let ξ (kmol) = extent of reaction

$$\left.\begin{aligned} n_{SO_2} &= 0.4646 - \xi \\ n_{SO_3} &= 0.697 + \xi \\ n_{O_2} &= 1.641 - \tfrac{1}{2}\xi \\ n_{N_2} &= 13.49 \\ \hline n &= 16.29 - \tfrac{1}{2}\xi \end{aligned}\right\} \Rightarrow \begin{aligned} y_{SO_2} &= \frac{0.4646 - \xi}{16.29 - \frac{1}{2}\xi}, \quad y_{SO_3} = \frac{0.697 + \xi}{16.29 - \frac{1}{2}\xi} \\ y_{O_2} &= \frac{1.641 - \frac{1}{2}\xi}{16.29 - \frac{1}{2}\xi}, \quad y_{N_2} = \frac{13.49}{16.29 - \frac{1}{2}\xi} \end{aligned}$$

$$K_p(T) = \frac{P \cdot y_{SO_3}}{P \cdot y_{SO_2} (P \cdot y_{O_2})^{\frac{1}{2}}} \Rightarrow \frac{(0.697 + \xi)(16.29 - \frac{1}{2}\xi)^{\frac{1}{2}}}{(0.4646 - \xi)(1.641 - \frac{1}{2}\xi)^{\frac{1}{2}}} \cdot P^{-\frac{1}{2}} = K_p(T)$$

$$\text{P=1 atm, T=600°C}, \; K_p = 9.53 \text{ atm}^{-\frac{1}{2}} \Rightarrow \xi = 0.1707 \text{ kmol}$$

$$\Rightarrow n_{SO_2} = 0.2939 \text{ kmol} \Rightarrow f_{SO_2} = \frac{(0.4646 - 0.2939) \text{ kmol SO}_2 \text{ reacted}}{0.4646 \text{ kmol SO}_2 \text{ fed}} = \underline{\underline{0.367}}$$

$$\text{P=1 atm, T=400°C}, \; K_p = 397 \text{ atm}^{-\frac{1}{2}} \Rightarrow \xi = 0.4548 \text{ kmol}$$

$$\Rightarrow n_{SO_2} = 0.0098 \text{ kmol} \Rightarrow f_{SO_2} = \underline{\underline{0.979}}$$

The gases are initially heated in order to get the reaction going at a reasonable rate. Once the reaction approaches equilibrium the gases are cooled to produce a higher equilibrium conversion of SO_2.

5.48 (cont'd)

c. SO$_3$ leaving converter: $(0.6970 + 0.4687)\text{ kmol} = 1.156\text{ kmol}$

$$\Rightarrow \frac{1.156\text{ kmol SO}_3}{\text{min}}\left|\frac{1\text{ kmol H}_2\text{SO}_4}{1\text{ kmol SO}_3}\right|\frac{98\text{ kg H}_2\text{SO}_4}{\text{kmol}} = 113.3\text{ kg H}_2\text{SO}_4$$

Sulfur in ore: $\dfrac{0.683\text{ kmol FeS}_2}{}\left|\dfrac{2\text{ kmol S}}{\text{kmol FeS}_2}\right|\dfrac{32.1\text{ kg S}}{\text{kmol}} = 43.8\text{ kg S}$

$$\frac{113.3\text{ kg H}_2\text{SO}_4}{43.8\text{ kg S}} = \underline{\underline{2.59\ \frac{\text{kg H}_2\text{SO}_4}{\text{kg S}}}}$$

$$100\%\text{ conv. of S:} \frac{0.683\text{ kmol FeS}_2}{}\left|\frac{2\text{ kmol S}}{\text{kmol FeS}_2}\right|\frac{1\text{ kmol H}_2\text{SO}_4}{1\text{ kmol S}}\left|\frac{98\text{ kg}}{\text{kmol}}\right. = 133.9\text{ kg H}_2\text{SO}_4$$

$$\Rightarrow \frac{133.9\text{ kg H}_2\text{SO}_4}{43.8\text{ kg S}} = \underline{\underline{3.06\frac{\text{kg H}_2\text{SO}_4}{\text{kg S}}}}$$

The sulfur is not completely converted to H_2SO_4 because of (i) incomplete oxidation of FeS_2 in the roasting furnace, (ii) incomplete conversion of SO_2 to SO_3 in the converter.

5.49 $N_2O_4 \Leftrightarrow 2NO_2$

a. $$n_0 = \frac{(P_{\text{gauge}} + 1.00)V}{RT_0} = \frac{(2.00\text{ atm})(2.00\text{ L})}{(473\text{K})(0.08206\text{ L}\cdot\text{atm/mol-K})} = \underline{\underline{0.103\text{ mol NO}_2}}$$

b. $n_1 = \text{mol NO}_2,\ n_2 = \text{mol N}_2\text{O}_4$

$$p_{NO_2} = y_{NO_2}P = \left(\frac{n_1}{n_1+n_2}\right)P,\ p_{N_2O_4} = \left(\frac{n_2}{n_1+n_2}\right)P \Rightarrow K_p = \frac{n_1^2}{n_2(n_1+n_2)}P$$

Ideal gas equation of state $\Rightarrow PV = (n_1 + n_2)RT \Rightarrow n_1 + n_2 = PV/RT \quad (1)$

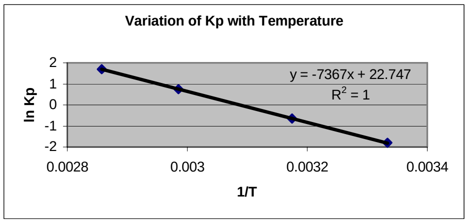
Stoichiometric equation $\Rightarrow$ each mole of N_2O_4 present at equilibrium represents a loss of two moles of NO_2 from that initially present $\Rightarrow n_1 + 2n_2 = 0.103 \quad (2)$

Solve (1) and (2) $\Rightarrow$ $n_1 = 2(PV/RT) - 0.103 \quad (3),\quad n_2 = 0.103 - (PV/RT) \quad (4)$

Substitute (3) and (4) in the expression for K_p, and replace P with $P_{\text{gauge}} + 1$

$$\underline{\underline{K_p = \frac{(2n_t - 0.103)^2}{n_t(0.103 - n_t)}(P_{\text{gauge}} + 1)}}\ \text{ where } n_t = \frac{(P_{\text{gauge}} + 1)V}{RT} \underset{V=2\text{ L}}{\Rightarrow} \underline{\underline{n_t = \frac{24.37(P_g + 1)}{T}}}$$

T(K)	Pgauge(atm)	nt	Kp(atm)	(1/T)	ln(Kp)
350	0.272	0.088568	5.46915	0.002857	1.699123
335	0.111	0.080821	2.131425	0.002985	0.756791
315	-0.097	0.069861	0.525954	0.003175	-0.64254
300	-0.224	0.063037	0.164006	0.003333	-1.80785

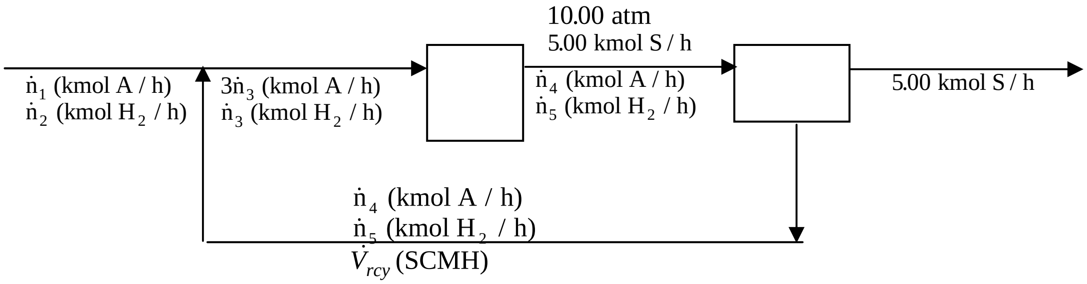


5.49 (cont'd)

c. A semilog plot of K_p vs. $\frac{1}{T}$ is a straight line. Fitting the line to the exponential law yields

$$\ln K_p = -\frac{7367}{T} + 22.747 \Rightarrow K_p = 7.567\times10^9 \exp\left(\frac{-7367}{T}\right) \Rightarrow \begin{array}{l} a = 7.567\times10^9 \text{ atm} \\ \underline{\underline{b = 7367\text{K}}} \end{array}$$

5.50



$$A + H_2 \rightleftarrows S$$

$$\underline{\text{Overall A balance}}:\ n_1 = \frac{5.00 \text{ kmol S}}{\text{h}}\left|\frac{1 \text{ kmol A react}}{1 \text{ kmol S form}}\right. = \underline{5.00 \text{ kmol A / h}}$$

$$\underline{\text{Overall } H_2 \text{ balance}}:\ n_2 = \frac{5.00 \text{ kmol S}}{\text{h}}\left|\frac{1 \text{ kmol } H_2 \text{ react}}{1 \text{ kmol S form}}\right. = \underline{5.00 \text{ kmol } H_2 \text{ / h}}$$

$\underline{\text{Extent of reaction equations}}$: $\dot{n}_i = \dot{n}_{i0} + \nu_i\dot{\xi}$

$A + H_2 \leftrightarrow S$

A: $\dot{n}_4 = 3\dot{n}_3 - \dot{\xi}$

H_2: $\dot{n}_5 = \dot{n}_3 - \dot{\xi}$

$$\text{S:}\quad 5.00 = \dot{\xi} \text{=====>} \left.\begin{array}{l} \dot{n}_4 = 3\dot{n}_3 - 5.00 \\ \dot{n}_5 = \dot{n}_3 - 5.00 \\ \underline{\dot{n}_S = 5.00} \\ \dot{n}_{tot} = 4\dot{n}_3 - 5.00 \end{array}\right\} \Rightarrow p_A = y_A P = \frac{\dot{n}_4}{\dot{n}_{tot}} P = \frac{3\dot{n}_3 - 5.00}{4\dot{n}_3 - 5.00} 10.0$$

$$p_{H_2} = y_{H_2} P = \frac{\dot{n}_5}{\dot{n}_{tot}} P = \frac{\dot{n}_3 - 5.00}{4\dot{n}_3 - 5.00} 10.0$$

$$p_S = y_S P = \frac{5.00}{4\dot{n}_3 - 5.00} 10.0$$

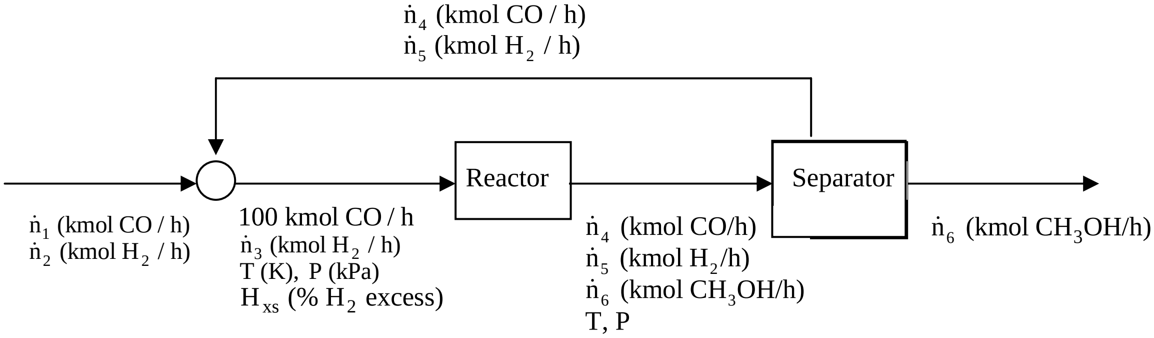
$$K_p = \frac{p_S}{p_A p_{H_2}} = \frac{5.00(4\dot{n}_3 - 5.00)}{10.0(3\dot{n}_3 - 5.00)(\dot{n}_3 - 5.00)} = 0.100 \Rightarrow \dot{n}_3 = 11.94 \text{ kmol } H_2 \text{ / h}$$

$\dot{n}_4 = 3(11.94) - 5.00 = 30.82$ kmol A / h

$\dot{n}_5 = 11.94 - 5.00 = 6.94$ kmol H_2 / h

$$\dot{V}_{rcy} = [(30.82 + 6.94) \text{ kmol / h}](22.4 \text{ m}^3\text{(STP) / kmol}) = \underline{\underline{846 \text{ SCMH}}}$$

5.51



a. Balances on reactor ⇒ 4 equations in $\dot{n}_3$, $\dot{n}_4$, $\dot{n}_5$, and $\dot{n}_6$.

5.0% XS H_2: $\dot{n}_3 = \dfrac{100 \text{ kmol CO fed}}{\text{h}} \left| \dfrac{2 \text{ kmol } H_2 \text{ reqd}}{1 \text{ kmol CO fed}} \right| \dfrac{1.05 \text{ kmol } H_2 \text{ fed}}{1 \text{ kmol } H_2 \text{ reqd}} = 210 \ \dfrac{\text{kmol } H_2}{\text{h}}$

C balance: $\dfrac{100 \text{ kmol CO}}{\text{h}} \left| \dfrac{1 \text{ kmol C}}{1 \text{ kmol CO}} \right. = \dot{n}_4(1) + \dot{n}_6(1) \Rightarrow 100 = \dot{n}_4 + \dot{n}_6$ (1)

H balance: $210(2) = \dot{n}_5(2) + \dot{n}_6(4) \Rightarrow 210 = \dot{n}_5 + 2\dot{n}_6$ (2)

(O balance: $100 = \dot{n}_4 + \dot{n}_6 \Rightarrow$ identical to C balance ⇒ not independent)

$(1) \Rightarrow \dot{n}_4 = 100 - \dot{n}_6$, $(2) \Rightarrow \dot{n}_5 = 210 - 2\dot{n}_6$

$\dot{n}_{tot} = \dot{n}_4 + \dot{n}_5 + \dot{n}_6 = (100 - \dot{n}_6) + (210 - 2\dot{n}_6) + \dot{n}_6 = 310 - 2\dot{n}_6$

$$K_p(T{=}500\text{K}) = 1.390 \times 10^{-4} \exp\begin{pmatrix} 21.225 + \dfrac{9143.6}{500 \text{ K}} - 7.492 \ln(500\text{K}) \\ +4.076 \times 10^{-3}(500\text{K}) - 1.161 \times 10^{-8}(500\text{K})^2 \end{pmatrix} = 9.11 \times 10^{-7} \text{ kPa}^{-2}$$

$$K_p = \frac{y_M P}{y_{CO} P (y_{H_2} P)^2} \Rightarrow K_p P^2 = \frac{y_M}{y_{CO} (y_{H_2})^2} \overset{(1)-(3)}{=\!=\!=\!=\!>} \frac{\dfrac{\dot{n}_6}{(310 - 2\dot{n}_6)}}{\dfrac{(100 - \dot{n}_6)}{(310 - 2\dot{n}_6)} \dfrac{(210 - 2\dot{n}_6)^2}{(310 - 2\dot{n}_6)^2}}$$

$$K_p P^2 = 9.11 \times 10^{-7} \text{ kPa}^{-2} (5000 \text{ kPa})^2 = 22.775 = \frac{\dot{n}_6 (310 - 2\dot{n}_6)^2}{(100 - \dot{n}_6)(210 - 2\dot{n}_6)^2}$$

Solving for $\dot{n}_6 \Rightarrow \dot{n}_6 = \underline{\underline{75.7 \text{ kmol } CH_3OH\text{/h}}}$, $\dot{n}_4 = 100 - \dot{n}_6 = \underline{\underline{24.3 \text{ kmol CO/h}}}$

$\dot{n}_5 = 210 - 2\dot{n}_6 = \underline{\underline{58.6 \text{ kmol } H_2 \text{ / h}}}$

Overall C balance: $\dot{n}_1(1) = \dot{n}_6(1) \Rightarrow \dot{n}_1 = \underline{\underline{75.7 \text{ kmol CO/h}}}$

Overall H balance: $\dot{n}_2(2) = \dot{n}_6(4) \Rightarrow \dot{n}_2 = \underline{\underline{151 \text{ kmol } H_2\text{/h}}}$

$\dot{V}_{rec} = (\dot{n}_4 + \dot{n}_5) \dfrac{22.4 \text{ m}^3\text{(STP)}}{\text{kmol}} = \underline{\underline{1860 \text{ SCMH}}}$

5.51 (cont'd)

b.

P(kPa)	T(K)	Hxs(%)	Kp(T)E8	KpP^2	n3 (kmol H2/h)	n4 (kmol CO/h)	n5 (kmol H2/h)
1000	500	5	9.1E+01	0.91	210	74.45	158.90
5000	500	5	9.1E+01	22.78	210	91.00	192.00
10000	500	5	9.1E+01	91.11	210	13.28	36.56
5000	400	5	3.1E+04	7849.77	210	1.07	12.15
5000	**500**	**5**	**9.1E+01**	**22.78**	**210**	**24.32**	**58.64**
5000	600	5	1.6E+00	0.41	210	85.42	180.84
5000	500	0	9.1E+01	22.78	200	26.65	53.30
5000	500	5	9.1E+01	22.78	210	24.32	58.64
5000	500	10	9.1E+01	22.78	220	22.23	64.45

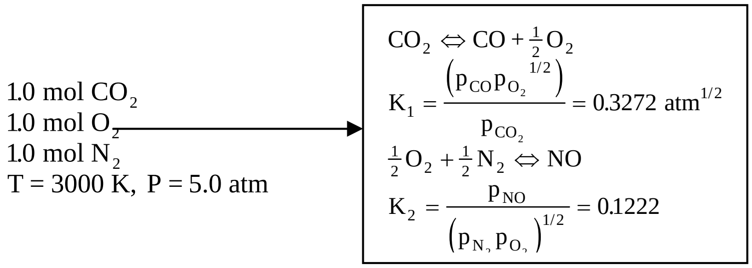
n6 (kmol M/h)	ntot (kmol/h)	KpcE8	KpP^2-KpcP^2	n1 (kmol CO/h)	n2 (kmol H2/h)	Vrec (SCMH)
25.55	258.90	9.1E-01	1.3E-05	25.55	51.10	5227
9.00	292.00	2.3E-01	2.3E+01	9.00	18.00	6339
86.72	136.56	9.1E+01	4.9E-03	86.72	173.44	1116
98.93	112.15	7.8E+03	3.2E-08	98.93	197.85	296
75.68	**158.64**	**2.3E+01**	**3.4E-03**	**75.68**	**151.36**	**1858**
14.58	280.84	4.1E-01	-2.9E-04	14.58	29.16	5964
73.35	153.30	2.3E+01	9.8E-03	73.35	146.70	1791
75.68	158.64	2.3E+01	3.4E-03	75.68	151.36	1858
77.77	164.45	2.3E+01	-3.1E-03	77.77	155.55	1942

c. Increase yield by raising pressure, lowering temperature, increasing H_{xs}. Increasing the pressure raises costs because more compression is needed.

d. If the temperature is too low, a low reaction rate may keep the reaction from reaching equilibrium in a reasonable time period.

e. Assumed that reaction reached equilibrium, ideal gas behavior, complete condensation of methanol, not steady-state measurement errors.

5.52



1.0 mol CO_2
1.0 mol O_2
1.0 mol N_2
T = 3000 K, P = 5.0 atm

$CO_2 \Leftrightarrow CO + \frac{1}{2}O_2$

$$K_1 = \frac{\left(p_{CO}p_{O_2}{}^{1/2}\right)}{p_{CO_2}} = 0.3272\ \text{atm}^{1/2}$$

$\frac{1}{2}O_2 + \frac{1}{2}N_2 \Leftrightarrow NO$

$$K_2 = \frac{p_{NO}}{\left(p_{N_2}p_{O_2}\right)^{1/2}} = 0.1222$$

$A \Leftrightarrow B + \dfrac{1}{2}C$ $\quad A - CO_2,\ B - CO,\ C - O_2,\ D - N_2,\ E - NO$ $\quad \xi_1$ - extent of rxn 1

$\dfrac{1}{2}C + \dfrac{1}{2}D = E$ $\quad n_{A0} = n_{C0} = n_{D0} = 1,\ n_{B0} = n_{E0} = 0$ $\quad \xi_2$ - extent of rxn 2

5.52 (cont'd)

$$\left.\begin{aligned}
n_A &= 1-\xi_1\\
n_B &= \xi_1\\
n_C &= 1+\frac{1}{2}\xi_1-\frac{1}{2}\xi_2\\
n_D &= 1-\frac{1}{2}\xi_2\\
\underline{n_E} &\underline{= \xi_2}\\
n_{tot} &= 3+\frac{1}{2}\xi_1=\frac{6+\xi_1}{2}
\end{aligned}\right\}
\begin{aligned}
y_A &= n_A/n_{tot} = 2(1-\xi_1)/(6+\xi_1)\\
y_B &= 2\xi_1/(6+\xi_1)\\
y_C &= (2+\xi_1-\xi_2)/(6+\xi_1)\\
y_D &= (2-\xi_2)/(6+\xi_1)\\
y_E &= 2\xi_2/(6+\xi_1)
\end{aligned}
\qquad p_i = y_i P$$

$$K_1=\frac{p_{CO}p_{O_2}^{1/2}}{p_{CO_2}}=\frac{y_B y_C^{1/2}}{y_A}p^{(1+½-1)}=\frac{2\xi_1(2+\xi_1-\xi_2)^{1/2}}{2(1-\xi_1)(6+\xi_1)^{1/2}}(5)^{1/2}=0.3272$$

$$\Rightarrow 0.3272(1-\xi_1)(6+\xi_1)^{1/2}=2.236\xi_1(2+\xi_1-\xi_2)^{1/2} \qquad (1)$$

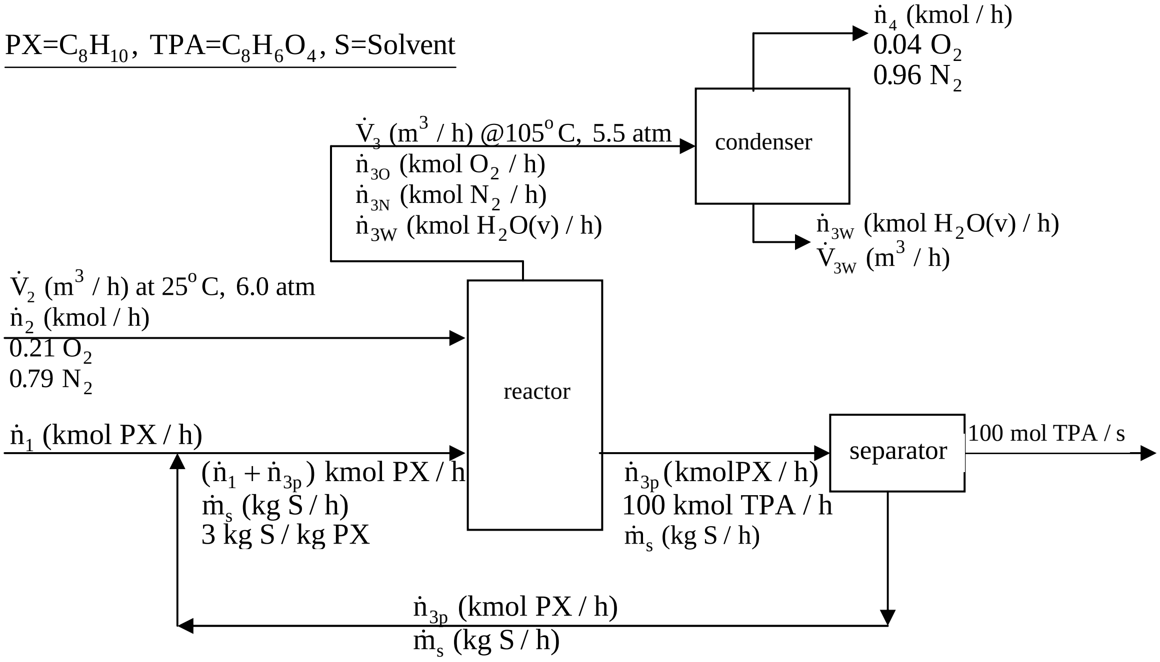
$$K_2=\frac{p_{NO}}{\left(p_{O_2}p_{N_2}\right)^{1/2}}=\frac{y_E}{y_C^{1/2}y_D^{1/2}}p^{1-1/2-1/2}=\frac{2\xi_2}{(2+\xi_1-\xi_2)^{1/2}(2-\xi_2)^{1/2}}=0.1222$$

$$\Rightarrow 0.1222(2+\xi_1-\xi_2)^{1/2}(2-\xi_2)^{1/2}=2\xi_2 \qquad (2)$$

Solve (1) and (2) simultaneously with E-Z Solve $\Rightarrow \xi_1 = 0.20167,\ \xi_2 = 0.12081,$

$$\begin{aligned}
y_A &= 2(1-\xi_1)/(6+\xi_1)=0.2574\text{ mol CO}_2/\text{mol} &\quad y_D &= 0.3030\text{ mol N}_2/\text{mol}\\
y_B &= 0.0650\text{ mol CO/mol} & y_E &= 0.0390\text{ mol NO/mol}\\
y_C &= 0.3355\text{ mol O}_2/\text{mol}
\end{aligned}$$

5.53 a. $PX=C_8H_{10}$, $TPA=C_8H_6O_4$, S=Solvent



5.53 (cont'd)

b. Overall C balance:

$$\dot{n}_1\left(\frac{\text{kmol PX}}{\text{h}}\right)\frac{8\text{ kmol C}}{\text{kmol PX}}=\frac{100\text{ kmol TPA}}{\text{h}}\bigg|\frac{8\text{ kmol C}}{\text{kmol TPA}}\Rightarrow \dot{n}_1=\underline{\underline{100\text{ kmol PX / h}}}$$

c. $$\underline{\text{O}_2\text{ consumed}}=\frac{100\text{ kmol TPA}}{\text{h}}\bigg|\frac{3\text{ kmol O}_2}{1\text{ kmol TPA}}=300\text{ kmol O}_2\text{/h}$$

$$\left.\begin{array}{l}\underline{\text{Overall O}_2\text{ balance:}}\;\;0.21\dot{n}_2=300\,\dfrac{\text{kmol O}_2}{\text{h}}+0.04\dot{n}_4\\ \underline{\text{Overall N}_2\text{ balance:}}\;\;0.79\dot{n}_2=0.96\dot{n}_4\end{array}\right\}\Rightarrow\quad\begin{array}{l}\dot{n}_2=1694\text{ kmol air/h}\\ \dot{n}_4=1394\text{ kmol/h}\end{array}$$

$$\underline{\text{Overall H}_2\text{O balance:}}\;\;\dot{n}_{3W}=\frac{100\text{ kmol TPA}}{\text{h}}\bigg|\frac{2\text{ kmol H}_2\text{O}}{1\text{ kmol TPA}}=200\text{ kmol H}_2\text{O / h}$$

$$\dot{V}_2=\frac{\dot{n}_2RT}{P}=\frac{1694\text{ kmol}}{\text{h}}\bigg|\frac{0.08206\text{ m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\bigg|\frac{298\text{ K}}{6.0\text{ atm}}=\underline{\underline{6.90\times10^3\text{ m}^3\text{ air/h}}}$$

$$\dot{V}_3=\frac{\left(\dot{n}_{3W}+\dot{n}_4\right)RT}{P}=\frac{\left(200+1394\right)\text{ kmol}}{\text{h}}\bigg|\frac{0.08206\text{ m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\bigg|\frac{378\text{ K}}{5.5\text{ atm}}=\underline{\underline{8990\text{ m}^3\text{/h}}}$$

$$\dot{V}_{3W}=\frac{200\text{ kmol H}_2\text{O (l)}}{\text{h}}\bigg|\frac{18.0\text{ kg}}{\text{kmol}}\bigg|\frac{1\text{ m}^3}{1000\text{ kg}}=\underline{\underline{3.60\text{ m}^3\text{ H}_2\text{O(l) / h leave condenser}}}$$

d. $$\underline{\text{90\% single pass conversion}}\Rightarrow\dot{n}_{3p}=0.10\left(\dot{n}_1+\dot{n}_{3p}\right)\overset{\dot{n}_1=100}{=\!=\!=\!=\!>}\dot{n}_{3p}=11.1\text{ kmol PX / h}$$

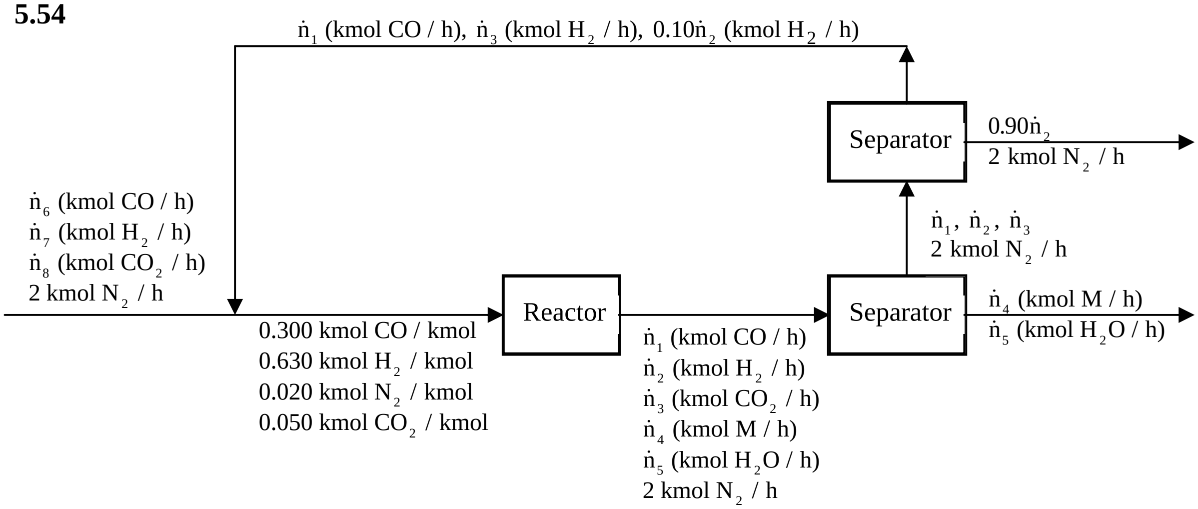
$$\dot{m}_{\text{recycle}}=\dot{m}_S+\dot{m}_{3P}=\frac{(100+11.1)\text{ kg PX}}{\text{h}}\bigg|\frac{106\text{ kg PX}}{1\text{ kmol PX}}\bigg|\frac{3\text{ kg S}}{\text{kg PX}}+\frac{11.1\text{ kmol PX}}{\text{h}}\bigg|\frac{106\text{ kg PX}}{1\text{ kmol PX}}$$

$$=\underline{\underline{3.65\times10^4\text{ kg/h}}}$$

e. O_2 is used to react with the PX. N_2 does not react with anything but enters with O_2 in the air. The catalyst is used to accelerate the reaction and the solvent is used to disperse the PX.

f. The stream can be allowed to settle and separate into water and PX layers, which may then be separated.

5.54



5.54 (cont'd)

$$\begin{aligned}&CO + 2H_2 \Leftrightarrow CH_3OH(M)\\ &CO_2 + 3H_2 \Leftrightarrow CH_3OH + H_2O\end{aligned}$$

a. Let ξ_1(kmol / h) = extent of rxn 1, ξ_2(kmol / h) = extent of rxn 2

$$\left.\begin{array}{ll}\underline{CO}: & \dot{n}_1 = 30 - \xi_1\\ \underline{H_2}: & \dot{n}_2 = 63 - 2\xi_1 - 3\xi_2\\ \underline{CO_2}: & \dot{n}_3 = 5 - \xi_2\\ \underline{M}: & \dot{n}_4 = \xi_1 + \xi_2\\ \underline{H_2O}: & \dot{n}_5 = \xi_2\\ \underline{N_2}: & \dot{n}_{N_2} = 2\\ \hline & \dot{n}_{tot} = 100 - 2\xi_1 - 2\xi_2\end{array}\right\} \Rightarrow \left(K_p\right)_1 = \frac{P\cdot y_M}{P\cdot y_{CO}\left(P\cdot y_{H_2}\right)^2},\ \left(K_p\right)_2 = \frac{\left(P\cdot y_M\right)\left(P\cdot y_{H_2O}\right)}{\left(P\cdot y_{CO_2}\right)\left(P\cdot y_{H_2}\right)^3}$$

$$\left(K_p\right)_1\cdot P^2 = \frac{\dfrac{\dot{n}_4}{\dot{n}_{tot}}}{\dfrac{\dot{n}_1}{\dot{n}_{tot}}\left(\dfrac{\dot{n}_2}{\dot{n}_{tot}}\right)^2} = \frac{\left(\xi_1+\xi_2\right)\left(100-2\xi_1-2\xi_2\right)^2}{\left(30-\xi_1\right)\left(63-2\xi_1-3\xi_2\right)^2} = 84.65 \qquad (1)$$

$$\left(K_p\right)_2\cdot P^2 = \frac{\left(\dfrac{\dot{n}_4}{\dot{n}_{tot}}\right)\left(\dfrac{\dot{n}_5}{\dot{n}_{tot}}\right)}{\left(\dfrac{\dot{n}_3}{\dot{n}_{tot}}\right)\left(\dfrac{\dot{n}_2}{\dot{n}_{tot}}\right)^3} = \frac{\xi_2\left(\xi_1+\xi_2\right)\left(100-2\xi_1-2\xi_2\right)^2}{\left(5-\xi_2\right)\left(63-2\xi_1-3\xi_2\right)^2} = 1.259 \qquad (2)$$

Solve (1) and (2) for $\xi_1, \xi_2 \Rightarrow \quad \xi_1 = 25.27$ kmol / h $\quad \xi_2 = 0.0157$ kmol / h

$$\Rightarrow \begin{array}{ll}\dot{n}_1 = 30.0 - 25.27 = \underline{\underline{4.73\text{ kmol CO / h}}} & \\ \dot{n}_2 = 63.0 - 2(25.27) - 3(0.0157) = \underline{\underline{12.4\text{ kmol }H_2\text{ / h}}} & \\ \dot{n}_3 = 5.0 - 0.0157 = \underline{\underline{4.98\text{ kmol }CO_2\text{ / h}}} & \\ \dot{n}_4 = 25.27 + 0.0157 = \underline{\underline{25.3\text{ kmol M / h}}} & \\ \dot{n}_5 = 0.0157 = \underline{\underline{0.0157\text{ kmol }H_2O\text{ / h}}} & \\ n_{total} = 49.4\text{ kmol / h} & \end{array} \Rightarrow \begin{array}{l}\underline{9.98\%\text{ CO}}\\ \underline{26.2\%\ H_2}\\ \underline{10.5\%\ CO_2}\\ \underline{53.4\%\text{ M}}\\ \underline{0.03\%\ H_2O}\end{array}$$

$$\left.\begin{array}{l}\underline{\text{C balance:}}\ \dot{n}_4 = 25.3\text{ kmol / h}\\ \underline{\text{O balance:}}\ \dot{n}_6 + 2\dot{n}_8 = \dot{n}_4 + \dot{n}_5 = 25.44\text{ mol / s}\end{array}\right\} \Rightarrow \begin{array}{l}\dot{n}_6 = \underline{\underline{25.4\text{ kmol CO / h}}}\\ \dot{n}_8 = \underline{\underline{0.02\text{ kmol }CO_2\text{ / h}}}\end{array}$$

$$\underline{\text{H balance:}}\ 2\dot{n}_7 = 2(0.9\dot{n}_2) + 4\dot{n}_4 + 2\dot{n}_5 = 123.7 \Rightarrow \dot{n}_7 = \underline{\underline{61.8\text{ mol }H_2\text{ / s}}}$$

b. $(\dot{n}_4)_{process} = 237$ kmol M / h

$$\Rightarrow \text{ Scale Factor} = \frac{237\text{ kmol M / h}}{25.3\text{ kmol / h}}$$

5.54 (cont'd)

$$\underline{\text{Process feed:}}\ (25.4+61.8+0.02+2.0)\left(\frac{237\text{ kmol / h}}{25.3\text{ kmol / h}}\right)\left(\frac{22.4\text{ m}^3\text{ (STP)}}{\text{kmol}}\right)=\underline{\underline{18{,}700\text{ SCMH}}}$$

$$\underline{\text{Reactor effluent flow rate:}}\ (\ 49.4\text{ kmol / h})\left(\frac{237\text{ kmol / h}}{25.3\text{ kmol / s}}\right)=444\text{ kmol / h}$$

$$\Rightarrow \dot{V}_{\text{std}}\left(444\ \frac{\text{kmol}}{\text{h}}\right)\left(\frac{22.4\text{ m}^3\text{ (STP)}}{\text{kmol}}\right)=\underline{\underline{9946\text{ SCMH}}}$$

$$\Rightarrow \dot{V}_{\text{actual}}=\frac{9950\text{ m}^3\text{(STP)}}{\text{h}}\bigg|\frac{473.2\text{ K}}{273.2\text{ K}}\bigg|\frac{101.3\text{ kPa}}{4925\text{ kPa}}=\underline{\underline{354\text{ m}^3\text{ / h}}}$$

c. $$\hat{V}=\frac{\dot{V}}{\dot{n}}=\frac{354\text{ m}^3\text{ / h}}{444\text{ kmol / h}}\bigg|\frac{1000\text{ L}}{\text{m}^3}\bigg|\frac{1\text{ kmol}}{1000\text{ mol}}=\underline{\underline{0.8\text{ L / mol}}}$$

$$\underline{\underline{\hat{V}<20\text{ L / mol}\overset{(5.2\text{-}36)}{====>}\text{ideal gas approximation is poor}}}$$

Most obviously, the calculation of $\dot{V}$ from $\dot{n}$ using the ideal gas equation of state is likely to lead to error. In addition, the reaction equilibrium expressions are probably strictly valid only for ideal gases, so that every calculated quantity is likely to be in error.

5.55 a. $$\frac{P\hat{V}}{RT}=1+\frac{B}{\hat{V}}\Rightarrow B=\frac{RT_c}{P_c}\left(B_o+\omega B_1\right)$$

From Table B.1 for ethane: $T_c=305.4\text{ K},\ P_c=48.2\text{ atm}$

From Table 5.3-1 $\omega=0.098$

$$B_o=0.083-\frac{0.422}{T_r^{1.6}}=0.083-\frac{0.422}{\left(308.2\text{K}/305.4\text{K}\right)^{1.6}}=-0.333$$

$$B_1=0.139-\frac{0.172}{T_r^{4.2}}=0.139-\frac{0.172}{\left(308.2\text{K}/305.4\text{K}\right)^{4.2}}=-0.0270$$

$$B(T)=\frac{RT_c}{P_c}\left(B_o+\omega B_1\right)=\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\bigg|\frac{305.4\text{K}}{48.2\text{ atm}}\left[-0.333-(0.098)0.0270\right]$$

$$=-0.1745\text{ L / mol}$$

$$\frac{P\hat{V}^2}{RT}-\hat{V}-B=\left(\frac{10.0\text{ atm}}{308.2\text{K}}\bigg|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}}\right)\hat{V}^2-\hat{V}+0.1745=0$$

$$\Rightarrow \hat{V}=\frac{1\pm\sqrt{1-4(0.395\text{ mol / L})(0.1745\text{ L / mol})}}{2(0.395\text{ mol / L})}=\underline{\underline{2.343\text{ L / mol},\ \cancel{0.188\text{ L / mol}}}}$$

$\hat{V}_{\text{ideal}}=RT/P=0.08206\times 308.2/10.0=2.53,$ so the second solution is likely to be a mathematical artifact.

b. $$z=\frac{P\hat{V}}{RT}=\frac{10.0\text{ atm}}{0.08206\frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\bigg|\frac{2.343\text{ L / mol}}{308.2\text{K}}=\underline{\underline{0.926}}$$

c. $$\dot{m}=\frac{\dot{V}}{\hat{V}}MW=\frac{1000\text{ L}}{\text{h}}\bigg|\frac{\text{mol}}{2.343\text{ L}}\bigg|\frac{30.0\text{ g}}{\text{mol}}\bigg|\frac{1\text{ kg}}{1000\text{ g}}=\underline{\underline{12.8\text{ kg / h}}}$$

5.56 $$\frac{P\hat{V}}{RT} = 1 + \frac{B}{\hat{V}} \Rightarrow B = \frac{RT_c}{P_c}\left(B_o + \omega B_1\right)$$

From Table B.1 $T_c\left(CH_3OH\right) = 513.2\text{ K},\ P_c = 78.50\text{ atm}$

$T_c\left(C_3H_8\right) = 369.9\text{ K},\ P_c = 42.0\text{ atm}$

From Table 5.3-1 $\omega\left(CH_3OH\right) = 0.559,\ \omega\left(C_3H_8\right) = 0.152$

$$B_o(CH_3OH) = 0.083 - \frac{0.422}{T_r^{1.6}} = 0.083 - \frac{0.422}{\left(373.2K/513.2K\right)^{1.6}} = -0.619$$

$$B_o(C_3H_8) = 0.083 - \frac{0.422}{T_r^{1.6}} = 0.083 - \frac{0.422}{\left(373.2K/369.9K\right)^{1.6}} = -0.333$$

$$B_1(CH_3OH) = 0.139 - \frac{0.172}{T_r^{4.2}} = 0.139 - \frac{0.172}{\left(373.2K/513.2K\right)^{4.2}} = -0.516$$

$$B_1(C_3H_8) = 0.139 - \frac{0.172}{T_r^{4.2}} = 0.139 - \frac{0.172}{\left(373.2K/369.9K\right)^{4.2}} = -0.0270$$

$$B(CH_3OH) = \frac{RT_c}{P_c}\left(B_o + \omega B_1\right)$$

$$= \left.\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\frac{513.2\text{K}}{78.5\text{ atm}}\left(-0.619 - \left(0.559\right)0.516\right) = -0.4868\ \tfrac{\text{L}}{\text{mol}}$$

$$B(C_3H_8) = \frac{RT_c}{P_c}\left(B_o + \omega B_1\right)$$

$$= \left.\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\frac{369.9\text{ K}}{42.0\text{ atm}}\left(-0.333 - \left(0.152\right)0.0270\right) = -0.2436\ \tfrac{\text{L}}{\text{mol}}$$

$$B_{mix} = \sum_i \sum_j y_i y_j B_{ij} \Rightarrow B_{ij} = 0.5\left(B_{ii} + B_{jj}\right)$$

$$B_{ij} = 0.5\left(-0.4868 - 0.2436\right)\text{L / mol} = \text{-}0.3652\text{ L / mol}$$

$$B_{mix} = \left(0.30\right)\left(0.30\right)\left(-0.4868\right) + 2\left(0.30\right)\left(0.70\right)\left(-0.3652\right) + \left(0.70\right)\left(0.70\right)\left(-0.2436\right)$$
$$= -0.3166\text{ L / mol}$$

$$\frac{P\hat{V}^2}{RT} - \hat{V} \text{ - } B_{mix} = \left(\left.\frac{10.0\text{ atm}}{373.2\text{K}}\right|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}}\right)\hat{V}^2 - \hat{V} + 0.3166 = 0$$

Solve for $\hat{V}$: $$\hat{V} = \frac{1 \pm \sqrt{1\text{ - }4\left(0.326\text{ mol / L}\right)\left(0.3166\text{ L / mol}\right)}}{2\left(0.326\text{ mol / L}\right)} = 2.70\text{ L / mol},\ 0.359\text{ L / mol}$$

$$\hat{V}_{ideal} = \frac{RT}{P} = \left.\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\frac{373.2\text{ K}}{10.0\text{ atm}} = 3.06\text{ L / mol} \Rightarrow \underline{\underline{\hat{V}_{virial} = 2.70\text{ L / mol}}}$$

$$\dot{V} = \hat{V}\dot{n} = \left.\frac{2.70\text{ L / mol}}{}\right|\left.\frac{15.0\text{ kmol }CH_3OH\text{ / h}}{0.30\text{ kmol }CH_3OH\text{ / kmol}}\right|\left.\frac{1000\text{ mol}}{1\text{ kmol}}\right|\frac{1\text{ m}^3}{1000\text{ L}} = \underline{\underline{135\text{ m}^3\text{ / h}}}$$

5.57 **a.** van der Waals equation: $P = \dfrac{RT}{\left(\hat{V} - b\right)} - \dfrac{a^2}{\hat{V}^2}$

Multiply both sides by $\hat{V}^2\left(\hat{V} - b\right) \Rightarrow P\hat{V}^3 - P\hat{V}^2 b = RT\hat{V}^2 - a\hat{V} + ab$

$P\hat{V}^3 + \left(-Pb - RT\right)\hat{V}^2 + a\hat{V} - ab = 0$

$c_3 = P = \underline{\underline{50.0 \text{ atm}}}$

$c_2 = \left(-Pb - RT\right) = \left(-50.0 \text{ atm}\right)\left(0.0366 \text{ L / mol}\right) - \left(0.08206 \ \tfrac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right)\left(223 \text{ K}\right) = \underline{\underline{-20.1 \text{ L}\cdot\text{atm / mol}}}$

$c_1 = -a = \underline{\underline{1.33 \text{ atm}\cdot\text{L}^2 \text{ / mol}^2}}$

$c_0 = -ab = -\left(1.33 \text{ atm}\cdot\text{L}^2 \text{ / mol}^2\right)\left(0.0366 \text{ L / mol}\right)$

$\underline{\underline{= -0.0487 \ \dfrac{\text{atm}\cdot\text{L}^3}{\text{mol}^3}}}$

b. $\hat{V}_{\text{ideal}} = \dfrac{RT}{P} = \dfrac{0.08206 \text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\left|\dfrac{223 \text{ K}}{50.0 \text{ atm}}\right. = 0.366 \text{ L / mol}$

c.

T(K)	P(atm)	c3	c2	c1	c0	V(ideal) (L/mol)	V (L/mol)	f(V)	% error	
223	1.0	1.0	-18.336	1.33	-0.0487	18.2994	18.2633	0.0000	0.2	
223	10.0	10.0	-18.6654	1.33	-0.0487	1.8299	1.7939	0.0000	2.0	← b
223	50.0	50.0	-20.1294	1.33	-0.0487	0.3660	0.3313	0.0008	10.5	
223	100.0	100.0	-21.9594	1.33	-0.0487	0.1830	0.1532	-0.0007	19.4	
223	200.0	200.0	-25.6194	1.33	-0.0487	0.0915	0.0835	0.0002	9.6	

d. 1 eq. in 1 unknown - use Newton-Raphson.

$$(1) \Rightarrow g\left(\hat{V}\right) = 50.0\hat{V}^3 + \left(-20.1294\right)\hat{V}^2 + \left(1.33\right)\hat{V} - .0487 = 0$$

$$\text{Eq. (A.2-13)} \Rightarrow a = \frac{\partial g}{\partial \hat{V}} = 150\hat{V}^2 - 40.259\hat{V} + 1.33$$

$$\text{Eq. (A.2-14)} \Rightarrow ad = -g \overset{\text{solve}}{\Rightarrow} d = \frac{-g}{a}$$

Then $\hat{V}^{(k+1)} = \hat{V}^{(k)} + d$ Guess $\hat{V}^{(1)} = \hat{V}_{\text{ideal}} = 0.3660 \text{ L / mol}$.

	$\hat{V}^{(k)}$	$\hat{V}^{(k+1)}$	
1	0.3660	0.33714	
2	0.33714	0.33137	
3	0.33137	0.33114	
4	0.33114	0.33114	converged

5.58 $\underline{C_3H_8}$: $T_C = 369.9\ \text{K}$ $\quad P_C = 42.0\ \text{atm}\left(4.26\times10^6\ \text{Pa}\right)$ $\quad \omega = 0.152$

<u>Specific Volume</u> $\quad \dfrac{5.0\ \text{m}^3}{75\ \text{kg}}\left|\dfrac{44.09\ \text{kg}}{1\ \text{kmol}}\right|\dfrac{1\ \text{kmol}}{10^3\ \text{mol}} = 2.93\times10^{-3}\ \text{m}^3/\text{mol}$

<u>Calculate constants</u>

$$a = \frac{0.42747\ \left|\ \left(8.314\ \text{m}^3\cdot\text{Pa/mol}\cdot\text{K}\right)^2\ \right|\ \left(369.9\ \text{K}\right)^2}{4.26\times10^6\ \text{Pa}} = 0.949\ \text{m}^6\cdot\text{Pa/mol}^2$$

$$b = \frac{0.08664\ \left|\ \left(8.314\ \text{m}^3\cdot\text{Pa/mol}\cdot\text{K}\right)\ \right|\ \left(369.9\ \text{K}\right)}{4.26\times10^6\ \text{Pa}} = 6.25\times10^{-5}\ \text{m}^3/\text{mol}$$

$$m = 0.48508 + 1.55171(0.152) - 0.15613(0.152)^2 = 0.717$$

$$\alpha = \left[1 + 0.717\left(1-\sqrt{298.2/369.9}\right)\right]^2 = 1.15$$

<u>SRK Equation:</u>

$$P = \frac{\left(8.314\ \text{m}^3\cdot\text{Pa/mol}\cdot\text{K}\right)\left(298.2\ \text{K}\right)}{\left(2.93\times10^{-3} - 6.25\times10^{-5}\right)\text{m}^3/\text{mol}} - \frac{1.15\left(0.949\ \text{m}^6\cdot\text{Pa/mol}^2\right)}{2.93\times10^{-3}\ \text{m}^3/\text{mol}\left(2.93\times10^{-3} + 6.25\times10^{-5}\right)\text{m}^3/\text{mol}}$$

$$\Rightarrow P = 7.40\times10^6\ \text{Pa} \Rightarrow \underline{\underline{7.30\ \text{atm}}}$$

<u>Ideal:</u> $\quad P = \dfrac{RT}{\hat{V}} = \dfrac{\left(8.314\ \text{m}^3\cdot\text{Pa/mol}\cdot\text{K}\right)\left(298.2\ \text{K}\right)}{2.93\times10^{-3}\ \text{m}^3/\text{mol}} = 8.46\times10^6\ \text{Pa} \Rightarrow 8.35\ \text{atm}$

<u>Percent Error:</u> $\quad \dfrac{(8.35-7.30)\ \text{atm}}{7.30\ \text{atm}}\times100\% = \underline{\underline{14.4\%}}$

5.59 $\underline{CO_2}$: $\quad T_C = 304.2\ \text{K}$ $\quad P_C = 72.9\ \text{atm}$ $\quad \omega = 0.225$

<u>Ar:</u> $\quad T_C = 151.2\ \text{K}$ $\quad P_C = 48.0\ \text{atm}$ $\quad \omega = -0.004$

$P = 51.0\ \text{atm}$, $\quad \hat{V} = 35.0\ \text{L} / 50.0\ \text{mol} = 0.70\ \text{L/mol}$

Calculate constants (use $R = 0.08206\ \text{L}\cdot\text{atm/mol}\cdot\text{K}$)

$\underline{CO_2}$: $a = 3.65\ \dfrac{\text{L}^2\cdot\text{atm}}{\text{mol}^2}$, $m = 0.826$, $b = 0.0297\ \dfrac{\text{L}}{\text{mol}}$, $\alpha = \left[1 + 0.826\left(1-\sqrt{T/304.2}\right)\right]^2$

<u>Ar</u>: $\quad a = 1.37\ \dfrac{\text{L}^2\cdot\text{atm}}{\text{mol}^2}$, $m = 0.479$, $b = 0.0224\ \dfrac{\text{L}}{\text{mol}}$, $\alpha = \left[1 + 0.479\left(1-\sqrt{T/151.2}\right)\right]^2$

$$f(T) = \frac{RT}{\hat{V}-b} - \frac{a}{\hat{V}\left(\hat{V}+b\right)}\left[1 + m\left(1-\sqrt{T/T_C}\right)\right]^2 - P = 0$$

Use E-Z Solve. Initial value (ideal gas):

$$T_{\text{ideal}} = (51.0\ \text{atm})\left(0.70\ \frac{\text{L}}{\text{mol}}\right)\Big/\left(0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right) = \underline{\underline{435.0\ \text{K}}}$$

$$\text{E - Z Solve} \Rightarrow \underline{\underline{\left(T_{\max}\right)_{CO_2} = 455.4\ \text{K},\ \left(T_{\max}\right)_{Ar} = 431.2\ \text{K}}}$$

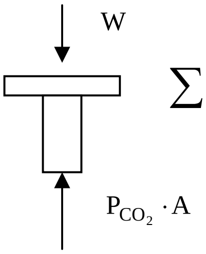
5.60 $\underline{O_2}$: $T_C = 154.4\text{ K}$; $P_C = 49.7\text{ atm}$; $\omega = 0.021$; $T = 208.2\text{ K}(65°\text{ C})$; $P = 8.3\text{ atm}$; $\dot{m} = 250\ \text{kg/h}$; $R = 0.08206\ \text{L}\cdot\text{atm/mol}\cdot\text{K}$

$\underline{\text{SRK constants:}}$ $a = 1.38\ \text{L}^2\cdot\text{atm/mol}^2$; $b = 0.0221\ \text{L/mol}$; $m = 0.517$; $\alpha = 0.840$

$\underline{\text{SRK equation}}$:
$$f(\hat{V}) = \frac{RT}{(\hat{V}-b)} - \frac{a\alpha}{\hat{V}(\hat{V}+b)} - P = 0 \overset{\text{E-Z Solve}}{=\!=\!=\!=\!=\!>} \hat{V} = 2.01\ \text{L / mol}$$

$$\Rightarrow \dot{V} = \frac{250\text{ kg}}{\text{h}}\left|\frac{\text{kmol}}{32.00\text{ kg}}\right|\frac{10^3\text{ mol}}{1\text{ kmol}}\left|\frac{2.01\text{ L}}{\text{mol}}\right. = \underline{\underline{15{,}700\ \text{L/h}}}$$

5.61



$$\sum F_y = P_{CO_2}\cdot A - W = 0 \quad \text{where } W = mg = 5500\text{ kg}\left(9.81\ \tfrac{\text{m}}{\text{s}^2}\right) = 53900\text{ N}$$

a. $$P_{CO_2} = \frac{W}{A_{\text{piston}}} = \frac{53900\text{ N}}{\frac{\pi}{4}(0.15\text{ m})^2}\left|\frac{1\text{ atm}}{1.013\times10^5\text{ N / m}^2}\right. = \underline{\underline{30.1\text{ atm}}}$$

b. SRK equation of state: $$P = \frac{RT}{(\hat{V}\text{ - }b)} - \frac{\alpha a}{\hat{V}(\hat{V}+b)}$$

For CO_2: $T_c = 304.2$, $P_c = 72.9\text{ atm}$, $\omega = 0.225$

$a = 3.654\ \text{m}^6\cdot\text{atm / kmol}^2$, $b = 0.02967\ \text{m}^3\text{ / kmol}$, $m = 0.8263$, $\alpha(25^\circ\text{C}) = 1.016$

$$30.1\text{ atm} = \frac{\left(0.08206\,\frac{\text{m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}\right)(298.2\text{ K})}{\left(\hat{V}\text{ - }0.02967\,\frac{\text{m}^3}{\text{kmol}}\right)} - \frac{(1.016)\left(3.654\,\frac{\text{m}^6\cdot\text{atm}}{\text{kmol}^2}\right)}{\hat{V}\left(\hat{V}+0.02967\right)\frac{\text{m}^6}{\text{kmol}^2}}$$

$$\overset{\text{E-Z Solve}}{=\!=\!=\!=\!=\!>} \hat{V} = \underline{\underline{0.675\text{ m}^3\text{ / kmol}}}$$

$V(\text{before expansion}) = 0.030\text{ m}^3$

$V(\text{after expansion}) = 0.030\text{ m}^3 + \frac{\pi}{4}(0.15\text{ m})^2(1.5\text{ m}) = 0.0565\text{ m}^3$

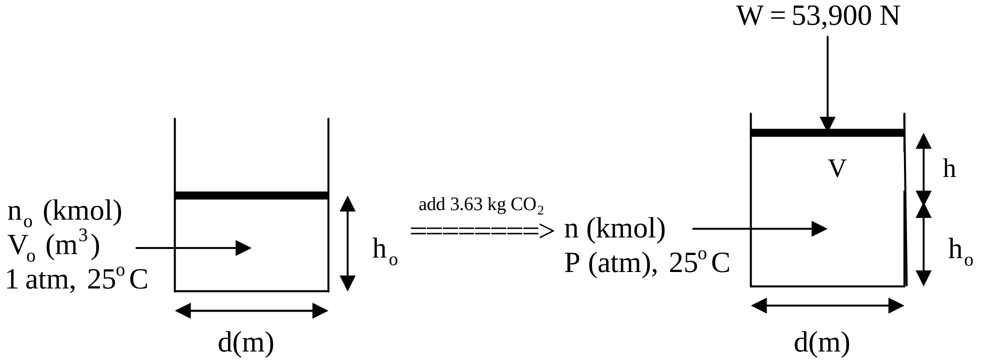
$$m_{CO_2} = \frac{V}{\hat{V}}MW = \frac{0.0565\text{ m}^3}{0.675\text{ m}^3\text{ / kmol}}\left|\frac{44.01\text{ kg}}{\text{kmol}}\right. = 3.68\text{ kg}$$

$$m_{CO_2}(\text{initially}) = \frac{PV}{RT}MW = \frac{1\text{ atm}}{0.08206\ \frac{\text{m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}}}\left|\frac{0.030\text{ m}^3}{298.2\text{ K}}\right|\frac{44.01\text{ kg}}{\text{kmol}} = 0.0540\text{ kg}$$

$$m_{CO_2}(\text{added}) = 3.68 - 0.0540\text{ kg} = \underline{\underline{3.63\text{ kg}}}$$

5.61 (cont'd)

c.



Given T, V_o, h, find d

$$\underline{\text{Initial:}}\ n_o = \frac{V_o}{RT}\quad (P_o = 1)$$

$$\underline{\text{Final:}}\ V = V_o + \frac{\pi d^2 h}{4},\quad n = n_o + \frac{3.63\ \text{(kg)}}{44\ \text{(kg / kmol)}} = \frac{V_o}{RT} + 0.0825$$

$$\hat{V} = \frac{V}{n} = \frac{V_o + \frac{\pi d^2 h}{4}}{\frac{V_o}{RT} + 0.0825}$$

$$P = \frac{W}{A_{\text{piston}}} = \frac{RT}{\hat{V} - b} - \frac{\alpha a}{\hat{V}\left(\hat{V} + b\right)} \Rightarrow \frac{53{,}900}{\pi d^2 / 4} = \frac{RT}{\hat{V} - b} - \frac{\alpha a}{\hat{V}\left(\hat{V} + b\right)} \qquad (1)$$

Substitute expression for $\hat{V}$ in $(1) \Rightarrow$ one equation in one unknown. Solve for d.

5.62 a. Using ideal gas assumption:

$$P_g = \frac{nRT}{V} - P_{atm} = \frac{35.3\ \text{lb}_m\ O_2}{} \left| \frac{1\ \text{lb-mole}}{32.0\ \text{lb}_m} \right| \frac{10.73\ \text{ft}^3 \cdot \text{psia}}{\text{lb-mole} \cdot {}^\circ\text{R}} \left| \frac{509.7^\circ\text{R}}{2.5\ \text{ft}^3} \right. - 14.7\ \text{psia} = \underline{\underline{2400\ \text{psig}}}$$

b. $\underline{\text{SRK Equation of state:}}\ P = \frac{RT}{\left(\hat{V} - b\right)} - \frac{\alpha a}{\hat{V}\left(\hat{V} + b\right)}$

$$\hat{V}_{\text{ideal}} = \frac{2.5\ \text{ft}^3}{} \left| \frac{32.0\ \text{lb}_m / \text{lb-mole}}{35.3\ \text{lb}_m} \right. = 2.27\ \frac{\text{ft}^3}{\text{lb-mole}}$$

(Use as a first estimate when solving the SRK equation)

For O_2: $T_c = 277.9^\circ\text{R}$, $P_c = 730.4$ psi, $\omega = 0.021$

$$a = 5203.8\ \frac{\text{ft}^6 \cdot \text{psi}}{\text{lb-mole}^2},\quad b = 0.3537\frac{\text{ft}^3}{\text{lb-mole}},\quad m = 0.518,\quad \alpha\left(50^\circ\text{F}\right) = 0.667$$

$$\left(2400 + 14.7\right)\ \text{psi} = \frac{\left(10.73\frac{\text{ft}^3 \cdot \text{psi}}{\text{lb-mole} \cdot {}^\circ\text{R}}\right)\left(509.7^\circ\ \text{R}\right)}{\left(\hat{V} - 0.3537\right)\frac{\text{ft}^3}{\text{lb-mole}}} - \frac{\left(0.667\right)\left(5203.8\frac{\text{ft}^6 \cdot \text{psi}}{\text{lb-mole}^2}\right)}{\hat{V}\left(\hat{V} + 0.3537\right)\frac{\text{ft}^6}{\text{lb-mole}^2}}$$

E-Z Solve $\Rightarrow \hat{V} = 2.139\ \text{ft}^3 / \text{lb-mole}$

5.62 (cont'd)

$$m_{O_2} = \frac{V}{\hat{V}} MW = \frac{2.5\ \text{ft}^3}{2.139\ \text{ft}^3/\text{lb-mole}} \bigg| \frac{32.0\ \text{lb}_m}{\text{lb-mole}} = \underline{\underline{37.4\ \text{lb}_m}}$$

Ideal gas gives a conservative estimate. It calls for charging less O_2 than the tank can safely hold.

c. 1. Pressure gauge is faulty
2. The room temperature is higher than 50°F
3. Crack or weakness in the tank
4. Tank was not completely evacuated before charging and O_2 reacted with something in the tank
5. Faulty scale used to measure O_2
6. The tank was mislabeled and did not contain pure oxygen.

5.63 **a.** SRK Equation of State: $P = \frac{RT}{(\hat{V} - b)} - \frac{\alpha a}{\hat{V}(\hat{V} + b)}$

$\Rightarrow$ multiply both sides of the equation by $\hat{V}(\hat{V} - b)(\hat{V} + b)$:

$$f(\hat{V}) = P\hat{V}(\hat{V} - b)(\hat{V} + b) - RT\hat{V}(\hat{V} + b) + \alpha a(\hat{V} - b) = 0$$

$$\underline{\underline{f(\hat{V}) = P\hat{V}^3 - RT\hat{V}^2 + (\alpha a - b^2 P - bRT)\hat{V} - \alpha ab = 0}}$$

b.

```
Problem 5.63-SRK Equation Spreadsheet

Species         CO2
Tc(K)          304.2             R=0.08206 m^3 atm/kmol K
Pc(atm)         72.9
ω              0.225
a          3.653924 m^6 atm/kmol^2
b          0.029668 m^3/kmol
m          0.826312

f(V)=B14*E14^3-0.08206*A14*E14^2+($B$7*C14-$B$8^2*B14-$B$8*0.08206*A14)*E14-C14*$B$7*$B$8

    T(K)   P(atm)    alpha   V(ideal)   V(SRK)      f(V)
     200      6.8   1.3370     2.4135   2.1125    0.0003
     250     12.3   1.1604     1.6679   1.4727    0.0001
     300      6.8   1.0115     3.6203   3.4972    0.0001
     300     21.5   1.0115     1.1450   1.0149    0.0000
     300     50.0   1.0115     0.4924   0.3392    0.0001
```

c. E-Z Solve solves the equation f(V)=0 in one step. Answers identical to V_{SRK} values in part b.

d.

```
   REAL T, P, TC, PC, W, R, A, B, M, ALP, Y, VP, F, FP
   INTEGER I
   CHARACTER A20 GAS
   DATA R 10.08206/
   READ (5, *) GAS
   WRITE (6, *) GAS
10 READ (5, *) TC, PC, W
```

5.63 (cont'd)

```
      READ (5, *) T, P
      IF (T.LT.Q.) STOP
       R = 0.42747 *R*R/PC*TC*TC
       B = 0.08664 *R*TC/PC
       M = 0.48508 + W = (1.55171 – W*0.15613)
       ALP = (1.+M*(1 – (T / TC)**0.5))**2 .
       VP = R*T / P
      DO 20  I = 7, 15
      V = VP
      F = R * T/(V – B) – ALP * A/V/(V + B) – P
      FP = ALP * A * (2. * V + B)/V/V/(V + B) ** 2 – R * T/(V – B) ** 2.
      VP = V – F/FP
      IF (ABS(VP – V)/VP.LT.0.0001) GOTO 30
20    CONTINUE
      WRITE (6, 2)
2     FORMAT ('DID NOT CONVERGE')
      STOP
30    WRITE (6, 3) T, P, VP
3     FORMAT (F6.1, 'K', 3X, F5.1, 'ATM', 3X, F5.2, 'LITER/MOL')
      GOTO 10
      END
```

```
$ DATA
CARBON                  DIOXIDE
  304.2          72.9           0.225
  200.0           6.8
  250.0          12.3
  300.0          21.5
  –1              0.
```

<u>RESULTS</u>

```
CARBON DIOXIDE
200.0 K         6.8 ATM             2.11 LITER/MOL
250.0 K        12.3 ATM             1.47 LITER/MOL
300.0 K        6.8 ATM              3.50 LITER/MOL
300.0 K        21.5 ATM             1.01 LITER/MOL
300.0 K        50.0 ATM             0.34 LITER/MOL
```

5.64 a.

$$\underline{N_2}:\ \begin{matrix} T_C = 126.2\text{ K} \\ P_C = 33.5\text{ atm} \end{matrix} \Rightarrow \left.\begin{matrix} T_r = (40+273.2)/126.2 = 2.48 \\ P_r = \dfrac{40\text{ MPa}}{33.5\text{ atm}}\left|\dfrac{10\text{ atm}}{1.013\text{ MPa}}\right. = 11.78 \end{matrix}\right\} \xRightarrow{\text{Fig. 5.4-4}} \underline{\underline{z = 1.2}}$$

b.

$$\underline{He}:\ \begin{matrix} T_C = 5.26\text{ K} \\ P_C = 2.26\text{ atm} \end{matrix} \Rightarrow \left.\begin{matrix} T_r = (-200+273.2)/(5.26+8) = 5.52 \\ P_r = 350/(2.26+8) = 34.11 \end{matrix}\right\} \xRightarrow{\text{Fig. 5.4-4}} \underline{\underline{z = 1.6}}$$

↑

Newton's correction

5.65 **a.** $\rho\left(\text{kg}/\text{m}^3\right)=\dfrac{\text{m (kg)}}{\text{V (m}^3)}=\dfrac{\text{(MW)P}}{\text{RT}}$

$$=\begin{array}{c|c|c}30\ \text{kg/kmol} & 9.0\ \text{MPa} & 10\ \text{atm}\\ \hline 465\ \text{K} & 0.08206\,\frac{\text{m}^3\cdot\text{atm}}{\text{kmol}\cdot\text{K}} & 1.013\ \text{MPa}\end{array}=\underline{\underline{69.8\ \text{kg}/\text{m}^3}}$$

b. $\left.\begin{array}{l}T_r=465/310=1.5\\ P_r=9.0/4.5=2.0\end{array}\right\}\overset{\text{Fig. 5.4-3}}{\Rightarrow}\ z=0.84$

$$\rho=\frac{\text{(MW)P}}{\text{zRT}}=\frac{69.8\ \text{kg}/\text{m}^3}{0.84}=\underline{\underline{83.1\ \text{kg}/\text{m}^3}}$$

5.66 Moles of CO_2: $\begin{array}{c|c}100\ \text{lb}_\text{m}\ CO_2 & 1\ \text{lb-mole}\ CO_2\\ \hline & 44.01\ \text{lb}_\text{m}\ CO_2\end{array}=2.27\ \text{lb-moles}$

$$\left.\begin{array}{l}T_C=304.2\ \text{K}\\ P_C=72.9\ \text{atm}\end{array}\right\}\Rightarrow P_r=P/P_C=\begin{array}{c|c}(1600+14.7)\text{psi} & 1\ \text{atm}\\ \hline 72.9\ \text{atm} & 14.7\ \text{psi}\end{array}=1.507$$

$$\hat{V}_r=\frac{\hat{V}P_C}{RT_C}=\begin{array}{c|c|c|c}10.0\ \text{ft}^3 & 72.9\ \text{atm} & \text{lb-mole}\cdot{}^\circ\text{R} & 1\ \text{K}\\ \hline 2.27\ \text{lb-moles} & 304.2\ \text{K} & 0.7302\ \text{ft}^3\cdot\text{atm} & 1.8\ {}^\circ\text{R}\end{array}=0.80$$

Fig. 5.4-3: $P_r=1.507$, $V_r=0.80\Rightarrow z=0.85$

$$T=\frac{PV}{znR}=\begin{array}{c|c|c|c}1614.7\ \text{psi} & 10.0\ \text{ft}^3 & \text{lb-mole}\cdot{}^\circ\text{R} & 1\ \text{atm}\\ \hline 0.85 & 2.27\ \text{lb-moles} & 0.7302\ \text{ft}^3\cdot\text{atm} & 14.7\ \text{psi}\end{array}=779^\circ\text{R}=\underline{\underline{320\ {}^\circ\text{F}}}$$

5.67 $\underline{O_2}$: $T_C=154.4\ \text{K}$, $P_C=49.7\ \text{atm}$

$$\left.\begin{array}{l}T_{r_1}=298/154.4=1.93\\ P_{r_1}=1/49.7=0.02\end{array}\right\}z_1=1.00\quad\text{(Fig. 5.4-2)}$$

$$\left.\begin{array}{l}T_{r_2}=358/154.4=2.23\\ P_{r_2}=1000/49.7=20.12\end{array}\right\}z_2=1.61\ \text{(Fig. 5.4-4)}$$

$$V_2=V_1\frac{z_2}{z_1}\frac{T_2}{T_1}\frac{P_1}{P_2}$$

$$V_2=\begin{array}{c|c|c|c}127\ \text{m}^3 & 1.61 & 358\ \text{K} & 1\ \text{atm}\\ \hline \text{h} & 1.00 & 298\ \text{K} & 1000\ \text{atm}\end{array}=\underline{\underline{0.246\ \text{m}^3/\text{h}}}$$

5.68 $\underline{O_2}$: $T_C=154.4\ \text{K}$, $P_C=49.7\ \text{atm}$

$T_r=(27+273.2)/154.4=1.94$

$P_{r_1}=175/49.7=3.52\Rightarrow z_1=0.95$ (Fig. 5.3-2)

$P_{r_2}=1.1/49.7=0.02\Rightarrow z_2=1.00$

$$n_1-n_2=\frac{V}{RT}\left(\frac{P_1}{z_1}-\frac{P_2}{z_2}\right)=\begin{array}{c|c}10.0\ \text{L} & \text{mol}\cdot\text{K}\\ \hline 300.2\ \text{K} & 0.08206\ \text{L}\cdot\text{atm}\end{array}\left(\frac{175\ \text{atm}}{0.95}-\frac{1.1\ \text{atm}}{1.00}\right)=\underline{\underline{74.3\ \text{mol}\ O_2}}$$

5.69 **a.** $\hat{V} = \dfrac{V}{n} = \dfrac{50.0\text{ mL}}{5.00\text{ g}}\left|\dfrac{44.01\text{ g}}{\text{mol}}\right. = 440.1\text{ mL / mol}$

$$P = \frac{RT}{\hat{V}} = \frac{82.06\text{ mL}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\left|\frac{1000\text{ K}}{440.1\text{ mL / mol}}\right. = \underline{\underline{186\text{ atm}}}$$

b. For CO_2: $T_c = 304.2\text{ K}$, $P_c = 72.9\text{ atm}$

$$T_r = \frac{T}{T_c} = \frac{1000\text{ K}}{304.2\text{ K}} = 3.2873$$

$$V_r^{\text{ideal}} = \frac{\hat{V}P_c}{RT_c} = \frac{440.1\text{ mL}}{\text{mol}}\left|\frac{72.9\text{ atm}}{304.2\text{ K}}\right|\frac{\text{mol}\cdot\text{K}}{82.06\text{ mL}\cdot\text{atm}} = 1.28$$

Figure 5.4-3: $V_r^{\text{ideal}} = 1.28$ and $T_r = 3.29 \Rightarrow z = 1.02$

$$P = \frac{zRT}{\hat{V}} = \frac{1.02}{}\left|\frac{82.06\text{ mL}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\frac{\text{mol}}{440.1\text{ mL}}\left|\frac{1000\text{ K}}{}\right. = \underline{\underline{190\text{ atm}}}$$

c. $a = 3.654\times10^6\ \text{mL}^2\cdot\text{atm / mol}^2$, $b = 29.67\text{ mL / mol}$, $m = 0.8263$, $\alpha(1000K) = 0.1077$

$$P = \frac{\left(82.06\,\frac{\text{mL}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right)(1000\text{ K})}{(440.1 - 29.67)\,\frac{\text{mL}}{\text{mol}}} - \frac{(0.1077)\left(3.654\times10^6\,\frac{\text{mL}^2\cdot\text{atm}}{\text{mol}^2}\right)}{440.1(440.1 + 29.67)\,\frac{\text{mL}^2}{\text{mol}^2}} = \underline{\underline{198\text{ atm}}}$$

5.70 **a.** The tank is being purged in case it is later filled with a gas that could ignite in the presence of O_2.

b. Enough N_2 needs to be added to make $x_{O_2} = 10\times10^{-6}$. Since the O_2 is so dilute at this condition, the properties of the gas will be that of N_2.

$T_c = 126.2\text{ K}$, $P_c = 33.5\text{ atm}$, $T_r = 2.36$

$$n_{\text{initial}} = n_1 = \frac{PV}{RT} = \frac{1\text{ atm}}{0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\left|\frac{5000\text{ L}}{298.2\text{ K}}\right. = 204.3\text{ mol}$$

$$n_{O_2} = 204.3\text{ mol air}\left(\frac{0.21\text{ mol }O_2}{\text{mol air}}\right) = 42.9\text{ mol }O_2$$

$$\frac{n_{O_2}}{n_2} = 10\times10^{-6} \Rightarrow n_2 = 4.29\times10^{-6}\text{ mol}$$

$$\hat{V} = \frac{5000\text{ L}}{4.29\times10^6\text{ mol}} = 1.16\times10^{-3}\text{ L / mol}$$

$$\hat{V}_r^{\text{ideal}} = \frac{\hat{V}P_c}{RT_c} = \frac{1.16\times10^{-3}\text{ L}}{\text{mol}}\left|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}}\right|\frac{33.5\text{ atm}}{126.2\text{ K}} = 3.8\times10^{-3}$$

$\Rightarrow$ not found on compressibility charts

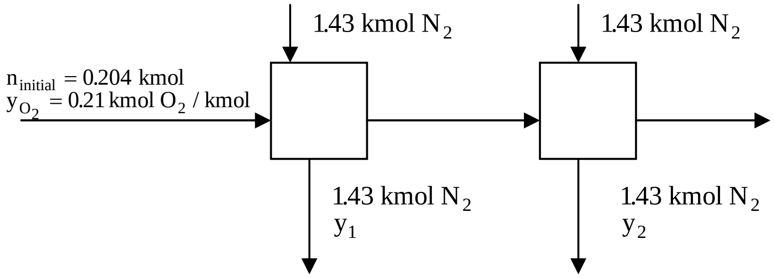
$$\text{Ideal gas: } P = \frac{RT}{\hat{V}} = \frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\left|\frac{298.2\text{ K}}{1.16\times10^{-3}\text{ L / mol}}\right. = \underline{\underline{2.1\times10^4\text{ atm}}}$$

The pressure required will be higher than 2.1×10^4 atm if $z \geq 1$, which from Fig. 5.3-3 is very likely.

$$n_{\text{added}} = 4.29\times10^6 - 204.3 \cong \left(4.29\times10^6\text{ mol }N_2\right)\left(0.028\text{ kg }N_2\text{ / mol}\right) = \underline{\underline{1.20\times10^5\text{ kg }N_2}}$$

5.70 (cont'd)

c.



$$N_2 \text{ at 700 kPa gauge} = 7.91 \text{ atm abs.} \Rightarrow P_r = 0.236,\ T_r = 2.36 \xRightarrow{\text{Fig 5.4-2}} z = 0.99$$

$$n_2 = \frac{P_2 V}{zRT} = \frac{7.91 \text{ atm}}{0.99}\left|\frac{5000 \text{ L}}{0.08206 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\right|\frac{}{298.2 \text{ K}} = 1.633 \text{ kmol}$$

$$y_1 = \frac{y_{init}\, n_{init}}{1.634} = \frac{(0.21)0.204}{1.634} = 0.026$$

$$y_2 = \frac{y_1 n_{init}}{1.634} = y_{init}\left(\frac{n_{init}}{1.634}\right)^2 = 0.0033$$

$$y_n = y_{init}\left(\frac{n_{init}}{1.634}\right)^n \Rightarrow n = \frac{\ln\left(\frac{y_n}{y_{init}}\right)}{\ln\left(\frac{n_{init}}{1.634}\right)} = \underline{\underline{4.8 \Rightarrow \text{Need at least 5 stages}}}$$

$$\text{Total } N_2 = 5(1.43 \text{ kmol } N_2)(28.0 \text{ kg / kmol}) = \underline{\underline{200 \text{ kg } N_2}}$$

d. Multiple cycles use less N$_2$ and require lower operating pressures. The disadvantage is that it takes longer.

5.71 **a.** $$\dot{m} = MW\frac{P\dot{V}}{RT} \Rightarrow \text{Cost (\$ / h)} = \dot{m}S = MW\frac{SP\dot{V}}{RT} = \left(\frac{44.09 \text{ lb}_m / \text{lb-mol}}{0.7302 \frac{\text{ft}^3\cdot\text{atm}}{\text{lb-mol}\cdot{}^o\text{R}}}\right)\frac{SP\dot{V}}{T} = \underline{\underline{60.4\frac{SP\dot{V}}{T}}}$$

b. $$\left.\begin{aligned} T_c &= 369.9 \text{ K} = 665.8^o \text{R} \Rightarrow & T_r &= 0.85 \\ P_c &= 42.0 \text{ atm} \Rightarrow & P_r &= 0.16 \end{aligned}\right\} \overset{\text{Fig. 5.4-2}}{\Rightarrow} z = 0.91$$

$$\dot{m} = 60.4\frac{P\dot{V}}{zT} = \frac{\dot{m}_{ideal}}{z} = 1.10\dot{m}_{ideal}$$

$\Rightarrow$ $\underline{\underline{\text{Delivering 10\% more than they are charging for (undercharging their customer)}}}$

5.72 **a.** For N_2: $T_c = 126.20\text{ K} = 227.16^{o}\text{R},\ \ P_c = 33.5\text{ atm}$

$$\left.\begin{array}{l}\text{After heater: } T_r = \dfrac{609.7^{o}\text{R}}{227.16^{o}\text{R}} = 2.68 \\ P_r = \dfrac{600\text{ psia}}{33.5\text{ atm}}\left|\dfrac{1\text{ atm}}{14.7\text{ psia}}\right. = 1.2\end{array}\right\}\Rightarrow z = 1.02$$

$$\dot{n} = \frac{150\text{ SCFM}}{359\text{ SCF / lb-mole}} = 0.418\text{ lb-mole / min}$$

$$\dot{V} = \frac{zRT\dot{n}}{P} = \frac{1.02}{}\left|\frac{0.418\text{ lb-mole}}{\text{min}}\right|\frac{10.73\text{ ft}^3\cdot\text{psia}}{\text{lb-mole}\cdot^{o}\text{R}}\left|\frac{609.7^{o}\text{R}}{600\text{ psia}}\right. = \underline{\underline{4.65\text{ ft}^3\text{ / min}}}$$

b.
$$\text{tank} = \frac{0.418\text{ lb-mole}}{\text{min}}\left|\frac{28\text{ lb}_m\text{ / lb-mole}}{(0.81)62.4\text{ lb}_m\text{ / ft}^3}\right|\frac{60\text{ min}}{\text{h}}\left|\frac{24\text{ h}}{\text{day}}\right|\frac{7\text{ days}}{\text{week}}\left|\frac{2\text{ weeks}}{}\right.$$

$$= \underline{\underline{4668\text{ ft}^3 = 34{,}900\text{ gal}}}$$

5.73 **a.** For CO: $T_c = 133.0\text{ K},\ \ P_c = 34.5\text{ atm}$

$$\left.\begin{array}{l}\text{Initially: } T_{r1} = \dfrac{300\text{ K}}{133.0\text{ K}} = 2.26 \\ P_{r1} = \dfrac{2514.7\text{ psia}}{34.5\text{ atm}}\left|\dfrac{1\text{ atm}}{14.7\text{ psia}}\right. = 5.0\end{array}\right\}\xRightarrow{\text{Fig. 5.4-3}} z = 1.02$$

$$n_1 = \frac{2514.7\text{ psia}}{1.02}\left|\frac{150\text{ L}}{300\text{ K}}\right|\frac{1\text{ atm}}{14.7\text{ psia}}\left|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}}\right. = 1022\text{ mol}$$

$$\left.\begin{array}{l}\text{After 60h: } T_{r1} = \dfrac{300\text{ K}}{133.0\text{ K}} = 2.26 \\ P_{r1} = \dfrac{2258.7\text{ psia}}{34.5\text{ atm}}\left|\dfrac{1\text{ atm}}{14.7\text{ psia}}\right. = 4.5\end{array}\right\}\xRightarrow{\text{Fig. 5.4-3}} z = 1.02$$

$$n_2 = \frac{2259.7\text{ psia}}{1.02}\left|\frac{150\text{ L}}{300\text{ K}}\right|\frac{1\text{ atm}}{14.7\text{ psia}}\left|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}}\right. = 918\text{ mol}$$

$$\dot{n}_{leak} = \frac{n_1 - n_2}{60\text{ h}} = \underline{\underline{1.73\text{ mol / h}}}$$

b.
$$n_2 = y_2 n_{air} = y_2\frac{PV}{RT} = \frac{200\times10^{-6}\text{ mol CO}}{\text{mol air}}\left|\frac{1\text{ atm}}{0.08206\,\frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\right|\frac{30.7\text{ m}^3}{300\text{ K}}\left|\frac{1000\text{ L}}{\text{m}^3}\right. = 0.25\text{ mol}$$

$$t_{min} = \frac{n_2}{\dot{n}_{leak}} = \frac{0.25\text{ mol}}{1.73\text{ mol / h}} = \underline{\underline{0.14\text{ h}}}$$

$$\Rightarrow \underline{\underline{t_{min}\text{ would be greater because the room is not perfectly sealed}}}$$

c. (i) CO may not be evenly dispersed in the room air; (ii) you could walk into a high concentration area; (iii) there may be residual CO left from another tank; (iv) the tank temperature could be higher than the room temperature, and the estimate of gas escaping could be low.

5.74 $\underline{\text{CH}_4}$: $T_c = 190.7\text{ K},\ P_c = 45.8\text{ atm}$

$\underline{\text{C}_2\text{H}_6}$: $T_c = 305.4\text{ K},\ P_c = 48.2\text{ atm}$

$\underline{\text{C}_2\text{H}_4}$: $T_c = 283.1\text{ K},\ P_c = 50.5\text{ atm}$

Pseudocritical temperature: $T_c' = (0.20)(190.7) + (0.30)(305.4) + (0.50)(283.1) = 271.3\text{ K}$

Pseudocritical pressure: $P_c' = (0.20)(45.8) + (0.30)(48.2) + (0.50)(50.5) = 48.9\text{ atm}$

$$\left.\begin{array}{ll}\text{Reduced temperature:} & T_r = \dfrac{(90+273.2)\text{K}}{271.3\text{ K}} = 1.34 \\ \text{Reduced pressure:} & P_r = \dfrac{200\text{ bars}}{48.9\text{ atm}}\left|\dfrac{1\text{ atm}}{1.01325\text{ bars}}\right. = 4.04\end{array}\right\} \overset{\text{Figure 5.4-3}}{\Rightarrow} z = 0.71$$

Mean molecular weight of mixture:

$$\begin{aligned}\overline{M} &= (0.20)M_{CH_4} + (0.30)M_{C_2H_6} + (0.50)M_{C_2H_4} \\ &= (0.20)(16.04) + (0.30)(30.07) + (0.50)(28.05) \\ &= 26.25\text{ kg/kmol}\end{aligned}$$

$$V = \frac{znRT}{P} = \frac{0.71}{}\left|\frac{10\text{ kg}}{}\right|\frac{1\text{ kmol}}{26.25\text{ kg}}\left|\frac{0.08314\text{ m}^3\cdot\text{bar}}{\text{kmol}\cdot\text{K}}\right|\frac{(90+273)\text{ K}}{200\text{ bars}} = \underline{\underline{0.041\text{ m}^3}}(41\text{ L})$$

5.75

$$\left.\begin{array}{l}\underline{N_2}:\ T_c = 126.2\text{ K},\ P_C = 33.5\text{ atm} \\ \underline{N_2O}:\ T_c = 309.5\text{ K},\ P_C = 71.7\text{ atm}\end{array}\right\}\begin{array}{l}T_c' = 0.10(309.5) + 0.90(126.2) = 144.5\text{ K} \\ P_c' = 0.10(71.7) + 0.90(33.5) = 37.3\text{ atm}\end{array}$$

$\overline{M} = 0.10(44.02) + 0.90(28.02) = 29.62$

$n = 5.0\text{ kg}(1\text{ kmol}/29.62\text{ kg}) = 0.169\text{ kmol} = 169\text{ mol}$

a.

$$\left.\begin{array}{l}T_r = (24+273.2)/144.5 = 2.06 \\ \hat{V}_r = \dfrac{30\text{ L}}{169\text{ mol}}\left|\dfrac{37.3\text{ atm}}{144.5\text{ K}}\right|\dfrac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}} = 0.56\end{array}\right\}\Rightarrow z = 0.97(\text{Fig. 5.4-3})$$

$$P = \frac{0.97}{}\left|\frac{169\text{ mol}}{30\text{ L}}\right|\frac{297.2\text{ K}}{}\left|\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right. = 133\text{ atm} \Rightarrow \underline{\underline{132\text{ atm gauge}}}$$

b.

$$\left.\begin{array}{l}P_r = 273/37.3 = 7.32 \\ \hat{V}_r = 0.56\ (\text{from a.})\end{array}\right\}\Rightarrow z = 1.14\ (\text{Fig. 5.4-3})$$

$$T = \frac{273\text{ atm}}{1.14}\left|\frac{30\text{ L}}{169\text{ mol}}\right|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}} = 518\text{ K} \Rightarrow \underline{\underline{245°\text{C}}}$$

5.76

$$\left.\begin{array}{l}\text{CO: } T_c = 133.0\text{ K},\ P_c = 34.5\text{ atm}\\ H_2\text{: } T_c = 33\text{ K},\ P_c = 12.8\text{ atm}\end{array}\right\}\begin{array}{l}T_c' = 0.60(133.0) + 0.40(33+8) = 96.2\text{ K}\\ P_c' = 0.60(34.5) + 0.40(12.8+8) = 29.0\text{ atm}\end{array}$$

Turbine inlet:

$$\left.\begin{array}{l}T_r = (150+273.2)/96.2 = 4.4\\ P_r = \dfrac{2000\text{ psi}}{29.0\text{ atm}}\left|\dfrac{1\text{ atm}}{14.7\text{ psi}}\right. = 4.69\end{array}\right\}\xrightarrow{\text{Fig. 5.4-1}} z \approx 1.01$$

Turbine exit:

$$\left.\begin{array}{l}T_r = 373.2/96.2 = 3.88\\ P_r = 1/29.0 = 0.03\end{array}\right\}\Rightarrow z = 1.0$$

$$\frac{P_{in}\dot{V}_{in}}{P_{out}\dot{V}_{out}} = \frac{z_{in}nRT_{in}}{z_{out}n\ RT_{out}} \Rightarrow V_{in} = V_{out}\times\frac{P_{out}}{P_{in}}\frac{z_{in}}{z_{out}}\frac{T_{in}}{T_{out}} = 15{,}000\frac{\text{ft}^3}{\text{min}}\left|\frac{14.7\text{ psia}}{2000\text{ psia}}\right|\frac{1.01}{1.00}\left|\frac{423.2\text{K}}{373.2}\right.$$

$$= \underline{\underline{126\text{ ft}^3/\text{min}}}$$

If the ideal gas equation of state were used, the factor 1.01 would instead be 1.00

$\Rightarrow \underline{\underline{-1\%\text{ error}}}$

5.77

$$\left.\begin{array}{l}\text{CO: } T_c = 133.0\text{ K},\ P_c = 34.5\text{ atm}\\ CO_2\text{: } T_c = 304.2\text{ K},\ P_c = 72.9\text{ atm}\end{array}\right\}\begin{array}{l}T_c' = 0.97(133.0) + 0.03(304.2) = 138.1\text{ K}\\ P_c' = 0.97(34.5) + 0.03(72.9) = 35.7\text{ atm} = 524.8\text{ psi}\end{array}$$

Initial:

$$\left.\begin{array}{l}T_r = 303.2/138.1 = 2.2\\ P_r = 2014.7/524.8 = 3.8\end{array}\right\}\xrightarrow{\text{Fig. 5.4-3}} z_1 = 0.97$$

Final: $P_r = 1889.7/524.8 = 3.6 \Rightarrow z_1 = 0.97$

Total moles leaked:

$$n_1 - n_2 = \left(\frac{P_1}{z_1} - \frac{P_2}{z_2}\right)\frac{V}{RT} = \frac{(2000-1875)\text{psi}}{0.97}\left|\frac{30.0\text{ L}}{303\text{ K}}\right|\frac{1\text{ atm}}{14.7\text{ psi}}\left|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}}\right.$$

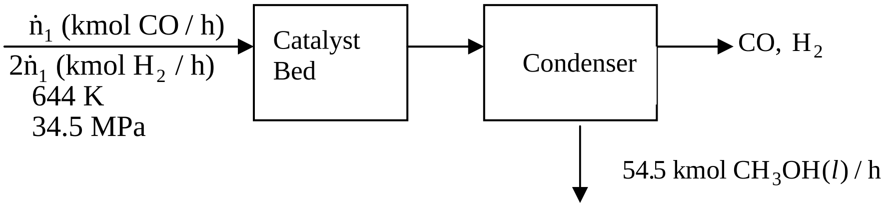
$$= 10.6\text{ mol leaked}$$

Moles CO leaked: $0.97(10.6) = 10.3\text{ mol CO}$

Total moles in room: $$\frac{24.2\text{ m}^3}{}\left|\frac{10^3\text{ L}}{1\text{ m}^3}\right|\frac{273\text{ K}}{303\text{ K}}\left|\frac{1\text{ mol}}{22.4\text{ L(STP)}}\right. = 973.4\text{ mol}$$

Mole% CO in room = $$\frac{10.3\text{ mol CO}}{973.4\text{ mol}}\times 100\% = \underline{\underline{1.0\%\text{ CO}}}$$

5.78 Basis: $54.5\ \text{kmol CH}_3\text{OH/h}$ $\qquad CO + 2H_2 \rightarrow CH_3OH$



a. $$\dot{n}_1 = \frac{54.5 \text{ kmol CH}_3\text{OH}}{\text{h}} \left| \frac{1 \text{ kmol CO react}}{1 \text{ kmol CH}_3\text{OH}} \right| \frac{1 \text{ kmol CO fed}}{0.25 \text{ kmol CO react}} = 218\ \text{kmol/h CO}$$

$$2\dot{n}_1 = 2(218) = 436 \text{ kmol } H_2/\text{h} \Rightarrow (218+436) = 654\ \text{kmol/h (total feed)}$$

CO: $T_c = 133.0$ K $\qquad P_c = 34.5$ atm

H_2: $T_c = 33$ K $\qquad P_c = 12.8$ atm

$\Downarrow$ Newton's corrections

$$T_c' = \frac{1}{3}(133.0) + \frac{2}{3}(33+8) = 71.7 \text{ K}$$

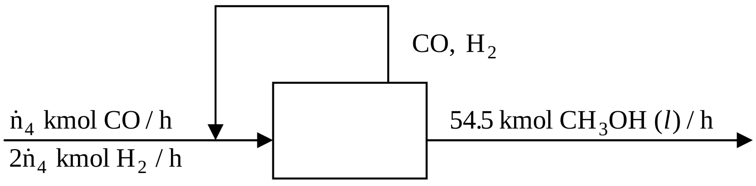
$$P_c' = \frac{1}{3}(34.5) + \frac{2}{3}(12.8+8) = 25.4 \text{ atm}$$

$$\left.\begin{array}{l} T_r = 644/71.7 = 8.98 \\ P_r = \dfrac{34.5 \text{ MPa}}{24.5 \text{ atm}} \left| \dfrac{10 \text{ atm}}{1.013 \text{ MPa}} \right. = 13.45 \end{array}\right\} \xrightarrow{\text{Fig. 5.4-4}} z_1 = 1.18$$

$$\dot{V}_{\text{feed}} = \frac{1.18}{} \left| \frac{654 \text{ kmol}}{\text{h}} \right| \frac{644 \text{ K}}{34.5 \text{ MPa}} \left| \frac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \right| \frac{1.013 \text{ MPa}}{10 \text{ atm}} = \underline{\underline{120\ \text{m}^3/\text{h}}}$$

$$V_{\text{cat}} = \frac{120\ \text{m}^3/\text{h}}{} \left| \frac{1 \text{ m}^3 \text{ cat}}{25{,}000 \text{ m}^3/\text{h}} \right. = \underline{\underline{0.0048 \text{ m}^3 \text{ catalyst (4.8 L)}}}$$

b.



Overall C balance $\Rightarrow \dot{n}_4 = 54.5$ mol CO/h

<u>Fresh feed:</u>

	54.5 kmol CO/h
	109.0 kmol H_2/h
	163.5 kmol feed gas/h

$$\dot{V}_{\text{feed}} = \frac{1.18}{} \left| \frac{163.5 \text{ kmol}}{\text{h}} \right| \frac{644 \text{ K}}{34.5 \text{ MPa}} \left| \frac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}} \right| \frac{1.013 \text{ MPa}}{10 \text{ atm}} = \underline{\underline{29.9\ \text{m}^3/\text{h}}}$$

5.79 $\underline{H_2}$: $T_c = (33.3+8)\text{ K} = 41.3\text{ K}$ $\quad$ $\underline{\text{1-butene}}$: $T_c = 419.6\text{ K}$

$P_c = (12.8+8)\text{ atm} = 20.8\text{ atm}$ $\quad$ $P_c = 39.7\text{ atm}$

$$\left.\begin{array}{ll} T_c' = 0.15(41.3\text{ K}) + 0.85(419.6\text{ K}) = 362.8\text{ K} & T_r' = 0.89 \\ P_c' = 0.15(20.8\text{ atm}) + 0.85(39.7\text{ atm}) = 36.9\text{ atm} & P_r' = 0.27 \end{array}\right\} \overset{\text{Fig. 5.4-2}}{\Rightarrow} z = 0.86$$

$$\dot{V} = \frac{z\dot{n}RT}{P} = \begin{array}{c|c|c|c|c} 0.86 & 35\text{ kmol} & 0.08206\text{ m}^3\cdot\text{atm} & 323\text{ K} & 1\text{ h} \\ \hline & \text{h} & \text{kmol}\cdot\text{K} & 10\text{ atm} & 60\text{ min} \end{array} = 1.33\text{ m}^3/\text{min}$$

$$\dot{V}\left(\frac{\text{m}^3}{\text{min}}\right) = u\left(\frac{\text{m}}{\text{min}}\right)A\left(\text{m}^2\right) = u \times \frac{\pi d^2}{4} \Rightarrow d = \sqrt{\frac{4\dot{V}}{\pi u}} = \sqrt{\frac{4\left(1.33\text{ m}^3/\text{min}\right)}{\pi\left(150\text{ m}/\text{min}\right)}}\left(\frac{100\text{ cm}}{\text{m}}\right) = \underline{\underline{10.6\text{ cm}}}$$

5.80 $\underline{CH_4}$: $T_c = 190.7\text{ K}$ $\quad P_c = 45.8\text{ atm}$

$\underline{C_2H_4}$: $T_c = 283.1\text{ K}$ $\quad P_c = 50.5\text{ atm}$

$\underline{C_2H_6}$: $T_c = 305.4\text{ K}$ $\quad P_c = 48.2\text{ atm}$

$$\left.\begin{array}{l} T_c' = 0.15(190.7\text{ K}) + 0.60(283.1\text{ K}) + 0.25(305.4\text{ K}) = 274.8\text{ K} \overset{T=90^\circ\text{C}}{=\!=\!=\!=\!>} \quad T_r' = 1.32 \\ P_c' = 0.15(45.8\text{ atm}) + 0.60(50.5\text{ atm}) + 0.25(48.2\text{ atm}) = 49.2\text{ atm} \overset{P=175\text{ bar}}{=\!=\!=\!=\!=\!>} P_r' = 3.5 \end{array}\right\}$$

$$\xrightarrow{\text{Fig. 5.4-3}} z = 0.67$$

$$\dot{V}\left(\frac{\text{m}^3}{s}\right) = u\left(\frac{\text{m}}{\text{s}}\right)A\left(\text{m}^2\right) = \left(10\ \frac{\text{m}}{\text{s}}\right)\left(60\ \frac{\text{s}}{\text{min}}\right)\frac{\pi}{4}\left(0.02\text{ m}\right)^2 = 0.188\ \frac{\text{m}^3}{\text{min}}$$

$$\dot{n} = \frac{P\dot{V}}{zRT} = \begin{array}{c|c|c|c} 175\text{ bar} & 1\text{ atm} & \text{kmol}\cdot\text{K} & 0.188\text{ m}^3/\text{min} \\ \hline 0.67 & 1.013\text{ bar} & .08206\text{ m}^3\cdot\text{atm} & 363\text{ K} \end{array} = \underline{\underline{1.63\text{ kmol}/\text{min}}}$$

5.81 $\underline{N_2}$: $T_c = 126.2\text{ K} = 227.16^\circ\text{R}$ $\quad P_c = 33.5\text{ atm}$

$\underline{\text{acetonitrile}}$: $T_c = 548\text{ K} = 986.4^\circ\text{R}$ $\quad P_c = 47.7\text{ atm}$

$\underline{\text{Tank 1 (acetonitrile)}}$: $T_1 = 550^\circ\text{F},\ P_1 = 4500\text{ psia} \Rightarrow T_{r1} = 1.02\ \ P_{r1} = 6.4 \overset{\text{Fig. 5.4-3}}{\Rightarrow} z_1 = 0.80$

$$\Rightarrow\ \dot{n}_1 = \frac{P_1V_1}{z_1RT_1} = \begin{array}{c|c|c} 306\text{ atm} & 0.200\text{ ft}^3 & \text{lb-mole}\cdot^\circ\text{R} \\ \hline 0.80 & 1009.7^\circ\text{R} & 0.7302\text{ ft}^3\cdot\text{atm} \end{array} = 0.104\text{ lb-mole}$$

$\underline{\text{Tank 2 }(N_2)}$: $T_2 = 550^\circ\text{F},\ P_2 = 10\text{ atm} \Rightarrow T_{r2} = 4.4,\ \ P_{r2} = 6.4 \overset{\text{Fig. 5.4-3}}{\Rightarrow} z_2 = 1.00$

$$\Rightarrow\ \dot{n}_2 = \frac{P_2V_2}{z_2RT_2} = \begin{array}{c|c|c} 10.0\text{ atm} & 2.00\text{ ft}^3 & \text{lb-mole}\cdot^\circ\text{R} \\ \hline 1.00 & 1009.7^\circ\text{R} & .7302\text{ ft}^3\cdot\text{atm} \end{array} = 0.027\text{ lb-mole}$$

5.81 (cont'd)

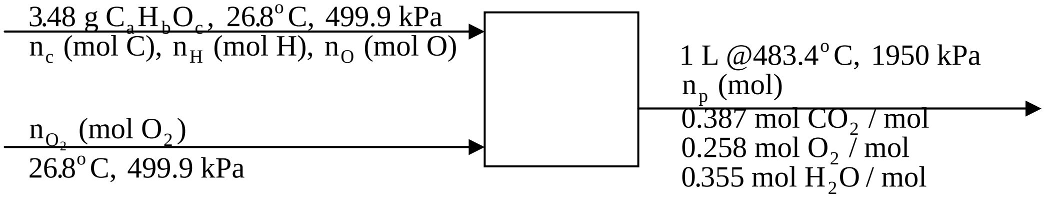
$$\underline{\text{Final}}:\ T_c' = \left(\frac{0.104}{0.131}\right)986.4^\circ\text{ R} + \left(\frac{0.027}{0.131}\right)227.16^\circ\text{ R} = 830^\circ\text{ R} \xrightarrow{T=550^\circ\text{ F}} T_r' = 1.22$$

$$P_c' = \left(\frac{0.104}{0.131}\right)47.7\text{ atm} + \left(\frac{0.027}{0.131}\right)33.5\text{ atm} = 44.8\text{ atm}$$

$$\left(\hat{V}_r\right)_{\text{ideal}} = \frac{\hat{V}P_c'}{RT_c'} = \frac{2.2\text{ ft}^3}{0.131\text{ lb-mole}}\left|\frac{44.8\text{ atm}}{830^\circ\text{ R}}\right|\frac{\text{lb-mole}\cdot^\circ\text{ R}}{0.7302\text{ ft}^3\cdot\text{atm}} = 1.24 \overset{\text{Fig. 5.4-2}}{\Rightarrow} z = 0.85$$

$$P = \frac{znRT}{V} = \frac{0.85}{}\left|\frac{0.131\text{ lb-mole}}{}\right|\frac{.7302\text{ ft}^3\cdot\text{atm}}{\text{lb-mole}\cdot^\circ\text{ R}}\left|\frac{1009.7^\circ\text{ R}}{2.2\text{ ft}^3}\right. = \underline{\underline{37.3\text{ atm}}}$$

5.82



a. $\underline{\text{Volume of sample}}$: $3.42\text{ g}\left(1\text{ cm}^3/1.59\text{ g}\right) = 2.15\text{ cm}^3$

$\underline{O_2\text{ in Charge}}$:

$$n_{O_2} = \frac{\left[1.000\text{ L} - 2.15\text{ cm}^3\left(10^{-3}\ \text{L/km}^3\right)\right]}{0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\left|\frac{499.9\text{ kPa}}{300\text{ K}}\right|\frac{1\text{ atm}}{101.3\text{ kPa}} = 0.200\text{ mol }O_2$$

Product

$$n_p = \frac{1.000\text{ L}}{0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}}\left|\frac{1950\text{ kPa}}{756.6\text{ K}}\right|\frac{1\text{ atm}}{101.3\text{ kPa}} = 0.310\text{ mol product}$$

Balances:

$\underline{\text{O}}$: $2(0.200) + n_O = 0.310\left[2(0.387) + 2(0.258) + 0.355\right] \Rightarrow n_O = 0.110$ mol O in sample

$\underline{\text{C}}$: $n_C = 0.387(0.310) = 0.120$ mol C in sample

$\underline{\text{H}}$: $n_H = 2(0.355)(0.310) = 0.220$ mol H in sample

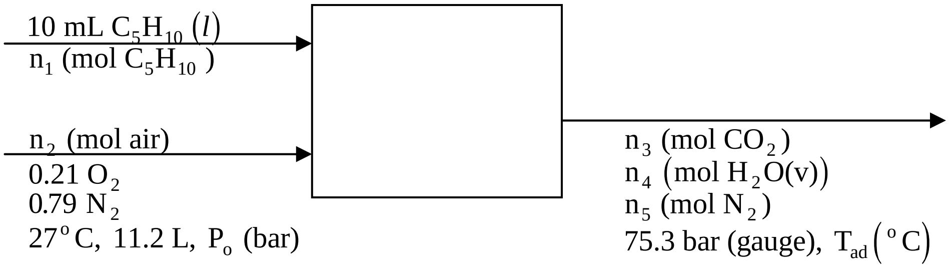
Assume $c = 1 \Rightarrow a = 0.120/0.110 = 1.1 \quad b = 0.220/0.110 = 2$

Since a, b, and c must be integers, possible solutions are (a,b,c) = (11,20,10), (22,40,20), etc.

b. $MW = 12.01a + 1.01b + 16.0c = 12.01(1.1c) + 1.01(2c) + 16.0c = 31.23c$

$300 < MW < 350 \Rightarrow c = 10 \Rightarrow \underline{\underline{C_{11}H_{20}O_{10}}}$

5.83 Basis: 10 mL $C_5H_{10}(l)$ charged to reactor $\qquad C_5H_{10} + \frac{15}{2}O_2 \rightarrow 5CO_2 + 5H_2O$



a. $$n_1 = \frac{10.0\text{ mL }C_5H_{10}(l)}{}\left|\frac{0.745\text{ g}}{\text{mL}}\right|\frac{1\text{ mol}}{70.13\text{ g}} = 0.1062\text{ mol }C_5H_{10}$$

Stoichiometric air: $$n_2 = \frac{0.1062\text{ mol }C_5H_{10}}{}\left|\frac{7.5\text{ mol }O_2}{1\text{ mol }C_2H_{10}}\right|\frac{1\text{ mol air}}{0.21\text{ mol }O_2} = 3.79\text{ mol air}$$

$$P_o = \frac{nRT}{V} = \frac{3.79\text{ mol}}{11.2\text{ L}}\left|\frac{0.08314\text{ L}\cdot\text{bar}}{\text{mol}\cdot\text{K}}\right|\frac{300\text{K}}{} = 8.44\text{ bars}$$

(We neglect the C_5H_{10} that may be present in the gas phase due to evaporation)

Initial gauge pressure = 8.44 bar − 1 bar = 7.44 bar

b.
$$\left.\begin{aligned}
n_3 &= \frac{0.1062\text{ mol }C_5H_{10}}{}\left|\frac{5\text{ mol }CO_2}{1\text{ mol }C_5H_{10}}\right. = 0.531\text{ mol }CO_2\\
n_4 &= \frac{0.531\text{ mol }CO_2}{}\left|\frac{1\text{ mol }H_2O}{1\text{ mol }CO_2}\right. = 0.531\text{ mol }H_2O\\
n_5 &= 0.79(3.79) = 2.99\text{ mol }N_2
\end{aligned}\right\}\Rightarrow 4.052\text{ mol product gas}$$

CO_2: $y_3 = 0.531/4.052 = 0.131$ mol CO_2 / mol, $T_c = 304.2$ K $P_c = 72.9$ atm

H_2O: $y_4 = 0.531/4.052 = 0.131$ mol H_2O / mol, $T_c = 647.4$ K $P_c = 218.3$ atm

N_2: $y_5 = 2.99/4.052 = 0.738$ mol N_2 / mol, $T_c = 126.2$ K $P_c = 33.5$ atm

$$T_c{}' = 0.131(304.2\text{ K}) + 0.131(647.4\text{ K}) + 0.738(126.2\text{ K}) = 217.8\text{ K}$$

$$P_c{}' = 0.131(72.9\text{ atm}) + 0.131(218.3\text{ atm}) + 0.738(33.5\text{ atm}) = 62.9\text{ atm} \Rightarrow P_r{}' = 1.21$$

$$\hat{V}_r^{\text{ ideal}} = \frac{\hat{V}P_c{}'}{RT_c{}'} = \frac{11.2\text{ L}}{4.052\text{ mol}}\left|\frac{62.9\text{ atm}}{217.8\text{ K}}\right|\frac{\text{mol}\cdot\text{K}}{.08206\text{ L}\cdot\text{atm}} = 9.7 \Rightarrow z \approx 1.04\text{ (Fig. 5.4-3)}$$

$$T = \frac{PV}{znR} = \frac{(75.3+1)\text{bars}}{1.04}\left|\frac{11.2\text{ L}}{4.052\text{ mol}}\right|\frac{\text{mol}\cdot\text{K}}{0.08314\text{ L}\cdot\text{bar}} = 2439\text{ K} - 273 = 2166^{\circ}\text{C}$$

CHAPTER SIX

6.1 **a**. $\underline{\text{AB: Heat liquid}}$ - - $V \approx$ constant

$\underline{\text{BC: Evaporate liquid}}$ - - V increases, system remains at point on vapor - liquid equilibrium curve as long as some liquid is present. $T = 100^{\circ}\,\text{C}$.

$\underline{\text{CD: Heat vapor}}$ - - T increases, V increases.

b. Point B: Neglect the variation of the density of liquid water with temperature, so ρ = 1.00 g/mL and $V_B = \underline{\underline{10\text{ mL}}}$

Point C: H_2O (v, 100°C)

$$n = \frac{10\text{ mL}}{} \left| \frac{1.00\text{ g}}{\text{mL}} \right| \frac{1\text{ mol}}{18.02\text{ g}} = 0.555\text{ mol}$$

$$P_C V_C = nRT_C \Rightarrow V_C = \frac{nRT_C}{P_C} = \frac{0.555\text{ mol}}{1\text{ atm}} \left| \frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} \right| \frac{373\text{ K}}{} = \underline{\underline{17\text{ L}}}$$

6.2 **a**. $P_{\text{final}} = \underline{\underline{243\text{ mm Hg}}}$. Since liquid is still present, the pressure and temperature must lie on the vapor-liquid equilibrium curve, where by definition the pressure is the vapor pressure of the species at the system temperature.

b. Assuming ideal gas behavior for the vapor,

$$\text{m(vapor)} = \frac{(3.000 - 0.010)\text{ L}}{(30 + 273.2)\text{ K}} \left| \frac{\text{mol}\cdot\text{K}}{0.08206\text{ L}\cdot\text{atm}} \right| \frac{243\text{ mm Hg}}{} \left| \frac{1\text{ atm}}{760\text{ mm Hg}} \right| \frac{119.39\text{ g}}{\text{mol}} = 4.59\text{ g}$$

$$\text{m(liquid)} = \frac{10\text{ mL}}{} \left| \frac{1.489\text{ g}}{\text{mL}} \right. = 14.89\text{ g}$$

$$\text{m}_{\text{total}} = \text{m(vapor)} + \text{m(liquid)} = \underline{\underline{19.5\text{ g}}}$$

$$\text{x}_{\text{vapor}} = \frac{4.59}{19.48} = \underline{\underline{0.235\text{ g vapor / g total}}}$$

6.3 **a**. $\log_{10} p^* = 7.09808 - \dfrac{1238.71}{45 + 217} = 2.370 \Rightarrow p^* = 10^{2.370} = \underline{\underline{234.5\text{ mm Hg}}}$

b. $\ln p^* = -\dfrac{\Delta\hat{H}_v}{R}\dfrac{1}{T} + B \Rightarrow -\dfrac{\Delta\hat{H}_v}{R} = \dfrac{\ln\left(p_2^* / p_1^*\right)}{\frac{1}{T_2} - \frac{1}{T_1}} = \dfrac{\ln(760 / 118.3)}{\frac{1}{(77.0+273.2)\text{K}} - \frac{1}{(29.5+273.2)\text{K}}} = -4151\text{K}$

$$B = \ln(p_1^*) + \frac{\Delta\hat{H}_v / R}{T_1} = \ln(118.3) + \frac{4151\text{ K}}{(29.5 + 273.2)\text{K}} = 18.49$$

6.3 (cont'd)

$$\ln p^*(45^\circ\text{C}) = -\frac{4151}{(45+273.2)} + 18.49 \Rightarrow \underline{\underline{p^* = 231.0 \text{ mm Hg}}}$$

$$\frac{231.0-234.5}{234.5}\times 100\% = \underline{\underline{-1.5\% \text{ error}}}$$

c. $$p^* = \left(\frac{118.3-760}{29.5-77}\right)(45-29.5)+118.3 = \underline{\underline{327.7 \text{ mm Hg}}}$$

$$\frac{327.7-234.5}{234.5}\times 100\% = \underline{\underline{39.7\% \text{ error}}}$$

6.4 Plot $p^*(\text{log scale})$ vs $\dfrac{1}{\text{T}+273.2}$ (rect. scale) on semilog paper

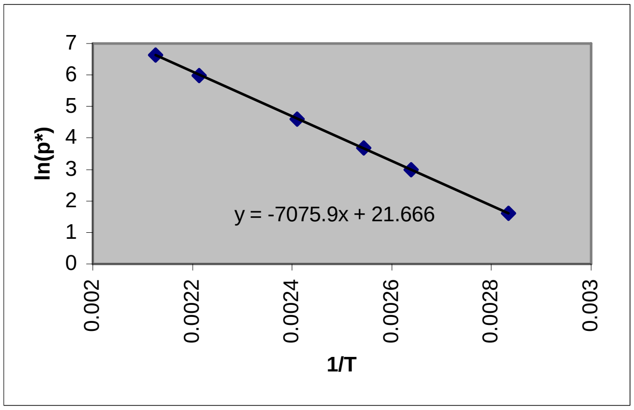
$\Rightarrow$ straight line: slope $=-7076\text{K}$, intercept $=21.67$

$$\ln p^*(\text{mm Hg}) = \frac{-7076}{T(^\circ\text{C})+273.2}+21.67 \Rightarrow \underline{\underline{p^*(\text{mm Hg}) = \exp\left[\frac{-7076}{T(^\circ\text{C})+273.2}+21.67\right]}}$$

$$\frac{\Delta H_v}{R} = 7076\text{K} \Rightarrow \Delta\hat{H}_v = \begin{array}{c|c|c} 7076\text{ K} & 8.314\text{ J} & 1\text{ kJ} \\ \hline & \text{mol}\cdot\text{K} & 10^3\text{ J} \end{array} = \underline{\underline{58.8 \text{ kJ/mol}}}$$

6.5 **ln p* = A/T(K) + B**

$T(^\circ C)$	p*(mm Hg)	1/T(K)	ln(p*)	p*(fitted)	$T(^\circ C)$	p*(fitted)	
79.7	5	0.002834	1.609	5.03	50	0.80	
105.8	20	0.002639	2.996	20.01	80	5.12	
120.0	40	0.002543	3.689	39.26	110	24.55	
141.8	100	0.002410	4.605	101.05	198	760.00	
178.5	400	0.002214	5.991	403.81	230	2000.00	Least confidence
197.3	760	0.002125	6.633	755.13			(Extrapolated)



6.6 **a.**

T(°C)	1/T(K)	p^*(mm Hg) =758.9 + h_{right} -h_{left}
42.7	3.17×10^{-3}	34.9
58.9	3.01×10^{-3}	78.9
68.3	2.93×10^{-3}	122.9
77.9	2.85×10^{-3}	184.9
88.6	2.76×10^{-3}	282.9
98.3	2.69×10^{-3}	404.9
105.8	2.64×10^{-3}	524.9

b. Plot is linear, $\ln p* = -\dfrac{\Delta\hat{H}_v}{RT} + B \Rightarrow \ln p* = \dfrac{-5143.8K}{T} + 19.855$

At the normal boiling point, $p* = 760 \text{ mmHg} \Rightarrow \underline{\underline{T_b = 116°\text{C}}}$

$$\Delta\hat{H}_v = \begin{array}{c|c|c} 8.314 \text{ J} & 5143.8 \text{ K} & 1 \text{ kJ} \\ \hline \text{mol}\cdot\text{K} & & 10^3 \text{ J} \end{array} = \underline{\underline{42.8 \text{ kJ/mol}}}$$

c. *Yes* — linearity of the $\ln p*$ vs $1/T$ plot over the full range implies validity.

6.7 **a.** $\ln p* = a/(T+273.2) + b \Rightarrow y = ax + b \quad [y = \ln p*;\ \ x = 1/(T+273.2)\ ]$

Perry's Handbook, Table 3-8:

$T_1 = 39.5°\text{C},\ p_1* = 400 \text{ mm Hg} \Rightarrow x_1 = 3.1980\times10^{-3},\ y_1 = 5.99146$

$T_2 = 56.5°\text{C},\ p_2* = 760 \text{ mm Hg} \Rightarrow x_2 = 3.0331\times10^{-3},\ y_2 = 6.63332$

$T = 50°\text{C} \Rightarrow x = 3.0941\times10^{-3}$

$$y = y_1 + \left(\frac{x - x_1}{x_2 - x_1}\right)(y_2 - y_1) = 6.39588 \Rightarrow p*(50°\text{C}) = e^{6.39588} = \underline{\underline{599 \text{ mm Hg}}}$$

b. $50°\text{C} = 122°\text{F} \xrightarrow{\text{Cox chart}} p* = \begin{array}{c|c} 12 \text{ psi} & 760 \text{ mm Hg} \\ \hline & 14.6 \text{ psi} \end{array} = \underline{\underline{625 \text{ mm Hg}}}$

c. $\log p* = 7.02447 - \dfrac{1161.0}{50 + 224} = 2.7872 \Rightarrow p* = 10^{2.7872} = \underline{\underline{613 \text{ mm Hg}}}$

6.8 Estimate $p*(35°\text{C})$: Assume $\ln p* = \dfrac{a}{T(K)} + b$, interpolate given data.

$$\left.\begin{array}{l} a = \dfrac{\ln(p_2*/p_1*)}{\frac{1}{T_2} - \frac{1}{T_1}} = \dfrac{\ln(200/50)}{\frac{1}{45+273.2} - \frac{1}{25+273.2}} = -6577.1 \\ b = \ln p_1* - \dfrac{a}{T_1} = \ln(50) + \dfrac{6577.1}{25 + 273.2} = 25.97 \end{array}\right\} \Rightarrow \begin{array}{l} \ln[p*(35°\text{C})] = -\dfrac{6577.1}{35 + 273.2} + 25.97 = 4.630 \\ p*(35°\text{C}) = e^{4.630} = 102.5 \text{ mm Hg} \end{array}$$

Moles in gas phase: $n = \begin{array}{c|c|c|c|c} 150 \text{ mL} & 273 \text{ K} & 102.5 \text{ mm Hg} & 1 \text{ L} & 1 \text{ mol} \\ \hline & (35 + 273.2) \text{ K} & 760 \text{ mm Hg} & 10^3 \text{m}L & 22.4 \text{ L(STP)} \end{array}$

$= \underline{\underline{8.0\times10^{-4} \text{ mol}}}$

6.9 **a.** $m = 2 \quad \pi = 2 \Rightarrow \underline{\underline{F = 2 + 2 - 2 = 2}}$. Two intensive variable values (e.g., T & P) must be specified to determine the state of the system.

b. $\log p^*_{MEK} = 6.97421 - \dfrac{1209.6}{55 + 216.} = 2.5107 \Rightarrow p^*_{MEK} = 10^{2.5107} = 324 \text{ mm Hg}$

Since vapor & liquid are in equilibrium $p_{MEK} = p^*_{MEK} = \underline{\underline{324 \text{ mm Hg}}}$

$\Rightarrow y_{MEK} = p_{MEK} / P = 324/1200 = \underline{\underline{0.27}} > 0.115$ The vessel does not constitute an explosion hazard.

6.10 **a**. The solvent with the lower flash point is easier to ignite and more dangerous. The solvent with a flash point of 15°C should always be prevented from contacting air at room temperature. The other one should be kept from any heating sources when contacted with air.

b. At the LFL, $y_M = 0.06 \Rightarrow p_M = p^*_M = 0.06 \times 760 \text{ mm Hg} = 45.60 \text{ mm Hg}$

$$\text{Antoine} \Rightarrow \log_{10} 45.60 = 7.87863 - \frac{1473.11}{\text{T} + 230} \Rightarrow T = \underline{\underline{6.85°\text{C}}}$$

c. The flame may heat up the methanol-air mixture, raising its temperature above the flash point.

6.11 **a.** At the dew point,

$$p^*(\text{H}_2\text{O}) = p(\text{H}_2\text{O}) = 500 \times 0.1 = 50 \text{ mm Hg} \Rightarrow \underline{\underline{T = 38.1° \text{C}}} \text{ from Table B.3.}$$

b. $$V_{\text{H}_2\text{O}} = \frac{30.0 \text{ L}}{} \left| \frac{273 \text{ K}}{(50 + 273) \text{ K}} \right| \frac{500 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right| \frac{0.100 \text{ mol H}_2\text{O}}{\text{mol}} \left| \frac{18.02 \text{ g}}{\text{mol}} \right| \frac{1 \text{ cm}^3}{\text{g}} = \underline{\underline{1.34 \text{ cm}^3}}$$

c. $\underline{\underline{\text{(iv)}}}$ (the gauge pressure)

6.12 **a.** $T_1 = 58.3^\circ\text{C}$, $p_1{*} = 755 \text{ mm Hg} - (747 - 52)\text{mm Hg} = 60 \text{ mm Hg}$

$T_2 = 110^\circ\text{C}$, $p_2{*} = 755 \text{ mm Hg} - (577 - 222)\text{mm Hg} = 400 \text{ mm Hg}$

$$\ln p{*} = \frac{a}{T(K)} + b$$

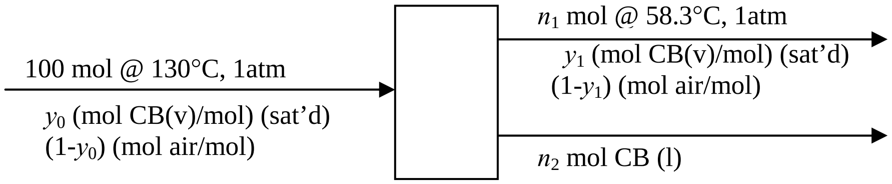
$$a = \frac{\ln(p_2{*}/p_1{*})}{\frac{1}{T_2} - \frac{1}{T_1}} = \frac{\ln(400/60)}{\frac{1}{110+273.2} - \frac{1}{58.3+273.2}} = -4661.4$$

$$b = \ln p_1{*} - \frac{a}{T_1} = \ln(60) + \frac{4661.4}{58.3 + 273.2} = 18.156$$

$$\ln p{*} = \frac{-4661.4}{T} + 18.156 \qquad \xrightarrow{\text{T=130°C=403.2 K}}$$

$$\ln p{*}(130^\circ\text{C}) = 6.595 \Rightarrow p{*}(130^\circ\text{C}) = \text{e}^{6.595} = \underline{\underline{731.4 \text{ mm Hg}}}$$

b. <u>Basis: 100 mol feed gas</u> CB denotes chlorobenzene.



<u>Saturation condition at inlet:</u> $y_o P = p_{\text{CB}}{*}(130^\circ\text{C}) \Rightarrow y_o = \dfrac{731 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.962 \text{ mol CB/mol}$

<u>Saturation condition at outlet:</u> $y_1 P = p_{\text{CB}}{*}(58.3^\circ\text{C}) \Rightarrow y_1 = \dfrac{60 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.0789 \text{ mol CB/mol}$

<u>Air balance:</u> $100(1 - y_o) = n_1(1 - y_1) \Rightarrow n_1 = (100)(1 - 0.962)/(1 - 0.0789) = 4.126 \text{ mol}$

<u>Total mole balance:</u> $100 = n_1 + n_2 \Rightarrow n_2 = 100 - 4.126 = 95.87 \text{ mol CB}(l)$

<u>% condensation:</u> $\dfrac{95.87 \text{ mol CB condensed}}{(0.962 \times 100) \text{ mol CB feed}} \times 100\% = \underline{\underline{99.7\%}}$

c. Assumptions: (1) Raoult's law holds at initial and final conditions;
(2) CB is the only condensable species (no water condenses);
(3) Clausius-Clapeyron estimate is accurate at 130°C.

6.13 $T = 78^\circ\text{F} = 25.56^\circ\text{C}$, $P_{bar} = 29.9 \text{ in Hg} = 759.5 \text{ mm Hg}$, $h_r = 87\%$

$$y_{\text{H}_2\text{O}}\text{P} = 0.87 p{*}(25.56^\circ\text{C}) \xrightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.87(24.559 \text{ mm Hg})}{759.5 \text{ mm Hg}} = \underline{\underline{0.0281 \text{ mol H}_2\text{O/mol air}}}$$

<u>Dew Point:</u> $p{*}(T_{dp}) = yp = 0.0281(759.5) = 21.34 \text{ mm Hg} \xrightarrow{\text{Table B.3}} \underline{\underline{T_{dp} = 23.2^\circ\text{C}}}$

6.13 (cont'd)

$$\underline{h_m} = \frac{0.0281}{1-0.0281} = \underline{\underline{0.0289\text{ mol H}_2\text{O/mol dry air}}}$$

$$\underline{h_a} = \begin{array}{c|c|c} 0.0289\text{ mol H}_2\text{O} & 18.02\text{ g H}_2\text{O} & \text{mol dry air} \\ \hline \text{mol dry air} & \text{mol H}_2\text{O} & 29.0\text{ g dry air} \end{array} = \underline{\underline{0.0180\text{ g H}_2\text{O/g dry air}}}$$

$$\underline{h_p} = \frac{h_m}{p*(25.56°\text{C})\big/\big[P - p*(25.56°\text{C})\big]} \times 100\% = \frac{0.0289}{24.559\big/\big[759.5 - 24.559\big]} \times 100\% = \underline{\underline{86.5\%}}$$

6.14 Basis I : 1 mol humid air @ 70° F (21.1° C), 1 atm, $h_r = 50\%$

$$\underline{h_\text{r} = 50\%} \Rightarrow y_{\text{H}_2\text{O}} P = 0.50 p_{\text{H}_2\text{O}}*(21.1°\text{C})$$

$$\xRightarrow{\text{Table B.3}} \quad y_{\text{H}_2\text{O}} = \frac{0.50 \times 18.765\text{ mm Hg}}{760.0\text{ mm Hg}} = 0.012 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\underline{\text{Mass of air:}} \quad \begin{array}{c|c} 0.012\text{ mol H}_2\text{O} & 18.02\text{ g} \\ \hline & 1\text{ mol} \end{array} + \begin{array}{c|c} 0.988\text{ mol dry air} & 29.0\text{ g} \\ \hline & 1\text{ mol} \end{array} = 28.87\text{ g}$$

$$\underline{\text{Volume of air:}} \quad \begin{array}{c|c|c} 1\text{ mol} & 22.4\text{ L (STP)} & (273.2 + 21.1)\text{K} \\ \hline & 1\text{ mol} & 273.2\text{K} \end{array} = 24.13\text{ L}$$

$$\underline{\text{Density of air}} = \frac{28.87\text{ g}}{24.13\text{ L}} = \underline{\underline{1.196\text{ g/L}}}$$

Basis II: 1 mol humid air @ 70° F (21.1° C), 1 atm, $h_r = 80\%$

$$\underline{h_\text{r} = 80\%} \Rightarrow y_{\text{H}_2\text{O}} P = 0.80 p_{\text{H}_2\text{O}}*(21.1°\text{C})$$

$$\xRightarrow{\text{Table B.3}} \quad y_{\text{H}_2\text{O}} = \frac{0.80 \times 18.765\text{ mm Hg}}{760.0\text{ mm Hg}} = 0.020 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\underline{\text{Mass of air:}} \quad \begin{array}{c|c} 0.020\text{ mol H}_2\text{O} & 18.02\text{ g} \\ \hline & 1\text{ mol} \end{array} + \begin{array}{c|c} 0.980\text{ mol dry air} & 29.0\text{ g} \\ \hline & 1\text{ mol} \end{array} = 28.78\text{ g}$$

$$\underline{\text{Volume of air:}} \quad \begin{array}{c|c|c} 1\text{ mol} & 22.4\text{ L (STP)} & (273.2 + 21.1)\text{K} \\ \hline & 1\text{ mol} & 273.2\text{K} \end{array} = 24.13\text{ L}$$

$$\underline{\text{Density of air}} = \frac{28.78\text{ g}}{24.13\text{ L}} = \underline{\underline{1.193\text{ g/L}}}$$

Basis III: 1 mol humid air @ 90° F (32.2° C), 1 atm, $h_r = 80\%$

$$\underline{h_\text{r} = 80\%} \Rightarrow y_{\text{H}_2\text{O}} P = 0.80 p_{\text{H}_2\text{O}}*(32.2°\text{C})$$

$$\xRightarrow{\text{Table B.3}} \quad y_{\text{H}_2\text{O}} = \frac{0.80 \times 36.068\text{ mm Hg}}{760.0\text{ mm Hg}} = 0.038 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

6.14 (cont'd)

$$\underline{\text{Mass of air:}}\quad \begin{array}{c|c} 0.038\text{ mol H}_2\text{O} & 18.02\text{ g} \\ \hline & 1\text{ mol} \end{array} + \begin{array}{c|c} 0.962\text{ mol dry air} & 29.0\text{ g} \\ \hline & 1\text{ mol} \end{array} = 28.58\text{ g}$$

$$\underline{\text{Volume of air:}}\quad \begin{array}{c|c|c} 1\text{ mol} & 22.4\text{ L (STP)} & (273.2+32.2)\text{K} \\ \hline & 1\text{ mol} & 273.2\text{K} \end{array} = 25.04\text{ L}$$

$$\underline{\text{Density}} = \frac{28.58\text{ g}}{25.04\text{ L}} = \underline{\underline{1.141\ \text{g/L}}}$$

Increase in $T \Rightarrow$ increase in $V \Rightarrow$ decrease in density

Increase in $h_r \Rightarrow$ more water (MW = 18), less dry air (MW = 29)

$\Rightarrow$ decrease in m $\Rightarrow$ decrease in density

Since the density in hot, humid air is lower than in cooler, dryer air, the buoyancy force on the ball must also be lower. Therefore, $\underline{\underline{\text{the statement is wrong.}}}$

6.15 a. $\underline{h_r = 50\%} \Rightarrow y_{H_2O} P = 0.50 p_{H_2O}*(90°\text{C})$

$$\xrightarrow{\text{Table B.3}} \quad y_{H_2O} = \frac{0.50 \times 525.76\text{ mm Hg}}{760.0\text{ mm Hg}} = 0.346\text{ mol H}_2\text{O / mol}$$

$$\underline{\text{Dew Point:}}\ y_{H_2O}p = p*(T_{dp}) = 0.346(760) = 262.9\text{ mm Hg} \quad \xrightarrow{\text{Table B.3}} \quad \underline{\underline{T_{dp} = 72.7°\text{C}}}$$

$$\text{Degrees of Superheat } = 90 - 72.7 = \underline{\underline{17.3°\text{C of superheat}}}$$

b. $$\underline{\text{Basis:}}\quad \begin{array}{c|c|c|c} 1\text{ m}^3\text{ feed gas} & 10^3\text{ L} & 273\text{K} & \text{mol} \\ \hline & \text{m}^3 & 363\text{K} & 22.4\text{ L (STP)} \end{array} = 33.6\text{ mol}$$

$$\underline{\text{Saturation Condition:}}\ y_1 = \frac{p^*_{H_2O}(25°\text{C})}{P} = \frac{23.756}{760} = 0.0313\text{ mol H}_2\text{O/mol}$$

$$\underline{\text{Dry air balance:}}\ 0.654(33.6) = n_1(1-0.0313) \Rightarrow n_1 = 22.7\text{ mol}$$

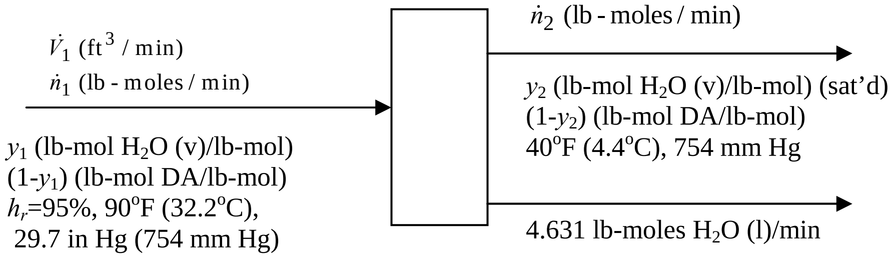
$$\underline{\text{Total mol balance:}}\ 33.6 = 22.7 + n_2 \Rightarrow \underline{\underline{n_2 = 10.9\text{ mol H}_2\text{O condense/m}^3}}$$

c. $$y_{H_2O}P = p*(90°\text{C}) \Rightarrow P = \frac{p^*(90°\text{C})}{y_{H_2O}} = \frac{525.76\text{ mmHg}}{0.346} = 1520\text{ mm Hg} = \underline{\underline{2.00\text{ atm}}}$$

6.16 $T = 90^\circ\text{F} = 32.2^\circ\text{C}$, $p = 29.7 \text{ in Hg} = 754.4 \text{ mm Hg}$, $h_r = 95\%$

Basis: 10 gal water condensed/min

$$\dot{n}_{condensed} = \begin{array}{c|c|c|c} 10 \text{ gal H}_2\text{O} & 1 \text{ ft}^3 & 62.43 \text{ lb}_\text{m} & 1 \text{ lb-mol} \\ \hline \text{min} & 7.4805 \text{ gal} & \text{ft}^3 & 18.02 \text{ lb}_\text{m} \end{array} = 4.631 \text{ lb-mole/min}$$



95% h_r at inlet: $y_{\text{H}_2\text{O}} P = 0.95 p*(32.2^\circ\text{C})$

$$\xRightarrow{\text{Table B.3}} y_{\text{H}_2\text{O}} = \frac{0.95(36.068 \text{ mm Hg})}{754.4 \text{ mm Hg}} = \underline{\underline{0.045 \text{ lb-mol H}_2\text{O/lb-mol}}}$$

Raoult's law: $y_2 P = p^*(4.4^\circ\text{C}) \xRightarrow{\text{Table B.3}} y_2 = \dfrac{6.274}{754.4} = 0.00817 \text{ lb-mol H}_2\text{O/lb-mol}$

$$\left.\begin{array}{l} \underline{\text{Mole balance}}: \dot{n}_1 = \dot{n}_2 + 4.631 \\ \underline{\text{Water balance}}: 0.045\dot{n}_1 = 0.00817\dot{n}_2 + 4.631 \end{array}\right\} \Rightarrow \left\{\begin{array}{l} \dot{n}_1 = 124.7 \text{ lb-moles/min} \\ \dot{n}_2 = 120.1 \text{ lb-moles/min} \end{array}\right.$$

$$\underline{\text{Volume in:}}\ \dot{V} = \begin{array}{c|c|c|c} 124.7 \text{ lb-moles} & 359 \text{ ft}^3 \text{ (STP)} & (460+90)^\text{o}\text{R} & 760 \text{ mm Hg} \\ \hline \text{min} & \text{lb-moles} & 492^\text{o}\text{R} & 754 \text{ mm Hg} \end{array}$$

$$= \underline{\underline{5.04 \times 10^4 \text{ ft}^3/\text{min}}}$$

6.17 **a.** Assume no water condenses and that the vapor at 15°C can be treated as an ideal gas.

$$p_{\text{final}} = \begin{array}{c|c} 760 \text{ mm Hg} & (15+273) \text{ K} \\ \hline & (200+273) \text{ K} \end{array} = 462.7 \text{ mm Hg} \Rightarrow (p_{\text{H}_2\text{O}})_{\text{final}} = 0.20 \times 462.7 = 92.6 \text{ mm Hg}$$

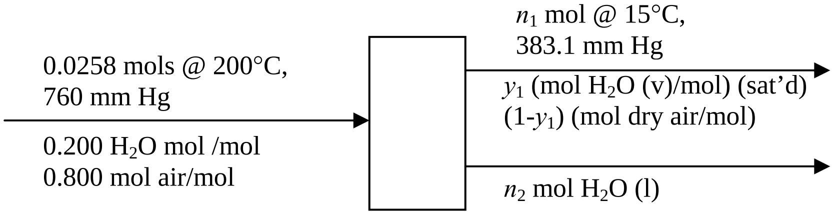
$p^*(15^\circ\text{C}) = 12.79 \text{ mm Hg} < p_{\text{H}_2\text{O}}$. Impossible $\Rightarrow$ condensation occurs.

$$(p_{\text{air}})_{\text{final}} = (p_{\text{air}})_{\text{initial}} \frac{T_{\text{final}}}{T_{\text{initial}}} = (0.80 \times 760) \text{ mm Hg} \times \frac{288 \text{ K}}{473 \text{ K}} = 370.2 \text{ mm Hg}$$

$$P = p_{\text{H}_2\text{O}} + p_{\text{air}} = 370.2 + 12.79 = \underline{\underline{383 \text{ mm Hg}}}$$

b. $\underline{\text{Basis:}}\ \begin{array}{c|c|c} 1 \text{ L} & 273 \text{ K} & \text{mol} \\ \hline & 473 \text{ K} & 22.4 \text{ L (STP)} \end{array} = 0.0258 \text{ mol}$

6.17 (cont'd)



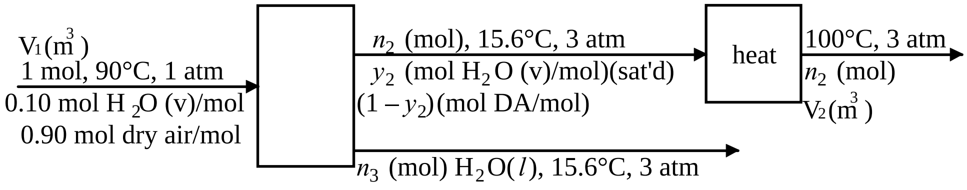
$$\underline{\text{Saturation Condition:}}\ y_1 = \frac{p^*_{\mathrm{H_2O}}(15^\circ\mathrm{C})}{P} = \frac{12.79\ \text{mm Hg}}{383.1\ \text{mm Hg}} = \underline{\underline{0.03339\ \text{mol}\ \ \mathrm{H_2O/mol}}}$$

c. $\underline{\text{Dry air balance:}}\ 0.800(0.0258) = n_1(1-0.03339) \Rightarrow n_1 = 0.02135\ \text{mol}$

$\underline{\text{Total mole balance:}}\ 0.0258 = 0.02135 + n_2 \Rightarrow n_2 = 0.00445\ \text{mol}$

$$\underline{\text{Mass of water condensed}} = \frac{0.00445\ \text{mol}}{} \left| \frac{18.02\ \text{g}}{\text{mol}} \right. = \underline{\underline{0.0802\ \text{g}}}$$

6.18 Basis: 1 mol feed



$$\underline{\text{Saturation:}}\ y_2 = \frac{p^*_{\mathrm{H_2O}}(15.6^\circ\mathrm{C})}{P} \xRightarrow{\text{Table B.3}} y_2 = \frac{13.29\ \text{mm Hg}}{3\ \text{atm}} \left| \frac{\text{atm}}{760\ \text{mm Hg}} \right. = 0.00583$$

$\underline{\text{Dry air balance:}}\ 0.90(1) = n_2(1-0.00583) \Rightarrow n_2 = 0.9053\ \text{mol}$

$\underline{\mathrm{H_2O}\ \text{mol balance:}}\ 0.10(1) = 0.00583(0.9053) + n_3 \Rightarrow n_3 = 0.0947\ \text{mol}$

$$\underline{\text{Fraction}\ \mathrm{H_2O}\ \text{condensed:}}\ \frac{0.0947\ \text{mol condensed}}{0.100\ \text{mol fed}} = \underline{\underline{0.947\ \text{mol condense/mol fed}}}$$

$$h_r = \frac{y_2 P \times 100\%}{p*(100^\circ\mathrm{C})} = \frac{0.00583(3\ \text{atm})}{1\ \text{atm}} \times 100\% = \underline{\underline{1.75\%}}$$

$$V_2 = \frac{0.9053\ \text{mol}}{} \left| \frac{22.4\ \text{L (STP)}}{\text{mol}} \right| \frac{373\text{K}}{273\text{K}} \left| \frac{1\ \text{atm}}{3\ \text{atm}} \right| \frac{1\ \text{m}^3}{10^3\ \text{L}} = 9.24 \times 10^{-3}\ \text{m}^3\ \text{outlet air @ } 100^\circ\mathrm{C}$$

$$V_1 = \frac{1\ \text{mol}}{} \left| \frac{22.4\ \text{L (STP)}}{\text{mol}} \right| \frac{363\text{K}}{273\text{K}} \left| \frac{1\ \text{m}^3}{10^3\ \text{L}} \right. = 2.98 \times 10^{-2}\ \text{m}^3\ \text{feed air @ } 90^\circ\mathrm{C}$$

$$\frac{V_2}{V_1} = \frac{9.24 \times 10^{-3}\ \text{m}^3\ \text{outlet air}}{2.98 \times 10^{-2}\ \text{m}^3\ \text{feed air}} = \underline{\underline{0.310\ \text{m}^3\ \ \text{outlet air/m}^3\ \text{feed air}}}$$

6.19 Liquid H_2O initially present: $\begin{array}{c|c|c} 25\text{ L} & 1.00\text{ kg} & 1\text{ kmol} \\ \hline & \text{L} & 18.02\text{ kg} \end{array} = 1.387\text{ kmol H}_2\text{O (l)}$

Saturation at outlet: $y_{H_2O} = \dfrac{p^*_{H_2O}(25°\text{C})}{P} = \dfrac{23.76\text{ mm Hg}}{1.5 \times 760\text{ mm Hg}} = 0.0208\text{ mol H}_2\text{O/mol air}$

$\Rightarrow \dfrac{0.0208}{1-0.0208} = 0.0212\text{ mol H}_2\text{O/mol dry air}$

Flow rate of dry air: $\begin{array}{c|c} 15\text{ L(STP)} & 1\text{ mol} \\ \hline \text{min} & 22.4\text{ L(STP)} \end{array} = 0.670\text{ mol dry air/min}$

Evaporation Rate: $\begin{array}{c|c} 0.670\text{ mol dry air} & 0.0212\text{ mol H}_2\text{O} \\ \hline \text{min} & \text{mol dry air} \end{array} = 0.0142\text{ mol H}_2\text{O/min}$

Complete Evaporation: $\begin{array}{c|c|c|c} 1.387\text{ kmol} & 10^3\text{ mol} & \text{min} & 1\text{ h} \\ \hline & \text{kmol} & 0.0142\text{ mol} & 60\text{ min} \end{array} = \underline{\underline{1628\text{ h}}} \quad (67.8\text{ days})$

6.20 **a.** Daily rate of octane use $= \dfrac{\pi}{4} \cdot 30^2 \cdot (18-8) = \begin{array}{c|c} 7.069 \times 10^3\text{ ft}^3 & 7.481\text{ gal} \\ \hline \text{day} & \text{ft}^3 \end{array} = \underline{\underline{5.288 \times 10^4\text{ gal / day}}}$

$(SG)_{C_8H_{18}} = 0.703 \Rightarrow \begin{array}{c|c|c} 5.288 \times 10^4\text{ gal} & 1\text{ ft}^3 & 0.703 \times 62.43\text{ lb}_\text{m} \\ \hline \text{day} & 7.481\text{ gal} & \text{ft}^3 \end{array}$

$= \underline{\underline{3.10 \times 10^5\text{ lb}_\text{m}\text{ C}_8\text{H}_{18}\text{ / day}}}$

b. $\Delta p = \begin{array}{c|c|c|c|c|c} 0.703 \times 62.43\text{ lb}_\text{m} & 32.174\text{ ft} & 1\text{ lb}_\text{f} & \text{(18-8) ft} & 1\text{ ft}^2 & 29.921\text{ in Hg} \\ \hline \text{ft}^3 & \text{s}^2 & 32.174\frac{\text{lb}_\text{m}\cdot\text{ft}}{\text{s}^2} & & 144\text{ in}^2 & 14.696\text{ lb}_\text{f}\text{ / in}^2 \end{array} = \underline{\underline{6.21\text{ in Hg}}}$

c. Table B.4: $p^*_{C_8H_{18}}(90^\text{o}\text{ F}) = \begin{array}{c|c} 20.74\text{ mm Hg} & 14.696\text{ psi} \\ \hline & 760\text{ mm Hg} \end{array} = 0.40\text{ lb}_\text{f}\text{ / in}^2 = p_\text{octane} = y_\text{octane}P$

Octane lost to environment = octane vapor contained in the vapor space displaced by liquid during refilling.

Volume: $\begin{array}{c|c} 5.288 \times 10^4\text{ gal} & 1\text{ ft}^3 \\ \hline & 7.481\text{ gal} \end{array} = 7069\text{ ft}^3$

Total moles: $n = \dfrac{pV}{RT} = \begin{array}{c|c} (16.0+14.7)\text{ psi} & 7069\text{ ft}^3 \\ \hline 10.73\text{ ft}^3\cdot\text{psi / (lb - mole}\cdot^\text{o}\text{ R)} & (90+460)\ ^\text{o}\text{R} \end{array} = 36.77\text{ lb - moles}$

Mole fraction of C_8H_{18}: $y = \dfrac{p_{C_8H_{18}}}{P} = \dfrac{0.40\text{ psi}}{(16.0+14.7)\text{ psi}} = 0.0130\text{ lb - mole C}_8\text{H}_{18}\text{ / lb - mole}$

Octane lost $= 0.0130(36.77)\text{ lb - mole} = \underline{\underline{0.479\text{ lb - mole}}}\ (= 55\text{ lb}_\text{m} = 25\text{ kg})$

d. A mixture of octane and air could ignite.

6.21 a. $\underline{\text{Antoine equation}} \underline{\Rightarrow p^*_{tol}(85^\circ\text{ F}) = p^*_{tol}(29.44^\circ\text{ C}) = 35.63\text{ mmHg} = p_{tol}}$

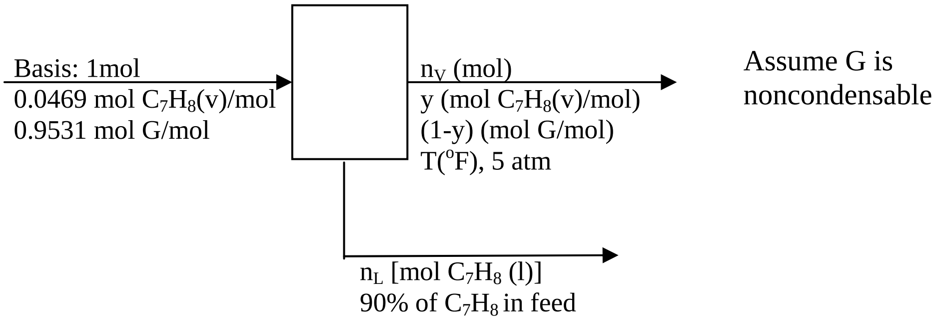
$\underline{\text{Mole fraction of toluene in gas:}}\; y = \dfrac{p_{tol}}{P} = \dfrac{35.63\text{ mmHg}}{760\text{ mmHg}} = 0.0469\text{ lb - mole toluene / lb - mole}$

$\underline{\text{Toluene displaced}} = yn_{total} = \dfrac{yPV}{RT}$

$$= \begin{array}{c|c|c|c|c} 0.0469\text{ lb - mole tol} & 1\text{ atm} & 900\text{ gal} & 1\text{ ft}^3 & 92.13\text{ lb}_\text{m}\text{ tol} \\ \hline \text{lb - mole} & 0.7302\ \dfrac{\text{ft}^3\cdot\text{atm}}{\text{lb - mole}\cdot^\circ\text{ R}} & (85+460)^\circ\text{ R} & 7.481\text{ gal} & \text{lb - mole} \end{array}$$

$= \underline{\underline{1.31\text{ lb}_\text{m}\text{ toluene displaced}}}$

b.



$\underline{\text{90\% condensation}} \Rightarrow n_L = 0.90(0.0469)(1)\text{ mol C}_7\text{H}_8 = 0.0422\text{ mol C}_7\text{H}_8(l)$

$\underline{\text{Mole balance:}}\quad 1 = n_V + 0.0422 \Rightarrow n_V = 0.9578\text{ mol}$

$\underline{\text{Toluene balance:}}\quad 0.0469(1) = y(0.9578) + 0.0422 \Rightarrow y = 0.004907\text{ mol C}_7\text{H}_8\text{ / mol}$

$\underline{\text{Raoult's law:}}\quad p_{tol} = yP = (0.004907)(5\times 760) = 18.65\text{ mmHg} = p^*_{tol}(T)$

$\underline{\text{Antoine equation:}}$

$$T = \frac{B - C(A - \log_{10} p^*)}{A - \log_{10} p^*} = \frac{1346.773 - 219.693(6.95805 - \log_{10} 18.65)}{6.95805 - \log_{10} 18.65} = 17.11^\circ\text{C} = \underline{\underline{62.8^\circ\text{F}}}$$

6.22 a. $\underline{\text{Molar flow rate}}:\; \dot{n} = \dfrac{\dot{V}P}{RT} = \begin{array}{c|c|c} 100\text{ m}^3 & \text{kmol}\cdot\text{K} & 2\text{ atm} \\ \hline \text{h} & 82.06\times 10^{-3}\text{ m}^3\cdot\text{atm} & (100+273)\text{ K} \end{array} = \underline{\underline{6.53\text{ kmol / h}}}$

b. $\underline{\text{Antoine Equation}}$:

$$\log_{10} p^*_{Hex}(100°\text{C}) = 6.88555 - \frac{1175.817}{100+224.867} = 3.26601$$

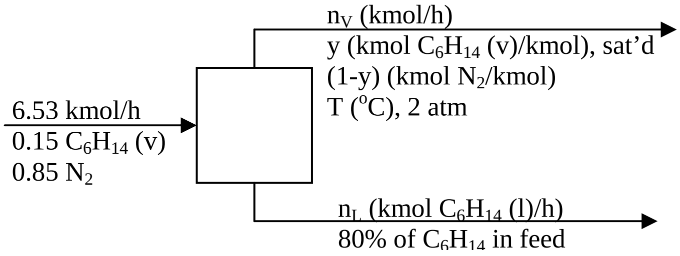
$$\Rightarrow p^* = 1845\text{ mm Hg}$$

$$p_{Hex} = y_{Hex}\cdot P = \begin{array}{c|c} 0.150(2.00)\text{ atm} & 760\text{ mm Hg} \\ \hline & \text{atm} \end{array} = 228\text{ mm Hg} < p^*_{Hex} \Rightarrow \text{not saturated}$$

$$p^*_{Hex}(T) = 228\text{ mm Hg} \Rightarrow \log_{10} 228 = 6.88555 - \frac{1175.817}{T+224.867} = 2.35793 \Rightarrow T = \underline{\underline{34.8°\text{C}}}$$

6.22 (cont'd)

c.



<u>80% condensation:</u> $n_L = 0.80(0.15)(6.53 \text{ kmol / h}) = 0.7836 \text{ kmol } C_6H_{14}(l) \text{ / h}$

<u>Mole balance:</u> $6.53 = n_V + 0.7836 \Rightarrow n_V = 5.746 \text{ kmol / h}$

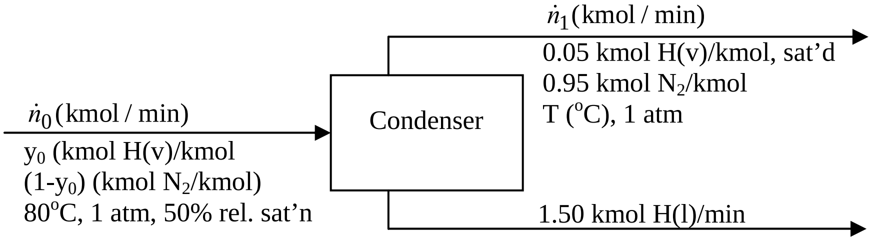
<u>Hexane balance:</u> $0.15(6.53) = y(5.746) + 0.7836 \Rightarrow y = 0.03409 \text{ kmol } C_6H_{14} \text{ / kmol}$

<u>Raoult's law:</u> $p_{Hex} = yP = (0.03409)(2 \times 760 \text{ mmHg}) = 51.82 \text{ mmHg} = p^*_{Hex}(T)$

<u>Antoine equation</u>: $\log_{10} 51.82 = 6.88555 - \dfrac{1175.817}{T + 224.867} \Rightarrow T = \underline{\underline{2.52^\circ \text{C}}}$

6.23 Let H=n-hexane

a.



<u>50% relative saturation at inlet:</u> $y_o P = 0.500 p^*_H (80^\circ \text{C})$

$$\xRightarrow{\text{Table B.4}} y_o = \frac{(0.500)(1068 \text{ mmHg})}{760 \text{ mmHg}} = 0.703 \text{ kmolH / kmol}$$

<u>Saturation at outlet</u>: $0.05P = p^*_H(T_1) \Rightarrow p^*_H(T_1) = 0.05(760 \text{ mmHg}) = 38 \text{ mmHg}$

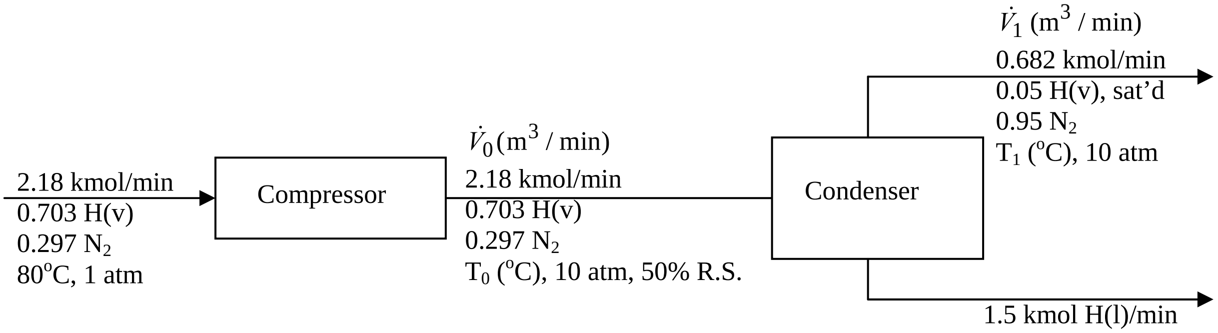
<u>Antoine equation:</u> $\log_{10} 38 = 6.88555 - \dfrac{1175.817}{T_1 + 224.867} \Rightarrow T_1 = \underline{\underline{-3.26^\circ \text{C}}}$

$$\left.\begin{array}{ll} \underline{\text{Mole balance:}} & \dot{n}_0 = \dot{n}_1 + 1.50 \\ \underline{N_2 \text{ balance:}} & (1 - 0.703)\dot{n}_0 = 0.95\dot{n}_1 \end{array}\right\} \Rightarrow \left\{\begin{array}{l} \dot{n}_0 = 2.18 \text{ kmol / min} \\ \dot{n}_1 = 0.682 \text{ kmol / min} \end{array}\right.$$

<u>N_2 volume</u>: $\dot{V}_{N_2} = \dfrac{(0.95)0.682 \text{ kmol}}{\text{min}} \left| \dfrac{22.4 \text{ m}^3(\text{STP})}{\text{kmol}} \right. = \underline{\underline{14.5 \text{ SCMM}}}$

6.23 (cont'd)

b. Assume no condensation occurs during the compression



<u>50% relative saturation at condenser inlet</u>:

$$0.500 p_H^*(T_0) = 0.703(7600 \text{ mmHg}) \Rightarrow p_H^*(T_0) = 1.068\times 10^4 \text{ mmHg} \xRightarrow[\text{Antoine}]{} T_0 = 187^\circ\text{C}$$

<u>Saturation at outlet:</u> $0.050(7600 \text{ mmHg}) = 380 \text{ mmHg} = p_H^*(T_1) \xRightarrow[\text{Antoine}]{} T_1 = \underline{\underline{48.2^\circ\text{C}}}$

<u>Volume ratio</u>: $\dfrac{\dot{V}_1}{\dot{V}_0} = \dfrac{n_1RT_1/P}{n_0RT_0/P} = \dfrac{n_1(T_1+273.2)}{n_0(T_0+273.2)} = \dfrac{0.682 \text{ kmol/min}}{2.18 \text{ kmol/min}} \times \dfrac{321 \text{ K}}{460 \text{ K}} = \underline{\underline{0.22}}\dfrac{\text{m}^3 \text{ out}}{\text{m}^3 \text{ in}}$

c. The cost of cooling to -3.26°C (installed cost of condenser + utilities and other operating costs) vs. the cost of compressing to 10 atm and cooling at 10 atm.

6.24 a. Maximum mole fraction of nonane achieved if all the liquid evaporates and none escapes.

$$\swarrow (SG)_{\text{nonane}}$$

$$n_{\max} = \begin{array}{c|c|r} 15 \text{ L } C_9H_{20}(l) & 0.718\times 1.00 \text{ kg} & \text{kmol} \\ \hline & \text{L } C_9H_{20} & 128.25 \text{ kg} \end{array} = 0.084 \text{ kmol } C_9H_{20}$$

Assume $T = 25^\circ\text{C}$, $\text{P} = 1$ atm

$$n_{gas} = \begin{array}{c|c|c} 2\times 10^4 \text{ L} & 273 \text{ K} & 1 \quad \text{kmol} \\ \hline & 298 \text{ K} & 22.4\times 10^3 \text{ L(STP)} \end{array} = 0.818 \text{ kmol}$$

$$y_{\max} = \frac{n_{\max}}{n_{gas}} = \frac{0.084 \text{ kmol } C_9H_{20}}{0.818 \text{ kmol}} = 0.10 \text{ kmol } C_9H_{20}/\text{kmol (10 mole\%)}$$

As the nonane evaporates, the mole fraction will pass through the explosive range (0.8% to 2.9%). The answer is therefore $\underline{\underline{\text{yes}}}$.

The nonane will not spread uniformly—it will be high near the sump as long as liquid is present (and low far from the sump). There will always be a region where the mixture is explosive at some time during the evaporation.

b. $\ln p^* = -\dfrac{A}{T} + B$ $\qquad T_1 = 25.8^\circ\text{C} = 299 \text{ K}, \ p_1^* = 5.00 \text{ mmHg}$

$$T_2 = 66.0^\circ\text{C} = 339 \text{ K}, \ p_2^* = 40.0 \text{ mmHg}$$

6.24 (cont'd)

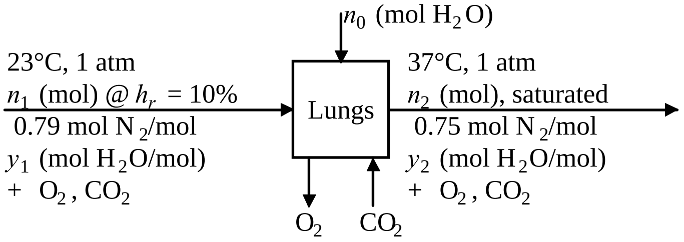
$$-A = \frac{\ln(40.0/5.00)}{\frac{1}{339}-\frac{1}{299}} \Rightarrow A = 5269,\quad B = \ln(5.00) + \frac{5269}{299} = 19.23 \Rightarrow \underline{\underline{p^* = \exp(19.23 - \frac{5269}{T(\mathrm{K})})}}$$

At lower explosion limit, $y = 0.008\ \mathrm{kmol\ C_9H_{20}/kmol} \Rightarrow p^*(T) = yP = (0.008)(760\ \mathrm{mm\ Hg})$

$$= 6.08\ \mathrm{mm\ Hg} \xrightarrow[\text{Formula for } p^*]{} T = 302\ \mathrm{K} = \underline{\underline{29^\circ\mathrm{C}}}$$

c. The purpose of purge is to evaporate and carry out the liquid nonane. Using steam rather than air is to make sure an explosive mixture of nonane and oxygen is never present in the tank. Before anyone goes into the tank, a sample of the contents should be drawn and analyzed for nonane.

6.25 Basis: 24 hours of breathing



Air inhaled: $n_1 = \frac{12\ \text{breaths}}{\text{min}} \left| \frac{500\ \text{ml}}{\text{breath}} \right| \frac{1\ \text{liter}}{10^3\ \text{ml}} \left| \frac{273\text{K}}{(23+273)\text{K}} \right| \frac{1\ \text{mol}}{22.4\ \text{liter(STP)}} \left| \frac{60\ \text{min}}{1\ \text{hr}} \right| \frac{24\ \text{hr}}{1\ \text{day}}$

$= 356$ mol inhaled/day

Inhaled air--10% r.h.: $y_1 = \frac{0.10 p^*_{H_2O}(23^\circ C)}{P} = \frac{0.10(21.07\ \mathrm{mm\ Hg})}{760\ \mathrm{mm\ Hg}} = 2.77\times10^{-3}\ \frac{\mathrm{mol\ H_2O}}{\mathrm{mol}}$

Inhaled air--50% r.h.: $y_1 = \frac{0.50 p^*_{H_2O}(23^\circ C)}{P} = \frac{0.50(21.07\ \mathrm{mm\ Hg})}{760\ \mathrm{mm\ Hg}} = 1.39\times10^{-2}\ \frac{\mathrm{mol\ H_2O}}{\mathrm{mol}}$

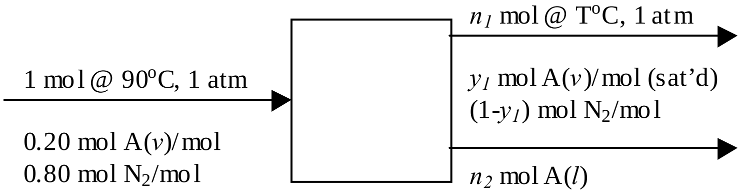
H_2O balance: $n_0 = n_2y_2 - n_1y_1 \Rightarrow (n_0)_{10\%\ \mathrm{rh}} - (n_0)_{50\%\ \mathrm{rh}} = (n_1y_1)_{50\%} - (n_1y_1)_{10\%}$

$$= \left(356\ \frac{\mathrm{mol}}{\mathrm{day}}\right)\left[(0.0139 - 0.00277)\frac{\mathrm{mol\ H_2O}}{\mathrm{mol}}\right]\left(\frac{18.0\ \mathrm{g}}{1\ \mathrm{mol}}\right) = \underline{\underline{71\ \mathrm{g/day}}}$$

Although the problem does not call for it, we could also calculate that n_2 = 375 mol exhaled/day, y_2 = 0.0619, and the rate of weight loss by breathing at 23°C and 50% relative humidity is $n_0(18) = (n_2y_2 - n_1y_1)18 =$ 329 g/day.

6.26 **a.** To increase profits and reduce pollution.

b. Assume condensation occurs. A=acetone



For cooling water at 20^{o}C

$$\log_{10} p_A^*\left(20^{\circ}\mathrm{C}\right) = 7.11714 - \frac{1210.595}{20+229.664} = 2.26824 \Rightarrow p_A^*\left(20^{\circ}\mathrm{C}\right) = 184.6 \text{ mmHg}$$

<u>Saturation</u>: $y_1 \cdot P = p_A^*\left(20^{\circ}\,\mathrm{C}\right) \Rightarrow y_1 = \dfrac{184.6}{760} = 0.243 > 0.2$, so no saturation occurs.

For refrigerant at –35^{o}C

$$\log_{10} p_A^*\left(-35^{\circ}\mathrm{C}\right) = 7.11714 - \frac{1210.595}{-35+229.664} = 0.89824 \Rightarrow p_A^*\left(-35^{\circ}\mathrm{C}\right) = 7.61 \text{ mmHg}$$

(<u>Note</u>: -35^{o}C is outside the range of validity of the Antoine equation coefficients in Table B.4. An alternative is to look up the vapor pressure of acetone at that temperature in a handbook. The final result is almost identical.)

<u>Saturation</u>: $y_1 \cdot P = p_A^*\left(-35^{\circ}\,\mathrm{C}\right) \Rightarrow y_1 = \dfrac{7.61}{760} = 0.0100$

<u>N$_2$ mole balance</u>: $1(0.8) = n_1(1-0.01) \Rightarrow n_1 = 0.808$ mol

<u>Total mole balance</u>: $1 = 0.808 + n_2 \Rightarrow n_2 = 0.192$ mol

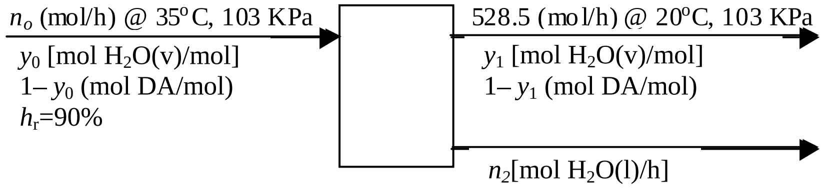
<u>Percentage acetone recovery</u>: $\dfrac{0.192}{2} \times 100\% = \underline{\underline{96\%}}$

c. Costs of acetone, nitrogen, cooling tower, cooling water and refrigerant

d. The condenser temperature could never be as low as the initial cooling fluid temperature because heat is transferred between the condenser and the surrounding environment. It will lower the percentage acetone recovery.

6.27

Basis: $$\frac{12500\ \text{L}}{\text{h}}\bigg|\frac{1\ \text{mol}}{22.4\ \text{L(STP)}}\bigg|\frac{273\ \text{K}}{293\ \text{K}}\bigg|\frac{103000\ \text{Pa}}{101325\ \text{Pa}} = 528.5\ \text{mol / h}$$



Inlet: $$y_o = \frac{h_r \cdot p^*_{H_2O}\left(35^\circ\text{C}\right)}{P} = \frac{0.90 \times 42.175\ \text{mmHg}}{103000\ \text{Pa}}\bigg|\frac{101325\ \text{Pa}}{760\ \text{mmHg}} = 0.04913\ \text{mol}\ H_2O\text{/mol}$$

Outlet: $$y_1 = \frac{p^*_{H_2O}\left(20^\circ\text{C}\right)}{P} = \frac{17.535\ \text{mmHg}}{103000\ \text{Pa}}\bigg|\frac{101325\ \text{Pa}}{760\ \text{mmHg}} = 0.02270\ \text{mol}\ H_2O\ \text{/ mol}$$

Dry air balance: $(1-0.04913)n_o = (1-0.02270)(528.5) \Rightarrow n_o = 543.2\ \text{mol / h}$

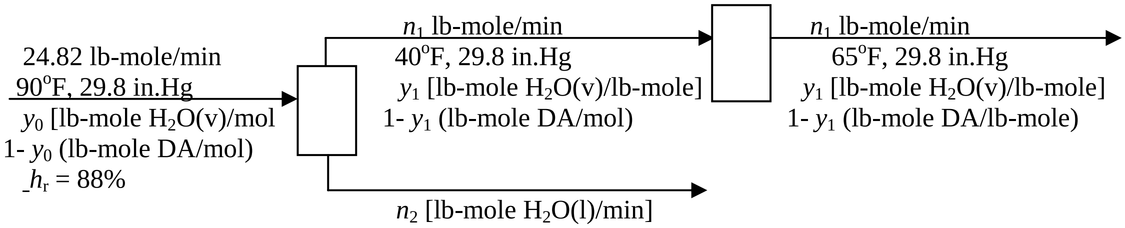
Inlet air: $$\frac{543.2\ \text{mol}}{\text{h}}\bigg|\frac{22.4\ \text{L(STP)}}{\text{mol}}\bigg|\frac{308\ \text{K}}{273\ \text{K}}\bigg|\frac{101325\ \text{Pa}}{103000\ \text{Pa}} = \underline{\underline{13500\ \text{L / h}}}$$

Total balance: $543.2 = 528.5 + n_2 \Rightarrow n_2 = 14.7\ \text{mol / h}$

Condensation rate: $$\frac{14.7\ \text{mol}}{\text{h}}\bigg|\frac{18.02\ \text{g}\ H_2O}{1\ \text{mol}\ H_2O}\bigg|\frac{1\ \text{kg}}{1000\ \text{g}} = \underline{\underline{0.265\ \text{kg / h}}}$$

6.28

Basis: $$\frac{10000\ \text{ft}^3}{\text{min}}\bigg|\frac{1\ \text{lb-mol}}{359\ \text{ft}^3\text{(STP)}}\bigg|\frac{492^\circ\text{R}}{550^\circ\text{R}}\bigg|\frac{29.8\ \text{in Hg}}{29.92\ \text{in Hg}} = 24.82\ \text{lb-mol / min}$$



Inlet: $$y_o = \frac{h_r \cdot p^*_{H_2O}\left(90^\circ\text{F}\right)}{P} = \frac{0.88(36.07\ \text{mmHg})}{29.8\ \text{in Hg}}\bigg|\frac{1\ \text{in Hg}}{25.4\ \text{mmHg}} = 0.0419\ \text{lb-mol}\ H_2O\ \text{/ lb-mol}$$

Outlet: $$y_1 = \frac{p^*_{H_2O}\left(40^\circ\text{F}\right)}{P} = \frac{6.274\ \text{mmHg}}{29.8\ \text{in Hg}}\bigg|\frac{1\ \text{in Hg}}{25.4\ \text{mmHg}} = 0.00829\ \text{lb-mol}\ H_2O\ \text{/ lb-mol}$$

Dry air balance: $24.82(1-0.0419) = n_1(1-0.00829) \Rightarrow n_1 = 23.98\ \text{lb-mol / min}$

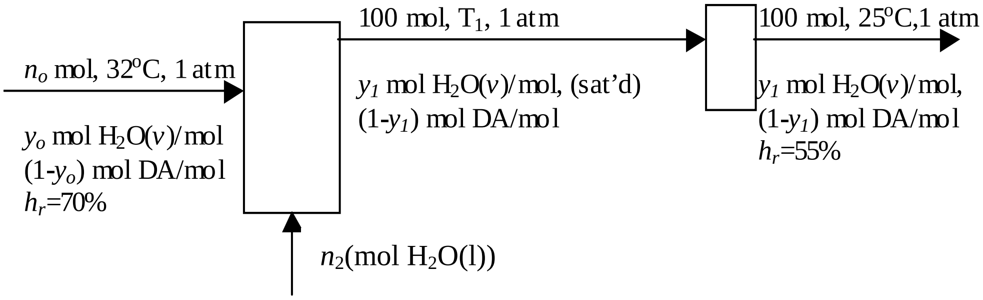
Total balance: $24.82 = 23.98 + n_2 \Rightarrow n_2 = 0.84\ \text{lb-mole / min}$

6.28 (cont'd)

Condensation rate: $\dfrac{0.84\text{ lb-mol}}{\text{min}}\bigg|\dfrac{18.02\text{ lb}_\text{m}}{\text{lb}-\text{mol}}\bigg|\dfrac{1\text{ ft}^3}{62.4\text{ lb}_\text{m}}\bigg|\dfrac{7.48\text{ gal}}{1\text{ ft}^3}=\underline{\underline{1.81\text{ gal / min}}}$

Air delivered @ 65°F: $\dfrac{23.98\text{ lb-mol}}{\text{min}}\bigg|\dfrac{359\text{ ft}^3(\text{STP})}{1\text{ lb}-\text{mol}}\bigg|\dfrac{525^\circ\text{R}}{492^\circ\text{R}}\bigg|\dfrac{29.92\text{ in Hg}}{29.8\text{ in Hg}}=\underline{\underline{9223\text{ ft}^3\text{ / min}}}$

6.29 Basis: 100 mol product gas



Outlet: $y_1=\dfrac{h_r\cdot p^*_{H_2O}\left(25^\circ\text{C}\right)}{P}=\dfrac{0.55(23.756)}{760}=0.0172\text{ mol H}_2\text{O / mol}$

Saturation at T_1: $0.0172(760)=13.07=p^*_{H_2O}(T_1)\Rightarrow T_1=\underline{\underline{15.3^\circ\text{C}}}$

Inlet: $y_\text{o}=\dfrac{h_r\cdot p^*_{H_2O}\left(32^\circ\text{C}\right)}{P}=\dfrac{0.70(35.663)}{760}=0.0328\text{ mol H}_2\text{O / mol}$

Dry air balance: $n_\text{o}(1-0.0328)=100(1-0.0172)\Rightarrow n_\text{o}=101.6\text{ mol}$

Total balance: $101.6+n_2=100.0\Rightarrow n_2=-1.6\text{ mol}$ (i.e. removed)

kg H_2O removed : $\dfrac{1.6\text{ mol}}{}\bigg|\dfrac{18.02\text{ g}}{1\text{ mol}}\bigg|\dfrac{1\text{ kg}}{1000\text{ g}}=0.0288\text{ kg H}_2\text{O}$

kg dry air: $\dfrac{100(1-0.0172)\text{ mol}}{}\bigg|\dfrac{29.0\text{ g}}{1\text{ mol}}\bigg|\dfrac{1\text{ kg}}{1000\text{ g}}=2.85\text{ kg dry air}$

Ratio: $\dfrac{0.0288}{2.85}=\underline{\underline{0.0101\text{ kg H}_2\text{O removed / kg dry air}}}$

6.30 a. Room air – $T = 22°\text{C}$, $P = 1 \text{ atm}$, $h_r = 40\%$:

$$y_1 P = 0.40 p*_{\text{H}_2\text{O}}(22°\text{C}) \Rightarrow y_1 = \frac{(0.40)19.827 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.01044 \text{ mol H}_2\text{O/mol}$$

Second sample – $T = 50°\text{C}$, $P = 839 \text{ mm Hg}$, saturated:

$$y_2 P = p*_{\text{H}_2\text{O}}(50°\text{C}) \Rightarrow y_2 = \frac{92.51 \text{ mm Hg}}{839 \text{ mm Hg}} = 0.1103 \text{ mol H}_2\text{O/mol}$$

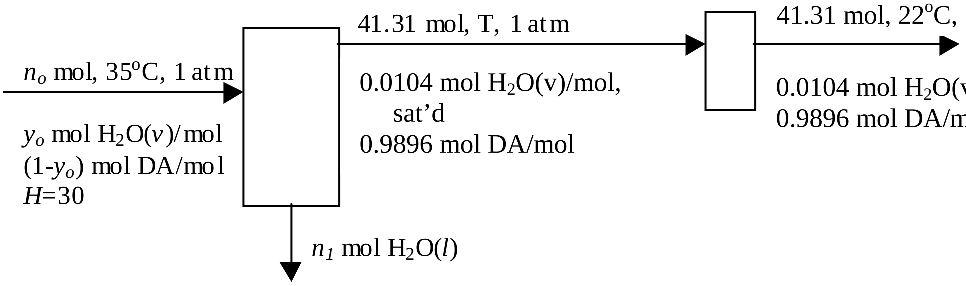
$$\ln y = bH + \ln a \Leftrightarrow y = ae^{bH},\ [y_1 = 0.01044,\ H_1 = 5],\ [y_2 = 0.1103,\ H_2 = 48]$$

$$b = \frac{\ln(y_2/y_1)}{H_2 - H_1} = \frac{\ln(0.1103/0.01044)}{48-5} = 0.054827$$

$$\ln a = \ln y_1 - bH_1 = \ln(0.01044) - (0.054827)(5) = -4.8362 \Rightarrow a = \exp(-4.8362) = 7.937 \times 10^{-3}$$

$$\Rightarrow \underline{\underline{y = 7.937 \times 10^{-3} \exp(0.054827H)}}$$

b. Basis: $$\frac{1 \text{ m}^3 \text{ delivered air}}{} \left| \frac{273\text{K}}{(22+273)\text{K}} \right| \frac{1 \text{ k mol}}{22.4\text{m}^3(\text{STP})} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right. = 41.31 \text{ mol air delivered}$$



Saturation condition prior to reheat stage:

$$y_{\text{H}_2\text{O}} P = p^*_{\text{H}_2\text{O}}(T) \Rightarrow (0.01044)(760 \text{ mm Hg}) = 7.93 \text{ mm Hg}$$

$$\Rightarrow \underline{\underline{T = 7.8°\text{C}}} \text{ (from Table B.3)}$$

Humidity of outside air: $H = 30 \overset{\text{Part (a)}}{\Rightarrow} y_0 = 0.0411 \text{ mol H}_2\text{O/mol}$

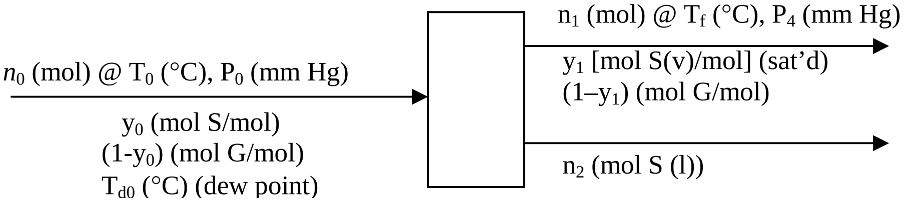
Overall dry air balance: $n_0(1-y_0) = 41.31(0.9896) \Rightarrow n_0 = \dfrac{(41.31)(0.9896)}{(1-0.0411)} = 42.63 \text{ mol}$

Overall water balance: $n_0 y_0 = n_1 + (41.31)(0.0104) \Rightarrow n_1 = (42.63)(0.0411) - (41.31)(0.0104)$
$= 1.32 \text{ mol H}_2\text{O condensed}$

$$\text{Mass of condensed water} = \frac{1.32 \text{ mol H}_2\text{O}}{} \left| \frac{18.02 \text{ g H}_2\text{O}}{1 \text{ mol H}_2\text{O}} \right| \frac{1 \text{ kg}}{10^3 \text{ g}}$$

$$= \underline{\underline{0.024 \text{ kg H}_2\text{O condensed/m}^3 \text{ air delivered}}}$$

6.31 a. Basis: $\dot{n}_0$ mol feed gas. S = solvent , G = solvent - free gas



Inlet dew point $= T_0 \Rightarrow$ $$y_o P_o = p*(T_{do}) \Rightarrow y_o = \frac{p*(T_{do})}{P_o} \qquad (1)$$

Saturation condition at outlet: $$y_1 P_f = p*(T_f) \Rightarrow y_1 = \frac{p*(T_f)}{P_f} \qquad (2)$$

Fractional condensation of S $= f$ $$\Rightarrow n_2 = n_0 y_0 f \xrightarrow{(1)} n_2 = n_0 f p*(T_0)/P_0 \qquad (3)$$

Total mole balance: $$\dot{n}_0 = n_1 + n_2 \Rightarrow n_1 = \dot{n}_0 - n_2 \overset{\text{Eq. (3) for } n_1}{\Rightarrow} n_1 = \dot{n}_0 - \frac{\dot{n}_0 f p*(T_{do})}{P_o} \qquad (4)$$

S balance: $(n_0)(y_0) = n_1 y_1 + n_2$

$$\overset{(1)\text{ - }(4)}{\Rightarrow} \frac{\dot{n}_0 p*(T_{do})}{P_o} = \left[\dot{n}_0 - \frac{\dot{n}_0 f p*(T_{do})}{P_o}\right]\left(\frac{p*(T_f)}{P_f}\right) + \frac{\dot{n}_0 f p*(T_{do})}{p_o}$$

$$\Rightarrow \underline{\frac{(1-f)p*(T_{do})}{P_o} = \left[1 - \frac{f p*(T_{do})}{P_o}\right]\frac{p*(T_f)}{P_f}} \Rightarrow P_f = \underline{\underline{\frac{p*(T_f)\left[1 - \frac{f p*(T_{do})}{P_o}\right]}{(1-f)\frac{p*(T_{do})}{P_o}}}}$$

b.

Condensation of ethylbenzene from nitrogen											
Antoine constants for ethylbenzene											
A=	6.9565										
B=	1423.5										
C=	213.09										
Run	T0	P0	Td0	f	Tf	p* (Td0)	p*(Tf)	Pf	Crefr	Ccomp	Ctot
1	50	765	40	0.95	45	21.472	27.60	19139	2675	107027	109702
2	50	765	40	0.95	40	21.472	21.47	14892	4700	83329	88029
3	50	765	40	0.95	35	21.472	16.54	11471	8075	64239	72314
4	50	765	40	0.95	**20**	21.472	7.07	4902	26300	27582	**53882**

6.31 (cont'd)

c. When T_f decreases, P_f decreases. Decreasing temperature and increasing pressure both to increase the fractional condensation. When you decrease T_f, less compression is required to achieve a specified fractional condensation.

d. A lower T_f requires more refrigeration and therefore a greater refrigeration cost (C_{refr}). However, since less compression is required at the lower temperature, C_{comp} is lower at the lower temperature. Similarly, running at a higher T_f lowers the refrigeration cost but raises the compression cost. The sum of the two costs is a minimum at an intermediate temperature.

6.32 a. <u>Basis</u>: $120\ \text{m}^3/\text{min feed @ } 1000^\circ\text{C(1273K), 35 atm}$. Use Kay's rule.

Cmpd.	$T_c(K)$	P_c(atm)	$(T_c)_{corr}$.	$(P_c)_{corr}$
H_2	33.2	12.8	41.3	20.8
CO	133.0	34.5	–	–
CO_2	304.2	72.9	–	–
CH_4	190.7	45.8	–	–

(Apply Newton's corrections for H_2)

$$T_c' = \sum y_i T_{ci} = 0.40(41.3) + 0.35(133.0) + 0.20(304.2) + 0.05(190.7) = 133.4K$$

$$P_c' = \sum y_i P_{ci} = 0.40(20.8) + 0.35(34.5) + 0.20(72.9) + 0.05(45.8) = 37.3\ \text{atm}$$

<u>Feed gas to cooler</u>

$$\left.\begin{array}{l} T_r = 1273\ K/133.4K = 9.54 \\ P_r = 35.0\ \text{atm}/37.3\ \text{atm} = 0.94 \end{array}\right\} \text{Generalized compressibility charts (Fig. 5.4-3)} \Rightarrow z = 1.02$$

$$\hat{V} = \begin{array}{c|c|c|c} 1.02 & 8.314\ \text{N}\cdot\text{m} & 1273\ \text{K} & 1\ \text{atm} \\ \hline 35\ \text{atm} & \text{mol}\cdot\text{K} & & 101325\ \text{N/m}^3 \end{array} = 3.04\times10^{-3}\ \text{m}^3/\text{mol}$$

$$\begin{array}{c|c|c} 120\ \text{m}^3 & \text{mol} & 1\ \text{kmol} \\ \hline \text{min} & 3.04\times10^{-3}\ \text{m}^3 & 10^3\ \text{mol} \end{array} = 39.5\ \text{kmol/min}$$

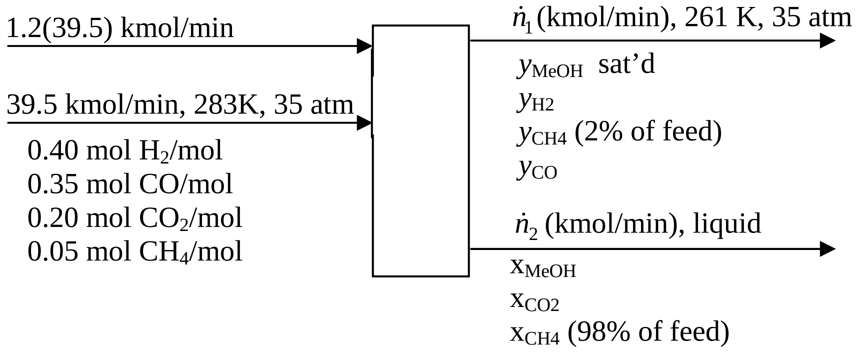
<u>Feed gas to absorber</u>

$$\left.\begin{array}{l} T_r = 283\ K/133.4K = 2.12 \\ P_r = 35.0\ \text{atm}/37.3\ \text{atm} = 0.94 \end{array}\right\} \text{Generalized compressibility charts (Fig. 5.4-3)} \Rightarrow z = 0.98$$

$$\hat{V} = \begin{array}{c|c|c|c} 0.98 & 8.314\ \text{N}\cdot\text{m} & 283\ \text{K} & 1\ \text{atm} \\ \hline 35\ \text{atm} & \text{mol}\cdot\text{K} & & 101325\ \text{N/m}^3 \end{array} = 6.50\times10^{-4}\ \text{m}^3/\text{mol}$$

$$V = \begin{array}{c|c|c} 39.5\ \text{kmol} & 10^3\ \text{mol} & 6.50\times10^{-4}\ \text{m}^3 \\ \hline \text{min} & 1\ \text{kmol} & \text{mol} \end{array} = 25.7\ \frac{\text{m}^3}{\text{min}}$$

6.32 (cont’d)



Saturation at Outlet: $y_{\text{McOH}} = \dfrac{p^*_{\text{MeOH}}(261K)}{P} = \dfrac{\left[10^{7.87863-1473.11/(-12+2300)}\right]\text{mm Hg}}{35\text{ atm}(760\text{ mm Hg/atm})}$

$$= 4.97 \times 10^{-4}\text{ mol MeOH/mol}$$

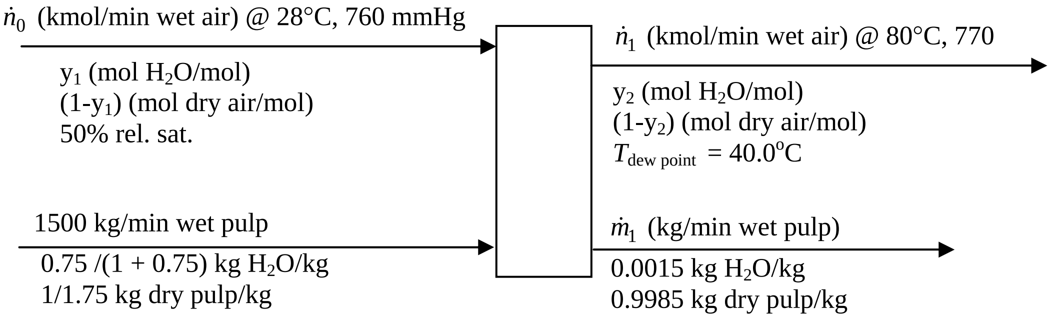
$$y_{\text{McOH}} = \frac{n_{\text{MeOH}}}{n_{\text{MeOH}} + \underset{\overset{\uparrow}{=\text{input}}}{n_{\text{H}_2}} + \underset{\overset{\uparrow}{=0.02\text{ of input}}}{n_{\text{CH}_4}} + \underset{\overset{\uparrow}{=\text{input}}}{n_{CO}}} = \frac{n_{\text{MeOH}}}{n_{\text{MeOH}} + 39.5\big(0.40 + 0.02(0.05) + 0.35\big)}$$

$$\Downarrow$$

$$\underline{\underline{n_{\text{MeOH}} = 0.0148\text{ kmol/min MeOH in gas}}}$$

b. The gas may be used as a fuel. CO_2 has no fuel value, so that the cost of the added energy required to pump it would be wasted.

6.33



Dry pulp balance: $1500 \times \dfrac{1}{1+0.75} = \dot{m}_1(1-0.0015) \Rightarrow \dot{m}_1 = 858 \text{ kg / min}$

50% rel. sat'n at inlet: $y_1 P = 0.50\, p^*_{H_2O}(28^{o}\text{C}) \Rightarrow y_1 = 0.50(28.349 \text{ mm Hg})/(760 \text{ mm Hg})$

$= 0.0187 \text{ mol } H_2O/\text{mol}$

40^{o}C dew point at outlet: $y_2 P = p^*_{H_2O}(40^{o}\text{ C}) \Rightarrow y_2 = (55.324 \text{ mm Hg}) / (770 \text{ mm Hg})$

$= 0.0718 \text{ mol } H_2O / \text{mol}$

Mass balance on dry air:

$\dot{n}_0(1-0.0187) = \dot{n}_1(1-0.0718)$ (1)

Mass balance on water:

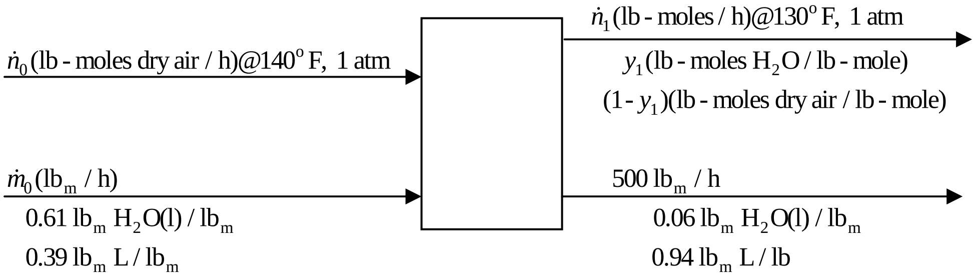
$\dot{n}_0(0.0187)(18.0 \text{ kg/kmol}) + 1500(0.75/1.75) = \dot{n}_1(0.0718)(18) + 858(0.0015)$ (2)

Solve (1) and (2) $\Rightarrow$ $\dot{n}_0 = 622.8 \text{ kmol / min},\ \dot{n}_1 = 658.4 \text{ kmol / min}$

Mass of water removed from pulp: [1500(0.75/1.75)–858(.0015)]kg H_2O = $\underline{\underline{642 \text{ kg / min}}}$

Air feed rate: $\dot{V}_0 = \dfrac{622.8 \text{ kmol}}{\text{min}} \bigg| \dfrac{22.4 \text{ m}^3(\text{STP})}{\text{kmol}} \bigg| \dfrac{(273+28)\text{ K}}{273 \text{ K}} = \underline{\underline{1.538 \times 10^4 \text{ m}^3 / \text{min}}}$

6.34 Basis: 500 $\text{lb}_\text{m}/\text{hr}$ dried leather (L)



Dry leather balance: $0.39m_0 = (0.94)(500) \Rightarrow m_0 = \underline{\underline{1205\ \text{lb}_\text{m}\ \text{wet leather/hr}}}$

Humidity of outlet air: $y_1 P = 0.50 p^*_{\text{H}_2\text{O}}(130°\text{ F}) \Rightarrow y_1 = \dfrac{0.50(115\text{ mm Hg})}{760\text{ mmHg}} = 0.0756 \dfrac{\text{mol H}_2\text{O}}{\text{mol}}$

H$_2$O balance: $(0.61)(1205\ \text{lb}_\text{m}/\text{hr}) = (0.06)\left(500\ \text{lb}_\text{m}/\text{hr}\right) + \dfrac{(0.0756 n_1)\text{lb - moles H}_2\text{O}}{\text{hr}} \Bigg| \dfrac{18.02\ \text{lb}_\text{m}}{1\ \text{lb - mole}}$

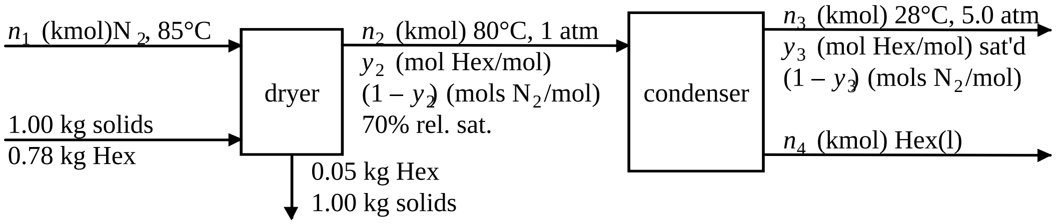
$$\Downarrow$$

$$n_1 = 517.5\ \text{lb - moles/hr}$$

Dry air balance: $n_0 = (1 - 0.0756)(517.5)\ \text{lb - moles/hr} = 478.4\ \text{lb - moles/hr}$

$$\underline{V_\text{inlet}} = \frac{478.4\ \text{lb - moles}}{\text{hr}} \Bigg| \frac{359\ \text{ft}^3(\text{STP})}{1\ \text{lb - mole}} \Bigg| \frac{(140+460)°\text{ R}}{492°\text{ R}} = \underline{\underline{2.09 \times 10^5\ \ \text{ft}^3/\text{hr}}}$$

6.35 a. Basis: 1 kg dry solids



Mol Hex in gas at 80°C: $\dfrac{(0.78 - 0.05)\text{kg}}{} \Bigg| \dfrac{\text{kmol}}{86.17\text{ kg}} = 8.47 \times 10^{-3}\ \text{kmol Hex}$

70% rel. sat.: $y_2 = \dfrac{0.70 \overset{\text{Antoine eq.}}{\overset{\downarrow}{p^*_{hex}}}(80°\text{C})}{P} = \dfrac{(0.70)10^{6.88555\ -\ 1175.817/(80+224.867)}}{760} = 0.984\ \text{mol Hex/mol}$

6.35 (cont'd)

$$n_2 = \frac{8.47\times10^{-3}\text{ kmol Hex}}{} \bigg| \frac{1\text{ kmol}}{0.984\text{ kmol Hex}} = 0.0086\text{ kmol}$$

N$_2$ balance on dryer: $n_1 = (1-0.984)0.0086 = 1.376\times10^{-4}\text{ kmol}$

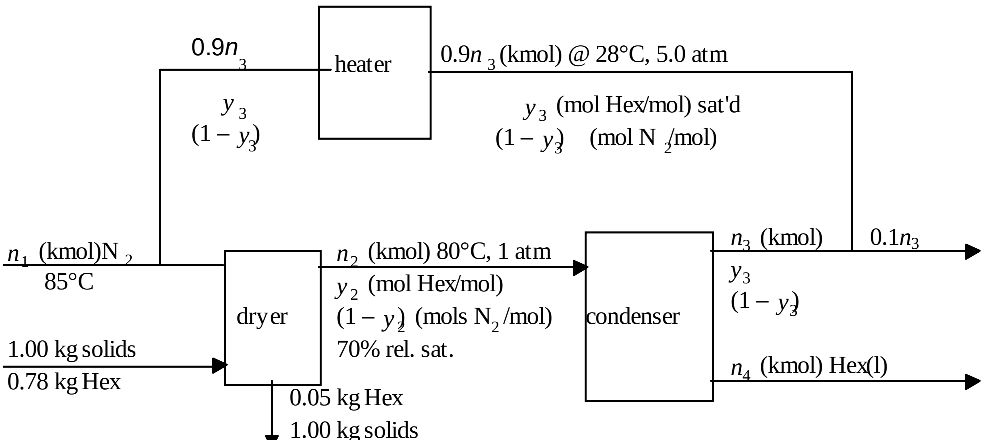
Saturation at outlet: $y_3 = \dfrac{\overset{\substack{\text{Antoine Eq.}\\ \downarrow}}{p^*_{hex}}(28°\text{C})}{\text{P}} = \dfrac{10^{6.88555\,-\,1175.817/(28+224.867)}}{5(760)} = 0.0452\text{ mol Hex/mol}$

Overall N$_2$ balance: $1.376\times10^{-4} = n_3(1-0.0452) \Rightarrow n_3 = 1.44\times10^{-4}\text{ kmol}$

Mole balance on condenser: $0.0086 = 1.44\times10^{-4} + n_4 \Rightarrow n_4 = 0.0085\text{ kmol}$

Fractional hexane recovery: $\dfrac{0.0085\text{ kmol cond.}}{0.78\text{ kg feed}}\bigg|\dfrac{86.17\text{ kg}}{\text{kmol}} = \underline{\underline{0.939\text{ kg cond./kg feed}}}$

b. Basis: 1 kg dry solids



Mol Hex in gas at 80°C: $8.47\text{x}10^{-3} + 0.9n_3(0.0452) = n_2(0.984)$ (1)

N$_2$ balance on dryer: $n_1 + 0.9n_3(1-0.0452) = n_2(1-0.984)$ (2)

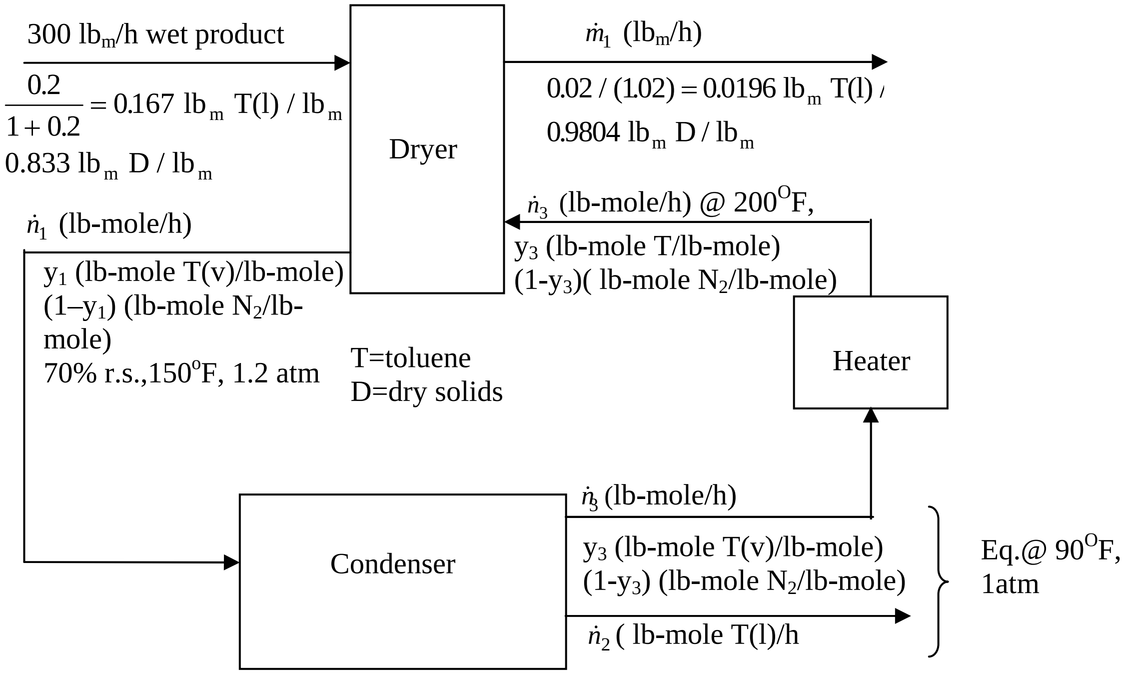
Overall N$_2$ balance: $n_1 = 0.1n_3(1-0.0452)$ (3)

$$\text{Equations (1) to (3)} \Rightarrow \begin{cases} n_1 = 1.38\times10^{-5}\text{ kmol} \\ n_2 = 0.00861\text{ kmol} \\ n_3 = 1.44\times10^{-4}\text{ kmol} \end{cases}$$

Saved fraction of nitrogen$= \dfrac{1.376\times10^{-4} - 1.38\times10^{-5}}{1.376\times10^{-4}}\times100\% = \underline{\underline{90\%}}$

Introducing the recycle leads to added costs for pumping (compression) and heating.

6.36 b.



Strategy: Overall balance$\Rightarrow \dot{m}_1$ & $\dot{n}_2$;

Relative saturation$\Rightarrow y_{1;}$, Gas and liquid equilibrium$\Rightarrow y_3$

Balance over the condenser$\Rightarrow \dot{n}_1$ & $\dot{n}_3$

$$\left.\begin{array}{l}\underline{\text{Toluene Balance:}}\quad 300\times 0.167 = \dot{m}_1\times 0.0196 + \dot{n}_2\times 92.13\\ \underline{\text{Dry Solids Balance:}}\quad 300\times 0.833 = \dot{m}_1\times 0.9804\end{array}\right\}\Rightarrow\left\{\begin{array}{l}\dot{m}_1 = 255\ \text{lb}_m/\text{h}\\ \dot{n}_2 = 0.488\ \text{lb-mole/h}\end{array}\right.$$

70% relative saturation of dryer outlet gas:

$$p^*_{C_7H_8}(150^O\text{F}{=}65.56^O\text{C}){=}10^{(6.95805-\frac{1346.773}{65.56+219.693})} = 172.47\ \text{mmHg}$$

$$y_1P = 0.70p^*_{C_7H_8}(150^O\ \text{F}) \Rightarrow\ y_1 = \frac{0.70p^*_{C_7H_8}}{P} = \frac{(0.70)(172.47)}{1.2\times 760} = \underline{\underline{0.1324\ \text{lb-mole T(v)/lb-mole}}}$$

Saturation at condenser outlet:

$$p^*_{C_7H_8}(90^O\text{F}{=}32.22^O\text{C}){=}10^{(6.95805-\frac{1346.773}{65.56+219.693})} = 40.90\ \text{mmHg}$$

$$y_3 = \frac{p^*_{C_7H_8}}{P} = \frac{40.90}{760} = \underline{\underline{0.0538\ \text{mol T(v)/mol}}}$$

$$\left.\begin{array}{l}\underline{\text{Condenser Toluene Balance:}}\quad \dot{n}_1\times 0.1324 = 0.488 + \dot{n}_3\times 0.0538\\ \underline{\text{Condenser N}_2\text{ Balance:}}\quad \dot{n}_1\times(1-0.1324) = \dot{n}_3\times(1-0.0538)\end{array}\right\}\Rightarrow\left\{\begin{array}{l}\dot{n}_1 = 5.875\ \text{lb-mole/h}\\ \dot{n}_3 = 5.387\ \text{lb-mole/h}\end{array}\right.$$

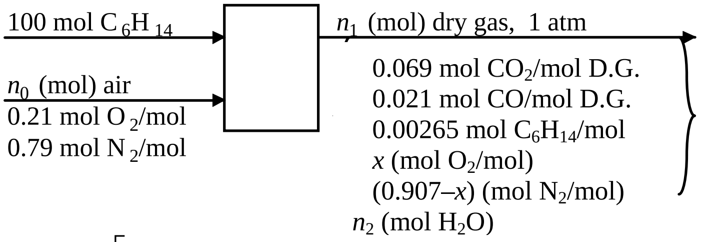
6.36 (cont'd)

$$\underline{\text{Circulation rate of dry nitrogen}} = 5.875 \times (1 - 0.1324) = \frac{5.097 \text{ lb-mole}}{\text{h}} \left| \frac{\text{lb-mole}}{28.02 \text{ lb}_m} \right. = \underline{\underline{0.182 \text{ lb}_m/\text{h}}}$$

$$\underline{V_{\text{inlet}}} = \frac{5.387 \text{ lb-moles}}{\text{hr}} \left| \frac{359 \text{ ft}^3(\text{STP})}{1 \text{ lb-mole}} \right| \frac{(200+460)°\text{R}}{492°\text{R}} = \underline{\underline{2590 \text{ ft}^3/\text{h}}}$$

6.37

$\underline{\text{Basis}}$: 100 mol C_6H_{14} $\qquad C_6H_{14} + \frac{19}{2}O_2 \rightarrow 6CO_2 + 7H_2O$



$$\underline{\text{C balance:}}\ 6(100) = n_1\Bigg[\underset{(CO_2)}{0.069} + \underset{(CO)}{0.021} + 6\underset{(C_6H_{14})}{(0.00265)}\Bigg] \Rightarrow n_1 = 5666 \text{ mol dry gas}$$

$$\underline{\text{Conversion}}: \frac{[100 - 0.00265(5666)] \text{ mol reacted}}{100 \text{ mol fed}} \times 100\% = \underline{\underline{85.0\%}}$$

$$\underline{\text{H balance:}}\ 14(100) = 2n_2 + 5666(14)(0.00265) \Rightarrow n_2 = 595 \text{ mol } H_2O$$

$$\underline{\text{Dew point:}}\ y_{H_2O} = \frac{595}{595+5666} = \frac{p^*(T_{dp})}{760 \text{ mm Hg}} \Rightarrow p^*(T_{dp}) = 72.2 \text{ mm Hg} \xRightarrow{\text{Table B.3}} \underline{\underline{T_{dp} = 45.1°\text{C}}}$$

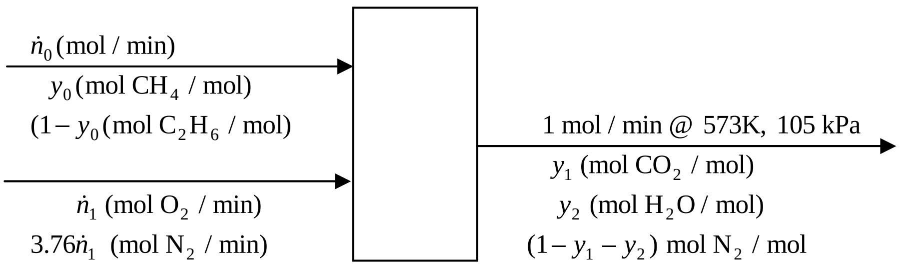
$$\left.\begin{aligned} &\underline{N_2 \text{ balance:}}\ 0.79n_0 = 5666(0.907 - x) \\ &\underline{\text{O balance:}}\ 0.21(n_0)(2) = 5666[(0.069)(2) + 0.021 + 2x) + 595 \end{aligned}\right\}$$

Solve simultaneously to obtain n_0 = 5888 mol air, x = 0.086 mol O_2/mol

$$\underline{\text{Theoretical air:}}\ \frac{100 \text{ mol } C_2H_{14}}{} \left| \frac{19 \text{ mol } O_2}{2 \text{ mol } C_2H_{14}} \right| \frac{1 \text{ mol air}}{0.21 \text{ mol } O_2} = 4524 \text{ mol air}$$

$$\underline{\text{Excess air:}}\ \frac{5888 - 4524}{4524} \times 100\% = \underline{\underline{30.2\% \text{ excess air}}}$$

6.38 Basis: 1 mol outlet gas/min



$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$

$$p_{CO_2} = 80 \text{ mmHg} \Rightarrow y_1 = \frac{80 \text{ mmHg}}{105000 \text{ Pa}}\left|\frac{101325 \text{ Pa}}{760 \text{ mmHg}}\right. = 0.1016 \text{ mol } CO_2 \text{ / mol}$$

100% O_2 conversion: $2n_o y_o + \frac{7}{2}n_o(1-y_o) = n_1$ (1)

C balance: $n_o y_o + 2n_o(1-y_o) = 0.1016$ (2)

N_2 balance: $3.76n_1 = 1 - y_1 - y_2$ (3)

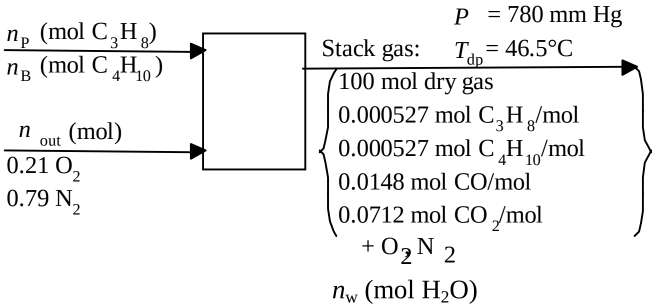
H balance: $4n_o y_o + 6n_o(1-y_o) = 2y_2$ (4)

$$\text{Solve equations 1 to 4} \Rightarrow \begin{cases} n_o = 0.0770 \text{ mol} \\ y_o = \underline{\underline{0.6924 \text{ mol } CH_4 \text{ / mol}}} \\ n_1 = 0.1912 \text{ mol } O_2 \\ y_2 = 0.1793 \text{ mol } H_2O \text{ / mol} \end{cases}$$

Dew point:

$$p^*_{H_2O}(T_{dp}) = \frac{0.1793(105000) \text{ Pa}}{}\left|\frac{760 \text{ mmHg}}{101325 \text{ Pa}}\right. = 141.2 \text{ mmHg} \Rightarrow T_{dp} = \underline{\underline{58.8^o\text{ C}}} \text{ (Table B.3)}$$

6.39 Basis: 100 mol dry stack gas



$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \qquad C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O$$

6.39 (cont'd)

$$\underline{\text{Dew point} = 46.5^\circ\text{C}} \Rightarrow y_w P = p^*_w\left(46.5^\circ\text{C}\right) \Rightarrow y_w = \frac{77.6 \text{ mm Hg}}{780 \text{ mm Hg}} = 0.0995 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

But $y_w = \dfrac{n_w}{100 + n_w} = 0.0995 \Rightarrow n_w = 11.05 \text{ mol H}_2\text{O}$ (Rounding off strongly affects the result)

$$\underline{\text{C balance:}}\ 3n_p + 4n_B = (100)\left[(0.000527)(3) + (0.000527)(4) + 0.0148 + 0.0712\right]$$

$$\Rightarrow \quad 3n_p + 4n_B = 8.969 \quad (1)$$

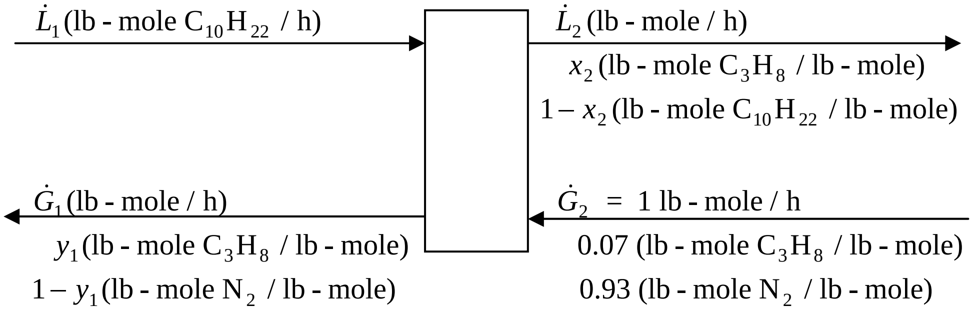
$$\underline{\text{H balance:}}\ 8n_p + 10n_B = (100)\left[(0.000527)(8) + (0.000527)(10)\right] + (11.05)(2)$$

$$\Rightarrow \ 8n_p + 10n_B = 23.047 \quad (2)$$

$$\text{Solve } (1) \ \& \ (2) \text{ simultaneously:} \Rightarrow \begin{Bmatrix} n_p = 1.25 \text{ mol C}_3\text{H}_8 \\ n_B = 1.30 \text{ mol C}_4\text{H}_{10} \end{Bmatrix} \Rightarrow \begin{cases} \underline{\underline{49\% \text{ C}_3\text{H}_8}} \\ \underline{\underline{51\% \text{ C}_4\text{H}_{10}}} \end{cases}$$

(Answers may vary ±8% due to loss of precision)

6.40 a.



$\underline{\text{Basis}}$: $\dot{G}_2 = 1$ lb - mole/h feed gas

$$\underline{\text{N}_2 \text{ balance:}}\ (1)(0.93) = \dot{G}_1(1 - y_1) \Rightarrow \dot{G}_1(1 - y_1) = 0.93 \qquad (1)$$

$$\underline{\text{98.5\% propane absorption}} \Rightarrow \dot{G}_1 y_1 = (1 - 0.985)(1)(0.07) \Rightarrow \dot{G}_1 y_1 = 1.05 \times 10^{-3} \qquad (2)$$

$$(1) \ \& \ (2) \Rightarrow \ \dot{G}_1 = 0.93105 \text{ lb - mol/h}, \ y_1 = 1.128 \times 10^{-3} \text{ mol } \text{C}_3\text{H}_8/\text{mol}$$

Assume $\dot{G}_2 - \dot{L}_2$ streams are in equilibrium

From Cox Chart (Figure 6.1-4), $p^*_{C_3H_8}\ (80^o F) = 160 \text{ lb / in}^2 = 10.89 \text{ atm}$

$$\underline{\text{Raoult's law:}}\ x_2 p^*_{\text{C}_3\text{H}_8}\left(80^\circ \text{F}\right) = 0.07p \Rightarrow x_2 = \frac{(0.07)(1.0 \text{ atm})}{10.89 \text{ atm}} = 0.006428 \frac{\text{mol H}_2\text{O}}{\text{mol}}$$

$$\underline{\text{Propane balance:}}\ (0.07)(1) = \dot{G}_1 y_1 + \dot{L}_2 x_2 \Rightarrow \dot{L}_2 = \frac{0.07 - (0.93105)\left(1.128 \times 10^{-3}\right)}{0.006428}$$

$$= 10.726 \text{ lb - mole/h}$$

$$\underline{\text{Decane balance:}}\ \ \dot{L}_1 = (1 - x_2)\left(\dot{L}_2\right) = (1 - 0.006428)(10.726) = 10.66 \text{ lb - mole/h}$$

$$\Rightarrow \ \left(\dot{L}_1 / \dot{G}_2\right)_{\min} = \underline{\underline{10.7 \text{ mol liquid feed / mol gas feed}}}$$

6.40 (cont'd)

b. The flow rate of propane in the exiting liquid must be the same as in Part (a) [same feed rate and fractional absorption], or

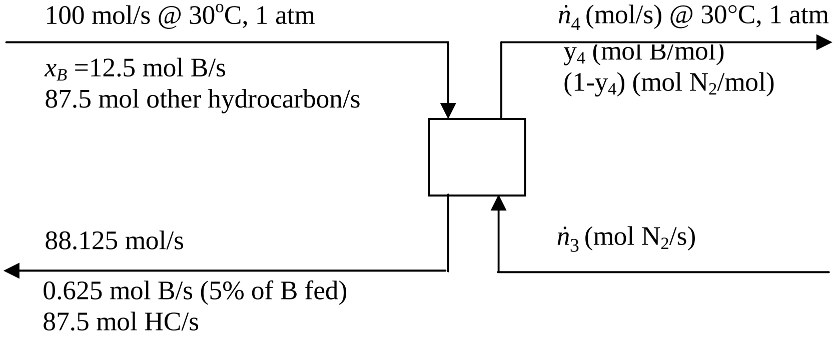
$$\dot{n}_{C_3H_8}= \frac{10.726\text{ lb - mole}}{\text{h}}\left|\frac{0.006428\text{ lb - mole }C_3H_3}{\text{lb - mole}}\right. = 0.06895\text{ lb - mol }C_3H_8/\text{h}$$

The decane flow rate is 1.2 x 10.66 = 12.8 lb-moles $C_{10}H_{22}$/h

$$\Rightarrow x_2 = \frac{0.06895\text{ lb - mole }C_3H_8/\text{h}}{(0.06895+12.8)\text{ lb - moles/h}} = \underline{\underline{0.00536\text{ lb - mole }C_3H_8\text{ / lb - mole}}}$$

c. Increasing the liquid/gas feed ratio from the minimum value decreases the size (and hence the cost) of the column, but increases the raw material (decane) and pumping costs. All three costs would have to be determined as a function of the feed ratio.

6.41 a. Basis: 100 mol/s liquid feed stream Let B = n - butane , HC = other hydrocarbons



$p_B^*(30^\circ\text{C}) \cong 41\text{ lb / in}^2 = 2120\text{ mm Hg}$ (from Figure 6.1-4)

Raoult's law: $y_4 P = x_B p_B^*(30^\circ\text{C}) \Rightarrow y_4 = \frac{x_B p_B^*(30^\circ\text{C})}{\text{P}} = \frac{0.125\times 2120}{760} = 0.3487$

95% n-butane stripped: $\dot{n}_4\cdot(0.3487)=(12.5)(0.95)\Rightarrow \dot{n}_4 = 34.06\text{ mol / s}$

Total mole balance: $100+\dot{n}_3 = 34.06+88.125 \Rightarrow \dot{n}_3 = 22.18\text{ mol/s}$

$$\Rightarrow \frac{\text{mol gas fed}}{\text{mol liquid fed}} = \frac{22.18\text{ mol/s}}{100\text{ mol/s}} = \underline{\underline{0.222\text{ mol gas fed/mol liquid fed}}}$$

b. If $y_4 = 0.8\times 0.3487 = 0.2790$, following the same steps as in Part (**a**),

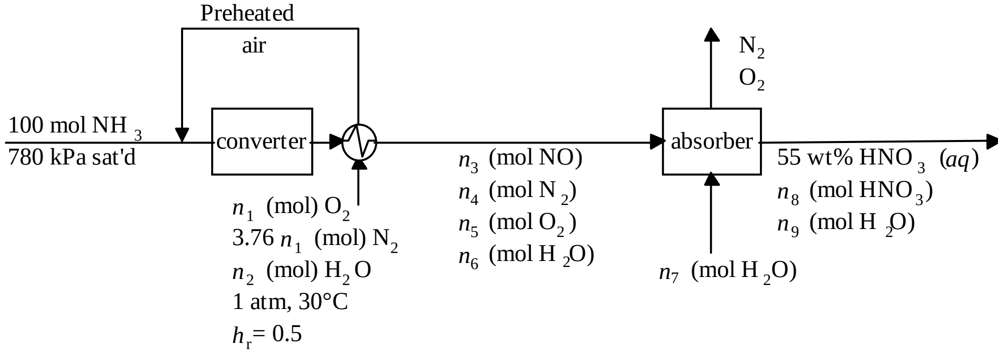
95% n-butane is stripped: $\dot{n}_4\cdot(0.2790)=(12.5)(0.95)\Rightarrow \dot{n}_4 = 42.56\text{ mol / s}$

Total mole balance: $100+\dot{n}_3 = 42.56+88.125 \Rightarrow \dot{n}_3 = 30.68\text{ mol / s}$

$$\Rightarrow \frac{\text{mol gas fed}}{\text{mol liquid fed}} = \frac{30.68\text{ mol/s}}{100\text{ mol/s}} = \underline{\underline{0.307\text{ mol gas fed/mol liquid fed}}}$$

c. When the N_2 feed rate is at the minimum value calculated in (a), the required column length is infinite and hence so is the column cost. As the N_2 feed rate increases for a given liquid feed rate, the column size and cost decrease but the cost of purchasing and compressing (pumping) the N_2 increases. To determine the optimum gas/liquid feed ratio, you would need to know how the column size and cost and the N_2 purchase and compression costs depend on the N_2 feed rate and find the rate at which the cost is a minimum.

6.42 Basis: 100 mol NH_3



a. i) NH_3 feed: $P = P*(T_{sat}) = 820 \text{ kPa} = 6150 \text{ mm Hg} = 8.09 \text{ atm}$

Antoine:
$$\log_{10}(6150) = 7.55466 - 1002.711/(T_{sat} + 247.885) \Rightarrow T_{sat} = 18.4°\text{C} = 291.6 \text{ K}$$

$$\text{Table B.1} \Rightarrow \left.\begin{array}{l} P_c = 111.3 \text{ atm} \Rightarrow P_r = 8.09/111.3 = 0.073 \\ T_c = 405.5K \Rightarrow T_r = 291.6/405.5 = 0.72 \end{array}\right\} \Rightarrow z = 0.92 \quad \text{(Fig. 5.3-1)}$$

$$V_{NH_3} = \frac{0.92(100 \text{ mol})}{} \left| \frac{8.314 \text{ Pa}}{\text{mol - K}} \right| \frac{291.6 \text{ K}}{820 \times 10^3 \text{ Pa}} = \underline{\underline{0.272 \text{ m}^3 \text{ NH}_3}}$$

Air feed: $NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$

$$n_1 = \frac{100 \text{ mol NH}_3}{} \left| \frac{2 \text{ mol O}_2}{\text{mol NH}_3} \right. = 200 \text{ mol O}_2$$

Water in Air: $$y_{H_2O} = \frac{h_r \cdot p^*(30°\text{C})}{\text{p}} = \frac{0.500 \times 31.824}{760} = 0.02094$$

$$\Rightarrow 0.02094 = \frac{n_2}{n_2 + \underset{\substack{\uparrow \\ (4.76 \text{ mol air/mol O}_2)}}{4.76(200)}} \Rightarrow n_2 = 20.36 \text{ mol H}_2\text{O}$$

$$V_{air} = \frac{[4.76(200) + 20.36]\text{mol}}{} \left| \frac{22.4 \text{ L (STP)}}{1 \text{ mol}} \right| \frac{303\text{K}}{273\text{K}} \left| \frac{1 \text{ m}^3}{10^3 \text{ L}} \right. = \underline{\underline{24.2 \text{ m}^3 \text{ air}}}$$

ii) Reactions: $4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$, $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$

Balances on converter

NO: $$n_3 = \frac{97 \text{ mol NH}_3}{} \left| \frac{4 \text{ mol NO}}{4 \text{ mol NH}_3} \right. = 97 \text{ mol NO}$$

6.42 (cont'd)

$$\underline{\text{N}_2}:\ n_4 = 3.76(2.00)\text{ mol} + \begin{array}{c|c} 3\text{ mol NH}_3 & 2\text{ mol N}_2 \\ \hline & 4\text{ mol NH}_3 \end{array} = 753.5\text{ mol N}_2$$

$$\underline{\text{O}_2}:\ n_5 = 200\text{ mol} - \begin{array}{c|c} 97\text{ mol NH}_3 & 5\text{ mol O}_2 \\ \hline & 4\text{ mol NH}_3 \end{array}$$

$$- \begin{array}{c|c} 3\text{ mol NH}_3 & 3\text{ mol O}_2 \\ \hline & 4\text{ mol NH}_3 \end{array} = 76.5\text{ mol O}_2$$

$$\underline{\text{H}_2\text{O}}:\ n_6 = 20.36\text{ mol} + \begin{array}{c|c} 100\text{ mol NH}_3 & 6\text{ mol H}_2\text{O} \\ \hline & 4\text{ mol NH}_3 \end{array} = 170.4\text{ mol H}_2\text{O}$$

$$\Rightarrow\ n_{\text{total}} = (97 + 753.5 + 76.5 + 170.4)\text{mol}$$

$$= \underline{\underline{1097\text{ mol converter effluent}}}$$

$$\underline{\underline{8.8\%\text{ NO},\ 68.7\%\text{ N}_2,\ 7.0\%\text{ O}_2,\ 15.5\%\text{ H}_2\text{O}}}$$

iii) Reaction: $4\text{NO} + 3\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{HNO}_3$

$$\underline{\text{HNO}_3\text{ bal. in absorber:}}\ n_8 = \begin{array}{c|c} 97\text{ mol NO react} & 4\text{ mol HNO}_3 \\ \hline & 4\text{ mol NO} \end{array} = 97\text{ mol HNO}_3$$

$$\underline{\text{H}_2\text{O in product:}}\ n_9 = \begin{array}{c|c|c|c} 97\text{ mol HNO}_3 & 63.02\text{ g HNO}_3 & 45\text{ g H}_2\text{O} & 1\text{ mol H}_2\text{O} \\ \hline & \text{mol} & 55\text{ g HNO}_3 & 18.02\text{ g H}_2\text{O} \end{array}$$

$$= 277.56\text{ mol H}_2\text{O}$$

$$\underline{\text{H balance on absorber:}}\ (170.4)(2) + 2n_7 = 97 + (277.6)(2)(\text{mol H})$$

$$\Rightarrow n_7 = 155.7\text{ mol H}_2\text{O added}$$

$$V_{\text{H}_2\text{O}} = \begin{array}{c|c|c|c} 155.7\text{ mol H}_2\text{O} & 18.02\text{ g H}_2\text{O} & 1\text{ cm}^3 & 1\text{ m}^3 \\ \hline & 1\text{ mol} & 1\text{ g} & 10^6\text{ cm}^3 \end{array} = \underline{\underline{2.81\times10^{-3}\text{ m}^3\text{ H}_2\text{O}(l)}}$$

b.

$$\underline{M_{\text{acid}}\text{ in old basis}} = \begin{array}{c|c} 97\text{ mol HNO}_3 & 63.02\text{ g HNO}_3 \\ \hline & \text{mol} \end{array} + \begin{array}{c|c} 277.6\text{ mol H}_2\text{O} & 18.02\text{ g H}_2\text{O} \\ \hline & \text{mol} \end{array}$$

$$= 11115\text{ g} = 11.115\text{ kg}$$

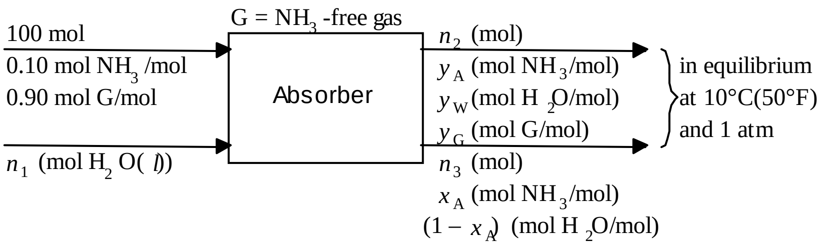
$$\underline{\text{Scale factor}} = \frac{(1000\text{ metric tons})(1000\text{ kg/metric ton})}{11.115\text{ kg}} = 8.997\times10^4$$

$$V_{\text{NH}_3} = (8.997\times10^4)(0.272\text{ m}^3\text{ NH}_3) = \underline{\underline{2.45\times10^4\text{ m}^3\text{ NH}_3}}$$

$$V_{\text{air}} = (8.997\times10^4)(24.2\text{ m}^3\text{ air}) = \underline{\underline{2.18\times10^6\text{ m}^3\text{ air}}}$$

$$V_{\text{H}_2\text{O}} = (8.997\times10^4)(2.81\times10^{-3}\text{ m}^3\text{ H}_2\text{O}) = \underline{\underline{253\text{ m}^3\text{ H}_2\text{O}(l)}}$$

6.43 **a**. Basis: 100 mol feed gas



Composition of liquid effluent . Basis: 100 g solution

Perry, Table 2.32, p. 2-99: $T = 10^oC\ (50^oF)$, $\rho = 0.9534$ g/mL $\Rightarrow$ 0.120 g NH_3/g solution

$$\Rightarrow \frac{12.0\text{ g NH}_3}{(17.0\text{ g / 1 mol})} = 0.706\text{ mol NH}_3,\ \frac{88.0\text{ g H}_2\text{O}}{(18.0\text{ g / 1 mol})} = 4.89\text{ mol NH}_3$$

$$\Rightarrow\ 12.6\text{ mole\% NH}_3\text{(aq)},\ 87.4\text{ mole\% H}_2\text{O(l)}$$

Composition of gas effluent

$$T = 50^o\text{ F}, x_A = 0.126 \xrightarrow{Perry} \left.\begin{aligned} p_{\text{NH}_3} &= 1.21\text{ psia}(\text{Table 2 - 23}) \\ p_{\text{H}_2\text{O}} &= 0.155\text{ psia}(\text{Table 2 - 21}) \\ p_{\text{total}} &= 14.7\text{ psia} \end{aligned}\right\}$$

$$\begin{aligned} y_A &= 1.21 / 14.7 = 0.0823\text{ mol NH}_3/\text{mol} \\ \Rightarrow y_W &= 0.155 / 14.7 = 0.0105\text{ mol H}_2\text{O}/\text{mol} \\ y_G &= 1 - y_A - y_W = 0.907\text{ mol G}/\text{mol} \end{aligned}$$

G balance: $(100)(0.90) = n_2 y_G \Rightarrow n_2 = (100)(0.90)/(0.907) = 99.2$ mol

$\underline{\text{NH}_3\text{ absorbed}} = (100)(0.10)_{\text{in}} - (99.2)(0.0823)_{\text{out}} = 1.84\text{ mol NH}_3$

$$\underline{\%\text{ absorption}} = \frac{1.84\text{ mol absorbed}}{(100)(0.10)\text{mol fed}} \times 100\% = \underline{\underline{18.4\%}}$$

b. If the slip stream or densitometer temperature were higher than the temperature in the contactor, dissolved ammonia would come out of solution and the calculated solution composition would be in error.

6.44 **a.**

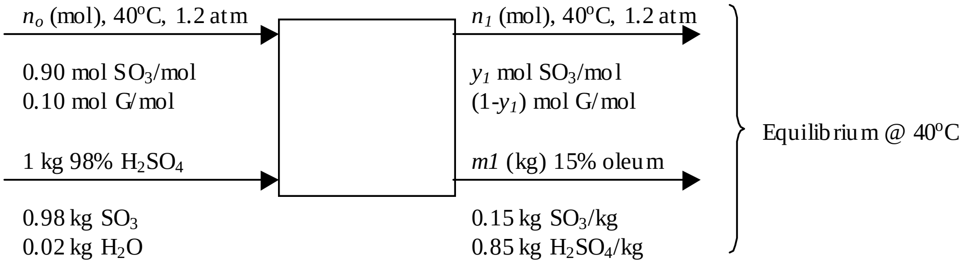
15% oleum: Basis - 100kg

$$15\text{ kg SO}_3 + \begin{array}{c|c|c|c} 85\text{ kg H}_2\text{SO}_4 & 1\text{ kmol H}_2\text{SO}_4 & 1\text{ kmol SO}_3 & 80.07\text{ kg SO}_3 \\ \hline & 98.08\text{ kg H}_2\text{SO}_4 & 1\text{ kmol H}_2\text{SO}_4 & 1\text{ kmol SO}_3 \end{array} = 84.4\text{ kg}$$

$\Rightarrow 84.4\%\text{ SO}_3$

6.44 (cont'd)

b. Basis 1 kg liquid feed



i) $$y_1 = \frac{p_{SO_3}(40°\text{C},\ 84.4\%)}{P} = \frac{1.15}{760} = \underline{\underline{1.51\times10^{-3}\ \text{mol}\ SO_3/\text{mol}}}$$

ii) $$\underline{\text{H balance:}}\ \frac{0.98\ \text{kg}\ H_2SO_4}{} \bigg| \frac{2.02\ \text{kg H}}{98.08\ \text{kg}\ H_2SO_4} + \frac{0.02\ \text{kg}\ H_2O}{} \bigg| \frac{2.02\ \text{kg H}}{18.02\ \text{kg}\ H_2O}$$

$$= \frac{0.85\ \text{m}_1\ H_2SO_4}{} \bigg| \frac{2.02\ \text{kg H}}{98.08\ \text{kg}\ H_2SO_4} \Rightarrow m_1 = 1.28\ \text{kg}$$

But since the feed solution has a mass of 1 kg,

$$\underline{SO_3\ \text{absorbed}} = (1.28-1.0)\ \text{kg} = \frac{0.28\ \text{kg}\ SO_3}{} \bigg| \frac{10^3\ \text{g}}{\text{kg}} \bigg| \frac{1\ \text{mol}}{80.07\ \text{g}} = 3.50\ \text{mol}$$

$$\underbrace{\begin{array}{l} \Rightarrow 3.5\ \text{mol} = n_0 - n_1 \\ \underline{\text{G balance:}}\ 0.10 n_0 = \left(1-1.51\times10^{-3}\right) n_1 \end{array}}_{\Downarrow}$$

$$n_0 = 3.89\ \text{mol}$$
$$n_1 = 0.39\ \text{mol}$$

$$V = \frac{3.89\ \text{mol}}{1\ \text{kg liquid feed}} \bigg| \frac{22.4\ \text{L (STP)}}{\text{mol}} \bigg| \frac{313\text{K}}{273\text{K}} \bigg| \frac{1\ \text{atm}}{1.2\ \text{atm}} \bigg| \frac{1\ \text{m}^3}{10^3\ \text{L}}$$

$$= \underline{\underline{8.33\times10^{-2}\ \text{m}^3/\text{kg liquid feed}}}$$

6.45 **a**. Raoult's law can be used for water and Henry's law for nitrogen.
b. Raoult's law can be used for each component of the mixture, but Henry's law is not valid here.
c. Raoult's law can be used for water, and Henry's law can be used for CO_2.

6.46 $$p_B^*(100°\text{C}) = 10^{**}\left(6.89272 - 1203.531/(100+219.888)\right) = 1350.1\ \text{mm Hg}$$
$$p_T^*(100°\text{C}) = 10^{**}\left(6.95805 - 1346.773/(100+219.693)\right) = 556.3\ \text{mm Hg}$$

$$\underline{\text{Raoult's Law:}}\ y_B P = x_B p_B^* \Rightarrow \quad y_B = \frac{0.40(1350.1)}{10(760)} = \underline{\underline{0.0711\ \text{mol Benzene/mol}}}$$

$$y_T = \frac{0.60(556.3)}{10(760)} = \underline{\underline{0.0439\ \text{mol Toluene/mol}}}$$

$$y_{N_2} = 1 - 0.0711 - 0.0439 = \underline{\underline{0.885\ \text{mol}\ N_2/\text{mol}}}$$

6.47 $\underline{N_2\text{ - Henry's law:}}$ Perry's Chemical Engineers' Handbook, Page. 2 - 127, Table 2 - 138

$$\Rightarrow H_{N_2}(80°C) = 12.6 \times 10^4 \text{ atm/mole fraction}$$

$$\Rightarrow p_{N_2} = x_{N_2} H_{N_2} = (0.003)(12.6 \times 10^4) = 378 \text{ atm}$$

$\underline{H_2O\text{ - Raoult's law:}}$ $p^*_{H_2O}(80°C) = \dfrac{355.1 \text{ mm Hg}}{} \left| \dfrac{1 \text{ atm}}{760 \text{ mm Hg}} \right. = 0.467 \text{ atm}$

$$\Rightarrow p_{H_2O} = (x_{H_2O})(p^*_{H_2O}) = (0.997)(0.467) = 0.466 \text{ atm}$$

$\underline{\text{Total pressure:}}$ $P = p_{N_2} + p_{H_2O} = 378 + 0.466 = \underline{\underline{378.5 \text{ atm}}}$

$\underline{\text{Mole fractions:}}$ $y_{H_2O} = p_{H_2O}/P = 0.466/378.5 = \underline{\underline{1.23 \times 10^{-3} \text{ mol } H_2O/\text{mol gas}}}$

$y_{N_2} = 1 - y_{H_2O} = \underline{\underline{0.999 \text{ mol } N_2/\text{mol gas}}}$

6.48 $\underline{H_2O\text{ - Raoult's law:}}$ $p^*_{H_2O}(70°C) = \dfrac{233.7 \text{ mm Hg}}{} \left| \dfrac{1 \text{ atm}}{760 \text{ mm Hg}} \right. = 0.3075 \text{ atm}$

$$\Rightarrow p_{H_2O} = x_{H_2O} p^*_{H_2O} = (1 - x_m)(0.3075)$$

$\underline{\text{Methane – Henry's law:}}$ $p_m = x_m \cdot H_m$

$\underline{\text{Total pressure:}}$ $P = p_m + p_{H_2O} = x_m \cdot 6.66 \times 10^4 + (1 - x_m)(0.3075) = 10$

$\Rightarrow x_m = \underline{\underline{1.46 \times 10^{-4} \text{ mol } CH_4 \text{ / mol}}}$

6.49 **a.**

$\underline{\text{Moles of water:}}$ $n_{H_2O} = \dfrac{1000 \text{ cm}^3}{} \left| \dfrac{1 \text{ g}}{\text{cm}^3} \right| \dfrac{\text{mol}}{18.02 \text{ g}} = 55.49 \text{ mol}$

$\underline{\text{Moles of nitrogen:}}$

$$n_{N_2} = \frac{(1 - 0.334) \times 14.1 \text{ cm}^3 (\text{STP})}{} \left| \frac{1 \text{ mol}}{22.4 \text{ L (STP)}} \right| \frac{1 \text{ L}}{1000 \text{ cm}^3} = 4.192 \times 10^{-4} \text{ mol}$$

$\underline{\text{Moles of oxygen:}}$

$$n_{O_2} = \frac{(0.334) \cdot 14.1 \text{ cm}^3 (\text{STP})}{} \left| \frac{\text{mol}}{22.4 \text{ L (STP)}} \right| \frac{\text{L}}{1000 \text{ cm}^3} = 2.102 \times 10^{-4} \text{ mol}$$

$\underline{\text{Mole fractions of dissolved gases:}}$

$$x_{N_2} = \frac{n_{N_2}}{n_{H_2O} + n_{N_2} + n_{O_2}} = \frac{4.192 \times 10^{-4}}{55.49 + 4.192 \times 10^{-4} + 2.102 \times 10^{-4}} = 7.554 \times 10^{-6} \ \frac{\text{mol } N_2}{\text{mol}}$$

$$x_{O_2} = \frac{n_{O_2}}{n_{H_2O} + n_{N_2} + n_{O_2}} = \frac{2.102 \times 10^{-4}}{55.49 + 4.192 \times 10^{-4} + 2.102 \times 10^{-4}} = 3.788 \times 10^{-6} \text{ mol } O_2 / \text{mol}$$

6.49 (cont'd)

Henry's law

Nitrogen: $$H_{\mathrm{N_2}} = \frac{p_{N_2}}{x_{N_2}} = \frac{0.79 \cdot 1}{7.554 \times 10^{-6}} = \underline{\underline{1.046 \times 10^{5}\ \text{atm / mole fraction}}}$$

Oxygen: $$H_{\mathrm{O_2}} = \frac{p_{O_2}}{x_{O_2}} = \frac{0.21 \cdot 1}{3.788 \times 10^{-6}} = \underline{\underline{5.544 \times 10^{4}\ \text{atm / mole fraction}}}$$

b. Mass of oxygen dissolved in 1 liter of blood:

$$\mathrm{m_{O_2}} = \begin{array}{c|c} 2.102 \times 10^{-4}\ \text{mol} & 32.0\ \text{g} \\ \hline & \text{mol} \end{array} = 6.726 \times 10^{-3}\ \text{g}$$

Mass flow rate of blood: $$\dot{m}_{\text{blood}} = \begin{array}{c|c} 0.4\ \text{g O}_2 & 1\ \text{L blood} \\ \hline \text{min} & 6.72 \times 10^{-3}\ \text{g O}_2 \end{array} = \underline{\underline{59\ \text{L blood / min}}}$$

c. Assumptions:

(1) The solubility of oxygen in blood is the same as it is in pure water (in fact, it is much greater)

(2) The temperature of blood is 36.9°C.

6.50 **a.** Basis: $1\ \text{cm}^3\ \mathrm{H_2O}(l)$

$$\xrightarrow{(\text{SG})_{\text{H2O}}=1.0} \begin{array}{c|c} 1\ \text{g H}_2\text{O} & 1\ \text{mol} \\ \hline & 18.0\ \text{g} \end{array} = 0.0555\ \text{mol H}_2\text{O}$$

$$\xrightarrow{(\text{SC})_{\text{CO2}}=\ 0.0901} \begin{array}{c|c} 0.0901\ \text{cm}^3\ (\text{STP})\text{CO}_2 & 1\ \text{mol} \\ \hline & 22{,}400\ \text{cm}^3(\text{STP}) \end{array} = 4.022 \times 10^{-6}\ \text{mol CO}_2$$

$$p_{\mathrm{CO_2}} = 1\ \text{atm} \Rightarrow x_{\mathrm{CO_2}} = \frac{\left(4.022 \times 10^{-6}\right)\ \text{mol CO}_2}{\left(0.0555 + 4.022 \times 10^{-6}\right)\ \text{mol}} = 7.246 \times 10^{-5}\ \ \text{mol CO}_2/\text{mol}$$

$$p_{\mathrm{CO_2}} = x_{\mathrm{CO_2}} H_{\mathrm{CO_2}} \Rightarrow H_{\mathrm{CO_2}}(20^\circ\,\text{C}) = \frac{1\ \text{atm}}{7.246 \times 10^{-5}} = \underline{\underline{13800\ \ \text{atm/mole fraction}}}$$

b. For simplicity, assume $n_{\text{total}} \approx n_{\mathrm{H_2O}}(\text{mol})$

$$x_{\mathrm{CO_2}} = p_{\mathrm{CO_2}}/H = (3.5\ \text{atm})/(13800\ \text{atm/mole fraction}) = 2.536 \times 10^{-4}\ \text{mol}\ \ \text{CO}_2/\text{mol}$$

$$n_{\mathrm{CO_2}} = \begin{array}{c|c|c|c|c|c} 12\ \text{oz} & 1\ \text{L} & 10^{3}\ \text{g H}_2\text{O} & 1\ \text{mol H}_2\text{O} & 2.536 \times 10^{-4}\ \text{mol CO}_2 & 44.0\ \text{g CO}_2 \\ \hline & 33.8\ \text{oz} & 1\ \text{L} & 18.0\ \text{g H}_2\text{O} & 1\ \text{mol H}_2\text{O} & 1\ \text{mol CO}_2 \end{array}$$

$$= \underline{\underline{0.220\ \text{g CO}_2}}$$

c. $$V = \begin{array}{c|c|c|c} 0.220\ \text{g CO}_2 & 1\ \text{mol CO}_2 & 22.4\ \text{L}\ (\text{STP}) & (273+37)\text{K} \\ \hline & 44.0\ \text{g CO}_2 & 1\ \text{mol} & 273\text{K} \end{array} = 0.127\ \text{L} = \underline{\underline{127\ \text{cm}^3}}$$

6.51 **a.** – SO_2 is hazardous and should not be released directly into the atmosphere, especially if the analyzer is inside.

– From Henry's law, the partial pressure of SO_2 increases with the mole fraction of SO_2 in the liquid, which increases with time. If the water were never replaced, the gas leaving the bubbler would contain 1000 ppm SO_2 (nothing would be absorbed), and the mole fraction of SO_2 in the liquid would have the value corresponding to 1000 ppm SO_2 in the gas phase.

b. Calculate $x(\text{mol } SO_2/\text{mol})$ in terms of $r(\text{g } SO_2/100 \text{ g } H_2O)$

Basis: $100 \text{ g } H_2O(1 \text{ mol}/18.02 \text{ g}) = 5.55 \text{ mol } H_2O$

$$r \text{ (g } SO_2)(1 \text{ mol}/64.07 \text{ g}) = 0.01561r \text{ (mol } SO_2)$$

$$\Rightarrow x_{SO_2} = \frac{0.01561r}{5.55 + 0.01561r}\left(\frac{\text{mol } SO_2}{\text{mol}}\right)$$

From this relation and the given data, $p_{SO_2} = 0 \text{ mmHg} \Leftrightarrow x_{SO_2} = 0 \text{ mol } SO_2/\text{mol}$

42	1.4×10^{-3}
85	2.8×10^{-3}
129	4.2×10^{-3}
176	5.6×10^{-3}

A plot of p_{SO_2} vs. x_{SO_2} is a straight line. Fitting the line using the method of least squares (Appendix A.1) yields $\left(p_{SO_2} = H_{SO_2} x_{SO_2}\right)$, $\underline{\underline{H_{SO_2} = 3.136 \times 10^4 \dfrac{\text{mm Hg}}{\text{mole fraction}}}}$

c. $$100 \text{ ppm } SO_2 \Rightarrow y_{SO_2} = \frac{100 \text{ mol } SO_2}{10^6 \text{ mols gas}} = \underline{\underline{1.00 \times 10^{-4} \ \frac{\text{mol } SO_2}{\text{mol}}}}$$

$$\Rightarrow p_{SO_2} = y_{SO_2} P = \left(1.0 \times 10^{-4}\right)(760 \text{ mm Hg}) = 0.0760 \text{ mm Hg}$$

$$\text{Henry's law} \Rightarrow x_{SO_2} = \frac{p_{SO_2}}{H_{SO_2}} = \frac{0.0760 \text{ mm Hg}}{3.136 \times 10^4 \ \text{ mm Hg/mole fraction}}$$

$$= 2.40 \times 10^{-6} \text{ mol } SO_2/\text{mol}$$

Since x_{SO_2} is so low, we may assume for simplicity that $V_{\text{final}} \approx V_{\text{initial}} = 140 \text{ L}$, and

$$n_{\text{final}} \approx n_{\text{initial}} = \frac{140 \text{ L}}{} \left| \frac{10^3 \text{ g } H_2O(l)}{1 \text{ L}} \right| \frac{1 \text{ mol}}{18 \text{ g}} = 7.78 \times 10^3 \text{ moles}$$

$$\Rightarrow n_{SO_2} = \frac{7.78 \times 10^3 \text{ mol solution}}{} \left| \frac{2.40 \times 10^{-6} \text{ mol } SO_2}{1 \text{ mol solution}} \right. = \underline{\underline{0.0187 \text{ mol } SO_2 \text{ dissolved}}}$$

$$\frac{0.0187 \text{ mol } SO_2 \text{ dissolved}}{140 \text{ L}} = \underline{\underline{1.34 \times 10^{-4} \text{ mol } SO_2/\text{L}}}$$

Raoult's law for water:

$$y_{H_2O} = \frac{x_{H_2O} p^*_{H_2O}(30^\circ \text{C})}{\text{P}} = \frac{(1)(31.824 \text{ mm Hg})}{760 \text{ mm Hg}} = \underline{\underline{0.419 \frac{\text{mol } H_2O(\text{v})}{\text{mol}}}}$$

$$y_{air} = 1 - y_{SO_2} - y_{H_2O} = \underline{\underline{0.958 \frac{\text{mol dry air}}{\text{mol}}}}$$

d. Agitate/recirculate the scrubbing solution, change it more frequently. Add a base to the solution to react with the absorbed SO_2.

6.52 Raoult's law + Antoine equation (S = styrene, T = toluene):

$$y_S P = x_S p_S^* \Rightarrow x_S = \frac{0.650(150 \text{ mm Hg})}{10^{7.06623 \,-\, 1507.434/(T+214.985)}}$$

$$y_T P = x_T p_T^* \Rightarrow x_T = \frac{0.350(150 \text{ mm Hg})}{10^{6.95334 \,-\, 1343.943/(T+219.377)}}$$

$$1 = x_S + x_T = \frac{0.65(150)}{10^{7.06623 \,-\, 1507.434/(T+214.985)}} + \frac{0.35(150)}{10^{6.95334 \,-\, 1343.943/(T+219.377)}}$$

$$\Rightarrow T = \underline{\underline{86.0°\text{C}}} \quad \text{(Determine using E-Z Solve or a spreadsheeet)}$$

$$x_S = \frac{0.65(150)}{10^{7.06623 \,-\, 1507.434/(86.0+214.985)}} = \underline{\underline{0.853 \text{ mol styrene/mol}}}$$

$$x_T = 1 - x_S = 1 - 0.853 = \underline{\underline{0.147 \text{ mol toluene/mol}}}$$

6.53

$$p_B^*(85°\text{C}) = 10^{6.89272 \,-\, 1205.531/(85+219.888)} = 881.6 \text{ mm Hg}$$

$$p_T^*(85°\text{C}) = 10^{6.95805 \,-\, 1346.773/(85+219.693)} = 345.1 \text{ mm Hg}$$

$$\underline{\text{Raoult's Law}}\text{: } y_B P = x_B p_B^* \Rightarrow \quad y_B = \frac{0.35(881.6)}{10(760)} = \underline{\underline{0.0406 \text{ mol Benzene/mol}}}$$

$$y_T = \frac{0.65(345.1)}{10(760)} = \underline{\underline{0.0295 \text{ mol Toluene/mol}}}$$

$$y_{N_2} = 1 - 0.0406 - 0.0295 = \underline{\underline{0.930 \text{ mol N}_2/\text{mol}}}$$

6.54 **a**. From the Cox chart, at 77° F, $p_P^* = 140$ psig, $p_{nB}^* = 35$ psig, $p_{iB}^* = 51$ psig

Total pressure $P = x_p \cdot p_p^* + x_{nB} \cdot p_{nB}^* + x_{iB} \cdot p_{iB}^*$

$$= 0.50(140) + 0.30(35) + 0.20(51) = \underline{\underline{91 \text{ psia} \Rightarrow 76 \text{ psig}}}$$

$P < 200$ psig, so the container is technically safe.

b. From the Cox chart, at $\underline{\underline{140° \text{F}}}$, $p_P^* = 300$ psig, $p_{nB}^* = 90$ psig, $p_{iB}^* = 120$ psig

Total pressure P = $0.50(300) + 0.30(90) + 0.20(120) \cong 200$ psig

The temperature in a room will never reach 140°F unless a fire breaks out, so the container is adequate.

6.55 **a.** Antoine:

$$p_{np}^*(120°\text{C}) = 10^{6.84471 \,-\, 1060.793/(120+231.541)} = 6717 \text{ mm Hg}$$

$$p_{ip}^*(120°\text{C}) = 10^{6.73457 \,-\, 992.019/(120+231.541)} = 7883 \text{ mm Hg}$$

(Note: We are using the Antoine equation at 120°C, well above the validity ranges in Table B.4 for *n*-pentane and isopentane, so that all calculated vapor pressures must be considered rough estimates. To get more accuracy, we would need to find a vapor pressure correlation valid at higher temperatures.)

When the first bubble of vapor forms,

6.55 (cont'd)

$x_{np} = \underline{\underline{0.500 \text{ mol } n\text{ - C}_5\text{H}_{12}\text{(l) / mol}}} \qquad x_{ip} = \underline{\underline{0.500 \text{ mol } i\text{-C}_5\text{H}_{12}\text{(l)/mol}}}$

$\underline{\text{Total pressure}}\text{: } P{=}x_{np} \cdot p^*_{np} {+} x_{ip} \cdot p^*_{ip} = 0.50(6717) + 0.50(7883) = \underline{\underline{7300 \text{ mm Hg}}}$

$$y_{np} = \frac{x_{np} \cdot p^*_{np}}{P} = \frac{0.500(6717)}{7300} = \underline{\underline{0.46 \text{ mol } n\text{-C}_5\text{H}_{12}\text{(v)/mol}}}$$

$y_{ip} = 1 - y_{np} = 1 - 0.46 = \underline{\underline{0.54 \text{ mol } i\text{-C}_5\text{H}_{12}\text{(v)/mol}}}$

When the last drop of liquid evaporates,

$y_{np} = \underline{\underline{0.500 \text{ mol } n\text{ - C}_5\text{H}_{12}\text{(v) / mol}}} \qquad y_{ip} = \underline{\underline{0.500 \text{ mol } i\text{-C}_5\text{H}_{12}\text{(v)/mol}}}$

$$x_{np} + x_{ip} = \frac{y_{np}P}{p^*_{np}(120^\text{o}\text{C})} + \frac{y_{ip}P}{p^*_{ip}(120^\text{o}\text{C})} = \frac{0.500P}{6725} + \frac{0.500P}{7960} = 1 \Rightarrow \underline{\underline{P = 7291 \text{ mm Hg}}}$$

$$x_{np} = \frac{0.5 * 7250 \text{ mm Hg}}{6717 \text{ mm Hg}} = \underline{\underline{0.54 \text{ mol n-C}_5\text{H}_{12}\text{(l)/mol}}}$$

$x_{ip} = 1 - x_{np} = 1 - 0.54 = \underline{\underline{0.46 \text{ mol } i\text{-C}_5\text{H}_{12}\text{(l)/mol}}}$

b. When the first drop of liquid forms,

$y_{np} = \underline{\underline{0.500 \text{ mol n - C}_5\text{H}_{12}\text{(v) / mol}}} \qquad y_{ip} = \underline{\underline{0.500 \text{ mol } i\text{ - C}_{12}\text{H}_{12}\text{(v) / mol}}}$

P = (1200 + 760) = 1960 mm Hg

$$x_{np} + x_{ip} = \frac{0.500P}{p^*_{np}(T_{dp})} + \frac{0.500P}{p^*_{ip}(T_{dp})} = \frac{980}{10^{6.84471-1060.793/(T_{dp}+231.541)}} + \frac{980}{10^{6.73457-992.019/(T_{dp}+231.541)}} = 1$$

$\Rightarrow \underline{\underline{T_{dp} = 63.1^\text{o}\text{C}}}$

$p^*_{np} = 10^{6.84471-1060.793/(63.1+231.541)} = 1758 \text{ mm Hg}$

$p^*_{ip} = 10^{6.73457-992.019/(63.1+231.541)} = 2215 \text{ mm Hg}$

$$x_{np} = \frac{0.5 * 1960 \text{ mm Hg}}{p^*_{np}(63.1^\text{o}\text{C})} = \underline{\underline{0.56 \text{ mol } n\text{-C}_5\text{H}_{12}\text{/mol}}}$$

$x_{ip} = 1 - x_{np} = 1 - 0.56 = \underline{\underline{0.44 \text{ mol } i\text{-C}_5\text{H}_{12}\text{/mol}}}$

When the last bubble of vapor condenses,

$x_{np} = \underline{\underline{0.500 \text{ mol n - C}_5\text{H}_{12}\text{(l) / mol}}} \qquad x_{ip} = \underline{\underline{0.500 \text{ mol } i\text{ - C}_5\text{H}_{12}\text{(l) / mol}}}$

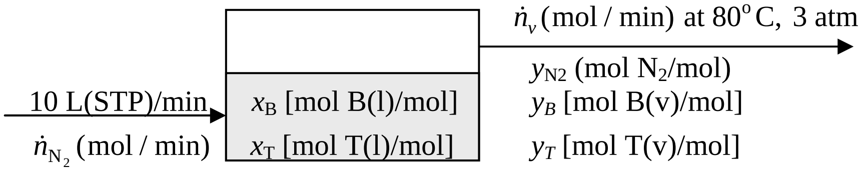
Total pressure: $P{=}x_{np} \cdot p^*_{np} {+} x_{ip} \cdot p^*_{ip}$

$$\Rightarrow 1960 = (0.5)10^{6.84471-1060.793/(T+231.541)} + (0.5)10^{6.73457-992.019/(T_{bp}+231.541)} \Rightarrow T = \underline{\underline{62.6°\text{C}}}$$

$$y_{np} = \frac{x_{np} \cdot p^*_{np}(62.6^\text{o}\text{C})}{P} = \frac{0.5(1734)}{1960} = \underline{\underline{0.44 \text{ mol } n\text{-C}_5\text{H}_{12}\text{(v)/mol}}}$$

$y_{ip} = 1 - y_{np} = 1 - 0.44 = \underline{\underline{0.56 \text{ mol } i\text{-C}_5\text{H}_{12}\text{(v)/mol}}}$

6.56 B = benzene, T = toluene



$$\dot{n}_{N_2} = \frac{10.0 \text{ L(STP) / min}}{22.4 \text{ L(STP) / mol}} = 0.4464 \text{ mol N}_2 \text{ / min}$$

Antoine: $p_B^*(80°\text{C}) = 10^{6.89272-1203.531/(80+219.888)} = 757.6 \text{ mm Hg}$

$p_T^*(80°\text{C}) = 10^{6.95805-1346.773/(80+219.693)} = 291.2 \text{ mm Hg}$

a. Initially, $x_B = 0.500$, $x_T = 0.500$.

N$_2$ balance: $0.4464 \text{ mol N}_2 \text{ / min} = \dot{n}_v(1-0.166-0.0639) \Rightarrow \dot{n}_v = 0.5797 \text{ mol / min}$

$$\Rightarrow \dot{n}_{B0} = \left(0.5797 \frac{\text{mol}}{\text{min}}\right)\left(0.166 \frac{\text{mol B}}{\text{mol}}\right) = \underline{\underline{0.0962 \frac{\text{mol B(v)}}{\text{min}}}}$$

$$\dot{n}_{T0} = \left(0.5797 \frac{\text{mol}}{\text{min}}\right)\left(0.0639 \frac{\text{mol B}}{\text{mol}}\right) = \underline{\underline{0.0370 \frac{\text{mol T(v)}}{\text{min}}}}$$

b. Since benzene is evaporating more rapidly than toluene, x_B decreases with time and x_T (= $1-x_B$) increases.

c. Since x_B decreases, y_B (= $x_B p_B^*/P$) also decreases. Since x_T increases, y_T (= $x_T p_T^*/P$) also increases.

6.57 **a.** $P = x_{hex} p_{hex}^*(T_{bp}) + x_{hep} p_{hep}^*(T_{bp})$, $y_i = \frac{x_i p_i^*(T_{bp})}{P}$, Antoine equation for p_i^*

$$760 \text{ mm Hg} = 0.500\left[10^{6.88555-1175.817/(T_{bp}+224.867)}\right] + 0.500\left[10^{6.90253-1267.828/(T_{bp}+216.823)}\right]$$

E-Z Solve or Goal Seek $\Rightarrow \underline{\underline{T_{bp} = 80.5°\text{C}}} \Rightarrow \underline{\underline{y_{hex} = 0.713,\ y_{hep} = 0.287}}$

b. $x_i = \frac{y_i P}{p_i^*(T_{dp})} \Rightarrow \sum_i x_i = P \sum_i \frac{y_i}{p_i^*(T_{dp})} = 1$

$$760 \text{ mmHg}\left[\frac{0.30}{10^{6.88555-1175.817/(T_{dp}+224.867)}} + \frac{0.30}{10^{6.90253-1267.828/(T_{dp}+216.823)}}\right] = 1$$

E-Z Solve or Goal Seek $\Rightarrow \underline{\underline{T_{dp} = 71.1°\text{C}}} \Rightarrow \underline{\underline{x_{hex} = 0.279,\ x_{hep} = 0.721}}$

6.58 **a.** $f(T) = P - \sum_{i=1}^{N} x_i p_i^*(T) = 0 \Rightarrow T$, where $p_i^*(T) = 10^{\left(A_i - \frac{B_i}{T+C_i}\right)}$

$$y_i \, (i = 1, 2, \cdots, N) = \frac{x_i p_i^*(T)}{P}$$

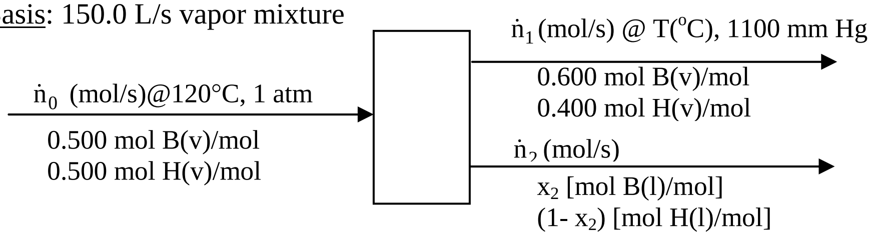
b.

Calculation of Bubble Points							
	A	B	C				
Benzene	6.89272	1203.531	219.888				
Ethylbenzene	6.95650	1423.543	213.091				
Toluene	6.95805	1346.773	219.693				
P(mmHg)=	760						
x_B	x_{EB}	x_T	**T_{bp}(°C)**	p_B	p_{EB}	p_T	f(T)
0.226	0.443	0.331	**108.09**	378.0	148.2	233.9	-0.086
0.443	0.226	0.331	**96.47**	543.1	51.6	165.2	0.11
0.226	0.226	0.548	**104.48**	344.0	67.3	348.6	0.07

$$\left.\begin{array}{l} \text{When } x_B = 1 (\text{pure benzene}),\ T_{bp} = \left(T_{bp}\right)_{\mathrm{C_6H_6}} = 80.1^\circ\mathrm{C} \\ \text{When } x_{EB} = 1 (\text{pure ethylbenzene}),\ T_{bp} = \left(T_{bp}\right)_{\mathrm{C_8H_{10}}} = 136.2^\circ\mathrm{C} \\ \text{When } x_T = 1 (\text{pure toluene}),\ T_{bp} = \left(T_{bp}\right)_{\mathrm{C_7H_8}} = 110.6^\circ\mathrm{C} \end{array}\right\} \Rightarrow T_{bp,EB} > T_{bp,T} > T_{bp,B}$$

Mixture 1 contains more ethylbenzene (higher boiling point) and less benzene (lower bp) than Mixture 2, and so $(T_{\mathrm{bp}})_1 > (T_{\mathrm{bp}})_2$. Mixture 3 contains more toluene (lower bp) and less ethylbenzene (higher bp) than Mixture 1, and so $(T_{\mathrm{bp}})_3 < (T_{\mathrm{bp}})_1$. Mixture 3 contains more toluene (higher bp) and less benzene (lower bp) than Mixture 2, and so $(T_{\mathrm{bp}})_3 > (T_{\mathrm{bp}})_2$

6.59 **a.** Basis: 150.0 L/s vapor mixture



Gibbs phase rule: $F=2+c-\pi=2+2-2=2$

Since the composition of the vapor and the pressure are given, the information is enough.
Equations needed: Mole balances on butane and hexane, Antoine equation and Raoult's law for butane and hexane

b. Molar flow rate of feed: $$\dot{n}_0 = \frac{150.0\text{ L}}{\text{s}}\left|\frac{273\text{ K}}{393\text{ K}}\right|\frac{\text{mol}}{22.4\text{ L (STP)}} = 4.652\text{ mol/s}$$

Raoult's law for butane: $0.600(1100)=x_2\cdot 10^{6.82485-943.453/(T+239.711)}$ (1)

Raoult's law for hexane: $0.400(1100)=(1-x_2)\cdot 10^{6.88555-1175.817/(T+224.867)}$ (2)

Mole balance on butane: $4.652(0.5)=\dot{n}_1\cdot 0.6+\dot{n}_2\cdot x_2$ (3)

Mole balance on hexane: $4.652(0.5)=\dot{n}_1\cdot 0.4+\dot{n}_2\cdot(1-x_2)$ (4)

c. From (1) and (2), $$1=\frac{1100(0.6)}{10**(6.82485-\dfrac{943.453}{T+239.711})}+\frac{1100(0.4)}{10**(6.88555-\dfrac{1175.817}{T+224.867})}$$

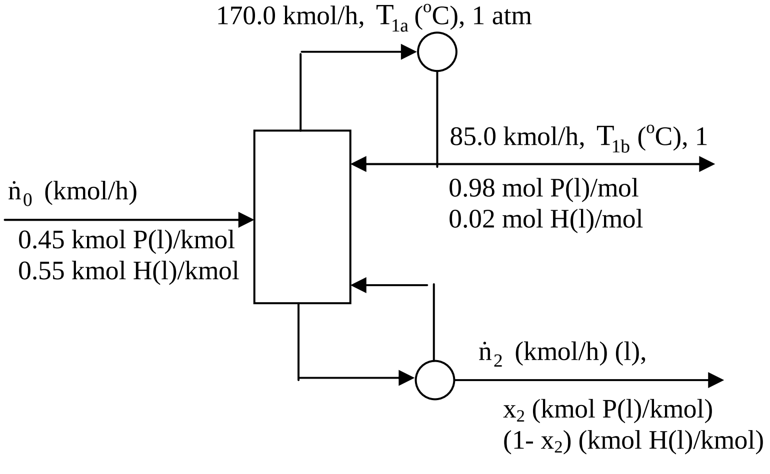
$\Rightarrow \text{T} = \underline{\underline{57.0\ ^\circ\text{C}}}$

$$x_2=\frac{1100(0.6)}{10^{6.82485-943.453/(57.0+239.711)}}=\underline{\underline{0.149\text{ mol butane /mol}}}$$

Solving (3) and (4) simultaneously $\Rightarrow$ $\dot{n}_1=\underline{\underline{3.62\text{ mol }C_4H_{10}/\text{s}}}$; $\dot{n}_2=\underline{\underline{1.03\text{ mol }C_6H_{14}/\text{s}}}$

d. Assumptions: (1) Antoine equation is accurate for the calculation of vapor pressure;
(2) Raoult's law is accurate;
(3) Ideal gas law is valid.

6.60 P = *n*-pentane, H = *n*-hexane



6.60 (cont'd)

a. Molar flow rate of feed: $\dot{n}_0(0.45)(0.95) = 85(0.98) \Rightarrow \dot{n}_0 = \underline{\underline{195 \text{ kmol / h}}}$

Total mole balance : $195 = 85.0 + \dot{n}_2 \Rightarrow \dot{n}_2 = \underline{\underline{110 \text{ kmol / h}}}$

Pentane balance: $195(0.45) = 85.0(0.98) + 110 \cdot x_2 \Rightarrow x_2 = \underline{\underline{0.0405 \text{ mol P / mol}}}$

b. Dew point of column overhead vapor effluent:

Eq. 6.4-7, Antoine equation

$$\Rightarrow \frac{0.98(760)}{10^{6.84471-1060.793/(T_{1a}+231.541)}} + \frac{0.02(760)}{10^{6.88555-1175.817/(T_{1a}+224.687)}} = 1 \Rightarrow \underline{\underline{T_{1a} = 37.3^{\circ}\text{C}}}$$

Flow rate of column overhead vapor effluent. Assuming ideal gas behavior,

$$\dot{V}_{\text{vapor}} = \frac{170 \text{ kmol}}{\text{h}}\left|\frac{0.08206 \text{ m}^3 \cdot \text{atm}}{\text{kmol} \cdot \text{K}}\right|\frac{(273.2 + 37.3) \text{ K}}{1 \text{ atm}} = \underline{\underline{4330 \text{ m}^3 \text{ / h}}}$$

Flow rate of liquid distillate product.

Table B.1 $\Rightarrow \rho_{\text{P}} = 0.621$ g / mL, $\rho_{\text{H}} = 0.659$ g / mL

$$\dot{V}_{\text{distillate}} = \frac{0.98(85) \text{ kmol P}}{\text{h}}\left|\frac{72.15 \text{ kg P}}{\text{kmol P}}\right|\frac{\text{L}}{0.621 \text{ kg P}}$$

$$+ \frac{0.02(85) \text{ kmol H}}{\text{h}}\left|\frac{86.17 \text{ kg H}}{\text{kmol H}}\right|\frac{\text{L}}{0.659 \text{ kg H}} = \underline{\underline{9.9 \times 10^3 \text{ L / h}}}$$

c. Reboiler temperature.

$$0.04 \cdot 10^{6.84471-1060.793/(T_2+231.541)} + 0.96 \cdot 10^{6.88555-1175.817/(T_2+224.867)} = 760 \Rightarrow \text{T}_2 = \underline{\underline{66.6°\text{C}}}$$

Boilup composition.

$$y_2 = \frac{x_2 p_{\text{P}}^*(66.6^{\circ}\text{C})}{P} = \frac{0.04 \cdot 10^{6.84471-1060.793/(66.6+231.541)}}{760} = \underline{\underline{0.102 \text{ mol P(v)/mol}}}$$

$$\Rightarrow (1 - y_2) = \underline{\underline{0.898 \text{ mol H(v) / mol}}}$$

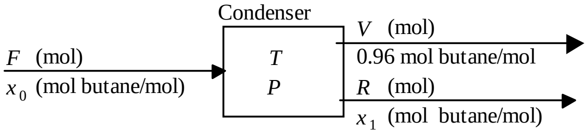
d. Minimum pipe diameter

$$\dot{V}\left(\frac{\text{m}^3}{\text{s}}\right) = u_{\max}\left(\frac{\text{m}}{\text{s}}\right) \times \frac{\pi D_{\min}^2}{4}(\text{m}^2)$$

$$\Rightarrow D_{\min} = \sqrt{\frac{4\dot{V}_{\text{vapor}}}{\pi \cdot u_{\max}}} = \sqrt{\frac{4}{\pi}\left|\frac{4330 \text{ m}^3 \text{ / h}}{10 \text{ m / s}}\right|\frac{1 \text{ h}}{3600 \text{ s}}} = \underline{\underline{0.39 \text{ m}}} \text{ (39 cm)}$$

Assumptions: Ideal gas behavior, validity of Raoult's law and the Antoine equation, constant temperature and pressure in the pipe connecting the column and the condenser, column operates at steady state.

6.61 a.



Partial condenser: 40° C is the dew point of a 96% C_4H_{10} – 4% C_5H_{12} vapor mixture at $P = P_{\min}$

Total condenser: 40° C is the bubble point of a 96% C_4H_{10} - 4% C_5H_{12} liquid mixture at $P = P_{\min}$

Dew Point: $1=\sum x_i = \sum \dfrac{y_i P}{p_i^*(40°\text{C})} \Rightarrow P_{\min} = \dfrac{1}{\sum y_i / p_i^*(40°\text{C})}$

(Raoult's Law)

$$\text{Antoine Eq. for } p_i^*(\text{C}_4H_{10}) = 10^{\left(6.82485-\frac{943.453}{40+239.711}\right)} = 2830.70 \text{ mmHg}$$

$$\text{Antoine Eq. for } p_i^*(\text{C}_5H_{12}) = 10^{\left(6.84471-\frac{1060.793}{40+231.541}\right)} = 867.22 \text{ mmHg}$$

$$\Rightarrow P_{\min} = \frac{1}{0.96/2830.70 + 0.04/867.22} = \underline{\underline{2595.63 \text{ mm Hg (partial condenser)}}}$$

Bubble Point: $P = \sum y_i P = \sum x_i p_i^*(40°\text{C})$

$$P = 0.96(2830.70) + 0.04(867.22) = \underline{\underline{2752.16 \text{ mm Hg (total condenser)}}}$$

b. $\dot{V} = 75$ kmol / h , $\dot{R}/\dot{V} = 1.5 \Rightarrow \dot{R} = 75 \times 1.5$ kmol / h $= \underline{\underline{112.5 \text{ kmol / h}}}$

Feed and product stream compositions are identical: $\underline{\underline{y = 0.96 \text{ kmol butane/kmol}}}$

Total balance: $\dot{F} = 75 + 112.5 = \underline{\underline{187.5 \text{ kmol / h}}}$

c. Total balance as in b. $\underline{\underline{\dot{R} = 112.5 \text{ kmol / h} \quad \dot{F} = 187.5 \text{ kmol / h}}}$

$$\left.\begin{array}{l} \text{Equilibrium: } 0.96P = x_1(2830.70) \\ \text{(Raoult's law) } 0.04P = (1-x_1)(867.22) \end{array}\right\} \begin{array}{l} \underline{\underline{P = 2596 \text{ mm Hg}}} \\ \underline{\underline{x_1 = 0.8803 \text{ mol butane/mol}}} \end{array}$$

Butane balance: $187.5x_0 = 112.5(0.8803) + 0.96(75) \Rightarrow \underline{\underline{x_0 = 0.9122 \text{ mol butane/mol reflux}}}$

6.62 a. Raoult's law: $\dfrac{y_i}{x_i} = \dfrac{p_i^*}{P} \Rightarrow \alpha_{AB} = \dfrac{y_A/x_A}{y_B/x_B} = \dfrac{p_A^*/P}{p_B^*/P} = \underline{\underline{\dfrac{p_A^*}{p_B^*}}} = \alpha_{AB}$

b.

$$p_S^*(85^\text{o}\text{C}) = 10^{\left(7.06623-\frac{1507.434}{85+214.985}\right)} = 109.95 \text{ mm Hg}$$

$$p_{EB}^*(85^\text{o}\text{C}) = 10^{\left(6.95650-\frac{1423.543}{85+213.091}\right)} = 151.69 \text{ mm Hg}$$

$$p_B^*(85^\text{o}\text{C}) = 10^{\left(6.89272-\frac{1203.531}{85+219.888}\right)} = 881.59 \text{ mm Hg}$$

6.62 (cont'd)

$$\alpha_{\text{S,EB}}=\frac{p_S^*}{p_{EB}^*}=\frac{109.95}{151.69}=0.725\ ,\quad \alpha_{\text{B,EB}}=\frac{p_B^*}{p_{EB}^*}=\frac{881.59}{151.69}=5.812$$

Styrene – ethylbenzene is the more difficult pair to separate by distillation because $\alpha_{\text{S,EB}}$ is closer to 1 than is $\alpha_{\text{B,EB}}$.

c. $$\alpha_{ij}=\frac{y_i/x_i}{y_j/x_j}\xrightarrow{\substack{y_j=1-y_i\\ x_j=1-x_i}}\alpha_{ij}=\frac{y_i/x_i}{(1-y_i)/(1-x_i)}\Rightarrow y_i=\underline{\underline{\frac{\alpha_{ij}x_i}{1+(\alpha_{ij}-1)x_i}}}$$

d. $$\alpha_{B,EB}=5.810\Rightarrow\ y_B=\frac{x_B\alpha_{B,EB}}{1+(\alpha_{B,EB}-1)x_B}=\frac{5.81x_B}{1+4.81x_B}\ ,\quad P=x_Bp_B^*+(1-x_B)p_{EB}^*$$

x_B	0.0	0.2	0.4	0.6	0.8	1.0	mol $B(l)$/mol
y_B	0.0	0.592	0.795	0.897	0.959	1.0	mol $B(v)$/mol
P	152	298	444	5900	736	882	mmHg

6.63 a. Since benzene is more volatile, *the fraction of benzene will increase moving up the column*. For ideal stages, the temperature of each stage corresponds to the bubble point temperature of the liquid. Since the fraction of benzene (the more volatile species) increases moving up the column, *the temperature will decrease moving up the column*.

b. Stage 1: $\dot{n}_1=150\text{ mol / h},\ \ \dot{n}_\text{v}=200\text{ mol / h}\,;\ x_1=0.55\text{ mol B/mol}\Rightarrow 0.45\text{ mol S/mol}\,;$ $y_0=0.65\text{ mol B/mol}\Rightarrow 0.35\text{ mol S/mol}$

Bubble point T: $P=\sum x_i p_i^*(T)$

$$P_1=(0.400\times760)\text{ mmHg}=(0.55)10^{6.89272-1203.531/(T+219.888)}+(0.45)10^{7.06623-1507.434/(T+214.985)}$$

$$\xrightarrow{\text{E-Z Solve}}\underline{\underline{T_1=67.6^\circ\text{C}}}$$

$$\Rightarrow\ y_1=\frac{x_1p_B^*(T)}{P}=\frac{0.55(508)}{0.400\times760}=\underline{\underline{0.920\text{ mol B/mol}\Rightarrow0.080\text{ mol S/mol}}}$$

B balance: $y_0\dot{n}_v+x_2\dot{n}_l=y_1\dot{n}_v+x_1\dot{n}_l\Rightarrow\underline{\underline{x_2=0.910\text{ mol B/mol}\Rightarrow0.090\text{ mol S/mol}}}$

Stage 2:

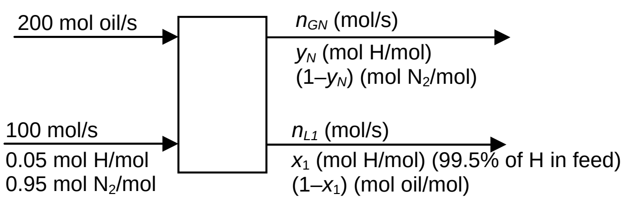
$$(0.400\times760)\text{ mmHg}=0.910p_B^*(T_2)+0.090p_S^*(T_2)\xrightarrow{\text{E-Z Solve}}\underline{\underline{T_2=55.3^\circ\text{C}}}$$

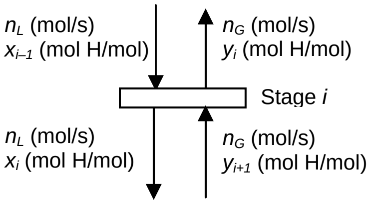
$$y_2=\frac{0.910(331.0)}{760\times0.400}=\underline{\underline{0.991\text{ mol B/mol}\Rightarrow0.009\text{ mol S/mol}}}$$

B balance: $y_1\dot{n}_v+x_3\dot{n}_l=y_2\dot{n}_v+x_2\dot{n}_l\Rightarrow\underline{\underline{x_3\approx1\text{ mol B/mol}\Rightarrow\ \ \approx0\text{ mol S/mol}}}$

c. In this process, the styrene content is less than 5% in two stages. In general, the calculation of part b would be repeated until $(1-y_n)$ is less than the specified fraction.

6.64 Basis: 100 mol/s gas feed. H=hexane.





a. $\left.\begin{array}{l}\underline{\text{N}_2\text{ balance:}}\ 0.95(100)=(1-y_N)\dot{n}_{GN}\\ \underline{\text{99.5\% absorption:}}\ 0.05(100)(0.005)=y_N\dot{n}_{GN}\end{array}\right\}\Rightarrow\begin{array}{l}\underline{\underline{\dot{n}_{GN}=95.025\ \text{mol/s}}}\\ \underline{\underline{y_N=2.63\times10^{-4}\ \text{mol H(v)/mol}}}\end{array}$

$\underline{\text{Mole Balance:}}\ 100+200=95.025+\dot{n}_{L1}\Rightarrow\underline{\underline{\dot{n}_{L1}=205\ \text{mol/s}}}$

$\underline{\text{Hexane Balance:}}\ 0.05(100)=2.63\times10^{-4}(95.025)+x_1(204.99)\Rightarrow\underline{\underline{x_1=0.0243\ \text{mol H(l)/mol}}}$

$\dot{n}_L=\frac{1}{2}(200+205)\Rightarrow\underline{\underline{\dot{n}_L=202.48\ \text{mol/s}}}$, $\dot{n}_G=\frac{1}{2}(100+95.025)\Rightarrow\underline{\underline{\dot{n}_G=97.52\ \text{mol/s}}}$

b. $y_1=x_1\,\overset{\substack{\text{Antoine}\\ \downarrow}}{p_H^*}(50^\circ\text{C})\,/\,P=0.0243(403.73)\,/\,760=\underline{\underline{0.0129\ \text{mol H(v)/mol}}}$

$\underline{\text{H balance on 1}^{\text{st}}\text{ Stage:}}\ y_0\dot{n}_v+x_2\dot{n}_l=y_1\dot{n}_v+x_1\dot{n}_l\Rightarrow\underline{\underline{x_2=0.00643\ \text{mol H(l)/mol}}}$

c. The given formulas follow from Raoult's law and a hexane balance on Stage *i*.

d.

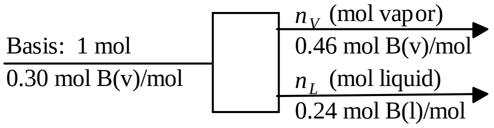
		Hexane Absorption						
P=	760	PR=	1					
y0=	0.05	x1=	0.0243	yN=	2.63E-04			
nGN=	95.025	nL1=	204.98	nG=	97.52	nL=	202.48	
A=	6.88555	B=	1175.817	C=	224.867			
T	p*(T)		T	p*(T)		T	p*(T)	
30	187.1		50	405.3059		70	790.5546	
i	x(i)	y(i)	i	x(i)	y(i)	i	x(i)	y(i)
0		5.00E-02	0		5.00E-02	0		5.00E-02
1	2.43E-02	5.98E-03	1	2.43E-02	1.30E-02	1	2.43E-02	2.53E-02
2	3.10E-03	7.63E-04	2	6.46E-03	3.45E-03	2	1.24E-02	1.29E-02
3	5.86E-04	1.44E-04	3	1.88E-03	1.00E-03	3	6.43E-03	6.69E-03
			4	7.01E-04	3.74E-04	4	3.44E-03	3.58E-03
			5	3.99E-04	2.13E-04	5	1.94E-03	2.02E-03
						...	...	...
						21	4.38E-04	4.56E-04

6.64 (cont'd)

e. If the column is long enough, the liquid flowing down eventually approaches equilibrium with the entering gas. At 70^{o}C, the mole fraction of hexane in the exiting liquid in equilibrium with the mole fraction in the entering gas is 4.56x10^{-4} mol H/mol, which is insufficient to bring the total hexane absorption to the desired level. To reach that level at 70^{o}C, either the liquid feed rate must be increased or the pressure must be raised to a value for which the final mole fraction of hexane in the vapor is 2.63x10^{-4} or less. The solution is $\underline{\underline{P_{\min} = 1037 \text{ mm Hg}}}$.

6.65 a. Intersection of vapor curve with $y_B = 0.30$ at $\underline{\underline{T = 104^\circ \text{C} \Rightarrow 13\% \text{ B(l)}, \ 87\% \text{T(l)}}}$

b. $T = 100^\circ\text{C} \Rightarrow \underline{\underline{x_B = 0.24 \text{ mol B/mol (liquid)}, \ y_B = 0.46 \text{ mol B/mol (vapor)}}}$



Balances

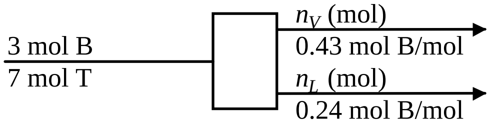
$$\left.\begin{array}{ll}\underline{\text{Total moles:}} & 1 = n_V + n_L \\ \underline{\text{B:}} & 0.30 = 0.46 n_V + 0.24 n_L\end{array}\right\} \Rightarrow \begin{array}{l} n_L = 0.727 \text{ mol} \\ n_V = 0.273 \text{ mol}\end{array} \Rightarrow \underline{\underline{\frac{n_V}{n_L} = 0.375 \frac{\text{mol vapor}}{\text{mol liquid}}}}$$

c. Intersection of liquid curve with $x_B = 0.3$ at $\underline{\underline{T = 98^\circ \text{C} \Rightarrow 50\% \text{ B(v)}, \ 50\% \text{T(v)}}}$

6.66 a. $\underline{\underline{P = 798 \text{ mm Hg}, \ y_B = 0.50 \text{ mol B(v)/mol}}}$

b. $\underline{\underline{P = 690 \text{ mm Hg}, \ x_B = 0.15 \text{ mol B(l)/mol}}}$

c. $\underline{\underline{P = 750 \text{ mm Hg}, \ y_B = 0.43 \text{ mol B(v)/mol}, \ x_B = 0.24 \text{ mol B(l)/mol}}}$



$$\left.\begin{array}{ll}\underline{\text{Mole bal.:}} & 10 = n_V + n_L \\ \underline{\text{B bal.:}} & 3 = 0.43 n_V + 0.24 n_L\end{array}\right\} \Rightarrow \begin{array}{l} n_V = 3.16 \text{ mol} \\ n_L = 6.84 \text{ mol}\end{array} \Rightarrow \frac{n_v}{n_l} = \underline{\underline{0.46 \frac{\text{mol vapor}}{\text{mol liquid}}}}$$

Answers may vary due to difficulty of reading chart.

d. i) $P = 1000 \text{ mm Hg} \Rightarrow \text{all liquid}$. Assume volume additivity of mixture components.

$$V = \frac{3 \text{ mol B}}{} \left| \frac{78.11 \text{ g B}}{\text{mol B}} \right| \frac{10^{-3} \text{ L}}{0.879 \text{ g B}} + \frac{7 \text{ mol T}}{} \left| \frac{92.13 \text{ g T}}{\text{mol T}} \right| \frac{10^{-3} \text{ L}}{0.866 \text{ g T}} = \underline{\underline{1.0 \text{ L}}}$$

ii) 750 mmHg. Assume liquid volume negligible

6.66 (cont'd)

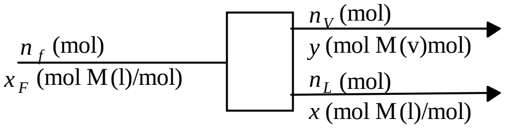
$$V=\frac{3.16\text{ mol vapor}}{}\left|\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\frac{373\text{ K}}{750\text{ mm Hg}}\left|\frac{760\text{ mm Hg}}{1\text{ atm}}\right.-0.6\text{ L}=\underline{\underline{97.4\text{ L}}}$$

(Liquid volume is about 0.6 L)

iii) 600 mm Hg

$$v=\frac{10\text{ mol vapor}}{}\left|\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\frac{373\text{K}}{600\text{ mm Hg}}\left|\frac{760\text{ mm Hg}}{1\text{ atm}}\right.=\underline{\underline{388\text{ L}}}$$

6.67 **a.** M = methanol

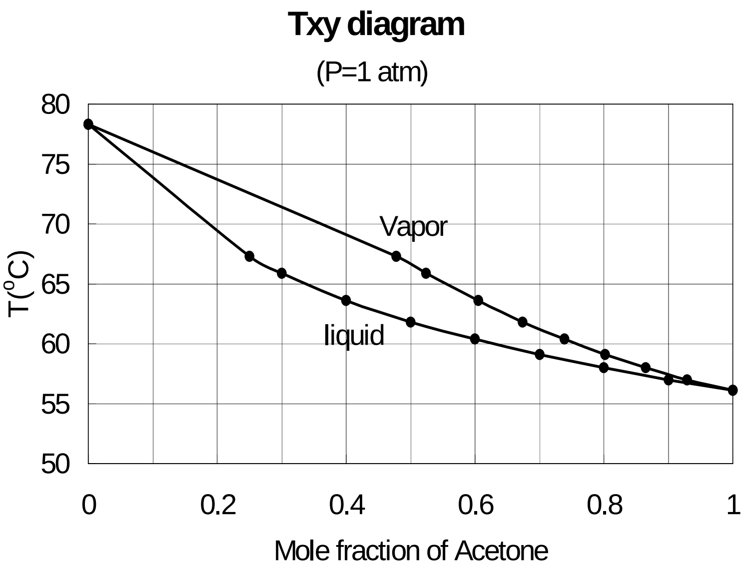


$$\left.\begin{array}{ll}\underline{\text{Mole balance:}} & n_f=n_V+n_L\\ \underline{\text{MeOH balance:}} & x_F n_f=yn_V+xn_L\end{array}\right\}\Rightarrow x_F n_V+x_F n_L=yn_V+xn_L\Rightarrow \underline{\underline{f=\frac{n_V}{n_L}=\frac{x_F-x}{y-x}}}$$

$$x_F=0.4,\ x=0.23,\ y=0.62\Rightarrow f=\frac{0.4-0.23}{0.62-0.23}=\underline{\underline{0.436}}$$

b. $\underline{\underline{T_{\min}=75^{\circ}\text{C}}},\ \underline{\underline{f=0}}\ ,\ \underline{\underline{T_{\max}=87^{\circ}\text{C}}},\ \underline{\underline{f=1}}$

6.68 **a.**



b. $\underline{\underline{x_A=0.47;\ y_A=0.66}}$

6.68 (cont'd)

c. (i) $\underline{\underline{x_A = 0.34;\ y_A = 0.55}}$

(ii) $\left.\begin{array}{ll}\underline{\text{Mole bal.:}} & 1 = n_V + n_L \\ \underline{\text{A bal.:}} & 0.50 = 0.55n_V + 0.34n_L\end{array}\right\} \Rightarrow n_V = 0.762 \text{ mol vapor, } n_L = 0.238 \text{ mol liquid } \partial$

$$\Rightarrow \underline{\underline{76.2 \text{ mole\% vapor}}}$$

(iii) $\rho_{A(l)} = 0.791 \text{ g/cm}^3,\ \rho_{E(l)} = 0.789 \text{ g/cm}^3 \Rightarrow \rho_l \approx 0.790 \text{ g/cm}^3$

(To be more precise, we could convert the given mole fractions to mass fractions and calculate the weighted average density of the mixture, but since the pure component densities are almost identical there is little point in doing all that.)

$M_A = 58.08 \text{ g/mol, M}_E = 46.07 \text{ g/mol}$

$\Rightarrow M_l = (0.34)(58.08) + (1-0.34)(46.07) = 50.15 \text{ g/mol}$

<u>Basis</u>: 1 mol liquid $\Rightarrow$ (0.762 mol vapor / 0.238 mol liquid) = 3.2 mol vapor

<u>Liquid volume:</u> $V_l = \dfrac{(1 \text{ mol})(50.15 \text{ g / mol})}{(0.790 \text{ g / cm}^3)} = 63.48 \text{ cm}^3$

<u>Vapor volume</u>:

$$V_v = \begin{array}{c|c|c} 3.2 \text{ mol} & 22400 \text{ cm}^3 \text{ (STP)} & (65+273)\text{K} \\ \hline & \text{mol} & 273\text{K} \end{array} = 88{,}747 \text{ cm}^3$$

$\underline{\text{Volume percent of vapor}} = \dfrac{88{,}747}{88747 + 63.48} \times 100\% = \underline{\underline{99.9 \text{ volume\% vapor}}}$

d. For a basis of 1 mol fed, guess T, calculate n_V as above; if $n_V \neq 0.20$, pick new T.

T	***x*A**	***y*A**	***f*V**
65 °C	0.34	0.55	0.333
64.5 °C	**0.36**	**0.56**	0.200

e. <u>Raoult's law:</u> $y_i P = x_i p_i^* \Rightarrow P = x_A p_A^* + x_E p_E^*$

$$760 = 0.5 \times 10^{7.11714 - 1210.595/(T_{bp}+229.664)} + 0.5 \times 10^{8.11220 - 1592.864/(T_{bp}+226.184)} \Rightarrow \underline{\underline{T_{bp} = 66.16^\circ \text{C}}}$$

$$y = \frac{xp_A^*}{P} = \frac{0.5 \times 10^{7.11714 - 1210.595/(66.25+229.664)}}{760} = \underline{\underline{0.696 \text{ mol acetone/mol}}}$$

The actual $T_{bp} = 61.8^\circ\text{C} \Rightarrow \dfrac{\Delta T_{bp}}{T_{bp}(\text{real})} = \dfrac{66.25 - 61.8}{61.8} \times 100\% = \underline{\underline{7.20\% \text{ error in } T_{bp}}}$

$$y_A = 0.674 \Rightarrow \frac{\Delta y_A}{y_A(\text{real})} = \frac{0.696 - 0.674}{0.674} \times 100\% = \underline{\underline{3.3\% \text{ error in } y_A}}$$

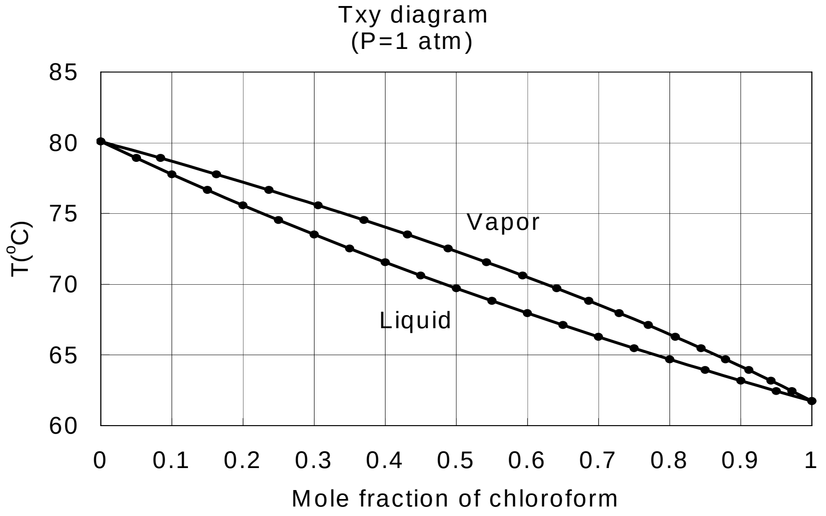
Acetone and ethanol are not structurally similar compounds (as are, for example, pentane and hexane or benzene and toluene). There is consequently no reason to expect Raoult's law to be valid for acetone mole fractions that are not very close to 1.

6.69 **a.** B = benzene, C = chloroform. At 1 atm, $(T_{bp})_B = 80.1^oC$, $(T_{bp})_C = 61.0^oC$

The *Txy* diagram should look like Fig. 6.4-1, with the curves converging at 80.1°C when $x_C = 0$ and at 61.0°C when $x_C = 1$. (See solution to part c.)

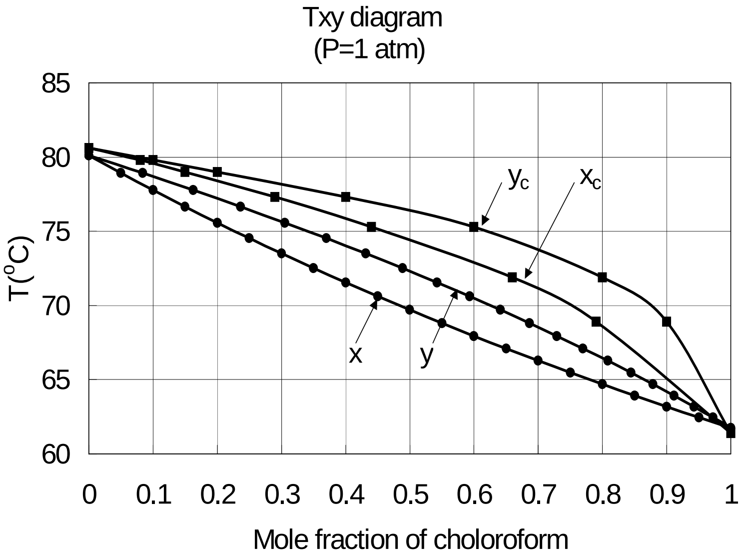
b.

Txy Diagram for an Ideal Binary Solution					
	A	**B**	**C**		
Chloroform	6.90328	1163.03	227.4		
Benzene	6.89272	1203.531	219.888		
P(mmHg)=	760				
x	**T**	**y**	**p1**	**p2**	**p1+p2**
0	80.10	0	0	760	760
0.05	78.92	0.084	63.90	696.13	760.03
0.1	77.77	0.163	123.65	636.28	759.93
0.15	76.66	0.236	179.63	580.34	759.97
0.2	75.58	0.305	232.10	527.86	759.96
0.25	74.53	0.370	281.34	478.59	759.93
0.3	73.51	0.431	327.61	432.30	759.91
0.35	72.52	0.488	371.15	388.79	759.94
0.4	71.56	0.542	412.18	347.85	760.03
0.45	70.62	0.593	450.78	309.20	759.99
0.5	69.71	0.641	487.27	272.79	760.07
0.55	68.82	0.686	521.68	238.38	760.06
0.6	67.95	0.729	554.15	205.83	759.98
0.65	67.11	0.770	585.00	175.10	760.10
0.7	66.28	0.808	614.02	145.94	759.96
0.75	65.48	0.844	641.70	118.36	760.06
0.8	64.69	0.879	667.76	92.17	759.93
0.85	63.93	0.911	692.72	67.35	760.07
0.9	63.18	0.942	716.27	43.75	760.03
0.95	62.45	0.972	738.72	21.33	760.05
1	61.73	1	760	0	760



6.69 (cont'd)

d.



Raoult's law: $T_{\text{bp}} = 71^{\circ}\text{C},\ \ y = 0.58 \Rightarrow$

$$\frac{\Delta T}{T_{\text{actual}}} = \frac{71-75.3}{75.3} \times 100\% = \underline{\underline{-5.7\%\ \text{error in}\ T_{\text{bp}}}}$$

$$\frac{\Delta y}{y_{\text{actual}}} = \frac{0.58-0.60}{0.60} \times 100\% = \underline{\underline{-3.33\%}}\ \text{error in}\ y$$

Benzene and chloroform are not structurally similar compounds (as are, for example, pentane and hexane or benzene and toluene). There is consequently no reason to expect Raoult's law to be valid for chloroform mole fractions that are not very close to 1.

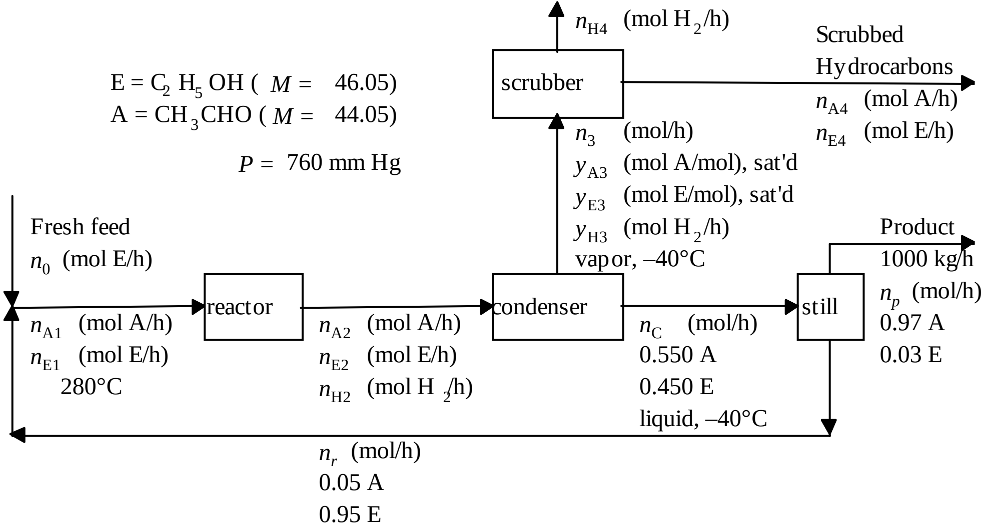
6.70 $P \approx 1\ \text{atm} = 760\ \text{mm Hg} = x_m p_m^*\left(T_{bp}\right) + \left(1 - x_m\right) p_P^*\left(T_{\text{bp}}\right)$

$$760 = 0.40 \times 10^{7.87863 - 1473.11/(T_{bp}+230)} + 0.60 \times 10^{7.74416 - 1437.686/(T_{bp}+198.463)} \xrightarrow{\text{E-Z Solve}} \underline{\underline{T = 79.9^{\circ}\text{C}}}$$

We assume (1) the validity of Antoine's equation and Raoult's law, (ii) that pressure head and surface tension effects on the boiling point are negligible.

The liquid temperature will rise until it reaches 79.9 °C, where boiling will commence. The escaping vapor will be richer in methanol and thus the liquid composition will become richer in propanol. The increasing fraction of the less volatile component in the residual liquid will cause the boiling temperature to rise.

6.71 Basis: 1000 kg/h product



Strategy

- Calculate molar flow rate of product $(\dot{n}_p)$ from mass flow rate and composition
- Calculate y_{A3} and y_{E3} from Raoult's law: $y_{H3} = 1 - y_{A3} - y_{E3}$. Balances about the still involve fewest unknowns $(\dot{n}_c$ and $\dot{n}_r)$
- $\left.\begin{array}{l}\text{Total mole balance about still}\\ \text{A balance about still}\end{array}\right\} \Rightarrow \dot{n}_c, \dot{n}_r$
- A, E and H_2 balances about scrubber $\Rightarrow \dot{n}_{A4}, \dot{n}_{E4}$, and $\dot{n}_{H4}$ in terms of $\dot{n}_3$. Overall atomic balances on C, H, and O now involve only 2 unknowns $(\dot{n}_0, \dot{n}_3)$
- $\left.\begin{array}{l}\text{Overall C balance}\\ \text{Overall H balance}\end{array}\right\} \Rightarrow \dot{n}_0, \dot{n}_3$
- A balance about fresh feed-recycle mixing point $\Rightarrow \dot{n}_{A1}$
- E balance about fresh feed-recycle mixing point $\Rightarrow \dot{n}_{E1}$
- A, E, H_2 balances about condenser $\dot{n}_{A2}, \dot{n}_{E2}, \dot{n}_{H2}$
- All desired quantities may now be calculated from known molar flow rates.

a. Molar flow rate of product

$$\overline{M} = 0.97M_A + 0.03M_E = (0.97)(44.05) + (0.03)(46.05) = 44.11 \text{ g/mol}$$

$$\dot{n}_p = \frac{1000 \text{ kg}}{\text{h}}\left|\frac{1 \text{ kmol}}{44.11 \text{ kg}}\right. = 22.67 \text{ kmol/h}$$

Table B.4 (Antoine) $\Rightarrow$ $p_A^*(-40°\text{C}) = 44.8$ mm Hg

$p_E^*(-40°\text{C}) = 0.360$ mm Hg

Note: The calculations that follow can at best be considered rough estimates, since we are using the Antoine correlations of Table B.4 far outside their temperature ranges of validity.

Raoult's law $\Rightarrow \underline{y_{A3}} = \dfrac{0.550 p_A^*(-40\text{ °C})}{P} = \dfrac{0.550(44.8)}{760} = 0.03242$ kmol A/kmol

6.71 (cont'd)

$$\underline{y_{\mathrm{E3}}} = \frac{0.450\,p_{\mathrm{E}}^{*}\left(-40\ ^{\circ}\mathrm{C}\right)}{P} = \frac{0.450(0.360)}{760} = 2.13\times10^{-4}\ \ \mathrm{kmol\ E/kmol}$$

$$\underline{y_{\mathrm{H3}}} = 1 - y_{\mathrm{A3}} - y_{\mathrm{E3}} = 0.9674\ \ \mathrm{kmol\ H_2/kmol}$$

$$\left.\begin{array}{l} \underline{\text{Mole balance about still}}\text{: } \dot{n}_c = \dot{n}_p + \dot{n}_r \Rightarrow \dot{n}_c = 22.67 + \dot{n}_r \\ \underline{\text{A balance about still}}\text{: } 0.550\dot{n}_c = 0.97(22.67) + 0.05\dot{n}_r \end{array}\right\} \Rightarrow \begin{array}{l} \dot{n}_r = 29.5\ \mathrm{kmol/h\ recycle} \\ \underline{\underline{\dot{n}_c = 52.1\ \mathrm{kmol/h}}} \end{array}$$

$\underline{\text{A balance about scrubber:}}$ $\dot{n}_{\mathrm{A4}} = \dot{n}_3 y_{\mathrm{A3}} = 0.03242\dot{n}_3$ (1)

$\underline{\text{E balance about scrubber:}}$ $\dot{n}_{\mathrm{E4}} = \dot{n}_3 y_{\mathrm{E3}} = 2.13\times10^{-4}\dot{n}_3$ (2)

$\underline{\mathrm{H_2}\text{ balance about scrubber:}}$ $\dot{n}_{\mathrm{H4}} = \dot{n}_3 y_{\mathrm{H3}} = 0.9764\dot{n}_3$ (3)

Overall C balance:

$$\frac{\dot{n}_0\ (\mathrm{mol\ E})}{\mathrm{h}}\left|\frac{2\ \mathrm{mol\ \ C}}{1\ \mathrm{mol\ E}}\right. = \left(\dot{n}_{\mathrm{A4}}\right)(2) + \left(\dot{n}_{\mathrm{E4}}\right)(2) + \left(0.97\dot{n}_p\right)(2) + \left(0.03\dot{n}_p\right)(2)$$

$$\Rightarrow\ \dot{n}_0 = \dot{n}_{\mathrm{A4}} + \dot{n}_{\mathrm{E4}} + 22.67 \qquad (4)$$

Overall H balance:

$$6\dot{n}_0 = 2\dot{n}_{\mathrm{H4}} + 4\dot{n}_{\mathrm{A4}} + 6\dot{n}_{\mathrm{E4}} + \dot{n}_p\left[(0.97)(4) + (0.03)(6)\right] \qquad (5)$$

Solve (1)–(5) simultaneously (E-Z Solve):

$\underline{\underline{\dot{n}_0 = 23.4\ \text{kmol E/h (fresh feed)}}}$, $\underline{\underline{\dot{n}_{\mathrm{H4}} = 22.7\ \text{kmol H}_2\text{/h (in off-gas)}}}$

$\dot{n}_3$ = 23.3 kmol/h, $\dot{n}_{\mathrm{A4}}$ = 0.755 kmol A/h, $\dot{n}_{\mathrm{E4}}$ = 0.00496 kmol E/h

$\underline{\text{A balance about feed mixing point:}}$ $\dot{n}_{\mathrm{A1}} = 0.05\dot{n}_r = 1.475\ \mathrm{kmol\ \ A/h}$

$\underline{\text{E balance about feed mixing point:}}$ $\dot{n}_{\mathrm{E1}} = \dot{n}_0 + 0.95\dot{n}_r = 51.5\ \mathrm{kmol\ \ E/h}$

$\underline{\text{E balance about condenser:}}$ $\dot{n}_{\mathrm{E2}} = \dot{n}_3 y_{\mathrm{E3}} + 0.450\dot{n}_c = 23.5\ \mathrm{kmol\ \ E/h}$

Ideal gas equation of state:

$$V_{\text{reactor feed}} = \frac{(1.47 + 51.5)\ \mathrm{kmol}}{\mathrm{h}}\left|\frac{22.4\ \mathrm{m^3\,(STP)}}{1\ \mathrm{kmol}}\right|\frac{(273{+}280)\mathrm{K}}{273\mathrm{K}} = \underline{\underline{2.40\times10^{3}\ \ \mathrm{m^3/h}}}$$

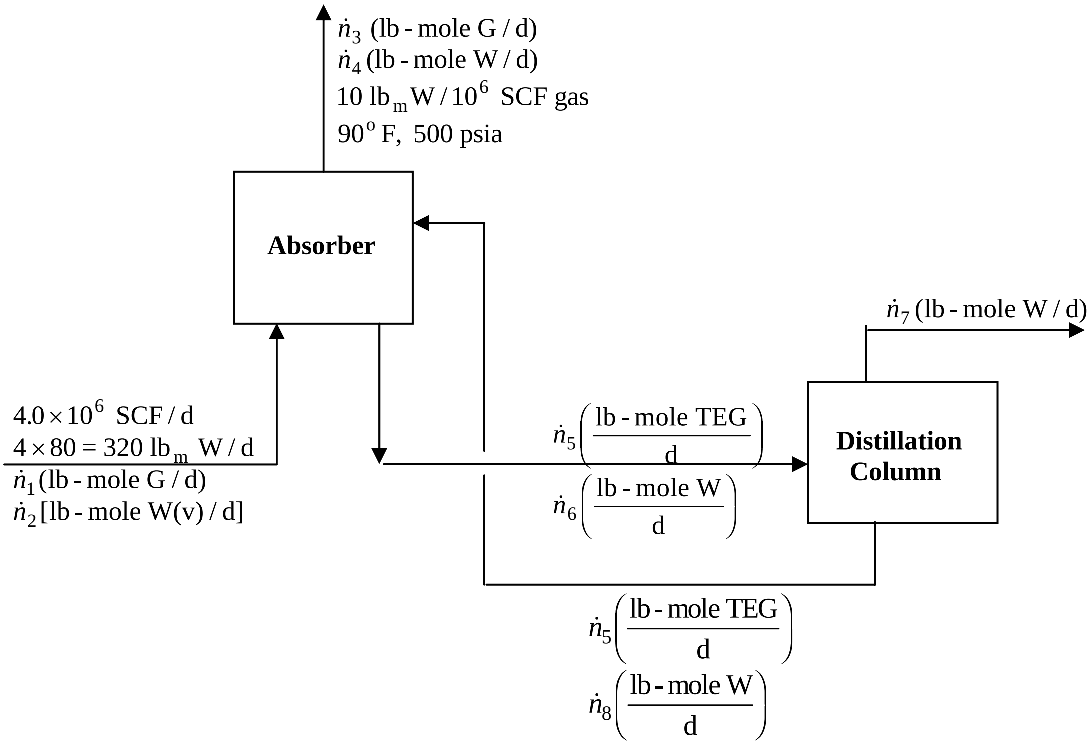
b. $\underline{\text{Overall conversion}} = \dfrac{\dot{n}_0 - 0.03\dot{n}_p}{\dot{n}_0}\times100\% = \dfrac{23.4 - (0.03)(22.67)}{23.4}\times100\% = \underline{\underline{97\%}}$

$\underline{\text{Single-pass conversion}} = \dfrac{\dot{n}_{\mathrm{E1}} - \dot{n}_{\mathrm{E2}}}{\dot{n}_{\mathrm{E1}}}\times100\% = \dfrac{51.5 - 23.5}{51.5}\times100\% = \underline{\underline{54\%}}$

$\underline{\text{Feed rate of A to scrubber:}}$ $\underline{\underline{\dot{n}_{\mathrm{A4}} = 0.76\ \text{kmol A/h}}}$

$\underline{\text{Feed rate of E to scrubber:}}$ $\underline{\underline{\dot{n}_{\mathrm{E4}} = 0.0050\ \mathrm{kmol\,E/h}}}$

6.72 **a.** G = dry natural gas, W = water



Overall system D.F. analysis: 5 unknowns $(\dot{n}_1, \dot{n}_2, \dot{n}_3, \dot{n}_4, \dot{n}_7)$
−2 feed specifications (total flow rate, flow rate of water)
−1 water content of dried gas
−2 balances (W, G)
0 D.F.

Water feed rate: $$\dot{n}_2 = \frac{320\ \text{lb}_\text{m}\ \text{W}}{\text{d}}\bigg|\frac{1\ \text{lb-mole}}{18.0\ \text{lb}_\text{m}} = 17.78\ \text{lb-moles W/d}$$

Dry gas feed rate:
$$\dot{n}_1 = \frac{4.0\times10^6\ \text{SCF}}{\text{d}}\bigg|\frac{1\ \text{lb-mole}}{359\ \text{SCF}} - 17.78\ \frac{\text{lb-moles W}}{\text{d}} = 1.112\times10^4\ \text{lb-moles G/d}$$

Overall G balance: $\dot{n}_1 = \dot{n}_3 \Rightarrow \dot{n}_3 = 1.112\times10^4$ lb-moles G/d

Flow rate of water in dried gas:
$$\dot{n}_4 = \frac{(\dot{n}_3+\dot{n}_4)\ \text{lb-moles}}{\text{d}}\bigg|\frac{359\ \text{SCF gas}}{\text{lb-mole}}\bigg|\frac{10\ \text{lb}_\text{m}\ \text{W}}{10^6\ \text{SCF}}\bigg|\frac{1\ \text{lb-mole W}}{18.0\ \text{lb}_\text{m}}$$
$$\xrightarrow{\dot{n}_3=1.112\times10^4} \dot{n}_4 = 2.218\ \text{lb-mole W(l)/d}$$

Overall W balance:
$$\dot{n}_7 = \frac{(17.78-2.218)\ \text{lb-moles W}}{\text{d}}\bigg|\frac{18.0\ \text{lb}_\text{m}}{1\ \text{lb-mole}} = \underline{\underline{280\ \frac{\text{lb}_\text{m}\ \text{W}}{\text{d}}}} \times \left(\frac{1\ \text{ft}^3}{62.4\ \text{lb}_\text{m}}\right) = \underline{\underline{4.5\ \frac{\text{ft}^3\ \text{W}}{\text{d}}}}$$

6.72 (cont'd)

b. Mole fraction of water in dried gas =

$$y_{\mathrm{w}} = \frac{\dot{n}_4}{\dot{n}_3 + \dot{n}_4} = \frac{2.218 \text{ lb - moles W / d}}{(2.218 \ + \ 1.112 \times 10^4) \text{ lb - moles / d}} = 1.99 \times 10^{-4} \ \frac{\text{lb - moles W(v)}}{\text{lb - mole}}$$

Henry's law: $y_{\mathrm{w}}P = H_{\mathrm{w}}x_{\mathrm{w}} \Rightarrow$

$$(x_{\mathrm{w}})_{\max} = \frac{(1.99 \times 10^{-4})(500 \text{ psia})(1 \text{ atm / 14.7 psia})}{0.398 \text{ atm / mole fraction}} = \underline{\underline{0.0170 \ \frac{\text{lb - mole dissolved W}}{\text{lb - mole solution}}}}$$

c. Solvent/solute mole ratio

$$\frac{\dot{n}_5}{\dot{n}_2 - \dot{n}_4} = \frac{37 \text{ lb}_{\mathrm{m}} \text{ TEG}}{\text{lb}_{\mathrm{m}} \text{ W}} \left| \frac{1 \text{ lb - mole TEG}}{150.2 \text{ lb}_{\mathrm{m}} \text{ TEG}} \right| \frac{18.0 \text{ lb}_{\mathrm{m}} \text{ W}}{1 \text{ lb}_{\mathrm{m}} \text{ W}} = 4.434 \ \frac{\text{lb - mole TEG}}{\text{lb - mole W absorbed}}$$

$$\Rightarrow \dot{n}_5 = 4.434(17.78 - 2.22) = 69.0 \text{ lb - moles TEG / d}$$

$$(x_{\mathrm{w}})_{\mathrm{in}} = 0.80(0.0170) = 0.0136 \ \frac{\text{lb-mole W}}{\text{lb-mole}} = \frac{\dot{n}_8}{\dot{n}_5 + \dot{n}_8} \xrightarrow{\dot{n}_5 = 69.0} \dot{n}_8 = 0.951 \text{ lb-mole W/d}$$

Solvent stream entering absorber

$$\dot{m} = \frac{0.951 \text{ lb - moles W}}{\text{d}} \left| \frac{18.0 \text{ lb}_{\mathrm{m}}}{\text{lb - mole}} \right. + \frac{69.0 \text{ lb - moles TEG}}{\text{d}} \left| \frac{150.2 \text{ lb}_{\mathrm{m}}}{\text{lb - mole}} \right.$$

$$= \underline{\underline{1.04 \times 10^4 \text{ lb}_{\mathrm{m}} \text{ / d}}}$$

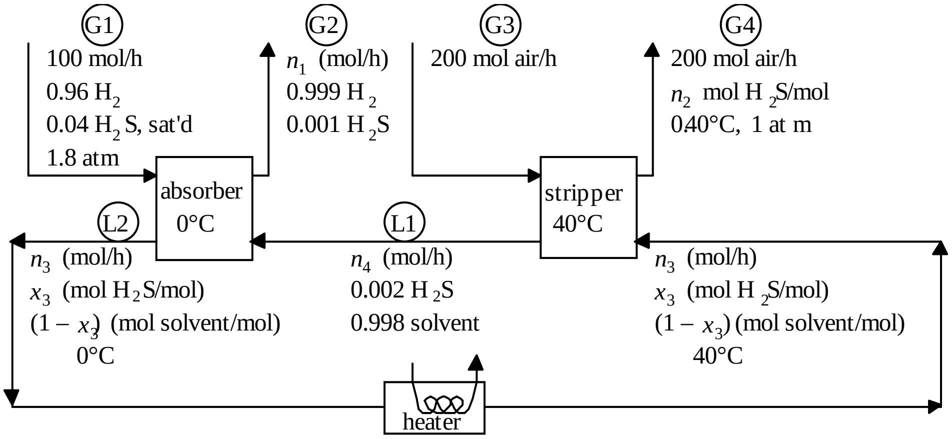
W balance on absorber

$$\dot{n}_6 = (17.78 + 0.95 - 2.22) \text{ lb-moles W/d} = 16.51 \text{ lb-moles W/d}$$

$$\Rightarrow (x_w)_{\mathrm{out}} = \frac{16.51 \text{ lb-moles W/d}}{(16.51 + 69.9) \text{ lb-moles/d}} = \underline{\underline{0.19 \text{ lb-mole W/lb-mole}}}$$

d. The distillation column recovers the solvent for subsequent re-use in the absorber.

6.73 Basis: Given feed rates



6.73 (cont'd)

<u>Equilibrium condition:</u> At G1, $p_{\mathrm{H_2S}} = (0.04)(1.8\text{ atm}) = 0.072\text{ atm}$

$$\Rightarrow x_3 = \frac{p_{\mathrm{H_2S}}}{H_{\mathrm{H_2S}}} = \frac{0.072\text{ atm}}{27\text{ atm/mol fraction}} = 2.67\times10^{-3}\ \text{ mole H}_2\text{S/mole}$$

<u>Strategy:</u> Overall H_2 and H_2S balances $\Rightarrow \dot{n}_1, \dot{n}_2$

$\dot{n}_2$ + air flow rate $\Rightarrow$ volumetric flow rate at G4

H_2S and solvent balances around absorber $\Rightarrow \dot{n}_3, \dot{n}_4$

$0.998\dot{n}_4 =$ solvent flow rate

<u>Overall H_2 balance:</u> $(100)(0.96) = 0.999n_1 \Rightarrow \dot{n}_1 = 96.1\text{ mol/h}$

<u>Overall H_2S balance:</u> $(100)(0.04) = 0.001\dot{n}_1 + \dot{n}_2 \overset{\dot{n}_1=96.1}{\Rightarrow} \dot{n}_2 = 3.90\text{ mol H}_2\text{S/h}$

<u>Volumetric flow rate at stripper outlet</u>

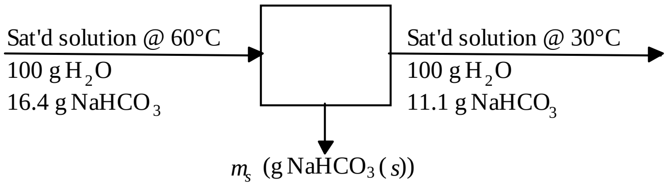
$$\dot{V}_{\mathrm{G4}} = \frac{(200+3.90)\text{mol}}{\text{h}}\left|\frac{22.4\text{ liters(STP)}}{1\text{ mol}}\right|\frac{(273+40)\text{K}}{273\text{ K}} = \underline{\underline{5240\text{ L/hr}}}$$

<u>H_2S and solvent balances around absorber:</u>

$$\left.\begin{aligned}&(100)(0.04)+0.002\dot{n}_4 = 0.001\dot{n}_1 + \dot{n}_3x_3 \Rightarrow \dot{n}_4 = 1.335\dot{n}_3 - 1952\\&0.998\dot{n}_4 = \dot{n}_3\left(1-2.67\times10^{-3}\right)\end{aligned}\right\}\Rightarrow \dot{n}_3 \approx \dot{n}_4 = 5830\text{ mol/h}$$

<u>Solvent flow rate</u> $= 0.998\dot{n}_4 = \underline{\underline{5820\text{ mol solvent/h}}}$

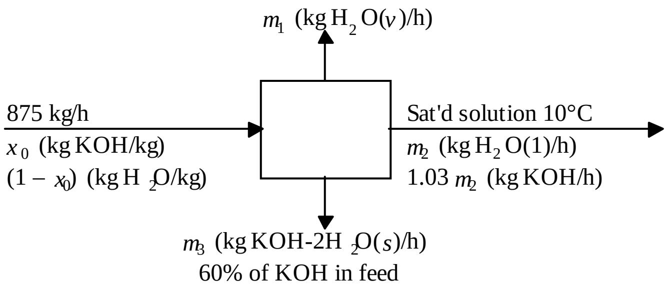
6.74 <u>Basis: 100 g H_2O</u>



<u>$NaHCO_3$ balance</u> $\Rightarrow 16.4 = 11.1 + m_s \Rightarrow m_s = 5.3\text{ g NaHCO}_3(\text{s})$

<u>% crystallization</u> $= \dfrac{5.3\text{ g crystallized}}{16.4\text{ g fed}}\times100\% = \underline{\underline{32.3\%}}$

6.75 <u>Basis</u>: 875 kg/h feed solution



6.75 (cont'd)

<u>Analysis of feed:</u> $2\text{KOH} + \text{H}_2\text{SO}_4 \rightarrow \text{K}_2\text{SO}_4 + 2\text{H}_2\text{O}$

$$x_0 = \frac{22.4\text{ mL H}_2\text{SO}_4(\text{l})}{5\text{ g feed soln}}\Big|\frac{1\text{ L}}{10^3\text{ mL}}\Big|\frac{0.85\text{ mol H}_2\text{SO}_4}{\text{L}}\Big|\frac{2\text{ mol KOH}}{1\text{ mol H}_2\text{SO}_4}\Big|\frac{56.11\text{ g KOH}}{1\text{ mol KOH}}$$

$$= 0.427\ \text{g KOH/g feed}$$

<u>60% recovery:</u> $875(0.427)(0.60) = 224.2\ \text{kg KOH/h}$

$$m_3 = \frac{224.2\text{ kg KOH}}{\text{h}}\Big|\frac{92.15\text{ kg KOH}\cdot 2\text{H}_2\text{O}}{56.11\text{ kg KOH}} = 368.2\text{ kg KOH}\cdot 2\text{H}_2\text{O/h}\ \ (143.8\text{ kg H}_2\text{O/h})$$

<u>KOH balance:</u> $0.427(875) = 224.2 + 1.03m_2 \Rightarrow m_2 = 145.1\ \text{kg/h}$

<u>Total mass balance:</u> $875 = 368.2 + 2.03(145.1) + m_1 \Rightarrow \underline{\underline{m_1 = 212\,\text{kg H}_2\text{O/h evaporated}}}$

6.76 a.

$$C_\text{A} = \frac{\text{g A dissolved}}{\text{mL solution}}$$

R	0	30	45
C_A	0	0.200	0.300

Plot C_A vs. R $\Rightarrow$ $\underline{\underline{C_\text{A} = R/150}}$

b. <u>Mass of solution:</u> $\dfrac{500\text{ mol}}{}\Big|\dfrac{1.10\text{ g}}{\text{ml}} = 550\text{ g}\ \ (160\text{ g A, }390\text{ g S})$

The initial solution is saturated at 10.2 °C.

<u>Solubility @ 10.2 °C</u> $= \dfrac{160\text{ g A}}{390\text{ g S}} = 0.410\,\text{g A/g S} = \underline{\underline{41.0\ \text{g A/100 g S @ 10.2° C}}}$

At 0°C, $R = 17.5 \Rightarrow C_\text{A} = \dfrac{17.5/150\text{ g A}}{\text{mL soln}}\Big|\dfrac{1\text{ mL soln}}{1.10\text{ g soln}} = 0.106\ \text{g A/g soln}$

Thus 1 g of solution saturated at 0°C contains 0.106 g A & 0.894 g S.

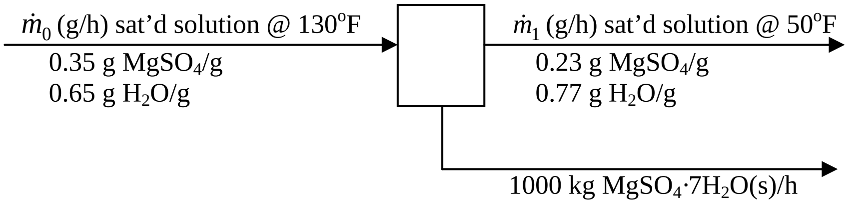
<u>Solubility @ 0°C</u> $\dfrac{0.106\text{ g A}}{0.894\text{ g S}} = 0.118\ \text{g A/g S} = \underline{\underline{11.8\ \text{g A/100 g S @ 0° C}}}$

<u>Mass of solid A:</u> $160\text{ g A} - \dfrac{390\text{ g S}}{}\Big|\dfrac{11.8\text{ g A}}{100\text{ g S}} = \underline{\underline{114\text{ g A(s)}}}$

c. $$\overbrace{(160-114)\text{g A}}^{\text{g A initial}} - \overbrace{\frac{0.5\times 390\text{ g S}}{}\Big|\frac{11.8\text{ g A}}{100\text{ g S}}}^{\text{g A remaining in soln}} = \underline{\underline{23.0\text{ g A(s)}}}$$

6.77 a. Table 6.5-1 shows that at 50°F (10.0°F), the salt that crystallizes is $\underline{\underline{\text{MgSO}_4\cdot 7\text{H}_2\text{O}}}$, which contains 48.8 wt% MgSO_4.

b. <u>Basis</u>: 1000 kg crystals/h.



6.77 (cont'd)

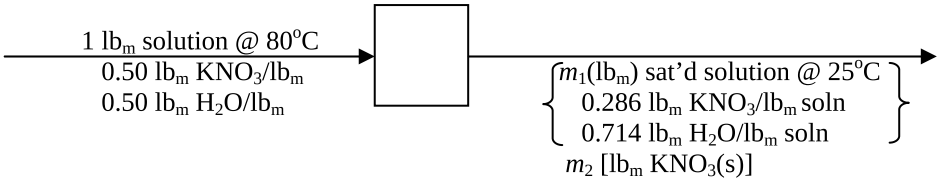
$$\left.\begin{array}{l}\underline{\text{Mass balance}}\text{: } \dot{m}_0 = \dot{m}_1 + 1000 \text{ kg / h} \\ \underline{\text{MgSO}_4 \text{ balance}}\text{: } 0.35\dot{m}_0 = 0.23\dot{m}_1 + 0.488(1000) \text{ kg MgSO}_4 \text{ / h}\end{array}\right\} \Rightarrow \begin{array}{l}\dot{m}_0 = 2150 \text{ kg feed / h} \\ \hline \hline \dot{m}_1 = 1150 \text{ kg soln / h} \\ \hline \hline\end{array}$$

$$\text{The crystals would yield } 0.488 \times 1000 \text{ kg / h} = \underline{\underline{488 \frac{\text{kg anhydrous MgSO}_4}{\text{h}}}}$$

6.78 Basis: 1 lb_m feed solution.

Figure 6.5-1 ⇒ a saturated KNO_3 solution at 25°C contains 40 g KNO_3/100 g H_2O

$$\Rightarrow x_{\text{KNO}_3} = \frac{40 \text{ g KNO}_3}{(40 + 100) \text{ g solution}} = 0.286 \text{ g KNO}_3 \text{ / g} = 0.286 \text{ lb}_\text{m} \text{ KNO}_3 \text{ / lb}_\text{m} x$$



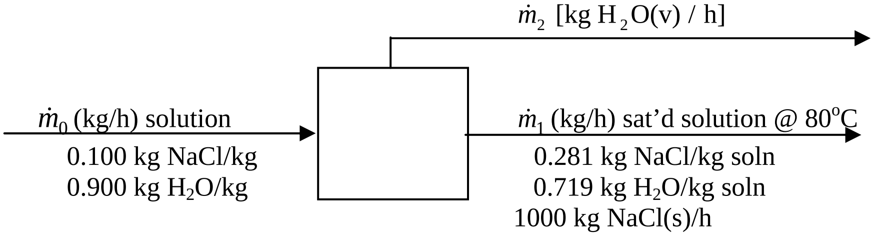
$$\left.\begin{array}{l}\underline{\text{Mass balance}}\text{: } 1 \text{ lb}_\text{m} = m_1 + m_2 \\ \underline{\text{KNO}_3 \text{ balance}}\text{: } 0.50 \text{ lb}_\text{m} \text{ KNO}_3 = 0.286 m_1 + m_2\end{array}\right\} \Rightarrow \begin{array}{l}m_1 = 0.700 \text{ lb}_\text{m} \text{ solution / lb}_\text{m} \text{ feed} \\ m_2 = \underline{\underline{0.300 \text{ lb}_\text{m} \text{ crystals / lb}_\text{m} \text{ feed}}}\end{array}$$

$$\underline{\text{Solid / liquid mass ratio}} = \frac{0.300 \text{ lb}_\text{m} \text{ crystals / lb}_\text{m} \text{ feed}}{0.700 \text{ lb}_\text{m} \text{ solution / lb}_\text{m} \text{ feed}} = \underline{\underline{0.429 \text{ lb}_\text{m} \text{ crystals / lb}_\text{m} \text{ solution}}}$$

6.79 a. Basis: 1000 kg NaCl(s)/h.

Figure 6.5-1 ⇒ a saturated NaCl solution at 80°C contains 39 g NaCl/100 g H_2O

$$\Rightarrow x_{\text{NaCl}} = \frac{39 \text{ g NaCl}}{(39 + 100) \text{ g solution}} = 0.281 \text{ g NaCl / g} = 0.281 \text{ kg NaCl / kg}$$



$$\left.\begin{array}{l}\underline{\text{Mass balance}}\text{: } \dot{m}_0 = \dot{m}_1 + \dot{m}_2 \\ \underline{\text{NaCl balance}}\text{: } 0.100 \text{ kg NaCl} = 0.281\dot{m}_1 + \dot{m}_2\end{array}\right\} \Rightarrow \begin{array}{l}\dot{m}_1 = 0.700 \text{ lb}_\text{m} \text{ solution / lb}_\text{m} \text{ feed} \\ \dot{m}_2 = \underline{\underline{0.300 \text{ lb}_\text{m} \text{ crystals / lb}_\text{m} \text{ feed}}}\end{array}$$

$$\underline{\text{Solid / liquid mass ratio}} = \frac{0.300 \text{ lb}_\text{m} \text{ crystals / lb}_\text{m} \text{ feed}}{0.700 \text{ lb}_\text{m} \text{ solution / lb}_\text{m} \text{ feed}} = \underline{\underline{0.429 \text{ lb}_\text{m} \text{ crystals / lb}_\text{m} \text{ solution}}}$$

The minimum feed rate would be that for which all of the water in the feed evaporates to produce solid NaCl at the specified rate. In this case

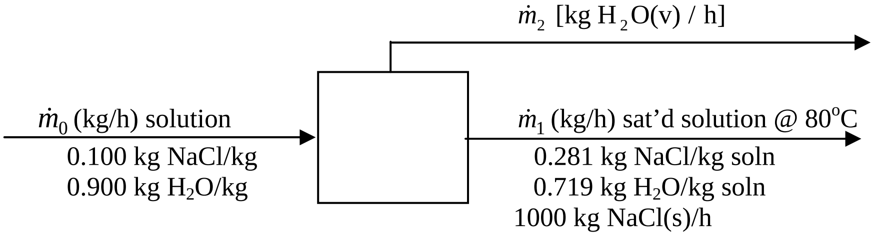
6.79 (cont'd)

$0.100(\dot{m}_0)_{\min} = 1000\ \text{kg NaCl / h} \Rightarrow \underline{\underline{(\dot{m}_0)_{\min} = 10{,}000\ \text{kg / min}}}$

Evaporation rate: $\underline{\underline{\dot{m}_2 = 9000\ \text{kg H}_2\text{O / h}}}$

Exit solution flow rate: $\underline{\underline{\dot{m}_1 = 0}}$

b.



40% solids content in slurry $\Rightarrow 1000\ \dfrac{\text{kg NaCl}}{\text{h}} = 0.400(\dot{m}_1)_{\max} \Rightarrow \underline{\underline{(\dot{m}_1)_{\max} = 2500\ \dfrac{\text{kg}}{\text{h}}}}$

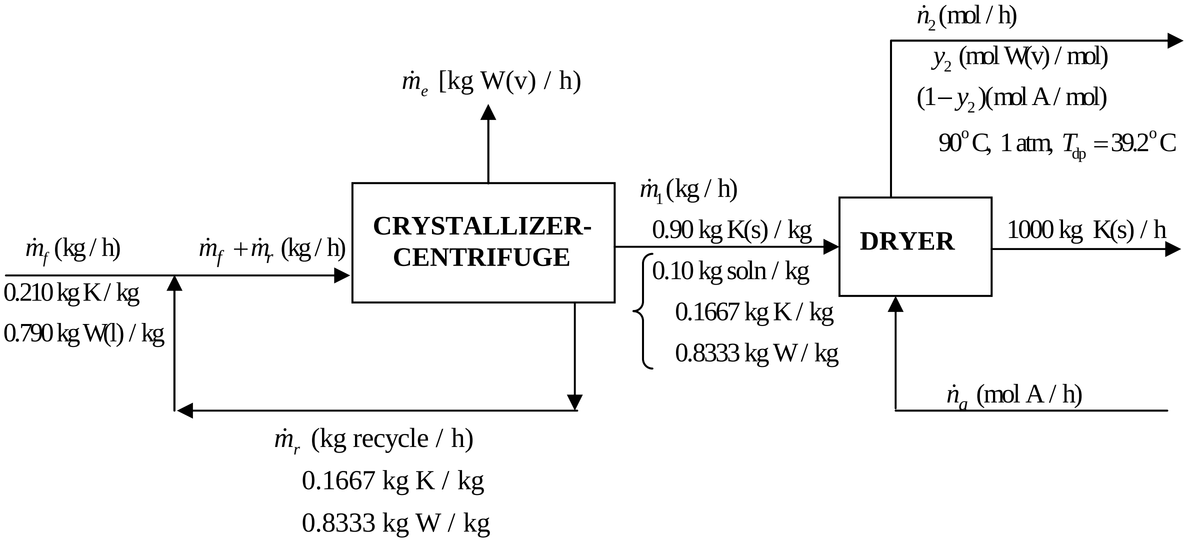
NaCl balance: $0.100\dot{m}_0 = 0.281(2500) \Rightarrow \underline{\underline{\dot{m}_0 = 7025\ \text{kg / h}}}$

Mass balance: $\dot{m}_0 = 2500 + \dot{m}_2 \Rightarrow \dot{m}_2 = \underline{\underline{4525\ \text{kg H}_2\text{O evaporate / h}}}$

6.80 Basis: 1000 kg $\text{K}_2\text{Cr}_2\text{O}_7(\text{s})/\text{h}$. Let K = $\text{K}_2\text{Cr}_2\text{O}_7$, A = dry air, S = solution, W = water.

Composition of saturated solution:

$$\frac{0.20\ \text{kg K}}{\text{kg W}} \Rightarrow \frac{0.20\ \text{kg K}}{(1+0.20)\ \text{kg soln}} = 0.1667\ \text{kg K/kg soln}$$



Dryer outlet gas: $y_2 P = p_\text{W}^*(39.2^\circ\text{C}) \Rightarrow y_2 = \dfrac{53.01\ \text{mm Hg}}{760\ \text{mm Hg}} = 0.0698\ \text{mol W/mol}$

Overall K balance: $0.210\dot{m}_f = 1000\ \text{kg K/h} \Rightarrow \dot{m}_f = \underline{\underline{4760\ \text{kg/h}}}$ feed solution

6.80 (cont'd)

K balance on dryer: $0.90\dot{m}_1 + (0.1667)(0.10\dot{m}_1) = 1000 \text{ kg/h} \Rightarrow \dot{m}_1 = 1090 \text{ kg/h}$

Mass balance around crystallizer-centrifuge

$$\dot{m}_f + \dot{m}_r = \dot{m}_e + \dot{m}_1 + \dot{m}_r \Rightarrow m_e = 4760 - 1090 = \underline{\underline{3670 \text{ kg/h water evaporated}}}$$

$$\underline{\text{95\% solution recycled}} \Rightarrow \dot{m}_r = \frac{(0.10 \times 1090) \text{ kg /h not recycled}}{} \left| \frac{\text{95 kg recycled}}{\text{5 kg not recycled}} \right. = \underline{\underline{2070 \text{ kg/h recycled}}}$$

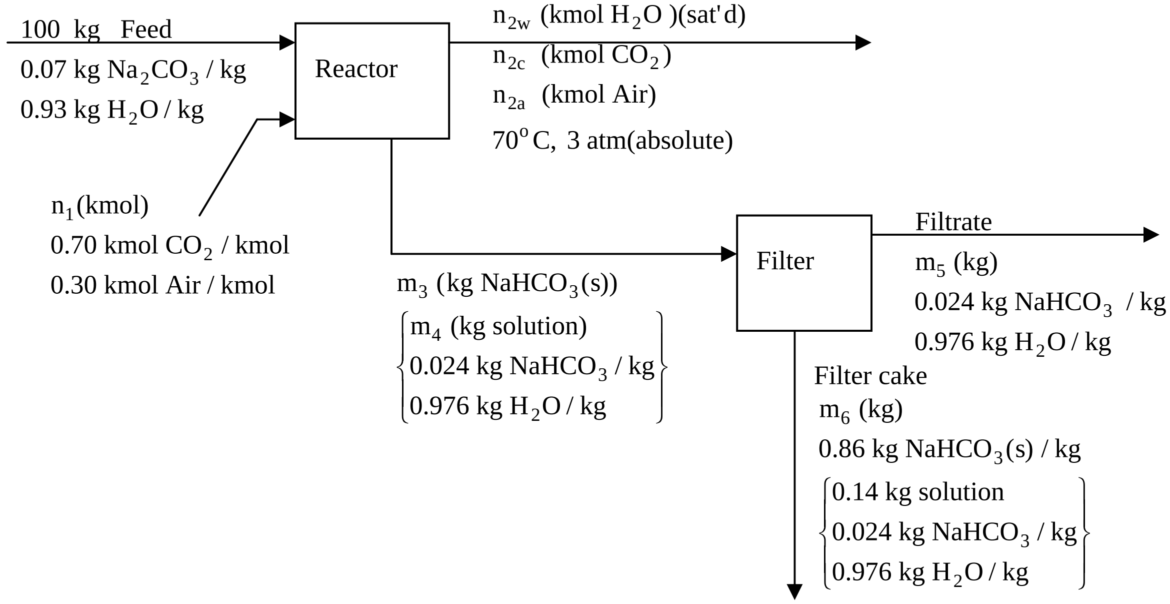
Water balance on dryer

$$\frac{(0.8333)(0.10)(1090) \text{ kg W/h}}{18.01 \times 10^{-3} \text{ kg/mol}} = 0.0698\dot{n}_2 \Rightarrow \dot{n}_2 = 7.225 \times 10^4 \text{ mol/h}$$

Dry air balance on dryer

$$n_a = \frac{(1 - 0.0698)7.225 \times 10^4 \text{ mol}}{\text{h}} \left| \frac{22.4 \text{ L(STP)}}{1 \text{ mol}} \right. = \underline{\underline{1.51 \times 10^6 \text{ L(STP)/h}}}$$

6.81. Basis : 100 kg liquid feed. Assume P_{atm}=1 atm



Degree of freedom analysis:

Reactor

6 unknowns (n_1, n_2, y_{2w}, y_{2c}, m_3, m_4)
–4 atomic species balances (Na, C, O, H)
–1 air balance
–1 (Raoult's law for water)
0 DF

Filter

2 unknowns
–2 balances
0 DF

Na balance on reactor

$$\begin{array}{c|c|c} 100\text{ kg} & 0.07\text{ kg Na}_2\text{CO}_3 & 46\text{ kg Na} \\ \hline & \text{kg} & 106\text{ kg Na}_2\text{CO}_3 \end{array} = \begin{array}{c|c} (m_3+0.024m_4)\text{ kg NaHCO}_3 & 23\text{ kg Na} \\ \hline & 84\text{ kg NaHCO}_3 \end{array}$$

$$\Rightarrow 3.038 = 0.2738(m_3 + 0.024m_4) \qquad (1)$$

Air balance: $0.300n_1 = n_{2a}$ (2)

C balance on reactor :

$$\begin{array}{c|c|c} n_1\text{ (kmol)} & 0.700\text{ kmol CO}_2 & 12\text{ kg C} \\ \hline & \text{kmol} & 1\text{ kmol CO}_2 \end{array} + \begin{array}{c|c|c} 100\text{ kg} & 0.07\text{ kg Na}_2\text{CO}_3 & 12\text{ kg C} \\ \hline & \text{kg} & 106\text{ kg Na}_2\text{CO}_3 \end{array}$$

$$= (n_{2c})(12) + (m_3 + 0.024m_2)(\frac{12}{84}) \ \Rightarrow 8.40n_1 + 0.7924 = 12n_{2c} + 0.1429(m_3 + 0.024m_4) \qquad (3)$$

H balance :

$$(100)(0.93)(\frac{2}{18}) = (n_{2w})(2) + (m_3 + 0.024m_4)(\frac{1}{84}) + 0.976m_4(\frac{2}{18})$$

$$\Rightarrow \quad 10.33 = 2n_{2w} + 0.01190(m_3 + 0.024m_4) + 0.1084m_4 \qquad (4)$$

6.81(cont'd)

O balance (not counting O in the air):

$$n_1(0.700)(932)+100(0.07)(\frac{48}{106})+100(0.93)(\frac{16}{18})$$

$$=(n_{2w})(16)+n_{2c}(32)+(m_3+0.024m_4)(\frac{48}{84})+0.976m_4(\frac{16}{18})$$

$$\Rightarrow 22.4n_1+85.84=16n_{2w}+32n_{2c}+0.5714(m_3+0.024m_4)+0.8676m_4 \qquad (5)$$

Raoult's Law :

$$y_w P = p_w^*(70^o\,C)\Rightarrow \frac{n_{2w}}{n_{2w}+n_{2c}+n_{2a}}=\frac{233.7 \text{ mm Hg}}{(3*760)\text{ mm Hg}}$$

$$\Rightarrow n_{2w}=0.1025(n_{2w}+n_{2c}+n_{2a}) \qquad (6)$$

Solve (1)-(6) simultaneously with E-Z solve (need a good set of starting values to converge).

$n_1 = 0.8086$ kmol, $n_{2a} = 0.2426$ kmol air, $n_{2c} = 0.500$ kmol CO_2,
$n_{2w} = 0.0848$ kmol H_2O(v), $m_3 = 8.874$ kg $NaHCO_3$(s), $m_4 = 92.50$ kg solution

$NaHCO_3$ balance on filter:

$$m_3+0.024m_4=0.024m_5+m_6[0.86+(0.14)(0.024)]$$

$$\xRightarrow[m_4=92.50]{m_3=8.874} 11.09=0.024\text{m}_5+0.8634\text{m}_6 \qquad (7)$$

Mass Balance on filter: $8.874+92.50=101.4=m_5+m_6$ (8)

Solve (7) & (8) $\Rightarrow \begin{array}{l} m_5 = 91.09 \text{ kg filtrate} \\ m_6 = 10.31 \text{ kg filter cake}\end{array} \Rightarrow (0.86)(10.31)=8.867 \text{ kg NaHCO}_3\text{(s)}$

$$\underline{\text{Scale factor}}=\frac{500\text{ kg / h}}{8.867\text{ kg}}=56.39\text{ h}^{-1}$$

(a) Gas stream leaving reactor

$$\left.\begin{array}{r}\dot{n}_{2\text{w}}=(0.0848)(56.39)=4.78\text{ kmol H}_2\text{O(v) / h}\\ \dot{n}_{2\text{c}}=(0.500)(56.39)=28.2\text{ kmol O}_2\text{ / h}\\ \dot{n}_{2\text{a}}=(0.2426)(56.39)=13.7\text{ kmol air / h}\end{array}\right\}\Rightarrow\left\{\begin{array}{l}46.7\text{kmol / h}\\ 0.102\text{ kmol H}_2\text{O(v) / kmol}\\ 0.604\text{ kmol CO}_2\text{ / kmol}\\ 0.293\text{ kmol Air / kmol}\end{array}\right.$$

$$\dot{V}_2=\frac{\dot{n}_2RT}{P}=\frac{(46.7\text{ kmol / h})(0.08206\,\frac{\text{m}^3\text{atm}}{\text{kmol}\cdot\text{K}})(343\text{ K})}{3\text{ atm}}=\underline{\underline{438\text{ m}^3\text{ / h}}}$$

(b) Gas feed rate: $\dot{V}_1=\dfrac{56.39\times 0.8086\text{ kmol}}{\text{h}}\left|\dfrac{22.4\text{ m}^3\text{(STP)}}{\text{kmol}}\right|\dfrac{1\text{ h}}{60\text{ min}}=\underline{\underline{17.0\text{ SCMM}}}$

6.81(cont'd)

(c) Liquid feed: $(100)(56.39) = \underline{\underline{5640\ \text{kg}/\text{h}}}$

To calculate $\dot{V}$, we would need to know the density of a 7 wt% aqueous Na_2CO_3 solution.

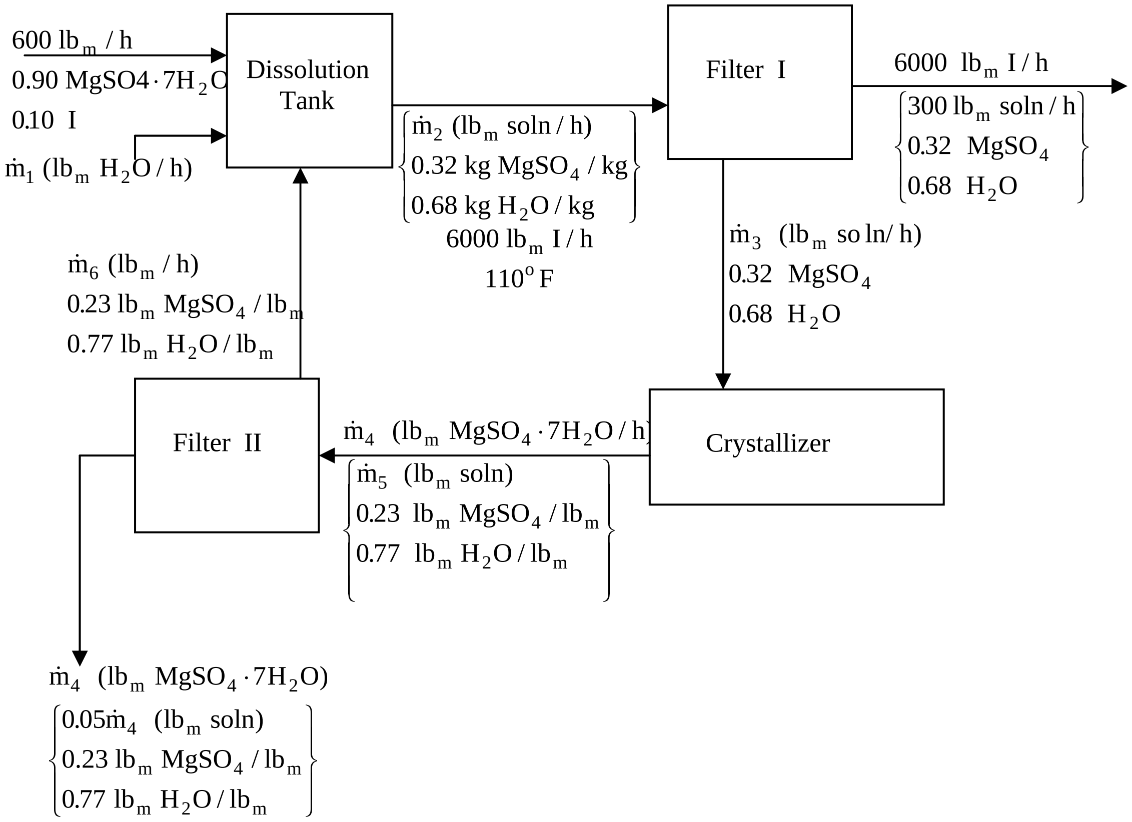
(d) If T dropped in the filter, more solid $NaHCO_3$ would be recovered and the residual solution would contain less than 2.4% $NaHCO_3$.

(e)

Benefit: Higher pressure $\Rightarrow$ greater $p_{CO_2} \xrightarrow{\text{Henry's law}}$ higher concentration of CO_2 in solution $\Rightarrow$ higher rate of reaction $\Rightarrow$ smaller reactor needed to get the same conversion $\Rightarrow$ lower cost

Penalty: Higher pressure $\Rightarrow$ greater cost of compressing the gas (purchase cost of compressor, power consumption)

6.82



a. Heating the solution dissolves all $MgSO_4$; filtering removes I, and cooling recrystallizes $MgSO_4$ enabling subsequent recovery.

(b) Strategy: Do D.F analysis.

6.82(cont'd)

$$\left.\begin{array}{l}\text{Overall mass balance}\\ \text{Overall MgSO}_4\text{ balance}\end{array}\right\}\Rightarrow \dot{m}_1,\dot{m}_4 \qquad \left.\begin{array}{c}\text{Diss. tank overall mass balance}\\ \text{Diss. tank MgSO}_4\text{ balance}\end{array}\right\}\Rightarrow \dot{m}_2,\dot{m}_6$$

$$(MW)_{\text{MgSO}_4}=(24.31+32.06+64.00)=120.37,\ (MW)_{\text{MgSO}_4\cdot 7\text{H}_2\text{O}}=(120.37+7*18.01)=246.44$$

<u>Overall $MgSO_4$ balance</u>:

$$\frac{60{,}000\text{ lb}_\text{m}}{\text{h}}\left|\frac{0.90\text{ lb}_\text{m}\text{ MgSO}_4\cdot 7\text{H}_2\text{O}}{\text{lb}_\text{m}}\right|\frac{120.37\text{ lb}_\text{m}\text{ MgSO}_4}{246.44\text{ lb}_\text{m}\text{ MgSO}_4\cdot 7\text{H}_2\text{O}}$$

$$=(300\text{ lb}_\text{m}/\text{h})(0.32\text{ lb}_\text{m}\text{ MgSO}_4/\text{lb}_\text{m})+\dot{m}_4(120.37/246.44)+0.05\dot{m}_4(0.23)$$

$$\Rightarrow\quad \dot{m}_4=\underline{\underline{5.257x10^4\text{ lb}_\text{m}\text{ crystals / h}}}$$

<u>Overall mass balance</u>: $60{,}000+\dot{m}_1=6300+1.05\dot{m}_4 \xrightarrow{\dot{m}_4=5.257x10^4\ \text{lb}_\text{m}/h} \dot{m}_1=\underline{\underline{1494\text{ lb}_\text{m}\text{ H}_2\text{O / h}}}$

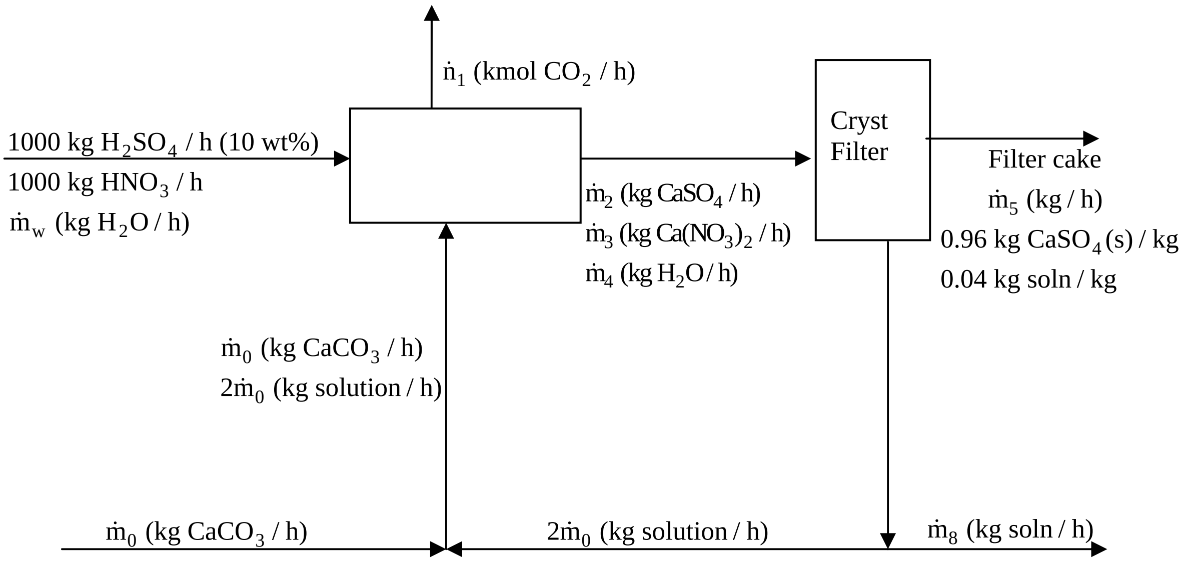
c.

$$\left.\begin{array}{ll}\underline{\text{Diss. tank overall mass balance}}: & 60{,}000+\dot{m}_1+\dot{m}_6=\dot{m}_2+6000\\ \underline{\text{Diss. tank MgSO}_4\text{ balance}}: & 54{,}000(120.37/246.44)+0.23\dot{m}_6=0.32\dot{m}_2\end{array}\right\}$$

$$\Rightarrow\begin{array}{l}\dot{m}_2=1.512x10^5\text{ lb}_\text{m}/\text{h}\\ \dot{m}_6=9.575x10^4\text{ lb}_\text{m}/\text{h}\quad\text{recycle}\end{array}$$

$$\underline{\text{Recycle/fresh feed ratio}}=\frac{9.575\text{x}10^4\text{ lb}_\text{m}/\text{h}}{1494\text{ lb}_\text{m}/\text{h}}=\underline{\underline{64\quad \text{lb}_\text{m}\text{ recycle / lb}_\text{m}\text{ fresh feed}}}$$

6.83 a.



$$\text{Solution composition: }\left\{\begin{array}{c}X_\text{a}\text{ (kg CaSO}_4\text{ / kg)}\\ 500X_\text{a}\text{ (kg H}_2\text{O / kg)}\\ (1-501X_\text{a})\text{(kg Ca(NO}_3)_2\text{ / kg)}\end{array}\right\}$$

6.83 (cont'd)

b. Acid is corrosive to pipes and other equipment in waste water treatment plant.

c. Acid feed: $\dfrac{1000\text{ kg H}_2\text{SO}_4\text{ / h}}{(2000+\dot{m}_\text{w})\text{ kg / h}} = 0.10 \Rightarrow \dot{m}_\text{w} = 8000\text{ kg H}_2\text{O / h}$

Overall S balance:

$$\begin{array}{c|c} 1000\text{ kg H}_2\text{SO}_4 & 32\text{ kg S} \\ \hline \text{h} & 98\text{ kg H}_2\text{SO}_4 \end{array} = \begin{array}{c|c|c} \dot{m}_5\text{ (kg / h)} & (0.96+0.04X_\text{a})\text{ (kg CaSO}_4) & 32\text{ kg S} \\ \hline & \text{kg} & 136\text{ kg CaSO}_4 \end{array}$$

$$+\begin{array}{c|c|c} \dot{m}_8\text{ (kg / h)} & X_\text{a}\text{ (kg CaSO}_4) & 32\text{ kg S} \\ \hline & \text{kg} & 136\text{ kg CaSO}_4 \end{array}$$

$$\Rightarrow 326.5 = 0.2353\dot{m}_5(0.96+0.04X_a) + 0.2353\dot{m}_8 X_a \qquad (1)$$

Overall N balance:

$$\begin{array}{c|c} 1000\text{ kg HNO}_3 & 14\text{ kg N} \\ \hline \text{h} & 63\text{ kg HNO}_3 \end{array} = \begin{array}{c|c|c} 0.04\dot{m}_5\text{ (kg / h)} & (1-501X_\text{a})\text{ (kg Ca(NO}_3)_2) & 28\text{ kg N} \\ \hline & \text{kg} & 164\text{ kg Ca(NO}_3)_2 \end{array}$$

$$+\begin{array}{c|c|c} \dot{m}_8\text{ (kg / h)} & (1-501X_\text{a})\text{ (kg Ca(NO}_3)_2) & 28\text{ kg N} \\ \hline & \text{kg} & 164\text{ kg Ca(NO}_3)_2 \end{array}$$

$$\Rightarrow 222.2 = 0.00683\dot{m}_5(1-501X_a) + 0.171\dot{m}_8(1-501X_a) \qquad (2)$$

Overall Ca balance:

$$\begin{array}{c|c} \dot{\text{m}}_0\text{ (kg / h)} & 40\text{ kg Ca} \\ \hline & 100\text{ kg CaCO}_3 \end{array} = \begin{array}{c|c|c} \dot{\text{m}}_5\text{ (kg / h)} & (0.96+0.04\text{X}_\text{a})\text{ (kg CaSO}_4) & 40\text{ kg Ca} \\ \hline & \text{kg} & 136\text{ kg CaSO}_4 \end{array}$$

$$+\begin{array}{c|c|c} (1-501\text{X}_\text{a})\text{ (kg Ca(NO}_3)_2) & 0.04\dot{\text{m}}_5\text{ (kg / h)} & 40\text{ kg Ca} \\ \hline \text{kg} & & 164\text{ kg Ca(NO}_3)_2 \end{array}$$

$$+\begin{array}{c|c|c} \dot{\text{m}}_8\text{ (kg / h)} & \text{X}_\text{a}\text{ (kg CaSO}_4) & 40\text{ kg Ca} \\ \hline & \text{kg} & 136\text{ kg CaSO}_4 \end{array}$$

$$+\begin{array}{c|c|c} \dot{\text{m}}_8\text{ (kg / h)} & (1-501\text{X}_\text{a})\text{ (kg Ca(NO}_3)_2) & 40\text{ kg Ca} \\ \hline & \text{kg} & 164\text{ kg Ca(NO}_3)_2 \end{array}$$

$$\begin{aligned} \Rightarrow 0.40\dot{m}_0 &= 0.294\dot{m}_5(0.96+0.04X_a) + 0.00976\dot{m}_5(1-501X_a) \\ &\quad + 0.294\dot{m}_8 X_a + 0.244\dot{m}_8(1-501X_a) \qquad (3) \end{aligned}$$

Overall C balance :

$$\begin{array}{c|c} \dot{\text{m}}_0\text{ (kg / h)} & 12\text{ kg C} \\ \hline & 100\text{ kg CaCO}_3 \end{array} = \begin{array}{c|c|c} \dot{\text{n}}_1\text{ (kmol CO}_2\text{ / h)} & 1\text{ kmol C} & 12\text{ kg C} \\ \hline & 1\text{ kmol CO}_2 & 1\text{ kmol C} \end{array}$$

$$\Rightarrow 0.01\dot{m}_0 = \dot{n}_1 \qquad (4)$$

6.83 (cont'd)

Overall H balance :

$$\frac{1000\,(\text{kg H}_2\text{SO}_4)}{\text{h}}\bigg|\frac{2\text{ kg H}}{98\text{ kg H}_2\text{SO}_4}+\frac{1000\text{ kg HNO}_3}{\text{h}}\bigg|\frac{1\text{ kg H}}{63\text{ kg HNO}_3}+\frac{\dot{m}_w\text{ (kg / h)}}{}\bigg|\frac{2\text{ kg H}}{18\text{ kg H}_2\text{O}}$$

$$=\frac{0.04\dot{m}_5\text{ (kg / h)}}{}\bigg|\frac{500X_a\text{ (kg H}_2\text{O)}}{\text{kg}}\bigg|\frac{2\text{ kg H}}{18\text{ kg H}_2\text{O}}+\frac{\dot{m}_8\text{ (kg / h)}}{}\bigg|\frac{500X_a\text{ (kg H}_2\text{O)}}{\text{kg}}\bigg|\frac{2\text{ kg H}}{18\text{ kg H}_2\text{O}}$$

$$\Rightarrow 925.17=2.22\dot{m}_5X_a+55.56\dot{m}_8X_a \qquad (5)$$

Solve eqns. (1)-(5) simultaneously, using E-Z Solve.

$\dot{m}_0=\underline{\underline{1812.5\text{ kg CaCO}_3\text{(s) / h}}}$, $\dot{m}_5=\underline{\underline{1428.1\text{ kg / h}}}$, $\dot{m}_8=\underline{\underline{9584.9\text{ kg soln / h}}}$,

$\dot{n}_1=18.1\text{ kmol CO}_2\text{ / h(v)}$, $X_a=0.00173\text{ kg CaSO}_4\text{ / kg}$

Recycle stream $=2*\dot{m}_0=\underline{\underline{3625\text{ kg soln / h}}}$

$$\left\{\begin{array}{c}0.00173(\text{kg CaSO}_4\text{ / kg})\\ 500*0.00173(\text{kg H}_2\text{O / kg})\\ (1-501*0.00173)(\text{kg Ca(NO}_3)_2\text{ / kg})\end{array}\right\}\Rightarrow\left\{\begin{array}{l}\underline{\underline{0.173\%\text{ CaSO}_4}}\\ \underline{\underline{86.5\%\text{ H}_2\text{O}}}\\ \underline{\underline{13.3\%\text{ Ca(NO}_3)_2}}\end{array}\right\}$$

d. From Table B.1, for CO_2:

$$T_c=304.2\ K,\qquad P_c=72.9\ atm$$

$$\Rightarrow T_r=\frac{T}{T_c}=\frac{(40+273.2)\ K}{304.2}=1.03,\qquad P_r=\frac{30\ atm}{72.9\ atm}=0.411$$

From generalized compressibility chart (Fig. 5.4-2):

$$z=0.86\Rightarrow\hat{V}=\frac{zRT}{P}=\frac{0.86}{}\bigg|\frac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\bigg|\frac{313.2\text{ K}}{30\text{ atm}}=0.737\ \frac{\text{L}}{\text{mol CO}_2}$$

Volumetric flow rate of CO_2:

$$\dot{V}=\dot{n}_1*\hat{V}=\frac{18.1\text{ kmol CO}_2}{\text{h}}\bigg|\frac{0.737\text{ L}}{\text{mol CO}_2}\bigg|\frac{1000\text{ mol}}{1\text{ kmol}}=\underline{\underline{1.33\text{x}10^4\text{ L / h}}}$$

e. Solution saturated with $Ca(NO_3)_2$:

$$\Rightarrow\frac{1-501\text{X}_\text{a}\ (\text{kg Ca(NO}_3)_2\text{ / kg})}{500\text{Xa (kg H}_2\text{O / kg)}}=1.526\Rightarrow\text{X}_\text{a}=0.00079\text{ kg CaSO}_4\text{ / kg}$$

Let $\dot{m}_1$ (kg HNO_3/h) = feed rate of nitric acid corresponding to saturation without crystallization.

6.83 (cont'd)

Overall S balance:

$$\begin{array}{c|c}1000\text{ kg H}_2\text{SO}_4 & 32\text{ kg S}\\ \hline \text{h} & 98\text{ kg H}_2\text{SO}_4\end{array}=\begin{array}{c|c|c}\dot{m}_5\text{ (kg / h)} & (0.96+(0.04)(0.00079))\text{ (kg CaSO}_4) & 32\text{ kg S}\\ \hline & \text{kg} & 136\text{ kg CaSO}_4\end{array}$$

$$+\begin{array}{c|c|c}\dot{m}_8\text{ (kg / h)} & 0.00079\text{ (kg CaSO}_4) & 32\text{ kg S}\\ \hline & \text{kg} & 136\text{ kg CaSO}_4\end{array}$$

$$\Rightarrow 326.5=0.226\dot{m}_5+0.000186\dot{m}_8 \qquad (1')$$

Overall N balance:

$$\begin{array}{c|c}\dot{m}_1\text{ (kg HNO}_3) & 14\text{ kg N}\\ \hline \text{h} & 63\text{ kg HNO}_3\end{array}=\begin{array}{c|c|c}0.04\dot{m}_5\text{ (kg / h)} & (1-(501)(0.00079))\text{ (kg Ca(NO}_3)_2) & 28\text{ kg N}\\ \hline & \text{kg} & 164\text{ kg Ca(NO}_3)_2\end{array}$$

$$+\begin{array}{c|c|c}\dot{m}_8\text{ (kg / h)} & (1-(501)(0.00079))\text{ (kg Ca(NO}_3)_2) & 28\text{ kg N}\\ \hline & \text{kg} & 164\text{ kg Ca(NO}_3)_2\end{array}$$

$$\Rightarrow 0.222\dot{m}_1=0.00413\dot{m}_5+0.103\dot{m}_8 \qquad (2')$$

Overall H balance:

$$\begin{array}{c|c}1000\text{ (kg H}_2\text{SO}_4) & 2\text{ kg H}\\ \hline \text{h} & 98\text{ kg H}_2\text{SO}_4\end{array}+\begin{array}{c|c}\dot{m}_1\text{ kg HNO}_3 & 1\text{ kg H}\\ \hline \text{h} & 63\text{ kg HNO}_3\end{array}$$

$$+\begin{array}{c|c}8000\text{ (kg / h)} & 2\text{ kg H}\\ \hline & 18\text{ kg H}_2\text{O}\end{array}=\begin{array}{c|c|c}0.04\dot{m}_5\text{ (kg / h)} & 500(0.00079)\text{ (kg H}_2\text{O)} & 2\text{ kg H}\\ \hline & \text{kg} & 18\text{ kg H}_2\text{O}\end{array}$$

$$+\begin{array}{c|c|c}\dot{m}_8\text{ (kg / h)} & 500(0.00079)\text{ (kg H}_2\text{O)} & 2\text{ kg H}\\ \hline & \text{kg} & 18\text{ kg H}_2\text{O}\end{array}$$

$$\Rightarrow 909.30+0.0159\dot{m}_1=0.00175\dot{m}_5+0.0439\dot{m}_8 \qquad (3')$$

Solve eqns (1')-(3') simultaneously using E-Z solve:

$$\dot{m}_1=1.155x10^4\text{ kg / h;}\qquad \dot{m}_5=1.424x10^3\text{ kg / h;}\qquad \dot{m}_8=2.484x10^4\text{ kg / h}$$

Maximum ratio of nitric acid to sulfuric acid in the feed

$$=\frac{1.155x10^4\text{ kg / h}}{1000\text{ kg / h}}=\underline{\underline{11.5\text{ kg HNO}_3\text{ / kg H}_2\text{SO}_4}}$$

6.84

$$\left.\begin{array}{l}\underline{\text{Moles of diphenyl (DP):}}\ \dfrac{56.0\text{ g}}{154.2\ \text{ g/mol}}=0.363\text{ mol}\\[2ex] \underline{\text{Moles of benzene (B):}}\ \ \dfrac{550.0\text{ ml}\ \big|\ 0.879\text{ g}\ \big|\ 1\text{ mol}}{\phantom{550.0\text{ ml}}\ \big|\ \text{ml}\ \big|\ 78.11\text{ g}}=6.19\text{ mol}\end{array}\right\}$$

$$\Rightarrow x_{\text{DP}}=\frac{0.363}{6.19+0.363}=0.0544\ \text{ mol DP/mol}$$

$$p_{\text{B}}^{*}(T)=(1-x_{DP})\,p_{\text{B}}^{*}(T)=0.945(120.67\text{ mm Hg})=\underline{\underline{114.0\text{ mm Hg}}}$$

$$\Delta T_{\text{m}}=\frac{RT_{\text{m0}}^{2}}{\Delta\hat{H}_{\text{m}}}x_{\text{DP}}=\frac{8.314(273.2+5.5)^{2}}{9837}(0.0554)=3.6\text{ K}=3.6^{\text{o}}C\ \Rightarrow T_{\text{m}}=5.5-3.6=\underline{\underline{1.9\ ^{\circ}\text{C}}}$$

$$\Delta T_{\text{bp}}=\frac{RT_{\text{b0}}^{2}}{\Delta\hat{H}_{\text{v}}}x_{\text{DP}}=\frac{8.314(273.2+80.1)^{2}}{30{,}765}(0.0554)=1.85\text{ K}=1.85^{\text{o}}\text{ C}$$

$$\Rightarrow T_{\text{b}}=80.1+1.85=\underline{\underline{82.0\ ^{\circ}\text{C}}}$$

6.85

$$T_{m0}=0.0^{\text{o}}\text{C},\ \Delta T_{m}=4.6^{\text{o}}\text{C=4.6K}$$

$$\xrightarrow[\text{Table B.1}]{\text{Eq. 6.5-5}}x_{u}=\frac{\Delta T_{m}\Delta\hat{H}_{m}}{R(T_{m0})^{2}}=\frac{(4.6\text{K})(600.95\text{ J/mol})}{(8.314\text{ J/mol}\cdot\text{K})(273.2\text{K})^{2}}=0.0445\text{ mol urea/mol}$$

$$\text{Eq. (6.5-4)}\ \Rightarrow\ \Delta T_{b}=\frac{RT_{b0}{}^{2}}{\Delta\hat{H}_{v}}x_{u}=\frac{(8.314)(373.2)^{2}}{40,656}0.0445=1.3\text{K}=\underline{\underline{1.3^{\text{o}}\text{C}}}$$

1000 grams of this solution contains m_u (g urea) and (1000 – m_u) (g water)

$$n_{u1}(\text{mol urea})=\frac{m_{u1}(\text{g})}{60.06\text{ g/mol}}\qquad n_{w1}(\text{mol water})=\frac{(1000-m_{u1})(\text{g})}{18.02\text{ g/mol}}$$

$$x_{u1}=0.0445=\frac{\dfrac{m_{u1}}{60.06}(\text{mol urea})}{\left[\dfrac{m_{u1}}{60.06}+\dfrac{(1000-m_{u1})}{18.02}\right](\text{mol solution})}\Rightarrow m_{u1}=134\text{ g urea, }m_{w1}=866\text{ g water}$$

$$\Delta T_{b}=3.0^{\text{o}}\text{C}=3.0\text{K}\Rightarrow x_{u2}=\frac{\Delta T_{b}\Delta\hat{H}_{v}}{R(T_{b0})^{2}}=\frac{(3.0\text{K})(40{,}656\text{ J/mol})}{(8.314\text{ J/mol}\cdot\text{K})(373.2\text{K})^{2}}=0.105\text{ mol urea/mol}$$

$$x_{u2}=0.105=\frac{\dfrac{m_{u2}}{60.06}(\text{mol urea})}{\left[\dfrac{m_{u2}}{60.06}+\dfrac{866}{18.02}\right](\text{mol solution})}\Rightarrow m_{u2}=339\text{ g urea}$$

$\Rightarrow$ Add (339-134) g urea = $\underline{\underline{\text{205 g urea}}}$

6.86 $$x_a^{\mathrm{I}} = \frac{(0.5150\text{ g})/(110.1\text{ g/mol})}{(0.5150\text{ g})/(110.1\text{ g/mol}) + (100.0\text{ g})/(94.10\text{ g/mol})} = 0.00438\text{ mol solute/mol}$$

$$\Delta T_m = \frac{RT_{m0}^2}{\Delta\hat{H}_m} x_s \Rightarrow \frac{\Delta T_m^{\mathrm{I}}}{\Delta T_m^{\mathrm{II}}} = \frac{x_s^{\mathrm{I}}}{x_s^{\mathrm{II}}} \Rightarrow x_s^{\mathrm{II}} = x_s^{\mathrm{I}} \frac{\Delta T_m^{\mathrm{II}}}{\Delta T_m^{\mathrm{I}}} = 0.00438 \frac{0.49^\circ\text{C}}{0.41^\circ\text{C}} = 0.00523 \frac{\text{mol solute}}{\text{mol solution}}$$

$$\Rightarrow \frac{(1-0.00523)\text{ mol solvent}}{0.00523\text{ mol solute}} \left| \frac{94.10\text{ g solvent}}{1\text{ mol solvent}} \right| \frac{0.4460\text{ g solute}}{95.60\text{ g solvent}} = \underline{\underline{83.50\text{ g solute/mol}}}$$

$$\Delta\hat{H}_m = \frac{RT_{m0}^2}{\Delta T_m} x_s = \frac{8.314(273.2-5.00)^2}{0.49}(0.00523) = 6380\text{ J/mol} = \underline{\underline{6.38\text{ kJ / mol}}}$$

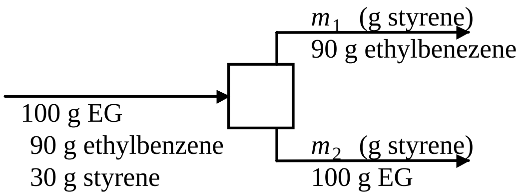
6.87 **a.** $$\ln p_s^*(T_{b0}) = -\frac{\Delta H_v^{\mathrm{I}}}{RT_{b0}} + B \;,\; \ln p_s^*(T_{bs}) = -\frac{\Delta H_v^{\mathrm{II}}}{RT_{bs}} + B$$

Assume $\Delta H_v^{\mathrm{I}} \cong \Delta H_v^{\mathrm{II}}$; $T_0 T_s \cong T_0^2$

$$\Rightarrow \ln P_s^*(T_{b0}) - \ln P_0^*(T_{bs}) = -\frac{\Delta H_v}{R}\left(\frac{1}{T_{b0}} - \frac{1}{T_{bs}}\right) \cong \frac{\Delta H_v}{R} \frac{T_{bs} - T_{b0}}{T_{b0}^2}$$

b. Raoult's Law: $p_s^*(T_{b0}) = (1-x)p_0^*(T_{bs}) \Rightarrow \ln(1-x) \approx -x = -\frac{\Delta H_v \Delta T_b}{RT_{b0}^2} \Rightarrow \underline{\underline{\Delta T_b = \frac{RT_{b0}^2}{\Delta H_v} x}}$

6.88



Styrene balance: $m_1 + m_2 = 30$ g styrene

Equilibrium relation: $$\frac{m_2}{100 + m_2} = 0.19\left(\frac{m_1}{90 + m_1}\right)$$

$$\Downarrow \text{ solve simultaneously}$$

$m_1 = 25.6$ g styrene in ethylbenzene phase

$\underline{\underline{m_2 = 4.4\text{ g styrene in ethylene glycol phase}}}$

6.89 Basis: 100 kg/h. A=oleic acid; C=condensed oil; P=propane

a. 90% extraction: $\dot{m}_3 = (0.09)(0.05)(100 \text{ kg / h}) = 4.5 \text{ kg A / h}$

Balance on oleic acid: $(0.05)(100) = \dot{m}_2 + 4.5 \text{ kg A / h} \Rightarrow \dot{m}_2 = 0.5 \text{ kg A / h}$

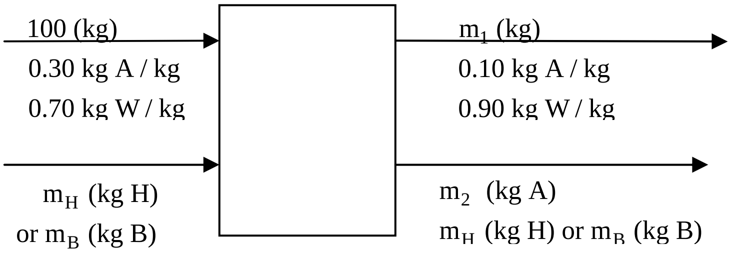
Equilibrium condition: $$0.15 = \frac{0.5 / (\dot{n}_1 + 0.5)}{4.5 / (4.5 + 95)} \Rightarrow \dot{n}_1 = \underline{\underline{73.2 \text{ kg P / h}}}$$

b. Operating pressure must be above the vapor pressure of propane at T=85°C=185°F
Figure 6.1-4 $\Rightarrow$ $p^*_{\text{propane}} = \underline{\underline{500 \text{ psi}}} = \underline{\underline{34 \text{ atm}}}$

c. Other less volatile hydrocarbons cost more and/or impose greater health or environmental hazards.

6.90 **a.** Benzene is the solvent of choice. It holds a greater amount of acetic acid for a given mass fraction of acetic acid in water.

Basis: 100 kg feed. A=Acetic acid, W=H_2O, H=Hexane, B=Benzene



Balance on W: $100 * 0.70 = m_1 * 0.90 \Rightarrow m_1 = 77.8 \text{ kg}$

Balance on A: $100 * 0.30 = m_2 + 77.8 * 0.10 \Rightarrow m_2 = 22.2 \text{ kg}$

Equilibrium for H:

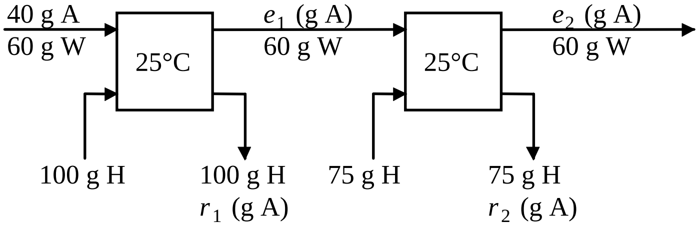
$$K_H = \frac{m_2 / (m_2 + m_H)}{x_A} = \frac{22.2 / (22.2 + m_H)}{0.10} = 0.017 \Rightarrow m_H = \underline{\underline{1.30x10^4 \text{ kg H}}}$$

Equilibrium for B:

$$K_B = \frac{m_2 / (m_2 + m_B)}{x_A} = \frac{22.2 / (22.2 + m_B)}{0.10} = 0.098 \Rightarrow m_B = \underline{\underline{2.20x10^3 \text{ kg B}}}$$

(b) Other factors in picking solvent include cost, solvent volatility, and health, safety, and environmental considerations.

6.91 **a.** Basis: 100 g feed $\Rightarrow$ 40 g acetone, 60 g H_2O. A = acetone, H = $n\text{-}C_6H_{14}$, W = water



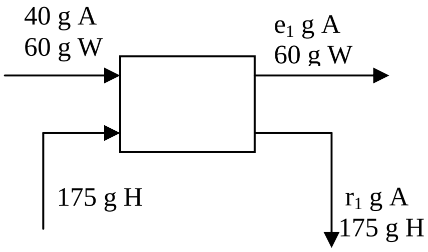
$x_{\text{A in H phase}} / x_{\text{A in W phase}} = 0.343$ (x = mass fraction)

$$\left.\begin{array}{ll}\underline{\text{Balance on A – stage 1:}} & 40 = e_1 + r_1 \\ \underline{\text{Equilibrium condition – stage 1:}} & \dfrac{r_1/(100+r_1)}{e_1/(60+e_1)} = 0.343\end{array}\right\} \Rightarrow \begin{array}{l} e_1 = 27.8 \text{ g acetone} \\ r_1 = 12.2 \text{ g acetone}\end{array}$$

$$\left.\begin{array}{ll}\underline{\text{Balance on A – stage 2:}} & 27.8 = e_2 + r_2 \\ \underline{\text{Equilibrium condition – stage 2:}} & \dfrac{r_2/(75+r_2)}{e_2/(60+e_2)} = 0.343\end{array}\right\} \Rightarrow \begin{array}{l} r_2 = 7.2 \text{ g acetone} \\ e_2 = 20.6 \text{ g acetone}\end{array}$$

$$\underline{\text{\% acetone not extracted}} = \frac{20.6 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{51.5\%}}$$

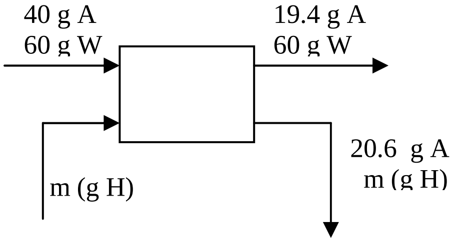
b.



$$\left.\begin{array}{ll}\underline{\text{Balance on A – stage 1:}} & 40.0 = e_1 + r_1 \\ \underline{\text{Equilibrium condition – stage 1:}} & \dfrac{r_1/(175+r_1)}{e_1/(60+e_1)} = 0.343\end{array}\right\} \Rightarrow \begin{array}{l} r_1 = 17.8 \text{ g acetone} \\ e_1 = 22.2 \text{g acetone}\end{array}$$

$$\underline{\text{\% acetone not extracted}} = \frac{22.2 \text{ g A remaining}}{40 \text{ g A fed}} \times 100\% = \underline{\underline{55.5\%}}$$

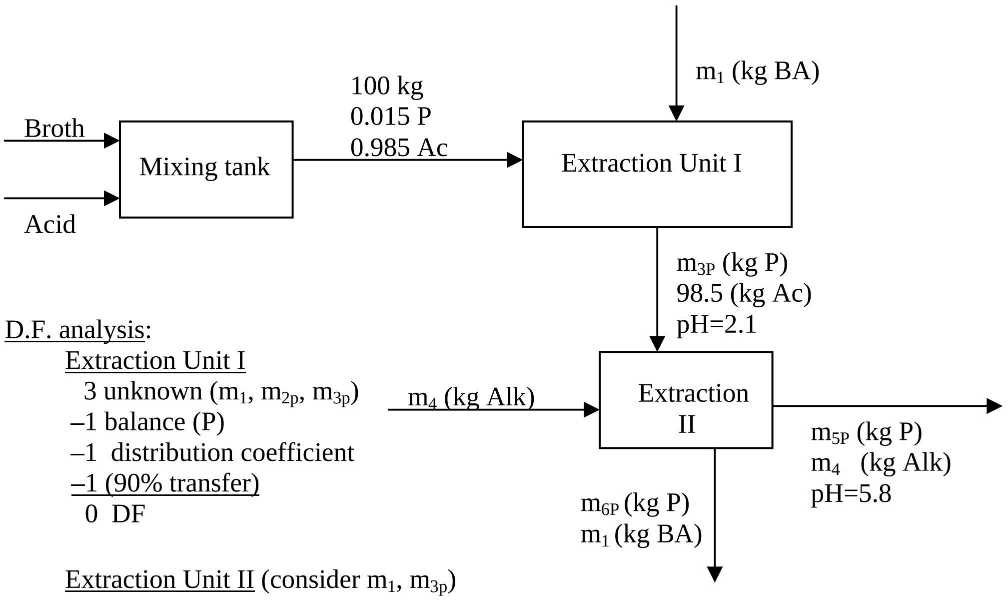
c.



Equilibrium condition: $\dfrac{20.6/(m+20.6)}{19.4/(60+19.4)} = 0.343 \Rightarrow m = \underline{\underline{225 \text{ g hexane}}}$

d. Define a function F=(value of recovered acetone over process lifetime)-(cost of hexane over process lifetime) – (cost of an equilibrium stage x number of stages). The most cost-effective process is the one for which F is the highest.

6.92 **a.** P--penicillin; Ac--acid solution; BA--butyl acetate; Alk--alkaline solution



D.F. analysis:

Extraction Unit I
3 unknown (m_1, m_{2p}, m_{3p})
–1 balance (P)
–1 distribution coefficient
–1 (90% transfer)
0 DF

Extraction Unit II (consider m_1, m_{3p})
3 unknowns
–1 balance (P)
–1 distribution coefficient
–1 (90% transfer)
0 DF

b. In Unit I, 90% transfer $\Rightarrow \ m_{3P} = 0.90(1.5) = 1.35$ kg P

P balance: $1.5 = m_{2P} + 1.35 \Rightarrow m_{2P} = 0.15$ kg P

pH=2.1 $\Rightarrow K = 25.0 = \dfrac{1.35/(1.35+m_1)}{0.15/(0.15+98.5)} \Rightarrow m_1 = 34.16$ kg BA

In Unit II, 90% transfer: $m_{5P} = 0.90(m_{3P}) = 1.215\, kg\ P$

P balance: $m_{3P} = 1.215 + m_{6P} \Rightarrow m_{6P} = 0.135\, kg\ P$

pH=5.8 $\Rightarrow K = 0.10 = \dfrac{m_{6P}\ /(m_{6P} + 34.16)}{1.215/(1.215+m_4)} \Rightarrow m_4 = 29.65$ kg Alk

$$\frac{m_1}{100} = \frac{34.16 \text{ kg BA}}{100 \text{ kg broth}} = \underline{\underline{0.3416 \text{ kg butyl acetate / kg acidified broth}}}$$

$$\frac{m_4}{100} = \frac{29.65 \text{ kg Alk}}{100 \text{ kg broth}} = \underline{\underline{0.2965 \text{ kg alkaline solution / kg acidified broth}}}$$

Mass fraction of P in the product solution:

$$x_P = \frac{m_{5P}}{m_4 + m_{5P}} = \frac{1.215 \text{ P}}{(29.65 + 1.215) \text{ kg}} = \underline{\underline{0.394 \text{ kg P / kg}}}$$

c. (i). The first transfer (low pH) separates most of the P from the other broth constituents, which are not soluble in butyl acetate. The second transfer (high pH) moves the penicillin back into an aqueous phase without the broth impurities.

(ii). Low pH favors transfer to the organic phase, and high pH favors transfer back to the aqueous phase.

(iii). The penicillin always moves from the raffinate solvent to the extract solvent.

6.93 W = water, A = acetone, M = methyl isobutyl ketone

$$\left.\begin{array}{l} x_{\mathrm{W}}=0.20 \\ x_{\mathrm{A}}=0.33 \\ x_{\mathrm{M}}=0.47 \end{array}\right\} \xRightarrow{\textit{Figure } 6.6\text{-}1} \begin{array}{l} \underline{\underline{\text{Phase 1: } x_{\mathrm{W}}=0.07, x_{\mathrm{A}}=0.35, x_{\mathrm{M}}=0.58}} \\ \underline{\underline{\text{Phase 2: } x_{\mathrm{W}}=0.71, x_{\mathrm{A}}=0.25, x_{\mathrm{M}}=0.04}} \end{array}$$

<u>Basis</u>: 1.2 kg of original mixture, m_1=total mass in phase 1, m_2=total mass in phase 2.

$$\left.\begin{array}{ll} \underline{\mathrm{H_2O}\text{ Balance}}: & 1.2*0.20=0.07m_1+0.71m_2 \\ \underline{\text{Acetone balance}}: & 1.2*0.33=0.35m_1+0.25m_2 \end{array}\right. \Rightarrow \left\{\begin{array}{l} m_1=\underline{\underline{0.95\text{ kg in MIBK - rich phase}}} \\ m_2=\underline{\underline{0.24\text{ kg in water - rich phase}}} \end{array}\right.$$

6.94 <u>Basis: Given feeds:</u> A = acetone, W = H_2O, M=MIBK

<u>Overall system composition:</u>

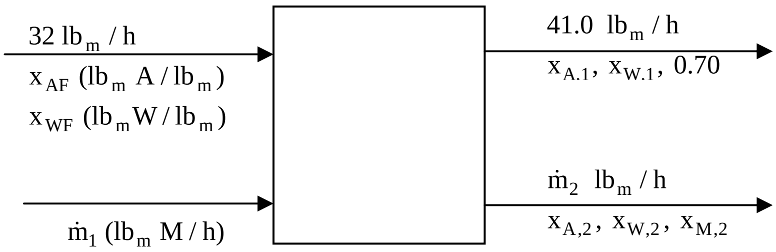
$$\left.\begin{array}{l} 5000\text{ g }(30\text{ wt\% A, }70\text{ wt\% W})\Rightarrow 1500\text{ g A, }3500\text{ g W} \\ 3500\text{ g }(20\text{ wt\% A, }80\text{ wt\% M})\Rightarrow 700\text{ g A, }2800\text{ g M} \end{array}\right\}$$

$$\Rightarrow \left.\begin{array}{l} 2200\text{ g A} \\ 3500\text{ g W} \\ 2800\text{ g M} \end{array}\right\} \Rightarrow 25.9\%\text{ A, }41.2\%\text{ W, }32.9\%\text{ M} \xrightarrow{\text{Fig. 6.6-1}} \begin{array}{l} \underline{\underline{\text{Phase 1: }31\%\text{ A, }63\%\text{ M, }6\%\text{ W}}} \\ \underline{\underline{\text{Phase 2: }21\%\text{ A, }3\%\text{ M, }76\%\text{ W}}} \end{array}$$

Let m_1=total mass in phase 1, m_2=total mass in phase 2.

$$\left.\begin{array}{ll} \underline{\mathrm{H_2O}\text{ Balance}}: & 3500=0.06m_1+0.76m_2 \\ \underline{\text{Acetone balance}}: & 2200=0.31m_1+0.21m_2 \end{array}\right. \Rightarrow \left\{\begin{array}{l} m_1=\underline{\underline{4200\text{ g in MIBK - rich phase}}} \\ m_2=\underline{\underline{4270\text{ g in water - rich phase}}} \end{array}\right.$$

6.95 A=acetone, W = H_2O, M=MIBK



$$\underline{\text{Figure 6.6-1}}\Rightarrow \begin{array}{l} \text{Phase 1: } x_M=0.700\Rightarrow x_{w,1}=0.05;\ x_{A,1}=0.25; \\ \text{Phase 2: } \underline{\underline{x_{w,2}=0.81}};\ \underline{\underline{x_{A,2}=0.81}};\ \underline{\underline{x_{M,2}=0.03}} \end{array}$$

$$\left.\begin{array}{ll} \underline{\text{Overall mass balance}}: & 32.0\text{ lb}_m/\text{h}+\dot{m}_1=41.0\text{ lb}_m/\text{h}+\dot{m}_2 \\ \underline{\text{MIBK balance}}: & \dot{m}_1=41.0*0.7+\dot{m}_2*0.03 \end{array}\right\} \Rightarrow \begin{array}{l} \dot{m}_1=\underline{\underline{28.1\text{ lb}_m\text{ MIBK / h}}} \\ \dot{m}_2=\underline{\underline{19.1\text{ lb}_m/\text{h}}} \end{array}$$

6.96 a. Basis: 100 kg; A=acetone, W=water, M=MIBK

System 1: $\underline{\underline{x_{\text{a,org}} = 0.375 \text{ mol A}, \; x_{\text{m,org}} = 0.550 \text{ mol M}, \; x_{\text{w,org}} = 0.075 \text{ mol W}}}$

$\underline{\underline{x_{\text{a,aq}} = 0.275 \text{ mol A}, \; x_{\text{m,aq}} = 0.050 \text{ mol M}, \; x_{\text{w,aq}} = 0.675 \text{ mol W}}}$

$$\left.\begin{array}{ll} \text{Mass balance:} & m_{aq,1} + m_{org,1} = 100 \\ \text{Acetone balance:} & m_{aq,1} * 0.275 + m_{org,1} * 0.375 = 33.33 \end{array}\right\} \Rightarrow \begin{array}{l} m_{\text{aq},1} = \underline{\underline{41.7 \text{ kg}}} \\ m_{org,1} = \underline{\underline{58.3 \text{ kg}}} \end{array}$$

System 2: $\underline{\underline{x_{\text{a,org}} = 0.100 \text{ mol A}, \; x_{\text{m,org}} = 0.870 \text{ mol M}, \; x_{\text{w,org}} = 0.030 \text{ mol W}}}$

$\underline{\underline{x_{\text{a,aq}} = 0.055 \text{ mol A}, \; x_{\text{m,aq}} = 0.020 \text{ mol M}, \; x_{\text{w,aq}} = 0.925 \text{ mol W}}}$

$$\left.\begin{array}{ll} \text{Mass balance:} & m_{aq,2} + m_{org,2} = 100 \\ \text{Acetone balance:} & m_{aq,2} * 0.055 + m_{org,2} * 0.100 = 9 \end{array}\right\} \Rightarrow \begin{array}{l} \text{m}_{\text{aq},2} = \underline{\underline{22.2 \text{ kg}}} \\ m_{\text{org},2} = \underline{\underline{77.8 \text{ kg}}} \end{array}$$

b. $K_{a,1} = \dfrac{x_{a,org,1}}{x_{a,aq,1}} = \dfrac{0.375}{0.275} = \underline{\underline{1.36}};\qquad K_{a,2} = \dfrac{x_{a,org,2}}{x_{a,aq,2}} = \dfrac{0.100}{0.055} = \underline{\underline{1.82}}$

High K_a to extract acetone from water into MIBK; low K_a to extract acetone from MIBK into water.

c. $\beta_{aw,1} = \dfrac{x_{a,org} / x_{w,org}}{x_{a,aq} / x_{w,aq}} = \dfrac{0.375/0.075}{0.275/0.675} = \underline{\underline{12.3}};\quad \beta_{aw,2} = \dfrac{0.100/0.040}{0.055/0.920} = \underline{\underline{41.8}}$

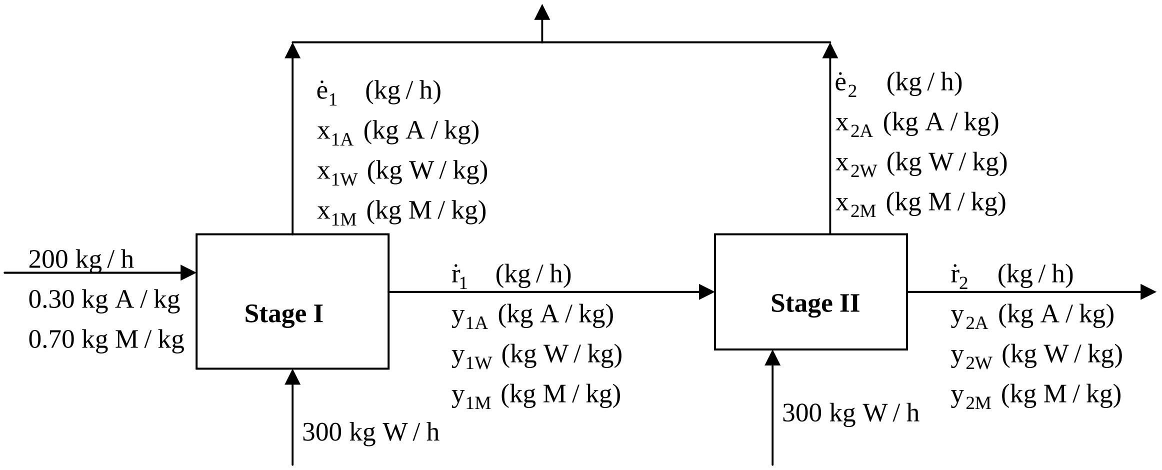
If water and MIBK were immiscible, $x_{w,org} = 0 \Rightarrow \underline{\underline{\beta_{aw} \to \infty}}$

d. Organic phase= extract phase; aqueous phase= raffinate phase

$$\beta_{a,w} = \frac{(x_a / x_w)_{org}}{(x_a / x_w)_{aq}} = \frac{(x_a)_{org} / (x_a)_{aq}}{(x_w)_{org} / (x_w)_{aq}} = \frac{K_a}{K_w}$$

When it is critically important for the raffinate to be as pure (acetone-free) as possible.

6.97 Basis: Given feed rates: A = acetone, W = water, M=MIBK



6.97(cont'd)

Overall composition of feed to Stage 1:

$$\left.\begin{aligned}(200)(0.30) &= 60\ \text{kg A/h}\\ 200-60 &= 140\ \text{kg M/h}\\ 300\ \text{kg W/h}\end{aligned}\right\}\Rightarrow \begin{array}{l}500\ \text{kg/h}\\ 12\%\ \text{A},\ 28\%\ \text{M},\ 60\%\ \text{W}\end{array}$$

$$\underline{\text{Figure 6.6-1}} \Rightarrow \begin{array}{l}\underline{\text{Extract:}}\ x_{1\text{A}}=0.095,\ x_{1\text{W}}=0.880,\ x_{1\text{M}}=0.025\\ \underline{\text{Raffinate:}}\ y_{1\text{A}}=0.15,\ y_{1\text{W}}=0.035,\ y_{1\text{M}}=0.815\end{array}$$

$$\begin{array}{ll}\underline{\text{Mass balance}} & 500=\dot{e}_1+\dot{r}_1\\ \underline{\text{Acetone balance}}: & 60=0.095\dot{e}_1+0.15\dot{r}_1\end{array}\Rightarrow\begin{cases}\dot{e}_1=\underline{\underline{273\ \text{kg / h}}}\\ \dot{r}_1=\underline{\underline{227\ \text{kg / h}}}\end{cases}$$

Overall composition of feed to Stage 2:

$$\left.\begin{aligned}(227)(0.15) &= 34\ \text{kg A/h}\\ (227)(0.815) &= 185\ \text{kg M/h}\\ (227)(0.035)+300 &= 308\ \text{kg W/h}\end{aligned}\right\}\Rightarrow \begin{array}{l}527\ \text{kg/h}\\ 6.5\%\ \text{A},\ 35.1\%\ \text{MIBK},\ 58.4\%\ \text{W}\end{array}$$

$$\underline{\text{Figure 6.6-1}} \Rightarrow \begin{array}{l}\underline{\text{Extract:}}\ x_{2\text{A}}=0.04,\ x_{2\text{W}}=0.94,\ x_{2\text{M}}=0.02\\ \underline{\text{Raffinate:}}\ y_{2\text{A}}=0.085,\ y_{2\text{W}}=0.025,\ y_{2\text{M}}=0.89\end{array}$$

$$\begin{array}{ll}\underline{\text{Mass balance:}} & 527=\dot{e}_2+\dot{r}_2\\ \underline{\text{Acetone balance}}: & 34=0.04e_2+0.085r_2\end{array}\Rightarrow\begin{cases}\dot{e}_2=\underline{\underline{240\ \text{kg / h}}}\\ \dot{r}_2=\underline{\underline{287\ \text{kg / h}}}\end{cases}$$

Acetone removed:

$$\frac{[60-(0.085)(287)]\ \text{kg A removed / h}}{60\ \text{kg A / h in feed}}=\underline{\underline{0.59\ \text{kg acetone removed / kg fed}}}$$

Combined extract:

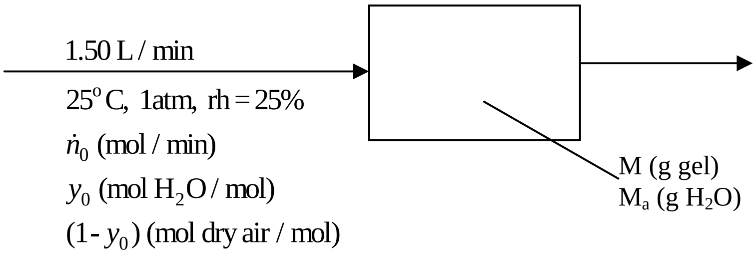
$$\underline{\text{Overall flow rate}}=\dot{e}_1+\dot{e}_2=273+240=513\ \text{kg / h}$$

$$\underline{\text{Acetone:}}\ \frac{(x_{1A}\dot{e}_1+x_{2A}\dot{e}_2)\ \text{kg A}}{}=\frac{0.095*273+0.04*240}{513}=\underline{\underline{0.069\ \text{kg A / kg}}}$$

$$\underline{\text{Water}}:\ \frac{(x_{1w}\dot{e}_1+x_{2w}\dot{e}_2)\ \text{kg W}}{\dot{e}_1+\dot{e}_2}=\frac{0.88*273+0.94*240}{513}=\underline{\underline{0.908\ \text{kg W / kg}}}$$

$$\underline{\text{MIBK}}:\ \frac{(x_{1M}\dot{e}_1+x_{2M}\dot{e}_2)\ \text{kg M}}{(\dot{e}_1+\dot{e}_2)\text{kg}}=\frac{0.025*273+0.02*240}{513}=\underline{\underline{0.023\ \text{kg M / kg}}}$$

6.98. a.



$$\dot{n}_0=\frac{P\dot{V}}{RT}=\frac{(1\ \mathrm{atm})(1.50\ \mathrm{L/min})}{(0.08206\ \mathrm{L\cdot atm/mol\cdot K})(298\ \mathrm{K})}=0.06134\ \mathrm{mol/min}$$

$$\underline{\text{r.h.}=25\%}\Rightarrow\ \frac{p_{\mathrm{H_2O}}}{p^*_{\mathrm{H_2O}}(25^{\mathrm{o}}\mathrm{C})}=0.25$$

<u>Silica gel saturation condition</u>: $X^*=12.5\dfrac{p_{\mathrm{H_2O}}}{p^*_{\mathrm{H_2O}}}=12.5*0.25=3.125\dfrac{\mathrm{g\ H_2O\ ads}}{100\ \mathrm{g\ silica\ gel}}$

<u>Water feed rate</u>: $y_0=\dfrac{0.25p^*_{\mathrm{H_2O}}(25^{o}C)}{p}=\dfrac{0.25(23.756\ \mathrm{mm\ Hg})}{760\ \mathrm{mm\ Hg}}=0.00781\dfrac{\mathrm{mol\ H_2O}}{\mathrm{mol}}$

$$\Rightarrow\ \dot{m}_{\mathrm{H_2O}}=\frac{0.06134\ \mathrm{mol}}{\mathrm{min}}\left|\frac{0.00781\ \mathrm{mol\ H_2O}}{\mathrm{mol}}\right|\frac{18.01\ \mathrm{g\ H_2O}}{\mathrm{mol\ H_2O}}=0.00863\ \ \mathrm{g\ H_2O/min}$$

<u>Adsorption in 2 hours</u> $=(0.00863\ \ \mathrm{g\ H_2O/min})(120\mathrm{min})=1.035\ \ \mathrm{g\ H_2O}$

<u>Saturation condition</u>: $\dfrac{1.035\ \mathrm{g\ H_2O}}{M\ (\mathrm{g\ silica\ gel})}=\dfrac{3.125\ \mathrm{g\ H_2O}}{100\ \mathrm{g\ silica\ gel}}\Rightarrow M=\underline{\underline{33.1\ \mathrm{g\ silica\ gel}}}$

Assume that all entering water vapor is adsorbed throughout the 2 hours and that P and T are constant.

b. Humid air is dehumidified by being passed through a column of silica gel, which absorbs a significant fraction of the water in the entering air and relatively little oxygen and nitrogen. The capacity of the gel to absorb water, while large, is not infinite, and eventually the gel reaches its capacity. If air were still fed to the column past this point, no further dehumidification would take place. To keep this situation from occurring, the gel is replaced at or (preferably) before the time when it becomes saturated.

6.99 a. Let c = CCl_4

$$\underline{\text{Relative saturation}=0.30}\Rightarrow\frac{p_{\mathrm{c}}}{p^*_{\mathrm{c}}(34^{\mathrm{o}}\mathrm{C})}\Rightarrow p_c=0.30*(169\ \mathrm{mm\ Hg})=\underline{\underline{50.7\ \mathrm{mm\ Hg}}}$$

b. <u>Initial moles of gas in tank</u>:

$$n_0=\frac{P_0V_0}{RT_0}=\frac{1\ \mathrm{atm}}{0.08206\ \mathrm{L\cdot atm/mol\cdot K}}\left|\frac{50.0\ \mathrm{L}}{307\ \mathrm{K}}\right.=1.985\ \mathrm{mol}$$

<u>Initial moles of CCl_4 in tank</u>:

$$n_{c0}=y_{c0}n_0=\frac{p_{c0}}{P_0}n_0=\frac{50.7\ \mathrm{mm\ Hg}}{760\ \mathrm{mm\ Hg}}\times1.985\ \mathrm{mol}=0.1324\ \mathrm{mol\ CCl_4}$$

6.99 (cont'd)

<u>50% CCl$_4$ adsorbed</u> $\Rightarrow n_c = 0.500 n_{c0} = 0662 \text{ mol CCl}_4$ (= n_{ads})

<u>Total moles in tank</u>: $n_{\text{tot}} = n_0 - n_{\text{ads}} = (1.985 - 0.0662)\text{ mol} = 1.919\text{ mol}$

<u>Pressure in tank</u>. Assume $T = T_0$ and $V = V_0$.

$$P = \frac{n_{\text{tot}} R T_0}{V_0} = \left(\frac{(1.919)(0.08206)(307)}{50.0}\text{ atm}\right)\left(\frac{760\text{ mm Hg}}{\text{atm}}\right) = \underline{\underline{735\text{ mm Hg}}}$$

$$y_C = \frac{n_c}{n_{\text{tot}}} = \frac{0.0662\text{ mol CCl}_4}{1.919\text{ mol}} = 0.0345\ \frac{\text{mol CCl}_4}{\text{mol}}$$

$$\Rightarrow p_c = 0.0345(760\text{ mm Hg}) = \underline{\underline{26.2\text{ mm Hg}}}$$

c. <u>Moles of air in tank</u>: $n_a = n_0 - n_{c0} = (1.985 - 0.1324)\text{ mol air} = 1.853\text{ mol air}$

$$y_c = \frac{n_c}{n_c + 1.853} = 0.001\ \frac{\text{mol CCl}_4}{\text{mol}} \Rightarrow n_c = 1.854 \times 10^{-3}\text{ mol CCl}_4$$

$$\Rightarrow n_{\text{tot}} = n_c + n_{\text{air}} = 1.854\text{ mol}$$

$$p_c = y_c P = 0.001\left[\frac{n_{tot} R T_0}{V_0}\right] = \begin{array}{c|r|c|c} 1.854 \times 10^{-3}\text{ mol} & 0.08206\text{ L}\cdot\text{atm} & 307\text{ K} & 760\text{ mm} \\ \hline 50.0\text{ L} & \text{mol}\cdot\text{K} & & 1\text{ atm} \end{array}$$

$$= 0.710\text{ mm Hg}$$

$$X^*\left(\frac{\text{g CCl}_4}{\text{g carbon}}\right) = \frac{0.0762 p_c}{1 + 0.096 p_c} \Rightarrow X^* = \frac{0.0762(0.710)}{1 + 0.096(0.710)} = 0.0506\frac{\text{g CCl}_4\text{ adsorbed}}{\text{g carbon}}$$

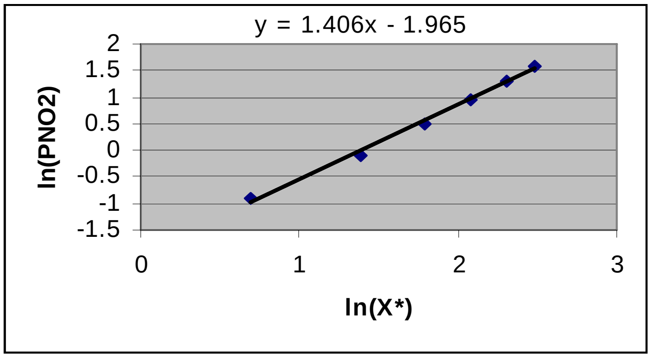
<u>Mass of CCl$_4$ adsorbed</u>

$$m_{\text{ads}} = (n_{c0} - n_c)(MW)_c = \begin{array}{c|c} (0.1324 - 0.001854)\text{ mol CCl}_4 & 153.85\text{ g} \\ \hline & 1\text{ mol CCl}_4 \end{array}$$

$$= 20.3\text{ mol CCl}_4\text{ adsorbed}$$

<u>Mass of carbon required</u>: $m_c = \dfrac{20.3\text{ g CCl}_4\text{ ads}}{0.0506\ \dfrac{\text{g CCl}_4\text{ ads}}{\text{g carbon}}} = \underline{\underline{400\text{ g carbon}}}$

6.100 **a.** $X^* = K_F p_{NO_2}^{\beta} \Rightarrow \ln X^* = \ln K_F + \beta \ln p_{NO_2}^{\beta}$



6.100 (cont'd)

$$\ln X^* = 1.406 \ln p_{NO_2} - 1.965 \Rightarrow X^* = e^{-1.965} p_{NO_2}^{1.406} = 0.140 p_{NO_2}^{1.406}$$

$$\underline{\underline{K_F = 0.140 \text{ (kg NO}_2 \text{ / 100 kg gel)(mm Hg)}^{-1.406}}}; \quad \underline{\underline{\beta = 1.406}}$$

b. Mass of silica gel : $m_g = \dfrac{\pi * (0.05\,\text{m})^2 (1\,\text{m})}{} \left| \dfrac{10^3\ \text{L}}{1\,\text{m}^3} \right| \dfrac{0.75\,\text{kg gel}}{\text{L}} = 5.89\ \text{kg gel}$

Maximum NO_2 adsorbed :

$$p_{\text{NO}_2} \text{ in feed} = 0.010(760 \text{ mm Hg}) = 7.60 \text{ mm Hg}$$

$$m_{ads} = \frac{0.140(7.60)^{1.406}\ \text{kg NO}_2}{100\ \text{kg gel}} \left| \frac{5.89\ \text{kg gel}}{} \right. = 0.143\ \text{kg NO}_2$$

Average molecular weight of feed :

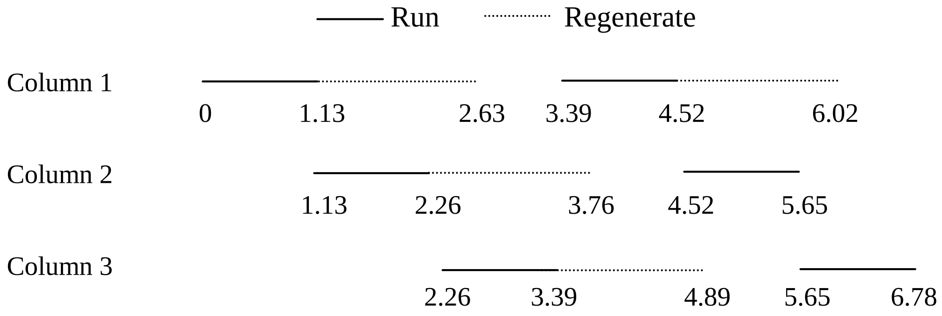
$$\overline{MW} = 0.01(MW)_{NO_2} + 0.99(MW)_{air} = (0.01)(46.01) + (0.99)(29.0) = 29.17 \frac{\text{kg}}{\text{kmol}}$$

Mass feed rate of NO_2:

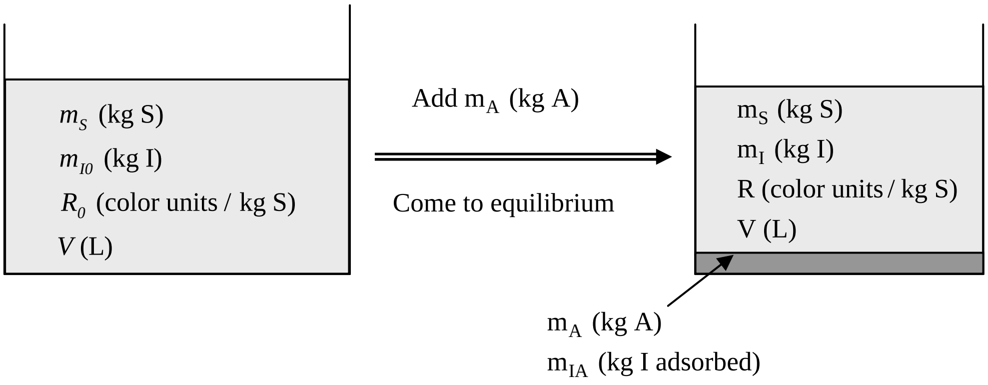
$$\dot{m} = \frac{8.00\ \text{kg}}{\text{h}} \left| \frac{1\ \text{kmol}}{29.17\ \text{kg}} \right| \frac{0.01\ \text{kmol NO}_2}{\text{kmol}} \left| \frac{46.01\ \text{kg NO}_2}{\text{kmol NO}_2} \right. = 0.126 \frac{\text{kg NO}_2}{\text{h}}$$

Breakthrough time: $t_b = \dfrac{0.143\ \text{kg NO}_2}{0.126\ \text{kg NO}_2\ /\ \text{h}} = 1.13\ \text{h} = \underline{\underline{68\ \text{min}}}$

c. The first column would start at time 0 and finish at 1.13 h, and would not be available for another run until (1.13+1.50) = 2.63 h. The second column could start at 1.13 h and finish at 2.26 h. Since the first column would still be in the regeneration stage, a third column would be needed to start at 2.26 h. It would run until 3.39 h, at which time the first column would be available for another run. The first few cycles are shown below on a Gantt chart.



6.101 Let S=sucrose, I=trace impurities, A=activated carbon



<u>Assume</u>
- no sucrose is adsorbed
- solution volume (V) is not affected by addition of the carbon

a. $$\text{R(color units/kg S)} = kC_i \text{ (kg I / L)} = k\frac{m_I}{V} \qquad (1)$$

$$\Rightarrow \Delta R = k(C_{i0} - C_i) = \frac{k}{V}(m_{I0} - m_I) \xrightarrow{m_{IA}=m_{I0}-m_I} \Delta R = \frac{km_{IA}}{V} \qquad (2)$$

$$\underline{\text{% removal of color}} = \frac{\Delta R}{R_0} x100\% = \frac{km_{IA}/V}{km_{I0}/V} x100 = 100\frac{m_{IA}}{m_{I0}} \qquad (3)$$

$$\underline{\text{Equilibrium adsorption ratio}}: \quad X_i^* = \frac{m_{IA}}{m_A} \qquad (4)$$

<u>Normalized percentage color removal</u>:

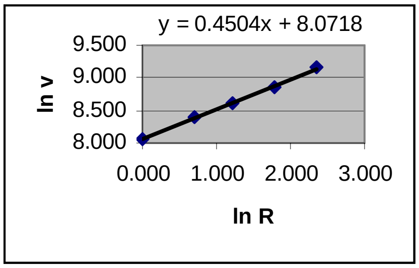
$$\upsilon = \frac{\text{% removal}}{m_A / m_S} \overset{(3)}{=} \frac{100 \text{ m}_{IA} / m_{I0}}{m_A / m_S} = 100\frac{m_{IA}}{m_A}\frac{m_S}{m_{I0}}$$

$$\Rightarrow \upsilon = 100\text{X}_i^* \frac{m_S}{m_{I0}} \Rightarrow X_i^* = \frac{m_{I0}}{100m_S}\upsilon \qquad (5)$$

$$\underline{\text{Freundlich isotherm}} \quad X_i^* = K_F C_i^{\beta} \quad \overset{(1),(5)}{\Longrightarrow} \quad \frac{m_{I0}}{100m_S}\upsilon = K_F(\frac{R}{k})^{\beta}$$

$$\Rightarrow \underline{\underline{\upsilon = \frac{100m_S K_F}{m_{I0}k^{\beta}} R^{\beta} = K_F^{'} R^{\beta}}}$$

A plot of $\ln \upsilon$ vs. $\ln R$ should be linear: slope = β; intercept = $\ln K_F^{'}$



6.101 (cont'd)

$$\ln \upsilon = 0.4504 \ln p_{NO_2} + 8.0718 \Rightarrow \upsilon = e^{8.0718} R^{0.4504} = 3203 R^{0.4504}$$

$$\Rightarrow K_F^{'} = \underline{\underline{3203}}, \quad \beta = \underline{\underline{0.4504}}$$

b. <u>100 kg 48% sucrose solution</u> ⇒ $m_S = 480$ kg

<u>95% reduction in color</u> ⇒ R = 0.025(20.0) = 0.50 color units / kg sucrose

$$\upsilon = K_F^{'} R^{\beta} = 3203(0.50)^{0.4504} = 2344$$

$$\Rightarrow \quad 2344 = \frac{\text{\% color reduction}}{m_A / m_S} = \frac{97.5}{m_A / 480} \Rightarrow \quad m_A = \underline{\underline{20.0 \text{ kg carbon}}}$$

CHAPTER SEVEN

7.1 $$\begin{array}{c|c|c|c|c} 0.80\text{ L} & 3.5\times10^4\text{ kJ} & 0.30\text{ kJ work} & 1\text{ h} & 1\text{ kW} \\ \hline \text{h} & \text{L} & 1\text{ kJ heat} & 3600\text{ s} & 1\text{ kJ/s} \end{array} = 2.33\text{ kW} \Rightarrow \underline{\underline{2.3\text{ kW}}}$$

$$\begin{array}{c|c|c} 2.33\text{ kW} & 10^3\text{ W} & 1.341\times10^{-3}\text{ hp} \\ \hline & 1\text{ kW} & 1\text{ W} \end{array} = 3.12\text{ hp} \Rightarrow \underline{\underline{3.1\text{ hp}}}$$

7.2 All kinetic energy dissipated by friction

(a) $E_k = \dfrac{mu^2}{2}$

$$= \begin{array}{c|c|c|c|c|c} 5500\text{ lb}_\text{m} & 55^2\text{ miles}^2 & 5280^2\text{ ft}^2 & 1^2\quad\text{h}^2 & 1\text{ lb}_\text{f} & 9.486\times10^{-4}\text{ Btu} \\ \hline 2 & \text{h}^2 & 1^2\text{ mile}^2 & 3600^2\text{ s}^2 & 32.174\text{ lb}_\text{m}\cdot\text{ft/s}^2 & 0.7376\text{ ft}\cdot\text{lb}_\text{f} \end{array}$$

$= \underline{\underline{715\text{ Btu}}}$

(b)

$$\begin{array}{c|c|c|c|c|c} 3\times10^8\text{ brakings} & 715\text{ Btu} & 1\text{ day} & 1\text{ h} & 1\text{ W} & 1\text{ MW} \\ \hline \text{day} & \text{braking} & 24\text{ h} & 3600\text{ s} & 9.486\times10^{-4}\text{ Btu/s} & 10^6\text{W} \end{array} = 2617\text{ MW}$$

$\Rightarrow \underline{\underline{3000\text{ MW}}}$

7.3 **(a)** Emissions:

Paper $\Rightarrow \begin{array}{c|c|c} 1000\text{ sacks} & (0.0510+0.0516)\text{ oz} & 1\text{ lb}_\text{m} \\ \hline & \text{sack} & 16\text{ oz} \end{array} = \underline{\underline{6.41\text{ lb}_\text{m}}}$

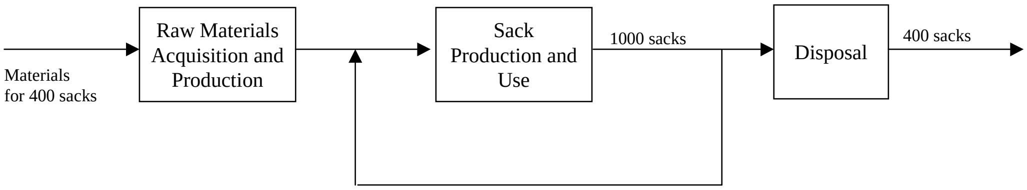
Plastic $\Rightarrow \begin{array}{c|c|c} 2000\text{ sacks} & (0.0045+0.0146)\text{ oz} & 1\text{ lb}_\text{m} \\ \hline & \text{sack} & 16\text{ oz} \end{array} = \underline{\underline{2.39\text{ lb}_\text{m}}}$

Energy:

Paper $\Rightarrow \begin{array}{c|c} 1000\text{ sacks} & (724+905)\text{ Btu} \\ \hline & \text{sack} \end{array} = \underline{\underline{1.63\times10^6\text{ Btu}}}$

Plastic $\Rightarrow \begin{array}{c|c} 2000\text{ sacks} & (185+464)\text{ Btu} \\ \hline & \text{sack} \end{array} = \underline{\underline{1.30\times10^6\text{ Btu}}}$

(b) For paper (double for plastic)



7.3 (cont'd)

Emissions:

$$\text{Paper} \Rightarrow \begin{array}{c|c|c} 400\text{ sacks} & 0.0510\text{ oz} & 1\text{ lb}_\text{m} \\ \hline & \text{sack} & 16\text{ oz} \end{array} + \begin{array}{c|c|c} 1000\text{ sacks} & 0.0516\text{ oz} & 1\text{ lb}_\text{m} \\ \hline & \text{sack} & 16\text{ oz} \end{array} = \underline{\underline{4.5\text{ lb}_\text{m}}}$$

$$\Rightarrow \underline{\underline{30\%\text{ reduction}}}$$

$$\text{Plastic} \Rightarrow \begin{array}{c|c|c} 800\text{ sacks} & 0.0045\text{ oz} & 1\text{ lb}_\text{m} \\ \hline & \text{sack} & 16\text{ oz} \end{array} + \begin{array}{c|c|c} 2000\text{ sacks} & 0.0146\text{ oz} & 1\text{ lb}_\text{m} \\ \hline & \text{sack} & 16\text{ oz} \end{array} = \underline{\underline{2.05\text{ lb}_\text{m}}}$$

$$\Rightarrow \underline{\underline{14\%\text{ reduction}}}$$

Energy:

$$\text{Paper} \Rightarrow \begin{array}{c|c} 400\text{ sacks} & 724\text{ Btu} \\ \hline & \text{sack} \end{array} + \begin{array}{c|c} 1000\text{ sacks} & 905\text{ Btu} \\ \hline & \text{sack} \end{array} = \underline{\underline{1.19 \times 10^6\text{ Btu; } 27\%\text{ reduction}}}$$

$$\text{Plastic} \Rightarrow \begin{array}{c|c} 800\text{ sacks} & 185\text{ Btu} \\ \hline & \text{sack} \end{array} + \begin{array}{c|c} 2000\text{ sacks} & 464\text{ Btu} \\ \hline & \text{sack} \end{array} = \underline{\underline{1.08 \times 10^6\text{ Btu; } 17\%\text{ reduction}}}$$

(c)
$$. \begin{array}{c|c|c|c|c|c|c} 3 \times 10^8\text{ persons} & 1\text{ sack} & 1\text{ day} & 1\text{ h} & 649\text{ Btu} & 1\text{ J} & 1\text{ MW} \\ \hline & \text{person-day} & 24\text{ h} & 3600\text{ s} & 1\text{ sack} & 9.486 \times 10^{-4}\text{ Btu} & 10^6\text{ J/s} \end{array}$$

$$= \underline{\underline{2{,}375\text{ MW}}}$$

Savings for recycling: $0.17(2{,}375\text{ MW}) = \underline{\underline{404\text{ MW}}}$

(d) Cost, toxicity, biodegradability, depletion of nonrenewable resources.

7.4 **(a)** Mass flow rate:
$$\dot{m} = \begin{array}{c|c|c|c} 3.00\text{ gal} & 1\text{ ft}^3 & (0.792)(62.43)\text{ lb}_\text{m} & 1\text{ min} \\ \hline \text{min} & 7.4805\text{ gal} & 1\text{ ft}^3 & 60\text{ s} \end{array} = 0.330\text{ lb}_\text{m}/\text{s}$$

Stream velocity:
$$u = \begin{array}{c|c|c|c|c} 3.00\text{ gal} & 1728\text{ in}^3 & 1 & 1\text{ ft} & 1\text{ min} \\ \hline \text{min} & 7.4805\text{ gal} & \Pi(0.5)^2\text{ in}^2 & 12\text{ in} & 60\text{ s} \end{array} = 1.225\text{ ft/s}$$

Kinetic energy:
$$E_k = \frac{mu^2}{2} = \begin{array}{c|c|c|c} 0.330\text{ lb}_\text{m} & (1.225)^2\text{ ft}^2 & 1 & 1 \qquad \text{lb}_\text{f} \\ \hline \text{s} & \text{s}^2 & 2 & 32.174\text{ lb}_\text{m} \cdot \text{ft/s}^2 \end{array} = \underline{\underline{7.70 \times 10^{-3}\,\frac{\text{ft} \cdot \text{lb}_\text{f}}{\text{s}}}}$$

$$= \left(7.70 \times 10^{-3}\text{ ft} \cdot \text{lb}_\text{f}\text{ / s}\right)\left(\frac{1.341 \times 10^{-3}\text{ hp}}{0.7376\text{ ft} \cdot \text{lb}_\text{f}\text{ / s}}\right) = \underline{\underline{1.40 \times 10^{-5}\text{ hp}}}$$

(b) Heat losses in electrical circuits, friction in pump bearings.

7.5 **(a)** Mass flow rate:

$$\dot{m}=\begin{array}{c|c|c|c|c|c|c} 42.0\text{ m} & \pi(0.07\text{ m})^2 & 10^3\text{ L} & 273\text{ K} & 130\text{ kPa} & 1\text{ mol} & 29\text{ g} \\ \hline \text{s} & 4 & 1\text{ m}^3 & 573\text{ K} & 101.3\text{ kPa} & 22.4\text{ L}\ (\text{STP}) & \text{mol} \end{array}=127.9\ \text{g/s}$$

$$\dot{E}_k=\frac{\dot{m}u^2}{2}=\begin{array}{c|c|c|c|c} 127.9\text{ g} & 1\text{ kg} & 42.0^2\text{ m}^2 & 1\text{ N} & 1\text{ J} \\ \hline 2\quad\text{s} & 1000\text{ g} & \text{s}^2 & 1\text{ kg}\cdot\text{m/s}^2 & \text{N}\cdot\text{m} \end{array}=\underline{\underline{113\ \text{J/s}}}$$

(b)

$$\begin{array}{c|c|c|c|c|c|c} 127.9\text{ g} & 1\text{ mol} & 673\text{ K} & 101.3\text{ kPa} & 22.4\text{ L}\ (\text{STP}) & 1\text{ m}^3 & 4 \\ \hline \text{s} & 29\text{ g} & 273\text{ K} & 130\text{ kPa} & 1\text{ mol} & 10^3\text{ L} & \pi(0.07)^2\text{ m}^2 \end{array}=49.32\ \text{m/s}$$

$$\dot{E}_k=\frac{\dot{m}u^2}{2}=\begin{array}{c|c|c|c|c} 127.9\text{ g} & 1\text{ kg} & 49.32^2\text{ m}^2 & 1\text{ N} & 1\text{ J} \\ \hline 2\quad\text{s} & 1000\text{ g} & \text{s}^2 & 1\text{ kg}\cdot\text{m/s}^2 & \text{N}\cdot\text{m} \end{array}=155.8\ \text{J/s}$$

$$\Delta\dot{E}_k=\dot{E}_k(400\,^\circ\text{C})-\dot{E}_k(300\,^\circ\text{C})=(155.8-113)\ \text{J/s}=42.8\ \text{J/s}\Rightarrow\underline{\underline{43\ \text{J/s}}}$$

(c) Some of the heat added goes to raise *T* (and hence *U*) of the air

7.6 **(a)**

$$\Delta E_p=mg\Delta z=\begin{array}{c|c|c|c|c|c} 1\text{ gal} & 1\text{ ft}^3 & 62.43\text{ lb}_\text{m} & 32.174\text{ ft} & -10\text{ ft} & 1\text{ lb}_\text{f} \\ \hline & 7.4805\text{ gal} & 1\text{ ft}^3 & \text{s}^2 & & 32.174\text{ lb}_\text{m}\cdot\text{ft/s}^2 \end{array}=\underline{\underline{-83.4\ \text{ft}\cdot\text{lb}_\text{f}}}$$

(b) $E_k=-\Delta E_p\Rightarrow\dfrac{mu^2}{2}=mg(-\Delta z)\Rightarrow u=\left[2g(-\Delta z)\right]^{1/2}=\left[2\left(32.174\dfrac{\text{ft}}{\text{s}^2}\right)(10\text{ ft})\right]^{1/2}=\underline{\underline{25.4\dfrac{\text{ft}}{\text{s}}}}$

(c) $\underline{\underline{\text{False}}}$

7.7 **(a)** $\underline{\underline{\Delta\dot{E}_k\Rightarrow\textit{positive}}}$ When the pressure decreases, the volumetric flow rate increases, and hence the velocity increases.

$\underline{\underline{\Delta\dot{E}_p\Rightarrow\textit{negative}}}$ The gas exits at a level below the entrance level.

(b)

$$\dot{m}=\begin{array}{c|c|c|c|c|c|c} 5\text{ m} & \pi(1.5)^2\text{ cm}^2 & 1\text{ m}^3 & 273\text{ K} & 10\text{ bars} & 1\text{ kmol} & 16.0\text{ kg CH}_4 \\ \hline \text{s} & & 10^4\text{ cm}^2 & 303\text{ K} & 1.01325\text{ bars} & 22.4\text{ m}^3\ (\text{STP}) & 1\text{ kmol} \end{array}$$

$$=0.0225\ \text{kg/s}$$

$$\frac{P_\text{out}\dot{V}_\text{out}}{P_\text{in}\dot{V}_\text{in}}=\frac{\dot{n}RT}{\dot{n}RT}\Rightarrow\frac{\dot{V}_\text{out}}{\dot{V}_\text{in}}=\frac{P_\text{in}}{P_\text{out}}\Rightarrow\frac{u_\text{out}\,(\text{m/s})\cdot\text{A}(\text{m}^2)}{u_\text{in}\,(\text{m/s})\cdot\text{A}(\text{m}^2)}=\frac{P_\text{in}}{P_\text{out}}$$

$$\Rightarrow\ u_\text{out}=u_\text{in}\frac{P_\text{in}}{P_\text{out}}=5(\text{m/s})\frac{10\text{ bar}}{9\text{ bar}}=5.555\ \text{m/s}$$

$$\Delta\dot{E}_k=\frac{1}{2}\dot{m}(u_{out}^2-u_{in}^2)=\begin{array}{c|c|c|c} 0.5(0.0225)\text{ kg} & (5.555^2-5.000^2)\text{m}^2 & 1\text{ N} & 1\text{ W} \\ \hline \text{s} & \text{s}^2 & 1\text{ kg}\cdot\text{m/s}^2 & 1\text{ N}\cdot\text{m/s} \end{array}$$

$$=\underline{\underline{0.0659\ \text{W}}}$$

$$\Delta\dot{E}_p=\dot{m}g(z_{out}-z_{in})=\begin{array}{c|c|c|c|c} 0.0225\text{ kg} & 9.8066\text{ m} & -200\text{ m} & 1\text{ N} & 1\text{ W} \\ \hline \text{s} & \text{s} & & \text{kg}\cdot\text{m/s}^2 & 1\text{ N}\cdot\text{m/s} \end{array}$$

$$=\underline{\underline{-44.1\ \text{W}}}$$

7.8

$$\Delta\dot{E}_p = \dot{m}g\Delta z = \begin{array}{c|c|c|c|c|c|c|c} 10^5\ \text{m}^3 & 10^3\ \text{L} & 1\ \text{kg}\ \text{H}_2\text{O} & 9.81\ \text{m} & -75\ \text{m} & 1\ \text{N} & 1\ \text{J} & 2.778\times10^{-7}\ \text{kW}\cdot\text{h} \\ \hline \text{h} & 1\ \text{m}^3 & 1\ \text{L} & \text{s}^2 & & 1\ \text{kg}\cdot\text{m/s}^2 & 1\ \text{N}\cdot\text{m} & 1\ \text{J} \end{array}$$

$$= -2.04\times10^4\ \text{kW}\cdot\text{h/h}$$

The maximum energy to be gained equals the potential energy lost by the water, or

$$\begin{array}{c|c|c} 2.04\times10^4\ \text{kW}\cdot\text{h} & 24\ \text{h} & 7\ \text{days} \\ \hline \text{h} & 1\ \text{day} & 1\ \text{week} \end{array} = \underline{\underline{3.43\times10^6\ \text{kW}\cdot\text{h/week}}}\ \text{(more than sufficient)}$$

7.9 **(b)** $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$$\Downarrow \begin{cases} \Delta E_k = 0\ \text{(system is stationary)} \\ \Delta E_p = 0\ \text{(no height change)} \end{cases}$$

$$\underline{\underline{Q - W = \Delta U,\ Q < 0, W > 0}}$$

(c) $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$$\Downarrow \begin{cases} Q = 0\ \text{(adiabatic)},\ W = 0\ \text{(no moving parts or generated currents)} \\ \Delta E_k = 0\ \text{(system is stationary)} \\ \Delta E_p = 0\ \text{(no height change)} \end{cases}$$

$$\underline{\underline{\Delta U = 0}}$$

(d). $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$$\Downarrow \begin{cases} W = 0\ \text{(no moving parts or generated currents)} \\ \Delta E_k = 0\ \text{(system is stationary)} \\ \Delta E_p = 0\ \text{(no height change)} \end{cases}$$

$\underline{\underline{Q = \Delta U,\ Q < 0}}$ Even though the system is isothermal, the occurrence of a chemical reaction assures that $\Delta U \neq 0$ in a non-adiabatic reactor. If the temperature went up in the adiabatic reactor, heat must be transferred from the system to keep *T* constant, hence $Q < 0$.

7.10 4.00 L, 30 °C, 5.00 bar $\Rightarrow$ V (L), T (°C), 8.00 bar

(a). Closed system: $\Delta U + \Delta E_k + \Delta E_p = Q - W$

$$\Downarrow \begin{cases} \Delta E_k = 0\ \text{(initial / final states stationary)} \\ \Delta E_p = 0\ \text{(by assumption)} \end{cases}$$

$$\underline{\underline{\Delta U = Q - W}}$$

(b) Constant $T \Rightarrow \Delta U = 0 \Rightarrow Q = W = \begin{array}{c|c} -7.65\ \text{L}\cdot\text{bar} & 8.314\ \text{J} \\ \hline & 0.08314\ \text{L}\cdot\text{bar} \end{array} = \underline{\underline{-765\ \text{J}}}$ transferred from gas to surroundings

(c) Adiabatic $\Rightarrow Q = 0 \Rightarrow \Delta U = -W = 7.65\ \text{L}\cdot\text{bar} > 0,\ \underline{\underline{T_{\text{final}} > 30^\circ\ \text{C}}}$

7.11 $A=\begin{array}{c|c} \pi(3)^2\ \text{cm}^2 & 1\ \text{m}^2 \\ \hline & 10^4\ \text{cm}^2 \end{array}=2.83\times10^{-3}\ \text{m}^2$

(a) Downward force on piston:

$$F_d=P_{\text{atm}}A+m_{\text{piston+weight}}g$$

$$=\begin{array}{c|c|c} 1\ \text{atm} & 1.01325\times10^5\ \text{N/m}^2 & 2.83\times10^{-3}\ \text{m}^2 \\ \hline & \text{atm} & \end{array}+\begin{array}{c|c|c} 24.50\ \text{kg} & 9.81\ \text{m} & 1\ \text{N} \\ \hline & \text{s}^2 & 1\ \text{kg}\cdot\text{m/s}^2 \end{array}=527\ \text{N}$$

Upward force on piston: $F_u=AP_{\text{gas}}=\left(2.83\times10^{-3}\ \text{m}^2\right)\left[P_g\left(\text{N/m}^2\right)\right]$

Equilibrium condition:

$$F_u=F_d\Rightarrow2.83\times10^{-3}\text{m}^2\cdot P_0=527\Rightarrow\underline{\underline{P_0=1.86\times10^5\ \text{N/m}^2=1.86\times10^5\ \text{Pa}}}$$

$$V_0=\frac{nRT}{P_0}=\begin{array}{c|c|c|c|c} 1.40\ \text{g N}_2 & 1\ \text{mol N}_2 & 303\ \text{K} & 1.01325\times10^5\ \text{Pa} & 0.08206\ \text{L}\cdot\text{atm} \\ \hline & 28.02\ \text{g} & 1.86\times10^5\ \text{Pa} & 1\ \text{atm} & \text{mol}\cdot\text{K} \end{array}=\underline{\underline{0.677\ \text{L}}}$$

(b) For any step, $\Delta U+\Delta E_k+\Delta E_p=Q-W\underset{\substack{\Delta E_k=0\\ \Delta E_p=0}}{\Rightarrow}\Delta U=Q-W$

Step 1: $Q\approx0\Rightarrow\underline{\underline{\Delta U=-W}}$

Step 2: $\underline{\underline{\Delta U=Q-W}}$ As the gas temperature changes, the pressure remains constant, so that $V=nRT/P_g$ must vary. This implies that the piston moves, so that W is not zero.

Overall: $T_{\text{initial}}=T_{\text{final}}\Rightarrow\Delta U=0\Rightarrow\underline{\underline{Q-W=0}}$

In step 1, the gas expands $\Rightarrow W>0\Rightarrow\Delta U<0\Rightarrow\underline{\underline{T\ \text{decreases}}}$

(c) Downward force $F_d=(1.00)\left(1.01325\times10^5\right)\left(2.83\times10^{-3}\right)+(4.50)(9.81)(1)=331\ \text{N}$ (units as in Part (a))

Final gas pressure $P_f=\dfrac{F}{A}=\dfrac{331\ \text{N}}{2.83\times10^{-3}\ \text{m}^2}=1.16\times10^5\ \text{N/m}^2$

Since $T_0=T_f=30°\text{C}$, $P_fV_f=P_0V_0\Rightarrow V_f=V_0\dfrac{P_0}{P_f}=(0.677\ \text{L})\dfrac{1.86\times10^5\ \text{Pa}}{1.16\times10^5\ \text{Pa}}=1.08\ \text{L}$

Distance traversed by piston $=\dfrac{\Delta V}{A}=\begin{array}{c|c|c} (1.08-0.677)\ \text{L} & 1\ \text{m}^3 & \\ \hline & 10^3\ \text{L} & 2.83\times10^{-3}\ \text{m}^2 \end{array}=0.142\ \text{m}$

$$\Rightarrow W=Fd=(331\ \text{N})(0.142\ \text{m})=47\ \text{N}\cdot\text{m}=47\ \text{J}$$

Since work is done by the gas on its surroundings, $W=+47\ \text{J}\underset{Q-W=0}{\Rightarrow}\underline{\underline{Q=+47\ \text{J}}}$

(heat transferred to gas)

7.12 $\hat{V}=\begin{array}{c|c|c} 32.00\ \text{g} & 4.684\ \text{cm}^3 & 10^3\ \text{L} \\ \hline \text{mol} & \text{g} & 10^6\ \text{cm}^3 \end{array}=0.1499\ \text{L/mol}$

$$\hat{H}=\hat{U}+P\hat{V}=1706\ \text{J/mol}+\begin{array}{c|c|c} 41.64\ \text{atm} & 0.1499\ \text{L} & 8.314\ \text{J/(mol}\cdot\text{K)} \\ \hline & \text{mol} & 0.08206\ \text{L}\cdot\text{atm/(mol}\cdot\text{K)} \end{array}=\underline{\underline{2338\ \text{J/mol}}}$$

7.13 **(a)** Ref state $\left(\hat{U}=0\right) \Rightarrow \underline{\underline{\text{liquid Bromine @ } 300\text{ K, } 0.310\text{ bar}}}$

(b) $\Delta\hat{U} = \hat{U}_{\text{final}} - \hat{U}_{\text{initial}} = 0.000 - 28.24 = \underline{\underline{-28.24\ \text{kJ/mol}}}$

$\Delta\hat{H} = \Delta\hat{U} + \Delta\left(P\hat{V}\right) = \Delta\hat{U} + P\Delta\hat{V}$ (Pressure Constant)

$$\Delta\hat{H} = -28.24\ \text{kJ/mol} + \frac{0.310\ \text{bar}\ \big|\ (0.0516-79.94)\ \text{L}\ \big|\ 8.314\ \text{J}\ \big|\ 1\ \text{kJ}}{\big|\ \text{mol}\ \big|\ 0.08314\ \text{L}\cdot\text{bar}\ \big|\ 10^3\ \text{J}} = \underline{\underline{-30.7\ \text{kJ/mol}}}$$

$\Delta H = n\Delta\hat{H} = (5.00\text{ mol})(-30.7\text{ kJ / mol}) = -153.58\text{ kJ} \Rightarrow \underline{\underline{-154\text{ kJ}}}$

(c) $\hat{U}$ independent of $P \Rightarrow \hat{U}(300\text{ K, } 0.205\text{ bar}) = \hat{U}(300\text{ K, } 0.310\text{ bar}) = 28.24\ \text{kJ/mol}$

$\hat{U}\left(340\text{ K, } P_f\right) = \hat{U}(340\text{ K, } 1.33\text{ bar}) = 29.62\ \text{kJ/mol}$

$\Delta\hat{U} \underset{\Downarrow}{=} \hat{U}_{\text{final}} - \hat{U}_{\text{initial}}$

$\Delta\hat{U} = 29.62 - 28.24 = \underline{\underline{1.380\ \text{kJ/mol}}}$

$\hat{V}$ changes with pressure. At constant temperature $\Rightarrow \text{P}\hat{\text{V}} = \text{P}'\,\hat{\text{V}}' \Rightarrow \hat{\text{V}}' = \text{P}\hat{\text{V}}\,/\,\text{P}'$

$$\hat{\text{V}}'(\text{T} = 300\text{K, P} = 0.205\text{ bar}) = \frac{(0.310\text{ bar})(79.94\text{ L / mol})}{0.205\text{ bar}} = 120.88\text{ L / mol}$$

$$n = \frac{5.00\text{ L}\ \big|\ 1\text{ mol}}{\big|\ 120.88\text{ L}} = 0.0414\text{ mol}$$

$\Delta U = n\Delta\hat{U} = (0.0414\text{ mol})(1.38\text{ kJ / mol}) = \underline{\underline{0.0571\text{ kJ}}}$

$$\Delta U + \underset{0}{\cancel{\Delta E_k}} + \underset{0}{\cancel{\Delta E_p}} = Q - \underset{0}{\cancel{W}} \Rightarrow \underline{\underline{Q = 0.0571\text{ kJ}}}$$

(d) Some heat is lost to the surroundings; the energy needed to heat the wall of the container is being neglected; internal energy is not completely independent of pressure.

7.14 **(a)** By definition $\hat{H} = \hat{U} + P\hat{V}$; ideal gas $P\hat{V} = RT \Rightarrow \hat{H} = \hat{U} + RT$

$\hat{U}(T,P) = \hat{U}(T) \Rightarrow \hat{H}(T,P) = \hat{U}(T) + RT = \hat{H}(T)$ independent of P

(b) $\Delta\hat{H} = \Delta\hat{U} + R\Delta T = 3500\dfrac{\text{cal}}{\text{mol}} + \dfrac{1.987\text{ cal}\ \big|\ 50\text{ K}}{\text{mol}\cdot\text{K}\ \big|} = 3599\ \text{cal/mol}$

$\Delta H = n\Delta\hat{H} = (2.5\text{ mol})(3599\text{ cal / mol}) = 8998\text{ cal} \Rightarrow \underline{\underline{9.0\times10^3\text{ cal}}}$

7.15 $\Delta U + \Delta E_k + \Delta E_p = Q - Ws$

$$\Bigg\Downarrow\ \begin{array}{l} \Delta E_k = 0\ (\text{no change in } m \text{ and } u) \\ \Delta E_p = 0\ (\text{no elevation change}) \\ W_s = P\Delta V\ (\text{since energy is transferred from the system to the surroundings}) \end{array}$$

$\Delta U = Q - W \Rightarrow \Delta U = Q - P\Delta V \Rightarrow Q = \Delta U + P\Delta V = \Delta(U + PV) = \Delta H$

7.16. (a) $\Delta E_k = 0 \ (u_1 = u_2 = 0)$

$\Delta E_p = 0$ (no elevation change)

$\Delta P = 0$ (the pressure is constant since restraining force is constant, and area is constrant)

$W_s = P\Delta V$ (the only work done is expansion work)

$\hat{H} = 34980 + 35.5T$ (J / mol), $V_1 = 785$ cm^3, $T_1 = 400$ K, $P = 125$ kPa, $Q = 83.8$ J

$$n = \frac{PV}{RT} = \begin{array}{c|c|c} 125\times 10^3\text{ Pa} & 785\text{ cm}^3 & 1\text{ m}^3 \\ \hline 8.314\text{ m}^3\cdot\text{Pa / mol}\cdot\text{K} & 400\text{ K} & 10^6\text{ cm}^3 \end{array} = 0.0295\text{ mol}$$

$$Q = \Delta H = n(\hat{H}_2 - \hat{H}_1) = 0.0295\text{ mol}\left[34980 + 35.5T_2 - 34980 - 35.5(400\text{K})\right]\text{ (J / mol)}$$

$$83.8\text{ J} = 0.0295\left[35.5T_2 - 35.5(400)\right] \Rightarrow \underline{\underline{T_2 = 480\text{ K}}}$$

$$i)\ V = \frac{nRT}{P} = \begin{array}{c|c|c|c} 0.0295\text{ mol} & 8.314\text{ m}^3\cdot\text{Pa} & 10^6\text{ cm}^3 & 480\text{ K} \\ \hline 125\times 10^5\text{ Pa} & \text{mol}\cdot\text{K} & 1\quad\text{m}^3 & \end{array} = \underline{\underline{941\text{ cm}^3}}$$

$$ii)\ W = P\Delta V = \begin{array}{c|c|c} 125\times 10^5\text{ N} & (941 - 785)\text{cm}^3 & 1\quad\text{m}^3 \\ \hline \text{m}^2 & & 10^6\text{ cm}^3 \end{array} = \underline{\underline{19.5\text{ J}}}$$

$$iii)\ Q = \Delta U + P\Delta V \Rightarrow \Delta U = Q - \Delta PV = 83.8\text{ J} - 19.5\text{ J} = \underline{\underline{64.3\text{ J}}}$$

(b) $\underline{\underline{\Delta E_p = 0}}$

7.17 (a) "The gas temperature remains constant while the circuit is open." (If heat losses could occur, the temperature would drop during these periods.)

(b) $\Delta U + \Delta E_p + \Delta E_R = \dot{Q}\Delta t - \dot{W}\Delta t$

$$\Big\Downarrow \begin{array}{l} \Delta E_p = 0,\ \Delta E_k = 0,\ \dot{W} = 0,\ \hat{U}(t = 0) = 0 \\ \dot{Q} = \begin{array}{c|c} 0.90\times 1.4\text{ W} & 1\ \text{J/s} \\ \hline & 1\text{ W} \end{array} = 1.26\ \text{J/s} \end{array}$$

$$U(\text{J}) = 1.26\,t$$

<u>Moles in tank:</u> $n = PV/RT = \begin{array}{c|c|c} 1\text{ atm} & 2.10\text{ L} & 1\quad\text{mol}\cdot\text{K} \\ \hline & (25+273)\text{K} & 0.08206\text{ L}\cdot\text{atm} \end{array} = 0.0859\text{ mol}$

$$\hat{U} = \frac{U}{n} = \frac{1.26t\text{ (J)}}{0.0859\text{ mol}} = 14.67t$$

<u>Thermocouple calibration:</u> $T = aE + b \xRightarrow[\substack{T=0,\ E=-0.249 \\ T=100,\ E=5.27}]{} T(^\circ\text{C}) = 18.1E(\text{mV}) + 4.51$

$\hat{U} = 14.67t$	0	440	880	1320
$T = 18.1E + 4.51$	25	45	65	85

(c) To keep the temperature uniform throughout the chamber.

(d) Power losses in electrical lines, heat absorbed by chamber walls.

(e) In a closed container, the pressure will increase with increasing temperature. However, at the low pressures of the experiment, the gas is probably close to ideal $\Rightarrow \hat{U} = f(T)$ only. Ideality could be tested by repeating experiment at several initial pressures $\Rightarrow$ same results.

7.18 **(b)** $\Delta\dot{H}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$ (The system is the liquid stream.)

$$\Bigg\Downarrow\ \begin{array}{l}\Delta\dot{E}_k=0\ \text{(no change in } m \text{ and } u\text{)}\\ \Delta\dot{E}_p=0\ \text{(no elevation change)}\\ \dot{W}_s=0\ \text{(no moving parts or generated currents)}\end{array}$$

$$\underline{\underline{\Delta\dot{H}=\dot{Q},\ \dot{Q}>0}}$$

(c) $\Delta\dot{H}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$ (The system is the water)

$$\Bigg\Downarrow\ \begin{array}{l}\Delta\dot{H}=0\ (T \text{ and } P\text{~constant})\\ \Delta\dot{E}_k=0\ \text{(no change in } m \text{ and } u\text{)}\\ \dot{Q}=0\ (\text{no } \Delta T \text{ between system and surroundings})\end{array}$$

$$\underline{\underline{\Delta\dot{E}_p=-\dot{W}_s,\ \dot{W}_s>0\ \text{(for water system)}}}$$

(d) $\Delta\dot{H}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$ (The system is the oil)

$$\Big\Downarrow\ \Delta\dot{E}_k=0\ \text{(no velocity change)}$$

$$\underline{\underline{\Delta\dot{H}+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s}}\quad \dot{Q}<0\ \text{(friction loss); } \dot{W}_s<0\ \text{(pump work).}$$

(e) $\Delta\dot{H}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$ (The system is the reaction mixture)

$$\Bigg\Downarrow\ \begin{array}{l}\Delta\dot{E}_k=\Delta\dot{E}_p=0\ \text{(given)}\\ \Delta\dot{W}_s=0\ \text{(no moving parts or generated current)}\end{array}$$

$$\underline{\underline{\Delta\dot{H}=\dot{Q},\ \dot{Q}\ \text{pos. or neg. depends on reaction}}}$$

7.19 **(a)** molar flow: $\dfrac{1.25\ \text{m}^3}{\text{min}}\left|\dfrac{273\ \text{K}}{423\ \text{K}}\right|\dfrac{122\ \text{kPa}}{101.3\ \text{kPa}}\left|\dfrac{1\ \text{mol}}{22.4\ \text{L(STP)}}\right|\dfrac{10^3\ \text{L}}{1\ \text{m}^3}=43.4\ \text{mol/min}$

$$\Delta\dot{H}+\Delta\dot{E}_k+\Delta\dot{E}_p=\dot{Q}-\dot{W}_s$$

$$\Bigg\Downarrow\ \begin{array}{l}\Delta\dot{E}_k=\Delta\dot{E}_p=0\ \text{(given)}\\ \dot{W}_s=0\ \text{(no moving parts)}\end{array}$$

$$\dot{Q}=\Delta\dot{H}=\dot{n}\Delta\hat{H}=\frac{43.37\ \text{mol}}{\text{min}}\left|\frac{1\ \text{min}}{60\text{s}}\right|\frac{3640\ \text{J}}{\text{mol}}\left|\frac{\text{kW}}{10^3\ \text{J/s}}\right|=\underline{\underline{2.63\ \text{kW}}}$$

(b) More information would be needed. The change in kinetic energy would depend on the cross-sectional area of the inlet and outlet pipes, hence the internal diameter of the inlet and outlet pipes would be needed to answer this question.

7.20 **(a)** $\hat H = 1.04\left[T(^\circ\text{C}) - 25\right] \quad \hat H \text{ in kJ/kg}$

$\hat H_{\text{out}} = 1.04[34.0 - 25] = 9.36 \text{ kJ/kg}$

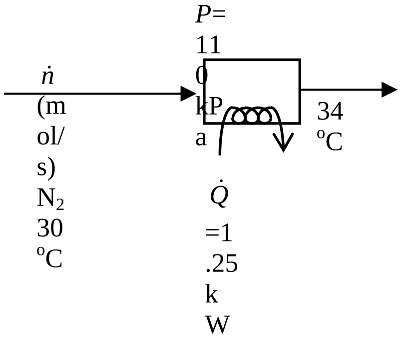
$\hat H_{\text{in}} = 1.04[30.0 - 25] = 5.20 \text{ kJ/kg}$

$\Delta \hat H = 9.36 - 5.20 = 4.16 \text{ kJ/kg}$

$\Delta \dot H + \Delta \dot E_k + \Delta \dot E_p = \dot Q - \dot W_s$

$$\Bigg\Downarrow \begin{array}{l} \Delta\dot E_k = \Delta \dot E_p = 0 \text{ (assumed)} \\ \dot W_s = 0 \text{ (no moving parts)} \end{array}$$

$\dot Q = \Delta \dot H = \dot n \Delta \hat H$



$$\Rightarrow \dot n = \frac{\dot Q}{\Delta \dot H} = \frac{1.25 \text{ kW}}{} \bigg| \frac{\text{kg}}{4.16 \text{ kJ}} \bigg| \frac{1 \text{ kJ/s}}{\text{kW}} \bigg| \frac{10^3 \text{ g}}{1 \text{ kg}} \bigg| \frac{1 \text{ mol}}{28.02 \text{ g}} = 10.7 \text{ mol/s}$$

$$\Rightarrow \dot V = \frac{10.7 \text{ mol}}{\text{s}} \bigg| \frac{22.4 \text{ L(STP)}}{\text{mol}} \bigg| \frac{303 \text{ K}}{273 \text{ K}} \bigg| \frac{101.3 \text{ kPa}}{110 \text{ kPa}} = 245.5 \text{ L/s} \Rightarrow \underline{\underline{246 \text{ L/s}}}$$

(b) Some heat is lost to the surroundings, some heat is needed to heat the coil, enthalpy is assumed to depend linearly on temperature and to be independent of pressure, errors in measured temperature and in wattmeter reading.

7.21 **(a)** $$\left.\begin{array}{l} \hat H = aT + b \quad a = \dfrac{\hat H_2 - \hat H_1}{T_2 - T_1} = \dfrac{129.8 - 25.8}{50 - 30} = 5.2 \\ \qquad\qquad b = \hat H_1 - aT_1 = 25.8 - (5.2)(30) = -130.2 \end{array}\right\} \Rightarrow \underline{\underline{\hat H(\text{kJ/kg}) = 5.2T(^\circ\text{C}) - 130.2}}$$

$$\hat H = 0 \Rightarrow T_{\text{ref}} = \frac{130.2}{5.2} = \underline{\underline{25^\circ \text{C}}}$$

Table B.1 $\Rightarrow (S.G.)_{\text{C}_6\text{H}_{14}(\text{l})} = 0.659 \Rightarrow \hat V = \dfrac{1 \text{ m}^3}{659 \text{ kg}} = 1.52 \times 10^{-3} \text{ m}^3/\text{kg}$

$$\hat U(\text{kJ/kg}) = \hat H - P\hat V = (5.2T - 130.2) \text{kJ/kg}$$

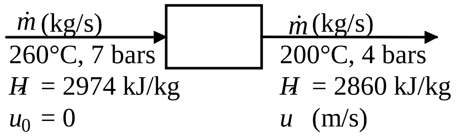
$$- \frac{1 \text{ atm}}{} \bigg| \frac{1.0132 \times 10^5 \text{ N/m}^2}{1 \quad \text{atm}} \bigg| \frac{1.52 \times 10^{-3} \text{ m}^3}{1 \quad \text{kg}} \bigg| \frac{1 \text{ J}}{1 \text{ N}\cdot\text{m}} \bigg| \frac{1 \text{ kJ}}{10^3 \text{ J}}$$

$$\Rightarrow \underline{\underline{\hat U(\text{kJ/kg}) = 5.2T - 130.4}}$$

(b) $\dfrac{\text{Energy balance:}}{\Delta E_k, \Delta E_p, W{=}0}$ $Q = \Delta U = \dfrac{20 \text{ kg}}{} \bigg| \dfrac{[(5.2 \times 20 - 130.4) - (5.2 \times 80 - 130.4)] \text{ kJ}}{1 \qquad\qquad \text{kg}} = -6240 \text{ kJ}$

$\underline{\text{Average rate of heat removal}} = \dfrac{6240 \text{ kJ}}{5 \text{ min}} \bigg| \dfrac{1 \text{ min}}{60 \text{ s}} = \underline{\underline{20.8 \text{ kW}}}$

7.22



$$\Delta\dot H + \Delta\dot E_k + \Delta\dot E_p = \dot Q - \dot W_s$$

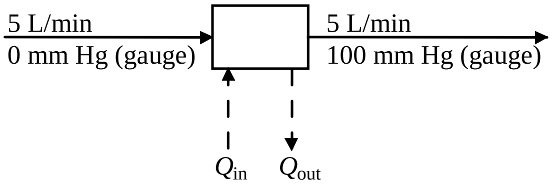
$$\Big\Downarrow \; \Delta\dot E_p = \dot Q = \dot W_s = 0$$

$$\Delta\dot E_k = -\Delta\dot H \;\Rightarrow\; \frac{\dot m u^2}{2} = -\dot m\left(\hat H_{\text{out}} - \hat H_{\text{in}}\right)$$

$$\Big\Downarrow$$

$$u^2 = 2\left(\hat H_{\text{in}} - \hat H_{\text{out}}\right) = \frac{(2)(2974-2860)\text{kJ}}{\text{kg}}\left|\frac{10^3\,\text{N}\cdot\text{m}}{1\text{ kJ}}\right|\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}} = 2.28\times10^5\,\frac{\text{m}^2}{\text{s}^2} \Rightarrow \underline{\underline{u = 477\text{ m/s}}}$$

7.23 **(a)**



Since there is only one inlet stream and one outlet stream, and $\dot m_{\text{in}} = \dot m_{\text{out}} \equiv \dot m$, Eq. (7.4-12) may be written

$$\dot m\Delta\hat U + \dot m\Delta\left(P\hat V\right) + \frac{\dot m}{2}\Delta\left(u^2\right) + \dot m g\Delta z = \dot Q - \dot W_s$$

$$\Big\Downarrow \quad \begin{aligned} &\Delta\hat U = 0 \text{ (given)} \\ &\dot m\Delta P\hat V = \dot m\hat V\left(P_{\text{out}} - P_{\text{in}}\right) = \dot V\Delta P \\ &\Delta u^2 = 0 \text{ (assume for incompressible fluid)} \\ &\Delta z = 0 \\ &\dot W_s = 0 \text{ (all energy other than flow work included in heat terms)} \\ &\dot Q = \dot Q_{\text{in}} - \dot Q_{\text{out}} \end{aligned}$$

$$\underline{\underline{\dot V\Delta P = \dot Q_{\text{in}} - \dot Q_{\text{out}}}}$$

(b) Flow work: $\dot V\Delta P = \dfrac{5\text{ L}}{\text{min}}\left|\dfrac{(100-0)\text{mm Hg}}{}\right|\dfrac{1\text{ atm}}{760\text{ mm Hg}}\left|\dfrac{8.314\ \text{J}}{0.08206\text{ liter}\cdot\text{atm}}\right. = 66.7\ \text{J/min}$

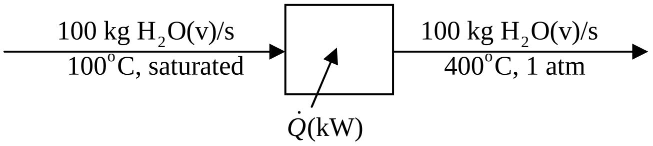
Heat input: $\dot Q_{\text{in}} = \dfrac{5\text{ ml O}_2}{\text{min}}\left|\dfrac{20.2\text{ J}}{1\text{ ml O}_2}\right. = 101\ \text{J/min}$

Efficiency: $\dfrac{\dot V\Delta P}{\dot Q_{\text{in}}} = \dfrac{66.7\ \text{J/min}}{101\ \text{J/min}}\times100\% = \underline{\underline{66\%}}$

7.24 **(a)** $\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$; $\Delta\dot{E}_k,\ \Delta\dot{E}_p,\ \dot{W}_s = 0 \Rightarrow \Delta\dot{H} = \dot{Q}$

$\hat{H}(400°\text{C, 1 atm}) = 3278\ \text{kJ/kg}$ (Table B.7)

$\hat{H}(100°\text{C, sat'd} \Rightarrow 1\ \text{atm}) = 2676\ \text{kJ/kg}$ (Table B.5)



$$\dot{Q} = \begin{array}{c|c|c} 100\ \text{kg} & (3278 - 2676.0)\text{kJ} & 10^3\ \text{J} \\ \hline \text{s} & \text{kg} & 1\ \text{kJ} \end{array} = \underline{\underline{6.02 \times 10^7\ \text{J/s}}}$$

(b) $\Delta U + \Delta E_k + \Delta E_p = Q - W$; $\Delta E_k,\ \Delta E_p,\ W = 0 \Rightarrow \Delta U = Q$

Table B.5 $\Rightarrow$ $\hat{U}\left(100°\text{C, 1 atm}\right) = 2507\dfrac{\text{kJ}}{\text{kg}}$, $\hat{V}\left(100°\text{C, 1 atm}\right) = 1.673\ \dfrac{\text{m}^3}{\text{kg}} = \hat{V}\left(400°\text{C}, P_{\text{final}}\right)$

Interpolate in Table B.7 to find P at which $\hat{V}$ =1.673 at 400°C, and then interpolate again to find $\hat{U}$ at 400°C and that pressure:

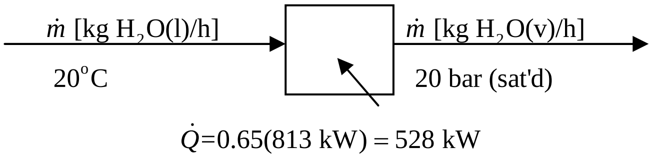
$$\hat{V} = 1.673\ \text{m}^3/\text{g} \Rightarrow P_{\text{final}} = 1.0 + 4.0\left(\frac{3.11 - 1.673}{3.11 - 0.617}\right) = 3.3\ \text{bar},\ \hat{U}(400°\text{C, 3.3 bar}) = 2966\ \text{kJ/kg}$$

$$\Rightarrow Q = \Delta U = m\Delta\hat{U} = 100\ \text{kg}\left[(2966 - 2507)\text{kJ/kg}\right]\left(10^3\ \text{J/kJ}\right) = \underline{\underline{4.59 \times 10^7\ \text{J}}}$$

The difference is the net energy needed to move the fluid through the system (flow work). (The energy change associated with the pressure change in Part (b) is insignificant.)

7.25 $\hat{H}(H_2O(l),\ 20°\text{C}) = 83.9\ \text{kJ/kg}$ (Table B.5)

$\hat{H}(\text{steam, 20 bars, sat'd}) = 2797.2\ \text{kJ/kg}$ (Table B.6)



(a) $\Delta\dot{H} + \Delta\dot{E}_k + \Delta\dot{E}_p = \dot{Q} - \dot{W}_s$; $\Delta\dot{E}_k,\ \Delta\dot{E}_p,\ \dot{W}_s = 0 \Rightarrow \Delta\dot{H} = \dot{Q}$

$$\Big\Downarrow\ \Delta\dot{H} = \dot{m}\Delta\hat{H}$$

$$\dot{m} = \frac{\dot{Q}}{\Delta\hat{H}} = \begin{array}{c|c|c|c} 528\ \text{kW} & \text{kg} & 1\ \text{kJ / s} & 3600\ \text{s} \\ \hline & (2797.2 - 83.9)\text{kJ} & 1\ \text{kW} & 1\quad \text{h} \end{array} = \underline{\underline{701\ \text{kg/h}}}$$

(b) $\dot{V} = (701\ \text{kg/h})\big(\underset{\substack{\uparrow \\ \text{Table B.6}}}{0.0995}\ \text{m}^3/\text{kg}\big) = \underline{\underline{69.7\ \text{m}^3/\text{h sat'd steam @ 20 bar}}}$

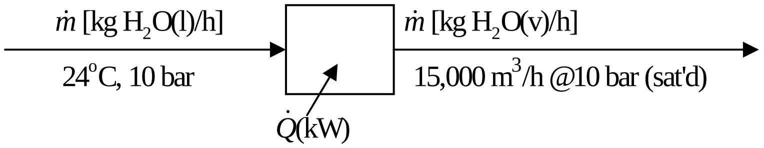
(c) $$\dot{V} = \frac{\dot{n}RT}{P} = \begin{array}{c|c|c|c|c} 701\ \text{kg / h} & 10^3\ \text{g / kg} & 485.4\ \text{K} & 0.08314\ \text{L}\cdot\text{bar} & 1\ \text{m}^3 \\ \hline 18.02\ \text{g / mol} & 20\ \text{bar} & & \text{mol}\cdot\text{K} & 10^3\ \text{L} \end{array} = \underline{\underline{78.5\ \text{m}^3/\text{h}}}$$

The calculation in (b) is more accurate because the steam tables account for the effect of pressure on specific enthalpy (nonideal gas behavior).

(d) Most energy released goes to raise the temperature of the combustion products, some is transferred to the boiler tubes and walls, and some is lost to the surroundings.

7.26 $\hat{H}\left(H_2O(l),\ 24^\circ C,\ 10\text{ bar}\right) = 100.6\ \text{kJ/kg}$ (Table B.5 for saturated liquid at 24°C; assume $\hat{H}$ independent of *P*).

$\hat{H}\left(10\text{ bar, sat'd steam}\right) = 2776.2\ \text{kJ/kg}$ (Table B.6) $\Rightarrow \Delta\hat{H} = 2776.2 - 100.6 = \underline{\underline{2675.6\ \text{kJ/kg}}}$



$$\dot{m} = \frac{15000\ \text{m}^3}{\text{h}}\left|\frac{\text{kg}}{\underset{\underset{(\text{Table 8.6})}{\uparrow}}{0.1943}\ \text{m}^3}\right. = 7.72\times 10^4\ \text{kg/h}$$

<u>Energy balance</u> $\left(\Delta\dot{E}_p,\ \dot{W}_s = 0\right)$: $\Delta\dot{H} + \Delta\dot{E}_k = \dot{Q}$

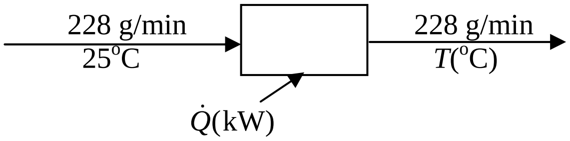
$$\Delta\dot{E}_k = \dot{E}_{k_{final}} - \dot{E}_{k_{initial}} \xRightarrow{\dot{E}_{k_{initial}} \approx 0} \Delta\dot{E}_k = \dot{E}_{k_{final}}$$

$$\Delta\dot{E}_k = \frac{\dot{m}u_f^{\,2}}{2} = \frac{7.72\times 10^4\ \text{kg}}{\text{h}}\left|\frac{\left(15{,}000\ \text{m}^3/\text{h}\right)^2}{\underset{\underset{A=\pi D^2/4}{\uparrow}}{\left[0.15^2\ \pi/4\right]^2}\ \text{m}^2}\right|\frac{1}{2}\left|\frac{1\quad \text{h}^3}{3600^3\ \text{s}^3}\right|\frac{1\ \text{J}}{1\ \text{kg}\cdot\text{m}^2/\text{s}^2} = 5.96\text{x}10^5\ \text{J/s}$$

$$\dot{Q} = \dot{m}\Delta\hat{H} + \Delta\dot{E}_k = \frac{7.72\times 10^4\ \text{kg}}{\text{h}}\left|\frac{2675.6\ \text{kJ}}{\text{kg}}\right|\frac{1\ \text{h}}{3600\ \text{s}} + \frac{5.96\times 10^5\ \text{J}}{\text{s}}\left|\frac{1\ \text{kJ}}{10^3\ \text{J}}\right.$$

$$= 57973\ \text{kJ/s} = \underline{\underline{5.80\times 10^4\ \text{kW}}}$$

7.27 (a)



<u>Energy balance:</u> $\underset{\Delta\dot{E}_x,\ \Delta\dot{E}_p,\ \dot{W}_s=0}{}$ $\dot{Q} = \Delta\dot{H} \Rightarrow \dot{Q}(\text{W}) = \frac{228\ \text{g}}{\text{min}}\left|\frac{1\ \text{min}}{60\ \text{s}}\right|\frac{(\hat{H}_{out} - \cancelto{=0}{\hat{H}_{in}})\ \text{J}}{\text{g}}$

$$\Rightarrow \hat{H}_{\text{out}}(\text{J/g}) = 0.263\dot{Q}(W)$$

$T(^\circ C)$	25	26.4	27.8	29.0	32.4
$\hat{H}(\text{J/g}) = 0.263\dot{Q}(W)$	0	4.47	9.28	13.4	24.8

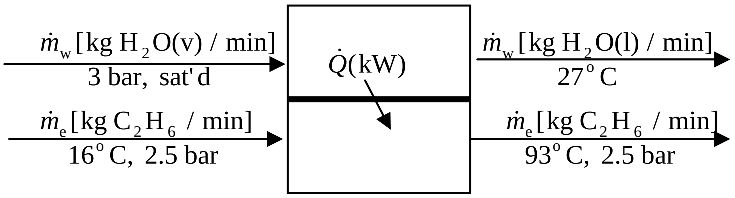
(b) $\hat{H} = b(T-25) \xRightarrow{\text{Fit to data by least squares (App. A.1)}} b = \sum_i \hat{H}_i\left(T_i - 25\right)\Big/\sum_i\left(T_i - 25\right)^2 = 3.34$

$$\Rightarrow \underline{\underline{\hat{H}(\text{J/g}) = 3.34\left[T(^\circ\text{C}) - 25\right]}}$$

(c) $\dot{Q} = \Delta\dot{H} = \frac{350\ \text{kg}}{\text{min}}\left|\frac{10^3\text{g}}{\text{kg}}\right|\frac{1\ \text{min}}{60\ \text{s}}\left|\frac{3.34(40-20)\text{J}}{\text{g}}\right|\frac{\text{kW}\cdot\text{s}}{10^3\ \text{J}} = \underline{\underline{390\ \text{kW}}}$ heat input to liquid

(d) Heat is absorbed by the pipe, lost through the insulation, lost in the electrical leads.

7.28



(a) $\underline{C_2H_6 \text{ mass flow: }}$ $\dot{m}_e = \begin{array}{r|r|r|r|r|r} 795\ \text{m}^3 & 10^3\ \text{L} & 2.50\ \text{bar} & 1\quad \text{K-mol} & 30.01\ \text{g} & 1\ \text{kg} \\ \hline \text{min} & \text{m}^3 & 289\ \text{K} & 0.08314\ \text{L-bar} & \text{mol} & 1000\ \text{g} \end{array}$

$= 2.487 \times 10^3\ \text{kg/min}$

$\hat{H}_{ei} = 941\ \text{kJ/kg}, \hat{H}_{ef} = 1073\ \text{kJ/kg}$

$\underline{\text{Energy Balance on } C_2H_6\text{:}}\ \Delta\dot{E}_p,\ \dot{W}_s = 0,\ \Delta\dot{E}_k \cong 0 \Rightarrow\ \dot{Q} = \Delta\dot{H}$

$$\dot{Q} = 2.487 \times 10^3 \frac{\text{kg}}{\text{min}}\left[(1073 - 941)\frac{\text{kJ}}{\text{kg}}\right] = \begin{array}{r|r} 2.487 \times 10^3\ \text{kJ} & 1\ \text{min} \\ \hline \text{min} & 60\ \text{s} \end{array} = \underline{\underline{5.47 \times 10^3\ \text{kW}}}$$

(b) $\hat{H}_{s_1}(3.00\ \text{bar, sat'd vapor}) = 2724.7\ \text{kJ/kg}$ (Table B.6)

$\hat{H}_{s_2}(\text{liquid, } 27°\text{C}) = 113.1\ \text{kJ/kg}$ (Table B.5)

Assume that heat losses to the surroundings are negligible, so that the heat given up by the condensing steam equals the heat transferred to the ethane $(5.47 \times 10^3\ \text{kW})$

$\underline{\text{Energy balance on H}_2\text{O:}}\ \dot{Q} = \Delta\dot{H} = \dot{m}(\hat{H}_{s_2} - \hat{H}_{s_1})$

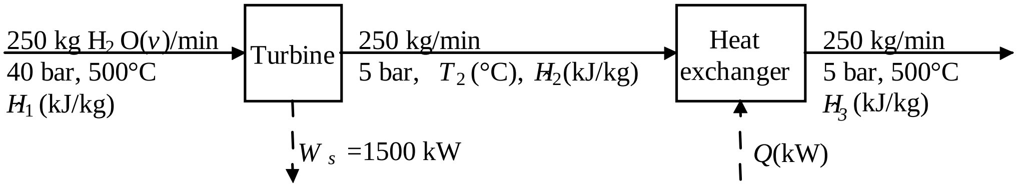
$$\Rightarrow \dot{m} = \frac{\dot{Q}}{\hat{H}_{s_2} - \hat{H}_{s_1}} = \begin{array}{r|r} -5.47 \times 10^3\ \text{kJ} & \text{kg} \\ \hline \text{s} & (113.1 - 2724.7)\text{kJ} \end{array} = 2.09\ \text{kg/s steam}$$

$$\Rightarrow \dot{V}_s = (2.09\ \text{kg / s})(\underset{\substack{\uparrow \\ \text{Table B.6}}}{0.606\ \text{m}^3/\text{kg}}) = \underline{\underline{1.27\ \text{m}^3/\text{s}}}$$

Too low. Extra flow would make up for the heat losses to surroundings.

(c) $\underline{\underline{\text{Countercurrent flow}}}$ Cocurrent (as depicted on the flowchart) would not work, since it would require heat flow from the ethane to the steam over some portion of the exchanger. (Observe the two outlet temperatures)

7.29



$$H_2O(v,\ 40\text{ bar},\ 500^\circ\text{C}):\ \hat{H}_1=3445\ \text{kJ/kg}\ \ (\text{Table B.7})$$

$$H_2O(v,\ 5\text{ bar},\ 500^\circ\text{C}):\ \hat{H}_3=3484\ \text{kJ/kg}\ \ (\text{Table B.7})$$

(a) Energy balance on turbine: $\Delta\dot{E}_p=0,\ \dot{Q}=0,\ \Delta\dot{E}_k\cong 0$

$$\Delta\dot{H}=-\dot{W}_s\Rightarrow \dot{m}\left(\hat{H}_2-\hat{H}_1\right)=-\dot{W}_s\Rightarrow \hat{H}_2=\hat{H}_1-\dot{W}_s/\dot{m}$$

$$=\frac{3445\text{ kJ}}{\text{kg}}-\frac{1500\text{ kJ}}{\text{s}}\Bigg|\frac{\text{min}}{250\text{ kg}}\Bigg|\frac{60\text{ s}}{1\text{ min}}=3085\ \text{kJ/kg}$$

$\hat{H}=3085\ \text{kJ/kg}$ and $P=5$ bars $\Rightarrow \underline{\underline{T=310^\circ\text{C}}}$ (Table B.7)

(b) Energy balance on heat exchanger: $\Delta\dot{E}_p=0,\ \dot{W}_s=0,\ \Delta\dot{E}_k\cong 0$

$$\dot{Q}=\Delta\dot{H}=\dot{m}\left(\hat{H}_3-\hat{H}_2\right)=\frac{250\text{ kg}}{\text{min}}\Bigg|\frac{(3484-3085)\text{kJ}}{\text{kg}}\Bigg|\frac{1\text{ min}}{60\text{ s}}\Bigg|\frac{1\text{ kW}}{1\text{ kJ/s}}=\underline{\underline{1663\text{ kW}}}$$

(c) Overall energy balance: $\Delta\dot{E}_p=0,\Delta\dot{E}_k\cong 0$

$$\Delta\dot{H}=\dot{Q}-\dot{W}_s\Rightarrow \dot{m}_s\left(\hat{H}_3-\hat{H}_1\right)=\dot{Q}-\dot{W}_s$$

$$\dot{Q}=\Delta\dot{H}+\Delta\dot{W}_s=\frac{250\text{ kg}}{\text{min}}\Bigg|\frac{(3484-3445)\text{kJ}}{\text{kg}}\Bigg|\frac{1\text{ min}}{60\text{ s}}\Bigg|\frac{1\text{ kW}}{1\text{ kJ/s}}+\frac{1500\text{ kJ}}{\text{s}}\Bigg|\frac{1\text{ kW}}{1\text{ kJ/s}}$$

$$=\underline{\underline{1663\text{ kW}}}\ \surd$$

(d) $H_2O(v,\ 40\text{ bar},\ 500^\circ\text{C}):\ \hat{V}_1=0.0864\ \text{m}^3/\text{kg}$ (Table B.7)

$$H_2O(v,\ 5\text{ bar},\ 310^\circ\text{C}):\ \hat{V}_2=0.5318\ \text{m}^3/\text{kg}\ \ (\text{Table B.7})$$

$$u_1=\frac{250\text{ kg}}{\text{min}}\Bigg|\frac{1\text{ min}}{60\text{ s}}\Bigg|\frac{0.0864\text{ m}^3}{\text{kg}}\Bigg|\frac{1}{0.5^2\ \pi/4\text{ m}^2}=1.83\ \text{m/s}$$

$$u_2=\frac{250\text{ kg}}{\text{min}}\Bigg|\frac{\text{min}}{60\text{ s}}\Bigg|\frac{0.5318\text{ m}^3}{\text{kg}}\Bigg|\frac{1}{0.5^2\ \pi/4\text{ m}^2}=11.3\ \text{m/s}$$

$$\Delta\dot{E}_k=\frac{\dot{m}}{2}\left[u_2^2-u_1^2\right]=\frac{250\text{ kg}}{\text{min}}\Bigg|\frac{1}{2}\Bigg|\frac{1\text{ min}}{60\text{ s}}\Bigg|\frac{\left[(11.3)^2-(1.83)^2\right]\text{m}^2}{\text{s}^2}\Bigg|\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\Bigg|\frac{1\text{ kW}\cdot\text{s}}{10^3\text{N}\cdot\text{m}}$$

$$=0.26\text{ kW}<<1500\text{ kW}$$

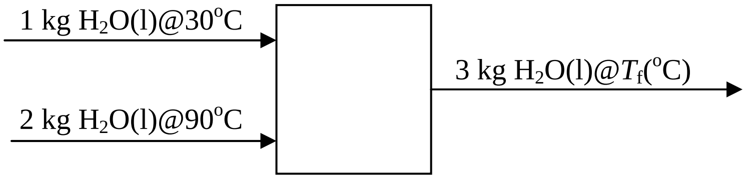
7.30 **(a)** $\Delta\dot{E}_p,\ \Delta\dot{E}_k,\ \dot{W}_s=0 \Rightarrow \dot{Q}=\Delta\dot{H} \Rightarrow -hA\left(T_s-T_o\right)=-300\ \text{kJ/h} \Rightarrow \underline{\underline{1.8h\left(T_s-T_o\right)=300\,\frac{\text{kJ}}{\text{h}}}}$

(b) Clothed: $\underset{T_s=34.2}{h=8} \Rightarrow \underline{\underline{T_o=13.4°\text{C}}}$

Nude, immersed: $\underset{T_s=34.2}{h=64} \Rightarrow \underline{\underline{T_o=31.6°\text{C}}}$ (Assuming T_s remains 34.2°C)

(c) *The wind raises the effective heat transfer coefficient*. (Stagnant air acts as a thermal insulator —i.e., in the absence of wind, *h* is low.) For a given T_o, the skin temperature must drop to satisfy the energy balance equation: when T_s drops, you feel cold.

7.31 Basis: 1 kg of 30°C stream



(a) $T_f=\frac{1}{3}\left(30°\text{C}\right)+\frac{2}{3}\left(90°\text{C}\right)=\underline{\underline{70°\text{C}}}$

(b) Internal Energy of feeds: $\left.\begin{array}{l}\hat{U}\left(30°\text{C, liq.}\right)=125.7\ \text{kJ/kg}\\ \hat{U}\left(90°\text{C, liq.}\right)=376.9\ \text{kJ/kg}\end{array}\right\}$

(Table B.5 - neglecting effect of *P* on $\hat{H}$)

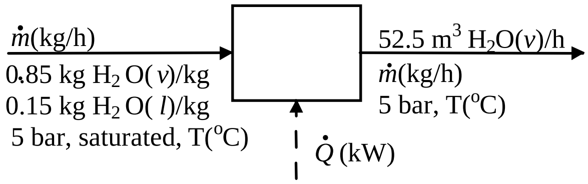
Energy Balance: $Q - W=\Delta U+\Delta E_p+\Delta E_k \xrightarrow{Q=W=\Delta E_p=\Delta E_k=0} \Delta U=0$

$\Rightarrow 3\hat{U}_f-(1\ \text{kg})(125.7\ \text{kJ / kg})-(2\ \text{kg})(376.9\ \text{kJ / kg})=0$

$\Rightarrow \underline{\underline{\hat{U}_f=293.2\ \text{kJ/kg}}} \Rightarrow \underline{\underline{T_f=70.05°\text{C}}}$ (Table B.5)

$\text{Diff.}=\frac{70.05-70.00}{70.05}\times 100\%=\underline{\underline{0.07\%}}$ (Any answer of this magnitude is acceptable).

7.32



(a) Table B.6 $\xrightarrow{P=5\text{ bars}}$ $\underline{\underline{T=151.8°\text{C}}}$, $\underline{\underline{\hat{H}_\text{L}=640.1\ \text{kJ/kg},\ \hat{H}_\text{V}=2747.5\ \text{kJ/kg}}}$

$\hat{V}(5\text{ bar, sat'd})=0.375\ \text{m}^3/\text{kg} \Rightarrow \dot{m}=\frac{52.5\ \text{m}^3}{\text{h}}\left|\frac{1\ \ \text{kg}}{0.375\ \text{m}^3}\right.=\underline{\underline{140\ \text{kg/h}}}$

(b) H$_2$O evaporated $=(0.15)(140\ \text{kg/h})=21\ \text{kg/h}$

Energy balance: $\dot{Q}=\Delta\dot{H}=\frac{21\ \text{kg}}{\text{h}}\left|\frac{(2747.5-640.1)\text{kJ}}{\text{kg}}\right|\frac{1\ \text{h}}{3600\ \text{s}}\left|\frac{1\ \text{kW}}{1\ \text{kJ/s}}\right.=\underline{\underline{12\ \text{kW}}}$

7.33 **(a)** $P = 5\text{ bar} \xrightarrow{\text{Table B.6}} \underline{\underline{T_{\text{saturation}} = 151.8^{o}\,\text{C}}}$. At 75°C the discharge is all liquid

(b) Inlet: *T*=350°C, *P*=40 bar $\xrightarrow{\text{Table B.7}} \hat{H}_{\text{in}} = 3095\text{ kJ / kg}$, $\hat{V}_{\text{in}} = 0.0665\text{ m}^3\text{ / kg}$

Outlet: *T*=75°C, *P*=5 bar $\xrightarrow{\text{Table B.7}} \hat{H}_{\text{out}} = 314.3\text{ kJ / kg}$, $\hat{V}_{\text{out}} = 1.03 \times 10^{-3}\text{ m}^3\text{ / kg}$

$$u_{\text{in}} = \frac{\dot{V}_{\text{in}}}{A_{\text{in}}} = \begin{array}{r|c|c} 200\text{ kg} & 1\text{ min} & 0.0665\text{ m}^3\text{ / kg} \\ \hline \text{min} & 60\text{ s} & \left[\pi(0.075)^2\ /\ 4\right]\text{m}^2 \end{array} = 50.18\text{ m / s}$$

$$u_{\text{out}} = \frac{\dot{V}_{\text{out}}}{A_{\text{out}}} = \begin{array}{r|c|c} 200\text{ kg} & 1\text{ min} & 0.00103\text{ m}^3\text{ / kg} \\ \hline \text{min} & 60\text{ s} & \left[\pi(0.05)^2\ /\ 4\right]\text{m}^2 \end{array} = 1.75\text{ m / s}$$

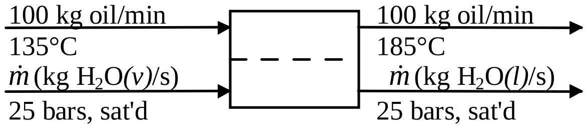
Energy balance: $\dot{Q} - \dot{W}_s \approx \Delta\dot{H} + \Delta\dot{E}_k = \dot{m}(\hat{H}_2 - \hat{H}_1) + \frac{\dot{m}}{2}(u_2^2 - u_1^2)$

$$\dot{Q} - \dot{W}_s = \begin{array}{r|c|r} 200\text{ kg} & 1\text{ min} & (314\text{-}3095)\text{ kJ} \\ \hline \text{min} & 60\text{ s} & \text{kg} \end{array} + \begin{array}{r|c|r} 200\text{ kg} & 1\text{ min} & (1.75^2\text{-}50.18^2)\text{ m}^2 \\ \hline 2\text{ min} & 60\text{ s} & \text{s}^2 \end{array}$$

$= \underline{\underline{-13,460\text{ kW}}}$ (⇒ 13,460 kW transferred from the turbine)

7.34 **(a)** Assume all heat from stream transferred to oil

$$\dot{Q} = \begin{array}{r|c} 1.00 \times 10^4\text{ kJ} & 1\text{ min} \\ \hline \text{min} & 60\text{ s} \end{array} = 167\text{ kJ/s}$$



Energy balance on H$_2$O: $\dot{Q} = \Delta\dot{H} = \dot{m}\left(\hat{H}_{\text{out}} - \hat{H}_{\text{in}}\right)$

$\Big\Downarrow$ $\Delta\dot{E}_p,\ \Delta\dot{E}_k,\ \dot{W}_s = 0$

$\hat{H}(l,\ 25\text{ bar, sat'd}) = 962.0\text{ kJ/kg}$, $\hat{H}(v,\ 25\text{ bar, sat'd}) = 2800.9\text{ kJ/kg}$ (Table B.6)

$$\dot{m} = \frac{\dot{Q}}{\hat{H}_{\text{out}} - \hat{H}_{\text{in}}} = \begin{array}{c|c} -167\text{ kJ} & \text{kg} \\ \hline \text{s} & (962.0 - 2800.9)\text{kJ} \end{array} = 0.091\text{ kg/s}$$

Time between discharges: $\begin{array}{c|c|c} 1200\text{ g} & 1\text{ s} & 1\text{ kg} \\ \hline \text{discharge} & 0.091\text{ kg} & 10^3\text{ g} \end{array} = \underline{\underline{13\text{ s/discharge}}}$

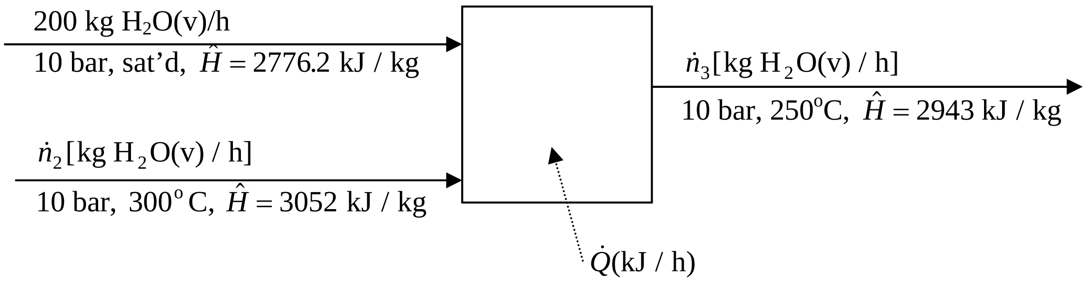
(b) Unit Cost of Steam: $\begin{array}{c|r|r} \$1 & (2800.9 - 83.9)\text{ kJ} & 0.9486\text{ Btu} \\ \hline 10^6\text{ Btu} & \text{kg} & \text{kJ} \end{array} = \$2.6 \times 10^{-3}\text{ / kg}$

Yearly cost:

$$\begin{array}{c|c|c|c|c|c|c} 1000\text{ traps} & 0.091\text{ kg stream} & 0.10\text{ kg last} & 2.6 \times 10^{-3}\$ & 3600\text{ s} & 24\text{ h} & 360\text{ day} \\ \hline & \text{trap}\cdot\text{s} & \text{kg stream} & \text{kg lost} & \text{h} & \text{day} & \text{year} \end{array}$$

$= \underline{\underline{\$7.4 \times 10^5\text{ / year}}}$

7.35 Basis: Given feed rate



$\hat{H}$ from Table B.6 (saturated steam) or Table B.7 (superheated steam)

$\underline{\text{Mass balance:}}$ $200 + \dot{n}_2 = \dot{n}_3$ (1)

$\underbrace{\text{Energy balance:}}_{\Delta\dot{E}_K,\ \Delta\dot{E}_p,\ \dot{W}=0}$ $\dot{Q} = \Delta\dot{H} = \dot{n}_3\,(2943) - 200(2776.2) - \dot{n}_2\,(3052)$, $\dot{Q}$ in kJ/h (2)

(a) $\dot{n}_3 = 300\ \text{kg/h} \xrightarrow{(1)} \dot{n}_2 = 100\ \text{kg/h} \xrightarrow{(2)} \dot{Q} = \underline{\underline{2.25 \times 10^4\ \text{kJ/h}}}$

(b) $\dot{Q} = 0 \xrightarrow{(1),(2)} \dot{n}_2 = \underline{\underline{306\ \text{kg/h}}}$, $\dot{n}_3 = \underline{\underline{506\ \text{kg/h}}}$

7.36 **(a)** $T_{\text{saturation}}$ @ 1.0 bar = 99.6 °C $\Rightarrow T_f = \underline{\underline{99.6^\circ\text{C}}}$

H_2O (1.0 bar, sat'd) $\Rightarrow \hat{H}_l = 417.5$ kJ / kg, $\hat{H}_v = 2675.4$ kJ / kg

H_2O (60 bar, 250°C) = 1085.8 kJ / kg

$\underline{\text{Mass balance:}}$ $m_v + m_l = 100$ kg (1)

$\underbrace{\text{Energy balance:}}_{\Delta\dot{E}_K,\ \dot{Q},\ \Delta\dot{E}_p,\ \dot{W}=0}$ $\Delta\dot{H} = 0$

$$\Rightarrow m_v\hat{H}_v + m_l\hat{H}_l - m_1\hat{H}_1 = m_v\hat{H}_v + m_l\hat{H}_l - (100\ \text{kg})(1085.8\ \text{kJ / kg}) = 0 \qquad (2)$$

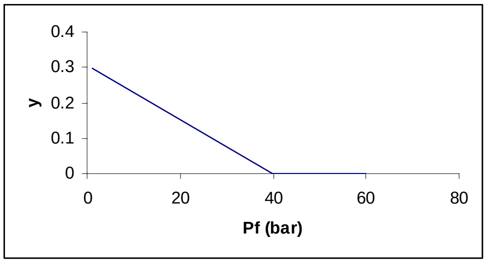
$$\xrightarrow{(1,2)} m_l = 70.4\ \text{kg},\ m_v = 29.6\ \text{kg} \Rightarrow y_v = \frac{29.6\ \text{kg vapor}}{100\ \text{kg}} = \underline{\underline{0.296\frac{\text{kg vapor}}{\text{kg}}}}$$

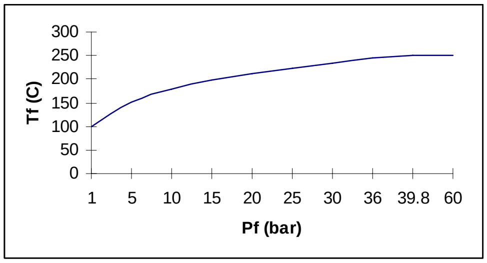
(b) $\underline{\underline{T\text{ is unchanged.}}}$ The temperature will still be the saturation temperature at the given final pressure. The system undergoes expansion, so assuming the same pipe diameter, $\Delta\dot{E}_k > 0$. $\underline{\underline{y_v\text{ would be less (less water evaporates)}}}$ because some of the energy that would have vaporized water instead is converted to kinetic energy.

(c) $P_f = \underline{\underline{39.8\ \text{bar}}}$ (pressure at which the water is still liquid, but has the same enthalpy as the feed)

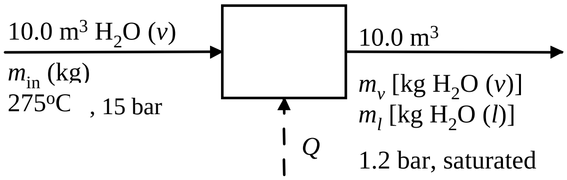
(d) Since enthalpy does not change, then when $P_f \geq 39.8$ bar the temperature cannot increase, because a higher temperature would increase the enthalpy. Also, when $P_f \geq 39.8$ bar, the product is only liquid ⇒ no evaporation occurs.

7.36 (cont'd)





7.37 $\boxed{10\text{ m}^3\text{, n moles of steam}(v)\text{, 275°C, 15 bar} \Rightarrow 10\text{ m}^3\text{, n moles of water }(v+l)\text{, 1.2 bar}}$



(a) P=1.2 bar, saturated, $\xrightarrow{\text{Table B.6}} T_2 = \underline{\underline{104.8^\circ\text{C}}}$

(b) Total mass of water: $m_{\text{in}} = \dfrac{10\text{ m}^3}{} \left| \dfrac{1\text{ kg}}{0.1818\text{ m}^3} \right. = 55\text{ kg}$

Mass Balance: $m_v + m_l = 55.0$

Volume additivity: $V_v + V_l = 10.0\text{ m}^3 = m_v(1.428\text{ m}^3/\text{kg}) + m_l(0.001048\text{ m}^3/\text{kg})$

$\Rightarrow m_v = 7.0\text{ kg},\ m_l = \underline{\underline{48.0\text{ kg condensed}}}$

(c) Table B.7 $\Rightarrow \hat{U}_{\text{in}} = 2739.2\text{ kJ/kg};\quad \hat{V}_{\text{in}} = 0.1818\text{ m}^3/\text{kg}$

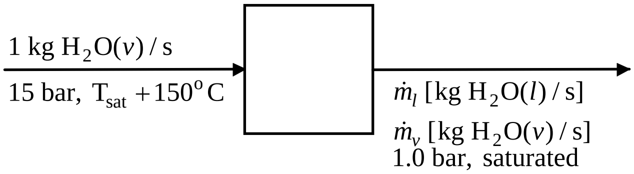
$$\text{Table B.6} \Rightarrow \begin{cases} \hat{U}_l = 439.2\text{ kJ/kg}; & \hat{V}_l = 0.001048\text{ m}^3/\text{kg} \\ \hat{U}_v = 2512.1\text{ kJ/kg}; & \hat{V}_v = 1.428\text{ m}^3/\text{kg} \end{cases}$$

$\underset{\Delta E_p, \Delta E_k,\ W=0}{\underline{\text{Energy balance:}}}\quad Q = \Delta U = m_v\hat{U}_v + m_l\hat{U}_l - m_{\text{in}}\hat{U}_{\text{in}}$

$$= [(7.0)(2512.1\text{ kJ/kg}) + (48.0)(439.2) - 55\text{ kg }(2739.2)]\text{ kJ}$$

$$= \underline{\underline{-1.12\times10^5\text{ kJ}}}$$

7.38 **(a)** Assume both liquid and vapor are present in the valve effluent.



(b) Table B.6 $\Rightarrow T_{\text{sat'n}}(15\text{ bar}) = 198.3^\circ\text{C} \Rightarrow T_{\text{in}} = 348.3^\circ\text{C}$

Table B.7 $\Rightarrow \hat{H}_{\text{in}} = \hat{H}(348.3^\circ\text{C, 15 bar}) \approx 3149\text{ kJ/kg}$

Table B.6 $\Rightarrow \hat{H}_l(1.0\text{ bar, sat'd}) = 417.5\text{ kJ/kg};\quad \hat{H}_v(1.0\text{ bar, sat'd}) = 2675.4\text{ kJ/kg}$

7.38 (cont'd)

$$\underset{\Delta\dot{E}_p,\Delta\dot{E}_k,\dot{Q},\dot{W}_s=0}{\underline{\text{Energy balance:}}}\quad \Delta\dot{H}=0\Rightarrow \dot{m}_l\hat{H}_l+\dot{m}_v\hat{H}_v-\dot{m}_{\text{in}}\hat{H}_{\text{in}}=0$$

$$\Rightarrow \dot{m}_{\text{in}}\hat{H}_{\text{in}}=\dot{m}_l\hat{H}_l+\dot{m}_v\hat{H}_v \xRightarrow{\dot{m}_v+\dot{m}_l} \underline{\underline{3149\text{ kJ / kg}}}=\dot{m}_l(417.5)+(1-\dot{m}_l)(2675.4)$$

There is no value of $\dot{m}_l$ between 0 and 1 that would satisfy this equation. (For any value in this range, the right-hand side would be between 417.5 and 2675.4). The two-phase assumption is therefore incorrect; the effluent must be pure vapor.

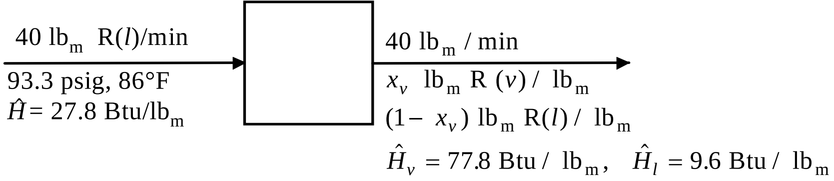
(c) Energy balance $\Rightarrow \dot{m}_{\text{out}}\hat{H}_{\text{out}}=\dot{m}_{\text{in}}\hat{H}_{\text{in}} \xRightarrow{\dot{m}_{\text{in}}=\dot{m}_{\text{out}}=1} 3149\text{ kJ / kg}=\hat{H}(1\text{ bar, T}_{\text{out}})$

$$\xRightarrow{\text{Table B.7}} T_{\text{out}}\approx\underline{\underline{337^\circ\text{C}}}$$

(This answer is only approximate, since $\Delta\dot{E}_k$ is not zero in this process).

7.39 Basis: $40\ \text{lb}_\text{m}/\text{min}$ circulation

(a) Expansion valve
R = Refrigerant 12



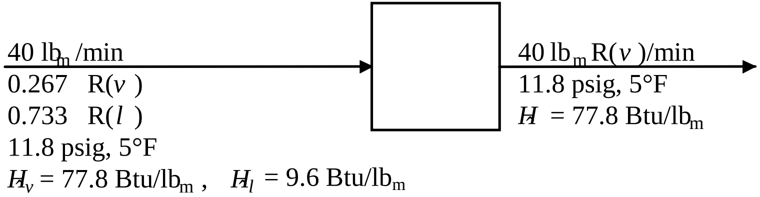
Energy balance: $\Delta\dot{E}_p,\ \dot{W}_s,\ \dot{Q}=0,$ neglect $\Delta\dot{E}_k\Rightarrow\Delta\dot{H}=\sum_{\text{out}}\dot{n}_i\hat{H}_i-\sum_{\text{in}}\dot{n}_i\hat{H}_i=0$

$$\frac{40X_v\ \text{lb}_\text{m}R(v)}{\text{min}}\left|\frac{77.8\text{ Btu}}{\text{lb}_\text{m}}\right.+\frac{40(1-X_v)\text{lb}_\text{m}R(l)}{\text{min}}\left|\frac{9.6\text{ Btu}}{\text{lb}_\text{m}}\right.-\frac{40\text{ lb}_\text{m}}{\text{min}}\left|\frac{27.8\text{ Btu}}{\text{lb}_\text{m}}\right.=0$$

$$\Downarrow$$

$$X_v=\underline{\underline{0.267}}\ (26.7\%\text{ evaporates})$$

(b) Evaporator coil



Energy balance: $\Delta\dot{E}_p,\ \dot{W}_s=0,$ neglect $\Delta\dot{E}_k\Rightarrow\dot{Q}=\Delta\dot{H}$

$$\dot{Q}=\frac{40\text{ lb}_\text{m}}{\text{min}}\left|\frac{77.8\text{ Btu}}{\text{lb}_\text{m}}\right.-\frac{(40)(0.267)\text{lb}_\text{m}R(v)}{\text{min}}\left|\frac{77.8\text{ Btu}}{\text{lb}_\text{m}}\right.-\frac{(40)(0.733)\text{lb}_\text{m}R(l)}{\text{min}}\left|\frac{9.6\text{ Btu}}{\text{lb}_\text{m}}\right.$$

$$=\underline{\underline{2000\ \text{Btu/min}}}$$

7.39 (cont'd)

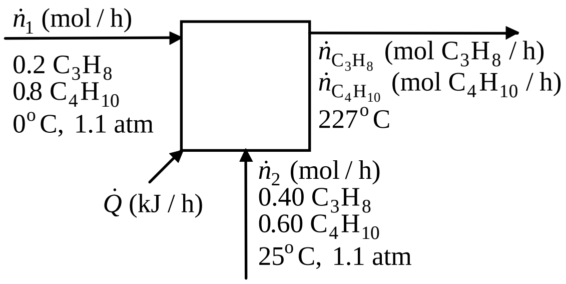
(c) We may analyze the overall process in several ways, each of which leads to the same result. Let us first note that the net rate of heat input to the system is

$$\dot{Q} = \dot{Q}_{\text{evaporator}} - \dot{Q}_{\text{condenser}} = 2000 - 2500 = -500 \text{ Btu/min}$$

and the compressor work W_c represents the total work done on the system. The system is closed (no mass flow in or out). Consider a time interval $\Delta t(\text{min})$. Since the system is at steady state, the changes ΔU, ΔE_k and ΔE_p over this time interval all equal zero. The total heat input is $\dot{Q}\Delta t$, the work input is $\dot{W}_c \Delta t$, and (Eq. 8.3-4) yields

$$\dot{Q}\Delta t - \dot{W}_c \Delta t = 0 \Rightarrow \dot{W}_c = \dot{Q} = \frac{-500 \text{ Btu}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| \frac{1.341 \times 10^{-3} \text{ hp}}{9.486 \times 10^{-4} \text{ Btu/s}} = \underline{\underline{11.8 \text{ hp}}}$$

7.40 Basis: Given feed rates



Molar flow rates of feed streams:

$$\dot{n}_1 = \frac{300 \text{ L}}{\text{hr}} \left| \frac{1.1 \text{ atm}}{1 \text{ atm}} \right| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} = 14.7 \text{ mol/h}$$

$$\dot{n}_2 = \frac{200 \text{ L}}{\text{hr}} \left| \frac{273 \text{ K}}{298 \text{ K}} \right| \frac{1.1 \text{ atm}}{1 \text{ atm}} \left| \frac{1 \text{ mol}}{22.4 \text{ L(STP)}} \right. = 9.00 \text{ mol/h}$$

Propane balance $\Rightarrow$ $\dot{n}_{C_3H_8} = \frac{14.7 \text{ mol}}{\text{h}} \left| \frac{0.20 \text{ mol } C_3H_8}{\text{mol}} \right. + \frac{9.00 \text{ mol}}{\text{h}} \left| \frac{0.40 \text{ mol } C_3H_8}{\text{mol}} \right.$

$= 6.54 \text{ mol } C_3H_8/\text{h}$

Total mole balance: $\dot{n}_{C_4H_{10}} = (14.7 + 9.00 - 6.54) \text{ mol } C_4H_{20}/\text{h} = 17.16 \text{ mol } C_4H_{20}/\text{h}$

Energy balance: $\Delta\dot{E}_p,\ \dot{W}_s = 0,$ neglect $\Delta\dot{E}_k \Rightarrow \dot{Q} = \Delta\dot{H}$

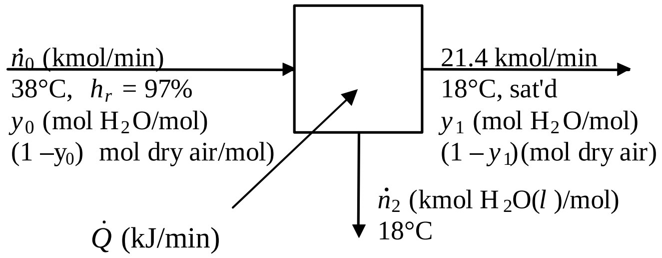
$$\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{N}_i \hat{H}_i - \sum_{\text{in}} \dot{N}_i \hat{H}_i = \frac{6.54 \text{ mol } C_3H_8}{\text{h}} \left| \frac{20.685 \text{ kJ}}{\text{mol}} \right. + \frac{17.16 \text{ mol } C_4H_{10}}{\text{h}} \left| \frac{27.442 \text{ kJ}}{\text{mol}} \right.$$

$$- \frac{(0.40 \times 9.00) \text{ mol } C_3H_8}{\text{h}} \left| \frac{1.772 \text{ kJ}}{\text{mol}} \right. - \frac{(0.60 \times 9.00) \text{ mol } C_4H_{10}}{\text{h}} \left| \frac{2.394 \text{ kJ}}{\text{mol}} \right. = \underline{\underline{587 \text{ kJ/h}}}$$

($\hat{H}_i = 0$ for components of 1st feed stream)

7.41 Basis: $\begin{array}{r|c|c|c|c} 510\text{ m}^3 & 273\text{ K} & 10^3\text{ L} & 1\text{ mol} & 1\text{ kmol} \\ \hline \text{min} & 291\text{ K} & \text{m}^3 & 22.4\text{ L(STP)} & 10^3\text{ mol} \end{array} = 21.4\ \text{kmol/min}$

(a)



Inlet condition: $y_o = \dfrac{h_r P^*_{H_2O}(38°\text{C})}{P} = \dfrac{0.97(49.692\text{ mm Hg})}{760\text{ mm Hg}} = 0.0634\text{ mol } H_2O/\text{mol}$

Outlet condition: $y_1 = \dfrac{P^*_{H_2O}(18°\text{C})}{P} = \dfrac{15.477\text{ mm Hg}}{760\text{ mm Hg}} = 0.0204\text{ mol } H_2O/\text{mol}$

Dry air balance: $(1-0.0634)\dot{n}_o = (1-0.0204)21.4 \Rightarrow \dot{n}_o = 22.4\ \text{kmol/min}$

Water balance: $(0.0634)22.4 = \dot{n}_2 + (0.0204)21.4 \Rightarrow \dot{n}_2 = 0.98\ \text{kmol/min}$

$$\begin{array}{r|r} 0.98\text{ kmol} & 18.02\text{ kg} \\ \hline \text{min} & \text{kmol} \end{array} = \underline{\underline{18\text{ kg / min } H_2O\text{ condenses}}}$$

(b). Enthaphies: $\hat{H}_{\text{air}}(38°\text{C}) = 0.0291(38-25) = 0.3783\ \text{kJ/mol}$

$\hat{H}_{\text{air}}(18°\text{C}) = 0.0291(18-25) = -0.204\ \text{kJ/mol}$

$$\left.\begin{aligned} \hat{H}_{H_2O}(v,\ 38°\text{C}) &= \begin{array}{r|r|r} 2570.8\text{ kJ} & 1\ \text{ kg} & 18.02\text{ g} \\ \hline \text{kg} & 10^3\text{ g} & \text{mol} \end{array} = 46.33\ \text{kJ/mol} \\ \hat{H}_{H_2O}(v,\ 18°\text{C}) &= \begin{array}{r|r|r} 2534.5\text{ kJ} & 1\ \text{ kg} & 18.02\text{ g} \\ \hline \text{kg} & 10^3\text{ g} & \text{mol} \end{array} = 45.67\ \text{kJ/mol} \\ \hat{H}_{H_2O}(l,\ 18°\text{C}) &= \begin{array}{r|r|r} 75.5\text{ kJ} & 1\text{ kg} & 18.02\text{ g} \\ \hline \text{kg} & 10^3\text{ g} & \text{mol} \end{array} = 1.36\ \text{kJ/mol} \end{aligned}\right\}\text{Table B.5}$$

Energy balance:

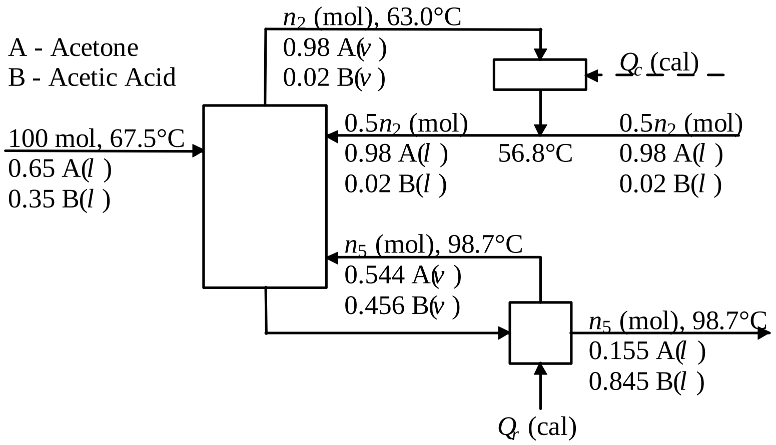
$$\underset{\Delta\dot{E}_p,\ \dot{W}_s=0,\ \Delta\dot{E}_k\cong 0}{}\quad \dot{Q} = \Delta\dot{H} = \sum_{\text{out}}\dot{n}_i\hat{H}_i - \sum_{\text{in}}\dot{n}_i\hat{H}_i \Rightarrow \dot{Q} = (1-0.0204)(21.4\times10^3)(-0.204)$$

$$+(0.0204)(21.4\times10^3)(45.67) + (0.98\times10^3)(1.36) - (1-0.0634)(22.4\times10^3)(0.3783)$$

$$-(0.0634)(22.4\times10^3)(46.33) = -5.67\times10^4\ \text{ kJ/min}$$

$$\Rightarrow \begin{array}{r|r|r|c} 5.67\times10^4\text{ kJ} & 60\text{ min} & 0.9486\text{ Btu} & 1\text{ ton cooling} \\ \hline \text{min} & \text{h} & \text{kJ} & 12000\text{ Btu} \end{array} = \underline{\underline{270\text{ tons of cooling}}}$$

7.42 Basis: 100 mol feed



(a) Overall balances:

$$\left.\begin{array}{l}\text{Total moles: } 100 = 0.5n_2 + n_5 \\ A\text{: } 0.65(100) = 0.98(0.5n_2) + 0.155n_5\end{array}\right\} \begin{array}{l} n_2 = 120 \text{ mol} \\ n_5 = 40 \text{ mol}\end{array}$$

Product flow rates: Overhead $0.5(120)0.98 = 58.8 \text{ mol } A$

$0.5(120)0.02 = 1.2 \text{ mol } B$

Bottoms $0.155(40) = 6.2 \text{ mol } A$

$0.845(40) = 33.8 \text{ mol } B$

$$\underset{\Delta E_p,\ W_s=0,\ \Delta E_k\cong 0}{\underline{\text{Overall energy balance:}}}\quad Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

$$\Rightarrow Q = 58.8(0) + 1.2(0) + 6.2(1385) + 33.8(1312) - 65\Big(\overset{\substack{\text{interpolate in table}\\ \downarrow}}{354}\Big) - 35\Big(\overset{\substack{\text{interpolate in table}\\ \downarrow}}{335}\Big) = \underline{\underline{1.82 \times 10^4 \text{ cal}}}$$

(b) Flow through condenser: $2(58.8) = 117.6 \text{ mols } A$

$2(1.2) = 2.4 \text{ mols } B$

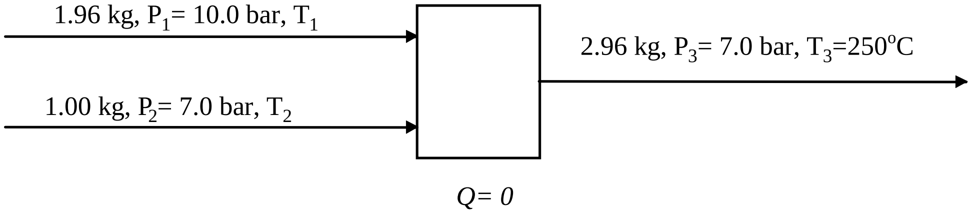
$$\underset{\Delta E_p,\ W_s=0,\ \Delta E_k\cong 0}{\underline{\text{Energy balance on condenser:}}}\quad Q_c = \Delta H$$

$Q_c = 117.6(0 - 7322) + 2.4(0 - 6807) = \underline{\underline{-8.77 \times 10^5 \text{ cal}}}$ heat removed from condenser

Assume negligible heat transfer between system & surroundings other than Q_c & Q_r

$Q_r = Q - Q_c = 1.82 \times 10^4 - \left(-8.77 \times 10^5\right) = \underline{\underline{8.95 \times 10^5 \text{ cal}}}$ heat added to reboiler

7.43



7.43 (cont'd)

(a) $T_2 = T(P = 7.0 \text{ bar, sat'd steam}) = \underline{\underline{165.0\ ^{\text{o}}\text{C}}}$

$\hat{H}_3(\text{H}_2\text{O}(v),\ \text{P} = 7.0 \text{ bar},\ \text{T} = 250\ ^{\text{o}}\text{C}) = 2954\ \text{kJ/kg}$ (Table B.7)

$\hat{H}_2(\text{H}_2\text{O}(v),\ \text{P} = 7.0 \text{ bar, sat'd}) = 2760\ \text{kJ/kg}$ (Table B.6)

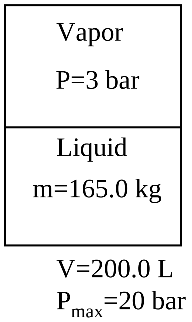
$$\underset{\Delta E_p,\, Q,\, W_s,\, \Delta E_k \cong 0}{\underline{\text{Energy balance}}}$$

$$\Delta H = 0 = 2.96\hat{H}_3 - 1.96\hat{H}_1 - 1.0\hat{H}_2 \Rightarrow 1.96\hat{H}_1 = 2.96 \text{ kg}(2954 \text{ kJ / kg}) \text{ - } 1.0 \text{ kg}(2760 \text{ kJ / kg})$$

$$\Rightarrow \hat{H}_1(10.0 \text{ bar, } \text{T}_1) = 3053 \text{ kJ / kg} \Rightarrow \underline{\underline{\text{T}_1 \cong 300^\circ \text{C}}}$$

(b) The estimate is <u>too low</u>. If heat is being lost the entering steam temperature would have to be higher for the exiting steam to be at the given temperature.

7.44 **(a)** $T_1 = T(P = 3.0 \text{ bar, sat'd.}) = \underline{\underline{133.5^\circ \text{C}}}$



$\hat{V}_l(P = 3.0 \text{ bar, sat'd.}) = 0.001074 \text{ m}^3 \text{ / kg}$

$\hat{V}_v(P = 3.0 \text{ bar, sat'd.}) = 0.606 \text{ m}^3 \text{ / kg}$

$$V_l = \frac{0.001074 \text{ m}^3}{\text{kg}}\left|\frac{1000 \text{ L}}{\text{m}^3}\right|\frac{165 \text{ kg}}{} = \underline{\underline{177.2 \text{ L}}}$$

$$V_{space} = 200.0 \text{ L - } 177.2 \text{ L} = \underline{\underline{22.8 \text{ L}}}$$

$$m_v = \frac{22.8 \text{ L}}{}\left|\frac{1 \text{ m}^3}{1000 \text{ L}}\right|\frac{1 \text{ kg}}{0.606 \text{ m}^3} = \underline{\underline{0.0376 \text{ kg}}}$$

(b) $P = P_{\max} = 20.0 \text{ bar};\qquad m_{total} = 165.0 + 0.0376 = 165.04 \text{ kg}$

$T_1 = T(P = 20.0 \text{ bar, sat'd.}) = \underline{\underline{212.4^\circ \text{C}}}$

$\hat{V}_l(P = 20.0 \text{ bar, sat'd.}) = 0.001177 \text{ m}^3 \text{ / kg};\ \ \hat{V}_v(P = 20.0 \text{ bar, sat'd.}) = 0.0995 \text{ m}^3 \text{ / kg}$

$$V_{total} = m_l\hat{V}_l + m_v\hat{V}_v \Rightarrow m_l\hat{V}_l + (m_{total} - m_l)\hat{V}_v$$

$$\Rightarrow \frac{200.0 \text{ L}}{}\left|\frac{1 \text{ m}^3}{1000 \text{ L}}\right. = m_l \text{ kg}(0.001177 \text{ m}^3 \text{ / kg}) + (165.04 \text{ - } m_l)\text{kg}(0.0995 \text{ m}^3 \text{ / kg})$$

$$\Rightarrow m_l = 164.98 \text{ kg};\ \ m_v = 0.06 \text{ kg}$$

$$V_l = \frac{0.001177 \text{ m}^3}{\text{kg}}\left|\frac{1000 \text{ L}}{\text{m}^3}\right|\frac{164.98 \text{ kg}}{} = \underline{\underline{194.2 \text{ L}}};\quad V_{space} = 200.0 \text{ L - } 194.2 \text{ L} = \underline{\underline{5.8 \text{ L}}}$$

$$m_{evaporated} = \frac{(0.06 \text{ - } 0.04) \text{ kg}}{}\left|\frac{1000 \text{ g}}{\text{kg}}\right. = \underline{\underline{20 \text{ g}}}$$

(c) $\underset{\Delta E_p,\, W_s,\, \Delta E_k \cong 0}{\underline{\text{Energy balance}}}$ $\text{Q} = \Delta U = U(P = 20.0 \text{ bar, sat'd}) - U(P = 3.0 \text{ bar, sat'd})$

$\hat{U}_l(P = 20.0 \text{ bar, sat'd.}) = 906.2 \text{ kJ / kg};\ \ \hat{U}_v(P = 20.0 \text{ bar, sat'd.}) = 2598.2 \text{ kJ / kg}$

$\hat{U}_l(P = 3.0 \text{ bar, sat'd.}) = 561.1 \text{ kJ / kg};\ \ \hat{U}_v(P = 3.0 \text{ bar, sat'd.}) = 2543 \text{ kJ / kg}$

$$Q = 0.06 \text{ kg}(2598.2 \text{ kJ / kg}) + 164.98 \text{ kg}(906.2 \text{ kJ / kg}) \text{ - } 0.04 \text{ kg}(2543 \text{ kJ / kg})$$
$$- 165.0 \text{ kg } (561.1 \text{ kJ / kg}) = \underline{\underline{5.70 \times 10^4 \text{ kJ}}}$$

Heat lost to the surroundings, energy needed to heat the walls of the tank

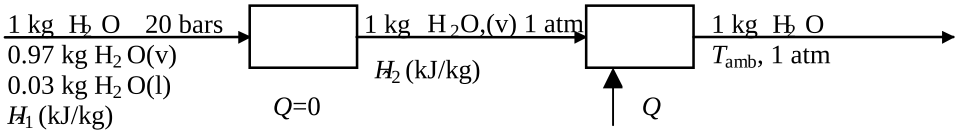
7.44 (cont'd)

(d) (i) The specific volume of liquid increases with the temperature, hence the same mass of liquid water will occupy more space; (ii) some liquid water vaporizes, and the lower density of vapor leads to a pressure increase; (iii) the head space is smaller as a result of the changes mentioned above.

(e) – Using an automatic control system that interrupts the heating at a set value of pressure
– A safety valve for pressure overload.
– Never leaving a tank under pressure unattended during operations that involve temperature and pressure changes.

7.45 Basis: 1 kg wet steam

(a)



Enthalpies: $\hat{H}(v,\ 20\text{ bars, sat'd}) = 2797.2\ \text{kJ/kg}$, $\hat{H}(l,\ 20\text{ bars, sat'd}) = 908.6\ \text{kJ/kg}$ (Table B.7)

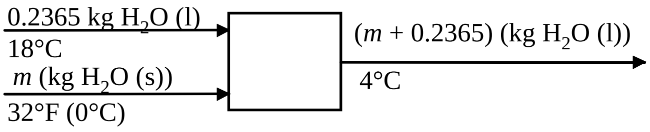
$$\underset{\Delta E_p,\,\Delta E_k,\,Q,\,W_s=0}{\underline{\text{Energy balance on condenser:}}}\quad \Delta H = 0 \Rightarrow \hat{H}_2 = \hat{H}_1 = 0.97(2797.2) + 0.03(908.6)$$

$$\Rightarrow \hat{H}_2 = 2740\text{ kJ / kg} \xrightarrow{\text{Table B.7}} \underline{\underline{T \approx 132^\circ\text{C}}}$$

(b) As the steam (which is transparent) moves away from the trap, it cools. When it reaches its saturation temperature at 1 atm, it begins to condense, so that $\underline{\underline{T = 100^\circ\text{C}}}$. The white plume is a mist formed by liquid droplets.

7.46 Basis:
$$\frac{8\text{ oz } H_2O(l)}{} \Big| \frac{1\text{ quart}}{32\text{ oz}} \Big| \frac{1\text{ m}^3}{1057\text{ quarts}} \Big| \frac{1000\text{ kg}}{\text{m}^3} = 0.2365\text{ kg } H_2O(l)$$

(For simplicity, we assume the beverage is water)



Assume $P = 1$ atm

Enthalpies (from Table B.5):
$\hat{H}(H_2O(l),\ 18°C) = 75.5$ kJ/kg; $\hat{H}(H_2O(l),\ 4°C) = 16.8$ kJ/kg; $\hat{H}(H_2O(s),\ 0°C) = -348$ kJ/kg

$$\underset{\Delta E_p,\ \Delta E_k,\ Q,\ W=0}{\underline{\text{Energy balance (closed isobaric system):}}}\ \Rightarrow \Delta H = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = 0$$

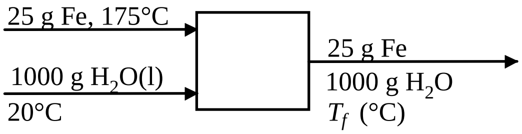
$$\Rightarrow (m + 0.2365)\text{kg}(16.8\text{ kJ / kg}) = 0.2365\text{ kg}(75.5\text{ kJ / kg}) + m\text{ kg }(-348\text{ kJ / kg})$$

$$\Rightarrow m = 0.038\text{ kg} = \underline{\underline{38\text{ g ice}}}$$

7.47 **(a)** When $T = 0^{\circ}\mathrm{C},\ \hat{H} = 0,\ \Rightarrow \underline{\underline{\mathrm{T_{ref}} = 0^{\circ}\mathrm{C}}}$

(b) Energy Balance-Closed System: $\Delta U = 0$

$\Delta E_k, \Delta E_p, Q, W = 0$



$$U_{\mathrm{Fe}}\left(T_f\right) + U_{\mathrm{H_2O}}\left(T_f\right) - U_{\mathrm{Fe}}\left(175^{\circ}\ \mathrm{C}\right) - U_{\mathrm{H_2O}}\left(20^{\circ}\ \mathrm{C},\ 1\ \mathrm{atm}\right) = 0 \ \text{ or } \ \Delta U_{\mathrm{Fe}} + \Delta U_{\mathrm{H_2O}} = 0$$

$$\Delta U_{\mathrm{Fe}} = \frac{25.0\ \mathrm{g}}{} \left| \frac{4.13\left(T_f - 175\right)\mathrm{cal}}{\mathrm{g}} \right| \frac{4.184\ \ \mathrm{J}}{\mathrm{cal}} = 432\left[T_f - 175\right]\mathrm{J}$$

$$\text{Table B.5} \Rightarrow \Delta U_{\mathrm{H_2O}} = \frac{1.0\ \ \mathrm{L}}{} \left| \frac{10^3\ \ \mathrm{g}}{1\ \ \mathrm{L}} \right| \frac{\left(\hat{U}_{\mathrm{H_2O}}\left(T_f\right) - 83.9\right)\mathrm{J}}{\mathrm{g}} = 1000\left(\hat{U}_{\mathrm{H_2O}}\left(T_f\right) - 83.9\right)\mathrm{J}$$

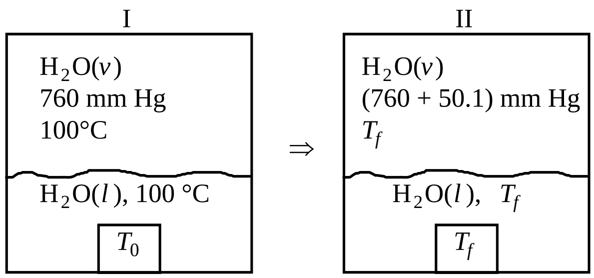
$$\Rightarrow 432T_f + 1000\hat{U}_{\mathrm{H_2O}}\left(T_f\right) - 1.60 \times 10^5 = f\left(T_f\right) = 0$$

⇒

T_f °C	30	40	35	34
$f\left(T_f\right)$	-2.1×10^4	$+2.5 \times 10^4$	1670	−2612

$\xRightarrow{\text{Interpolate}} \underline{\underline{T_f = 34.6^{\circ}\mathrm{C}}}$

7.48



⇒ 1.08 bar sat'd
⇒ T_f = 101.8°C (Table 8.5)

Energy balance - closed system:

$\Delta E_p,\ \Delta E_K,\ W,\ Q = 0$

$$\Delta U = 0 = m_v^{\mathrm{II}}\hat{U}_v^{\mathrm{II}} + m_l^{\mathrm{II}}\hat{U}_l^{\mathrm{II}} + m_b^{\mathrm{II}}\hat{U}_b^{\mathrm{II}} - m_v^{\mathrm{I}}\hat{U}_v^{\mathrm{I}} - m_l^{\mathrm{I}}\hat{U}_l^{\mathrm{I}} - m_b^{\mathrm{I}}\hat{U}_b^{\mathrm{I}}$$

v-vapor
l-liquid
b-block

	$I(1.01\text{ bar},\ 100°\text{C})$	$II(1.08\text{ bar},\ 101.8°\text{C})$
$\hat{V}_l$ (L/kg)	1.044	1.046
$\hat{V}_v$ (L/kg)	1673	1576
$\hat{U}_l$ (L/kg)	419.0	426.6
$\hat{U}_v$ (L/kg)	2506.5	2508.6

Initial vapor volume: $V_v^{\mathrm{I}} = 20.0\text{ L} - 5.0\text{ L} - \begin{array}{c|c} 50\text{ kg} & 1\text{ L} \\ \hline & 8.92\text{ kg} \end{array} = 14.4\text{ L H}_2\text{O}(v)$

Initial vapor mass: $m_v^{\mathrm{I}} = 14.4\text{ L}/(1673\text{ L/kg}) = 8.61 \times 10^{-3}\text{ kg H}_2\text{O}(v)$

Initial liquid mass: $m_l^{\mathrm{I}} = 5.0\text{ L}/(1.044\text{ L/kg}) = 4.79\text{ kg H}_2\text{O}(l)$

Final energy of bar: $\hat{U}_b^{\mathrm{II}} = 0.36(101.8) = 36.6\text{ kJ/kg}$

Assume negligible change in volume & liquid $\Rightarrow V_v^{\mathrm{II}} = 14.4\text{ L}$

Final vapor mass: $m_v^{\mathrm{II}} = 14.4\text{ L}/(1576\text{ L/kg}) = 9.14 \times 10^{-3}\text{ kg H}_2\text{O}(v)$

Initial energy of the bar:

$$\hat{U}_b^{\mathrm{I}} = \frac{1}{5.0\text{ kg}}\left(9.14\times10^{-3}(2508.6) + 4.79(426.6) + 5.0(36.6) - 8.61\times10^{-3}(2506.5) - 4.79(419.0)\right)$$
$$= 44.1\text{ kJ/kg}$$

(a) Oven Temperature: $T_o = \dfrac{44.1\text{ kJ / kg}}{0.36\text{ kJ / kg}\cdot{}^\circ\text{C}} = \underline{\underline{122.5°\text{C}}}$

$\text{H}_2\text{O}_{\text{evaporated}} = m_v^{\mathrm{II}} - m_v^{\mathrm{I}} = 9.14\times10^{-3}\text{ kg} - 8.61\times10^{-3}\text{ kg} = 5.30\times10^{-4}\text{ kg} = \underline{\underline{0.53\text{ g}}}$

(b) $\hat{U}_b^{\mathrm{I}} = 44.1 + 8.3/5.0 = 45.8\text{ kJ/kg}$

$T_o = 45.8/0.36 = \underline{\underline{127.2°\text{C}}}$

(c) Meshuggeneh forgot to turn the oven on ($T_o < 100°\text{C}$)

7.49 **(a)** Pressure in cylinder $= \dfrac{\text{weight of piston}}{\text{area of piston}} + \text{atmospheric pressure}$

$$P = \frac{30.0\text{ kg}}{400.0\text{ cm}^2}\left|\frac{9.807\text{ N}}{\text{kg}}\right|\frac{(100\text{ cm})^2}{1^2(\text{m})^2}\left|\frac{1.0\text{ bar}}{10^5\text{ N/m}^2}\right. + \frac{1\text{ atm}}{}\left|\frac{1.013\text{ bar}}{\text{atm}}\right. = \underline{\underline{1.08\text{ bar}}}$$

$$\Rightarrow T_{sat} = 101.8°\text{C}$$

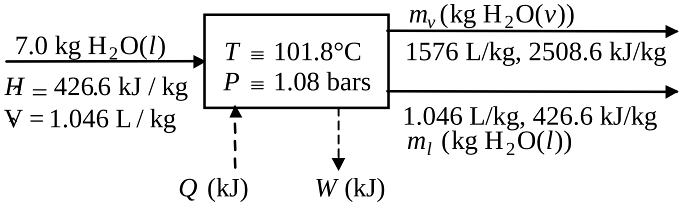
Heat required to bring the water and block to the boiling point

$$Q = \Delta U = m_w\left(\hat{U}_{wl}(1.08\text{ bar, sat'd}) - \hat{U}_{wl}(\text{l, }20°\text{C})\right) + m_{Al}\left(\hat{U}_{Al}(T_{sat}) - \hat{U}_{Al}(20°\text{C})\right)$$

$$= \frac{7.0\text{ kg}}{}\left|\frac{(426.6-83.9)\text{kJ}}{\text{kg}}\right. + \frac{3.0\text{ kg}}{}\left|\frac{[0.94(101.8-20)]\text{kJ}}{\text{kg}}\right. = 2630\text{ kJ}$$

2630 kJ < 3310 kJ ⇒ $\underline{\underline{\text{Sufficient heat for vaporization}}}$

(b) $\underline{\underline{T_f = T_{sat} = 101.8°\text{C}}}$. Table B.5 ⇒ $\begin{array}{l}\hat{V}_l = 1.046\text{ L/kg},\ \hat{U}_l = 426.6\text{ kJ/kg}\\ \hat{V}_v = 1576\text{ L/kg},\ \hat{U}_v = 2508.6\text{ kJ/kg}\end{array}$



(Since the Al block stays at the same temperature in this stage of the process, we can ignore it -i.e., $\hat{U}_{\text{in}} = \hat{U}_{\text{out}}$)

Water balance: $7.0 = m_l + m_v$ **(1)**

Work done by the piston: $W = F\Delta z = \left[w_{\text{piston}} + P_{\text{atm}}A\right]\Delta z$

$$= \left[\frac{w}{A} + P_{\text{atm}}\right](A\Delta z) = P\Delta V \Rightarrow W = (1.08\text{ bar})\left[1576m_v + 1.046m_l - (1.046)(7.0)\right]\text{ L}$$

$$\times \frac{8.314\text{ J / mol}\cdot\text{K}}{0.08314\text{ liter - bar / mol}\cdot\text{K}}\left|\frac{1\text{ kJ}}{10^3\text{ J}}\right. = (170.2m_v + 0.113m_l - 0.7908)\text{kJ}$$

Energy balance: $\Delta U = Q - W$

$$\Rightarrow \overbrace{2508.6m_v + 426.6m_L - 426.6(7)}^{\Delta U} = \overbrace{(3310-2630)}^{Q} - \overbrace{(170.2m_v + 0.113m_L - 0.7908)}^{W}$$

$$\Rightarrow 2679m_v + 426.7m_L - 3667 = 0 \quad \textbf{(2)}$$

Solving (1) and (2) simultaneously yields $m_v = 0.302$ kg, $m_l = 6.698$ kg

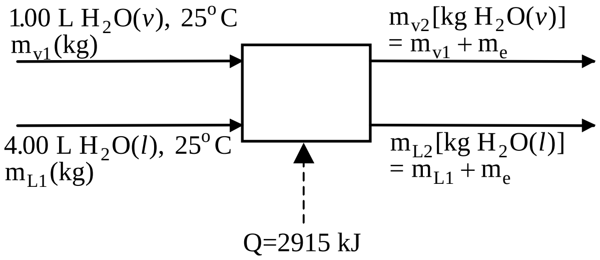
Liquid volume $= (6.698\text{ kg})(1.046\text{ L/kg}) = \underline{\underline{7.01\text{ L liquid}}}$

Vapor volume $= (0.302\text{ kg})(1576\text{ L/kg}) = \underline{\underline{476\text{ L vapor}}}$

Piston displacement: $\Delta z = \dfrac{\Delta V}{A} = \dfrac{[7.01 + 476 - (7.0)(1.046)]\text{L}}{}\left|\dfrac{10^3\text{ cm}^3}{1\text{ L}}\right|\dfrac{1}{400\text{ cm}^2} = \underline{\underline{1190\text{ cm}}}$

(c) T_{upper} ⇒ All 3310 kJ go into the block before a measurable amount is transferred to the water. Then $\Delta U_{AL} = Q \Rightarrow (3.0\text{ kg})\left[0.94(T_u - 20)\text{ kJ/kg}\right] = 3310 \Rightarrow T_u = 1194°\text{C}$ *if melting is neglected.* In fact, the bar would melt at $\underline{660^{\text{o}}\text{C}}$.

7.50



$\left.\right\}$ Assume not all the liquid is vaporized. Eq. at T_f, P_f. m_e = kg H_2O vaporized.

<u>Initial conditions:</u> Table B.5 $\Rightarrow \hat{U}_{L1} = 104.8$ kJ/kg, $\hat{V}_{L1} = 1.003$ L/kg $P = 0.0317$ bar

$T = 25°\text{C, sat'd} \Rightarrow \hat{U}_{v1} = 2409.9$ kJ/kg, $\hat{V}_{L1} = 43{,}400$ L/kg

$m_{v1} = (1.00\text{ l})/(43400\text{ l/kg}) = 2.304\times10^{-5}$ kg, $m_{LI} = (4.00\text{ l})/(1.003\text{ l/kg}) = 3.988$ kg

<u>Energy balance:</u>

$$\Delta U = Q \Rightarrow \left(2.304\times10^{-5} + m_e\right)\hat{U}_v\left(T_f\right) + \left(3.988 - m_e\right)\hat{U}_L\left(T_f\right) - \left(2.304\times10^{-5}\right)(2409.9)$$
$$-(3.988)(104.8) = 2915\text{ kJ}$$

$$\Rightarrow \left(2.304\times10^{-5} + m_e\right)\hat{U}_v\left(T_f\right) + \left(3.988 - m_e\right)\hat{U}_v\left(T_f\right) = 3333$$
$$\Downarrow$$
$$\Rightarrow m_e = \frac{3333 - \left(2.304\times10^{-5}\right)\hat{U}_v - 3.988\hat{U}_L}{\hat{U}_v - \hat{U}_L} \qquad \textbf{(1)}$$

$$\underline{V_L + V_v = V_{\text{tank}}} \Rightarrow \left(2.304\times10^{-5} + \underset{\overset{\uparrow}{\text{kg}}}{m_e}\right)\underset{\overset{\uparrow}{\text{liters/kg}}}{\hat{V}_L}\left(T_f\right) + \left(3.988 - m_e\right)\hat{V}_L\left(T_f\right) = 5.00\text{ L}$$

$$\Rightarrow m_e = \frac{5.00 - \left(2.304\times10^{-5}\right)\hat{V}_v - 3.988\hat{V}_L}{\hat{V}_v - \hat{V}_L} \qquad (2)$$

$$(1)-(2) \Rightarrow f\left(T_f\right) = \frac{3333 - \left(2.304\times10^{-5}\right)\hat{U}_v\left(T_f\right) - 3.988\hat{U}_L\left(T_f\right)}{\hat{U}_v - \hat{U}_L}$$
$$-\frac{5.00 - \left(2.304\times10^{-5}\right)\hat{V}_v - 3.988\hat{V}_L}{\hat{V}_v - \hat{V}_L} = 0$$

<u>Procedure:</u> Assume $T_f \overset{\text{Table 8.5}}{\Rightarrow} \hat{U}_v,\ \hat{U}_L,\ \hat{V}_v,\ \hat{V}_L \Rightarrow f\left(T_f\right)$ Find T_f such that $f\left(T_f\right) = 0$

T_f	$\hat{U}_v$	$\hat{U}_L$	$\hat{V}_v$	$\hat{V}_L$	f
201.4	2593.8	856.7	123.7	1.159	-5.12×10^{-2}
198.3	2592.4	842.9	131.7	1.154	-1.93×10^{-2}
195.0	2590.8	828.5	140.7	1.149	1.34×10^{-2}
196.4	2591.5	834.6	136.9	1.151	-4.03×10^{-4}

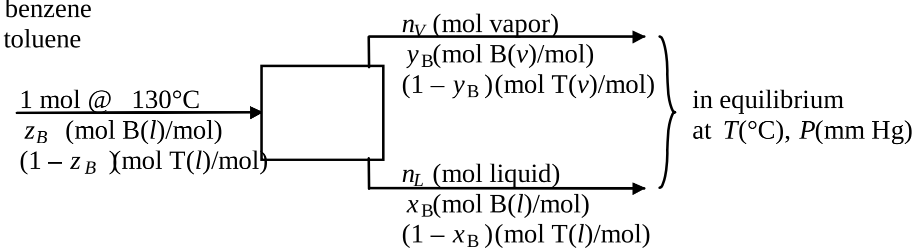
$\Rightarrow \underline{\underline{T_f \cong 196.4°\text{C},\ P_f = 14.4\text{ bars}}}$

$$\xrightarrow[\text{or Eq}(2)]{\text{Eq}(1)} m_e = 2.6\times10^{-3}\text{ kg} \Rightarrow \underline{\underline{\text{2.6 g evaporated}}}$$

7.51. Basis: 1 mol feed

B = benzene

T = toluene



(a) 7 variables: $(n_V, y_B, n_L, x_B, Q, T, P)$

–2 equilibrium equations

–2 material balances

–1 energy balance

2 degrees of freedom. If T and P are fixed, we can calculate n_V, y_B, n_L, x_B, and Q.

(b) Mass balance: $n_V + n_L = 1 \Rightarrow n_V = 1 - n_2$ **(1)**

Benzene balance: $z_B = n_V y_B + n_L x_B$ **(2)**

$C_6H_6(l)$: $(T=0,\ \hat{H}=0),\ (T=80,\ \hat{H}=10.85) \Rightarrow \hat{H}_{BL} = 0.1356T$ **(3)**

$C_6H_6(v)$: $(T=80,\ \hat{H}=41.61),(T=120,\ \hat{H}=45.79) \Rightarrow \hat{H}_{BV} = 0.1045T + 33.25$ **(4)**

$C_7H_8(l)$: $(T=0,\ \hat{H}=0),\ (T=111,\ \hat{H}=18.58) \Rightarrow \hat{H}_{TL} = 0.1674T$ **(5)**

$C_7H_8(v)$: $(T=89,\ \hat{H}=49.18),\ (T=111,\ \hat{H}=52.05) \Rightarrow \hat{H}_{TV} = 0.1304T + 37.57$ **(6)**

Energy balance: $\Delta E_p,\ W_s = 0,$ neglect ΔE_k

$$Q = \Delta H = n_V y_B \hat{H}_{BV} + n_V(1-y_B)\hat{H}_{TV} + n_L x_B \hat{H}_{BL} + n_L(1-x_B)\hat{H}_{TL} - (1)z_B\hat{H}_{BL}(T_F) - (1)(1-z_B)\hat{H}_{TL}(T_F) \qquad \textbf{(7)}$$

Raoult's Law: $y_B P = x_B p_B^*$ **(8)**

$(1 - y_B)P = (1 - x_B)p_T^*$ **(9)**

Antoine Equation. For T= 90°C and P=652 mmHg:

$$p_B^*(90^o\text{C}) = 10^{[6.89272-1203.531/(90+219.888)]} = 1021 \text{ mmHg}$$

$$p_T^*(90^o\text{C}) = 10^{[6.95805-1346.773/(90+219.693)]} = 406.7 \text{ mmHg}$$

Adding equations (8) and (9) $\Rightarrow$

$$P = x_B p_B^* + (1-x_B)p_T^* \Rightarrow x_B = \frac{P - p_T^*}{p_B^* - p_T^*} = \frac{P - p_T^*}{p_B^* - p_T^*} = \frac{652 - 406.7}{1021 - 406.7} = \underline{\underline{0.399 \text{ mol B}(l)/\text{mol}}}$$

$$y_B = \frac{x_B p_B^*}{P} = \frac{0.399(1021 \text{ mmHg})}{652 \text{ mmHg}} = \underline{\underline{0.625 \text{ mol B}(v)/\text{mol}}}$$

Solving (1) and (2) $\Rightarrow$ $n_V = \dfrac{z_B - x_B}{y_B - x_B} = \dfrac{0.5 - 0.399}{0.625 - 0.399} = \underline{\underline{0.446 \text{ mol vapor}}}$

$$n_L = 1 - n_V = 1 - 0.446 = \underline{\underline{0.554 \text{ mol liquid}}}$$

7.51 (cont'd)

Substituting (3), (4), (5), and (6) in (7) ⇒

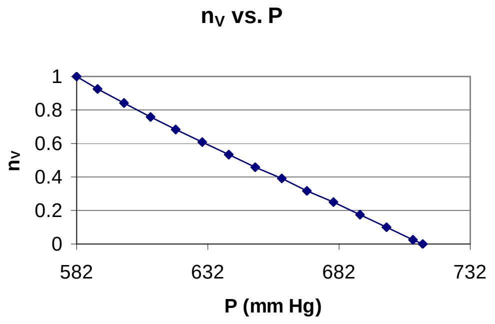
$$Q = 0.446(0.625)[0.1045(90) + 33.25] + 0.446(1 - 0.625)[0.1304(90) + 37.57]$$
$$+ 0.554(0.399)[0.1356(90)] + 0.554(1 - 0.399)[0.1674(90)] - 0.5[0.1356(130)]$$
$$- 0.5[0.1674(130)] \Rightarrow Q = \underline{\underline{8.14 \text{ kJ / mol}}}$$

(c). If P<P$_{\text{min}}$, all the output is vapor. If P>P$_{\text{max}}$, all the output is liquid.

(d) At P=652 mmHg it is necessary to add heat to achieve the equilibrium and at P=714 mmHg, it is necessary to release heat to achieve the equilibrium. The higher the pressure, there is more liquid than vapor, and the liquid has a lower enthalpy than the equilibrium vapor: enthalpy out < enthalpy in.

z_B	T	P	p_B	p_T	x_B	y_B	n_V	n_L	Q
0.5	90	652	1021	406.7	0.399	0.625	0.446	0.554	8.14
0.5	90	714	1021	406.7	0.500	0.715	-0.001	1.001	-6.09
0.5	90	582	1021	406.7	0.285	0.500	0.998	0.002	26.20
0.5	90	590	1021	406.7	0.298	0.516	0.925	0.075	23.8
0.5	90	600	1021	406.7	0.315	0.535	0.840	0.160	21.0
0.5	90	610	1021	406.7	0.331	0.554	0.758	0.242	18.3
0.5	90	620	1021	406.7	0.347	0.572	0.680	0.320	15.8
0.5	90	630	1021	406.7	0.364	0.589	0.605	0.395	13.3
0.5	90	640	1021	406.7	0.380	0.606	0.532	0.468	10.9
0.5	90	650	1021	406.7	0.396	0.622	0.460	0.540	8.60
0.5	90	660	1021	406.7	0.412	0.638	0.389	0.611	6.31
0.5	90	670	1021	406.7	0.429	0.653	0.318	0.682	4.04
0.5	90	680	1021	406.7	0.445	0.668	0.247	0.753	1.78
0.5	90	690	1021	406.7	0.461	0.682	0.176	0.824	-0.50
0.5	90	700	1021	406.7	0.477	0.696	0.103	0.897	-2.80
0.5	90	710	1021	406.7	0.494	0.710	0.029	0.971	-5.14

(e). $P_{\max} = 714 \text{ mmHg}, \; P_{\min} = 582 \text{ mmHg}$



$$\underline{\underline{n_V = 0.5 \text{ @ } P \cong 640 \text{ mmHg}}}$$

7.52 (a). Bernoulli equation: $\dfrac{\Delta P}{\rho}+\dfrac{\Delta u^2}{2}+g\Delta z=0$

$$\frac{\Delta P}{\rho}=\begin{array}{l|l|l}\left(0.977\times10^{-5}-1.5\times10^{5}\right)\text{Pa} & 1\ \text{N}/\text{m}^2 & \text{m}^3\\ \hline & \text{Pa} & 1.12\times10^{3}\ \text{kg}\end{array}=-46.7\,\frac{\text{m}^2}{\text{s}^2}$$

$$g\Delta z=(9.8066\ \text{m}/\text{s}^2)(6)\text{m}=58.8\ \text{m}^2\ /\ \text{s}^2$$

$$\underline{\text{Bernoulli}}\Rightarrow\frac{\Delta u^2}{2}=\left(46.7-58.8\right)\ \text{m}^2\ /\ \text{s}^2\Rightarrow u_2^2=u_1^2+2\left(-12.1\ \text{m}^2\ /\ \text{s}^2\right)$$

$$=\left(5.00\right)^2\ \text{m}^2\ /\ \text{s}^2-(2)(12.1)\ \text{m}^2\ /\ \text{s}^2=0.800\ \text{m}^2\ /\ \text{s}^2\Rightarrow u_2=\underline{\underline{0.894\ \text{m}/\text{s}}}$$

(b). Since the fluid is incompressible, $\dot{V}\left(m^3/s\right)=\pi d_1^2\,u_1/4=\pi d_2^2\,u_2/4$

$$\Rightarrow d_1=d_2\sqrt{\frac{u_2}{u_1}}=\left(6\ \text{cm}\right)\sqrt{\frac{0.894\ \text{m/s}}{5.00\ \text{m/s}}}=\underline{\underline{2.54\ \text{cm}}}$$

7.53 (a). $\dot{V}\left(\text{m}^3/\text{s}\right)=A_1\left(\text{m}^2\right)u_1\left(\text{m/s}\right)=A_2\left(\text{m}^2\right)u_2\left(\text{m/s}\right)\Rightarrow u_2=u_1\dfrac{A_1}{A_2}\xrightarrow{A_1=4A_2}\underline{\underline{u_2=4u_1}}$

(b). Bernoulli equation ($\Delta z=0$)

$$\frac{\Delta P}{\rho}+\frac{\Delta u^2}{2}=0\Rightarrow\Delta P=P_2-P_1=-\frac{\rho\left(u_2^2-u_1^2\right)}{2}$$

Multiply both sides by -1

Substitute $u_2^2=16u_1^2$

Multiply top and bottom of right - hand side by A_1^2

note $\dot{V}^2=A_1^2u_1^2$

$$\Downarrow$$

$$\underline{\underline{P_1-P_2=\frac{15\rho\dot{V}^2}{2A_1^2}}}$$

(c) $P_1-P_2=\left(\rho_{\text{Hg}}-\rho_{\text{H}_2\text{O}}\right)gh=\dfrac{15\rho_{\text{H}_2\text{O}}\dot{V}^2}{2A_1^2}\Rightarrow\dot{V}^2=\dfrac{2A_1^2gh}{15}\left(\dfrac{\rho_{\text{Hg}}}{\rho_{\text{H}_2\text{O}}}-1\right)$

$$\dot{V}^2=\begin{array}{c|c|c|c|c|c}2\left[\pi(7.5)^2\right]^2\text{cm}^4 & 1\quad \text{m}^4 & 9.8066\ \text{m} & 38\ \text{cm} & 1\ \text{m} & (13.6-1)\\ \hline 15 & 10^8\ \text{cm}^4 & \text{s}^2 & & 10^2\ \text{cm} & \end{array}=1.955\times10^{-3}\ \frac{\text{m}^6}{\text{s}^2}$$

$$\Rightarrow\dot{V}=0.044\ \text{m}^3/\text{s}=\underline{\underline{44\ \text{L/s}}}$$

7.54 **(a)**. Point 1 - surface of fluid. $P_1 = 3.1$ bar, $z_1 = +7\text{m}$, $u_1 = 0(\text{m/s})$

Point 2 - discharge pipe outlet. $\underset{(=1.013\text{ bar})}{P_2 = 1\text{ atm}}$, $z_2 = 0(\text{m})$, $u_2 = ?$

$$\frac{\Delta\rho}{\rho} = \begin{array}{c|c|c} (1.013-3.1)\text{bar} & 10^5\,\text{N} & 1 \qquad \text{m}^3 \\ \hline & \text{m}^2\cdot\text{bar} & 0.792\times10^3\ \text{kg} \end{array} = -263.5\ \text{m}^2/\text{s}^2$$

$$g\Delta z = \begin{array}{c|c} 9.8066\text{ m} & -7\text{m} \\ \hline \text{s}^2 & \end{array} = -68.6\ \text{m}^2/\text{s}^2$$

$$\underline{\text{Bernoulli equation}} \Rightarrow \frac{\Delta u^2}{2} = -\frac{\Delta P}{\rho} - g\Delta z = (263.5+68.6)\ \text{m}^2/\text{s}^2 = 332.1\ \text{m}^2/\text{s}^2$$

$$\Big\Downarrow \ \Delta u^2 = u_2^2 - 0^2$$

$$u_2^2 = 2(332.1\ \text{m}^2/\text{s}^2) = 664.2\ \text{m}^2/\text{s}^2 \Rightarrow u_2 = \underline{\underline{25.8\text{ m / s}}}$$

$$\dot{V} = \begin{array}{c|c|c|c} \pi(1.00^2)\ \text{cm}^2 & 2580\text{ cm} & 1 \quad \text{L} & 60\text{ s} \\ \hline 4 & 1 \qquad \text{s} & 10^3\ \text{cm}^3 & 1\text{ min} \end{array} = \underline{\underline{122\text{ L / min}}}$$

(b) The friction loss term of Eq. (7.7-2), which was dropped to derive the Bernoulli equation, becomes increasingly significant as the valve is closed.

7.55 Point 1 - surface of lake. $P_1 = 1$ atm, $z_1 = 0$, $u_1 = 0$

Point 2 - pipe outlet. $P_2 = 1$ atm, $z_2 = z(\text{ft})$

$$u_2 = \frac{\dot{V}}{A} = \begin{array}{c|c|c|c|c} 95\text{ gal} & 1 \quad \text{ft}^3 & 1 & 144\text{ in}^2 & 1\text{ min} \\ \hline \text{min} & 7.4805\text{ gal} & \pi(0.5\times1.049)^2\,\text{in}^2 & 1\ \text{ft}^2 & 60\text{ s} \end{array} = 35.3\ \text{ft/s}$$

Pressure drop: $\Delta P/\rho = 0 \quad (P_1 = P_2)$

Friction loss: $F = 0.041(2z)\ \text{ft}\cdot\text{lb}_\text{f}/\text{lb}_\text{m} = 0.0822\,z\ (\text{ft}\cdot\text{lb}_\text{f}/\text{lb}_\text{m})$

$\left(L = \frac{Z}{\sin 30°} = 2z\right)$

$$\text{Shaft work: } \frac{\dot{W}_s}{\dot{m}} = \begin{array}{c|c|c|c|c|c} \text{-8 hp} & 0.7376\text{ ft}\cdot\text{lb}_\text{f}\ /\text{ s} & 1\ \text{min} & 7.4805\text{ gal} & 1 \quad \text{ft}^3 & 60\text{ s} \\ \hline & 1.341\times10^{-3}\ \text{hp} & 95\text{ gal} & 1\ \text{ft}^3 & 62.4\ \text{lb}_\text{m} & 1\text{ min} \end{array}$$

$$= -333\ \text{ft}\cdot\text{lb}_\text{f}/\text{lb}_\text{m}$$

$$\text{Kinetic energy: } \Delta u^2/2 = \begin{array}{c|c} \left[(35.3)^2 - 0^2\right]\text{ft}^2 & 1 \qquad \text{lb}_\text{f} \\ \hline 2 \qquad \text{s}^2 & 32.174\ \text{lb}_\text{m}\cdot\text{ft / s}^2 \end{array} = 19.4\ \text{ft}\cdot\text{lb}_\text{f}/\text{lb}_\text{m}$$

$$\text{Potential energy: g}\Delta z = \begin{array}{c|c|c} 32.174\text{ ft} & z(\text{ft}) & 1\,\text{lb}_\text{f} \\ \hline \text{s}^2 & & 32.174\ \text{lb}_\text{m}\cdot\text{ft / s}^2 \end{array} = z(\text{ft}\cdot\text{lb}_\text{f}/\text{lb}_\text{m})$$

$$\underline{\text{Eq. }(7.7\text{ - }2)} \Rightarrow \frac{\Delta P}{\rho} + \frac{\Delta u^2}{2} + g\Delta z + F = \frac{-\dot{W}_s}{\dot{m}} \Rightarrow 19.4 + z + 0.082z = 333 \Rightarrow z = \underline{\underline{290\text{ ft}}}$$

7.56 Point 1 - surface of reservoir. $P_1 = 1$ atm (assume), $u_1 = 0$, $z_1 = 60$ m
Point 2 - discharge pipe outlet. $P_2 = 1$ atm (assume), $u_2 = ?$, $z_2 = 0$

$\Delta P/\rho = 0$

$$\frac{\Delta u^2}{2} = \frac{u_2^2}{2} = \frac{\left(\dot{V}/A\right)^2}{2} = \begin{array}{c|c|c|c} \dot{V}^2(\text{m}^6/\text{s}^2) & 1 & 10^8\ \text{cm}^4 & 1\ \text{N} \\ \hline (2) & \left[\pi(35)^2\right]^2\text{cm}^4 & 1\ \text{m}^4 & 1\ \text{kg}\cdot\text{m}/\text{s}^2 \end{array}$$

$$= 3.376\dot{V}^2\left(\text{N}\cdot\text{m}/\text{kg}\right)$$

$$g\Delta z = \begin{array}{c|c|c} 9.8066\ \text{m} & -65\ \text{m} & 1\ \text{N} \\ \hline \text{s}^2 & & 1\ \text{kg}\cdot\text{m}/\text{s}^2 \end{array} = -637\ \text{N}\cdot\text{m}/\text{kg}$$

$$\frac{\dot{W}_s}{\dot{m}} = \begin{array}{c|c|c|c} 0.80\times 10^6\,\text{W} & 1\ \text{N}\cdot\text{m}/\text{s} & \text{s} & 1\ \text{m}^3 \\ \hline & \text{W} & \dot{V}\left(\text{m}^3\right) & 1000\ \text{kg} \end{array} = 800/\dot{V}\left(\text{N}\cdot\text{m}/\text{kg}\right)$$

Mechanical energy balance: neglect F (Eq. 7.7 - 2)

$$\frac{\Delta P}{\rho} + \frac{\Delta u^2}{2} + g\Delta z = \frac{-\dot{W}_s}{\dot{m}} \Rightarrow 3.376\dot{V}^2 - 637 = -\frac{800}{\dot{V}} \xRightarrow{T+E} \dot{V} = \begin{array}{c|c} 1.27\ \text{m}^3 & 60\ \text{s} \\ \hline \text{s} & 1\ \text{min} \end{array} = \underline{\underline{76.2\ \text{m}^3/\text{min}}}$$

Include friction (add $F > 0$ to left side of equation) $\Rightarrow \dot{V}$ increases.

7.57 **(a)**. Point 1: Surface at fluid in storage tank, $P_1 = 1$ atm, $u_1 = 0$, $z_1 = H(\text{m})$
Point 2 (just within pipe): Entrance to washing machine. $P_2 = 1$ atm, $z_2 = 0$

$$u_2 = \begin{array}{c|c|c|c|c} 600\ \text{L} & & 10^3\ \text{cm}^3 & 1\ \text{min} & 1\ \text{m} \\ \hline \text{min} & \pi(4.0\ \text{cm})^2/4 & 1\quad \text{L} & 60\ \text{s} & 100\ \text{cm} \end{array} = 7.96\ \text{m/s}$$

$$\frac{\Delta P}{\rho} = 0;\ \frac{\Delta u^2}{2} = \frac{u_2^2}{2} = \begin{array}{c|c} (7.96\ \text{m/s})^2 & 1\quad \text{J} \\ \hline 2 & 1\ \text{kg}\cdot\text{m}^2/\text{s}^2 \end{array} = 31.7\ \text{J}/\text{kg}$$

$$g\Delta z = \begin{array}{c|c|c} 9.807\ \text{m} & \left(0 - H(\text{m})\right) & 1\quad \text{J} \\ \hline \text{s}^2 & & 1\ \text{kg}\cdot\text{m}^2/\text{s}^2 \end{array} = -9.807H\ \ (\text{J}/\text{kg})$$

Bernoulli Equation: $\dfrac{\Delta P}{\rho} + \dfrac{\Delta u^2}{2} + g\Delta z = 0 \Rightarrow \underline{\underline{H = 3.23\ \text{m}}}$

(b). Point 1: Fluid in washing machine. $P_1 = 1$ atm, $u_1 \approx 0$, $z_1 = 0$
Point 2: Entrance to storage tank (within pipe). $P_2 = 1$ atm, $u_2 = 7.96$ m/s, $z_2 = 3.23$ m

$$\frac{\Delta P}{\rho} = 0;\ \frac{\Delta u^2}{2} = 31.7\ \frac{\text{J}}{\text{kg}};\ g\Delta z = 9.807(3.23 - 0) = 31.7\ \frac{\text{J}}{\text{kg}};\ F = 72\ \frac{\text{J}}{\text{kg}}$$

Mechanical energy balance: $\dot{W}_s = -\dot{m}\left[\dfrac{\Delta P}{\rho} + \dfrac{\Delta u^2}{2} + g\Delta z + F\right]$

$$\Rightarrow \dot{W}_s = -\begin{array}{c|c|c|c|c} 600\ \text{L} & 0.96\ \text{kg} & 1\ \text{min} & (31.7 + 31.7 + 72)\ \ \text{J} & 1\quad \text{kW} \\ \hline \text{min} & \text{L} & 60\ \text{s} & \text{kg} & 10^3\ \ \text{J/s} \end{array} = -1.30\ \text{kW}$$

(work applied to the system)

Rated Power $= 1.30\ \text{kW}/0.75 = \underline{\underline{1.7\ \text{kW}}}$

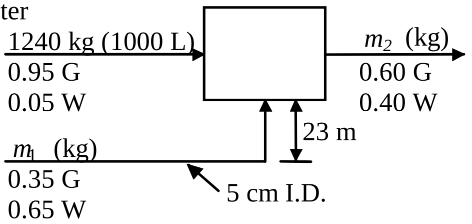
7.58 Basis: 1000 liters of 95% solution. Assume volume additivity.

Density of 95% solution (Eq. 6.1-1): $\frac{1}{\rho} = \sum \frac{x_i}{\rho_i} = \frac{0.95}{1.26} + \frac{0.05}{1.00} = 0.804 \frac{\text{l}}{\text{kg}} \Rightarrow \rho = 1.24 \text{ kg/liter}$

Density of 35% solution: $\frac{1}{\rho} = \frac{0.35}{1.26} + \frac{0.65}{1.00} = 0.9278 \frac{\text{l}}{\text{kg}} \Rightarrow \rho = 1.08 \text{ kg/liter}$

Mass of 95% solution: $\begin{array}{c|c} 1000 \text{ liters} & 1.24 \text{ kg} \\ \hline & \text{liter} \end{array} = 1240 \text{ kg}$

G = glycerol
W = water



$$\left.\begin{array}{l} \text{Mass balance: } 1240 + m_1 = m_2 \\ \text{Glycerol balance: } (0.95)(1240) + (0.35)(m_1) = (0.60)(m_2) \end{array}\right\} \Rightarrow \begin{array}{l} m_1 = 1740 \text{ kg 35\% solution} \\ m_2 = 2980 \text{ kg 60\% solution} \end{array}$$

Volume of 35% solution added $= \begin{array}{c|c} 1740 \text{ kg} & 1 \text{ L} \\ \hline & 1.08 \text{ kg} \end{array} = 1610 \text{ L}$

$\Rightarrow$ Final solution volume $= (1000 + 1610) \text{ L} = \underline{\underline{2610 \text{ L}}}$

Point 1. Surface of fluid in 35% solution storage tank. $P_1 = 1 \text{ atm}$, $u_1 = 0$, $z_1 = 0$

Point 2. Exit from discharge pipe. $P_2 = 1 \text{ atm}$, $z_2 = 23 \text{ m}$

$$u_2 = \begin{array}{c|c|c|c|c} 1610 \text{ L} & 1 \text{ m}^3 & 1 \text{ min} & 1 & 10^4 \text{ cm}^2 \\ \hline 13 \text{ min} & 10^3 \text{ L} & 60 \text{ s} & \pi(2.5)^2 \text{ cm}^2 & 1 \text{ m}^2 \end{array} = 1.051 \text{ m/s}$$

$$\Delta P/\rho = 0, \quad \frac{\Delta u^2}{2} = \frac{\Delta u_2^2}{2} = \begin{array}{c|c} (1.051)^2 \text{ m}^2/\text{s}^2 & 1 \text{ N} \\ \hline (2) & 1 \text{ kg} \cdot \text{m/s}^2 \end{array} = 0.552 \text{ N} \cdot \text{m/kg}$$

$$g\Delta z = \begin{array}{c|c|c} 9.8066 \text{ m} & 23 \text{ m} & 1 \text{ N} \\ \hline \text{s}^2 & & 1 \text{ kg} \cdot \text{m/s}^2 \end{array} = 225.6 \text{ N} \cdot \text{m/kg}, \quad F = 50 \text{ J/kg} = 50 \text{ N} \cdot \text{m/kg}$$

Mass flow rate: $\dot{m} = \begin{array}{c|c} 1740 \text{ kg} & 1 \text{ min} \\ \hline 13 \text{ min} & 60 \text{ s} \end{array} = 2.23 \text{ kg/s}$

Mechanical energy balance (Eq. 7.7-2)

$$\dot{W}_s = -\dot{m}\left[\frac{\Delta P}{\rho} + \frac{\Delta u^2}{2} + g\Delta z + F\right] = -\begin{array}{c|c|c|c} 2.23 \text{ kg} & (0.552 + 225.6 + 50) \text{N} \cdot \text{m} & 1 \text{ J} & 1 \text{ kW} \\ \hline \text{s} & \text{kg} & 1 \text{ N} \cdot \text{m} & 10^3 \text{ J/s} \end{array}$$

$= -0.62 \text{ kW} \Rightarrow \underline{\underline{0.62 \text{ kW}}}$ delivered to fluid by pump.

CHAPTER EIGHT

8.1 **a**. $\hat{U}(T) = 25.96T + 0.02134T^2 \text{ J / mol}$

$\underline{\underline{\hat{U}(0^{\text{o}}\text{ C}) = 0 \text{ J / mol}}} \quad \underline{\underline{\hat{U}(100^{\text{o}}\text{ C}) = 2809 \text{ J / mol}}} \quad \underline{\underline{T_{ref} = 0^{\text{o}}\text{ C (since } \hat{\text{U}}(0^{\text{o}}\text{ C}) = 0)}}$

b. We can never know the true internal energy. $\hat{U}(100^{\text{o}}\text{ C})$ is just the change from $\hat{U}(0^{\text{o}}\text{ C})$ to $\hat{U}(100^{\text{o}}\text{ C})$.

c. $Q - W = \Delta U + \Delta E_k + \Delta E_p$

$$\Big\Downarrow \; \scriptstyle \Delta E_k = 0, \; \Delta E_p = 0, \; W = 0$$

$Q = \Delta U = (3.0 \text{ mol})[(2809 - 0) \text{ J / mol}] = 8428 \text{ J} \Rightarrow \underline{\underline{8400 \text{ J}}}$

d. $C_v = \left(\dfrac{\partial \hat{U}}{\partial T}\right)_{\hat{V}} = \dfrac{d\hat{U}}{dT} = \underline{\underline{[25.96 + 0.04268T] \text{ J / (mol}\cdot^{\text{o}}\text{ C)}}}$

$$\Delta\hat{U} = \int_{T_1}^{T_2} C_v(T)dT = \int_0^{100} (25.96 + 0.04268T)dT = \left(25.96T + 0.04268\frac{T^2}{2}\Big]_0^{100} \right) \text{ J / mol}$$

$\Delta U = (3.0 \text{ mol}) \cdot \Delta\hat{U}(\text{J / mol})$

$\quad = (3.0 \text{ mol}) \cdot [25.96(100 - 0) + 0.02134(100^2 - 0)] \text{ (J / mol)} = 8428 \text{ J} \Rightarrow \underline{\underline{8400 \text{ J}}}$

8.2 **a.** $C_v = C_p - R \Rightarrow C_v = (35.3 + 0.0291T)[\text{J / (mol}\cdot^\circ\text{ C)}] - (8.314 \text{ [J / (mol}\cdot\text{K)]})(1 \text{ K}/1^\circ \text{ C})$

$\Rightarrow \underline{\underline{C_v = 27.0 + 0.0291T \text{ [J / (mol}\cdot^\circ\text{ C)]}}}$

b. $\Delta\hat{H} = \displaystyle\int_{25}^{100} C_p dT = 35.3T\Big]_{25}^{100} + 0.0291\frac{T^2}{2}\Big]_{25}^{100} = \underline{\underline{2784 \text{ J/mol}}}$

c. $\Delta\hat{U} = \displaystyle\int_{25}^{100} C_v dT = \int_{25}^{100} C_p dT - \int_{25}^{100} RdT = \Delta\hat{H} - R\Delta T = 2784 - (8.314)(100 - 25) = \underline{\underline{2160 \text{ J/mol}}}$

d. $\underline{\underline{\hat{H} \text{ is a state property}}}$

8.3 **a.** $C_v[\text{kJ / (mol}\cdot^{\text{o}}\text{ C)}] = 0.0252 + 1.547 \times 10^{-5} T - 3.012 \times 10^{-9} T^2$

$$n = \frac{PV}{RT} = \frac{(2.00 \text{ atm})(3.00 \text{ L})}{(0.08206[\text{atm}\cdot\text{L / (mol}\cdot\text{K)}](298 \text{ K})} = 0.245 \text{ mol}$$

$Q_1 = n\Delta\hat{U}_1 = (0.245 \text{ mol}) \cdot \displaystyle\int_{25}^{1000} 0.0252 \; dT \text{ (kJ / mol)} = \underline{\underline{6.02 \text{ kJ}}}$

$Q_2 = n\Delta\hat{U}_2 = (0.245) \cdot \displaystyle\int_{25}^{1000} [0.0252 + 1.547 \times 10^{-5} T] \; dT = \underline{\underline{7.91 \text{ kJ}}}$

$Q_3 = n\Delta\hat{U}_3 = (0.245) \cdot \displaystyle\int_{25}^{1000} [0.0252 + 1.547 \times 10^{-5} T - 3.012 \times 10^{-9} T^2] \; dT = \underline{\underline{7.67 \text{ kJ}}}$

$\% \text{ error in } Q_1 = \dfrac{6.02 - 7.67}{7.67} \times 100\% = \underline{\underline{-21.5\%}}$

$\% \text{ error in } Q_2 = \dfrac{7.91 - 7.67}{7.67} \times 100\% = \underline{\underline{3.13\%}}$

8.3 (cont'd)

b. $C_p = C_v + R$

$$C_p[\text{kJ}/(\text{mol}\cdot{}^\circ\text{C})] = (0.0252 + 1.547\times10^{-5}T - 3.012\times10^{-9}T^2) + 0.008314$$

$$= \underline{\underline{0.0335 + 1.547\times10^{-5}T - 3.012\times10^{-9}T^2}}$$

$$Q = \Delta H = n\int_{T_1}^{T_2} C_P\,dT$$

$$= (0.245\text{ mol})\cdot\int_{25}^{1000}[0.0335 + 1.547\times10^{-5}T - 3.012\times10^{-9}T^2]\,dT\ [\text{kJ}/(\text{mol}\cdot{}^\circ\text{C})] = \underline{\underline{9.65\times10^3\ \text{J}}}$$

Piston moves upward (gas expands).

c. The difference is the work done on the piston by the gas in the constant pressure process.

8.4 **a.** $\left(C_p\right)_{\text{C}_6\text{H}_6(l)}\left(40^\circ\text{C}\right) = 0.1265 + 23.4\times10^{-5}\left(40\right) = \underline{\underline{0.1360\ [\text{kJ/(mol}\cdot\text{K)}]}}$

b. $\left(C_p\right)_{\text{C}_6\text{H}_6(v)}\left(40^\circ\text{C}\right) = 0.07406 + 32.95\times10^{-5}\left(40\right) - 25.20\times10^{-8}\left(40\right)^2 + 77.57\times10^{-12}\left(40\right)^3$

$$= \underline{\underline{0.08684\ [\text{kJ}/(\text{mol}\cdot{}^\circ\text{C})]}}$$

c. $\left(C_p\right)_{\text{C}(s)}\left(313\text{ K}\right) = 0.01118 + 1.095\times10^{-5}\left(313\right) - 4.891\times10^{2}\left(313\right)^{-2} = \underline{\underline{0.009615\ [\text{kJ}/(\text{mol}\cdot\text{K})]}}$

d. $\Delta\hat{H}_{\text{C}_6\text{H}_6(v)} = 0.07406T + \frac{32.95\times10^{-5}}{2}T^2 - \frac{25.20\times10^{-8}}{3}T^3 + \frac{77.57\times10^{-12}}{4}T^4\Big]_{40}^{300} = \underline{\underline{31.71\ \text{kJ/mol}}}$

e. $\Delta\hat{H}_{C(s)} = 0.01118T + \frac{1.095\times10^{-5}}{2}T^2 + 4.891\times10^2T^{-1}\Big]_{313}^{573} = \underline{\underline{3.459\ \text{kJ/mol}}}$

8.5 $\text{H}_2\text{O (v, }100^\circ\text{C, 1 atm)} \rightarrow \text{H}_2\text{O (v, }350^\circ\text{C, 100 bar)}$

a. $\hat{H} = 2926\ \text{kJ/kg} - 2676\ \text{kJ/kg} = \underline{\underline{250\ \text{kJ/kg}}}$

b. $\hat{H} = \int_{100}^{350}\left[0.03346 + 0.6886\times10^{-5}T + 0.7604\times10^{-8}T^2 - 3.593\times10^{-12}T^3\right]dT$

$$= 8.845\ \text{kJ/mol} \Rightarrow \underline{\underline{491.4\ \text{kJ/kg}}}$$

Difference results from assumption in (b) that $\hat{H}$ is independent of P. The numerical difference is $\Delta\hat{H}$ for $\text{H}_2\text{O}(\text{v, }350^\circ\text{C, 1 atm}) \rightarrow \text{H}_2\text{O}(\text{v, }350^\circ\text{C, 100 bar})$

8.6 **b.** $\left(C_p\right)_{\text{n-C}_6\text{H}_{14}(\text{l})} = 0.2163\ \text{kJ}/(\text{mol}\cdot{}^\circ\text{C}) \Rightarrow \Delta\hat{H} = \int_{25}^{80}[0.2163]\,dT = \underline{\underline{11.90\ \text{kJ/mol}}}$

The specific enthalpy of liquid n-hexane at 80°C relative to liquid n-hexane at 25°C is 11.90 kJ/mol

c. $\left(C_p\right)_{\text{n-C}_6\text{H}_{14}(\text{v})}[\text{kJ}/(\text{mol}\cdot{}^\circ\text{C})] = 0.13744 + 40.85\times10^{-5}T - 23.92\times10^{-8}T^2 + 57.66\times10^{-12}T^3$

$$\Delta\hat{H} = \int_{500}^{0}[0.13744 + 40.85\times10^{-5}T - 23.92\times10^{-8}T^2 + 57.66\times10^{-12}T^3]\,dT = \underline{\underline{-110.7\ \text{kJ/mol}}}$$

The specific enthalpy of hexane vapor at 500°C relative to hexane vapor at 0°C is 110.7 kJ/mol. The specific enthalpy of hexane vapor at 0°C relative to hexane vapor at 500°C is –110.7 kJ/mol.

8.7 $$T(^\circ\text{C})=\frac{1}{1.8}\left[T'(^\circ\text{F})-32\right]=0.5556T'(^\circ\text{F})-17.78$$

$$C_p(\text{cal/mol}\cdot{}^\circ\text{C})=6.890+0.001436\left[0.5556T'(^\circ\text{F})-17.78\right]=6.864+0.0007978T'(^\circ\text{F})$$

$$C_p'(\text{Btu/lb-mole}\cdot{}^\circ\text{F})\underset{\text{drop primes}}{\underset{\Downarrow}{=}}C_p\begin{array}{c|c|c|c}\text{cal} & 453.6\text{ mol} & 1\text{ Btu} & 1^\circ\text{C}\\ \hline \text{mol}\cdot{}^\circ\text{C} & 1\text{ lb-mole} & 252\text{ cal} & 1.8^\circ\text{F}\end{array}=(1.00)C_p$$

$$\underline{\underline{C_p(\text{Btu/lb-mole}\cdot{}^\circ\text{F})=6.864+0.0007978T(^\circ\text{F})}}$$

8.8 $$\left(C_p\right)_{\text{CH}_3\text{CH}_2\text{OH(l)}}(T)=0.1031+\frac{(0.1588-0.1031)}{100}T=\underline{\underline{0.1031+0.000557T\ [\text{kJ}/(\text{mol}\cdot{}^\text{o}\text{C})]}}$$

$$Q=\Delta H=\begin{array}{c|c|c}55.0\text{ L} & 789\text{ g} & 1\text{ mol}\\ \hline \text{s} & 1\text{ L} & 46.07\text{ g}\end{array}\underbrace{\left(0.1031T+\frac{0.000557}{2}T^2\right]_{20}^{78.5}}_{\text{kJ/mol}}$$

$$=941.9\times7.636\text{ kJ/s}=\underline{\underline{7193\text{ kW}}}$$

8.9 **a.**

$$\dot{Q}=\Delta\dot{H}=(5{,}000\ \text{mol/s})\cdot\overbrace{\int_{100}^{200}\left[0.03360+1.367\times10^{-5}T-1.607\times10^{-8}T^2+6.473\times10^{-12}T^3\right]dT}^{\text{kJ/mol}}$$

$$=\underline{\underline{17{,}650\text{ kW}}}$$

b. $$Q=\Delta U=\Delta H-\Delta PV=\Delta H-nR\Delta T=17{,}650\text{ kJ}-(5.0\text{ kmol})\cdot(8.314\ [\text{kJ}/(\text{kmol}\cdot\text{K})])\cdot(100\text{ K})$$

$$=\underline{\underline{13{,}490\text{ kJ}}}$$

The difference is the flow work done on the gas in the continuous system.

c. $Q_{\text{additional}}$ = heat needed to raise temperature of vessel wall + heat that escapes from wall to surroundings.

8.10 **a.** $\underline{\underline{C_p\text{ is a constant, i.e. }C_p\text{ is independent of T.}}}$

b. $$Q=mC_p\Delta T\Rightarrow C_p=\frac{Q}{m\Delta T}$$

$$C_p=\frac{Q}{m\Delta T}=\begin{array}{c|c|c|c}(16.73\text{-}6.14)\text{ kJ} & 1\text{ L} & 86.17\text{ g} & 10^3\text{ J}\\ \hline (2.00\text{ L})(3.10\text{ K}) & 659\text{ g} & 1\text{ mol} & 1\text{ kJ}\end{array}=\underline{\underline{0.223\text{ kJ}/(\text{mol}\cdot\text{K})}}$$

Table B.2 $\Rightarrow C_p=0.216\text{ kJ}/(\text{mol}\cdot{}^\text{o}\text{C})=0.216\text{ kJ}/(\text{mol}\cdot\text{K})$

8.11 $$\hat{H}=\hat{U}+P\hat{V}\xRightarrow{P\hat{V}=RT}\hat{H}=\hat{U}+RT\xRightarrow{(\partial/\partial T)_P}\left(\frac{\partial\hat{H}}{\partial T}\right)_p=\left(\frac{\partial\hat{U}}{\partial T}\right)_p+R\Rightarrow C_p=\left(\frac{\partial\hat{U}}{\partial T}\right)_p+R$$

But since $\hat{U}$ depends only on T, $\left(\frac{\partial\hat{U}}{\partial T}\right)_p=\frac{d\hat{U}}{dT}=\left(\frac{\partial\hat{U}}{\partial T}\right)_{\hat{V}}\equiv C_v\Rightarrow\underline{\underline{C_p=C_v+R}}$

8.12 **a.** $\left(C_p\right)_{\mathrm{H_2O(l)}}$ = 75.4 kJ / (kmol·$^{\mathrm{o}}$ C) =75.4 kJ/(kmol·$^{\mathrm{o}}$C)   V = 1230 L ,

$$n=\frac{V\rho}{M}=\frac{1230\ \mathrm{L}}{}\bigg|\frac{1\ \mathrm{kg}}{1\ \mathrm{L}}\bigg|\frac{1\ \mathrm{kmol}}{18\ \mathrm{kg}}=68.3\ \mathrm{kmol}$$

$$\dot{Q}=\frac{Q}{t}=\frac{n\cdot\int_{T_1}^{T_2}\left(C_p\right)_{\mathrm{H_2O(l)}}dT}{t}=\frac{68.3\ \mathrm{kmol}}{}\bigg|\frac{75.4\ \mathrm{kJ}}{\mathrm{kmol}\cdot{}^{\mathrm{o}}\mathrm{C}}\bigg|\frac{(40-29)\ {}^{\mathrm{o}}\mathrm{C}}{8\ \mathrm{h}}\bigg|\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}=\underline{\underline{1.967\ \mathrm{kW}}}$$

b. $\dot{Q}_{\text{total}}=\dot{Q}_{\text{to the surroundings}}+\dot{Q}_{\text{to water}}$, $\dot{Q}_{\text{to the surroundings}}=1.967\ \mathrm{kW}$

$$\dot{Q}_{\text{to water}}=\frac{Q_{\text{to water}}}{t}=\frac{n\cdot\int_{29}^{40}C_{P(H_2O)}dT}{t}=\frac{68.3\ \mathrm{kmol}}{3\ \mathrm{h}}\bigg|\frac{75.4\ \mathrm{kJ}/(\mathrm{kmol}\cdot{}^{\mathrm{o}}\mathrm{C})}{3600\ \mathrm{s}/\mathrm{h}}\bigg|\frac{11\ {}^{\mathrm{o}}\mathrm{C}}{}=5.245\ \mathrm{kW}$$

$$\dot{Q}_{\text{total}}=\underline{\underline{7.212\ \mathrm{kW}}}\quad\Rightarrow\ E_{\text{total}}=7.212\ \mathrm{kW}\ \times\ 3\ \mathrm{h}\ =\underline{\underline{21.64\ \mathrm{kW\cdot h}}}$$

c. $Cost_{\text{heating up from 29 }^{\mathrm{o}}\text{C to 40 }^{\mathrm{o}}\text{C}}=21.64\ \mathrm{kW\cdot h}\times\$0.10/(\mathrm{kW\cdot h})=\underline{\underline{\$2.16}}$

$Cost_{\text{keeping temperature constant for 13 h}}=1.967\ \mathrm{kW}\times 13\ \mathrm{h}\times\$0.10/(\mathrm{kW\cdot h})=\underline{\underline{\$2.56}}$

$Cost_{\text{total}}=\$2.16+\$2.56=\underline{\underline{\$4.72}}$

d. If the lid is removed, more heat will be transferred into the surroundings and lost, resulting in higher cost.

8.13 **a.** $\Delta\hat{H}_{\mathrm{N_2(25^o\,C)\rightarrow N_2(700^o\,C)}}=\hat{H}_{\mathrm{N_2(700^o\,C)}}-\hat{H}_{\mathrm{N_2(25^o\,C)}}=(20.59-0)=\underline{\underline{20.59\ \ \mathrm{kJ/mol}}}$

b. $\Delta\hat{H}_{\mathrm{H_2(800^o\,F)\rightarrow H_2(77^o\,F)}}=\hat{H}_{\mathrm{H_2(77^o\,F)}}-\hat{H}_{\mathrm{H_2(800^o\,F)}}=(0-5021)=\underline{\underline{-5021\ \mathrm{Btu/lb\text{-}mol}}}$

c. $\Delta\hat{H}_{\mathrm{CO_2(300^o\,C)\rightarrow CO_2(1250^o\,C)}}=\hat{H}_{\mathrm{CO_2(1250^o\,C)}}-\hat{H}_{\mathrm{CO_2(300^o\,C)}}=(63.06-11.58)=\underline{\underline{51.48\ \ \mathrm{kJ/mol}}}$

d. $\Delta\hat{H}_{\mathrm{O_2(970^o\,F)\rightarrow O_2(0^o\,F)}}=\hat{H}_{\mathrm{O_2(0^o\,F)}}-\hat{H}_{\mathrm{O_2(970^o\,F)}}=(-539-6774)=\underline{\underline{-7313\ \mathrm{Btu/lb\text{-}mol}}}$

8.14 **a.** $\dot{m}=300\ \mathrm{kg/min}\quad \dot{n}=\frac{300\ \mathrm{kg}}{\mathrm{min}}\bigg|\frac{1\ \mathrm{min}}{60\ \mathrm{s}}\bigg|\frac{1000\ \mathrm{g}}{1\ \mathrm{kg}}\bigg|\frac{1\ \mathrm{mol}}{28.01\ \mathrm{g}}=178.5\ \mathrm{mol/s}$

$$\dot{Q}=\dot{n}\cdot\Delta\hat{H}=\dot{n}\cdot\int_{T_1}^{T_2}C_p dT$$

$$=(178.5\ \mathrm{mol/s})\cdot\int_{450}^{50}[0.02895+0.411\times10^{-5}T+0.3548\times10^{-8}T^2-2.22\times10^{-12}T^3]\ dT\ [\mathrm{kJ/mol}]$$

$$=(178.5\ \mathrm{mol/s})(-12.076\ [\mathrm{kJ/mol}])\ =\ \underline{\underline{-2{,}156\ \mathrm{kW}}}$$

b. $\dot{Q}=\dot{n}\cdot\Delta\hat{H}=\dot{n}\cdot\left[\hat{H}_{(50^o\,C)}-\hat{H}_{(450^o\,C)}\right]\ =(178.5\ \mathrm{mol/s})(0.73\text{-}12.815[\mathrm{kJ/mol}])=\underline{\underline{-2{,}157\ \mathrm{kW}}}$

8.15 **a.** $\dot{n}=250\ \mathrm{mol/h}$

i) $$\dot{Q}=\dot{n}\Delta\hat{H}=\frac{250\ \mathrm{mol}}{\mathrm{h}}\bigg|\frac{(2676-3697)\ \mathrm{kJ}}{1\ \mathrm{kg}}\bigg|\frac{1\ \mathrm{kg}}{1000\ \mathrm{g}}\bigg|\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}\bigg|\frac{18.02\ \mathrm{g}}{1\ \mathrm{mol}}=\underline{\underline{-1.278\ \mathrm{kW}}}$$

ii) $$\dot{Q}=\dot{n}\Delta\hat{H}=\dot{n}\cdot\int_{T_1}^{T_2}C_p dT\bigg|$$

$$=\frac{250\ \mathrm{mol}}{\mathrm{h}}\bigg|\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}\int_{600}^{100}[0.03346+0.6880\times10^{-5}T+0.7604\times10^{-8}T^2-3.593\times10^{-12}T^3]=\underline{\underline{-1.274\ \mathrm{kW}}}$$

8.15 (cont'd)

iii) $\dot{Q} = \dfrac{250\text{ mol}}{3600\text{ s}}\cdot\left(2.54-20.91\right)\ [\text{kJ / mol}] = \underline{\underline{-1.276\text{ kW}}}$

b. Method (i) is most accurate since it takes into account the dependence of enthalpy on pressure and (ii) and (iii) do not.

c. The enthalpy change for steam going from 10 bar to 1 atm at 600$^\text{o}$C.

8.16 Assume ideal gas behavior, so that pressure changes do not affect $\Delta\hat{H}$.

$$\dot{n} = \begin{array}{c|c|c|c} 200\text{ ft}^3 & 492^\text{o}R & 1.2\text{ atm} & 1\text{ lb-mol} \\ \hline \text{h} & 537^\text{o}R & 1\text{ atm} & 359\text{ ft}^3(\text{STP}) \end{array} = 0.6125\text{ lb-mole / h}$$

$$\dot{Q} = \dot{n}\Delta\hat{H} = (0.6125\ \frac{\text{lb-mole}}{\text{h}})\cdot\left((2993-0)\ [\text{Btu / lb-mole}]\right) = \underline{\underline{1833\text{ Btu / h}}}$$

8.17 a. $\begin{array}{c|c|c} 50\text{ kg} & 1.14\text{ kJ} & \left(50-10\right)^\circ\text{C} \\ \hline & \text{kg}\cdot{}^\circ\text{C} & \end{array} = \underline{\underline{2280\text{ kJ}}}$

b.

$$\left(C_p\right)_{\text{Na}_2\text{CO}_3} \approx 2\left(C_p\right)_{\text{Na}} + \left(C_p\right)_{\text{C}} + 3\left(C_p\right)_{\text{O}} = 2\left(0.026\right) + 0.0075 + 3\left(0.017\right) = 0.1105\ \text{kJ/mol}\cdot{}^\circ\text{C}$$

$$\begin{array}{c|c|c|c} 50{,}000\text{ g} & 0.1105\text{ kJ} & 1\text{ mol} & \left(50-10\right)^\circ\text{C} \\ \hline & \text{mol}\cdot{}^\circ\text{C} & 105.99\text{ g} & \end{array} = \underline{\underline{2085\text{ kJ}}}$$

$$\underline{\%\text{ error}} = \frac{2085-2280}{2280}\times 100\% = \underline{\underline{-8.6\%\ \text{error}}}$$

8.18 $\left(C_p\right)_{\text{C}_6\text{H}_{14}\text{O(l)}} = 6\left(0.012\right) + 14\left(0.018\right) + 1\left(0.025\right) = 0.349\ \text{kJ / (mol}\cdot{}^\text{o}\text{ C)}$ (Kopp's Rule)

$\left(C_p\right)_{\text{CH}_3\text{COCH}_3\text{(l)}} = 0.1230 + 18.6\times 10^{-5}\text{T}\ \ \text{kJ/(mol}\cdot{}^\circ\text{ C)}$

Assume $\Delta H_{\text{mix}} \cong 0$

$$C_{pm} = \overset{\downarrow\ \text{CH}_3\text{COCH}_3}{\begin{array}{c|c} 0.30\left(0.1230{+}18.6{\times}10^{-5}T\right)\text{ kJ} & 1\text{ mol} \\ \hline \text{mol}\cdot{}^\circ\text{C} & 58.08\text{ g} \end{array}} + \overset{\downarrow\ \text{C}_6\text{H}_{14}\text{O}}{\begin{array}{c|c} 0.70\left(0.349\right)\text{ kJ} & 1\text{ mol} \\ \hline \text{mol}\cdot{}^\circ\text{C} & 102.17\text{ g} \end{array}}$$

$$= [0.003026 + 9.607\times 10^{-7}\text{T}]\ \ \text{kJ/(g}\cdot{}^\circ\text{C)}$$

$$\Delta\hat{H} = \int_{45}^{20}[0.003026 + 9.607\times 10^{-7}\text{T}]\ dT = \underline{\underline{-0.07643\ \ \text{kJ/g}}}$$

8.19 Assume ideal gas behavior, $\Delta H_{\text{mix}} \cong 0$

$$\overline{M}_w = \frac{1}{3}\left(16.04\right) + \frac{2}{3}\left(32.00\right) = 26.68\,\frac{\text{g}}{\text{mol}}$$

$$\Delta\hat{H}_{\text{O}_2} = \int_{25}^{350}\left(C_p\right)_{\text{O}_2}dT = 10.08\text{ kJ / mol},\ \Delta\hat{H}_{\text{CH}_4} = \int_{25}^{350}\left(C_p\right)_{\text{CH}_4}dT = 14.49\text{ kJ / mol}$$

$$\hat{H} = \left[\frac{1}{3}\left(14.49\text{ kJ / mol}\right) + \frac{2}{3}\left(10.08\text{ kJ / mol}\right)\right]\left(\frac{1000\text{ g}}{1\text{ kg}}\right)\left(\frac{1\text{ mol}}{26.68\text{ g}}\right) = \underline{\underline{433\,\text{kJ/kg}}}$$

8.20 $$n=\frac{1000\text{ m}^3}{\text{min}}\bigg|\frac{1\text{ min}}{60\text{ s}}\bigg|\frac{273\text{ K}}{303\text{ K}}\bigg|\frac{1\text{ kmol}}{22.4\text{ m}^3(\text{STP})}=0.6704\ \text{ kmol/s}=670.4\text{ mol / s}$$

<u>Energy balance on air:</u>

$$Q=\Delta H=n\Delta H\xrightarrow{\text{Table B.8 for }\Delta\hat{H}}Q=\frac{670.4\text{ mol}}{\text{s}}\bigg|\frac{0.73\text{ kJ}}{\text{mol}}\bigg|\frac{1\text{ kW}}{1\ \text{kJ/s}}=489.4\text{ kW}$$

$$\underline{\text{Solar energy required}}=\frac{489.4\text{ kW heating}}{}\bigg|\frac{1\text{ kW solar energy}}{0.3\text{ kW heating}}=1631\text{ kW}$$

$$\underline{\text{Area required}}=\frac{1631\text{ kW}}{}\bigg|\frac{1000\text{ W}}{1\text{ kW}}\bigg|\frac{1\text{ m}^2}{900\text{ W}}=\underline{\underline{1813\text{ m}^2}}$$

8.21 $C_3H_8+5O_2\rightarrow 3CO_2+4H_2O$

$$\dot{n}_{\text{fuel}}=\frac{1.35\times10^5\ \text{ SCFH}}{\text{h}}\bigg|\frac{1\text{ lb-mol}}{359\text{ ft}^3}=376\ \frac{\text{lb-mol}}{\text{h}}$$

$$\dot{n}_{\text{air}}=\frac{376\text{ lb}-\text{mol}}{\text{h}}\bigg|\frac{5\text{ lb-mol }O_2}{1\text{b-mol }C_3H_8}\bigg|\frac{1\text{ lb-mol air}}{0.211\text{b-mol }O_2}\bigg|\frac{1.15}{}=1.03\times10^4\ \frac{\text{lb}-\text{mol}}{\text{h}}$$

$$Q=\Delta H=\dot{n}\cdot\int_{T_1}^{T_2}C_p dT$$

$$=\left(1.03\times10^4\ \frac{\text{lb}-\text{mol}}{\text{h}}\right)\cdot\int_0^{302}[0.02894+0.4147\times10^{-5}T+0.3191\times10^{-8}T^2-1.965\times10^{-12}T^3]\ dT$$

$$=\frac{1.03\times10^4\ \text{ lb-mol}}{\text{h}}\bigg|\frac{8.954\text{ kJ}}{\text{mol}}\bigg|\frac{453.593\text{ mol}}{\text{lb-mol}}\bigg|\frac{9.486\times10^{-1}\ \text{ Btu}}{\text{kJ}}=\underline{\underline{3.97\times10^7\ \text{ Btu/h}}}$$

8.22 **a.** <u>Basis</u>: 100 mol feed (95 mol CH_4 and 5 mol C_2H_6)

$$CH_4+2O_2\rightarrow CO_2+2H_2O\qquad C_2H_6+\frac{7}{2}O_2\rightarrow 2CO_2+3H_2O$$

$$n_{O_2}=1.25\cdot\left[\frac{95\text{ mol }CH_4}{}\bigg|\frac{2\text{ mol }O_2}{1\text{ mol }CH_4}+\frac{5\text{ mol }C_2H_6}{}\bigg|\frac{3.5\text{ mol }O_2}{1\text{ mol }C_2H_6}\right]=259.4\text{ mol }O_2$$

<u>Product Gas</u>:

CO_2: 95(1)+5(2)=105 mol CO_2 $\qquad$ H_2O: 95(2)+5(3)=205 mol H_2O

O_2: 259.4-95(2)-5(3.5)=51.9 mol O_2 $\qquad$ N_2: 3.76(259.4)=975 mol N_2

<u>Energy balance</u> (enthalpies from Table B.8)

$$\Delta\hat{H}_{CO_2}=\hat{H}_{(CO_2,\ 450^\circ C)}-\hat{H}_{(CO_2,\ 900^\circ C)}=18.845-42.94=-24.09\text{ kJ / mol}$$

$$\Delta\hat{H}_{H_2O}=\hat{H}_{(H_2O,\ 450^\circ C)}-\hat{H}_{(H_2O,\ 900^\circ C)}=15.12-33.32=-18.20\text{ kJ / mol}$$

$$\Delta\hat{H}_{O_2}=\hat{H}_{(O_2,\ 450^\circ C)}-\hat{H}_{(O_2,\ 900^\circ C)}=13.375-28.89=-15.51\text{ kJ / mol}$$

$$\Delta\hat{H}_{N_2}=\hat{H}_{(N_2,\ 450^\circ C)}-\hat{H}_{(N_2,\ 900^\circ C)}=12.695-27.19=-14.49\text{ kJ / mol}$$

$$Q=\Delta H=[105(-24.09)+205(-18.20)+51.9(-15.51)+975(-14.49)]$$

$$Q=\underline{\underline{21{,}200\text{ kJ / 100 mol feed}}}$$

b. From Table B.5: $\hat{H}_{\text{liq}}(40^\circ C)=167.5$ kJ / kg; $\hat{H}_{\text{vap}}(50\text{ bars})=2794.2$ kJ / kg;

$$Q=n\cdot\Delta\hat{H}=n(2794.2-167.5)=21200\ \Rightarrow\ n=\underline{\underline{8.07\text{ kg / 100 mol feed}}}$$

8.22 (cont'd)

c. From part (b), 8.07 kg steam is produced per 100 mol feed

$$\dot{n}_{feed} = \frac{1250 \text{ kg steam}}{\text{h}}\bigg|\frac{0.1 \text{ kmol feed}}{8.07 \text{ kg steam}}\bigg|\frac{1 \text{ h}}{3600 \text{ s}} = \underline{\underline{4.30\times10^{-3} \text{ kmol/s}}}$$

$$\dot{V}_{\text{product gas}} = \frac{4.30 \text{ mol feed}}{\text{s}}\bigg|\frac{1336.9 \text{ mol product gas}}{100 \text{ mol feed}}\bigg|\frac{8.314 \text{ Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}}\bigg|\frac{723 \text{ K}}{1.01325\times10^5 \text{ Pa}} = \underline{\underline{3.41 \text{ m}^3/\text{s}}}$$

d. Steam produced from the waste heat boiler is used for heating, power generation, or process application. Without the waste heat boiler, the steam required will have to be produced with additional cost to the plant.

8.23 Assume $\Delta H_{mix} \cong 0 \Rightarrow \Delta H = \Delta H_{C_{10}H_{12}O_2} + \Delta H_{C_6H_6}$

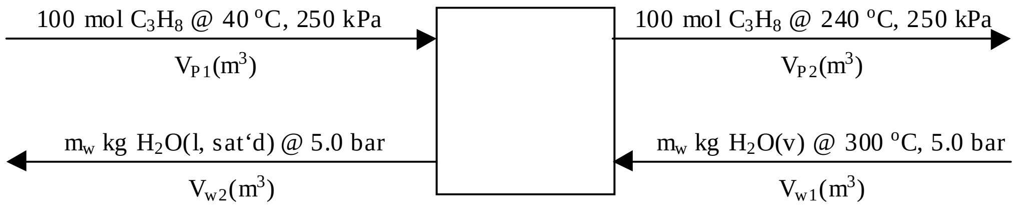
Kopp's rule: $(C_p)_{C_{10}H_{12}O_2} = 10(12) + 12(18) + 2(25) = 386 \text{ J}/(\text{mol}\cdot{}^\circ\text{C}) = 2.35 \text{ J}/(\text{g}\cdot{}^\circ\text{C})$

$$\Delta H_{C_{10}H_{12}O_2} = \frac{20.0 \text{ L}}{}\bigg|\frac{1021 \text{ g}}{\text{L}}\bigg|\frac{1 \text{ kJ}}{10^3 \text{ J}}\bigg|\frac{2.35 \text{ J}}{\text{g}\cdot{}^\circ\text{C}}\bigg|\frac{(71-25)\ {}^\circ\text{C}}{} = 2207 \text{ kJ}$$

$$\Delta H_{C_6H_6} = \frac{15.0 \text{ L}}{}\bigg|\frac{879 \text{ g}}{\text{L}}\bigg|\frac{1 \text{ mol}}{78.11 \text{ g}}\cdot\left[\int_{298}^{348}[0.06255 + 23.4\times10^{-5}\text{T}]\ \text{dT}\right] = 1166 \text{ kJ}$$

$\Delta H = 2207 + 1166 = \underline{\underline{3373 \text{ kJ}}}$

8.24 **a.**



b. References: H_2O (l, 0.01 °C), C_3H_8 (gas, 40 °C)

$\underline{C_3H_8}$: $\hat{H}_{in} = \underline{\underline{0 \text{ kJ/mol}}}$; $\hat{H}_{out} = \int_{40}^{240} C_{p_{C_3H_8}} dT = \underline{\underline{19.36 \text{ kJ/mol}}}$ (C_p from Table B.2)

$\underline{H_2O}$: $\hat{H}_{in} = \underline{\underline{3065 \text{ kJ/kg}}}$ (Table B.7); $\hat{H}_{out} = \underline{\underline{640.1 \text{ kJ/kg}}}$ (Table B.6)

c. $\Delta\hat{H}_{C_3H_8} = 19.36 \text{ kJ/mol}$, $\Delta\hat{H}_w = (640.1 - 3065) \text{ kJ/kg} = -2425 \text{ kJ/kg}$

$Q = \Delta H = 100\Delta\hat{H}_{C_3H_8} + m_w\Delta\hat{H}_w = 0 \Rightarrow m_w = \underline{\underline{0.798 \text{ kg}}}$

From Table B.7: $\hat{V}_{steam}(5.0 \text{ bar, } 300^\circ\text{C}) = 0.522 \text{ m}^3/\text{kg}$

$$\hat{V}_{C_3H_8}(40^\circ\text{C, } 250 \text{ kPa}) = \frac{0.008314 \text{ m}^3\cdot\text{kPa}/(\text{mol}\cdot\text{K})}{250 \text{ kPa}}\bigg|\frac{313 \text{ K}}{} = 0.0104 \text{ m}^3/\text{mol C}_3\text{H}_8$$

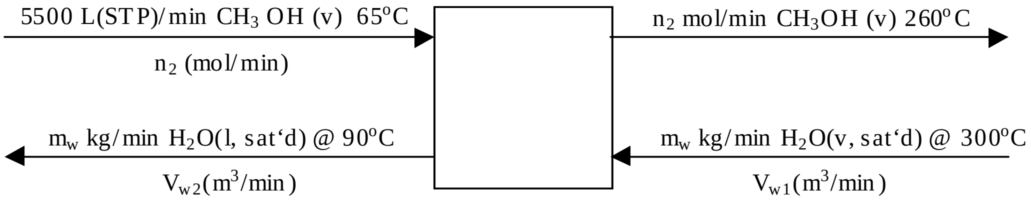
$$\frac{0.798 \text{ kg steam}}{100 \text{ mol C}_3\text{H}_8}\bigg|\frac{0.522 \text{ m}^3 \text{ steam}}{1 \text{ kg steam}}\bigg|\frac{1 \text{ mol C}_3\text{H}_8}{0.0104 \text{ m}^3 \text{ C}_3\text{H}_8} = \underline{\underline{0.400 \text{ m}^3 \text{ steam}/\text{m}^3 \text{ C}_3\text{H}_8}}$$

d.

$$Q = m_w\Delta\hat{H}_w = \frac{0.798 \text{ kg steam}}{100 \text{ mol C}_3\text{H}_8}\bigg|\frac{2425 \text{ kJ}}{\text{kg steam}}\bigg|\frac{1 \text{ mol C}_3\text{H}_8}{0.0104 \text{ m}^3 \text{ C}_3\text{H}_8} = \underline{\underline{1860 \frac{\text{kJ}}{\text{m}^3 \text{ C}_3\text{H}_8 \text{ fed}}}}$$

e. A lower outlet temperature for propane and a higher outlet temperature for steam.

8.25 a.

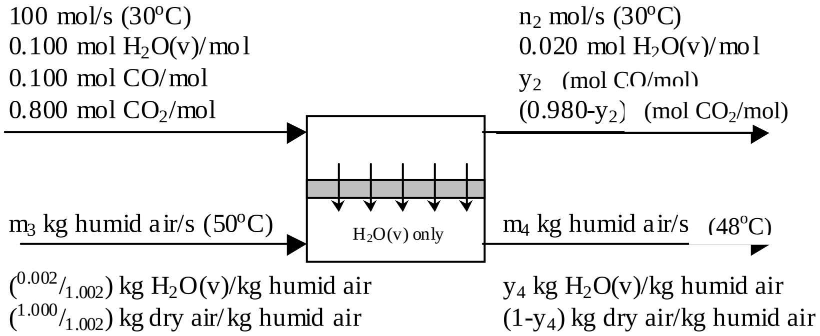


$$n_2 = \frac{5500\text{ L(STP)}}{\text{min}}\left|\frac{1\text{ mol}}{22.4\text{ L(STP)}}\right. = 245.5\text{ mol CH}_3\text{OH(v)/min}$$

An energy balance on the unit is then written, using Tables B.5 and B.6 for the specific enthalpies of the outlet and inlet water, respectively, and Table B.2 for the heat capacity of methanol vapor. The only unknown is the flow rate of water, which is calculated to be $\underline{\underline{1.13\text{ kg H}_2\text{O/min}}}$.

b. $\dot{Q} = \left(1.13\frac{\text{kg}}{\text{min}}\right)\left(2373.9\frac{\text{kJ}}{\text{kg}}\right)\left(\frac{1\text{ min}}{60\text{ sec}}\right)\left(\frac{1\text{ kW}}{1\text{ kJ/s}}\right) = \underline{\underline{44.7\text{ kW}}}$

8.26 a.



Basis: 100 mol gas mixture/s

5 unknowns: n_2, m_3, m_4, y_2, y_4

– 4 independent material balances, H_2O(v), CO, CO_2 , dry air

– 1 energy balance equation

0 degrees of freedom (all unknowns may be determined)

b.

$$\left.\begin{array}{ll}(1)\ \underline{\text{CO balance}}: & (100)(0.100) = \dot{n}_2 y_2 \\ (2)\ \underline{\text{CO}_2\text{ balance}}: & (100)(0.800) = n_2(1-y_2)\end{array}\right\} \Rightarrow \dot{n}_2 = 91.84\text{ mol/s},\ \ x_2 = 0.1089\text{ mol CO/mol}$$

$$(3)\ \underline{\text{Dry air balance}}:\ m_3\frac{1.000}{1.002} = m_4(1-y_4)$$

$$(4)\ \underline{\text{H}_2\text{O balance}}:\ \frac{(100)(0.100)(18)}{1000} + \dot{m}_3\frac{0.002}{1.002} = 91.84\frac{(0.020)(18)}{1000} + \dot{m}_4 y_4$$

References: CO, CO_2, H_2O(v), air at 25°C ($\hat{H}$ values from Table B.8)

substance	$\dot{n}_{\text{in}}$ (mol / s)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{\text{out}}$ (mol / s)	$\hat{H}_{out}$ (kJ / mol)
H_2O(v)	10	0.169	91.84(0.020)	0.169
CO	10	0.146	10	0.146
CO_2	80	0.193	80	0.193
H_2O(v)	$m_3(^{0.002}/_{1.002})(^{1000}/_{18})$	0.847	$m_4y_4(^{1000}/_{18})$	0.779
dry air	$m_3(^{1.000}/_{1.002})(^{1000}/_{29})$	0.727	$m_4(1-y_4)(^{1000}/_{29})$	0.672

8.26 (cont'd)

(5) Energy balance:

$$10(0.169)+m_3\left(\frac{0.002}{1.002}\right)\left(\frac{1000}{18}\right)(0.847)+m_3\left(\frac{1.000}{1.002}\right)\left(\frac{1000}{29}\right)(0.727)$$

$$=\;91.84(0.020)(0.169)+m_4y_4(0.779)\left(\frac{1000}{18}\right)+m_4(1-y_4)(0.672)\left(\frac{1000}{29}\right)$$

Solve Eqs. (3)–(5) simultaneously $\Rightarrow m_3 = 2.55$ kg/s, $m_4 = 2.70$ kg/s, $y_4 = 0.0564$ kg H_2O/kg

$$\frac{2.55\text{ kg humid air / s}}{100\text{ mol gas / s}}=\underline{\underline{0.0255\frac{\text{kg humid air}}{\text{mol gas}}}}$$

Mole fraction of water: $\dfrac{0.0564\text{ kg H}_2\text{O}}{(1\text{-}.0564)\text{ kg dry air}}\left|\dfrac{29\text{ kg DA}}{\text{kmol DA}}\right|\dfrac{1\text{ kmol H}_2\text{O}}{18\text{ kg H}_2\text{O}}=.0963\dfrac{\text{kmol H}_2\text{O}}{\text{kmol DA}}$

$$\Rightarrow\frac{0.0963\text{ kmol H}_2\text{O}}{(1+0.0963)\text{ kmol humid air}}=0.0878\frac{\text{kmol H}_2\text{O}}{\text{kmol humid air}}$$

Relative humidity: $\dfrac{p_{H_2O}}{p^*_{H_2O}(48^\circ\text{ C})}=\dfrac{(0.0878)(760\text{ mm Hg})}{83.71\text{ mm Hg}}\times 100\%=\underline{\underline{79.7\%}}$

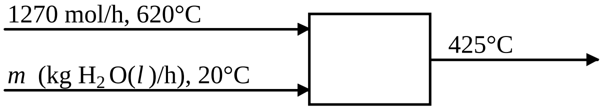
c. The membrane must be permeable to water, impermeable to CO, CO_2, O_2, and N_2, and both durable and leakproof at temperatures up to 50°C.

8.27 a. $y_{H_2O}=\dfrac{p^*(57^\circ\text{ C})}{P}=\dfrac{129.82\text{ mm Hg}}{760\text{ mm Hg}}=0.171\text{ mol H}_2\text{O/mol}$

$$\downarrow$$

$$\frac{28.5\text{ m}^3(\text{STP})}{\text{h}}\left|\frac{1\text{ mol}}{0.0224\text{ m}^3(\text{STP})}\right.=1270\text{ mol/h}\Rightarrow 217.2\text{ mol H}_2\text{O/h}\quad(3.91\text{ kg H}_2\text{O/h})$$

$$1270-217.2=1053\frac{\text{mol dry gas}}{\text{h}}\xrightarrow[\text{percentages}]{\text{given}}\begin{cases}89.5\text{ mol CO/h}\\110.5\text{ mol CO}_2\text{/h}\\5.3\text{ mol O}_2\text{/h}\\847.6\text{ mol N}_2\text{/h}\end{cases}$$



References for enthalpy calculations:

CO, CO_2, O_2, N_2 at 25°C (Table B.8); $H_2O(l,\ 0.01^\circ\text{ C})$ (steam tables)

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
CO	89.5	18.22	89.5	12.03
CO_2	110.6	27.60	110.6	17.60
O_2	5.3	19.10	5.3	12.54
N_2	847.6	18.03	847.6	11.92
$H_2O(v)$	3.91	3749	$3.91+m$	3330
$H_2O(l)$	m	83.9	--	--

CO, CO_2, O_2, N_2: n in mol/h, $\hat{H}$ in kJ/mol

$H_2O(v)$, $H_2O(l)$: n in kg/h, $\hat{H}$ in kJ/kg

8.27 (cont'd)

$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow -8504 + 3246m = 0 \Rightarrow \underline{\underline{m = 2.62 \text{ kg/h}}}$$

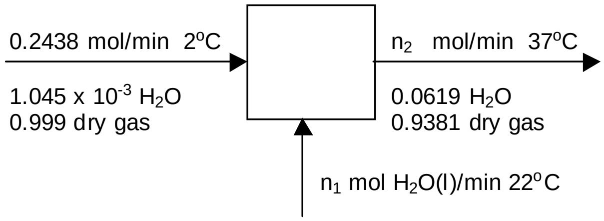
b. When cold water contacts hot gas, heat is transferred from the hot gas to the cold water lowering the temperature of the gas (the object of the process) and raising the temperature of the water.

8.28 2°C, 15% rel. humidity $\Rightarrow p_{\text{H}_2\text{O}} = (0.15)(5.294 \text{ mm Hg}) = 0.7941 \text{ mm Hg}$

$\left(y_{\text{H}_2\text{O}}\right)_{\text{inhaled}} (0.7941)/(760) = 1.045 \times 10^{-3}$ mol H_2O/mol inhaled air

$$\dot{n}_{\text{inhaled}} = \frac{5500 \text{ ml}}{\text{min}} \left| \frac{273 \text{ K}}{275 \text{ K}} \right| \frac{1 \text{ liter}}{10^3 \text{ ml}} \left| \frac{1 \text{ mol}}{22.4 \text{ liters(STP)}} \right. = 0.2438 \text{ mol air inhaled/min}$$

Saturation at 37 °C $\Rightarrow y_{\text{H}_2\text{O}} = \dfrac{p^*(37°\text{C})}{760 \text{ mm Hg}} = \dfrac{47.067}{760} = 0.0619$ mol H_2O/mol exhaled dry gas



Mass of dry gas inhaled (and exhaled) $= \dfrac{(0.2438)(0.999)\text{mol dry gas}}{\text{min}} \left| \dfrac{29.0 \text{ g}}{\text{mol}} \right. = 7.063 \text{ g/min}$

Dry gas balance: $(0.999)(0.2438) = 0.9381\, \dot{n}_2 \Rightarrow \dot{n}_2 = 0.2596$ mols exhaled/min

H_2O balance: $(0.2438)\left(1.045 \times 10^{-3}\right) + \dot{n}_1 = (0.2596)(0.0619) \Rightarrow \dot{n}_1 = 0.0158$ mol H_2O/min

References for enthalpy calculations: $\text{H}_2\text{O}(l)$ at triple point, dry gas at 2 °C

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$
Dry gas	7.063	0	7.063	36.75
$\text{H}_2\text{O}(v)$	0.00459	2505	0.290	2569
$\text{H}_2\text{O}(l)$	0.285	92.2	—	—

$\dot{m}$ in g/min

$\hat{H}$ in J/g

$\dot{m}_{\text{H}_2\text{O}} = 18.02\dot{n}_{\text{H}_2\text{O}}$

$\hat{H}_{\text{H}_2\text{O}}$ from Table 8.4

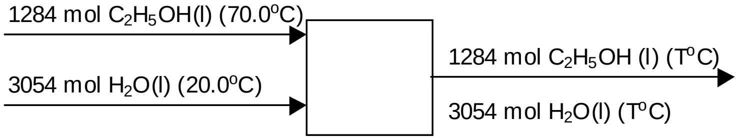
$\hat{H}_{\text{dry gas}} = 1.05(T - 2)$

$$Q = \Delta H = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = \frac{966.8 \text{ J}}{\text{min}} \left| \frac{60 \text{ min}}{1 \text{ hr}} \right| \frac{24 \text{ hr}}{1 \text{ day}} = \underline{\underline{1.39 \times 10^6 \text{ J/day}}}$$

8.29 **a.** $$\frac{75 \text{ liters } C_2H_5OH(l)}{} \left| \frac{789 \text{ g}}{\text{liter}} \right| \frac{1 \text{ mol}}{46.07 \text{ g}} = 1284 \text{ mol } C_2H_3OH(l)$$

$$(C_p)_{CH_3OH} = 0.1031 + 0.557 \times 10^{-3} T \left(\text{kJ / (mol}\cdot{}^\circ\text{C)}\right) \text{ (fitting the two values in Table B.2)}$$

$$\frac{55 \text{ L } H_2O(l)}{} \left| \frac{1000 \text{ g}}{\text{liter}} \right| \frac{1 \text{ mol}}{18.01 \text{ g}} = 3054 \text{ mol } H_2O(l) \quad (C_p)_{H_2O} = 0.0754 \left(\text{kJ/mol}\cdot{}^\circ\text{C}\right)$$



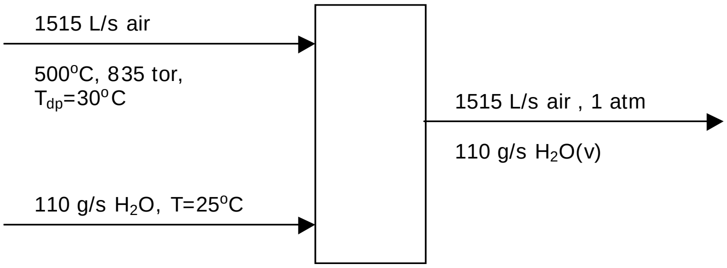
$$0 = 1284\int_{70}^{T}\left(0.1031 + 0.557\times10^{-3}T\right)dT + 3054\int_{25}^{T}\left(0.0754\right)dT$$

$$\left.\begin{array}{l} Q = \Delta U \cong \Delta H\left(\text{liquids}\right) \\ Q = 0\left(\text{adiabatic}\right) \end{array}\right\} \Rightarrow \Downarrow \text{ Integrate, solve quadratic equation}$$

$$\underline{\underline{T = 44.3\ {}^\circ\text{C}}}$$

b.
1. Heat of mixing could affect the final temperature.
2. Heat loss to the outside (not adiabatic)
3. Heat absorbed by the flask wall & thermometer
4. Evaporation of the liquids will affect the final temperature.
5. Heat capacity of ethanol may not be linear; heat capacity of water may not be constant
6. Mistakes in measured volumes & initial temperatures of feed liquids
7. Thermometer is wrong

8.30 **a.**



Let $\dot{n}_1$ (mol / s) be the molar flow rate of dry air in the air stream, and $\dot{n}_2$ (mol / s) be the molar flow rate of H_2O in the air stream.

$$\dot{n}_1 + \dot{n}_2 = \frac{1515 \text{ L}}{\text{s}} \left| \frac{835 \text{ mm Hg}}{773 \text{ K}} \right| \frac{\text{mol}\cdot\text{K}}{62.36 \text{ L}\cdot\text{mm Hg}} = 26.2 \text{ mol / s}$$

$$\frac{\dot{n}_2}{\dot{n}_1 + \dot{n}_2} = y = \frac{p^*(30^\circ\text{ C})}{P_{\text{total}}} = \frac{31.824 \text{ mmHg}}{835 \text{ mmHg}} = 0.0381 \text{ mol } H_2O \text{ / mol air}$$

$$\Rightarrow \dot{n}_1 = 25.2 \text{ mol dry air / s; } \dot{n}_2 = 1.0 \text{ mol } H_2O\text{ / s}$$

8.30 (cont'd)

References: H_2O (l, 25^{o}C), Air (v, 25^{o}C)

substances	$\dot{n}_{in}$ (mol / s)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / s)	$\hat{H}_{out}$ (kJ / mol)
dry air	25.2	14.37	25.2	$\int_{25}^{T}(C_p)_{air}\,dT$
$H_2O(v)$	1.0	$\int_{25}^{100}(C_p)_{H_2O(l)}\,dT+\hat{H}_{vap}$ $\int_{100}^{500}(C_p)_{H_2O(v)}\,dT$	7.1	$\int_{25}^{100}(C_p)_{H_2O(l)}\,dT+\hat{H}_{vap}$ $\int_{100}^{T}(C_p)_{H_2O(v)}\,dT$
$H_2O(l)$	6.1	0	--	--

$$\Delta H=0=\dot{n}_{out}\cdot\hat{H}_{out}-\dot{n}_{in}\cdot\hat{H}_{in}$$

$$(25.2)\left(\int_{25}^{T}(C_p)_{air}\,dT\right)+(7.1)\left(\int_{25}^{100}(C_p)_{H_2O(l)}\,dT+\hat{H}_{vap}+\int_{100}^{T}(C_p)_{H_2O(v)}\,dT\right)$$

$$-(25.2)(14.37)-(1.00)\left(\int_{25}^{100}(C_p)_{H_2O(l)}\,dT+\hat{H}_{vap}+\int_{100}^{500}(C_p)_{H_2O(v)}\,dT\right)=0$$

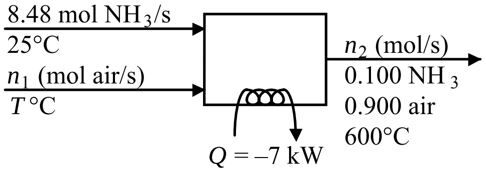
Integrate, solve : $\underline{\underline{T=139^{o}\,\mathrm{C}}}$

b. $\dot{Q}=-(25.2)\int_{500}^{139}(C_p)_{air}\,dT-(1.00)\int_{500}^{139}(C_p)_{H_2O(v)}\,dT=\underline{\underline{-290\ \mathrm{kW}}}$

This heat goes to vaporize the entering liquid water and bring it to the final temperature of 139^{o}C.

c. When cold water contacts hot air, heat is transferred from the air to the cold water mist, lowering the temperature of the gas and raising the temperature of the cooling water.

8.31 Basis: $$\frac{520\text{ kg NH}_3}{\text{h}}\left|\frac{10^3\text{ g}}{1\text{ kg}}\right|\frac{1\text{ mol}}{17.03\text{ g}}\left|\frac{1\text{ h}}{3600\text{ s}}\right.=8.48\text{ mol NH}_3/\text{s}$$



NH$_3$ balance: $8.48=0.100n_2 \Rightarrow n_2=84.8\ \text{mol/s}$

Air balance: $n_1=(0.900)(84.8)=76.3\ \text{mol air/s}$

References for enthalpy calculations: $\text{NH}_3(\text{g})$, air at 25° C

NH$_3$ $\hat{H}_{\text{in}}=0.0$

$$\hat{H}_{\text{out}}=\int_{25}^{600}\left(C_p\right)_{\text{NH}_3}dT \overset{C_p\text{ from}}{\underset{\text{Table B.2}}{\Rightarrow}} \hat{H}_{\text{out}}=25.62\ \text{kJ/mol}$$

Air: $C_p\left(\text{J/mol}\cdot{}^\circ\text{C}\right)=0.02894+0.4147\times10^{-5}T+0.3191\times10^{-8}T^2-1.965\times10^{-12}T^3$

$$\hat{H}_{\text{in}}=\int_{25}^{T}C_p dT$$

$$=\left(-0.4913\times10^{-12}T^4+0.1064\times10^{-8}T^3+0.20735\times10^{-5}T^2+0.02894T-0.7248\right)\left(\text{kJ/mol}\right)$$

$$\hat{H}_{\text{out}}=\int_{25}^{600}C_p dT=17.55\ \text{kJ/mol}$$

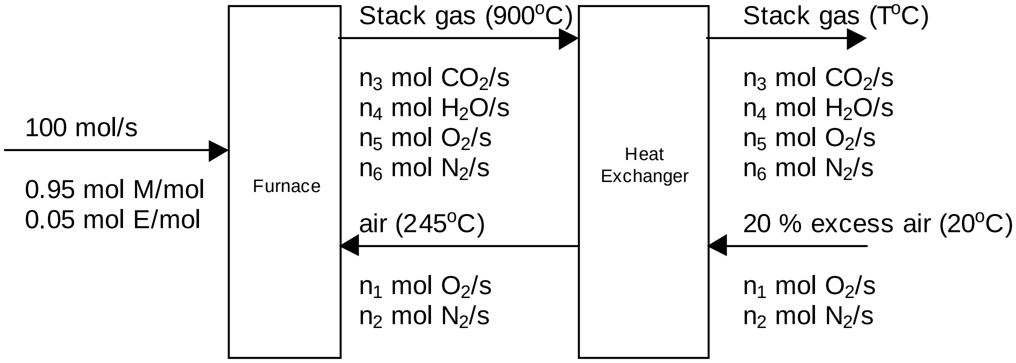
Energy balance: $Q=\Delta H=\sum_{\text{out}}n_i\hat{H}_i-\sum_{\text{in}}n_i\hat{H}_i$

$$\Downarrow$$

$$-7\ \text{kJ/s}=\left(8.48\text{ mols NH}_3/\text{s}\right)\left(25.62\ \text{kJ/mol}\right)+\left(76.3\text{ mols air/s}\right)\left(17.55\ \text{kJ/mol}\right)-\left(8.48\right)\left(0.0\right)$$
$$-\left(76.3\right)\left(-0.4913\times10^{-12}T^4+0.1064\times10^{-8}T^3+0.20735\times10^{-5}T^2+0.02894T-0.7248\right)$$

Solve for *T* by trial-and-error, E-Z Solve, or Excel/Goal Seek $\Rightarrow$ $T=\underline{\underline{691^\circ\text{C}}}$

8.32 **a.** Basis: 100 mol/s of natural gas. Let M represent methane, and E for ethane



$$\text{CH}_4+2\text{O}_2\rightarrow\text{CO}_2+2\text{H}_2\text{O}$$
$$\text{C}_2\text{H}_6+(7/2)\text{O}_2\rightarrow2\text{CO}_2+3\text{H}_2\text{O}$$

8.32 (cont'd)

$$\dot{n}_{air}=1.2\left[\frac{95\text{ mol M}}{\text{s}}\bigg|\frac{2\text{ mol O}_2}{1\text{ mol M}}\bigg|\frac{4.76\text{ mol air}}{\text{mol O}_2}+\frac{5\text{ mol E}}{\text{s}}\bigg|\frac{3.5\text{ mol O}_2}{1\text{ mol E}}\bigg|\frac{4.76\text{ mol air}}{\text{mol O}_2}\right]$$

$$\dot{n}_{air}=\underline{\underline{1185\text{ mol air/s}}}$$

$$\dot{n}_1=0.21\times1185=249\text{ mol O}_2\text{/s},\ \dot{n}_2=0.79\times1185=936\text{ mol N}_2\text{/s}$$

$$\dot{n}_3=\frac{95\text{ mol M}}{\text{s}}\bigg|\frac{1\text{ mol CO}_2}{1\text{ mol M}}+\frac{5\text{ mol E}}{\text{s}}\bigg|\frac{2\text{ mol CO}_2}{1\text{ mol E}}=\underline{\underline{105\text{ mol CO}_2\text{/s}}}$$

$$\dot{n}_4=\frac{95\text{ mol M}}{\text{s}}\bigg|\frac{2\text{ mol H}_2\text{O}}{1\text{ mol M}}+\frac{5\text{ mol E}}{\text{s}}\bigg|\frac{3\text{ mol H}_2\text{O}}{1\text{ mol E}}=\underline{\underline{205\text{ mol H}_2\text{O/s}}}$$

$$\dot{n}_5=249-\frac{95\text{ mol M}}{\text{s}}\bigg|\frac{2\text{ mol O}_2}{1\text{ mol M}}+\frac{5\text{ mol E}}{\text{s}}\bigg|\frac{3.5\text{ mol O}_2}{1\text{ mol E}}=\underline{\underline{41.5\text{ mol O}_2\text{/s}}}$$

$$\dot{n}_6=\dot{n}_2=\underline{\underline{936\text{ mol N}_2\text{/s}}}$$

Energy balance on air:

$$\dot{Q}=\dot{n}_{air}\int_{20}^{245}(C_p)_{air}\,dT=\left(1185\frac{\text{mol air}}{\text{s}}\right)\left(6.649\frac{\text{kJ}}{\text{mol air}}\right)=7879\frac{\text{kJ}}{\text{s}}(=7879\text{ kW})$$

Energy balance on stack gas:

$$\dot{Q}=-\Delta H=-\sum_{i=3}^{6}\left(\dot{n}_i\int_{900}^{T}\left(C_p\right)_i\,dT\right)$$

$$-7879=\dot{n}_3\int_{900}^{T}\left(C_p\right)_{CO_2}dT+\dot{n}_4\int_{900}^{T}\left(C_p\right)_{H_2O(v)}dT+\dot{n}_5\int_{900}^{T}\left(C_p\right)_{O_2}dT+\dot{n}_6\int_{900}^{T}\left(C_p\right)_{N_2}dT$$

Substitute for the heat capacities (Table B.2), integrate, solve for *T* using E-Z Solve $\Rightarrow \underline{\underline{T=732^{\circ}\text{C}}}$

b.

$$\frac{350\text{ m}^3\text{(STP)}}{\text{h}}\bigg|\frac{\text{mol}}{22.4\text{ L(STP)}}\bigg|\frac{1000\text{ L}}{\text{m}^3}\bigg|\frac{1\text{ h}}{3600\text{ s}}=4.34\text{ mol / s}$$

$$\underline{\text{Scale factor}}=\frac{4.34\text{ mol / s}}{100\text{ mol / s}}=0.0434$$

$$\dot{Q}'=0.0434(7851)=\underline{\underline{341\text{ kW}}}$$

8.33 a.

$$\Delta\hat{H}=\int_0^{600}C_p dT=\frac{100}{3}\left[33.5+4(35.1+38.4+42.0)+2(36.7+40.2)43.9\right]=23100\ \text{J/mol}$$

$$Q=\Delta H=n\Delta\hat{H}=\frac{150\text{ mol}}{\text{s}}\bigg|\frac{23100\text{ J}}{\text{mol}}\bigg|\frac{1\text{ kW}}{1000\text{ J / s}}=\underline{\underline{3465\text{ kW}}}$$

b. The method of least squares (Equations A1-4 and A1-5) yields (for $X=T$, $y=C_p$)

$$\underline{\underline{C_p=0.0334+1.732\times10^{-5}T(^{\circ}\text{C})\left[\text{kJ/(mol}\cdot^{\circ}\text{C)}\right]}}\Rightarrow Q=150\int_0^{600}\left[0.0334+1.732\times10^{-5}T\right]dT=\underline{\underline{3474\text{ kW}}}$$

The estimates are exactly identical; in general, (a) would be more reliable, since a linear fit is forced in (b).

8.34 a.

$$\ln C_p=bT^{1/2}+\ln a\Rightarrow C_p=a\exp\left(bT^{1/2}\right),\ \sqrt{T_1}=7.1,\ C_{p1}=0.329,\ \sqrt{T_2}=17.3,\ C_{p2}=0.533$$

$$\left.\begin{aligned}b&=\frac{\ln C_{p2}/C_{p1}}{\sqrt{T_2}-\sqrt{T_1}}=0.0473\\ \ln a&=\ln C_{p1}-b\sqrt{T_1}=-1.4475\Rightarrow a=e^{-1.4475}=0.235\end{aligned}\right\}\Rightarrow\underline{\underline{C_p=0.235\exp\left(0.0473T^{1/2}\right)}}$$

8.34 (cont'd)

b. $\int_{1800}^{150} 0.235\exp\left(0.0473T^{1/2}\right)dT = \frac{(0.235)(2)}{0.0473}\left\{\exp\left(0.473T^{1/2}\right)\left[T^{1/2}-\frac{1}{.0473}\right]\right\}_{1800}^{150} = -1730 \text{ cal/g}$

```
      DIMENSIONS CP(101), NPTS(2)
      WRITE (6, 1)
    1 FORMAT (1H1, 20X'SOLUTION TO PROBLEM 8.37'/)
      NPTS(1) = 51
      NPTS(2) = 101
      DO 200K = 1, 2
      N = NPTS (K)
      NM1 = N – 1
      NM2 = N – 2
      DT = (150.0 – 1800.0)/FLOAT (NM1)
      T = 1800.0
      DO 20 J = 1, N
      CP (J) = 0.235*EXP(0.0473*SQRT(T))
   20 T = T + DT
      SUMI = 0.0
      DO 30 J = 2, NM1, 2
   30 SUMI = SUMI + CP(J)
      SUM2 = 0.0
      DO 40 J = 3, NM2, 2
   40 SUM2 = SUM2 + CP (J)
      DH = DT*(CP(1) + 4.0 = SUM1 + 2.0 =  SUM2 + CP(N))/3.0
      WRITE (6, 2) N, DH
    2 FORMAT (1H0, 5XI3, 'bPOINT INTEGRATIONbbbDELTA(H)b= ', E11.4,'bCAL/G')
  200 CONTINUE
      STOP
      END
```

Solution: $N = 11 \Rightarrow \Delta\hat{H} = -1731 \text{ cal/g}$

$N = 101 \Rightarrow \Delta\hat{H} = \underline{\underline{-1731 \text{ cal/g}}}$

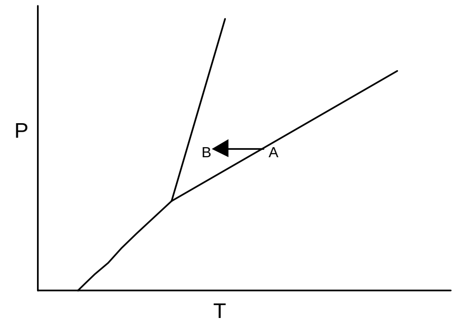
Simpson's rule with $N = 11$ thus provides an excellent approximation

8.35 **a.**

$$\left.\begin{aligned}\dot{m} &= 175 \text{ kg / min}\\ M.W. &= 62.07 \text{ g / mol}\\ \Delta\hat{H}_v &= 56.9 \text{ kJ / mol}\end{aligned}\right\} \Rightarrow \dot{Q} = \Delta H = \frac{175 \text{ kg}}{\text{min}}\left|\frac{1000 \text{ g}}{\text{kg}}\right|\frac{1 \text{ mol}}{62.07 \text{ g}}\left|\frac{56.9 \text{ kJ}}{\text{mol}}\right|\frac{1 \text{ min}}{60 \text{ s}} = \underline{\underline{2670 \text{ kW}}}$$

b. The product stream will be a mixture of vapor and liquid.

c. The product stream will be a supercooled liquid. The stream goes from state A to state B as shown in the following phase diagram.



8.36 **a.** Table B.1 $\Rightarrow T_b = 68.74^\circ\text{C},\ \Delta\hat{H}_v(T_b) = 28.85\ \text{kJ / mol}$

Assume: n-hexane vapor is an ideal gas, i.e. $\Delta\hat{H}$ is not a function of pressure

$$\begin{tikzcd}
(C_6H_{14})_{l,\ 20^\circ C} \arrow[r, "\Delta\hat{H}_{Total}"] \arrow[d, "\Delta\hat{H}_1"] & (C_6H_{14})_{v,\ 200^\circ C} \\
(C_6H_{14})_{l,\ 68.74^\circ C} \arrow[r, "\Delta\hat{H}_v(T_b)"] & (C_6H_{14})_{v,\ 68.74^\circ C} \arrow[u, "\Delta\hat{H}_2"]
\end{tikzcd}$$

$$\Delta\hat{H}_1 = \int_{20}^{68.74} 0.2163\, dT = 10.54\ \text{kJ / mol}$$

$$\Delta\hat{H}_2 = \int_{68.74}^{200} \left[0.13744 + 40.85\times10^{-5}T - 23.92\times10^{-8}T^2 + 57.66\times10^{-9}T^3\right] dT$$

$$\Delta\hat{H}_2 = 24.66\ \text{kJ / mol}$$

$$\Delta\hat{H}_{Total} = \Delta\hat{H}_1 + \Delta\hat{H}_2 + \Delta\hat{H}_v(T_b) = 10.54 + 24.66 + 28.85 = \underline{\underline{64.05\ \text{kJ / mol}}}$$

b. $\Delta\hat{H} = \underline{\underline{-64.05\ \text{kJ / mol}}}$

c. $\hat{U}(200^\circ C,\ 2\ \text{atm}) = \hat{H} - P\hat{V}$

Assume ideal gas behavior $\Rightarrow P\hat{V} = RT = 3.93\ \text{kJ / mol}$

$\hat{U} = 64.05 - 3.93 = \underline{\underline{60.12\ \text{kJ / mol}}}$

8.37 $T_b = 100.00^\circ\text{C} \qquad \Delta\hat{H}_v(t_b) = 40.656\ \text{kJ/mol}$

$$\begin{tikzcd}
H_2O\,(l,\ 50^\circ C) \arrow[r, "\Delta\hat{H}_v(50^\circ C)"] \arrow[d, "\Delta\hat{H}_1"] & H_2O\,(v,\ 50^\circ C) \\
H_2O\,(l,\ 100^\circ C) \arrow[r, "\Delta\hat{H}_v(100^\circ C)"] & H_2O\,(v,\ 100^\circ C) \arrow[u, "\Delta\hat{H}_2"]
\end{tikzcd}$$

$$\Delta\hat{H}_1 = \int_{25}^{100} C_{pH_2O(l)}\, dT = 3.77\ \text{kJ/mol}$$

$$\Delta\hat{H}_2 = \int_{100}^{25} C_{pH_2O(v)}\, dT = -1.69\ \text{kJ/mol}$$

$$\Delta\hat{H}_v(50^\circ C) = 3.77 + \overset{\substack{\text{Table B.1}\\ \downarrow}}{40.656} - 1.69 = \underline{\underline{42.7\ \text{kJ/mol}}}$$

$$\text{Steam table: } \begin{array}{c|c|c} (2547.3 - 104.8)\text{kJ} & 18.01\ \text{g} & 1\ \text{kg} \\ \hline \text{kg} & 1\ \text{mol} & 1000\ \text{g} \end{array} = 44.0\ \text{kJ/mol}$$

The first value uses physical properties of water at 1 atm (Tables B.1, B.2, and B.8), while the heat of vaporization at 50°C in Table B.5 is for a pressure of 0.1234 bar (0.12 atm). The difference is ΔH for liquid water going from 50°C and 0.1234 bar to 50°C and 1 atm plus ΔH for water vapor going from 50°C and 1 atm to 50°C and 0.1234 bar.

8.38

$$\begin{array}{c|r|c|c|c} 1.75\ \text{m}^3 & 879\ \text{kg} & 1\ \text{kmol} & 1000\ \text{mol} & 1\ \text{min} \\ \hline 2.0\ \text{min} & \text{m}^3 & 78.11\ \text{kg} & 1\ \text{kmol} & 60\ \text{s} \end{array} = 164.1\ \text{mol/s}$$

$T_b = 80.1^\circ\text{C}\ ,\ \Delta\hat{H}_v(T_b) = 30.765\ \text{kJ/mol}$

8.38 (cont'd)

$$\begin{tikzcd} C_6H_6\left(\text{v, }580^\circ\text{C}\right) \arrow[r] \arrow[d, "\Delta\hat{H}_1"] & C_6H_6\left(\text{l, }25^\circ\text{C}\right) \\ C_6H_6\left(\text{v, }80.1^\circ\text{C}\right) \arrow[r, "-\Delta\widehat{H}_v"] & C_6H_6\left(\text{l, }80.1^\circ\text{C}\right) \arrow[u, "\Delta\hat{H}_2"'] \end{tikzcd}$$

$$\Delta\hat{H}_1 = \int_{580}^{80.1} C_{pC_6H_6(v)}dT = -77.23\ \text{kJ/mol}$$

$$\Delta\hat{H}_2 = \int_{353.1}^{298} C_{pC_6H_6(l)}dT = -7.699\ \text{kJ/mol}$$

$$\Delta\hat{H} = \Delta\hat{H}_1 - \Delta\hat{H}_v\left(80.1^\circ\text{ C}\right) + \Delta\hat{H}_2 = -115.7\text{ kJ / mol}$$

$$Q = \Delta H = n\Delta\hat{H} = \left(164.1\text{ mol / s}\right)\left(-115.7\text{ kJ / mol}\right) = \underline{\underline{-1.90x10^{-4}\ \text{kW}}}$$

8.39

$$\left.\begin{array}{l}35^\circ\text{C}\\ 15\%\text{ relative saturation}\end{array}\right\} \Rightarrow y_{\text{CCl}_4} = 0.15\frac{\overset{\text{Antoine}}{\overset{\downarrow}{P_V^*}}(25^\circ\text{C})}{1\text{ atm}} = 0.15\frac{176.0\text{ mm Hg}}{760\text{ mm Hg}} = 0.0347\text{ mol CCl}_4/\text{mol}$$

$$(\Delta\hat{H}_v)_{\text{CCl}_4} \overset{\text{Table B.1}}{=} 30.0\ \frac{\text{kJ}}{\text{mol}} \Rightarrow Q = \Delta H = \begin{array}{c|c|c} 10\text{ mol} & 0.0347\text{ mol CCl}_4 & 30.0\text{ kJ} \\ \hline \text{min} & \text{mol} & \text{mol CCl}_4 \end{array} = \underline{\underline{10.4\ \text{kJ/min}}}$$

<u>Time to Saturation</u>

$$\begin{array}{c|c|c|c|c} 6\text{ kg carbon} & 0.40\text{ g CCl}_4 & 1\text{ mol CCl}_4 & 1\text{ mol gas} & 1\text{ min} \\ \hline & \text{g carbon} & 153.84\text{ g CCl}_4 & 0.0347\text{ mol CCl}_4 & 10\text{ mol gas} \end{array} = \underline{\underline{45.0\text{ min}}}$$

8.40 **a.** $\text{CO}_2(\text{g, }20^\circ\text{C}) \rightarrow \text{CO}_2(\text{s, }-78.4^\circ\text{C})$: $\Delta\hat{H} = \int_{20}^{-78.4}\left(C_p\right)_{\text{CO}_2(\text{g})}dT - \Delta\hat{H}_{sub}(-78.4^\circ\text{C})$

In the absence of better heat capacity data; we use the formula given in Table B.2 (which is strictly applicable only above 0°C).

$$\Delta\hat{H} \approx \int_{20}^{-78.4}\left[.03611 + 4.233\times10^{-5}T - 2.887\times10^{-8}T^2 + 7.464\times10^{-12}T^3\right]dT\left(\frac{\text{kJ}}{\text{mol}}\right)$$

$$-6030\begin{array}{c|c} \text{cal} & 4.184\times10^{-3}\ \text{kJ} \\ \hline \text{mol} & 1\text{ cal} \end{array} = -28.66\ \text{kJ/mol}$$

$$Q = \Delta H = n\Delta\hat{H} = \begin{array}{c|c|c|c} 300\text{ kg CO}_2 & 10^3\text{ g} & 1\text{ mol} & 28.66\text{ kJ removed} \\ \hline \text{h} & 1\text{ kg} & 44.01\text{ g} & \text{mol CO}_2 \end{array} = \underline{\underline{1.95\times10^5\ \text{k J/h}}}$$

(or 6.23×10^7 cal/hr or 72.4 kW)

b. According to Figure 6.1-1b, T_{fusion}=-56°C

$$\dot{Q} = \Delta H = \dot{n}\Delta\hat{H}$$

$$\text{where, } \Delta\hat{H} = \int_{20}^{-56}\left(C_p\right)_{\text{CO}_2(\text{v})}dT + \Delta\hat{H}_v\left(-56^\circ\text{ C}\right) + \int_{-56}^{-78.4}\left(C_p\right)_{\text{CO}_2(\text{l})}dT$$

$$\underline{\underline{\dot{Q} = \dot{n}\left[\int_{20}^{-56}\left(C_p\right)_{\text{CO}_2(\text{v})}dT + \Delta\hat{H}_v\left(-56^\circ\text{ C}\right) + \int_{-56}^{-78.4}\left(C_p\right)_{\text{CO}_2(\text{l})}dT\right]}}$$

8.41 **a.** $C_p = a + bT$

$$\left.\begin{aligned} b &= \frac{53.94-50.41}{500-300} = 0.01765 \\ a &= 53.94-(0.01765)(500) = 45.12 \end{aligned}\right\} \Rightarrow C_p(\text{J/mol}\cdot\text{K}) = \underline{\underline{45.12+0.01765T(\text{K})}}$$

$$\text{NaCl }(s, 300\text{ K}) \to \text{NaCl}(s, 1073\text{ K}) \to \text{NaCl}(l, 1073\text{ K})$$

$$\Delta\hat{H} = \int_{300}^{1073} C_{ps}\,dT + \Delta\hat{H}_m(1073\text{ K}) = \left[\int_{300}^{1073}(45.12+0.01765T)\,dT\right]\frac{\text{J}}{\text{mol}} + \frac{30.21\text{ kJ}}{\text{mol}}\left|\frac{10^3\text{ J}}{1\text{ kJ}}\right.$$

$$= \underline{\underline{7.44\times10^4\ \text{J/mol}}}$$

b. $Q = \Delta U = n\int_{300}^{1073} C_v\,dT + \Delta\hat{U}_m(1073\text{ K})$

$$\Big\Downarrow \begin{matrix} C_v \approx C_p \\ \Delta U_m \cong \Delta H_m \end{matrix}$$

$$Q \approx \Delta H = n\Delta\hat{H} = \frac{200\text{ kg}}{}\left|\frac{10^3\text{ g}}{1\text{ kg}}\right|\frac{1\text{ mol}}{58.44\text{ g}}\left|\frac{74450\text{ J}}{\text{mol}}\right. = \underline{\underline{2.55\times10^8\ \text{J}}}$$

c. $t = \dfrac{2.55\times10^8\text{ J}}{}\left|\dfrac{\text{s}}{0.85\times3000\text{ kJ}}\right|\dfrac{1\text{ kJ}}{10^3\text{ J}} = \underline{\underline{100\text{ s}}}$

8.42 $\Delta\hat{H}_v = 35.98$ kJ/mol , $T_b = 136.2°\text{C} = 409.4$ K , $P_c = 37.0$ atm , $T_c = 619.7$ K (from Table B.1)

Trouton's rule: $\Delta\hat{H}_v \approx 0.088T_b = (0.088)(409.4\text{ K}) = \underline{\underline{36.0\ \text{kJ/mol}}}(0.1\%\text{ error})$

Chen's rule:

$$\Delta\hat{H}_v \approx \frac{T_b\left[0.0331\left(\dfrac{T_b}{T_c}\right) - 0.0327 + 0.0297\log_{10} P_c\right]}{1.07 - \left(\dfrac{T_b}{T_c}\right)} = \underline{\underline{35.7\ \text{kJ/mol}}}\ (-0.7\%\text{ error})$$

Watson's correlation : $\Delta\hat{H}_v(100°\text{C}) \approx 35.98\left(\dfrac{619.7-373.2}{619.7-409.4}\right)^{0.38} = \underline{\underline{38.2\ \text{kJ/mol}}}$

8.43 $\underline{C_7H_2N}$: Kopp's Rule $\Rightarrow C_p \approx 7(0.012) + 12(0.018) + 0.033 = 0.333$ kJ/(mol·°C)

Trouton's Rule $\Rightarrow \Delta\hat{H}_v(200°\text{C}) = 0.088(200+273.2) = 41.6$ kJ/mol

$$C_7H_{12}N(l,\ 25°\text{C}) \to C_7H_{12}N(l,\ 200°\text{C}) \to C_7H_{12}N(v,\ 200°\text{C})$$

$$\boxed{\Delta\hat{H} = \int_{25}^{200} C_p\,dT + \Delta\hat{H}_v(200°\text{C}) \approx 0.333(200-25)\frac{\text{kJ}}{\text{mol}} + 41.6\frac{\text{kJ}}{\text{mol}} = \underline{\underline{100\ \text{kJ/mol}}}}$$

8.44 a. Antoine equation: $T_b\left({}^\circ\text{C}\right)=\dfrac{1211.033}{6.90565-\log(100)}-220.790=26.1^\circ\text{C}$

Watson Correction: $\Delta\hat{H}_v\left(26.1^\circ\text{C}\right)=30.765\left(\dfrac{562.6-299.3}{562.6-353.1}\right)^{0.38}=\underline{\underline{33.6\ \text{kJ/mol}}}$

b. Antoine equation: $T_b\left(50\text{ mm Hg}\right)=11.8^\circ\text{C}\ ;\ T_b\left(150\text{ mm Hg}\right)=35.2^\circ\text{C}$

Clausius-Clapeyron: $\ln p=-\dfrac{\Delta\hat{H}_v}{RT}+C\Rightarrow\Delta\hat{H}_v=-R\dfrac{\ln\left(p_2/p_1\right)}{1/T_2-1/T_1}$

$$\Delta\hat{H}_v=-0.008314\frac{\text{kJ}}{\text{mol}\cdot\text{K}}\left\{\frac{\ln\left(150/50\right)}{1/308.4\text{ K}\ -\ 1/285.0\text{ K}}\right\}=\underline{\underline{34.3\ \text{kJ/mol}}}$$

c.

$$\begin{tikzcd}
C_6H_6\ (l,\,26.1^\circ\text{C}) \arrow[r, dashed] \arrow[d, "\Delta\hat{H}_1"] & C_6H_6\ (v,\,26.1^\circ\text{C}) \\
C_6H_6\ (l,\,80.1^\circ\text{C}) \arrow[r, "\Delta\hat{H}_v\ (80.1^\circ\text{C})"] & C_6H_6\ (v,\,80.1^\circ\text{C}) \arrow[u, "\Delta\hat{H}_2"']
\end{tikzcd}$$

$$\Delta\hat{H}_1=\int_{26.1}^{80.1}\left(C_p\right)_l dT=7.50\ \text{kJ/mol}$$

$$\Delta\hat{H}_2=\int_{80.1}^{26.1}\left(C_p\right)_v dT=-4.90\ \text{kJ/mol}$$

$$\Delta\hat{H}_v\left(26.1^\circ\text{C}\right)=7.50+30.765-4.90=\underline{\underline{33.4\ \text{kJ/mol}}}$$

8.45 a. $\underline{\underline{T_{\text{out}}=49.3^\circ\text{C}}}$. The only temperature at which a pure species can exist as both vapor and liquid at 1 atm is the normal boiling point, which from Table B.1 is 49.3°C for cyclopentane.

b. Let $\dot{n}_f$, $\dot{n}_v$, and $\dot{n}_l$ denote the molar flow rates of the feed, vapor product, and liquid product streams, respectively.

Ideal gas equation of state

$$\dot{n}_f=\frac{1550\text{ L}}{\text{s}}\left|\frac{273\text{ K}}{423\text{ K}}\right|\frac{1\text{ mol}}{22.4\text{ L(STP)}}=44.66\text{ mol }C_5H_{10}\text{(v)/s}$$

55% condensation: $\dot{n}_l=0.550(44.66\text{ mol/s})\ =\ 24.56\text{ mol }C_5H_{10}\text{(l)/s}$

Cyclopentane balance $\Rightarrow$ $\dot{n}_v=(44.66-24.56)\text{ mol }C_5H_{10}\text{ /s}\ =\ 20.10\text{ mol }C_5H_{10}\text{(v)/s}$

Reference: C_5H_{10}(l) at 49.3°C

Substance	$\dot{n}_{\text{in}}$ (mol/s)	$\hat{H}_{\text{in}}$ (kJ/mol)	$\dot{n}_{\text{out}}$ (mol/s)	$\hat{H}_{\text{out}}$ (kJ/mol)
C_5H_{10} (l)	—	—	24.56	0
C_5H_{10} (v)	44.66	$\hat{H}_f$	20.10	$\hat{H}_v$

$$H_i=\Delta\hat{H}_v+\int_{49.3^\circ\text{C}}^{T_i}C_p\ dT$$

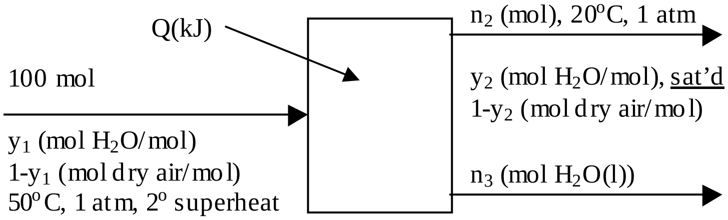
8.45 (cont'd)

Substituting for $\Delta\hat{H}_v$ from Table B.1 and for C_p from Table B.2

$$\Rightarrow \hat{H}_f = 38.36 \text{ kJ / mol}, \ \hat{H}_v = 27.30 \text{ kJ / mol}$$

<u>Energy balance</u>: $\dot{Q} = \sum n_{\text{out}} \hat{H}_{\text{out}} - \sum n_{\text{in}} \hat{H}_{\text{in}} = -1.16\times 10^3 \text{ kJ / s} = \underline{\underline{-1.16\times 10^3 \text{ kW}}}$

8.46 a. <u>Basis: 100 mol humid air fed</u>



There are five unknowns (n_2, n_3, y_1, y_2, Q) and five equations (two independent material balances, 2°C superheat, saturation at outlet, energy balance). The problem can be solved.

b.

<u>2° C superheat</u> $\Rightarrow \underline{\underline{y_1}} = \dfrac{p*(48°\text{C})}{p}$

<u>saturation at outlet</u> $\Rightarrow \underline{\underline{y_2}} = \dfrac{p*(20°\text{C})}{p}$

<u>dry air balance:</u> $(100)(1-y_1) = \underline{\underline{n_2}}(1-y_2)$

<u>H_2O balance:</u> $(100)(y_1) = (n_2)(y_2) + \underline{\underline{n_3}}$

c. <u>References</u>: Air $(25°\text{C})$, $H_2O(l,\ 20°\text{C})$

Substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
Air	$100\cdot(1-y_1)$	$\hat{H}_1$	$n_2\cdot(1-y_2)$	$\hat{H}_3$	n in mol
$H_2O(v)$	$100\cdot y_1$	$\hat{H}_2$	$n_2\cdot y_2$	$\hat{H}_4$	$\hat{H}$ in kJ/mol
$H_2O(l)$	–	–	n_3	0	

$$\hat{H}_1 = \int_{25}^{50} (C_p)_{\text{air}}\, dT = \int_{25}^{50} \left[0.02894 + 0.4147\times 10^{-5} T + 0.3191\times 10^{-8} T^2 - 1.965\times 10^{-12} T^3\right] dT$$

$$\hat{H}_2 = \int_{20}^{100} (C_p)_{H_2O(l)}\, dT + \Delta\hat{H}_v(100°\text{C}) + \int_{100}^{50} (C_p)_{H_2O(v)}\, dT$$

$$= \int_{20}^{100} [0.0754]\, dT + 40.656 +$$

$$\int_{100}^{50} \left[0.03346 + 0.688\times 10^{-5} T + 0.7604\times 10^{-8} T^2 - 3.593\times 10^{-12} T^3\right] dT$$

$$\hat{H}_3 = \int_{25}^{20} (C_p)_{\text{air}}\, dT$$

$$\hat{H}_2 = \int_{20}^{100} (C_p)_{H_2O(l)}\, dT + \Delta\hat{H}_v(100°\text{C}) + \int_{100}^{20} (C_p)_{H_2O(v)}\, dT$$

8.46 (cont'd)

c.

$$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i \qquad V_{\text{air}} = \frac{100 \text{ mol}}{} \bigg| \frac{8.314 \text{ Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}} \bigg| \frac{323 \text{ K}}{1.01325\times 10^5 \text{ Pa}}$$

$$\Rightarrow \frac{Q}{V_{\text{air}}} = \underline{\underline{\frac{\displaystyle\sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i}{\dfrac{100 \text{ mol}}{} \bigg| \dfrac{8.314 \text{ Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}} \bigg| \dfrac{323 \text{ K}}{1.01325\times 10^5 \text{ Pa}}}}}$$

d.

$$\underline{2^\circ\text{C superheat}} \Rightarrow y_1 = \frac{p*(48^\circ\text{C})}{p} = \frac{83.71 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.110 \text{ mol } H_2O/\text{mol}$$

$$\underline{\text{saturation at outlet}} \Rightarrow y_2 = \frac{p*(20^\circ\text{C})}{p} = \frac{17.535 \text{ mm Hg}}{760 \text{ mm Hg}} = 0.023 \text{ mol } H_2O/\text{mol}$$

$$\underline{\text{dry air balance:}} \quad (100)(1-0.110) = n_2(1-0.023) \Rightarrow n_2 = 91.10 \text{ mol}$$

$$\underline{H_2O \text{ balance:}} \quad (100)(0.110) = (91.10)(0.023) + n_3 \Rightarrow n_3 = \frac{8.90 \text{ mol } H_2O}{} \bigg| \frac{0.018 \text{ kg}}{1 \text{ mol}}$$

$$= 0.160 \text{ kg } H_2O \text{ condensed}$$

$$Q = \Delta H = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = -480.5 \text{ kJ}$$

$$V_{\text{air}} = \frac{100 \text{ mol}}{} \bigg| \frac{8.314 \text{ Pa}\cdot\text{m}^3}{\text{mol}\cdot\text{K}} \bigg| \frac{323 \text{ K}}{1.01325\times 10^5 \text{ Pa}} = 2.65 \text{ m}^3$$

$$\Rightarrow \frac{0.160 \text{ kg } H_2O \text{ condensed}}{2.65 \text{ m}^3 \text{ air fed}} = \underline{\underline{0.0604 \text{ kg } H_2O \text{ condensed / m}^3 \text{ air fed}}}$$

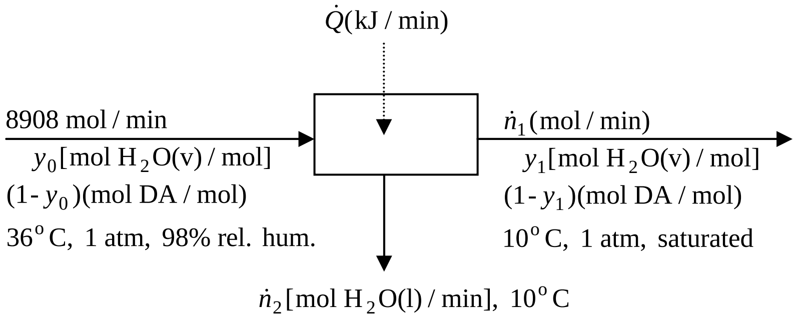
$$\Rightarrow \frac{-480.5 \text{ kJ}}{2.65 \text{ m}^3 \text{ air fed}} = \underline{\underline{-181 \text{ kJ / m}^3 \text{ air fed}}}$$

e. Solve equations with E-Z Solve.

f.

$$Q = \frac{-181 \text{ kJ}}{\text{m}^3 \text{ air fed}} \bigg| \frac{250 \text{ m}^3 \text{ air fed}}{\text{h}} \bigg| \frac{1 \text{ h}}{3600 \text{ s}} \bigg| \frac{1 \text{ kW}}{1 \text{ kJ / s}} = \underline{\underline{-12.6 \text{ kW}}}$$

8.47 Basis: $\dfrac{226\ \text{m}^3}{\text{min}}\Bigg|\dfrac{273\ \text{K}}{309\ \text{K}}\Bigg|\dfrac{10^3\ \text{mol}}{22.415\ \text{m}^3(\text{STP})} = 8908\ \text{mol humid air/min}$. DA = Dry air



a. Degree of freedom analysis: 5 unknowns – (1 relative humidity + 2 material balances + 1 saturation condition at outlet + 1 energy balance) = 0 degrees of freedom.

b. Inlet air: $y_0 P = 0.98 p_w^* \overset{\text{Table B.3}}{\overset{\downarrow}{(36°\text{C})}} \Rightarrow y_0 = \dfrac{0.98(44.563\ \text{mm Hg})}{760\ \text{mm Hg}} = 0.0575\ \text{mol}\ \ H_2O(\text{v})/\text{mol}$

Outlet air: $y_1 = p^*(10°\text{C})/P = (9.209\ \text{mm Hg})/(760\ \text{mm Hg}) = 0.0121\ \text{mol}\ \ H_2O(\text{v})/\text{mol}$

Air balance: $(1-0.0575)(8908\ \text{mol/min}) = (1-0.0121)\dot{n}_1 \Rightarrow \dot{n}_1 = 8499\ \text{mol/min}$

H_2O balance: $0.0575\left(8908\dfrac{\text{mol}}{\text{min}}\right) = 0.0121(8499\dfrac{\text{mol}}{\text{min}}) + \dot{n}_2 \Rightarrow \dot{n}_2 = \underline{\underline{409\ \text{mol}\ \ H_2O(\text{l})/\text{min}}}$

References: $H_2O(l$, triple point), air (77° F)

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Air	8396	0.3198	8396	–0.4352	$\dot{n}$ in mol/min
$H_2O(v)$	512	46.2	103	45.3	$\hat{H}$ in kJ/mol
$H_2O(l)$	–	–	409	0.741	

Air: $\hat{H}$ from Table B.8

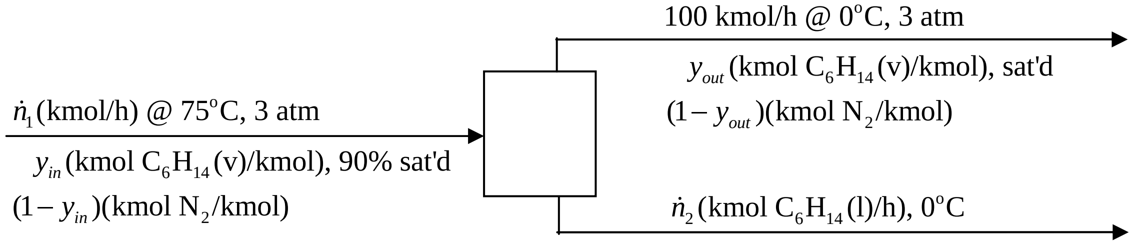
H_2O: $\hat{H}$(kJ / kg) from Table B.5 × (0.018 kg / mol)

Energy balance:

$$Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = \frac{-2.50\times10^4\ \text{kJ}}{\text{min}}\bigg|\frac{60\ \text{min}}{1\ \text{h}}\bigg|\frac{9.486\times10^{-4}\ \text{Btu}}{0.001\ \text{kJ}}\bigg|\frac{1\ \text{ton}}{-12000\ \text{Btu/h}} = \underline{\underline{119\ \text{tons}}}$$

8.48

Basis: $\dfrac{746.7\ \text{m}^3\ \text{outlet gas / h}}{} \left| \dfrac{3\ \text{atm}}{1\ \text{atm}} \right| \dfrac{1\ \text{kmol}}{22.4\ \text{m}^3(\text{STP})} \Bigg| = 100.0\ \text{kmol / h}$



Antoine:

$$\log p_v^* = 6.88555 - \frac{1175.817}{224.867+T} \qquad p_v^*(0°\text{C}) = 45.24\ \text{mm Hg},\ p_v^*(75°\text{C}) = 920.44\ \text{mm Hg}$$

$$y_{\text{out}} = \frac{p_v^*(0°\,\text{C})}{P} = \frac{45.24}{3(760)} = 0.0198\ \text{kmol}\ \ C_6H_{14}/\text{kmol}\ ,$$

$$y_{\text{in}} = \frac{0.90p_v^*(75°\,\text{C})}{P} = \frac{(0.90)(920.44)}{3(760)} = 0.363\frac{\text{kmol}\ C_6H_{14}}{\text{kmol}}$$

<u>N_2 balance:</u> $\dot{n}_1(1-0.363) = 100(1-0.0198) \Rightarrow \dot{n}_1 = 153.9\ \ \text{kmol/h}$

<u>C_6H_{14} balance:</u> $(153.9)(0.363) = (100)(0.0198) + \dot{n}_2 \Rightarrow \dot{n}_2 = 53.89\ \ \text{kmol}\ C_6H_{14}(l)/\text{h}$

<u>Percent Condensation:</u> $(53.89\ \ \text{kmol/h condense})/(0.363\times153.9)(\text{kmol/h in feed})\times100\% = \underline{\underline{96.5\%}}$

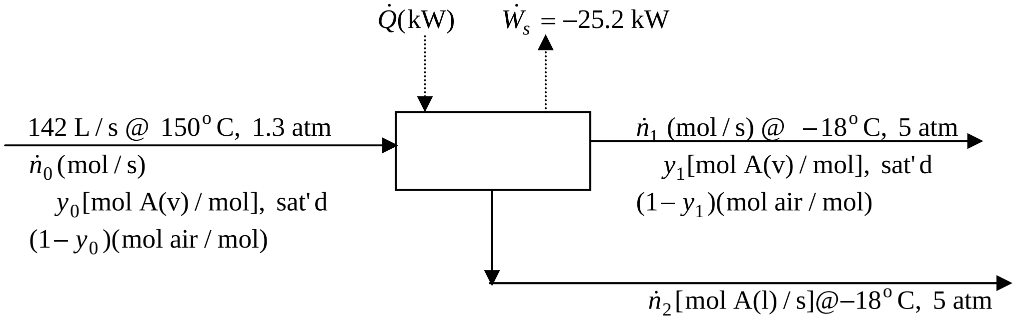
<u>References</u>: N_2(25°C), n-C_6H_{14}(l, 0°C)

Substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
N_2	98000	1.46	98000	–0.726	$\dot{n}$ in mol/h
n-$C_6H_{14}(r)$	55800	44.75	2000	33.33	$\hat{H}$ in kJ/mol
n-$C_6H_{14}(l)$	–	–	53800	0.0	

<u>N_2</u>: $\hat{H} = \overline{C}_p(T-25)$, <u>$n-C_6H_{14}$(v)</u>: $\hat{H} = \displaystyle\int_0^{68.7} C_{p\ell}\,dT + \Delta\hat{H}_v(68.7) + \int_{68.7}^{T} C_{pv}\,dT$

<u>Energy balance</u>: $Q = \Delta \underset{\substack{\Uparrow \\ \sum\limits_{\text{out}} n_i\hat{H}_i - \sum\limits_{\text{in}} n_i\hat{H}_i}}{H} = (-2.64\times10^6\ \ \text{kJ/h})(1\ \text{h / 3600 s}) \Rightarrow \underline{\underline{-733\ \text{kW}}}$

8.49 Let A denote acetone.



a. Degree of freedom analysis: 6 unknowns ($\dot{n}_0$, $\dot{n}_1$, $\dot{n}_2$, y_0, y_1, $\dot{Q}$)
–2 material balances
–1 equation of state for feed gas
–1 sampling result for feed gas
–1 saturation condition at outlet
–1 energy balance
0 degrees of freedom

b. Ideal gas equation of state Raoult's law

(1) $\dot{n}_0 = \dfrac{P_0\dot{V}_0}{RT_0}$ **(2)** $y_1 = \dfrac{p_A^*(-18^\circ\text{C})}{5\text{ atm}}$ (Antoine equation for p_A^*)

Feed stream analysis

(3) $y_0\left(\dfrac{\text{mol A}}{\text{mol}}\right) = \dfrac{[(4.973-4.017)\text{ g A}][1\text{ mol A}/58.05\text{ g}]}{[(3.00\text{ L})P_0/RT_0]\text{ mol feed gas}}$

Air balance: $\dot{n}_1 = \dfrac{\dot{n}_0(1-y_0)}{(1-y_1)}$ **(4)** Acetone balance: $\dot{n}_2 = \dot{n}_0 y_0 - \dot{n}_1 y_1$ **(5)**

Reference states: A(l, –18°C), air(25 °C)

Substance	$\dot{n}_{\text{in}}$ (mol/s)	$\hat{H}_{\text{in}}$ (kJ/mol)	$\dot{n}_{\text{out}}$ (mol/s)	$\hat{H}_{\text{out}}$ (kJ/mol)
A(l)	–	–	$\dot{n}_2$	0
A(v)	$\dot{n}_0 y_0$	$\hat{H}_{A0}$	$\dot{n}_1 y_1$	$\hat{H}_{A1}$
air	$\dot{n}_0(1-y_0)$	$\hat{H}_{a0}$	$\dot{n}_1(1-y_1)$	$\hat{H}_{a1}$

(6) $$\hat{H}_{\text{A(v)}}(T) = \int_{-18^\circ\text{C}}^{56^\circ\text{C}} \underbrace{(C_p)_{\text{A(l)}}}_{\text{Table B.2}}\,dT + \underbrace{(\Delta\hat{H}_v)_{\text{A}}}_{\text{Table B.1}} + \int_{56^\circ\text{C}}^{T} \underbrace{(C_p)_{\text{A(v)}}}_{\text{Table B.2}}\,dT$$

(7) $\hat{H}_{\text{air}}(T)$ from Table B.8

(8) $\dot{Q} = \dot{W}_s + \sum \dot{n}_{\text{out}}\hat{H}_{\text{out}} - \sum \dot{n}_{\text{in}}\hat{H}_{\text{in}}$ ($\dot{W}_s = -25.2$ kJ/s)

8.49 (cont'd)

c.

$(1) \Rightarrow \dot{n}_0 = \underline{\underline{5.32 \text{ mol feed gas/s}}}$ $\qquad (2) \Rightarrow y_1 = \underline{\underline{6.58\times 10^{-3} \text{ mol A(v)/mol outlet gas}}}$

$(3) \Rightarrow y_0 = \underline{\underline{0.147 \text{ mol A(v)/mol feed gas}}}$

$(4) \Rightarrow \dot{n}_1 = 4.57 \text{ mol outlet gas/s}$ $\qquad (5) \Rightarrow \dot{n}_2 = 0.75 \text{ mol A(l)/s}$

$(6) \Rightarrow \hat{H}_{A0} = 48.1 \text{ kJ/mol}, \ \hat{H}_{A1} = 34.0 \text{ kJ/mol}$

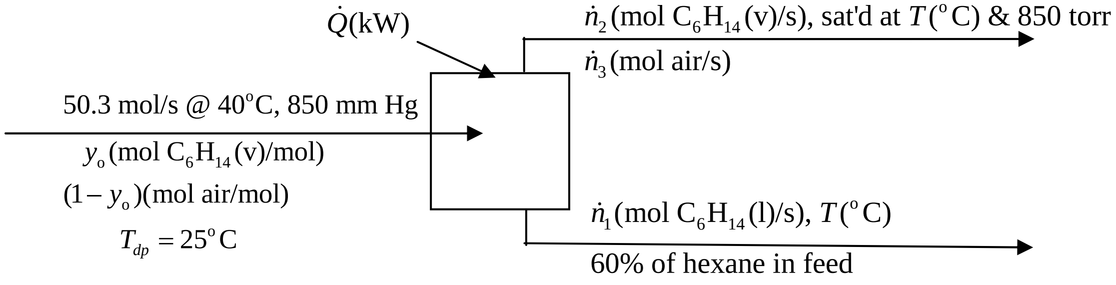
$(7) \Rightarrow \hat{H}_{a0} = 3.666 \text{ kJ/mol}, \ \hat{H}_{a1} = -1.245 \text{ kJ/mol}$

$(8) \Rightarrow \underline{\underline{\dot{Q} = -84.1 \text{ kW}}}$

8.50 a. Feed:

$$\begin{array}{c|c|c|c|c|c|c}
3\text{ m} & \pi(35)^2\text{ cm}^2 & 1\text{ m}^2 & 273\text{ K} & 850\text{ torr} & 1\text{ kmol} & 10^3\text{ mol} \\
\hline
\text{s} & & 10^4\text{ cm}^2 & (273+40)\text{K} & 760\text{ torr} & 22.4\text{ m}^3\text{(STP)} & 1\text{ kmol}
\end{array} = 50.3\frac{\text{mol}}{\text{s}}$$

Assume outlet gas is at 850 mm Hg.



Degree-of-freedom analysis

6 unknowns $(y_0, \dot{n}_1, \dot{n}_2, \dot{n}_3, T, \dot{Q})$
– 2 independent material balances
– 2 Raoult's law (for feed and outlet gases)
– 1 60% recovery equation
– 1 energy balance
0 degrees of freedom ⇒ All unknowns can be calculated.

b. Let H = C_6H_{14}

Antoine equation, Table B.4

$$\underline{(T_{\text{dp}})_{\text{feed}} = 25\ ^\circ\text{C}} \Rightarrow y_0 = \frac{p_H^*(25^\circ\text{C})}{P} = \frac{151 \text{ mm Hg}}{850 \text{ mm Hg}} = 0.178 \text{ mol H/mol}$$

$$\underline{\text{60\% recovery}} \Rightarrow \dot{n}_1 = \frac{0.600 \ \big| \ (50.3)(0.178) \text{ mols H feed}}{\text{s}} = 5.37 \text{ mol H}(l)/\text{s}$$

Hexane balance: $(0.178)(50.3) = 5.37 + \dot{n}_2 \Rightarrow \dot{n}_2 = 3.58 \text{ mol H}(v)/\text{s}$

8.50 (cont'd)

Air balance: $\dot{n}_3 = (50.3)(1-0.178) = 41.3 \text{ mol air/s}$

Mole fraction of hexane in outlet gas:

$$\frac{\dot{n}_2}{\dot{n}_2+\dot{n}_3} = \frac{3.58}{(3.58+41.3)} = \frac{p_H(T)}{850 \text{ mm Hg}} \Rightarrow p_H(T) = 67.8 \text{ mm Hg}$$

Saturation at outlet: $p_{\mathrm{H}}^*(T) = p_H(T) = 67.8 \text{ mm Hg} \xrightarrow{\text{Table B.4}} \underline{\underline{T = 7.8°\text{C}}}$

Reference states: $C_6H_{14}(l, 7.8°\text{C})$, air (25°C)

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$
$C_6H_{14}(v)$	8.95	37.5	3.58	32.7
$C_6H_{14}(l)$	—	—	5.37	0
Air	41.3	0.435	41.3	–0.499

$\dot{n}$ in mol/s
$\hat{H}$ in kJ/mol

$$C_6H_{14}(v): \ \hat{H} = \int_{7.8}^{68.74} C_{pl}\,dT + \Delta\hat{H}_v(68.74\ °\text{C}) + \int_{68.74}^{T} C_{pv}\,dT,$$

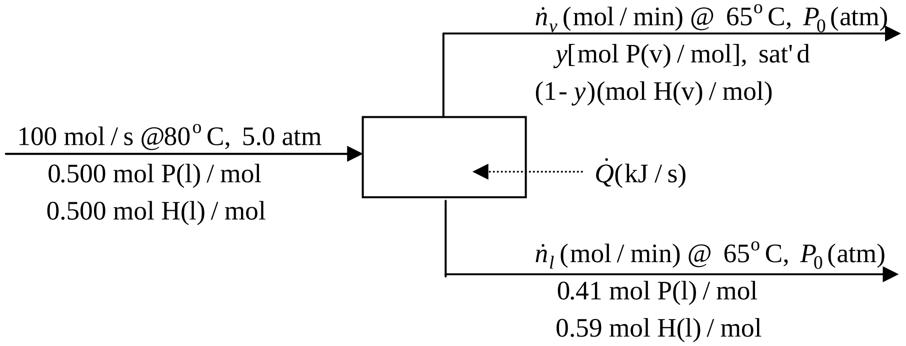
C_p from Table B.2
$\Delta\hat{H}_v$ from Table B.1

Air: $\hat{H}$ from Table B.8

Energy balance: $Q = \Delta H = \sum_{\text{out}} \dot{n}_i\hat{H}_i - \sum_{\text{in}} \dot{n}_i\hat{H}_i = \dfrac{-257 \text{ kJ/s}}{} \left| \dfrac{1 \text{ kW cooling}}{-1 \text{ kJ/s}} \right. = \underline{\underline{257 \text{ kW}}}$

c. $\left. u\cdot A = u'\cdot A';\ A = \dfrac{\pi\cdot D^2}{4};\ D' = \dfrac{1}{2}D \right\} \Rightarrow u' = 4\cdot u = \underline{\underline{12.0 \text{ m/s}}}$

8.51



a. Degree of freedom analysis

5 unknowns – 2 material balances – 2 equilibrium relations (Raoult's law) at outlet – 1 energy balance

= 0 degrees of freedom

Antoine equation (Table B.4) $\Rightarrow$ $p_P^*(65^\circ\text{C}) = 1851$ mm Hg, $p_H^*(65^\circ\text{C}) = 675$ mm Hg

Raoult's law for pentane and hexane

$$\left.\begin{array}{l} 0.410\,p_P^*(65^\circ\text{C}) = yP_0 \\ 0.590\,p_H^*(65^\circ\text{C}) = (1-y)P_0 \end{array}\right. \Rightarrow \begin{array}{l} \underline{\underline{y = 0.656 \text{ mol P(v) / mol}}} \\ \underline{\underline{P_0 = 1157 \text{ mm Hg (1.52 atm)}}} \end{array}$$

$$\left.\begin{array}{l} \text{Total mole balance: } 100 \text{ mol} = \dot{n}_v + \dot{n}_l \\ \text{Pentane balance: } 50 \text{ mole P} = 0.656\dot{n}_v + 0.410\dot{n}_l \end{array}\right. \Rightarrow \begin{array}{l} \dot{n}_v = 36.6 \text{ mol vapor / s} \\ \dot{n}_l = 63.4 \text{ mol liquid / s} \end{array}$$

Ideal gas equation of state: $V_v = \dfrac{n_v RT}{P_0} = \dfrac{36.6\text{ mol}}{\text{s}}\left|\dfrac{0.08206\text{ L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right|\dfrac{(65+273)\text{K}}{1.52\text{ atm}} = \underline{\underline{667\text{ L / s}}}$

Fractional vaporization of propane: $f = \dfrac{(0.656\times 36.6)\text{ mol P(v)/s}}{50.0\text{ mol P(l) fed/s}} = \underline{\underline{0.480\dfrac{\text{mol P vaporized}}{\text{mol fed}}}}$

References: P(l), H(l) at 65°C

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
P(v)	–	–	24.0	24.33	$\dot{n}$ in mol/s
P(l)	50	2.806	26.0	0	$\hat{H}$ in kJ / mol
H(v)	–	–	12.6	29.05	
H(l)	50	3.245	37.4	0	

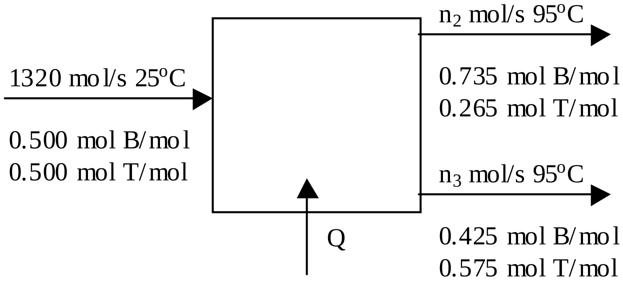
Vapor: $\hat{H}(T) = \int_{65^\circ\text{C}}^{T_b} C_{pl}\,dT + \Delta\hat{H}_v(T_b) + \int_{T_b}^{T} C_{pv}\,dT$

Liquid: $\hat{H}(T) = \int_{65^\circ\text{C}}^{T} C_{pl}\,dT$

T_b and $\Delta\hat{H}_v$ from Table B.1, C_p from Table B.2

Energy balance: $\dot{Q} = \sum \dot{n}_{\text{out}}\hat{H}_{\text{out}} - \sum \dot{n}_{\text{in}}\hat{H}_{\text{in}} = \underline{\underline{647\text{ kW}}}$

8.52 **a.** B=benzene; T=toluene



$$\left.\begin{array}{ll}\text{Total mole balance:} & 1320 = n_2 + n_3 \\ \text{Benzene balance:} & 1320(0.500) = n_2(0.735) + n_3(0.425)\end{array}\right\} \Rightarrow \left\{\begin{array}{l} n_2 = 319 \text{ mol / s} \\ n_3 = 1001 \text{ mol / s}\end{array}\right.$$

References: B(l, 25°C), T(l, 25°C)

Substance	$\dot{n}_{\text{in}}$ (mol / s)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{\text{out}}$ (mol / s)	$\hat{H}_{out}$ (kJ / mol)
B(l)	660	0	425	9.838
B(v)	--	--	234	39.91
T(l)	660	0	576	11.78
T(v)	--	--	85	46.06

$$Q = \sum_{out} n_i \hat{H}_i - \sum_{in} n_i \hat{H}_i = \underline{\underline{2.42\times 10^4 \text{ kW}}}$$

b. Antoine equation (Table B.4) $\Rightarrow$ $p_B^*\left(95^\circ\text{ C}\right) = 1176$ torr , $p_T^*\left(95^\circ\text{ C}\right) = 476.9$ torr

Raoult's law

$$\left.\begin{array}{ll}\text{Benzene:} & (0.425)(1176) = (0.735)P \Rightarrow P = 680 \text{ torr} \\ \text{Toluene:} & (0.575)(476.9) = (0.265)P' \Rightarrow P' = 1035 \text{ torr}\end{array}\right\} \Rightarrow P \neq P'$$

$\Rightarrow$ Analyses are inconsistent.

Possible reasons: The analyses are wrong; the evaporator had not reached steady state when the samples were taken; the vapor and liquid product streams are not in equilibrium; Raoult's law is invalid at the system conditions (not likely).

8.53 Kopp's rule (Table B.10): $C_5H_{12}O(s)$ — $C_p = (5)(7.5) + (12)(9.6) + 17 = 170$ J/mol

$C_5H_{12}O(l)$ — $C_p = (5)(12) + (12)(18) + 25 = 301$ J/mol

Trouton's rule — Eq. (8.4-3): $\Delta H_v = (0.109)(113 + 273) = 42.1$ kJ/mol

Eq. (8.4-5) $\Rightarrow$ $\Delta\hat{H}_m = (0.050)(52 + 273) = 16.25$ kJ/mol

Basis: $$\frac{235 \text{ m}^3}{\text{h}} \left| \frac{273 \text{ K}}{389 \text{ K}} \right| \frac{1 \text{ kmol}}{22.4 \text{ m}^3(\text{STP})} \left| \frac{10^3 \text{ mol}}{1 \text{ kmol}} \right| \frac{1 \text{ h}}{3600 \text{ s}} = 2.05 \text{ mol/s}$$

Neglect enthalpy change for the vapor transition from 116°C to 113°C.

$$C_5H_{12}O(v, 113^\circ\text{C}) \rightarrow C_5H_{12}O(l, 113^\circ\text{C}) \rightarrow C_5H_{12}O(v, 52^\circ\text{C})$$
$$\rightarrow C_5H_{12}O(s, 52^\circ\text{C}) \rightarrow C_5H_{12}O(s, 25^\circ\text{C})$$

8.53 (cont'd)

$$\Delta\hat{H} = -\Delta\hat{H}_v + C_{pl}(52-113) - \Delta\hat{H}_m + C_{ps}(25-52)$$

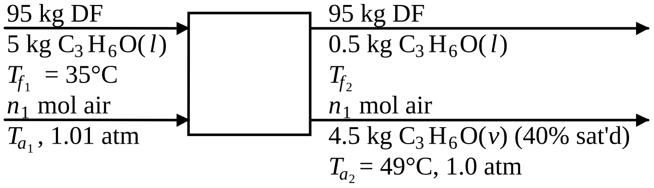
$$= -42.1\frac{\text{kJ}}{\text{mol}} - 16.2\frac{\text{kJ}}{\text{mol}} - \left[(301)(61)+(170)(27)\right]\frac{\text{J}}{\text{mol}}\times\frac{1\text{ kJ}}{10^3\text{ J}} = -81.3\text{ kJ/mol}$$

Required heat transfer: $Q = \Delta H = n\Delta\hat{H} = \dfrac{2.05\text{ mol}}{\text{s}}\left|\dfrac{-81.3\text{ kJ}}{\text{mol}}\right|\dfrac{1\text{ kW}}{1\text{ kJ/s}} = \underline{\underline{-167\text{ kW}}}$

8.54

Basis: 100 kg wet film $\Rightarrow \left.\begin{array}{l}\text{95 kg dry film}\\ \text{5 kg acetone}\end{array}\right\}\xrightarrow{\text{90\% A evaporation}}\begin{array}{l}\text{0.5 kg acetone remain in film}\\ \text{4.5 kg acetone exit in gas phase}\end{array}$

a.



Antoine equation (Table B.4) $\Rightarrow p^*_{C_3H_6O} = 591.18$ mm Hg

$$\frac{4.5\text{ kg }C_3H_6O}{}\left|\frac{1\text{ kmol}}{58.08\text{ kg}}\right|\frac{10^3\text{ mol}}{\text{kmol}} = 77.5\text{ mol }C_3H_6O(v)\text{ in exit gas}$$

$$\Rightarrow y = \frac{77.5}{77.5+n_1} = \frac{0.40(591.18\text{ mm Hg})}{760\text{ mm Hg}} \Rightarrow n_1 = \frac{171.6\text{ mol}}{}\left|\frac{22.4\text{ L(STP)}}{\text{mol}}\right|\frac{}{95\text{ kg DF}} = \underline{\underline{40.5\frac{\text{L(STP)}}{\text{kg DF}}}}$$

b. References: Air(25° C), $C_3H_6O(l, 35°\text{ C})$, DF(35° C)

Substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
DF	95	0	95	$1.33(T_{f2}-35)$	n in kg $\hat{H}$ in kJ/kg
$C_6H_{14}O(l)$	86.1	0	8.6	$0.129(T_{f2}-35)$	n in mol $\hat{H}$ in kJ/mol
$C_6H_{14}O(v)$	—	—	77.5	32.3	
Air	171.6	$\int_{25}^{T_{a1}}(C_p)_{\text{air}}dT$	171.6	0.70	

$$\hat{H}_{A(v)} = \int_{35}^{86}(C_p)_l dT + \Delta\hat{H}_v + \int_{86}^{49}(C_p)_v dT, \quad \hat{H}_{DF} = C_p(T-35)$$

Energy balance

$$\Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 126.4(T_{f2}-35) + 1.11(T_{f2}-35) + 2623.4 - 171.6\int_{25}^{T_{a1}}(C_p)_{\text{air}}dT = 0$$

$$\Rightarrow \underline{\underline{\int_{25}^{T_{a_1}}(C_p)_{\text{air}}dT = \frac{127.5(T_{f2}-35)+2623.4}{171.6}}}$$

c. $T_{a_1} = 120°\text{ C} \Rightarrow \int_{25}^{T_{a_1}}(C_p)_{\text{air}}dT = 2.78\text{ kJ/mol} \Rightarrow (T_{f2}-35)\ °\text{C} = \underline{\underline{-16.8°\text{ C}}}$

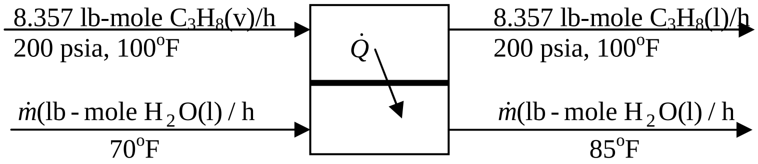
8.54 (cont'd)

d. $T_{f2} = 34°\text{C} \overset{\text{T\&E}}{\Rightarrow} \underline{\underline{T_{a_1} = 506°\text{C}}}$, $T_{f2} = 36°\text{C} \overset{\text{T\&E}}{\Rightarrow} \underline{\underline{T_{a1} = 552°\text{C}}}$

e. In an adiabatic system, when a liquid evaporates, the temperature of the remaining condensed phase drops. In this problem, the heat transferred from the air goes to (1) vaporize 90% of the acetone in the feed; (2) raise the temperature of the remaining wet film above what it would be if the process were adiabatic. If the feed air temperature is above about 530 °C, enough heat is transferred to keep the film above its inlet temperature of 35 °C; otherwise, the film temperature drops.

8.55 $T_{\text{set}}(p = 200 \text{ psia}) \approx 100°\text{ F}$ (Cox chart – Fig. 6.1-4)

a. Basis: $\begin{array}{c|c} 3.00\times10^3 \text{ SCF} & 1 \text{ lb-mole} \\ \hline \text{h} & 359 \text{ SCF} \end{array} = 8.357 \text{ lb}\cdot\text{mole/h } C_3H_8$



The outlet water temperature is <u>85°F</u>. It must be <u>less</u> than the outlet propane temperature; otherwise, heat would be transferred from the water to the propane near the outlet, causing vaporization rather than condensation of the propane.

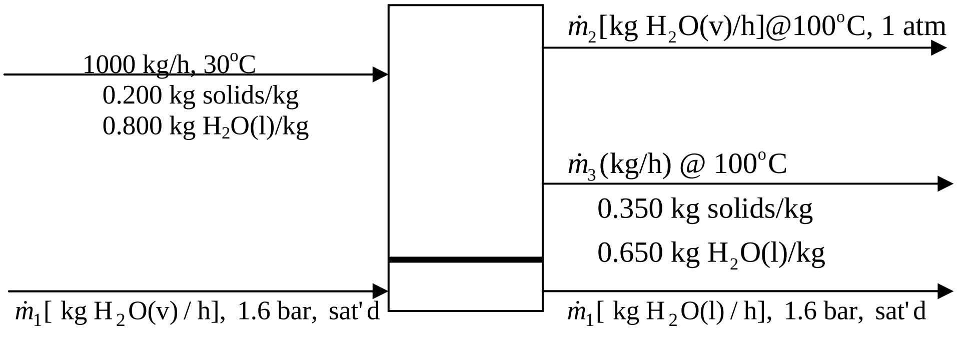
b. <u>Energy balance on propane</u>:

$$\dot{Q} = \Delta\dot{H} = -\dot{n}\Delta\hat{H}_v = \begin{array}{c|c|c|c} 8.357 \text{ lb-moles} & \overset{\text{Table B.1}}{\overset{\downarrow}{-18.77 \text{ kJ}}} & 0.9486 \text{ Btu} & 453.593 \text{ mol} \\ \hline \text{h} & \text{mol} & \text{kJ} & 1 \text{ lb}\cdot\text{mole} \end{array} = \underline{\underline{-6.75\times10^4 \frac{\text{Btu}}{\text{h}}}}$$

<u>Energy balance on cooling water:</u> Assume no heat loss to surroundings.

$$\dot{Q} = \Delta\dot{H} = \dot{m}C_p\Delta T \Rightarrow \dot{m} = \begin{array}{c|c|c} 6.75\times10^4 \text{ Btu} & \text{lb}_\text{m}\cdot°\text{F} & \\ \hline \text{h} & 1.0 \text{ Btu} & 15\ °\text{F} \end{array} = \underline{\underline{4500 \frac{\text{lb}_\text{m} \text{ cooling water}}{\text{h}}}}$$

8.56



a. <u>Solids balance:</u> $200 = 0.35m_3 \quad \Rightarrow m_3 = 571.4$ kg/h slurry

<u>H_2O balance:</u> $800 = m_2 + 0.65(571.4) \quad \Rightarrow m_2 = 428.6$ kg/h $H_2O(v)$

8.56 (cont'd)

References: Solids (0.01°C), H_2O (l, 0.01°C)

Substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Solids	200	62.85	200	209.6	$\dot{m}(\text{kg/h})$ $\hat{H}(\text{kJ/kg})$
$H_2O(l)$	800	125.7	571.4	419.1	
$H_2O(v)$	—	—	428.6	2676	
H_2O, 1.6 bar	$\dot{m}_1$	2696.2	$\dot{m}_1$	475.4	

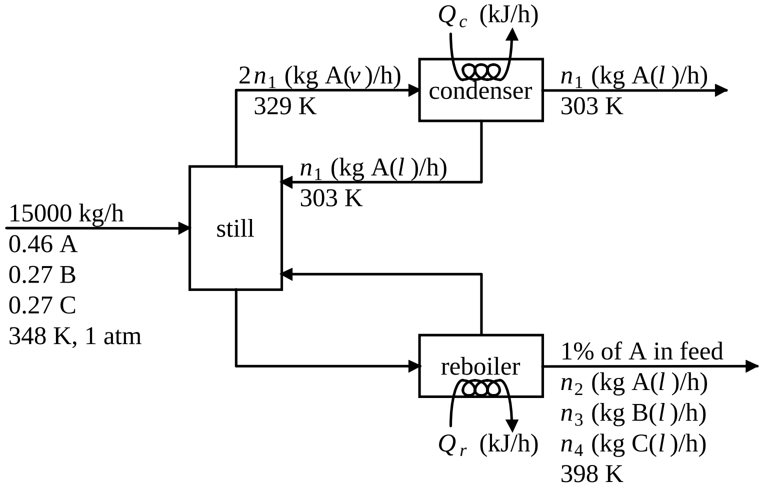
$\hat{H}_{H_2O}$ from steam tables

E.B. $$Q = \Delta H = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = 0 \Rightarrow 1.315\times 10^6 - 2221\dot{m}_1 = 0 \Rightarrow \dot{m}_1 = \underline{\underline{592 \text{ kg steam/h}}}$$

b. $(592.0 - 428.6) = \underline{\underline{163 \text{ kg/h additional steam}}}$

c. The cost of compressing and reheating the steam vs. the cost of obtaining it externally.

8.57 Basis: 15,000 kg feed/h. A = acetone, B = acetic acid, C = acetic anhydride



a. $\dot{n}_2 = (0.01)(0.46)(15{,}000 \text{ kg/h}) = 69 \text{ kg A/h}$

Acetic acid balance: $\dot{n}_3 = (0.27)(15{,}000) = 4050 \text{ kg B/h}$

Acetic anhydride balance: $\dot{n}_4 = (0.27)(15{,}000) = 4050 \text{ kg/h}$

Acetone balance: $(0.46)(15{,}000) = n_1 + 69 \Rightarrow n_1 = 6831 \text{ kg/h}$ `

$\Downarrow$

Distillate product: $\underline{\underline{6831 \text{ kg acetone/h}}}$

Bottoms product: $(69 + 4050 + 4050) \text{ kg/h} = \begin{array}{l} 8169 \text{ kg/h} \\ 0.8\% \text{ acetone} \\ 49.6\% \text{ acetic acid} \\ \underline{\underline{49.6\% \text{ acetic anhydride}}} \end{array}$

b. Energy balance on condenser

8.57 (cont'd)

$$C_3H_6O(v, 329\text{ K}) \rightarrow C_3H_6O(l, 329\text{ K}) \rightarrow C_3H_6O(l, 303\text{ K})$$

$$\Delta\hat{H} = -\Delta\hat{H}_v(329\text{ K}) + \int_{329}^{303} C_{pl}\,dT = -520.6 + (2.3)(-26) = -580.4\ \text{kJ/kg}$$

$$\dot{Q}_c = \Delta\dot{H} = \dot{n}\Delta\hat{H} = \frac{(2\times 6831)\text{kg}}{\text{h}}\left|\frac{-580.4\text{ kJ}}{\text{kg}}\right. = \underline{\underline{-7.93\times 10^6\ \ \text{kJ/h}}}$$

c. Overall process energy balance

Reference states: A(*l*), B(*l*), C(*l*) at 348 K (All $\hat{H}_m = 0$)

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
A $(l, 303\text{ K})$	—	0	6831	–103.5	$\dot{n}$ in kg/h
A $(l, 398\text{ K})$	—	0	69	115.0	$\hat{H}$ in kJ/kg
B $(l, 398\text{ K})$	—	0	4050	109.0	
C $(l, 398\text{ K})$	—	0	4050	113	

Acetic anhydride (*l*): $C_p \approx \left[(4\times 12)+(6\times 18)+(3\times 25)\right]\dfrac{\text{J}}{\text{mol}\cdot{}^\circ\text{C}}\left|\dfrac{1\text{ mol}}{102.1\text{ g}}\right|\dfrac{10^3\text{ g}}{1\text{ kg}}\left|\dfrac{1\text{ kJ}}{10^3\text{ J}}\right.$

$= 2.3\ \text{kJ/kg}\cdot{}^\circ\text{C}$

$\hat{H}(T) = C_p(T-348)$ (all substances)

$$\dot{Q} = \Delta\dot{H} \Rightarrow \dot{Q}_c + \dot{Q}_r = \sum_{\text{out}} \dot{n}_i\hat{H}_i - \underbrace{\sum_{\text{in}} \dot{n}_i\hat{H}_i}_{\uparrow = 0} \Rightarrow \dot{Q}_r = -\dot{Q}_c + \sum_{\text{out}} \dot{n}_i\hat{H}_i = \left(7.93\times 10^6 + 2.00\times 10^5\right)\text{kJ/h}$$

$$= \underline{\underline{8.13\times 10^6\ \ \text{kJ/h}}}$$

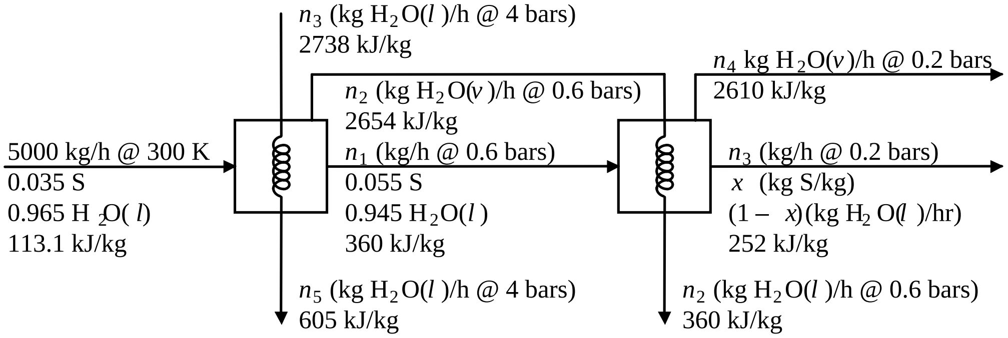
(We have neglected heat losses from the still.)

d. H_2O (saturated at ≈ 11 bars): $\Delta\hat{H}_v = 1999\ \text{kJ/kg}$ (Table 8.6)

$$\dot{Q}_r = \dot{n}_{H_2O}\Delta\hat{H}_v \Rightarrow \dot{n}_{H_2O} = \frac{8.13\times 10^6\ \ \text{kJ/h}}{1999\ \ \text{kJ/kg}} = \underline{\underline{4070\ \ \text{kg steam/h}}}$$

8.58 Basis: 5000 kg seawater/h

a. S = Salt



b. S balance on 1st effect: $(0.035)(5000) = 0.055\dot{n}_1 \Rightarrow \dot{n}_1 = 3182\ \ \text{kg/h}$

Mass balance on 1st effect: $5000 = 3182 + \dot{n}_2 \Rightarrow \dot{n}_2 = 1818\ \ \text{kg/h}$

8.58 (cont'd)

Energy balance on 1st effect:

$$\Delta\dot{H} = 0 \Rightarrow (\dot{n}_2)(2654) + (\dot{n}_1)(360) + (\dot{n}_5)(605 - 2738) - (5000)(113.1) = 0$$

$$\xrightarrow[\substack{\dot{n}_1 = 3182 \\ \dot{n}_2 = 1818}]{} \underline{\underline{\dot{n}_5 = 2534 \text{ kg } \mathrm{H_2O}(v)/\mathrm{h}}}$$

c. Mass balance on 2nd effect: $3182 = \dot{n}_3 + \dot{n}_4$ (1)

Energy balance on 2nd effect: $(\Delta H = 0)$

$$(n_4)(2610) + (n_3)(252) + (n_2)(360 - 2654) - (n_1)(360) = 0$$

$$\Downarrow n_1 = 3182,\ n_2 = 1818$$

$$5.316 \times 10^6 = 252 n_3 + 2610 n_4 \qquad (2)$$

Solve (1) and (2) simultaneously:

$$\dot{n}_3 = 1267 \text{ kg/h brine solution}$$

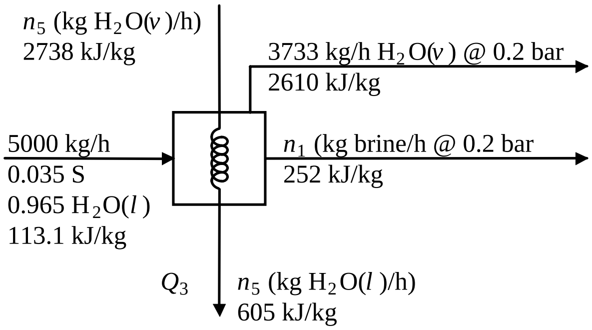
$$\dot{n}_4 = 1915 \text{ kg/h } \mathrm{H_2O}(v)$$

Production rate of fresh water $= \dot{n}_2 + \dot{n}_4 = (1818 + 1915) = \underline{\underline{3733 \text{ kg/h fresh water}}}$

Overall S balance: $(0.035)(5000) = 1267x \Rightarrow \underline{\underline{x = 0.138 \text{ kg salt/kg}}}$

d. The entering steam must be at a higher temperature (and hence a higher saturation pressure) than that of the liquid to be vaporized for the required heat transfer to take place.

e.



Mass balance: $5000 = 3733 + \dot{n}_1 \Rightarrow \dot{n}_1 = 1267 \text{ kg/h}$

Energy balance: $(\Delta\dot{H} = 0)$

$$(3733)(2610) + (1267)(252) + \dot{n}_5(605 - 2738) - (5000)(113.1) = 0$$

$$\Rightarrow \underline{\underline{\dot{n}_5 = 4452 \text{ kg } \mathrm{H_2O}(v)/\mathrm{h}}}$$

Which costs more: the additional 1918 kg/hr fresh steam required for the single-stage process, or the construction and maintenance of the second effect?

8.59 **a.** Salt balance: $x_{L7}\dot{n}_{L7} = x_{L1}\dot{n}_{L1} \Rightarrow \dot{n}_{L1} = \dfrac{(0.035)(5000)}{0.30} = \underline{\underline{583\ \text{kg/h}}}$

Fresh water produced: $n_{L7} - n_{L1} = 5000 - 583 = \underline{\underline{4417\ \text{kg fresh water/h}}}$

b. Final result given in Part (d).

c. Salt balance on i^{th} effect:

$$\dot{n}_{\text{L}i}x_{\text{L}i} = (\dot{n}_L)_{i+1}(x_L)_{i+1} \Rightarrow x_{Li} = \frac{(\dot{n}_L)_{i+1}(x_L)_{i+1}}{\dot{n}\theta_{Li}} \tag{1}$$

Energy balance on i^{th} effect:

$$\Delta\dot{H} = 0 \Rightarrow \dot{n}_{vi}\hat{H}_{vi} + (\dot{n}_v)_{L-1}(\hat{H}_v)_{L-1} + \dot{n}_{Li}\hat{H}_{Li} - (\dot{n}_L)_{L+1}(\hat{H}_L)_{L+1} - (\dot{n}_v)_{L-1}(\hat{H}_v)_{L-1} = 0$$

$$\Rightarrow \quad (\dot{n}_v)_{L-1} = \frac{\dot{n}_{vi}\hat{H}_{vi} + \dot{n}_{Li}\hat{H}_{Li} - (\dot{n}_L)_{i+1}(\hat{H}_L)_{i+1}}{(\hat{H}_v)_{i-1} - (\hat{H}_L)_{L-1}} \tag{2}$$

Mass balance on $(i-1)^{\text{th}}$ effect:

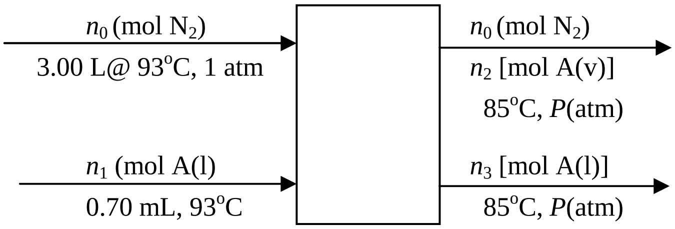
$$\dot{n}_{Li} = (\dot{n}_v)_{i-1} + (\dot{n}_L)_{i-1} \Rightarrow (\dot{n}_L)_{i-1} = \dot{n}_{Li} - (\dot{n}_v)_{i-1} \tag{3}$$

d.

	P (bar)	**T** (K)	$\mathbf{n_L}$ (kg/h)	$\mathbf{x_L}$	$\mathbf{n_V}$ (kg/h)	$\mathbf{H_L}$ (kJ/kg)	$\mathbf{H_V}$ (kJ/kg)
Fresh steam	2.0	393.4	---	---	981	504.7	2706.3
Effect 1	0.9	369.9	584	0.2997	934	405.2	2670.9
Effect 2	0.7	363.2	1518	0.1153	889	376.8	2660.1
Effect 3	0.5	354.5	2407	0.0727	809	340.6	2646.0
Effect 4	0.3	342.3	3216	0.0544	734	289.3	2625.4
Effect 5	0.2	333.3	3950	0.0443	612	251.5	2609.9
Effect 6	0.1	319.0	4562	0.0384	438	191.8	2584.8
Effect (7)	1.0	300.0	5000	0.0350	---	113.0	---

8.60 a. $(C_p)_v = (C_p)_l = \underline{\underline{20\ \text{cal/(mol}\cdot{}^\circ\text{C)}}}$; $(C_v)_v \approx (C_p)_v - R \approx (10-2)\dfrac{\text{cal}}{\text{mol}\cdot{}^\circ\text{C}} = \underline{\underline{8\ \text{cal/(mol}\cdot{}^\circ\text{C)}}}$

b.



$$n_0 = \frac{3.00\ \text{L}}{}\Bigg|\frac{273\ \text{K}}{(273+93)\text{K}}\Bigg|\frac{1\ \text{mol}}{22.4\ \text{L(STP)}} = 0.100\ \text{mol N}_2$$

$$n_1 = \frac{70.0\ \text{mL}}{}\Bigg|\frac{0.90\ \text{g}}{\text{mL}}\Bigg|\frac{1\ \text{mol}}{42\ \text{g}} = 1.5\ \text{mol}\ A(l)$$

Energy balance $\Rightarrow \Delta U = 0 \Rightarrow \underline{\underline{\sum_{\text{out}} n_i\hat{U}_i - \sum_{\text{in}} n_i\hat{U}_i = 0}}$

c. References: $\text{N}_2(\text{g}),\ A(l)(85^\circ\text{C, 1 atm})$

Substance	n_{in}	$\hat{U}_{\text{in}}$	n_{out}	$\hat{U}_{\text{out}}$	
N_2	0.10	39.8	0.10	0	n in mol
$A(l)$	1.5	160	n_3	0	$\hat{U}$ in cal/mol
$A(v)$	–	–	n_2	20050	

$A(l,\ 93^\circ\text{C})$ and $\text{N}_2(g,\ 93^\circ\text{C})$: $\hat{U} = C_v(93-85)$

$A(v,\ 85^\circ\text{C})$: $\hat{U}_{A(v)} = 20(90-85)+20{,}000+10(85-90) = 20050\ \text{cal/mol}$

$\Delta U = 0 \Rightarrow n_{v1}(20050)-(0.10)(39.8)-(1.5)(160) = 0 \Rightarrow n_{v1} = 0.012$ mol A evaporate

$$\Rightarrow \frac{0.012\ \text{mol}\ A}{}\Bigg|\frac{42\ \text{g}\ A}{\text{mol}\ A} = \underline{\underline{0.51\ \text{g evaporate}}}$$

d. Ideal gas equation of state

$$P = \frac{(n_0+n_2)RT}{V} = \frac{0.112\ \text{mol}}{3.00\ \text{liters}}\Bigg|\frac{(273+85)\text{K}}{}\Bigg|\frac{0.08206\ \text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}} = 1.097\ \text{atm}$$

Raoult's law

$$p_A^*(85^\circ\text{C}) = y_A P = \frac{n_2}{n_0+n_2}P = \frac{0.012\ \text{mol}}{0.112\ \text{mol}}\Bigg|\frac{1.097\ \text{atm}}{} = \underline{\underline{0.117\ \text{atm}}} \quad (= 89.3\ \text{mmHg})$$

8.61 (a) i) $\underline{\text{Expt 1}} \Rightarrow \left(\frac{m}{V}\right)_{\text{liquid}} = \frac{(4.4553-3.2551)\text{kg}}{2.000\text{ L}} = 0.600\,\frac{\text{kg}}{\text{L}} \Rightarrow \underline{\underline{(SG)_{\text{liquid}} = 0.600}}$

ii) $\underline{\text{Expt 2}} \Rightarrow \underline{\text{Mass of gas}} = (3.2571-3.2551)\text{kg} = 0.0020\text{ kg} = 2.0\text{ g}$

$$\underline{\text{Moles of gas}} = \begin{array}{c|c|c|c} 2.000\text{ L} & 273\text{ K} & (763-500)\text{mm Hg} & 1\text{ mol} \\ \hline & 363\text{ K} & 760\text{ mm Hg} & 22.4\text{ liters(STP)} \end{array} = 0.0232\text{ mol}$$

$\underline{\text{Molecular weight}} = (2.0\text{ g})/(0.0232\text{ mol}) = \underline{\underline{86\ \text{g/mol}}}$

iii) $$\underset{(\text{liquid})}{\underline{\text{Expt. }1}} \Rightarrow n = \begin{array}{c|c|c|c} 2.000\text{ liters} & 10^3\text{ cm}^3 & 0.600\text{ g} & 1\text{ mol} \\ \hline & 1\text{ liter} & \text{cm}^3 & 86\text{ g} \end{array} = 14\text{ mol}$$

Energy balance: The data show that C_v is independent of temperature

$$Q = \Delta U = nC_v\Delta T$$

$$\Rightarrow (C_v)_{\text{liquid}} = \frac{Q}{n\Delta T} = \frac{800\text{ J}}{(14\text{ mols})(2.4\text{ K})} = 24\ \text{J/mol}\cdot\text{K}@284.2\text{ K}$$

$$= \frac{800\text{ J}}{(14\text{ mols})(2.4\text{ K})} = 24\ \text{J/mol}\cdot\text{K}@331.2\text{ K}$$

$$\Rightarrow \underline{\underline{(C_v)_{\text{liquid}} \equiv 24\ \text{J/mol}\cdot\text{K}}}$$

$$\underset{(\text{vapor})}{\underline{\text{Expt. }2}} \Rightarrow n = 0.0232\text{ mol}\ [\text{from (ii)}]$$

$$C_v = a + bT \Rightarrow Q = 0.0232\int_{T_1}^{T_2}(a+bT)dT = 0.0232\left[a(T_2-T_1) + \frac{b}{2}(T_2^2 - T_1^2)\right]$$

$$\left.\begin{array}{l} 1.30\text{ J} = 0.0232\left[\text{a}(366.9-363.0) + \dfrac{\text{b}}{2}(366.9^2 - 363.0^2)\right] \\ 1.30\text{ J} = 0.0232\left[\text{a}(492.7-490.0) + \dfrac{\text{b}}{2}(492.7^2 - 490.0^2)\right] \end{array}\right\} \Rightarrow \begin{array}{l} a = -4.069 \\ b = 0.05052 \end{array}$$

$$\Rightarrow \underline{\underline{(C_v)_{\text{vapor}}(\text{J / mol}\cdot\text{K}) = -4.069 + 0.05052T(\text{K})}}$$

iv) $\underline{\text{Liquid:}}\ \underline{\underline{C_p \approx C_v \equiv 24\ \text{J/mol}\cdot\text{K}}}$

$\underline{\text{Vapor:}}$ Assuming ideal gas behavior, $C_p = C_v + R = C_v + 8.314\ \text{J/mol}\cdot\text{K}$

$$\Rightarrow \underline{\underline{C_p(\text{J/mol}\cdot\text{K}) = 4.245 + 0.05052T(\text{K})}}$$

v) $\underline{\text{Expt. }3} \Rightarrow$ $T = 315K,\ p^* = (763-564)\text{mm Hg} = 199\text{ mm Hg}$
$T = 334K,\ p^* = 401\text{ mm Hg}$
$T = 354K,\ p^* = 761\text{ mm Hg}$
$T = 379K,\ p^* = 1521\text{ mm Hg}$

8.61 (cont'd)

Plot p^* (log scale) vs. $1/T$ (linear scale); straight line fit yields

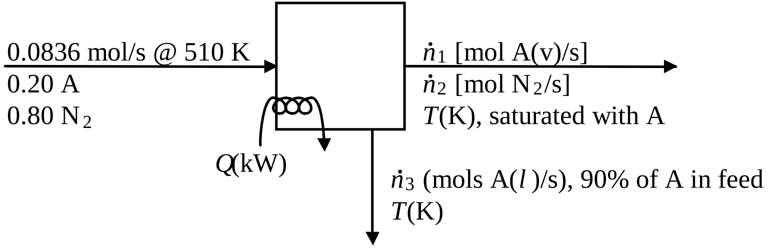
$$\underline{\underline{\ln p^* = \frac{-3770}{T(\text{K})} + 17.28}} \quad \text{or} \quad p^* = 3.196\times 10^7 \exp(-3770/T)$$

vi) $p^* = 760 \text{ mm Hg} \underset{\text{Part v}}{\underset{\uparrow}{\Rightarrow}} \dfrac{1}{T_b} = \dfrac{17.28 - \ln(760)}{3770} = 2.824\times10^{-3}\,\text{K}^{-1} \Rightarrow \underline{\underline{T_b = 354\text{ K}}}$

vii) $\dfrac{\Delta\hat{H}_v}{R} \underset{\text{Part v}}{\underset{\uparrow}{=}} 3770(\text{K}) \Rightarrow \Delta\hat{H}_v = (3770\text{ K})(8.314\ \text{J/mol}\cdot\text{K}) \Rightarrow \underline{\underline{\Delta\hat{H}_v = 31{,}300\ \text{J/mol}}}$

(b) Basis: $\dfrac{3.5\text{ L feed}}{\text{s}}\left|\dfrac{273\text{ K}}{510\text{ K}}\right|\dfrac{1\text{ mol}}{22.4\,l(\text{STP})} = 0.0836\ \text{mol/s feed gas}$

Let A denote the drug



N$_2$ balance: $\dot{n}_2 = (0.800)(0.0836\ \text{mol/s}) = 0.0669\ \text{mol N}_2/\text{s}$

90% condensation: $\dot{n}_3 = (0.900)(0.200\times0.0836) = 0.01505\ \text{mol } A(l)/\text{s}$

$$\dot{n}_1 = (0.100)(0.200\times0.0836) = 1.67\times10^{-3}\ \text{mol } A(v)/\text{s}$$

Partial pressure of *A* in outlet gas:

$$p_A = \frac{\dot{n}_1}{(\dot{n}_1+\dot{n}_2)}P = \frac{1.67\times10^{-3}\ \text{mol}}{0.0686\ \text{mol}}(760\text{ mm Hg}) = 18.5\text{ mm Hg} = p_A^*(T)$$

$$\Downarrow \text{Part (a) - (v)}$$

$$\frac{1}{T} = \frac{17.28 - \ln(18.5)}{3770} = 3.81\times10^{-3}\,\text{K}^{-1}$$

$$\Downarrow$$

$$T = 262\text{ K}$$

(c) Reference states: N$_2$, $A(l)$ at 262 K

substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
N$_2$	0.0669	7286	0.0669	0	$\dot{n}$ in mol/s
$A(v)$	0.0167	37575	1.67×10^{-3}	31686	$\hat{H}$ in J/mol
$A(l)$	–	–	0.01505	0	

8.61 (cont'd)

$$\underline{N_2(510\text{ K})}:\ \hat{H}_{N_2}(510\text{K}) - \hat{H}_{N_2}(262\text{K}) = \hat{H}_{N_2}(237^\circ\text{C}) - \hat{H}_{N_2}(-11^\circ\text{C})$$

$$\overset{\substack{\text{Table B.8}\\ \downarrow}}{=}\ [6.24 - (-1.05)]\text{ kJ/mol} = 7.286\text{ kJ/mol} = 7286\text{ J/mol}$$

$$\underline{A(v,\ 262K)}:\ \hat{H} = C_{pl}(T_b - 262) + \Delta\hat{H}_v(359K) + \int_{T_b}^{262} C_{pv}\,dT$$

$$\Big\Downarrow \text{ Part (a) results for } T_b,\ C_{pl},\ C_{pv},\ \Delta\hat{H}_v$$

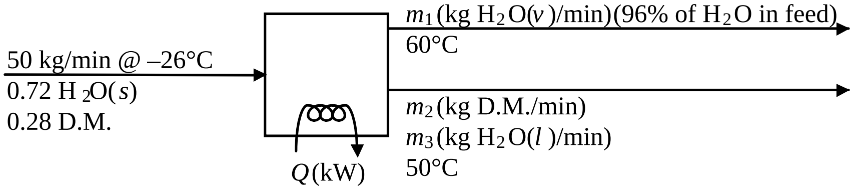
$$\hat{H} = 24(354 - 262) + 31300 + \left[4.245 + 0.05052\frac{T^2}{2}\right]_{354}^{262} = 31686\ \text{J/mol}$$

$$\underline{A(v,\ 510K)}:\ \hat{H} = C_{pl}(T_b - 262) + \Delta\hat{H}_v(354K) + \int_{T_b}^{510} C_{pv}\,dT = 37575\ \text{J/mol}$$

$$\underline{\text{Energy balance:}}\ \ \dot{Q} = \Delta\dot{H} = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = \frac{-1060\ \text{J/s}}{} \Bigg| \frac{1\text{ kW cooling}}{-10^3\ \text{kJ/s}} = \underline{\underline{1.06\text{ kW}}}$$

8.62 a. Basis: 50 kg wet steaks/min

D.M. = dry meat



96% vaporization:

$$\dot{m}_1 = 0.96(0.72 \times 50\ \text{kg/min}) = 34.56\text{ kg } H_2O(v)/\text{min}$$

$$\dot{m}_3 = 0.04(0.72 \times 50\ \text{kg/min}) = 1.44\text{ kg } H_2O(l)/\text{min}$$

Dry meat balance:

$$\dot{m}_2 = (0.28)(50) = 14.0\text{ kg D.M./min}$$

Reference states: Dry meat at –26°C , $H_2O(l,\ 0^\circ\text{C})$

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
dry meat	14.0	0	14.0	105	$\dot{m}$ in kg/min
$H_2O(\text{s},\ -26^\circ\text{C})$	36.0	–390	–	–	$\hat{H}$ in kJ/kg
$H_2O(l,\ 50^\circ\text{C})$	–	–	1.44	209	
$H_2O(v,\ 60^\circ\text{C})$	–	–	34.56	2599	

$$\underline{\text{Dry meat:}}\ \ \hat{H}(50^\circ\text{C}) = C_p[50 - (-26)] = \frac{1.38\text{ kJ}}{\text{kg}\cdot\text{C}^\circ} \Bigg| \frac{76^\circ\text{C}}{} = 105\ \text{kJ/kg}$$

$$\underline{H_2O(\text{s},\ -26^\circ\text{C})}:\ \ H_2O(l,\ 0^\circ\text{C}) \rightarrow H_2O(\text{s},\ 0^\circ\text{C}) \rightarrow H_2O(\text{s},\ -26^\circ\text{C})$$

8.62 (cont'd)

$$\Delta\hat{H} = -\Delta\hat{H}_m(0°\text{C}) + \int_0^{-26} C_p\,dT = \frac{-6.01\text{ kJ}}{\underset{\substack{\uparrow\\ \text{Table B.1}}}{\text{mol}}}\left|\frac{1\text{ mol}}{18.02\text{ g}}\right|\frac{10^3\text{ g}}{1\text{ kg}} + \frac{2.17\text{ kJ}}{\text{kg}\cdot°\text{C}}\left|\frac{-26°\text{C}}{}\right. = -390\ \text{kJ/kg}$$

$\underline{H_2O(l, 50°C)}$: $H_2O(l, 0°C) \rightarrow H_2O(l, 50°C)$

$$\Delta\hat{H} = \int_0^{50} C_p\,dT = \frac{0.0754\text{ kJ}}{\underset{\substack{\uparrow\\ \text{Table B.2}}}{\text{mol}}\ °\text{C}}\left|\frac{(50-0)°\text{C}}{}\right|\frac{1\text{ mol}}{18.02\text{ g}}\left|\frac{1000\text{ g}}{1\text{ kg}}\right. = 209\ \text{kJ/kg}$$

$\underline{H_2O(v,\ 60°C)}$: $H_2O(l,\ 0°C) \rightarrow H_2O(l,\ 100°C) \rightarrow H_2O(v,\ 100°C) \rightarrow H_2O(v,\ 60°C)$

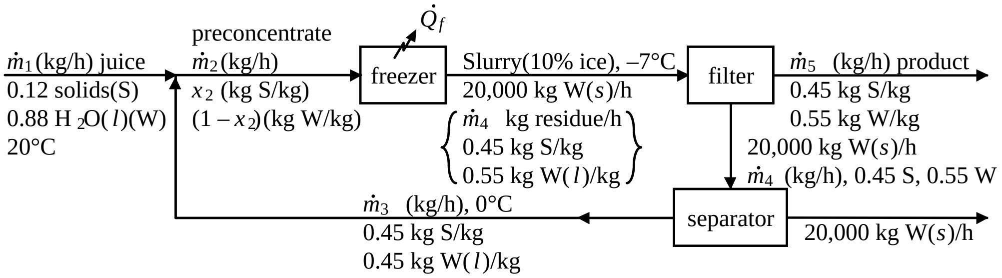
$$\Delta\hat{H} = \frac{0.0754\text{ kJ}}{\underset{\substack{\uparrow\\ \text{Table B.2}}}{\text{mol}}\cdot°\text{C}}\left|\frac{(100-0)°\text{C}}{}\right. + \underset{\substack{\uparrow\\ \text{Table B.1 }(\Delta\hat{H}_v)}}{40.656}\frac{\text{kJ}}{\text{mol}} + \int_{100}^{60}\underset{\substack{\uparrow\\ \text{Table B.2}}}{(C_p)_{H_2O(v)}}\,dT$$

$$= \frac{46.830\text{ kJ}}{\text{mol}}\left|\frac{1\text{ mol}}{18.02\text{ g}}\right|\frac{1000\text{ g}}{1\text{ kg}} = 2599\ \text{kJ/kg}$$

Energy balance:

$$Q = \Delta H = \sum_{\text{out}} m_i\hat{H}_i - \sum_{\text{in}} m_i\hat{H}_i = \frac{1.06\times10^5\text{ kJ}}{\text{min}}\left|\frac{1\text{ min}}{60\text{ s}}\right|\frac{1\text{ kW}}{1\text{ kJ/s}} = \underline{\underline{1760\text{ kW}}}$$

8.63 Basis: 20,000 kg/h ice crystallized. S = solids in juice. W = water



(a) 10% ice in slurry $\Rightarrow \dfrac{20000}{\dot{m}_4} = \dfrac{10}{90} \Rightarrow \dot{m}_4 = 180000\ \text{kg/h}$ concentrate leaving freezer

$$\left.\begin{array}{l}\underline{\text{Overall S balance:}}\ \ 0.12\dot{m}_1 = 0.45\dot{m}_5 \\ \underline{\text{Overall mass balance:}}\ \ \dot{m}_1 = \dot{m}_5 + 20000\end{array}\right\} \Rightarrow \begin{array}{l}\dot{m}_1 = \underline{\underline{27273\ \text{kg/h feed}}} \\ \dot{m}_5 = \underline{\underline{7273\ \text{kg/h concentrate product}}}\end{array}$$

Mass balance on filter: $20000 + \dot{m}_4 + \dot{m}_5 + 20000 + \dot{m}_6 \underset{\substack{\dot{m}_4=180000\\ \dot{m}_5=7273}}{\Rightarrow} \dot{m}_6 = 172730\ \text{kg/h}$ recycle

Mass balance on mixing point:

$27273 + 172730 = \dot{m}_2 \Rightarrow \dot{m}_2 = \underline{\underline{2.000\times10^5\ \text{kg/h preconcentrate}}}$

8.63 (Cont'd)

S balance on mixing point:

$$(0.12)(27273)+(0.45)(172730)=2.000\times10^{5}X_2 \Rightarrow X_2\cdot100\%=\underline{\underline{40.5\%\ \text{S}}}$$

(b) Draw system boundary for every balance to enclose freezer and mixing point (Inputs: fresh feed and recycle streams; output; slurry leaving freezer)

Refs: S, $H_2O(l)$ at $-7°C$

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
12% soln	27273	108	–	–	$\dot{m}(\text{kg/h})$
45% soln	172730	28	180000	0	$\hat{H}(\text{kJ/kg})$
$H_2O(s)$	–	–	20000	–337	

Solutions: $\hat{H}(T)=4.00[T-(-7)]$ kJ/kg

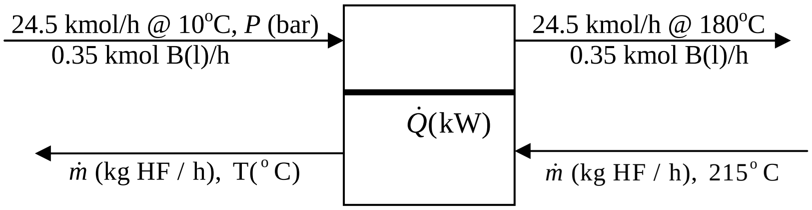
Ice: $\hat{H}=-\Delta\hat{H}_m(-T°C)\approx-\Delta\hat{H}_m(0°C)$

$=-6.0095\ \text{kJ/mol}\Rightarrow-337\ \text{kJ/kg}$

$\Uparrow$ Table B.1

E.B. $\dot{Q}_c=\Delta\dot{H}=\sum_{\text{out}}\dot{m}_i\hat{H}_i-\sum_{\text{in}}\dot{m}_i\hat{H}_i=\dfrac{-1.452\times10^{7}\ \text{kJ}}{\text{h}}\left|\dfrac{1\ \text{h}}{3600\ \text{s}}\right|\dfrac{1\ \text{kW}}{1\ \text{kJ/s}}=\underline{\underline{-4030\ \text{kW}}}$

8.64 a. B=n-butane, I=iso-butane, hf=heating fluid. $(C_p)_{hf}=2.62\ \text{kJ}/(\text{kg}\cdot°\text{C})$



From the Cox chart (Figure 6.1-4)

$p_B^*(10°C)=22$ psi, $p_I^*(10°C)=32$ psi

$$p_{\min}=p_B+p_I=x_B p_B^*+x_I p_I^*=28.5\ \text{psi}\left(\frac{1.01325\ \text{bar}}{14.696\ \text{psi}}\right)=\underline{\underline{1.96\ \text{bar}}}$$

b. $B\,(l,\ 10°C)\xrightarrow{\Delta\hat{H}_v}B\,(v,\ 10°C)\xrightarrow{\Delta\hat{H}_1}B\,(v,\ 180°C)$

$I\,(l,\ 10°C)\xrightarrow{\Delta\hat{H}_v}I\,(v,\ 10°C)\xrightarrow{\Delta\hat{H}_2}I\,(v,\ 180°C)$

Assume temperature remains constant during vaporization.
Assume mixture vaporizes at 10°C i.e. won't vaporize at respective boiling points as a pure component.

8.64 (cont'd)

References: B(l, 10^{o}C), I(l, 10^{o}C)

substance	$\dot{n}_{in}(\text{mol / h})$	$\hat{H}_{in}(\text{kJ / mol})$	$\dot{n}_{out}(\text{mol / h})$	$\hat{H}_{out}(\text{kJ / mol})$
B (l)	8575	0	--	--
B (v)	--	--	8575	42.21
I (l)	15925	0	--	--
I (v)	--	--	15925	41.01

$$\left(\hat{H}_{out}\right)_{\text{B}} = \left(\Delta\hat{H}_v\right)_{\text{B}} + \int_{10}^{180}\left(C_p\right)_{\text{B}} = 42.21 \text{ kJ / mol}$$

$$\left(\hat{H}_{out}\right)_{\text{I}} = \left(\Delta\hat{H}_v\right)_{\text{I}} + \int_{10}^{180}\left(C_p\right)_{\text{I}} = 41.01 \text{ kJ / mol}$$

$$\Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 8575(42.21) - 15825(41.01)$$

$$\underline{\underline{\Delta\dot{H} = 1.015\times 10^6 \text{ kJ / h}}}$$

c. $Q = 1.015\times 10^6 \text{ kJ / h} = \dot{m}_{\text{hf}}\left[2.62 \text{ kJ / }\left(\text{kg}\cdot^{\text{o}}\text{C}\right)\right]\left[(215-45)^{\text{o}}\text{C}\right]$

$\underline{\underline{\dot{m}_{\text{hf}} = 2280 \text{ kg / h}}}$

d. $(2540 \text{ kg / h})\left[2.62 \text{ kJ / }\left(\text{kg}\cdot^{\text{o}}\text{C}\right)\right]\left[(215-45)^{\text{o}}\text{C}\right] = 1.131\times 10^6 \text{ kJ / h}$

Heat transfer rate $= 1.131\times 10^6 - 1.015\times 10^6 = \underline{\underline{1.16\times 10^5 \text{ kJ / h}}}$

e. The heat loss leads to a pumping cost for the additional heating fluid and a greater heating cost to raise the additional fluid back to 215^{o}C.

f. Adding the insulation reduces the costs given in part (e). The insulation is probably preferable since it is a one-time cost and the other costs continue as long as the process runs. The final decision would depend on how long it would take for the savings to make up for the cost of buying and installing the insulation.

8.65 **(a)** Basis: 100 g of mixture, SG_{Benzene}=0.879: SG_{Toluene}=0.866

$$n_{\text{total}} = \frac{50 \text{ g}}{78.11 \text{ g / mol}} + \frac{50 \text{ g}}{92.13 \text{ g / mol}} = (0.640+0.542) \text{ mol} = 1.183 \text{ mol}$$

$$\text{V}_{\text{total}} = \frac{50 \text{ g}}{0.879 \text{ g / cm}^3} + \frac{50 \text{ g}}{0.866 \text{ g / cm}^3} = 114.6 \text{ cm}^3$$

$$\left(x_f\right)_{\text{C}_6\text{H}_6} = \frac{0.640 \text{ mol C}_6\text{H}_6}{1.183 \text{ mol}} = \underline{\underline{0.541 \text{ mol C}_6\text{H}_6/\text{mol}}}$$

Actual feed: $\dfrac{32.5 \text{ m}^3}{\text{h}}\left|\dfrac{10^6 \text{cm}^3}{1 \text{ m}^3}\right|\dfrac{1.183 \text{ mol mixture}}{114.6 \text{ cm}^3 \text{ mixture}}\left|\dfrac{1 \text{ h}}{3600 \text{ s}}\right. = \underline{\underline{93.19 \text{ mol / s}}}$

$T = 90°\text{C} \Rightarrow p^*_{\text{C}_6\text{H}_6} = 1021 \text{ mm Hg}$, $p^*_{\text{C}_7\text{H}_8} = 407 \text{ mm Hg}$ (from Table 6.1-1)

Raoult's law: $p_{tot} = x_{\text{C}_6\text{H}_6}p^*_{\text{C}_6\text{H}_6} + x_{\text{C}_7\text{H}_8}p^*_{\text{C}_7\text{H}_8} = (0.541)(1021) + (0.459)(407)$

$$= \frac{739.2 \text{ mmHg}}{}\left|\frac{1 \text{ atm}}{760 \text{ mmHg}}\right. = 0.973 \text{ atm} \Rightarrow \underline{\underline{P_0 > 0.973 \text{ atm}}}$$

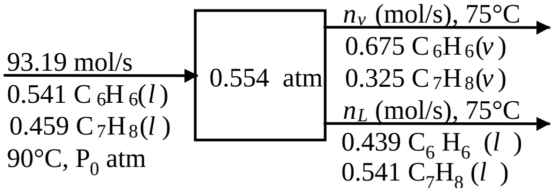
8.65 (cont'd)

(b) $T = 75°\text{C} \Rightarrow p^*_{C_6H_6} = 648 \text{ mm Hg}$, $p^*_{C_7H_8} = 244 \text{ mm Hg}$ (from Table 6.1-1)

$$\underline{\text{Raoult's law}} \Rightarrow p_{\text{tank}} = x_{C_6H_6}p^*_{C_6H_6} + x_{C_7H_8}p^*_{C_7H_8} = (0.439)(648) + (0.561)(244)$$

$$= (284 + 137)\text{mm Hg} = 421 \text{ mmHg} \Rightarrow \underline{\underline{\text{P}_{\text{tank}} = 0.554 \text{ atm}}}$$

$$y_{C_6H_6} = \frac{284 \text{ mm Hg}}{421 \text{ mm Hg}} = \underline{\underline{0.675 \text{ mol } C_6H_6(v)/\text{mol}}}$$



$$\left.\begin{array}{l}\underline{\text{Mole balance:}}\;\; 93.19 = n_v + n_L \\ \underline{C_6H_6 \text{ balance:}}\;\; (0.541)(93.19) = 0.675n_v + 0.439n_L\end{array}\right\} \Rightarrow \begin{array}{l} n_v = \underline{\underline{40.27 \text{ mol vapor/s}}} \\ n_L = \underline{\underline{52.92 \text{ mol liquid/s}}}\end{array}$$

(c) $\underline{\text{Reference states}}$: $C_6H_6(l)$, $C_6H_6(l)$ at 75°C

Substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
$C_6H_6(v)$	–	–	27.18	31.0	$\dot{n}$ in mol/s
$C_6H_6(l)$	50.41	2.16	23.23	0	$\hat{H}$ in kJ/mol
$C_7H_8(v)$	–	–	13.09	35.3	
$C_7H_8(l)$	42.78	2.64	29.69	0	

$$\underline{C_6H_6(l,\ 90°\text{C})}\text{:}\;\; \hat{H} = (0.144)(90-75) = 2.16 \text{ kJ/mol}$$

$$\underline{C_7H_8(l,\ 90°\text{C})}\text{:}\;\; \hat{H} = (0.176)(90-75) = 2.64 \text{ kJ/mol}$$

$$\underline{C_6H_6(v,\ 75°\text{C})}\text{:}\;\; \hat{H} = (0.144)(80.1-75) + \underset{\substack{\uparrow \\ \Delta\hat{H}_v(80.1°\text{C})}}{30.77} + \int_{80.1}^{75}\left[0.074 + 0.330\times10^{-3}T\right]dT$$

$$= 31.0 \text{ kJ/mol}$$

$$\underline{C_7H_8(v,\ 75°\text{C})}\text{:}\;\; \hat{H} = (0.176)(110.6-75) + 33.47 + \int_{110.6}^{75}\left[0.0942 + 0.380\times10^{-3}T\right]dT$$

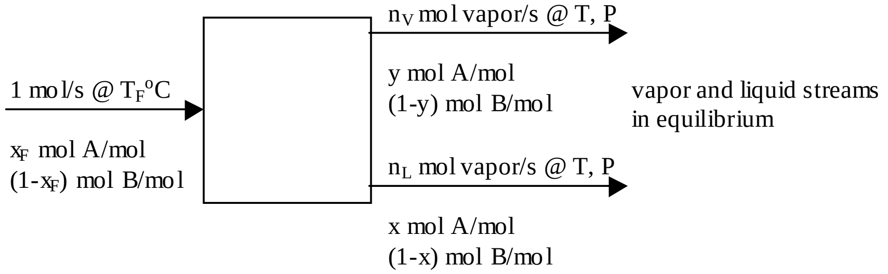
$$= 35.3 \text{ kJ/mol}$$

$$\underline{\text{Energy balance:}}\;\; \dot{Q} = \Delta\dot{H} = \sum_{\text{out}}\dot{n}_i\hat{H}_i - \sum_{\text{in}}\dot{n}_i\hat{H}_i = \begin{array}{c|c} 1082 \text{ kJ} & 1 \text{ kW} \\ \hline \text{s} & 1 \text{ kJ/s}\end{array} = \underline{\underline{1082 \text{ kW}}}$$

(d) The feed composition changed; the chromatographic analysis is wrong; the heating rate changed; the system is not at steady state; Raoult's law and/or the Antoine equation are only approximations; the vapor and liquid streams are not in equilibrium.

(e) Heat is required to vaporize a liquid and heat is lost from any vessel for which $T>T_{\text{ambient}}$. If insufficient heat is provided to the vessel, the temperature drops. To run the experiment isothermally, a greater heating rate is required.

8.66 a. Basis: 1 mol feed/s



$$\text{Raoult's law} \Rightarrow x\cdot p_A^*(T)+(1-x)\cdot p_B^*(T)=P\Rightarrow \underline{\underline{x=\frac{P-p_B^*(T)}{p_A^*(T)-p_B^*(T)}}} \qquad \textbf{(1)}$$

$$p_A=y\cdot P=x\cdot p_A^*(T)\Rightarrow \underline{\underline{y=\frac{x\cdot p_A^*(T)}{P}}} \qquad \textbf{(2)}$$

$$\text{Mole balance: } 1=\dot{n}_L+\dot{n}_V\Rightarrow \underline{\underline{\dot{n}_V=1-\dot{n}_L}} \qquad \textbf{(4)}$$

$$A\text{ balance: } (x_F)(1)=y\cdot\dot{n}_V+x\cdot\dot{n}_L \xrightarrow{\text{Substitute for } n_v \text{ from (4)}} \underline{\underline{\dot{n}_L=\frac{y-x_F}{y-x}}} \qquad \textbf{(3)}$$

$$\text{Energy balance: } \Delta\dot{H}=\sum_{\text{out}}\dot{n}_i\hat{H}_i-\sum_{\text{in}}\dot{n}_i\hat{H}_i=0 \qquad \textbf{(5)}$$

b.

ref(deg.C) = 25

Compound	A	B	C	al	av	bv	Tbp	DHv
n-pentane	6.84471	1060.793	231.541	0.195	0.115	3.41E-04	36.07	25.77
n-hexane	6.88555	1175.817	224.867	0.216	0.137	4.09E-04	68.74	28.85
xF	0.5	0.5	0.5					
Tf(deg.C)	110	110	150					
P(mm Hg)	760	1000	1000					
HAF(kJ/mol)	16.6	16.6	24.4					
HBF(kJ/mol)	18.4	18.4	27.0					
T(deg.C)	**51.8**	**60.0**	**62.3**					
pA*(mm Hg)	1262	1609	1714					
pB*(mm Hg)	432	573	617					
x	0.395	0.412	0.349					
y	0.656	0.663	0.598					
nL(mol/s)	0.598	0.648	0.394					
nV(mol/s)	0.402	0.352	0.606					
HAL(kJ/mol)	5.2	6.8	7.3					
HBL(kJ/mol)	5.8	7.6	8.0					
HAV(kJ/mol)	31.4	32.5	32.8					
HBV(kJ/mol)	42.4	43.7	44.1					
DH(kJ/s)	0.00	0.00	0.00					

8.66 (cont'd)

c.

```
C*    PROGRAM FOR PROBLEM 8.66
      IMPLICIT REAL (N)
      READ (5, 1) A1, B1, C1, A2, B2, C2
C*    ANTOINE EQUATION COEFFICIENTS FOR A AND B

  1   FORMAT (8F10.4)
      READ (5, 1) TRA, TRB
C*    ARBITRARY REFERENCE TEMPERATURES (DEG.C.) FOR A AND B
      READ (5, 1) CAL, TBPA, DHVA, CAV1, CAV2
      READ (5, 1) CBL, TBPB, DHVB, CBV1, CBV2
C*    CP(LIQ, KS/MBL-DEG.C.), NORMAL BOILING POINT (DEG.C), HEAT
          OF
      VAPORIZATION
C*    (KJ/MOL), COEFFICIENTS OF CP(VAP., KJ/MOL-DEG.C) = CV1 +
          CV2*T(DEG.C)
      READ (5, 1) XF, TF, P
C*    MOLE FRACTION OF A IN FEED, FEED TEMP.(DEG.C), EVAPORATOR
      PRESSURE (MMHG)
      WRITE (6, 2) TF, XF, P
  2   FORMAT (1H0, 'FEEDbATb', F6.1, 'bDEG.CbCONTAINSb', F6.3,'
      bMOLESbA/MOLEbT
      *OTAL'//1X'EVAPORATORbPRESSUREb=', E11.4, 'bMMbHG'/)
      ITER = 0
      DT = 0.5
      HAF = CAL*(TF – TRA)
      HBF = CBL*(TF – TRB)
      F1 = XF*HAF + (1.0 – XF)*HBF
      F2 = CAL*(TBPA – TRA) + DHVA – CAV1*TBPA – 0.5*CAV2*TBPA**2
      F3 = CBL*(TBPB – TRB) + DHVB – CBV1*TBPB – 0.5*CBV2*TBPB**2
      T = TF
 20   INTER = ITER + 1
      IF(ITER – 200) 30, 30, 25
 25   WRITE (6, 3)
  3   FORMAT (1H0, 'NO CONVERGENCE')
      STOP
 30   PAV = 10.0** (A1 – B1/(T + C1))
      PAV = 10.0** (A2 – B2/(T + C2))
      XL = (P – PBV)/(PAV – PBV)
      XV = XL*PAV/P
      NL = (XV – XF)/(XV – XL)
      NV = 1.0 – NL
      IF (XL.LE.00.OR.XL.GE.1.0.OR.NL.LE.0.0.OR.NL.GE.1.0) GO TO 45
      HAL = CAL*(T – TRA)
      HBL = CBL*(T – TRB)
      HAV = F2 + CAV1*T + 0.5*CAV2*T**2
      HBV = F3 + CBV1*T + 0.5*CBV2*T**2
```

8.66(cont'd)

```
      DELH = NL *(XL*HAL + (1.0 – XL)*HBL) + NV*(XV*HAV + (1.0 –
             XV)*HBV) – F1
      WRITE (6, 4) T, NL, NV, DELH
    4 FORMAT (1Hb, 5X' Tb=', F6.1, 3X' NLb=', F7.4, 3X' NVb=', F7.4, 3X'DELHb
             =',* E11.4)
      WRITE (6, 5) PAV, PBV, XL, HAL, HBL, XV, HAV, HBV
    5 FORMAT (1Hb, 5X' PAV, PBVb=', 2F8.1, 3X' XL, HAL, HBLb=', F7.4,
             2E13.4,3X' XV, HAV, HBVb=', F7.4, 2E13.4/)
      IF (DELH) 50, 50, 40
   40 DHOLD = DELH
      TOLD = T
   45 T = T – DT
      GO TO 20
   50 T = (T*DHOLD – TOLD*DELH)/(DHOLD – DELH)
      PAV = 10.0**(A1 – B1/(T + C1))
      PBV = 10.0**(A2 – B2/(T + C2))
      XL = (P – PBV)/(PAV – PBV)
      XV = XL * PAV/P
      NL = (XV – XF)/(XV – XL)
      NV = 1.0 – NL
      WRITE (6, 6) T, NL, XL, NV, XV
    6 FORMAT (1H0, 'PROCEDUREbCONVERGED'//3X'EVAPORATORb
      TEMPERATUREb=', F6.
      *1//3X' LIQUIDbPRODUCTb--', F6.3, 'bMOLEbCONTAININGb', F6.3,
             'bMOLEbA/
      *MOLEbTOTAL'//3X' VAPORbPRODUCTb--', F6.3,
             MOLEbCONTAININGb,' F6.3,
      *'bMOLEbA/MOLEb TOTAL')
      STOP
      END
```

<u>$DATA</u> (Fields of 10 Columns)

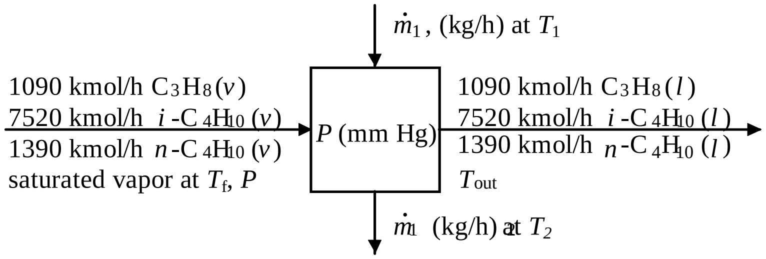
<u>Solution:</u>

$$\underline{\underline{T_{\text{evaportor}} = 52.2°\text{C}}}$$

$$\underline{\underline{n_L = 0.552 \text{ mol}, \left(x_{C_5H_{12}}\right)_{\text{liquid}} = 0.383 \text{ mol } C_5H_{12}/\text{mol liquid}}}$$

$$\underline{\underline{n_v = 0.448 \text{ mol}, \left(x_{C_5H_{12}}\right)_{\text{vapor}} = 0.644 \text{ mol } C_5H_{12}/\text{mol liquid}}}$$

8.67 Basis: $\frac{2500 \text{ kmol product}}{\text{h}}\Big|\frac{1 \text{ kmol condensate}}{.25 \text{ kmol product}} = 10{,}000 \text{ kmol/h}$ fed to condenser



(a) Refrigerant: $T_{out} = 0^o\text{C}$, $T_1 = T_2 = -6^o\text{C}$.

Antoine constants	A	B	C
C_3H_8	7.58163	1133.65	283.26
$i-C_4H_{10}$	6.78866	899.617	241.942
$n-C_4H_{10}$	6.82485	943.453	239.711

Calculate P for $T_{out} = T_{\text{bubble pt.}}$

$$P = \sum_i x_i p_i^*(0°\text{C}) = 0.109(3797 \text{ mm Hg}) + 0.752(1176 \text{ mm Hg}) + 0.139(775 \text{ mm Hg})$$

$$\Rightarrow \underline{\underline{P = 1406 \text{ mm Hg}}}$$

Dew pt. $T_f = T_{dp} \Rightarrow f(T_f) = 1 - P\sum_i \frac{y_i}{p_i^*(T_f)} = 0$ trial & error to find $T_f \Rightarrow \underline{\underline{T_f = 5.00^o\text{C}}}$

Refs: $C_3H_8(l)$, $C_4H_{10}(l)$ at 0 °C, Refrigerant @ –6°C

Assume: $\Delta\hat{H}_v(T_b)$, Table B.1 ↓

substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$	
C_3H_8 $i-C_4H_{10}$ $n-C_4H_{10}$	1090 7520 1390	19110 21740 22760	1090 7520 1390	0 0 0	$\dot{n}$ (kmol/h) $\hat{H}$ (kJ/kmol)
Refrigerant	$\dot{m}_1$	0	$\dot{m}_1$	151	$\dot{m}$ (kg/h) $\hat{H}$ (kJ/kmol)

$\Big\}\ \hat{H}_2(\text{vapor}) = \Delta\hat{H}_v(0°\text{C}) - \int_0^{4.95} C_p dT(\text{Table B.2})$

$\Big\}\ \hat{H} = \Delta\hat{H}_v$

E.B.:

$$\Delta H = \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i = 0 \Rightarrow 151\dot{m}_1 - 2.16\times10^6 = 0 \Rightarrow \dot{m}_1 = \underline{\underline{1.43\times10^6 \text{ kg/h refrigerant}}}$$

8.67 (cont'd)

(b) Cooling water: $T_{\text{out}} = 40°\text{C}$, $T_2 = 34°\text{C}$, $T_1 = 25°\text{C}$

$$P = \sum_i x_i p_i^*(40°\text{C}) = 0.109(11{,}877) + 0.752(3961) + 0.139(2831) = \underline{\underline{4667 \text{ mm Hg}}}$$

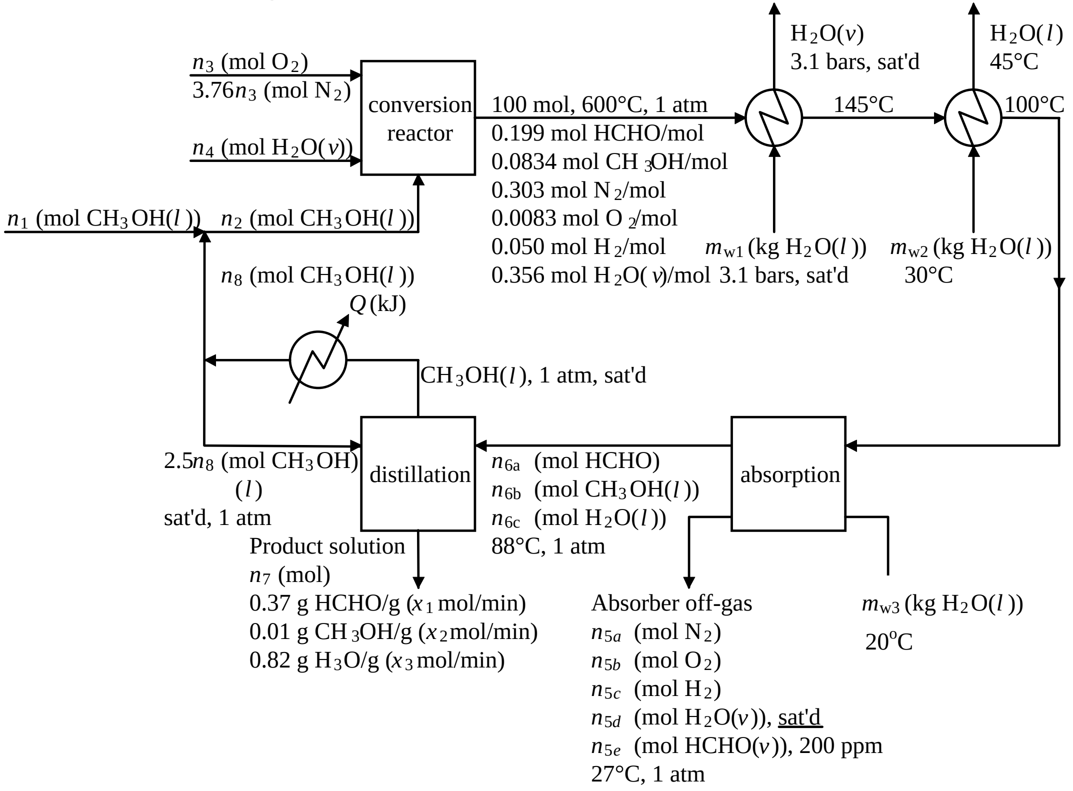
$$f(T_f) = 1 - P\sum_i \frac{y_i}{p_i^*(T_f)} = 0 \overset{T+E}{\Rightarrow} \underline{\underline{T_f = 45.7°\text{C}}}$$

Refs: $C_3H_8(l)$, $C_4H_{10}(l)$ @ 40°C, $H_2O(l)$ @ 25°C.

$$\Delta\dot{H} = 0 \Rightarrow 37.7\dot{m}_1 - 2.17 \times 10^8 = 0 \Rightarrow \underline{\underline{\dot{m}_1 = 5.74 \times 10^6 \text{ kg } H_2O/\text{h}}}$$

(c) Cost of refrigerant pumping and recompression, cost of cooling water pumping, cost of maintaining system at the higher pressure of part (b).

8.68 Basis: 100 mol leaving conversion reactor



a. Strategy

C balance on conversion reactor $\Rightarrow n_2$, N_2 balance on conversion reactor $\Rightarrow n_3$

H balance on conversion reactor $\Rightarrow n_4$, (O balance on conversion reactor to check consistency)

N_2 balance on absorber $\Rightarrow n_{5a}$, O_2 balance on absorber $\Rightarrow n_{5b}$

H_2 balance on absorber $\Rightarrow n_{5e}$

$$\left.\begin{array}{l}H_2O \text{ saturation of absorber off-gas} \\ 200 \text{ ppm HCHO in absorber off-gas}\end{array}\right\} \Rightarrow n_{5d}, n_{5b}$$

8.68 (cont'd)

HCHO balance on absorber $\Rightarrow n_{6a}$, $\mathrm{CH_3OH}$ balance on absorber $\Rightarrow n_{6b}$
Wt. fractions of product solution $\Rightarrow x_1, x_2, x_3$
HCHO balance on distillation column $\Rightarrow n_7$
$\mathrm{CH_3OH}$ balance on distillation column $\Rightarrow n_8$
$\mathrm{CH_3OH}$ balance on recycle mixing point $\Rightarrow n_1$
Energy balance on waste heat boiler $\Rightarrow m_{w1}$, E.B. on cooler $\Rightarrow m_{w2}$
Energy balance on reboiler $\Rightarrow Q$

<u>C balance on conversion reactor:</u>

$$n_2 = 19.9 \text{ mol HCHO} + 8.34 \text{ mol } \mathrm{CH_3OH} = 28.24 \text{ mol } \mathrm{CH_3OH}$$

<u>N_2 balance on conversion reactor:</u>

$$3.76 n_3 = 30.3 \Rightarrow n_3 = 8.06 \text{ mol } \mathrm{O_2},\ 3.76 \times 8.06 = 30.3 \text{ mol } \mathrm{N_2} \text{ feed}$$

<u>H balance on conversion reactor:</u>

$$n_4(2) + 28.24(4) - 19.9(2) + 8.34(4) + 5(2) + 35.6(2) \Rightarrow n_4 = 20.7 \text{ mol } \mathrm{H_2O} \text{ fed}$$

<u>O balance:</u> 65.1 mol O in, 65.5 mol O out. Accept (precision error)

<u>N_2 balance on absorber:</u> $30.3 = n_{5a} \Rightarrow n_{5a} = 30.3 \text{ mol } \mathrm{N_2}$

<u>O_2 balance on absorber:</u> $0.83 = n_{5b} \Rightarrow n_{5b} = 0.83 \text{ mol } \mathrm{O_2}$

<u>H_2 balance on absorber:</u> $5.00 = n_{5c} \Rightarrow n_{5c} = 5.00 \text{ mol } \mathrm{H_2}$

<u>H_2O saturation of off - gas:</u>

$$y_w = \frac{p_w^*(27^\circ\mathrm{C})}{P} = \left[\frac{26.739 \text{ mm Hg}}{760 \text{ mm Hg}} = \frac{n_{5d}}{30.3 + 0.83 + 5.00 + n_{5d} + n_{5e}}\right]$$

$$\left.\begin{array}{l} \Rightarrow n_{5d} = 0.03518(36.13 + n_{5d} + n_{5e})\,[1] \\ \\ \underline{\text{200 ppm HCHO in off gas:}} \\ \Rightarrow \quad \dfrac{n_{5e}}{36.13 + n_{5d} + n_{5e}} = \dfrac{200}{10^6}\,[2] \end{array}\right\} \overset{\text{solve}}{\Rightarrow} \begin{array}{l} n_{5d} = 1.318 \text{ mol } \mathrm{H_2O} \\ n_{5e} = 7.49 \times 10^{-3} \text{ mol HCHO} \end{array}$$

<u>Moles of absorber off-gas</u> $= n_{5a} + n_{5b} + n_{5c} + n_{5e} = 37.46$ mol off - gas

<u>HCHO balance on absorber:</u> $19.9 = n_{6a} + 7.49 \times 10^{-3} \Rightarrow n_{6a} - 19.89$ mol HCHO

<u>CH_3OH balance on absorber:</u> $8.34 = n_{6b} \Rightarrow n_{6b} = 8.34 \text{ mol } \mathrm{CH_3OH}$

<u>Product solution</u>

$$\text{Basis - 100 g} \Rightarrow \left.\begin{array}{l} 37.0 \text{ g HCHO} \overset{\%\text{MW}}{\Rightarrow} 1.232 \text{ mol HCHO} \\ 1.0 \text{ g } \mathrm{CH_3OH} \Rightarrow 0.031 \text{ mol } \mathrm{CH_3OH} \\ 62.0 \text{ g } \mathrm{H_2O} \Rightarrow 3.441 \text{ mol } \mathrm{H_2O} \end{array}\right\} \Rightarrow \begin{array}{l} x_1 = 0.262 \text{ mol HCHO/mol} \\ x_2 = 0.006 \text{ mol } \mathrm{CH_3OH/mol} \\ x_3 = 0.732 \text{ mol } \mathrm{H_2O/mol} \end{array}$$

8.68 (cont'd)

HCHO balance on distillation column (include the condenser + reflux stream within the system for this and the next balance):

$$19.89 = 0.262 n_7 \Rightarrow n_7 = 75.9 \text{ mol product}$$

CH$_3$OH balance on distillation column:

$$8.34 = 0.006(75.9) + n_8 \Rightarrow n_8 = 7.88 \text{ mol } CH_3OH$$

CH$_3$OH balance on recycle mixing point:

$$n_1 + n_8 = n_2 \Rightarrow n_1 = 28.24 - 7.83 = 20.36 \text{ mol } CH_3OH \text{ fresh feed}$$

Summary of requested material balance results:

$n_1 = \underline{\underline{20.4 \text{ mol } CH_3OH(l) \text{ fresh feed}}}$

$n_2 = \underline{\underline{75.9 \text{ mol product solution}}}$

$n_3 = \underline{\underline{7.88 \text{ mol } CH_3OH(l) \text{ recycle}}}$

$n_4 = \underline{\underline{37.5 \text{ mol absorber off - gas}}}$

Waste heat boiler:

Refs: HCHO$(v, 145°\text{C})$, CH$_3$OH$(v, 145°\text{C})$; N$_2$, O$_2$, H$_2$, H$_2$O(v) at 25°C for product gas, H$_2$O$(l$, triple point$)$ for boiler water

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
HCHO	19.9	22.55	19.9	0	
CH$_3$OH	8.34	32.02	8.34	0	n (mol)
N$_2$	30.3	17.39	30.3	3.51	
O$_2$	0.83	18.41	0.83	3.60	$\hat{H}$ (kJ/mol)
H$_2$	5.0	16.81	5.0	3.47	
H$_2$O	35.6	20.91	35.6	4.09	
H$_2$O (boiler)	m_{w1}	566.2	m_{w1}	2726.32	m (kg) $\hat{H}$ (kJ/kg)

$\hat{H} = \int_{145}^{T} C_p dT$

$\hat{H} = \overline{C}_p(T)[T - 25]$

$\hat{H}$ from steam tables

E.B. $\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow -1814 + 2160 m_{w1} = 0 \Rightarrow m_{w1} = \underline{\underline{0.84 \text{ kg } 3.1 \text{ bar steam}}}$

8.68 (cont'd)

Gas cooler: Same refs. as above for product gas, $H_2O(l, 30°C)$ for cooling water

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
HCHO	19.9	0	19.9	–1.78	
CH_3OH	8.34	0	8.34	–2.38	n (mol)
N_2	30.3	3.51	30.3	2.19	$\hat{H}$ (kJ/mol)
O_2	0.83	3.60	0.83	2.24	
H_2	5.0	3.47	5.0	2.16	
H_2O	35.6	4.09	35.6	2.54	
H_2O (coolant)	m_{w2}	0	m_{w2}	62.76	m (kg) $\hat{H}$ (kJ/kg)

$$\hat{H} = 4.184 \frac{\text{kJ}}{\text{kg}\cdot°\text{C}}(T - 30)°\text{C}$$

E.B. $\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow -158.1 + 62.6 m_{w2} = 0 \Rightarrow m_{w2} = \underline{\underline{2.52 \text{ kg cooling water}}}$

Condener: CH_3OH condensed $= n_8 + 2.5 n_8 = (3.5)(7.88) = 27.58$ mol CH_3OH condensed

E.B.: $Q = -n\Delta\hat{H}_v(1 \text{ atm}) = -(27.58 \text{ mol})(35.27 \text{ kJ/mol})$
$= \underline{\underline{-973 \text{ kJ}}}$ (transferred from condenser)

b. $$\frac{3.6\times10^4 \text{ tonne / y}}{} \left| \frac{10^6 \text{ g}}{1 \text{ metric ton}} \right| \frac{1 \text{ yr}}{350 \text{ d}} \left| \frac{1 \text{ d}}{24 \text{ h}} \right. = 4.286\times10^6 \text{ g/h product soln}$$

$$\Rightarrow \left.\begin{aligned} &(0.37)(4.286\times10^6) = 1.586\times10^6 \text{ g HCHO/h} \Rightarrow 5.281\times10^4 \text{ mol HCHO/h} \\ &(0.01)(4.286\times10^6) = 4.286\times10^6 \text{ g } CH_3OH\text{/h} \Rightarrow 1338 \text{ mol } CH_3OH\text{/h} \\ &(0.62)(4.286\times10^6) = 2.657\times10^6 \text{ g } H_2O\text{/h} \Rightarrow 1.475\times10^5 \text{ mol } H_2O\text{/h} \end{aligned}\right\}$$

$$\Rightarrow 2.016\times10^5 \text{ mol/h} \quad \Rightarrow \quad \text{Scale factor} = \frac{2.016\times10^5 \text{ mol/h}}{75.9 \text{ mol}} = \underline{\underline{2657 \text{ h}^{-1}}}$$

8.69 **(a)** For 24°C and 50% relative humidity, from Figure 8.4-1,
Absolute humidity = $\underline{\underline{0.0093 \text{ kg water / kg DA}}}$, Humid volume ≈ $\underline{\underline{0.856 \text{ m}^3 \text{ / kg DA}}}$
Specific enthalpy = (48 - 0.2) kJ / kg DA = $\underline{\underline{47.8 \text{ kJ / kg DA}}}$, Dew point = $\underline{\underline{13^\circ\text{C}}}$, $T_{wb} = \underline{\underline{17^\circ\text{C}}}$

(b) $\underline{\underline{24^\circ\text{C}}}$ (T_{db})

(c) $\underline{\underline{13^\circ\text{C}}}$ (Dew point)

(d) Water evaporates, causing your skin temperature to drop. $\underline{\underline{T_{\text{skin}} \approx 13^\circ\text{C}}}$ (T_{wb}). At 98% R.H. the rate of evaporation would be lower, T_{skin} would be closer to T_{ambient}, and you would not feel as cold.

8.70 $V_{\text{room}} = 141\ \text{ft}^3$. DA = dry air.

$$m_{\text{DA}} = \frac{140\ \text{ft}^3}{} \left| \frac{\text{lb-mol}\cdot{}^\text{o}\text{R}}{0.7302\ \ \text{ft}^3\cdot\text{atm}} \right| \frac{29\ \text{lb}_\text{m}\ \text{DA}}{\text{lb-mol}} \left\| \frac{1\ \text{atm}}{550\ {}^\text{o}\text{R}} \right. = 10.1\ \text{lb}_\text{m}\ \text{DA}$$

$$h_\text{a} = \frac{0.205\ \text{lb}_\text{m}\ \text{H}_2\text{O}}{10.1\ \text{lb}_\text{m}\ \text{DA}} = 0.0203\ \text{lb}_\text{m}\ \text{H}_2\text{O} / \text{lb}_\text{m}\ \text{DA}$$

From the psychrometric chart, $T_{\text{db}} = 90^\text{o}\,\text{F},\ h_\text{a} = 0.0903$

$$\Downarrow$$

$$\underline{\underline{\text{h}_\text{r} = 67\%}} \quad \underline{\underline{\text{T}_{\text{wb}} = 80.5^\text{o}\,\text{F}}} \quad \underline{\underline{\hat{\text{V}} = 14.3\ \text{ft}^3 / \text{lb}_\text{m}\ \text{DA}}}$$

$$\underline{\underline{\text{T}_{\text{dew point}} = 77.3^\text{o}\,\text{F}}} \quad \underline{\underline{\hat{\text{H}} = 44.0 - 0.11 \cong 43.9\ \text{Btu} / \text{lb}_\text{m}}}$$

8.71

$$\left.\begin{array}{l} T_{\text{db}} = 35^\circ\text{C} \\ T_{\text{ab}} = 27^\circ\text{C} \end{array}\right. \Rightarrow \underline{\underline{h_r = 55\%}}\ \ \underline{\underline{\text{He wins}}}$$

8.72 **a.** $T_{\text{db}} = 40^\circ\text{C},\ T_{\text{dew point}} = 20^\circ\text{C} \ \overset{\text{Fig. 8.4-1}}{\Rightarrow}\ \underline{\underline{h_r = 33\%, h_a = 0.0148\ \text{kg H}_2\text{O/kg dry air}}}$

$$\underline{\underline{T_{wb} = 25.5^\circ\text{C}}}$$

b. Mass of dry air: $m_{da} = \dfrac{2.00\ \text{L}}{} \left| \dfrac{1\ \text{m}^3}{10^3\ \text{L}} \right| \dfrac{1\ \text{kg dry air}}{0.92\ \text{m}^3} = 2.2\times10^{-3}\ \text{kg dry air}$

↑ from Fig. 8.4-1

Mass of water: $\dfrac{2.2\times10^{-3}\ \text{kg dry air}}{} \left| \dfrac{0.0148\ \text{kg H}_2\text{O}}{1\ \text{kg dry air}} \right| \dfrac{10^3\ \text{g}}{1\ \text{kg}} = \underline{\underline{0.033\ \text{g H}_2\text{O}}}$

c. $\hat{H}(40^\circ\text{C},\ 33\%\ \text{relative humidity}) \approx (78.0 - 0.65)\ \text{kJ/kg dry air} = 77.4\ \text{kJ/kg dry air}$

$\hat{H}(20^\circ\text{C},\ \text{saturated}) \approx 57.5\ \text{kJ/kg dry air}$ (both values from Fig. 8.4-1)

$$\Delta H_{40\to20} = \frac{2.2\times10^{-3}\ \text{kg dry air}}{} \left| \frac{(57.5 - 77.4)\ \text{kJ}}{\text{kg dry air}} \right| \frac{10^3\ \text{J}}{1\ \text{kJ}} = \underline{\underline{-44\ \text{J}}}$$

d. Energy balance: closed system

$$n = \frac{2.2\times10^{-3}\ \text{kg dry air}}{} \left| \frac{10^3\ \text{g}}{1\ \text{kg}} \right| \frac{1\ \text{mol}}{29\ \text{g}} + \frac{0.033\ \text{g H}_2\text{O}}{} \left| \frac{1\ \text{mol}}{18\ \text{g}} \right. = 0.078\ \text{mol}$$

$$Q = \Delta U = n\Delta\hat{U} = n\left(\Delta\hat{H} - R\Delta T\right) = \Delta H - nR\Delta T$$

$$= -44\ \text{J} - \frac{0.078\ \text{mol}}{} \left| \frac{8.314\ \text{J}}{\text{mol}\cdot\text{K}} \right| \frac{(20-40)^\circ\text{C}}{} \left| \frac{1\ \text{K}}{1^\circ\text{C}} \right. = \underline{\underline{-31\ \text{J}}}(23\ \text{J transferred from the air})$$

8.73 **(a)** $$\begin{array}{c|c} 400\text{ kg} & 2.44\text{ kg water} \\ \hline \text{min} & 97.56\text{ kg air} \end{array} = \underline{\underline{10.0\text{ kg water evaporates / min}}}$$

(b) $$h_a = \frac{10\ \text{kg H}_2\text{O/min}}{400\ \text{kg dry air/min}} = 0.025\ \text{kg H}_2\text{O/kg dry air}\ ,\ T_{\text{db}} = 50°\text{C}$$

$$\xrightarrow{\text{Fig. 8.4-1}} \underline{\underline{\hat{H} = (116 - 1.1) = 115\ \text{kJ/kg dry air}\,,\ T_{wb} = 33°\text{C},\ h_r = 32\%,\ T_{\text{dew point}} = 28.5°\text{C}}}$$

(c) $T_{\text{db}} = 10°\text{C}$, saturated $\Rightarrow \underline{\underline{h_a = 0.0077\ \text{kg H}_2\text{O/kg dry air}\,,\ \hat{H} = 29.5\ \text{kJ/kg dry air}}}$

(d) $$\begin{array}{c|c} 400\text{ kg dry air} & (0.0250 - 0.0077)\text{ kg H}_2\text{O} \\ \hline \text{min} & \text{kg dry air} \end{array} = \underline{\underline{6.92\ \text{kg H}_2\text{O/min condense}}}$$

<u>References:</u> Dry air at 0° C, $H_2O(l)$ at 0° C

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Air	400	115	400	29.5	$\dot{m}_{\text{air}}$ in kg dry air/min, $\dot{m}_{H_2O}$ in kg/min
$H_2O(l)$	—	—	6.92	42	$\hat{H}_{\text{air}}$ in kJ/kg dry air, $\hat{H}_{H_2O}$ in kJ/kg

$H_2O(l, 0°\text{C}) \rightarrow H_2O(l, 20°\text{C})$:

$$\hat{H} = \begin{array}{c|c|c|c|c} 75.4\quad \text{J} & 1\text{ mol} & (10-0)°\text{C} & 1\text{ kJ} & 10^3\text{ g} \\ \hline \text{mol·°C} & 18\text{ g} & & 10^3\text{ J} & 1\text{ kg} \end{array} = 42\ \text{kJ/kg}$$

$$Q = \Delta H = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i = \begin{array}{c|c|c} -34027.8\text{ kJ} & 1\text{ min} & 1\text{ kW} \\ \hline \text{min} & 60\text{ s} & 1\text{ kJ/s} \end{array} = \underline{\underline{-565\text{ kW}}}$$

(e) T>50°C, because the heat required to evaporate the water would be transferred from the air, causing its temperature to drop. To calculate $(T_{\text{air}})_{\text{in}}$, you would need to know the flow rate, heat capacity and temperature change of the solids.

8.74 **a.** <u>Outside air:</u> $T_{\text{db}} = 87°\text{F}$, $h_r = 80\% \Rightarrow h_a = 0.0226\ \text{lb}_\text{m}\ \text{H}_2\text{O/lb}_\text{m}\ \text{D.A.}$,

$\hat{H} = 45.5 - 0.01 = 45.5\ \text{Btu/lb}_\text{m}\ \text{D.A.}$

<u>Room air:</u> $T_{\text{db}} = 75°\text{F}$, $h_r = 40\% \Rightarrow h_a = 0.0075\ \text{lb}_\text{m}\ \text{H}_2\text{O/lb}_\text{m}\ \text{D.A.}$,

$\hat{H} = 26.2 - 0.02 = 26.2\ \text{Btu/lb}_\text{m}\ \text{D.A.}$

<u>Delivered air:</u> $T_{\text{db}} = 55°\text{F}$, $h_a = 0.0075\ \text{lb}_\text{m}\ \text{H}_2\text{O/lb}_\text{m}\ \text{D.A.}$

$\Rightarrow\ \hat{H} = 21.4 - 0.02 = 21.4\ \text{Btu/lb}_\text{m}\ \text{D.A.}$, $\hat{V} = 13.07\ \text{ft}^3\text{/lb}_\text{m}\ \text{D.A.}$

<u>Dry air delivered:</u> $$\begin{array}{c|c} 1{,}000\text{ ft}^3 & 1\text{ lb}_\text{m}\text{ D.A.} \\ \hline \text{min} & 13.07\text{ ft}^2 \end{array} = 76.5\ \text{lb}_\text{m}\ \text{D.A./min}$$

<u>H_2O condensed:</u>

$$\begin{array}{c|c} 76.5\text{ lb}_\text{m}\text{ D.A.} & (0.0226 - 0.0075)\text{ lb}_\text{m}\text{ H}_2\text{O} \\ \hline \text{min} & \text{lb}_\text{m}\text{ D.A.} \end{array} = \underline{\underline{1.2\ \text{lb}_\text{m}\ \text{H}_2\text{O/min condensed}}}$$

8.74 (cont'd)

The outside air is first cooled to a temperature at which the required amount of water is condensed, and the cold air is then reheated to 55°F. Since h_a remains constant in the second step, the condition of the air following the cooling step must lie at the intersection of the $h_a = 0.0075$ line and the saturation curve $\Rightarrow \underline{\underline{T = 49^\circ \mathrm{F}}}$

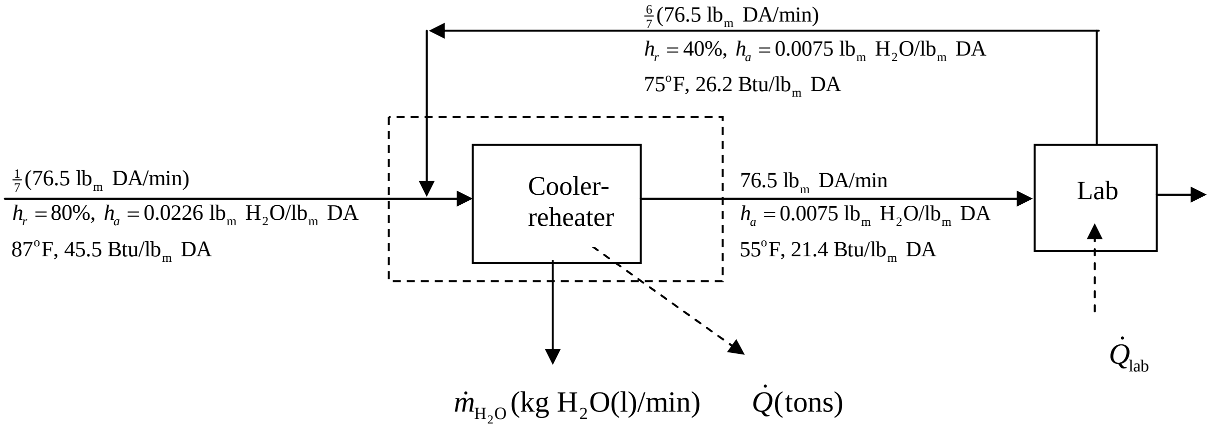
References: Same as Fig. 8.4-2 [including $\mathrm{H_2O}(l, 32^\circ \mathrm{F})$]

substance	$\dot{m}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{m}_{\text{out}}$	$\hat{H}_{\text{out}}$	
Air	76.5	45.5	76.5	21.4	$\dot{m}_{\text{air}}$ in $\mathrm{lb_m}$ D.A./min
$\mathrm{H_2O}(l, 49^\circ \mathrm{F})$	—	—	1.2	17.0	$\hat{H}_{\text{air}}$ in Btu/$\mathrm{lb_m}$ D.A.
					$\dot{m}_{\mathrm{H_2O}}$ in $\mathrm{lb_m}$/min, $\hat{H}_{\mathrm{H_2O}}$ in Btu/$\mathrm{lb_m}$

$$Q = \Delta H = \frac{(76.5)[21.4 - 45.5] + 1.2(17.0)\ \text{(Btu)}}{\text{min}} \left| \frac{60\ \text{min}}{1\ \text{h}} \right| \frac{1\ \text{ton cooling}}{-12{,}000\ \text{Btu/h}}$$

$$= \underline{\underline{9.1\ \text{tons cooling}}}$$

b.



Water balance on cooler-reheater (system shown as dashed box in flow chart)

$$\tfrac{1}{7}\left(76.5\ \frac{\mathrm{lb_m\ DA}}{\text{min}}\right)\left(0.0226\frac{\mathrm{lb_m\ _{H_2O}}}{\mathrm{lb_m\ DA}}\right) + \tfrac{6}{7}(76.5\ )(0.0075) = (76.5)(0.0075) + \dot{m}_{\mathrm{H_2O}}$$

$$\Rightarrow\ \dot{m}_{\mathrm{H_2O}} = \underline{\underline{0.165\ \text{kg H}_2\text{O condensed/min}}}$$

8.74 (cont'd)

Energy balance on cooler-reheater

References: Same as Fig. 8.4-2 [including H_2O(l, 32°F)]

Substance	$\dot{m}_{in}$	$\hat{H}_{in}$	$\dot{m}_{out}$	$\hat{H}_{out}$	
Fresh air feed	10.93	45.5	—	—	$\dot{m}_{DA}$ in lb_m dry air/min
Recirculated air feed	65.57	26.2	—	—	$\hat{H}_{air}$ in Btu/lb_m dry air
Delivered air	—	—	76.5	21.4	$\dot{m}_{H_2O(l)}$ in lb_m/min
Condensed water (49°F)	—	—	0.165	17.0	$\hat{H}_{H_2O(l)}$ in Btu/lb_m

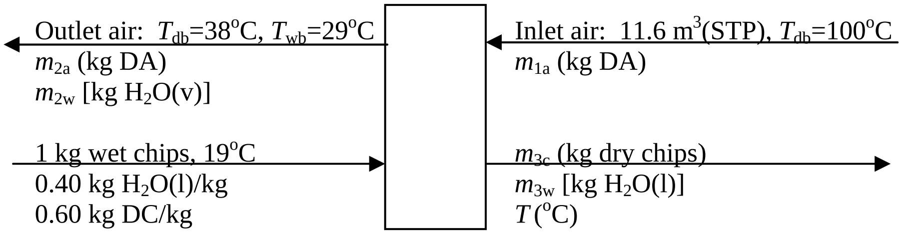
$$\dot{Q} = \Delta\dot{H} = \sum_{out}\dot{m}_i\hat{H}_i - \sum_{in}\dot{m}_i\hat{H}_i = \frac{-575.3\text{ Btu}}{\text{min}}\left|\frac{60\text{ min}}{1\text{ h}}\right|\frac{1\text{ ton cooling}}{-12{,}000\text{ Btu/h}} = \underline{\underline{2.9\text{ tons}}}$$

$$\text{Percent saved by recirculating} = \frac{(9.1\text{ tons} - 2.9\text{ tons})}{9.1\text{ tons}} \times 100\% = \underline{\underline{68\%}}$$

Once the system reaches steady state, most of the air passing through the conditioner is cooler than the outside air, and (more importantly) much less water must be condensed (only the water in the fresh feed).

c. Total recirculation could eventually lead to an unhealthy depletion of oxygen and buildup of carbon dioxide in the laboratory.

8.75 Basis: 1 kg wet chips. DA = dry air, DC = dry chips



(a) Dry air: $m_{1a} = \frac{11.6\text{ m}^3(\text{STP})\text{ DA}}{}\left|\frac{1\text{ kmol}}{22.4\text{ m}^3(\text{STP})}\right|\frac{29.0\text{ kg}}{1\text{ kmol}} = 15.02\text{ kg DA} = m_{2a}$

Outlet air:

$$(T_{db} = 38°\text{C}, T_{wb} = 29°\text{C}) \xrightarrow{\text{Fig. 8.4-1}} \hat{H}_2 = (95.3 - 0.48) = \underline{\underline{94.8\ \frac{\text{kJ}}{\text{kg DA}}}} \qquad h_{a_2} = \underline{\underline{0.0223\ \frac{\text{kg } H_2O}{\text{kg DA}}}}$$

Water in outlet air: $m_{2w} = h_{a_2} m_{2a} = 0.0223(15.02) = \underline{\underline{0.335\text{ kg } H_2O}}$

(b) H_2O balance: $0.400\text{ kg} = 0.335\text{ kg} + m_{3w} \Rightarrow m_{3w} = 0.065\text{ kg } H_2O$

8.75 (cont'd)

Moisture content of exiting chips:

$$\frac{0.065\text{ kg water}}{0.600\text{ kg dry chips + 0.065 kg water}}\times 100\% = \underline{\underline{9.8\% < 15\%\ \therefore \text{meets design specification}}}$$

(c) References: Dry air, $H_2O(l)$, dry chips @ 0°C.

substance	m_{in}	$\hat{H}_{\text{in}}$	m_{out}	$\hat{H}_{\text{out}}$	
Air	15.02	100.2	15.02	94.8	m_{air} in kg DA, $\hat{H}_{\text{air}}$ in kJ/kg DA
$H_2O(l)$	0.400	79.5	0.065	$4.184T$	m in kg DC, $\hat{H}_{\text{in}}$ in kJ/kg DC
dry chips	0.600	39.9	0.6	$2.10T$	

Energy Balance:

$$\Delta H = \sum m_{\text{out}}\hat{H}_{\text{out}} - \sum m_{\text{in}}\hat{H}_{\text{in}} = 0 \Rightarrow -136.8 + 1.532T = 0 \Rightarrow \underline{\underline{T = 89.3°\text{C}}}$$

8.76 a. $\begin{matrix} T_{\text{db}} = 45°\text{C} \\ h_r = 10\% \end{matrix} \xrightarrow[\text{Fig. 8.4-1}]{} T_{as} = T_{wb} = \underline{\underline{21.0°\text{C}}} \quad h_a = 0.0059\ \text{kg H}_2\text{O/kg DA}$

b. $\begin{matrix} T_{wb} = 21.0°\text{C} \\ h_r = 60\% \end{matrix} \xrightarrow[\text{Fig. 8.4-1}]{} T_{db} = \underline{\underline{26.8°\text{C}}} \quad h_a = 0.0142\ \text{kg H}_2\text{O/kg DA}$

$\underline{H_2O\text{ added:}}$ $\dfrac{15\text{ kg air}}{\text{min}}\left|\dfrac{1\text{ kg D.A.}}{1.0059\text{ kg air}}\right|\dfrac{(0.0142-0.0059)\text{ kg H}_2\text{O}}{1\text{ kg D.A.}} = \underline{\underline{0.12\ \text{kg H}_2\text{O/min}}}$

8.77 Inlet air: $\left.\begin{matrix} T_{\text{db}} = 50°\text{C} \\ T_{\text{dew pt.}} = 4°\text{C}\end{matrix}\right\} \xrightarrow{\text{Fig. 8.4-1}} \begin{matrix} \underline{\underline{\hat{V} = 0.92\ \text{m}^3/\text{kg D.A.}}},\ T_{\text{wb}} = 22°\text{C} \\ \underline{\underline{h_a = 0.0050\text{ kg H}_2\text{O/kg D.A.}}}\end{matrix}$

$$\frac{11.3\text{ m}^3}{\text{min}}\left|\frac{1\text{ kg D.A.}}{0.92\text{ m}^3}\right. = \underline{\underline{12.3\text{ kg D.A./min}}}$$

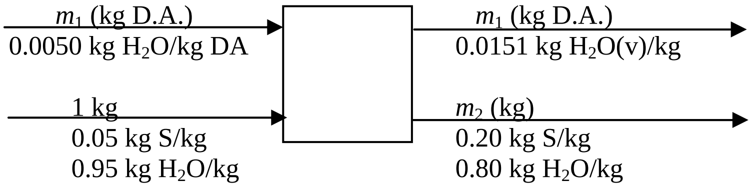
Outlet air: $\begin{matrix} T_{\text{wb}} = T_{\text{as}} = 22°\text{C} \\ \text{saturated}\end{matrix} \Rightarrow \underline{\underline{T = 22°\text{C}}} \quad h_a = 0.0165\text{ kg H}_2\text{O/kg D.A.}$

Evaporation: $\dfrac{12.3\text{ kg D.A.}}{\text{min}}\left|\dfrac{(0.0165-0.0050)\text{ kg H}_2\text{O}}{\text{kg D.A.}}\right. = \underline{\underline{0.14\ \text{kg H}_2\text{O/min}}}$

8.78 a. $\left.\begin{array}{l} T_{\text{db}} = 45^\circ\text{C} \\ T_{\text{dew point}} = 4^\circ\text{C} \end{array}\right\} \xrightarrow[\text{Fig. 8.4-1}]{} \begin{array}{l} \underline{\underline{(h_a)_{\text{in}} = 0.0050 \ \text{kg H}_2\text{O/kg D.A.}}} \\ T_{wb} = 20.4^\circ\text{C}, \ \hat{V} = 0.908 \ \text{m}^3/\text{kg D.A.} \end{array}$

$T_{wb} = T_{as} = 20.4^\circ\text{C}$, saturated $\Rightarrow \underline{\underline{(h_a)_{\text{out}} = 0.0151 \ \text{kg H}_2\text{O/kg D.A.}}}$

b. Basis: 1 kg entering sugar (S) solution

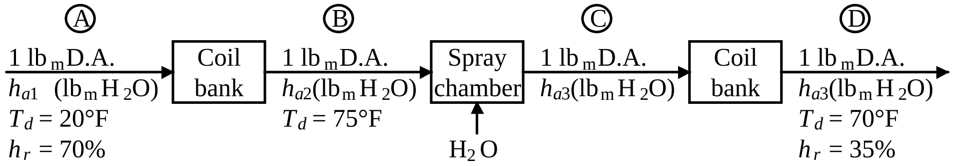


Sugar balance: $(0.05)(1) = (0.20)m_2 \Rightarrow m_2 = 0.25 \text{ kg}$

Water balance: $(m_1)(0.0050) + (1)(0.95) = (m_1)(0.0151) + (0.25)(0.80)$

$$\Rightarrow \begin{cases} m_1 = \underline{\underline{74 \text{ kg dry air}}} \\ V = \dfrac{74 \text{ kg dry air}}{} \left| \dfrac{0.908 \text{ m}^3}{1 \text{ kg D.A.}} \right. = \underline{\underline{67 \text{ m}^3}} \end{cases}$$

8.79



Inlet air (A): $\left.\begin{array}{l} T_{db} = 20^\circ\text{F} \\ h_r = 70\% \end{array}\right\} \xrightarrow{\text{Fig. 8.4-2}} \begin{array}{l} h_{a1} \approx 0.0017 \ \text{lb}_\text{m} \ \text{H}_2\text{O/lb}_\text{m} \ \text{D.A.} \\ \hat{V} \approx 12.2 \ \text{ft}^3/\text{lb}_\text{m} \ \text{D.A.} \end{array}$

Outlet air (D): $\left.\begin{array}{l} T_{\text{db}} = 70^\circ\text{F} \\ h_r = 35\% \end{array}\right\} \xrightarrow{\text{Fig. 8.4-2}} h_{a3} = 0.0054 \ \text{lb}_\text{m} \ \text{H}_2\text{O/lb}_\text{m} \ \text{D.A.}$

a. Inlet of spray chamber (B): $\left.\begin{array}{l} h_a = 0.0017 \ \text{lb}_\text{m} \ \text{H}_2\text{O/lb}_\text{m} \ \text{D.A.} \\ T_{\text{db}} = 75^\circ\text{F} \end{array}\right\} \Rightarrow \underline{\underline{T_{wb} = 49.5^\circ\text{F}}}$

The state of the air at (C) must lie on the same adiabatic saturation curve as does the state at (B), or $T_{wb} = 49.5^\circ\text{F}$. Thus,

Outlet of spray chamber (C): $\left.\begin{array}{l} h_a = 0.0054 \ \text{lb}_\text{m} \ \text{H}_2\text{O/lb}_\text{m} \ \text{D.A.} \\ T_{wb} = 49.5^\circ\text{F} \end{array}\right\} \Rightarrow \underline{\underline{h_r = 52\%}}$

At point C, $\underline{\underline{T_{\text{db}} = 58.5^\circ\text{F}}}$

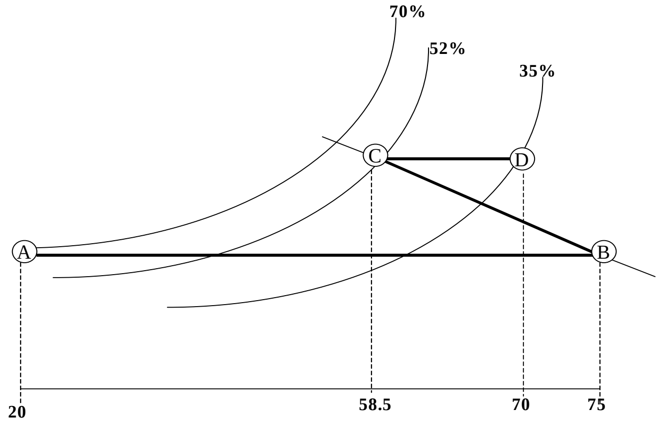
b. $\dfrac{(h_{a3} - h_{a1}) \ \text{lb}_\text{m} \ \text{H}_2\text{O evaporate}}{\text{lb}_\text{m} \ \text{DA}} \left| \dfrac{\text{lb}_\text{m} \ \text{DA}}{\hat{V}_A(\text{ft}^3 \text{ inlet air})} \right. = \dfrac{(0.0054 - 0.0017)}{12.2} = \underline{\underline{3.0 \times 10^{-4} \ \dfrac{\text{lb}_\text{m} \ \text{H}_2\text{O}}{\text{ft}^3 \ \text{air}}}}$

8.79 (cont'd)

c. $Q_{BA} = \Delta H = \hat{H}_B - \hat{H}_A \cong \dfrac{(20 - 6.4)\text{ Btu / lb}_\text{m}\text{ dry air}}{12.2\text{ ft}^3\text{ / lb}_\text{m}\text{ dry air}} = \underline{\underline{1.1\text{ Btu / ft}^3}}$

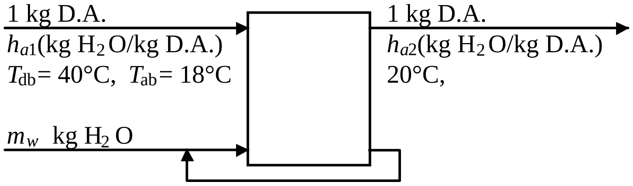
$Q_{DC} = \Delta H = \hat{H}_D - \hat{H}_C \cong \dfrac{(23 - 20)\text{ Btu / lb}_\text{m}\text{ dry air}}{12.2\text{ ft}^3\text{ / lb}_\text{m}\text{ dry air}} = \underline{\underline{0.25\text{ Btu / ft}^3}}$

d.



8.80 Basis: 1 kg D.A.

a.



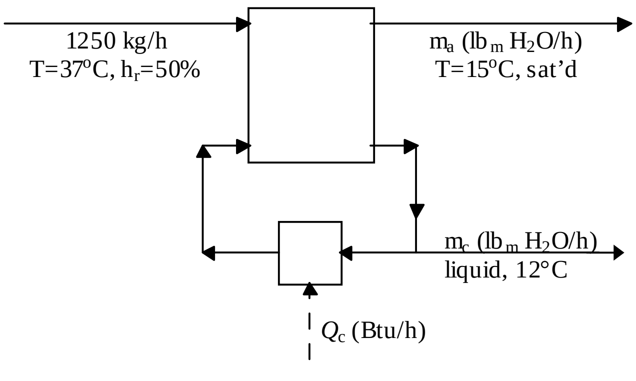
Inlet air: $\begin{matrix} T_\text{db} = 40^\circ\text{C} \\ T_\text{wb} = 18^\circ\text{C} \end{matrix} \Rightarrow h_{a1} = 0.0039\text{ kg } H_2O/\text{kg D.A.}$

Outlet air: $\begin{matrix} T_\text{db} = 20^\circ\text{C} \\ T_\text{wb} = 18^\circ\text{C (adiabatic humidification)} \end{matrix} \Rightarrow h_{a2} = 0.0122\text{ kg } H_2O/\text{kg D.A.}$

Overall H_2O balance: $m_w + (1)(h_{a1}) = (1)(h_{a2}) \Rightarrow m_n = (0.0122 - 0.0039)\text{kg } H_2O/\text{kg D.A.}$

$= \underline{\underline{0.0083\text{ kg } H_2O/\text{kg D.A.}}}$

b.



8.80 (cont'd)

Inlet air: $\left.\begin{matrix} T_{\text{db}} = 37^\circ\text{C} \\ h_r = 50\% \end{matrix}\right\} \overset{\text{Fig. 8.4-1}}{\Rightarrow} \begin{cases} h_{a1} = 0.0198 \text{ kg } H_2O/\text{kg DA} \\ \hat{H}_1 = (88.5 - 0.5) \text{ kJ/kg DA} = 88.0 \text{ kJ/kg DA} \end{cases}$

Moles dry air: $\dot{m}_a = \frac{1250 \text{ kg}}{\text{h}}\left|\frac{1 \text{ kg DA}}{1.0198 \text{ kg}}\right. = 1226 \text{ kg DA/h}$

Outlet air: $T_{\text{db}} = 15^\circ\text{C}, \text{ sat'd} \overset{\text{Fig. 8.4-1}}{\Rightarrow} \begin{cases} h_a = 0.0106 \text{ kg } H_2O/\text{kg DA} \\ \hat{H}_2 = 42.1 \text{ kJ/kg DA} \end{cases}$

Overall water balance $\Rightarrow \dot{m}_c = \frac{1226 \text{ kg DA}}{\text{h}}\left|\frac{(0.0198 - 0.0106) \text{ kg } H_2O}{\text{kg DA}}\right.$

$= \underline{\underline{11.3 \text{ kg } H_2O/\text{h withdrawn}}}$

Reference states for enthalpy calculations: $H_2O(l)$, dry air at 0°C. $(C_p)_{H2O(l)} = 4.184 \frac{\text{kJ}}{\text{kg}\cdot^\circ\text{C}}$

$H_2O(l, 12^\circ\text{C})$: $\hat{H} = \int_0^{12} C_p dT = 50.3 \text{ kJ / kg}$

Overall system energy balance:

$$\dot{Q}_c = \Delta\dot{H} = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i$$

$$= \left[\frac{11.3 \text{ kg } H_2O}{\text{h}}\left|\frac{50.3 \text{ kJ}}{\text{kg } H_2O}\right. + \frac{1226 \text{ kg DA}}{\text{h}}\left|\frac{(42.1 - 88) \text{ kJ}}{\text{kg DA}}\right.\right]\left(\frac{1 \text{ h}}{3600 \text{ s}}\right)\left(\frac{1 \text{ kW}}{1 \text{ kJ / s}}\right)$$

$$= \underline{\underline{-15.5 \text{ kW}}}$$

8.81 $\Delta H = \frac{400 \text{ mol } NH_3}{}\left|\frac{-78.2 \text{ kJ}}{\text{mol } NH_3}\right. = \underline{\underline{-31{,}280 \text{ kJ}}}$

8.82 a. $\text{HCl}(g, 25^\circ\text{C}), H_2O(l, 25^\circ\text{C}) \rightarrow \text{HCl}(25^\circ\text{C}, r = 5)$.

$\Delta\hat{H} = \Delta\hat{H}_s(25^\circ\text{C}, r = 5) \xrightarrow{\text{Table B.11}} \Delta\hat{H} = \underline{\underline{-64.05 \text{ kJ/mol HCl}}}$

b. $\text{HCl}(\text{aq}, r = \infty) \rightarrow \text{HCl}(r = 5), H_2O(l)$

$\Delta\hat{H} = \Delta\hat{H}_s(25^\circ\text{C}, n = 5) - \Delta\hat{H}_s(25^\circ\text{C}, n = \infty)$

$= (-64.05 + 75.14) \text{ kJ/mol HCl} = \underline{\underline{11.09 \text{ kJ / mol HCl}}}$

8.83 Basis: 100 mol solution $\Rightarrow$ 20 mol NaOH, 80 mol H_2O

$$\Rightarrow r=\frac{80\text{ mol H}_2\text{O}}{20\text{ mol NaOH}}=4.00\text{ mol H}_2\text{O/mol NaOH}$$

Refs: NaOH(s), $H_2O(l)$@25° C

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
NaOH(s)	20.0	0.0	–	–	n in mol
$H_2O(l)$	80.0	0.0	–	–	$\hat{H}$ in kJ/mol
NaOH$(r=4.00)$	–	–	20.0	–34.43	$\leftarrow n$ in mol NaOH

$$\hat{H}(\text{NaOH, } r=4.00)=-34.43\text{ kJ/mol NaOH (Table B.11)}$$

$$\Delta H=\sum_{\text{out}} n_i\hat{H}_i-\sum_{\text{in}} n_i\hat{H}_i=(20)(-34.43)=\frac{-688.6\text{ kJ}}{}\left|\frac{9.486\times10^{-4}\text{ Btu}}{10^{-3}\text{ kJ}}\right.=-653.2\text{ Btu}$$

$$Q=\frac{-653.2\text{ Btu}}{[20.0(40.00)+80.0(18.01)]\text{g}}\left|\frac{10^3\text{ g}}{2.20462\text{ lb}_\text{m}}\right.=\underline{\underline{-132.3\text{ Btu/lb}_\text{m}\text{ product solution}}}$$

8.84 Basis: 1 liter solution

$$n_{H_2SO_4}=\frac{1\text{ L}}{}\left|\frac{8\text{ g - eq}}{\text{L}}\right|\frac{1\text{ mol}}{2\text{ g - eq}}=4\text{ mol H}_2\text{SO}_4\times\left(\frac{0.09808\text{ kg}}{1\text{ mol}}\right)=0.392\text{ kg H}_2\text{SO}_4$$

$$m_{\text{total}}=\frac{1\text{ L}}{}\left|\frac{1.230\text{ kg}}{\text{L}}\right.=1.230\text{ kg solution}$$

$$n_{H_2O}=\frac{(1.230-0.392)\text{kg H}_2\text{O}}{}\left|\frac{1000\text{ mol H}_2\text{O}}{18.02\text{ kg H}_2\text{O}}\right.=46.5\text{ mol H}_2\text{O}$$

$$\Rightarrow r=\frac{n_{H_2O}}{n_{H_2SO_4}}=\frac{46.49\text{ mol H}_2\text{O}}{4\text{ mol H}_2\text{SO}_4}=11.6\frac{\text{mol H}_2\text{O}}{\text{mol H}_2\text{SO}_4}$$

$$H_2SO_4(\text{aq, } r=\infty, 25^\circ\text{C})\rightarrow H_2SO_4(\text{aq, } r=11.6,\ 25^\circ\text{C})+\ H_2O(l,\ 25^\circ\text{C})$$

$$\Delta\hat{H}_1=\Delta\hat{H}_s(r=11.6)-\Delta\hat{H}_s(r=\infty)\overset{\text{Table B.11}}{=}(-67.6+96.19)=28.6\ \frac{\text{kJ}}{\text{mol H}_2\text{SO}_4}$$

$$\hat{H}(H_2SO_4,\ r=11.6,\ 60^\circ\text{C})=\frac{\left[n_{H_2SO_4}\Delta H_1+m\int_{25}^{60}C_p\,dT\right]\text{kJ}}{n_{H_2SO_4}\text{ (mol H}_2\text{SO}_4)}$$

$$=\frac{1}{4\text{ mol H}_2\text{SO}_4}\left\{\frac{4\text{ mol H}_2\text{SO}_4}{}\left|\frac{28.6\text{ kJ}}{\text{mol H}_2\text{SO}_4}\right.+\frac{1.230\text{ kg}}{}\left|\frac{3.00\text{ kJ}}{\text{kg}\cdot^\circ\text{C}}\right|\frac{(60-25)^\circ\text{C}}{}\right\}$$

$$=\underline{\underline{60.9\text{ kJ/mol H}_2\text{SO}_4}}$$

8.85 $2\text{ mol } H_2SO_4 = 0.30\left(2.00 + n_{H_2O}\right) \Rightarrow n_{H_2O} = 4.67\text{ mol } H_2O \Rightarrow r = \frac{4.67}{2} = 2.33\frac{\text{mol } H_2O}{\text{mol } H_2SO_4}$

a. For this closed constant pressure system,

$$Q = \Delta H = n_{H_2SO_4}\Delta\hat{H}_s\left(25°\text{C},\ r = 2.33\right) = \begin{array}{c|c} 2\text{ mol } H_2SO_4 & -44.28\text{ kJ} \\ \hline & \text{mol } H_2SO_4 \end{array} = \underline{\underline{-88.6\text{ kJ}}}$$

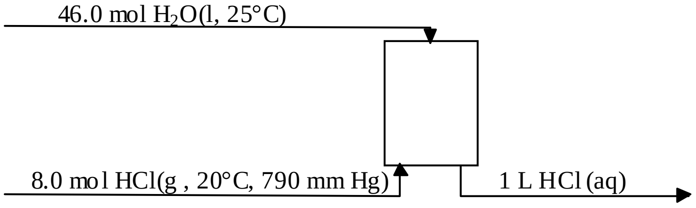
b. $$m_{\text{solution}} = \begin{array}{c|c} 2\text{ mol } H_2SO_4 & 98.08\text{ g } H_2SO_4 \\ \hline & \text{mol} \end{array} + \begin{array}{c|c} 4.67\text{ mol } H_2O & 18.0\text{ g } H_2O \\ \hline & \text{mol} \end{array} = 280.2\text{ g}$$

$$\Delta H = 0 \Rightarrow n_{H_2SO_4}\ \Delta\hat{H}_s\left(25°\text{C},\ r = 2.33\right) + m\int_{25}^{T} C_p dT = 0$$

$$-88.6\text{ kJ} + \begin{array}{c|c|c|c} (280.6 + 150)\text{g} & 3.3\text{ J} & (T - 25)°\text{C} & 1\text{ kJ} \\ \hline & \text{g}\cdot°\text{C} & & 1000\text{ J} \end{array} = 0 \Rightarrow \underline{\underline{T = 87°\text{C}}}$$

8.86 **a.** Basis: $\begin{array}{c|c} 1\text{ L product solution} & 1.12\left(10^3\text{g}\right) \\ \hline & \text{L} \end{array} = 1120\text{ g solution}$

$$\begin{array}{c|c|c} 1\text{ L} & 8\text{ mol HCl} & 36.47\text{ g HCl} \\ \hline & \text{L} & \text{mol HCl} \end{array} = 292\text{ g HCl}$$



$1120\text{ g} - 292\text{ g} = 828\text{ g } H_2O$

$$\begin{array}{c|c} 828\text{ g } H_2O & \text{mol} \\ \hline & 18.0\text{ g} \end{array} = 46.0\text{ mol } H_2O$$

$$n = \frac{46.0\text{ mol } H_2O}{8.0\text{ mol HCl}} = 5.75\text{ mol } H_2O/\text{mol HCl}$$

Assume all HCl is absorbed

Volume of gas:

$$\begin{array}{c|c|c|c} 8\text{ mol} & 293\text{ K} & 760\text{ mm Hg} & 22.4\text{ L (STP)} \\ \hline & 273\text{ K} & 790\text{ mm Hg} & \text{mol} \end{array} = \underline{\underline{185\text{ liter (STP) gas feed/L HCl solution}}}$$

b. Ref: 25°C

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
$H_2O(l)$	46.0	0.0	–	–	n in mol
$HCl(g)$	8.0	–0.15	–	–	$\hat{H}$ in kJ/mol
$HCl(n = 5.75)$	–	–	8.0	–59.07	

8.86 (cont'd)

$$\hat{H}(\text{HCl},\ n=5.75)=\Delta\hat{H}_s(25^\circ\text{C},\ n=5.75)+\frac{1}{n_{\text{HCl}}}\int_{25}^{40} mC_p\,dT$$

$$=-64.87\ \text{kJ/mol}+\frac{1120\ \text{g}}{8\ \text{mols}}\left|\frac{0.66\ \text{cal}}{\text{g}\cdot^\circ\text{C}}\right|\frac{(40-25)^\circ\text{C}}{}\left|\frac{4.184\ \text{J}}{\text{cal}}\right|\frac{\text{kJ}}{10^3\ \text{J}}$$

$$\hat{H}\left(\text{HCl},\ 20^\text{o}\,\text{C}\right)=\int_{25}^{20}\left[0.02913-0.1341\times10^{-5}T+0.9715\times10^{-8}T^2-4.335\times10^{-12}T^3\right]dT$$

$= -0.15\ \text{kJ / mol}$

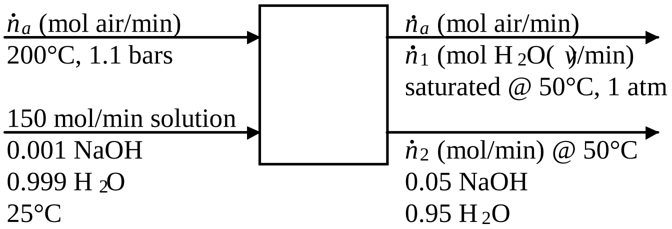
$$Q=\Delta H=\underline{\underline{-471\ \text{kJ/L product}}}$$

c. $Q=0=\Delta H=8\left(\hat{H}\right)-8(-0.15)$

$$-0.15=\hat{H}=-64.87+\frac{1120\ \text{g}}{8\ \text{mol}}\left|\frac{0.66\ \text{cal}}{\text{g}\cdot^\text{o}\,\text{C}}\right|\frac{(T-25)^\text{o}\,\text{C}}{}\left|\frac{4.184\ \text{J}}{\text{cal}}\right|\frac{1\ \text{kJ}}{1000\ \text{J}}$$

$$\underline{\underline{T=192\ ^\text{o}\text{C}}}$$

8.87 Basis: Given solution feed rate



NaOH balance: $(0.001)(150)=0.05\dot{n}_2\Rightarrow\dot{n}_2=3.0\ \text{mol/min}$

H_2O balance: $(0.999)(150)=\dot{n}_1+0.95(3.0)\Rightarrow\dot{n}_1=147\ \text{mol H}_2\text{O/min}$

Raoult's law: $y_{\text{H}_2\text{O}}P=\dfrac{\dot{n}_1}{\dot{n}_1+\dot{n}_a}P=p^*_{\text{H}_2\text{O}}(50^\circ\text{C})\overset{\text{Table B.4}}{=}92.51\ \text{mm Hg}\underset{\substack{\dot{n}_1=147\\P=760}}{\Rightarrow}\dot{n}_a=1061\dfrac{\text{mol air}}{\text{min}}$

$$\dot{V}_{\text{inlet air}}=\frac{1061\ \text{mol}}{\text{min}}\left|\frac{22.4\ \text{L(STP)}}{1\ \text{mol}}\right|\frac{473\ \text{K}}{273\ \text{K}}\left|\frac{1.013\ \text{bars}}{1.1\ \text{bars}}\right.=\underline{\underline{37{,}900\ \text{L/min}}}$$

References for enthalpy calculations: $\text{H}_2\text{O}(l)$, NaOH(s), air @ 25°C

0.1% solution @ 25°C: $r=\dfrac{999\ \text{mol H}_2\text{O}}{1\ \text{mol NaOH}}\overset{\text{Table B.11}}{\Rightarrow}\Delta\hat{H}_s(25^\circ\text{C})=-42.47\ \text{kJ/mol NaOH}$

5% solution @ 50°C: $r=\dfrac{95\ \text{mol H}_2\text{O}}{5\ \text{mol NaOH}}=\dfrac{19\ \text{mol H}_2\text{O}}{\text{mol NaOH}}\Rightarrow\Delta\hat{H}_s(25^\circ\text{C})=-42.81\dfrac{\text{kJ}}{\text{mol NaOH}}$

Solution mass: $m=\dfrac{1\ \text{mol NaOH}}{}\left|\dfrac{40.0\ \text{g}}{1\ \text{mol}}\right.+\dfrac{19\ \text{mol H}_2\text{O}}{}\left|\dfrac{18.0\ \text{g}}{1\ \text{mol}}\right.=382\ \dfrac{\text{g solution}}{\text{mol NaOH}}$

$$\hat{H}(50^\circ\text{C})=\Delta\hat{H}_s(25^\circ\text{C})+m\int_{25}^{50}C_p\,dT$$

$$=-42.81\frac{\text{kJ}}{\text{mol NaOH}}+\frac{382\ \text{g}}{\text{mol NaOH}}\left|\frac{4.184\ \text{J}}{1\ \text{g}\cdot^\circ\text{C}}\right|\frac{(50-25)^\circ\text{C}}{}\left|\frac{1\ \text{kJ}}{10^3\ \text{J}}\right.=-2.85\ \text{kJ}$$

8.87 (cont'd)

Air @ 200°C: Table B.8 $\Rightarrow \hat{H} = 5.15\ \text{kJ/mol}$

Air (dry) @ 50°C: Table B.8 $\Rightarrow \hat{H} = 0.73\ \text{kJ/mol}$

$$\underline{H_2O(v,\ 50^\circ C)}\text{: Table B.5} \Rightarrow \hat{H} = \frac{(2592 - 104.8)\ \text{kJ}}{\text{kg}}\left|\frac{1\ \text{kg}}{10^3\ \text{g}}\right|\frac{18.0\ \text{g}}{1\ \text{mol}} = 44.81\ \text{kJ/mol}$$

substance	$\dot{n}_{\text{in}}$	$\hat{H}_{\text{in}}$	$\dot{n}_{\text{out}}$	$\hat{H}_{\text{out}}$	
$NaOH(aq)$	0.15	−42.47	0.15	−2.85	$\dot{n}$ in mol/min
$H_2O(v)$	–	–	147	44.81	$\hat{H}$ in kJ/mol
Dry air	1061	5.15	1061	0.73	

$$\underset{(\text{neglect } \Delta E_n)}{\underline{\text{Energy balance:}}}\ \ \dot{Q} = \Delta\dot{H} = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = \underline{\underline{1900\ \text{kJ/min transferred to unit}}}$$

8.88 a. Basis: 1 L 4.00 molar H_2SO_4 solution (S.G. = 1.231)

$$\frac{1\ \text{L}}{}\left|\frac{1231\ \text{g}}{\text{L}}\right. = 1231\ \text{g} \Rightarrow \begin{matrix} 4.00\ \text{mol}\ H_2SO_4 \\ = \underline{\underline{392.3\ \text{g}\ H_2SO_4}} \end{matrix} \Rightarrow \begin{matrix} 1231 - 392.3 = \underline{\underline{838.7\ \text{g}\ H_2O}} \\ = 46.57\ \text{mol}\ H_2O \end{matrix}$$

$$\Rightarrow r = 11.64\ \text{mol}\ H_2O / \text{mol}\ H_2SO_4 \xrightarrow{\text{Table B.11}} \Delta\hat{H}_s = -67.6\ \text{kJ / mol}\ H_2SO_4$$

Ref: $H_2O(l,\ 25^\circ C)$, $H_2SO_4(25^\circ C)$

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
$H_2O(l)$	46.57	$0.0754(T-25)$	–	–	n in mol
$H_2SO_4(l)$	4.00	0	–	–	$\hat{H}$ in kJ/mol
$H_2SO_4(25^\circ C,\ n = 11.64)$	–	–	4.00	−67.6	

$$Q = \Delta H = 0 = 4.00(-67.6) - 46.57(0.0754)(T-25) \Rightarrow \underline{\underline{T = -52^\circ C}}$$

(*The water would not be liquid at this temperature ⇒ impossible alternative!*)

b. Ref: $H_2O(l,\ 25^\circ C)$, $H_2SO_4(25^\circ C)$

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
$H_2O(l)$	n_l	$0.0754(0-25)$	–	–	n in mols
$H_2O(s)$	n_s	$-6.01 + 0.0754(0-25)$	–	–	$\hat{H}$ in kJ/mol
$H_2SO_4(l)$	4.00	0	–	–	
$H_2SO_4(25^\circ C,\ n = 11.64)$			4.00	−67.61	

$$\Delta\hat{H}_m(H_2O,\ 0^\circ C) = \underset{\substack{\uparrow \\ \text{Table B.1}}}{6.01}\ \ \text{kJ/mol}$$

$$\left.\begin{matrix} n_\ell + n_s = 46.57 \\ \Delta H = 0 = 4.00(-67.61) - n_l(-1.885) - (46.57 - n_l)(-7.895) \end{matrix}\right\} \Rightarrow \begin{matrix} n_l = 16.18\ \text{mol liquid}\ H_2O \\ n_s = 30.39\ \text{mol ice} \end{matrix}$$

$$\Rightarrow \underline{\underline{291.4\ \text{g}\ H_2O(\ell) + 547.3\ \text{g}\ H_2O(s) @ 0^\circ C}}$$

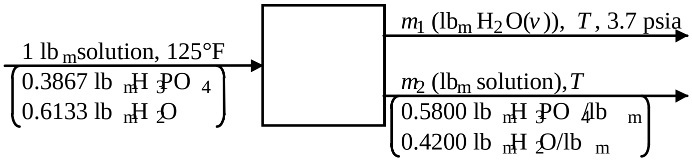
8.89 $P_2O_5 + 3H_2O \rightarrow 2H_3PO_4$

a. $$\text{wt\% } P_2O_5 = \frac{n(141.96)}{m_t}\times 100\%\ , \quad \text{wt\% } H_3PO_4 = \frac{\overset{\overset{\text{mol } H_3PO_4}{\downarrow}}{\overbrace{2n}}\ \ \overset{\overset{\text{g } H_3PO_4/\text{mol}}{\downarrow}}{(98.00)}}{\underset{\underset{\text{g total}}{\uparrow}}{m_c}}\times 100\%$$

where $n = \text{mol } P_2O_5$ and $m_t = \text{total mass}$.

$$\underline{\underline{\text{wt\% } H_3PO_4 = \frac{2(98.00)}{141.96}\ \text{wt\% } P_2O_5 = 1.381 \text{ wt\% } P_2O_5}}$$

b. Basis: 1 lb_m feed solution 28 wt% $P_2O_5 \Rightarrow 38.67$ wt% H_3PO_4



$\underline{H_3PO_4\text{ balance:}}$ $0.3867 = 0.5800 m_2 \Rightarrow m_2 0.667\ \ lb_m$ solution

Total balance: $1 = m_1 + m_2 \Rightarrow m_1 = 0.3333\ lb_m\ H_2O(r)$

Evaporation ratio: $\underline{\underline{0.3333\ lb_m\ H_2O(v)/lb_m \text{ feed solution}}}$

c. Condensate:

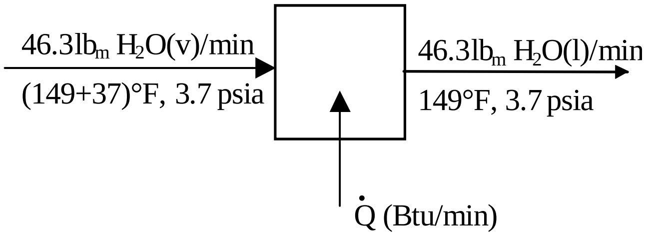
$P = 3.7$ psia (0.255 bar)

$$\overset{\text{Table B.6}}{\Rightarrow} T_{sat} = 65.4^o\text{C} = 149^o\text{F},\ \ V_{liq} = \frac{0.00102 \text{ m}^3}{\text{kg}}\left|\frac{35.3145 \text{ ft}^3/\text{m}^3}{2.205\ lb_m/\text{kg}}\right. = 0.0163\frac{\text{ft}^3}{lb_m\ H_2O(l)}$$

$$\dot{m} = \frac{100 \text{ tons feed}}{\text{day}}\left|\frac{2000\ lb_m}{1 \text{ ton}}\right|\frac{1\ lb_m\ H_2O}{3\ lb_m}\left|\frac{1 \text{ day}}{(24\times 60)\text{ min}}\right. = 46.3\ lb_m/\text{min}$$

$$\dot{V} = \frac{46.3\ lb_m}{\text{min}}\left|\frac{0.0163 \text{ ft}^3}{lb_m}\right|\frac{7.4805 \text{ gal}}{\text{ft}^3} = \underline{\underline{5.65 \text{ gal condensate / min}}}$$

Heat of condensation process:



8.89 (cont'd)

$$\text{Table B.6} \Rightarrow \begin{cases} \hat{H}_{H_2O(v)}(186^\circ\text{F} = 85.6^\circ\text{C}) = (2652\text{ kJ / kg})\left(0.4303\dfrac{\text{Btu}/\text{lb}_\text{m}}{\text{kJ}/\text{kg}}\right) = 1141\text{ Btu / lb}_\text{m} \\[2ex] \hat{H}_{H_2O(l)}(149^\circ\text{F} = 65.4^\circ\text{C}) = (274\text{ kJ / kg})(0.4303) = 118\text{ Btu / lb}_\text{m} \end{cases}$$

$$\dot{Q} = \dot{m}\Delta\hat{H} = (46.3\ \frac{\text{lb}_\text{m}}{\text{min}})\left[(118 - 1141)\frac{\text{Btu}}{\text{lb}_\text{m}}\right] = -47{,}360\text{ Btu / min}$$

$$\Rightarrow \underline{\underline{4.74\times10^4\text{ Btu/min available at }149^\circ\text{F}}}$$

d. <u>Refs:</u> $H_3PO_4(l),\ H_2O(l)@77^\circ F$

substance	m_{in}	$\hat{H}_{\text{in}}$	m_{out}	$\hat{H}_{\text{out}}$	
$H_3PO_4(28\%)$	1.00	13.95	–	–	m in lb_m
$H_3PO_4(42\%)$	–	–	0.667	34.13	$\hat{H}$ in Btu/lb_m
$H_2O(v)$	–	–	0.3333	1099	

$$\underline{\hat{H}(H_3PO_4,\ 28\%)} = \begin{array}{c|c|c} -5040\text{ Btu} & 1\text{ lb - mole }H_3PO_3 & 0.3867\text{ lb}_\text{m}\ H_3PO_4 \\ \hline \text{lb - mole }H_3PO_4 & 98.00\text{ lb}_\text{m}\ H_3PO_4 & 1.00\text{ lb}_\text{m}\text{ soln} \end{array}$$

$$+\begin{array}{c|c} 0.705\text{ Btu} & (125-77)^\circ\text{F} \\ \hline \text{lb}_\text{m}\cdot{}^\circ\text{F} & \end{array} = 13.95\ \text{Btu/lb}_\text{m}\text{ soln}$$

$$\underline{\hat{H}(H_3PO_4,\ 42\%)} = \begin{array}{c|c|c} -5040\text{ Btu} & 1\text{ lb - mole }H_3PO_4 & 0.5800\text{ lb}_\text{m}\ H_3PO_4 \\ \hline \text{lb - mole }H_3PO_4 & 98.00\text{ lb}_\text{m}\ H_3PO_4 & 1.00\text{ lb}_\text{m}\text{ sol.} \end{array}$$

$$+\begin{array}{c|c} 0.705\text{ Btu} & (186.7-77)^\circ\text{F} \\ \hline \text{lb}_\text{m}\cdot{}^\circ\text{F} & \end{array} = 34.13\ \text{Btu/lb}_\text{m}\ \text{soln}$$

$$\hat{H}(H_2O) = \hat{H}(3.7\text{psia},\ 186^\circ\text{F}) - \hat{H}(l,\ 77^\circ\text{F}) = (2652-104.7)\ \text{kJ/kg} \Rightarrow 1096\ \text{Btu/lb}_\text{m}$$

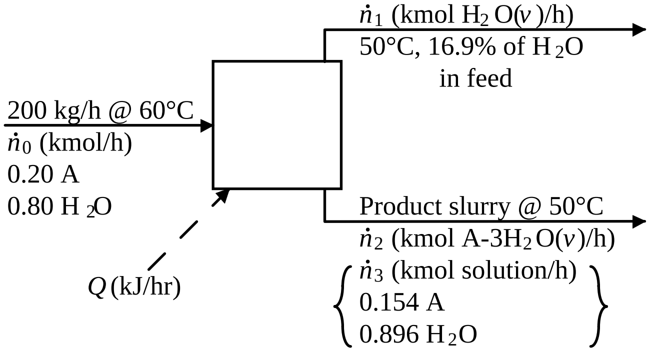
At 27.6 psia (=1.90 bar), Table B.6 $\Rightarrow \Delta\hat{H}_v = 2206\text{ kJ / kg} = 949\text{ Btu / lb}_\text{m}$

$$\Delta H = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = 375\text{ Btu} = \text{m}_{\text{steam}}\Delta\hat{H}_v \Rightarrow \text{m}_{\text{steam}} = \frac{375\text{ Btu}}{949\text{ Btu / lb}_\text{m}} = 0.395\text{ lb}_\text{m}\text{ steam}$$

$$\Rightarrow \begin{array}{c|c|c} 0.395\text{ lb}_\text{m}\text{ steam} & 100\times2000\text{ lb}_\text{m}\ H_3PO_4 & 1\text{ day} \\ \hline \text{lb}_\text{m}\ 28\%\ H_3PO_4 & \text{day} & 24\text{ h} \end{array} = \underline{\underline{3292\text{ lb}_\text{m}\text{ steam / h}}}$$

$$\Rightarrow \frac{3292\text{ lb}_\text{m}\text{ steam}}{(46.3\times60)\text{ lb}_\text{m}\ H_2O\text{ evaporated / h}} = \underline{\underline{1.18\ \frac{\text{lb}_\text{m}\text{ steam}}{\text{lb}_\text{m}\ H_2O\text{ evaporated}}}}$$

8.90 Basis: 200 kg/h feed solution. A = $NaC_2H_3O_2$



a. Average molecular weight of feed solution: $\overline{M} = 0.200 M_A + 0.800 M_{H_2O}$

$$= (0.200)(82.0) + (0.800)(18.0) = 30.8 \text{ kg/k}$$

Molar flow rate of feed: $n_0 = \dfrac{200 \text{ kg}}{\text{h}} \left| \dfrac{1 \text{ kmol}}{30.8 \text{ kg}} \right. = \underline{\underline{6.49 \text{ kmol/h}}}$

b. 16.9% evaporation $\Rightarrow n_1 = (0.169)(0.80)(6.49 \text{ kmol/h}) = 0.877 \text{ kmol } H_2O(v)/\text{h}$

A balance: $(0.20)(6.49 \text{ kmol/h}) \underset{\Downarrow}{=} \dfrac{n_2 (\text{kmol } A \cdot 3\, H_2O)}{\text{h}} \left| \dfrac{1 \text{ mole } A}{1 \text{ mole } A \cdot 3\, H_2O} \right. + 0.154 n_3$

$$\Rightarrow n_2 + 0.154 n_3 = 1.30 \qquad \textbf{(1)}$$

H_2O balance: $(0.80)(6.49 \text{ kmol/h}) = 0.877 + \dfrac{n_2 (\text{kmol } A \cdot 3\, H_2O)}{\text{h}} \left| \dfrac{3 \text{ moles } H_2O}{1 \text{ mole } A \cdot 3\, H_2O} \right.$

$$+ 0.846 n_3 \quad \Rightarrow \quad 3n_2 + 0.846 n_3 = 4.315 \qquad (\mathbf{2})$$

Solve (1) and (2) simultaneously $\Rightarrow$ $n_2 = 1.13 \text{ kmol } A \cdot 3H_2O(s)/\text{h}$

$n_3 = 1.095 \text{ kmol solution/h}$

Mass flow rate of crystals

$$\frac{1.13 \text{ kmol } A \cdot 3H_2O}{\text{h}} \left| \frac{136 \text{ kg } A \cdot 3H_2O}{1 \text{ kmol}} \right. = \underline{\underline{\frac{154 \text{ kg } NaC_2H_3O_2 \cdot 3H_2O(s)}{\text{h}}}}$$

Mass flow rate of product solution

$$\frac{200 \text{ kg feed}}{\text{h}} - \frac{154 \text{ kg crystals}}{\text{h}} - \frac{(0.877)(18.0) \text{kg } H_2O(v)}{\text{h}} = \underline{\underline{30 \text{ kg solution/h}}}$$

c. References for enthalpy calculations: $NaC_2H_3O_2(s)$, $H_2O(l)$@25° C

Feed solution: $n\hat{H} = n_A \Delta\hat{H}_s(25° \text{C}) + m\int_{25}^{60} C_p dT$ (form solution at 25° C, heat to 60° C)

$$n\hat{H} = \frac{(0.20)6.49 \text{ kmol } A}{\text{h}} \left| \frac{-1.71 \times 10^4 \text{ kJ}}{\text{kmol } A} \right. + \frac{200 \text{ kg}}{\text{hr}} \left| \frac{3.5 \text{ kJ}}{\text{kg} \cdot °\text{C}} \right| \frac{(60-25)°\text{C}}{} = 2300 \text{ kJ/h}$$

8.90 (cont'd)

<u>Product solution:</u> $n\hat{H} = n_A \Delta\hat{H}_s(25^\circ\text{C}) + m\int_{25}^{50} C_p dT$

$$= \frac{(0.154)1.095 \text{ kmol } A}{\text{h}}\left|\frac{-1.71\times10^4 \text{ kJ}}{\text{kmol } A}\right. + \frac{30 \text{ kg}}{\text{h}}\left|\frac{3.5 \text{ kJ}}{\text{kg}\cdot{}^\circ\text{C}}\right|\frac{(50-25)^\circ\text{C}}{}$$

$$= -259 \text{ kJ/h}$$

<u>Crystals:</u> $n\hat{H} = n_A \Delta\hat{H}_{\text{hydration}} + m\int_{25}^{50} C_p dT$ (hydrate at 25°C, heat to 50°C)

$$= \frac{1.13 \text{ kmol } A\cdot 3\text{H}_2\text{O(s)}}{\text{h}}\left|\frac{-3.66\times10^4 \text{ kJ}}{\text{kmol}}\right. + \frac{154 \text{ kg}}{\text{h}}\left|\frac{1.2 \text{ kJ}}{\text{kg}\cdot{}^\circ\text{C}}\right|\frac{(50-25)^\circ\text{C}}{}$$

$$= -36700 \text{ kJ/h}$$

<u>$H_2O(v,\ 50^\circ C)$:</u> $n\Delta H = n\left[\Delta\hat{H}_v + \int_{25}^{50} C_p dT\right]$ (vaporize at 25°C, heat to 50°C)

$$= \frac{0.877 \text{ kmol H}_2\text{O}}{\text{h}}\left|\frac{\left[4.39\times10^4 + (32.4)(50-25)\right] \text{kJ}}{}\right. = 39200 \text{ kJ/h}$$

<u>Energy balance:</u> (neglect ΔE_R) $Q = \Delta H = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = \left[(-259 - 36700 + 39200) - (2300)\right]$ kJ/h

$$= \underline{\underline{-60 \text{ kJ/h}}} \quad \text{(Transfer heat from unit)}$$

8.91

$$\left.\begin{array}{l} \frac{50 \text{ mL H}_2\text{SO}_4}{}\left|\frac{1.834 \text{ g}}{\text{mL}}\right. = 91.7 \text{ g H}_2\text{SO}_4 \Rightarrow 0.935 \text{ mol H}_2\text{SO}_4 \\ \frac{84.2 \text{ mL H}_2\text{O}(l)}{}\left|\frac{1.00 \text{ g}}{\text{mL}}\right. = 84.2 \text{ g H}_2\text{O}(l) \Rightarrow 4.678 \text{ mol H}_2\text{O}(l) \end{array}\right\} \Rightarrow r = 5.00 \text{ mol H}_2\text{O/mol H}_2\text{SO}_4$$

<u>Ref:</u> H_2O, H_2SO_4 @ 25 °C

$\hat{H}(\text{H}_2\text{O}(l),\ 15^\circ\text{C}) = [0.0754 \text{ kJ / (mol}\cdot{}^\circ\text{ C)}](15-25)^\circ\text{C} = -0.754 \text{ kJ / mol}$

$$\hat{H}(\text{H}_2\text{SO}_4, r = 5.00) = -58.03\frac{\text{kJ}}{\text{mol}} + \frac{(91.7+84.2) \text{ g}}{0.935 \text{ mol H}_2\text{SO}_4}\left|\frac{2.43 \text{ J}}{\text{g}\cdot{}^\circ\text{C}}\right|\frac{(T-25)^\circ\text{C}}{}\left|\frac{1 \text{ kJ}}{10^3 \text{ J}}\right.$$

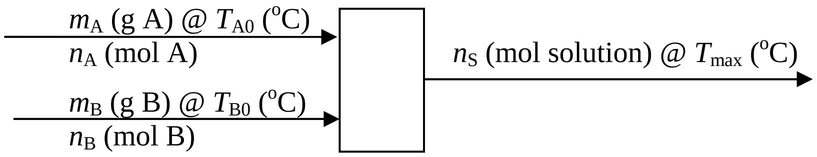
$$= (-69.46 + 0.457T)(\text{kJ / mol H}_2\text{SO}_4)$$

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
$H_2O(l)$	4.678	−0.754	—	—	n in mol
H_2SO_4	0.935	0.0	—	—	$\hat{H}$ in kJ/mol
$H_2SO_4(r = 4.00)$	—	—	0.935	$(-69.46 + 0.457T)$	n (mol H_3SO_4)

<u>Energy Balance:</u> $\Delta H = 0 = 0.935(-69.46 + 0.457T) - 4.678(-0.754) \Rightarrow \underline{\underline{T = 144\ ^\circ\text{C}}}$

<u>Conditions:</u> Adiabatic, negligible heat absorbed by the solution container.

8.92 a.



<u>Refs</u>: A(l), B(l) @ 25 °C

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
A	n_A	$\hat{H}_A$	—	—
B	n_B	$\hat{H}_B$	—	—
S	—	—	n_A	$\hat{H}_S$ (J/mol A)

n in mol

$\hat{H}$ in J / mol

<u>Moles of feed materials</u>: $n_A \text{ (mol A)} = \dfrac{m_A \text{ (g A)}}{M_A \text{ (g A / mol A)}}$, $n_B = \dfrac{m_B}{M_B}$

<u>Enthalpies of feeds and product</u>

$$\hat{H}_A = m_A C_{pA}(T_{A0} - 25^\circ\text{C}),\ \hat{H}_B = m_B C_{pB}(T_{B0} - 25^\circ\text{C})$$

$$r \text{ (mol B/mol A)} = n_B / n_A = \frac{m_B / M_B}{m_A / M_A}$$

$$\hat{H}_S \left(\frac{\text{J}}{\text{mol A}}\right) = \frac{1}{n_A \text{(mol A)}} \left[\begin{array}{l} n_A \text{(mol A)} \times \Delta\hat{H}_m(r)\left(\dfrac{\text{J}}{\text{mol A}}\right) \\ +\ (m_A + m_B)\text{(g soln)} \times C_{ps}\left(\dfrac{\text{J}}{\text{g soln}\cdot^\circ\text{C}}\right) \times (T_{\max} - 25)(^\circ\text{C}) \end{array} \right]$$

$$\Rightarrow \hat{H}_S = \frac{1}{n_A}\left[n_A \Delta\hat{H}_m(r) + (m_A + m_B) C_{ps}(T_{\max} - 25)\right]$$

<u>Energy balance</u>

$$\Delta H = n_A \hat{H}_S - n_A \hat{H}_A - n_B \hat{H}_B = 0$$

$$\Rightarrow \frac{m_A}{M_A}\Delta\hat{H}_m(r) + (m_A + m_B)C_{ps}(T_{\max} - 25) - m_A C_{pA}(T_{A0} - 25) - m_B C_{pB}(T_{B0} - 25) = 0$$

$$\Rightarrow \underline{\underline{T_{\max} = 25 + \frac{m_A C_{pA}(T_{A0} - 25) + m_B C_{pB}(T_{B0} - 25) - \dfrac{m_A}{M_A}\Delta\hat{H}_m(r)}{(m_A + m_B)C_{ps}}}}$$

<u>Conditions for validity</u>: Adiabatic mixing; negligible heat absorbed by the solution container, negligible dependence of heat capacities on temperature between 25°C and T_{A0} for A, 25°C and T_{B0} for B, and 25°C and $T_{\max}$ for the solution.

b. $$\left.\begin{array}{llll} m_A = 100.0 \text{ g} & M_A = 40.00 & T_{A0} = 25^\circ\text{C} & C_{pA} = ?\text{(irrelevant)} \\ m_B = 225.0 \text{ g} & M_B = 18.01 & T_{B0} = 40^\circ\text{C} & C_{pB} = 4.18 \text{ J/(g}\cdot^\circ\text{C)} \end{array}\right\} \Rightarrow r = 5.00 \ \frac{\text{mol H}_2\text{O}}{\text{mol NaOH}}$$

$$C_{ps} = 3.35 \text{ J/(g}\cdot^\circ\text{C)} \quad \Delta\hat{H}_m(n = 5.00) = -37{,}740 \text{ J/mol A} \Rightarrow \underline{\underline{T_{\max} = 125^\circ\text{C}}}$$

8.93 Refs: Sulfuric acid and water @ 25 °C

b.

substance	n_{in}	$\hat{H}_{\text{in}}$	n_{out}	$\hat{H}_{\text{out}}$	
H_2SO_4	1	$M_A C_{pA}(T_0-25)$	—	—	n in mol
H_2O	r	$M_w C_{pw}(T_0-25)$	—	—	$\hat{H}$ in J/mol
$H_2SO_4(aq)$	—	—	1	$\Delta\hat{H}_m(r)+(M_A+rM_w)C_{ps}(T_s-25)$ (J/mol H_2SO_4)	

$$\Delta H = 0 = \Delta\hat{H}_m(r)+(M_A+rM_w)C_{ps}(T_s-25)-M_A C_{pa}(T_0-25)-rM_w C_{pw}(T_0-25)$$

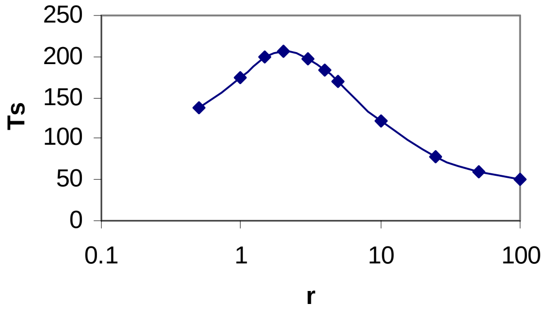
$$= \Delta\hat{H}_m(r)+(98+18r)C_{ps}(T_s-25)-(98C_{pa}+18rC_{pw})(T_0-25)$$

$$\Rightarrow \underline{\underline{T_s = 25+\frac{1}{(98+18r)C_{ps}}\left[(98C_{pa}+18rC_{pw})(T_0-25)-\Delta\hat{H}_m(r)\right]}}$$

c.

	C_p (J/mol-K)	C_p (J/g-K)
$H_2O(l)$	75.4	4.2
H_2SO_4	185.6	1.9

r	C_{ps}	$\Delta\hat{H}_m(r)$	T_s
0.5	1.58	-15,730	137.9
1	1.85	-28,070	174.0
1.5	1.89	-36,900	200.2
2	1.94	-41,920	205.7
3	2.1	-48,990	197.8
4	2.27	-54,060	184.0
5	2.43	-58,030	170.5
10	3.03	-67,030	121.3
25	3.56	-72,300	78.0
50	3.84	-73,340	59.6
100	4	-73,970	50.0



d. Some heat would be lost to the surroundings, leading to a lower final temperature.

8.94 a. Ideal gas equation of state $n_{A0} = P_0 V_g \ / \ RT_0$ (1)

Total moles of B: $n_{B0}(\text{mol B}) = \dfrac{V_l(\text{L}) \times \left(SG_B \times 1\ \text{kg / L}\right)\left(10^3\ \text{g / kg}\right)}{M_B\ (\text{g / mol B})}$ (2)

Total moles of A: $n_{Ao} = n_{Av} + n_{Al}$ (3)

Henry's Law: $r\left(\dfrac{\text{mol A(l)}}{\text{mol B}}\right) = k_s p_A \Rightarrow \dfrac{n_{Al}}{n_{B0}} = \left(c_0 + c_1 T\right) \dfrac{n_{Av} RT}{V_g}$ (4)

Solve (3) and (4) for n_{Al} and n_{Av}.

$$n_{Al} = \frac{\dfrac{n_{B0}RT}{V_g}\left(c_0 + c_1 T\right)}{\left[1 + \dfrac{n_{B0}RT}{V_g}\left(c_0 + c_1 T\right)\right]} \qquad (5)$$

$$n_{Av} = \frac{n_{Ao}}{\left[1 + \dfrac{n_{B0}RT}{V_g}\left(c_0 + c_1 T\right)\right]} \qquad (6)$$

Ideal gas equation of state

$$P = \frac{n_{Av}RT}{V_g} \overset{(6)}{=} \frac{n_{A0}RT}{V_g + n_{B0}RT\left(c_0 + c_1 T\right)} \qquad (7)$$

Refs: $A(g), B(l)$ @ 298 K

substance	n_{in}	$\hat{U}_{\text{in}}$	n_{eq}	$\hat{U}_{\text{eq}}$
$A(g)$	n_{Ao}	$M_A C_{vA}\left(T_0 - 298\right)$	n_{Av}	$M_A C_{vA}\left(T - 298\right)$
$B(l)$	n_{B0}	$M_B C_{vB}\left(T_0 - 298\right)$	—	—
Solution	—	—	n_{Al}	$\hat{U}_1$ (kJ/mol A)

n in mol
$\hat{U}$ in kJ/mol

$$\hat{U}_1 = \Delta \hat{U}_s + \frac{1}{n_{Al}}\left(n_{Al} M_A + n_{B0} M_B\right) C_{vs}\left(T - 298\right)$$

E.B.: $\Delta U = 0 = \sum\limits_{\text{out}} n_i \hat{U}_i - \sum\limits_{\text{in}} n_i \hat{U}_i$

$$0 = \left(n_{Av} C_{vA} + \left(n_{Al} M_A + n_B M_B\right) C_{vs}\right)\left(T - 298\right) + n_{Al} \Delta \hat{U}_s - \left(n_{Ao} C_{vA} + n_B C_{vB}\right)\left(T_0 - 298\right)$$

$$\Rightarrow T = 298 + \frac{n_{Al}\left(-\Delta \hat{U}_s\right) + \left(n_{Ao} C_{vA} + n_B C_{vB}\right)\left(T_0 - 298\right)}{n_{Av} C_{vA} + \left(n_{Al} M_A + n_B M_B\right) C_{vs}}$$

8.94 (cont’d)

b.

Vt	MA	CvA	MB	CvB	SGB	c0	c1	Dus	Cvs
20.0	47.0	0.831	26.0	3.85	1.76	0.00154	-1.60E-06	-174000	3.80

Vl	T0	P0	Vg	nB0	nA0	T	nA(v)	nA(l)	P	Tcalc
3.0	300	1.0	17.0	203.1	0.691	301.4	0.526	0.164	0.8	301.4
3.0	300	5.0	17.0	203.1	3.453	307.0	2.624	0.828	3.9	307.0
3.0	300	10.0	17.0	203.1	6.906	313.9	5.234	1.671	7.9	313.9
3.0	300	20.0	17.0	203.1	13.811	327.6	10.414	3.397	16.5	327.6
3.0	330	1.0	17.0	203.1	0.628	331.3	0.473	0.155	0.8	331.3
3.0	330	5.0	17.0	203.1	3.139	336.4	2.359	0.779	3.8	336.4
3.0	330	10.0	17.0	203.1	6.278	342.8	4.709	1.569	7.8	342.8
3.0	330	20.0	17.0	203.1	12.555	355.3	9.381	3.174	16.1	355.3

c.

```
 C*    REAL R, NB, T0, P0, VG, C, D, DUS, MA, MB, CVA, CVB, CVS
       REAL NA0, T, DEN, P, NAL, NAV, NUM, TN
       INTEGER K
       R = 0.08206
  1    READ (5, *) NB
       IF (NB.LT.0) STOP
       READ (1, *) T0, P0, VG, C, D, DUS, MA, MB, CVA, CVB, CVS
       WRITE (6, 900)
       NA0 = P0 * VG/R/T0
       T = 1.1 * T0
       K = 1
 10    DEN = VG/R/T/NB + C + D * T
       P = NA0/NB/DEN
       NAL = (C + D * T) * NA0/DEN
       NAV = VG/R/T/NB * NA0/DEN
       NUM = NAL * (–DUS) + (NA0 * CVA + NB * CVB) * (TO – 298)
       DEN = NAV * CVA + (NAL * MA + NB * MB) * CVS
       TN = 298 + NUM/DEN
       WRITE (6, 901) T, P, NAV, NAL, TN
       IF (ABS(T – TN).LT.0.01) GOTO 20
       K = K + 1
       T = TN
       IF (K.LT.15) GOTO 10
       WRITE (6, 902)
       STOP
 20    WRITE (6, 903)
       GOTO 1
900    FORMAT ('T(assumed)      P       Nav     Nal     T(calc.)'/
      *               '       (K)       (atm)  (mols)  (mols)      (K)')
901    FORMAT (F9.2, 2X, F6.3, 2X, F7.3, 2X, F7.3, 2X, F7.3, 2)
902    FORMAT (' ***  DID NOT CONVERGE  ***')
903    FORMAT ('CONVERGENCE'/)
       END
$ DATA
    300
    291          10.0          15.0          1.54E–3        –2.6E–6          –74
    35.0         18.0          0.0291        0.0754         4.2E–03
```

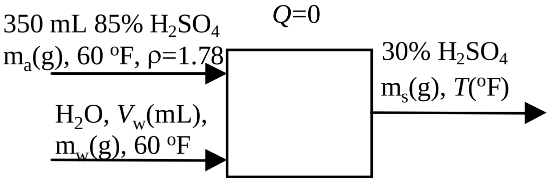
8.94 (cont'd)

```
300
291        50.0       15.0       1.54E–3     –2.6E–6       –74
35.0       18.0       0.0291     0.0754      4.2E–03
–1
```

```
Program Output
 T (assumed)        P          Nav         Nal        T(calc.)
    (K)           (atm)       (mols)      (mols)        (K)
   321.10         8.019       4.579       1.703       296.542
   296.54         7.415       4.571       1.711       296.568
   296.57         7.416       4.571       1.711       296.568
 Convergence

 T (assumed)        P          Nav         Nal        T(calc.)
    (K)           (atm)       (mols)      (mols)        (K)
   320.10        40.093      22.895       8.573       316.912
   316.91        39.676      22.885       8.523       316.942
   316.94        39.680      22.885       8.523       316.942
```

8.95



a.

$$V_w = \frac{350 \text{ mL feed}}{} \left| \frac{1.78 \quad \text{g}}{1 \text{ mL feed}} \right| \frac{[0.85(70/30) - 0.15] \text{ g H}_2\text{O added}}{\text{g feed}} \left| \frac{1 \text{ mL water}}{1 \text{ g water}} \right.$$

$$= \underline{\underline{1140 \text{ mL H}_2\text{O}}}$$

b. Fig. 8.5-1$\Rightarrow$ $\hat{H}_{\text{a}} \approx \underline{\underline{-103 \text{ Btu/lb}_{\text{m}}}}$; Water: $\hat{H}_{\text{water}} \approx \underline{\underline{27 \text{ Btu/lb}_{\text{m}}}}$

Mass Balance: $m_{\text{p}}=m_{\text{f}}+m_{\text{w}}$=(350 mL)(1.78 g/mL)+(1142 mL)(1 g/mL)=623+1142=1765 g

Energy Balance: $\Delta H = 0 = m_p \hat{H}_{\text{product}} - m_{\text{a}}\hat{H}_{\text{a}} - m_w \hat{H}_w \Rightarrow \hat{H}_s = \dfrac{m_{\text{f}}\hat{H}_{\text{f}} + m_w \hat{H}_w}{m_p}$

$$\Rightarrow \hat{H}_{\text{product}} = \frac{(623)(-103)+(1140)(27)}{1765} = \underline{\underline{-18.9 \text{ Btu/lb}_{\text{m}}}}$$

c. $T(\hat{H} = -18.9 \text{ Btu/lb}_{\text{m}}, 30\%) \approx \underline{\underline{130^{\circ}\text{F}}}$

d. When acid is added slowly to water, the rate of temperature change is slow: few isotherms are crossed on Fig. 8.5-1 when x_{acid} increases by, say, 0.10. On the other hand, a change from x_{acid}=1 to x_{acid}=0.9 can lead to a temperature increase of 200°F or more.

8.96 **a.**

$$\left.\begin{array}{l} 2.30\ \text{lb}_\text{m}\ 15.0\ \text{wt\%}\ H_2SO_4 \\ @\ 77^\circ\text{F} \Rightarrow \hat{H}_1 = -10\ \text{Btu}/\text{lb}_\text{m} \\ \\ m_2\ (\text{lb}_\text{m})\ 80.0\ \text{wt\%}\ H_2SO_4 \\ @\ 60^\circ\text{F} \Rightarrow \hat{H}_2 = -120\ \text{Btu}/\text{lb}_\text{m} \end{array}\right\} \xrightarrow{\text{adiabatic mixing}} m_3(\text{lb}_\text{m})\ 60.0\ \text{wt\%}\ H_2SO_4\ @\ T^\circ\text{F},\ \hat{H}_3$$

$$\left.\begin{array}{l} \underline{\text{Total mass balance}}:\quad 2.30 + m_2 = m_3 \\ \underline{H_2SO_4\ \text{mass balance}}:\ 2.30(0.150) + m_2(0.800) = m_3(0.600) \end{array}\right\} \Rightarrow \left\{\begin{array}{l} m_2 = 5.17\ \text{lb}_\text{m}\ (80\%) \\ \underline{\underline{m_3 = 7.47\ \text{lb}_\text{m}\ (60\%)}} \end{array}\right.$$

b. $\underline{\text{Adiabatic mixing}} \Rightarrow Q = \Delta H = 0$

$$(7.47)\hat{H}_3 - (2.30)(-10) - (5.17)(-120) = 0 \Rightarrow \hat{H}_3 = -86.1\ \text{Btu}/\text{lb}_\text{m}$$

$$\Downarrow \text{Figure 8.5-1}$$

$$\underline{\underline{T = 140^\circ\text{F}}}$$

c. $\hat{H}(60\ \text{wt\%},\ 77^\circ\text{F}) = -130\ \text{Btu}/\text{lb}_\text{m}$

$$Q = m_3\left[\hat{H}(60\ \text{wt\%},\ 77^\circ\text{F}) - \hat{H}_3\right] = (7.475)(-130 + 86.1) = \underline{\underline{-328\ \text{Btu}}}$$

d. $\underline{\underline{\text{Add the concentrated solution to the dilute solution}}}$. The rate of temperature rise is much lower (isotherms are crossed at a lower rate) when moving from left to right on Figure 8.5-1.

8.97 **a.** $x_{NH_3} = 0.30 \xrightarrow{\text{Fig. 8.5-2}} y_{NH_3} = \underline{\underline{0.96\ \text{lb}_\text{m}\ NH_3/\text{lb}_\text{m}\ \text{vapor}}},\ T = \underline{\underline{80^\circ\text{F}}}$

b. $\underline{\text{Basis}}$: 1 lb_m system mass

$$\Rightarrow 0.90\ \text{lb}_\text{m}\ \text{liquid} \xrightarrow{x_{NH_3}=0.30} \begin{array}{l} 0.27\ \text{lb}_\text{m}\ NH_3 \\ 0.63\ \text{lb}_\text{m}\ H_2O \end{array}$$

$$\Rightarrow 0.10\ \text{lb}_\text{m}\ \text{vapor} \xrightarrow{x_{NH_3}=0.96} \begin{array}{l} 0.096\ \text{lb}_\text{m}\ NH_3 \\ 0.004\ \text{lb}_\text{m}\ H_2O \end{array}$$

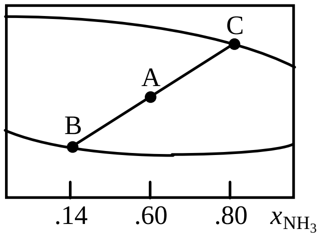
$$\underline{\text{Mass fractions:}}\quad z_{NH_3} = \frac{(0.27 + 0.096)\text{lb}_\text{m}\ NH_3}{1\ \text{lb}_\text{m}} = \underline{\underline{0.37\ \text{lb}_\text{m}\ NH_3/\text{lb}_\text{m}}}$$

$$1 - 0.37 = \underline{\underline{0.63\ \text{lb}_\text{m}\ H_2O/\text{lb}_\text{m}}}$$

$$\underline{\text{Enthalpy:}}\quad \hat{H} = \begin{array}{c|c} 0.90\ \text{lb}_\text{m}\ \text{liquid} & -25\ \text{Btu} \\ \hline 1\ \text{lb}_\text{m} & 1\ \text{lb}_\text{m}\ \text{liquid} \end{array} + \begin{array}{c|c} 0.10\ \text{lb}_\text{m}\ \text{vapor} & 670\ \text{Btu} \\ \hline 1\ \text{lb}_\text{m} & 1\ \text{lb}_\text{m}\ \text{vapor} \end{array} = \underline{\underline{44\ \text{Btu}/\text{lb}_\text{m}}}$$

8.98 $\underline{T = 140^\circ\text{ F}} \xrightarrow{\text{Fig. 8.5-2}}$ $\underline{\text{Vapor:}}$ 80% NH_3, 20% H_2O

$\underline{\text{Liquid:}}$ 14% NH_3, 86% H_2O



$\underline{\text{Basis:}}$ 250 g system mass

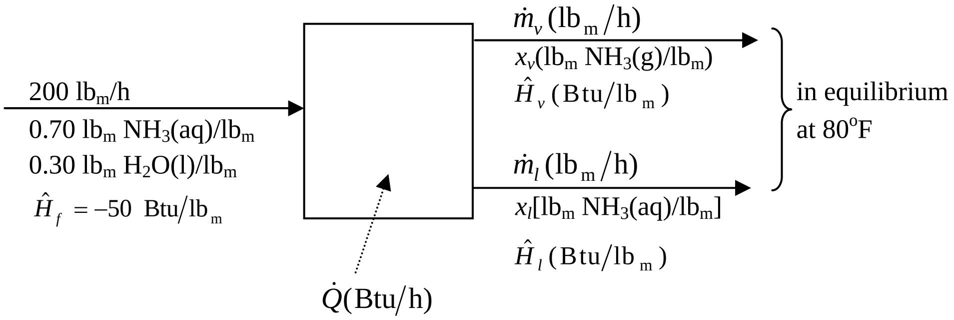
$\Rightarrow m_v$ (g vapor), m_L (g liquid)

$\underline{\text{Mass Balance:}}$ $m_v + m_L = 250$

$\underline{\text{NH}_3\text{ Balance:}}$ $0.80m_g + 0.14m_L = (0.60)(250) \Rightarrow m_v = 175\text{ g},\ m_L = 75g$

$$\Longrightarrow \begin{cases} \underline{\text{Vapor:}}\quad m_{NH_3} = (0.80)(175\text{ g}) = \underline{\underline{140\text{ g NH}_3,\ 35\text{ g H}_2\text{O}}} \\ \underline{\text{Liquid:}}\quad m_{NH_3} = (0.14)(75\text{ g}) = \underline{\underline{10.5\text{ g NH}_3,\ 64.5\text{ g H}_2\text{O}}}\ \underline{\text{Liquid}} \end{cases}$$

8.99 $\underline{\text{Basis: } 200\text{ lb}_m\text{ feed/h}}$



$\underline{\text{Figure 8.5-2}} \Rightarrow \underline{\text{Mass fraction of NH}_3\text{ in vapor:}}$ $\underline{\underline{x_v = 0.96\text{ lb}_m\text{ NH}_3/\text{lb}_m}}$

$\underline{\text{Mass fraction of NH}_3\text{ in liquid:}}$ $\underline{\underline{x_l = 0.30\text{ lb}_m\text{ NH}_3/\text{lb}_m}}$

$\underline{\text{Specific enthalpies:}}$ $\hat{H}_v = 650\text{ Btu/lb}_m,\ \hat{H}_l = -30\text{ Btu/lb}_m$

$$\left.\begin{array}{ll} \underline{\text{Mass balance:}} & 200 = \dot{m}_v + \dot{m}_l \\ \underline{\text{Ammonia balance:}} & (0.70)(200) = 0.96\dot{m}_v + 0.30\dot{m}_l \end{array}\right\} \Rightarrow \begin{array}{l} \dot{m}_v = \underline{\underline{120\text{ lb}_m/\text{h vapor}}} \\ \dot{m}_l = \underline{\underline{80\text{ lb}_m/\text{h liquid}}} \end{array}$$

$\underline{\text{Energy balance}}$: Neglect $\Delta\dot{E}_k$.

$$\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{m}_i\hat{H}_i - \dot{m}_f\hat{H}_f = \frac{120\text{ lb}_m}{\text{h}}\left|\frac{650\text{ Btu}}{\text{lb}_m}\right. + \frac{80\text{ lb}_m}{\text{h}}\left|\frac{-30\text{ Btu}}{\text{lb}_m}\right. - \frac{200\text{ lb}_m}{\text{h}}\left|\frac{-50\text{ Btu}}{\text{lb}_m}\right.$$

$$= \underline{\underline{86{,}000\frac{\text{Btu}}{\text{h}}}}$$

CHAPTER NINE

9.1

$$4NH_3(g)+5O_2(g)\rightarrow 4NO(g)+6H_2O(g)$$
$$\Delta\hat{H}_r^o=-904.7\text{ kJ / mol}$$

a. When 4 g-moles of NH_3(g) and 5 g-moles of O_2(g) at 25°C and 1 atm react to form 4 g-moles of NO(g) and 6 g-moles of water vapor at 25°C and 1 atm, the change in enthalpy is -904.7 kJ.

b. Exothermic at 25°C. The reactor must be cooled to keep the temperature constant. The temperature would increase under adiabatic conditions. The energy required to break the molecular bonds of the reactants is less than the energy released when the product bonds are formed.

c.
$$2NH_3(g)+\frac{5}{2}O_2(g)\rightarrow 2NO(g)+3H_2O(g)$$

Reducing the stoichiometric coefficients of a reaction by half reduces the heat of reaction by half.

$$\Delta\hat{H}_r^o=-\frac{904.7}{2}=\underline{\underline{-452.4\text{ kJ / mol}}}$$

d.
$$NO(g)+\frac{3}{2}H_2O(g)\rightarrow NH_3(g)+\frac{5}{4}O_2(g)$$

Reversing the reaction reverses the sign of the heat of reaction. Also reducing the stoichiometric coefficients to one-fourth reduces the heat of reaction to one-fourth.

$$\Delta\hat{H}_r^o=-\frac{(-904.7)}{4}=\underline{\underline{+226.2\text{ kJ / mol}}}$$

e.
$$\dot{m}_{NH_3}=340\text{ g/s}$$
$$\dot{n}_{NH_3}=\begin{array}{c|c|}340\text{ g} & 1\text{ mol}\\ \hline \text{s} & 17.03\text{ g}\end{array}=20.0\text{ mol/s}$$
$$\dot{Q}=\Delta\dot{H}=\frac{\dot{n}_{NH_3}\Delta\hat{H}_r^o}{\nu_{NH_3}}=\begin{array}{c|c|}20.0\text{ mol }NH_3 & -904.7\text{ kJ}\\ \hline \text{s} & 4\text{ mol }NH_3\end{array}=\underline{\underline{-4.52\times10^3\text{ kJ/s}}}$$

The reactor pressure is low enough to have a negligible effect on enthalpy.

f. Yes. Pure water can only exist as vapor at 1 atm above 100°C, but in a mixture of gases, it can exist as vapor at lower temperatures.

9.2

$$C_9H_{20}(l)+14O_2(g)\rightarrow 9CO_2(g)+10H_2O(l)$$
$$\Delta\hat{H}_r^o=-6124\text{ kJ / mol}$$

a. When 1 g-mole of C_9H_{20}(l) and 14 g-moles of O_2(g) at 25°C and 1 atm react to form 9 g-moles of CO_2(g) and 10 g-moles of water vapor at 25°C and 1 atm, the change in enthalpy is -6124 kJ.

b. Exothermic at 25°C. The reactor must be cooled to keep the temperature constant. The temperature would increase under adiabatic conditions. The energy required to break the molecular bonds of the reactants is less than the energy released when the product bonds are formed.

c.
$$\dot{Q}=\Delta\dot{H}=\frac{\dot{n}_{C_9H_{20}}\Delta\hat{H}_r^0}{\nu_{C_9H_{20}}}=\begin{array}{c|c|c}25.0\text{ mol }C_9H_{20} & -6124\text{ kJ} & 1\text{ kW}\\ \hline \text{s} & 1\text{ mol }C_9H_{20} & 1\text{ kJ / s}\end{array}=\underline{\underline{-1.53\times10^5\text{ kW}}}$$

9.2 (cont'd)

Heat Output = 1.53×10^5 kW.
The reactor pressure is low enough to have a negligible effect on enthalpy.

d.

$$C_9H_{20}(g) + 14O_2(g) \rightarrow 9CO_2(g) + 10H_2O(l) \qquad (1)$$

$$\Delta\hat{H}_r^o = -6171\text{ kJ / mol}$$

$$C_9H_{20}(l) + 14O_2(g) \rightarrow 9CO_2(g) + 10H_2O(l) \qquad (2)$$

$$\Delta\hat{H}_r^o = -6124\text{ kJ / mol}$$

$$(2) - (1) \Rightarrow C_9H_{20}(l) \rightarrow C_9H_{20}(g)$$

$$\Delta\hat{H}_v^o(C_9H_{20}, 25^\circ C) = -6124\text{ kJ / mol} - (-6171\text{ kJ / mol}) = \underline{\underline{47\text{ kJ / mol}}}$$

e. Yes. Pure n-nonane can only exist as vapor at 1 atm above 150.6°C, but in a mixture of gases, it can exist as a vapor at lower temperatures.

9.3 **a.** Exothermic. The reactor will have to be cooled to keep the temperature constant. The temperature would increase under adiabatic conditions. The energy required to break the reactant bonds is less than the energy released when the product bonds are formed.

b.

$$C_6H_{14}(g) + \frac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(g) \quad (1) \quad \Delta\hat{H}_r^o = ?$$

$$C_6H_{14}(l) + \frac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(l) \quad (2) \quad \Delta\hat{H}_2 = \Delta\hat{H}_r^o = -1.791\times10^6\text{ Btu/lb-mole}$$

$$C_6H_{14}(g) \rightarrow C_6H_{14}(l) \quad (3) \quad \Delta\hat{H}_3 = -\left(\Delta\hat{H}_v\right)_{C_2H_{14}} = -13{,}550\text{ Btu/lb-mole}$$

$$H_2O(l) \rightarrow H_2O(g) \quad (4) \quad \Delta\hat{H}_4 = \left(\Delta\hat{H}_v\right)_{H_2O} = 18{,}934\text{ Btu/lb-mole}$$

$$(1) = (2) + (3) + 7\times(4) \overset{\text{Hess's law}}{\Rightarrow} \Delta\hat{H}_1 = \Delta\hat{H}_2 + \Delta\hat{H}_3 + 7\Delta\hat{H}_4 = \underline{\underline{-1.672\times10^6\text{ Btu/lb-mole}}}$$

c.

$$\dot{m} = 120\text{ lb}_m\text{ / s} \overset{M_{O_2}=32.0}{\Rightarrow} \dot{n} = 3.75\text{ lb-mole / s.}$$

$$\dot{Q} = \Delta\dot{H} = \frac{\dot{n}_{O_2}\Delta\hat{H}_r^o}{\nu_{O_2}} = \frac{3.75\text{ lb-mole/s}}{9.5}\left|\frac{-1.672\times10^6\text{ Btu}}{1\text{ lb-mole O}_2}\right. = \underline{\underline{-6.60\times10^5\text{ Btu/s}\ \left(\text{from reactor}\right)}}$$

9.4

$$CaC_2(s) + 5H_2O(l) \rightarrow CaO(s) + 2CO_2(g) + 5H_2(g), \ \Delta\hat{H}_r^o = 69.36\text{ kJ/kmol}$$

a. Endothermic. The reactor will have to be heated to keep the temperature constant. The temperature would decrease under adiabatic conditions. The energy required to break the reactant bonds is more than the energy released when the product bonds are formed.

b.

$$\Delta\hat{U}_r^o = \Delta\hat{H}_r^o - RT\left[\sum_{\substack{\text{gaseous}\\\text{products}}}\nu_i - \sum_{\substack{\text{gaseous}\\\text{reactants}}}\nu_i\right] = 69.36\frac{\text{kJ}}{\text{mol}} - \frac{8.314\text{ J}}{\text{mol}\cdot\text{K}}\left|\frac{1\text{ kJ}}{10^3\text{ J}}\right|\frac{298\text{ K}}{}\left|\frac{(7-0)}{}\right.$$

$$= \underline{\underline{52.0\text{ kJ/mol}}}$$

9.4 (cont'd)

$\Delta\hat{U}_r^o$ is the change in internal energy when 1 g-mole of $CaC_2(s)$ and 5 g-moles of $H_2O(l)$ at 25°C and 1 atm react to form 1 g-mole of CaO(s), 2 g-moles of $CO_2(g)$ and 5 g-moles of $H_2(g)$ at 25°C and 1 atm.

c. $$Q = \Delta U = \frac{n_{CaC_2}\Delta\hat{U}_r^o}{\nu_{CaC_2}} = \frac{150\text{ g CaC}_2}{} \left|\frac{1\text{ mol}}{64.10\text{ g}}\right| \frac{52.0\text{ kJ}}{1\text{ mol CaC}_2} = \underline{\underline{121.7\text{ kJ}}}$$

Heat must be transferred to the reactor.

9.5

a. Given reaction = (1) – (2) $\overset{\text{Hess's law}}{\Rightarrow}$ $\Delta\hat{H}_r^o = \Delta\hat{H}_{r1}^o - \Delta\hat{H}_{r2}^o = (1226 - 18{,}935)\text{ Btu/lb-mole}$
$= \underline{\underline{-17{,}709\text{ Btu/lb-mole}}}$

b. Given reaction = (1) – (2) $\overset{\text{Hess's law}}{\Rightarrow}$ $\Delta\hat{H}_r^o = \Delta\hat{H}_{r1}^o - \Delta\hat{H}_{r2}^o = (-121{,}740 + 104{,}040)\text{ Btu/lb-mole}$
$= \underline{\underline{-17{,}700\text{ Btu/lb-mole}}}$

9.6

a. Reaction (3) $= 0.5\times(1) - (2) \overset{\text{Hess's law}}{\Rightarrow} \Delta\hat{H}_r^o = 0.5\left(-326.2\ \frac{\text{kJ}}{\text{mol}}\right) - \left(-285.8\ \frac{\text{kJ}}{\text{mol}}\right) = \underline{\underline{122.7\frac{\text{kJ}}{\text{mol}}}}$

b. Reactions (1) and (2) are easy to carry out experimentally, but it would be very hard to decompose methanol with only reaction (3) occurring.

9.7

a. $N_2(g) + O_2(g) \rightarrow 2NO(g)$, $\Delta\hat{H}_r^o = 2\left(\Delta\hat{H}_f^o\right)_{NO(g)} = 2\left(90.37\ \overset{\substack{\text{Table B.1}\\ \downarrow}}{\text{kJ/mol}}\right) = \underline{\underline{180.74\text{ kJ/mol}}}$

b. $n-C_5H_{12}(g) + \frac{11}{2}O_2(g) \rightarrow 5CO(g) + 6H_2O(l)$

$\Delta\hat{H}_r^o = 5\left(\Delta\hat{H}_f^o\right)_{CO(g)} + 6\left(\Delta\hat{H}_f^o\right)_{H_2O(l)} - \left(\Delta\hat{H}_f^o\right)_{n-C_5H_{12}(g)}$

$=\left[(5)(-110.52) + (6)(-285.84) - (-146.4)\right]\text{ kJ/mol} = \underline{\underline{-2121.2\text{ kJ/mol}}}$

c. $C_6H_{14}(l) + \frac{19}{2}O_2(g) \rightarrow 6CO_2(g) + 7H_2O(g)$

$\Delta\hat{H}_r^o = 6\left(\Delta\hat{H}_f^o\right)_{CO_2} + 7\left(\Delta\hat{H}_f^o\right)_{H_2O(g)} - \left(\Delta\hat{H}_f^o\right)_{C_6H_{14}(l)}$

$= \left[(6)(-393.5) + 7(-241.83) - (-198.8)\right]\text{ kJ/mol} = \underline{\underline{-3855\text{ kJ/mol}}}$

d. $Na_2SO_4(l) + 4CO(g) \rightarrow Na_2S(l) + 4CO_2(g)$

$\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o\right)_{Na_2S(l)} + 4\left(\Delta\hat{H}_f^o\right)_{CO_2(g)} - \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(l)} - 4\left(\Delta\hat{H}_f^o\right)_{CO(g)}$

$= \left[(-373.2 + 6.7) + (4)(-393.5) - (-1384.5 + 24.3) - 4(-110.52)\right]\text{ kJ/mol} = \underline{\underline{-138.2\text{ kJ/mol}}}$

9.8 **a.**

$$\Delta\hat{H}^{o}_{r1} = \left(\Delta\hat{H}^{o}_{f}\right)_{C_2H_2Cl_4(l)} - \left(\Delta\hat{H}^{o}_{f}\right)_{C_2H_4(g)} \Rightarrow \left(\Delta\hat{H}^{o}_{f}\right)_{C_2H_2Cl_4(l)} = -385.76 + 52.28 = \underline{\underline{-333.48\ \text{kJ/mol}}}$$

$$\Delta\hat{H}^{o}_{r2} = \left(\Delta\hat{H}^{o}_{f}\right)_{C_2HCl_3(l)} + \left(\Delta\hat{H}^{o}_{f}\right)_{HCl(g)} - \left(\Delta\hat{H}^{o}_{f}\right)_{C_2H_2Cl_4(l)} = -276.2 - 92.31 + 333.48 = \underline{\underline{-35.03\ \text{kJ/mol}}}$$

b. Given reaction $= (1) + (2) \Rightarrow -385.76 - 35.03 = \underline{\underline{-420.79\ \text{kJ/mol}}}$

c.

$$\dot{Q} = \Delta\dot{H} = \frac{300\ \text{mol}\ C_2HCl_3}{\text{h}}\left|\frac{-420.79\ \text{kJ}}{\text{mol}}\right. = \underline{\underline{-1.26\times10^{5}\ \text{kJ/h}}}\ (= -35\ \text{kW})$$

Heat is evolved.

9.9

a.

$$C_2H_2(g) + \frac{5}{2}O_2(g) \rightarrow 2CO_2(g) + H_2O(l) \qquad \Delta\hat{H}^{o}_{c} = -1299.6\ \text{kJ/mol}$$

The enthalpy change when 1 g-mole of $C_2H_2(g)$ and 2.5 g-moles of $O_2(g)$ at 25°C and 1 atm react to form 2 g-moles of $CO_2(g)$ and 1 g-mole of $H_2O(l)$ at 25°C and 1 atm is -1299.6 kJ.

b.

$$\Delta\hat{H}^{o}_{c} = 2\left(\Delta\hat{H}^{o}_{f}\right)_{CO_2(g)} + \left(\Delta\hat{H}^{o}_{f}\right)_{H_2O(l)} - \left(\Delta\hat{H}^{o}_{f}\right)_{C_2H_2(g)}$$

$$\overset{\substack{\text{Table B.1}\\ \downarrow}}{=} \left[2(-393.5) + (-285.84) - (226.75)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-1299.6\ \frac{\text{kJ}}{\text{mol}}}}$$

c.

(i) $$\Delta\hat{H}^{o}_{r} = \left(\Delta\hat{H}^{o}_{f}\right)_{C_2H_6(g)} - \left(\Delta\hat{H}^{o}_{f}\right)_{C_2H_2(g)}$$

$$\overset{\substack{\text{Table B.1}\\ \downarrow}}{=} \left[(-84.67) - (226.75)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-311.4\ \frac{\text{kJ}}{\text{mol}}}}$$

(ii) $$\Delta\hat{H}^{o}_{r} = \left(\Delta\hat{H}^{o}_{c}\right)_{C_2H_2(g)} + 2\left(\Delta\hat{H}^{o}_{c}\right)_{H_2(g)} - \left(\Delta\hat{H}^{o}_{c}\right)_{C_2H_6(g)}$$

$$\overset{\substack{\text{Table B.1}\\ \downarrow}}{=} \left[(-1299.6) + 2(-285.84) - (-1559.9)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-311.4\ \frac{\text{kJ}}{\text{mol}}}}$$

d.

$$C_2H_2(g) + \frac{5}{2}O_2(g) \rightarrow 2CO_2(g) + H_2O(l) \qquad (1) \quad \Delta\hat{H}^{o}_{c1} = -1299.6\ \text{kJ/mol}$$

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) \qquad (2) \quad \Delta\hat{H}^{o}_{c2} = -285.84\ \text{kJ/mol}$$

$$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l) \qquad (3) \quad \Delta\hat{H}^{o}_{c3} = -1559.9\ \text{kJ/mol}$$

The acetylene dehydrogenation reaction is $(1) + 2\times(2) - (3)$

$$\overset{\text{Hess's law}}{\Rightarrow} \quad \Delta\hat{H}^{o}_{r} = \Delta\hat{H}^{o}_{c1} + 2\times\Delta\hat{H}^{o}_{c2} - \Delta\hat{H}^{o}_{c3}$$

$$= \left(-1299.6 + 2(-285.84) - (-1559.9)\right)\ \text{kJ/mol} = \underline{\underline{-311.4\ \text{kJ / mol}}}$$

9.10

a.

$$C_8H_{18}(l)+\frac{25}{2}O_2(g)\rightarrow 8CO_2(g)+9H_2O(g) \qquad \Delta\hat{H}_r^o=-4850\text{ kJ / mol}$$

When 1 g-mole of $C_8H_{18}(l)$ and 12.5 g-moles of $O_2(g)$ at 25°C and 1 atm react to form 8 g-moles of $CO_2(g)$ and 9 g-moles of $H_2O(g)$, the change in enthalpy equals -4850 kJ.

b.

Energy balance on reaction system (not including heated water):

$$\Delta E_k,\ \Delta E_p,\ W=0\Rightarrow Q=\Delta U=n\left(\text{mol } C_8H_{18}\text{ consumed}\right)\Delta\hat{U}_c^o\left(\text{kJ/mol}\right)$$

$(C_p)_{H_2O(l)}$ from Table B.2 = $75.4\times10^{-3}\text{kJ / mol.}^\circ\text{C}$

$$-Q=m_{H_2O}(C_p)_{H_2O(l)}\Delta T=\begin{array}{c|c|c|c} 1.00\text{ kg} & 1\text{ mol} & 75.4\times10^{-3}\text{kJ} & 21.34^\circ\text{C} \\ \hline & 18.0\times10^{-3}\text{kg} & \text{mol.}^\circ\text{ C} & \end{array}=89.4\text{ kJ}$$

$$Q=\Delta U\Rightarrow-89.4\text{ kJ}=\begin{array}{c|c|c} 2.01\text{ g } C_8H_{18}\text{ consumed} & 1\text{ mol } C_8H_{18} & \Delta\hat{U}_c^o\text{ (kJ)} \\ \hline & 114.2\text{ g} & 1\text{ mol } C_8H_{18} \end{array}$$

$$\Rightarrow \underline{\underline{\Delta\hat{U}_c^o=-5079\text{ kJ/mol}}}$$

$$\Delta\hat{H}_c^o=\Delta\hat{U}_c^o+RT\left[\sum_{\substack{\text{gaseous}\\\text{products}}}\nu_i-\sum_{\substack{\text{gaseous}\\\text{reactants}}}\nu_i\right]$$

$$=-5079\text{ kJ/mol}+\begin{array}{c|c|c|c} 8.314\text{ J} & 1\text{ kJ} & 298\text{ K} & (8+9-12.5) \\ \hline \text{mol}\cdot\text{K} & 10^3\text{ J} & & \end{array}$$

$$\Rightarrow \underline{\underline{\Delta\hat{H}_c^o=-5068\text{ kJ/mol}}}$$

$$\%\text{ difference}=\frac{(-5068)-(-4850)}{\left|-5068\right|}\times100=-4.3\ \%$$

c.

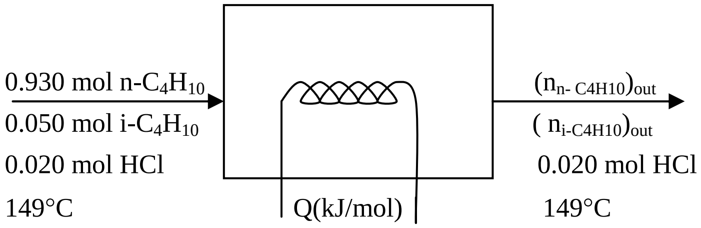
$$\Delta\hat{H}_c^o=8\left(\Delta\hat{H}_f^o\right)_{CO_2(g)}+9\left(\Delta\hat{H}_{ff}^o\right)_{H_2O(g)}-\left(\Delta\hat{H}_f^o\right)_{C_8H_{18}(l)}$$

$$\Rightarrow\left(\Delta\hat{H}_f^o\right)_{C_8H_{18}(l)}=\left[8(-393.5)+9(-241.83)+5068\right]\text{kJ/mol}=\underline{\underline{-256.5\text{ kJ/mol}}}$$

There is no practical way to react carbon and hydrogen such that 2,3,3-trimethylpentane is the only product.

9.11 **a.** $n-\mathrm{C_4H_{10}}(\mathrm{g}) \rightarrow i-\mathrm{C_4H_{10}}(\mathrm{g})$

Basis: 1 mol feed gas



$$(\mathrm{n}_{\mathrm{n\text{-}CH_4H_{10}}})_{\mathrm{out}} = 0.930(1-0.400) = \underline{\underline{0.560\ \mathrm{mol}}}$$

$$(\mathrm{n}_{\mathrm{i\text{-}CH_4H_{10}}})_{\mathrm{out}} = 0.050 + 0.930 \times 0.400 = \underline{\underline{0.420\ \mathrm{mol}}}$$

$$\xi = \frac{\left|(n_{\mathrm{n\text{-}C_4H_{10}}})_{\mathrm{out}} - (n_{\mathrm{n\text{-}C_4H_{10}}})_{\mathrm{in}}\right|}{\left|\nu_{\mathrm{n\text{-}C_4H_{10}}}\right|} = \frac{|0.560-0.930|}{|1|} = \underline{\underline{0.370\ \mathrm{mol}}}$$

b. $$\Delta\hat{H}_{\mathrm{r}}^{\mathrm{o}} = \left(\Delta\hat{H}_{\mathrm{f}}^{\mathrm{o}}\right)_{i-\mathrm{C_4H_{10}}} - \left(\Delta\hat{H}_{\mathrm{f}}^{\mathrm{o}}\right)_{n-\mathrm{C_4H_{10}}} \overset{\text{Table B.1}}{\Longrightarrow} \Delta\hat{H}_{\mathrm{r}}^{\mathrm{o}} = \left[-134.5-(-124.7)\right]\ \mathrm{kJ/mol} = \underline{\underline{-9.8\ \mathrm{kJ/mol}}}$$

c. References: $n-\mathrm{C_4H_{10}}(\mathrm{g}),\ i-\mathrm{C_4H_{10}}(\mathrm{g})$ at 25°C

substance	n_{in} (mol)	$\hat{H}_{\mathrm{in}}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{\mathrm{out}}$ (kJ/mol)
$n-\mathrm{C_4H_{10}}$	1	$\hat{H}_1$	0.600	$\hat{H}_1$
$i-\mathrm{C_4H_{10}}$	–	–	0.400	$\hat{H}_2$

$$\hat{H}_1 = \left[\int_{25}^{149} \overset{\substack{\text{Table B.2}\\ \downarrow}}{C_p}\, dT\right]\frac{\mathrm{kJ}}{\mathrm{mol}} = \underline{\underline{14.29\ \mathrm{kJ/mol}}} \qquad \hat{H}_2 = \left[\int_{25}^{149} \overset{\substack{\text{Table B.2}\\ \downarrow}}{C_p}\, dT\right]\frac{\mathrm{kJ}}{\mathrm{mol}} = \underline{\underline{14.14\ \mathrm{kJ/mol}}}$$

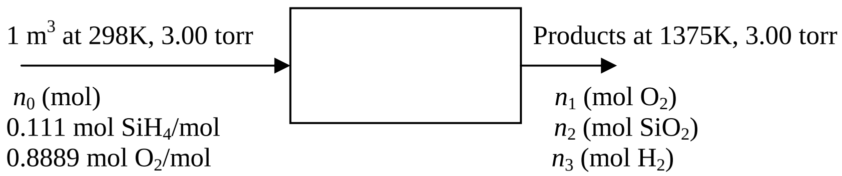
$$Q = \Delta H = \xi[\Delta\hat{H}_{\mathrm{r}}^{\mathrm{o}} + \sum_{\mathrm{out}} n_i\hat{H}_i - \sum_{\mathrm{in}} n_i\hat{H}_i] = 0.370\left[-9.8+(1)(14.142)-(1)(14.287)\right]\ \mathrm{kJ}$$

$$= \underline{\underline{-3.68\ \mathrm{kJ}}}$$

For 325 mol/h fed, $$\dot{Q} = \frac{-9.8\ \mathrm{kJ}}{1\ \mathrm{mol\ feed}}\left|\frac{325\ \mathrm{mol\ feed}}{\mathrm{h}}\right|\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}\left|\frac{1\ \mathrm{kW}}{1\ \mathrm{kJ/s}}\right. = \underline{\underline{-0.90\ \mathrm{kW}}}$$

d. $$\Delta\hat{H}_{\mathrm{r}}(149°\mathrm{C}) = \frac{-3.68\ \mathrm{kJ}}{0.370\ \mathrm{mol}} = \underline{\underline{-9.95\ \mathrm{kJ/mol}}}$$

9.12 **a.**



$$SiH_4(g) + O_2(g) \rightarrow SiO_2(s) + 2H_2(g)$$

Ideal Gas Equation of state : $n_o = \frac{1\text{ m}^3 \mid 273\text{ K} \mid 3.00\text{ torr} \mid 1\text{ mol}}{\mid 298\text{ K} \mid 760\text{ torr} \mid 22.4\times10^{-3}\text{ m}^3} = 0.1614\text{ mol}$

$$n_i = n_{io} + \nu_i\xi$$

$\underline{SiH_4}$: $0 = 0.1111(0.1614\text{ mol}) - \xi \Rightarrow \underline{\underline{\xi = 0.0179\text{ mol}}}$

$\underline{O_2}$: $n_1 = 0.8889(0.1614\text{ mol}) - \xi = \underline{\underline{0.1256\text{ mol }O_2}}$

$\underline{SiO_2}$: $n_2 = \xi = \underline{\underline{0.0179\text{ mol }SiO_2}}$

$\underline{H_2}$: $n_3 = 2\xi = \underline{\underline{0.0358\text{ mol }H_2}}$

b. $\Delta\hat{H}_r^o = (\Delta\hat{H}_f^o)_{SiO_2(s)} - (\Delta\hat{H}_f^o)_{SiH_4(g)}$

$= [-851 - (-61.9)]\text{ kJ/mol} = -789.1\text{ kJ / mol}$

References : $SiH_4(g), O_2(g), SiO_2(g), H_2(g)$ at 298 K

Substance	n_{in} (mol/h)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol/h)	$\hat{H}_{out}$ (kJ/mol)
SiH_4	0.0179	0	–	–
O_2	0.1435	0	0.1256	$\hat{H}_1$
SiO_2	–	–	0.0179	$\hat{H}_2$
H_2	–	–	0.0358	$\hat{H}_3$

$$O_2(g,1375K):\ \hat{H}_1 = \hat{H}_{O_2}(1102^o C) \overset{\text{Table B.8}}{\overset{\downarrow}{=}} 36.14\text{ kJ / mol}$$

$$SiO_2(s,1375K):\ \hat{H}_2 = \int_{298}^{1375} (C_p)_{SiO_2(s)}\,dT = 79.18\text{ kJ / mol}$$

$$H_2(g,1375K):\ \hat{H}_3 = \hat{H}_{H_2}(1102^o C) \overset{\text{Table B.8}}{\overset{\downarrow}{=}} 32.35\text{ kJ / mol}$$

c. $Q = \Delta H = \xi\ \Delta\hat{H}_r^o + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = -7.01\text{ kJ/m}^3\text{ feed}$

$\dot{Q} = \frac{-7.01\text{ kJ} \mid 27.5\text{ m}^3 \mid 1\text{ h} \mid 1\text{ kW}}{\text{m}^3 \mid \text{h} \mid 3600\text{ s} \mid 1\text{ kJ/s}} = \underline{\underline{-0.0536\text{ kW}}}$ (transferred from reactor)

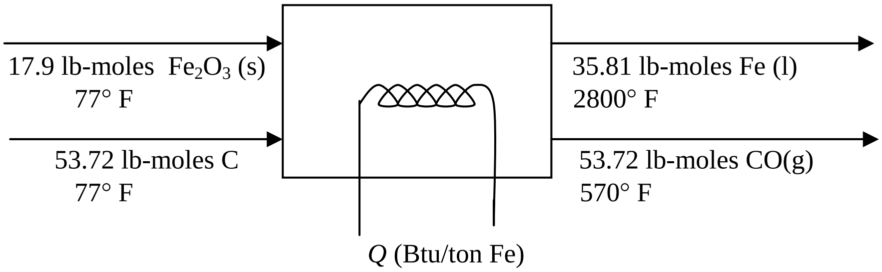
9.13 **a.** $Fe_2O_3(s) + 3C(s) \rightarrow 2Fe(s) + 3CO(g)$, $\Delta\hat{H}_r\,(77^\circ\text{F}) = 2.111\times10^5\ \text{Btu/lb-mole}$

$$\underline{\text{Basis}}:\ \frac{2000\ \text{lb}_\text{m}\ \text{Fe}\ \Big|\ 1\ \text{lb-mole}}{\Big|\ 55.85\ \text{lb}_\text{m}} = 35.81\ \text{lb-moles Fe produced}$$

53.72 lb-moles CO produced

17.9 lb-moles Fe_2O_3 fed

53.72 lb-moles C fed



b. $\underline{\text{References}}$: $Fe_2O_3(s)$, $C(s)$, $Fe(s)$, $CO(g)$ at 77° F

Substance	n_in (lb-moles)	$\hat{H}_\text{in}$ (Btu/lb-mole)	n_out (lb-moles)	$\hat{H}_\text{out}$ (Btu/lb-mole)
$Fe_2O_3(s, 77^\circ\text{F})$	17.91	0	–	–
$C(s, 77^\circ\text{F})$	53.72	0	–	–
$Fe(l, 2800^\circ\text{F})$	–	–	35.81	$\hat{H}_1$
$CO(g, 570^\circ\text{F})$	–	–	53.72	$\hat{H}_2$

$$\text{Fe}(l,2800^\circ\text{F}): \hat{H}_1 = \int_{77}^{2794} \left(C_p\right)_{\text{Fe(s)}} dT + \Delta\hat{H}_m\left(2794^\circ\text{F}\right) + \int_{2794}^{2800} \left(C_p\right)_{\text{Fe(l)}} dT = \underline{\underline{28400\ \text{Btu/lb-mole}}}$$

$$\text{CO}(g,570^\circ\text{F}):\ \hat{H}_2 = \hat{H}_\text{CO}\,(570^\circ\text{F}) \underset{\substack{\uparrow \\ \left(\text{interpolating} \atop \text{from Table B.9}\right)}}{=} \underline{\underline{3486\ \text{Btu/lb-mole}}}$$

c.

$$Q = \Delta H = \frac{n_\text{Fe}\Delta\hat{H}_r^\text{o}}{\nu_\text{Fe}} + \sum_\text{out} n_i\hat{H}_i - \sum_\text{in} n_i\hat{H}_i$$

$$= \frac{(35.81)\left(2.111\times10^5\right)}{2} + (35.81)(28400) + (53.72)(3486) - 0 = \underline{\underline{4.98\times10^6\ \text{Btu / ton Fe produced}}}$$

d. Effect of any pressure changes on enthalpy are neglected.

Specific heat of Fe(s) is assumed to vary linearly with temperature from 77°F to 570°F.

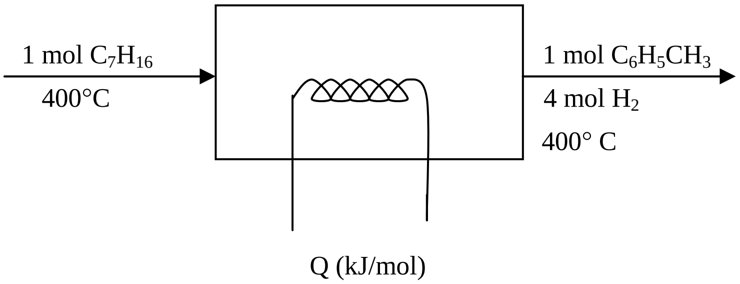
Specific heat of Fe(l) is assumed to remain constant with temperature.

Reaction is complete.

No vaporization occurs.

9.14 **a.** $C_7H_{16}(g) \rightarrow C_6H_5CH_3(g) + 4H_2(g)$

<u>Basis</u>: 1 mol C_7H_{16}



b. <u>References</u>: $C(s), H_2(g)$ at 25°C

substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
C_7H_{16}	1	$\hat{H}_1$	–	–
C_7H_8	–	–	1	$\hat{H}_2$
H_2	–	–	4	$\hat{H}_3$

$$C_7H_{16}(g,400°C):\ \hat{H}_1 = (\Delta\hat{H}_f^\circ)_{C_7H_{16}(g)} + \left[\int_{25}^{400} \overset{\overset{0.2427}{\downarrow}}{C_p}\, dT\right]$$

$$= (-187.8 + 91.0)\text{ kJ/mol} = \underline{\underline{-96.8\text{ kJ/mol}}}$$

$$C_6H_5CH_3(g,400°C):\ \hat{H}_2 = (\Delta\hat{H}_f^\circ)_{C_6H_5CH_3(g)} + \left[\int_{25}^{400} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p}\, dT\right]$$

$$= (+50 + 60.2)\text{ kJ / mol} = \underline{\underline{110.2\text{ kJ / mol}}}$$

$$H_2(g,400°C):\ \hat{H}_3 = \hat{H}_{H_2}(400^\circ C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{10.89\text{ kJ/mol}}}$$

c.

$$Q = \Delta H = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i$$

$$= \left[(1)(110.2) + (4)(10.89) - (1)(-96.8)\right]\text{kJ} = 251\text{ kJ (transferred to reactor)}$$

d.

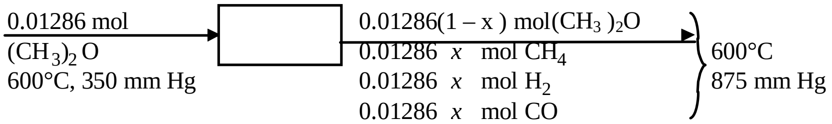
$$\Delta\hat{H}_r(400^\circ C) = \frac{251\text{ kJ}}{1\text{ mol } C_7H_{16}\text{ react}} = \underline{\underline{251\text{ kJ/mol}}}$$

9.15 **a.** $(CH_3)_2O(g) \rightarrow CH_4(g) + H_2(g) + CO(g)$

<u>Moles charged:</u> (Assume ideal gas)

$$\begin{array}{l|l|l|c} 2.00\text{ liters} & 273\text{ K} & 350\text{ mm Hg} & 1\text{ mol} \\ \hline & 873\text{ K} & 760\text{ mm Hg} & 22.4\text{ liters(STP)} \end{array} = 0.01286\text{ mol }(CH_3)_2O$$

Let x = fraction $(CH_3)_2O$ decomposed (Clearly x<1 since $P_f < 3P_0$)



Total moles in tank at $t = 2h = 0.01286[(1-x)+3x] = 0.01286(1+2x)$mol

$$\frac{P_f V}{P_0 V} = \frac{n_f RT}{n_0 RT} \Rightarrow \frac{n_f}{n_0} = \frac{P_f}{P_0} \Rightarrow \frac{0.01286(1+2x)}{0.01286} = \frac{875}{350} \Rightarrow x = 0.75 \Rightarrow \underline{\underline{75\%\ \text{decomposed}}}$$

b. <u>References</u>**:** $C(s),\ H_2(g),\ O_2(g)$ at $25^\circ C$

substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ / mol)
$(CH_3)_2O(g)$	0.01286	$\hat{H}_1$	0.25×0.01286	$\hat{H}_1$
$CH_4(g)$	–	–	0.75×0.01286	$\hat{H}_2$
$H_2(g)$	–	–	0.75×0.01286	$\hat{H}_3$
$CO(g)$	–	–	0.75×0.01286	$\hat{H}_4$

$$(CH_3)_2O(g,600^\circ C)\text{: } \hat{H}_1 = (\Delta\hat{H}_f^o)_{(CH_3)_2O} + \left[\int_{298}^{873} \overset{\overset{\text{given}}{\downarrow}}{C_p}\, dT\right] \frac{J}{mol} \times \frac{1\text{ kJ}}{10^3\text{ J}} = (-180.16\ +\ 62.40)\text{ kJ / mol}$$

$$= \underline{\underline{-118\ \text{kJ/mol}}}$$

$$CH_4(g,600^\circ C)\text{:}\hat{H}_2 = (\Delta\hat{H}_f^o)_{CH_4} + \left[\int_{25}^{600} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p}\, dT\right] = -74.85 + 29.46 = \underline{\underline{-45.39\ \text{kJ/mol}}}$$

$$H_2(g,600^\circ C)\text{: } \hat{H}_3 = \hat{H}_{H_2}(600^\circ C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{16.81\ \text{kJ/mol}}}$$

$$CO(g,600^\circ C)\text{:} \hat{H}_4 = (\Delta\hat{H}_f^o)_{CO} + \overset{\overset{\text{Table B.8}}{\downarrow}}{\hat{H}_{CO}}(600^\circ C) = \ -110.52 + 17.57\ \text{kJ/mol} \overset{\overset{\text{Table B.1}}{\overset{\text{Table B.8}}{\downarrow}}}{=} \underline{\underline{-92.95\ \text{kJ/mol}}}$$

c. For the reaction of parts (a) and (b), the enthalpy change and extent of reaction are :

$$\Delta H = \sum n_{out}\hat{H}_{out} - \sum n_{in}\hat{H}_{in} = [-1.5515 - (-1.5175)]\text{ kJ} = -0.0340\text{ kJ}$$

9.15 (cont'd)

$$\xi = \frac{(n_{CH_4})_{out} - (n_{CH_4})_{in}}{\nu_{CH_4}} = \frac{0.75\times 0.01286}{1}\,\text{mol} = 0.009645\text{ mol}$$

$$\Delta H = \xi\,\Delta\hat{H}_r(600°\text{C}) \Rightarrow \Delta\hat{H}_r(600°\text{C}) = \frac{-0.0340\text{ kJ}}{0.009645} = \underline{\underline{-3.53\text{ kJ/mol}}}$$

d.

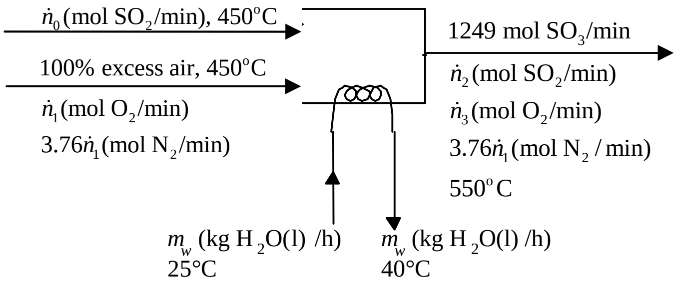
$$\Delta\hat{U}_r(600°\text{C}) = \Delta\hat{H}_r(600°\text{C}) - RT\,[\sum_{\substack{\text{gaseous}\\\text{products}}}\nu_i - \sum_{\substack{\text{gaseous}\\\text{reactants}}}\nu_i\,]$$

$$= -3.53\text{ kJ/mol} - \left.\frac{8.314\text{ J}}{\text{mol}\cdot\text{K}}\right|\left.\frac{1\text{ kJ}}{10^3\text{ J}}\right|\left.\frac{873\text{ K}}{}\right|\frac{(1+1+1-1)}{} = \underline{\underline{-18.0\text{ kJ/mol}}}$$

$$Q = \xi\,\Delta\hat{U}_r(600°\text{C}) = (0.009645\text{ mol})(-18.0\text{ kJ/mol}) = \underline{\underline{-0.174\text{ kJ}}}\text{ (transferred from reactor)}$$

9.16 **a.** $SO_2(g) + \frac{1}{2}O_2(g) \rightarrow SO_3(g)$

$$\underline{\text{Basis}}: \left.\frac{100\text{ kg }SO_3}{\text{min}}\right|\left.\frac{10^3\text{ mol }SO_3}{80.07\text{ kg }SO_3}\right| = 1249\text{ mol }SO_3/\text{min}$$



Assume low enough pressure for $\hat{H}$ to be independent of P.

$$\underset{(\text{Generation=output})}{\underline{SO_3\text{ balance}}}: \left.\frac{\dot{n}_0\text{ (mol }SO_2\text{ fed)}}{\text{min}}\right|\left.\frac{0.65\text{ mol }SO_2\text{ react}}{1\text{ mol }SO_2\text{ fed}}\right|\frac{1\text{ mol }SO_3\text{ produced}}{1\text{ mol }SO_2\text{ react}} = 1249\frac{\text{mol }SO_3}{\text{min}}$$

$$\Rightarrow \dot{n}_0 = \underline{\underline{1922\text{ mol }SO_2\text{ / min fed}}}$$

$$\underline{\text{100\% excess air}}:\ \dot{n}_1 = \left.\frac{1922\text{ mol }SO_2}{\text{min}}\right|\left.\frac{0.5\text{ mol }O_2\text{ reqd}}{1\text{ mol }SO_2}\right|\frac{(1+1)\text{ mol }O_2\text{ fed}}{1\text{ mol }O_2\text{ reqd}} = \underline{\underline{1922\text{ mol }O_2/\text{min fed}}}$$

$$\underline{N_2\text{ balance}}:\ 3.76(1922) = \underline{\underline{7227\text{ mol / min (in \& out)}}}$$

$$\underline{\text{65\% conversion}}:\ \dot{n}_2 = 1922(1-0.65)\text{ mol/s} = \underline{\underline{673\text{ mol }SO_2/\text{min out}}}$$

$$\underline{\text{O balance:}}\ (2)(1922) + (2)(1922) = (3)(1249) + (2)(673) + 2\dot{n}_3 \Rightarrow \dot{n}_3 = 1298\text{ mol / min out}$$

9.16 (cont'd)

b.

$$\underline{\text{Extent of reaction}}:\quad \dot{\xi} = \frac{\left|(\dot{n}_{SO_2})_{out} - (\dot{n}_{SO_2})_{in}\right|}{\left|\nu_{SO_2}\right|} = \frac{|673-1922|}{|1|} = \underline{\underline{1249 \text{ mol / min}}}$$

$$\Delta\hat{H}_r^o = (\Delta\hat{H}_f^o)_{SO_3(g)} - (\Delta\hat{H}_f^o)_{SO_2(g)} \overset{\overset{\text{Table B.1}}{\downarrow}}{=} -395.18 - (-296.9) = \underline{\underline{-99.28 \text{ kJ / mol}}}$$

$\underline{\text{References}}$: $SO_2(g)$, $O_2(g)$, $N_2(g)$, $SO_3(g)$ at 25°C

Substance	$\dot{n}_{in}$ (mol / min)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / min)	$\hat{H}_{out}$ (kJ / mol)
SO_2	1922	$\hat{H}_1$	673	$\hat{H}_4$
O_2	1922	$\hat{H}_2$	1298	$\hat{H}_5$
N_2	7227	$\hat{H}_3$	7227	$\hat{H}_6$
SO_3	–	–	1249	$\hat{H}_7$

$$SO_2(g, 450^\circ C):\ \hat{H}_1 = \int_{25}^{450} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p}\, dT = \underline{\underline{19.62 \text{ kJ / mol}}}$$

$$O_2(g, 450^\circ C) = \hat{H}_2 = \hat{H}_{O_2}(450^\circ C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{13.36 \text{ kJ / mol}}}$$

$$N_2(g, 450^\circ C) = \hat{H}_3 = \hat{H}_{N_2}(450^\circ C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{12.69 \text{ kJ / mol}}}$$

$\underline{\text{Out}}$:

$$SO_2(g, 550^\circ C):\ \hat{H}_4 = \int_{25}^{550} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p}\, dT = \underline{\underline{24.79 \text{ kJ/mol}}}$$

$$O_2(g, 550^\circ C) = \hat{H}_5 = \hat{H}_{O_2}(550^\circ C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{16.71 \text{ kJ / mol}}}$$

$$N_2(g, 550^\circ C) = \hat{H}_6 = \hat{H}_{N_2}(550^\circ C) \overset{\overset{\text{Table B.8}}{\downarrow}}{=} \underline{\underline{15.81 \text{ kJ / mol}}}$$

$$SO_3(g, 550^\circ C):\ \hat{H}_7 = \int_{25}^{550} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p}\, dT = \underline{\underline{35.34 \text{ kJ / mol}}}$$

$$\dot{Q} = \Delta\dot{H} = \dot{\xi}\Delta\hat{H}_r^o + \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i$$

$$= (1249)(-98.28) + (673)(24.796) + (179.8)(16.711) + (7227)(15.808) + (1249)(35.336) - (19$$

$$-1922(13.362) - (7227)(12.691)$$

$$= \frac{-8.111\times10^4 \text{ kJ}}{\text{min}}\left|\frac{1 \text{ min}}{60 \text{ s}}\right|\frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-1350 \text{ kW}}}$$

c. Assume system is adiabatic, so that $\dot{Q}_{\text{lost from reactor}} = \dot{Q}_{\text{gained by cooling water}}$

9.16 (cont’d)

$$\dot{Q} = \Delta\dot{H} = \dot{m}_w\left[\underset{\substack{\uparrow \\ \text{Table B.5}}}{\hat{H}_w}\left(\text{l, }40^\circ\text{C}\right) - \hat{H}_w\underset{\substack{\uparrow \\ \text{Table B.5}}}{\left(\text{l, }25^\circ\text{C}\right)}\right]$$

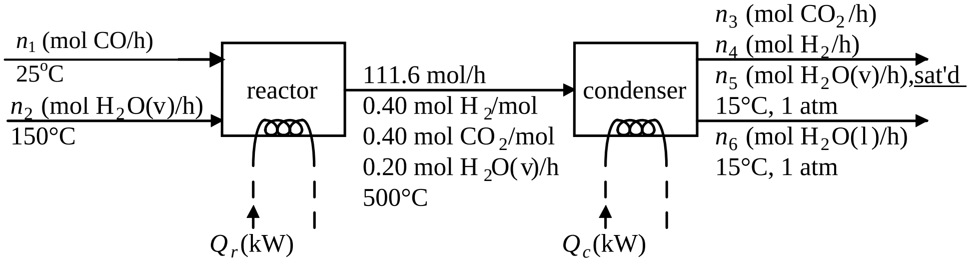
d. $$\Rightarrow 8.111\times 10^4\,\frac{\text{kJ}}{\text{min}} = \dot{m}_w\left(\frac{\text{kg}}{\text{min}}\right)\left[167.5-104.8\right]\frac{\text{kJ}}{\text{kg}} \Rightarrow \underline{\underline{\dot{m}_w = 1290\ \text{kg/min cooling water}}}$$

If elemental species were taken as references, the heats of formation of each molecular species would have to be taken into account in the enthalpy calculations and the heat of reaction term would not have been included in the calculation of $\Delta\dot{H}$.

9.17 $\text{CO(g)} + \text{H}_2\text{O(v)} \rightarrow \text{H}_2\text{(g)} + \text{CO}_2\text{(g)}$,

$$\Delta\hat{H}_\text{r}^\text{o} = \left(\Delta\hat{H}_\text{f}^\text{o}\right)_{\text{CO}_2\text{(g)}} - \left(\Delta\hat{H}_\text{f}^\text{o}\right)_{\text{CO(g)}} - \left(\Delta\hat{H}_\text{f}^\text{o}\right)_{\text{H}_2\text{O(v)}} \overset{\substack{\text{Table B.1} \\ \downarrow}}{=} -41.15\frac{\text{kJ}}{\text{mol}}$$

a. Basis : $\left[2.5\ \text{m}^3\text{(STP) product gas/h}\right]\left[1000\ \text{mol}/22.4\ \text{m}^3\text{(STP)}\right] = 111.6\ \text{mol/h}$



<u>C balance on reactor :</u> $\dot{n}_1 = (0.40)(111.6\ \text{mol/h}) = 44.64\ \text{mol CO/h}$

<u>H balance on reactor :</u> $2\dot{n}_2 = 111.6\left[(2)(0.40)+(2)(0.20)\right]\text{mol/h} \Rightarrow \dot{n}_2 = 66.96\ \text{mol H}_2\text{O(v)/h}$

<u>Steam theoretically required</u> $= \dfrac{44.64\ \text{mol CO}}{\text{h}}\left|\dfrac{1\ \text{mol H}_2\text{O}}{1\ \text{mol CO}}\right. = 44.64\ \text{mol H}_2\text{O}$

<u>% excess steam</u> $= \dfrac{(66.96-44.64)\ \text{mol/h}}{44.64\ \text{mol/h}}\times 100\% = \underline{\underline{50\%\ \text{excess steam}}}$

<u>CO_2 balance on condenser :</u> $\dot{n}_3 = (0.40)(111.6\ \text{mol/h}) = 44.64\ \text{mol CO}_2\text{/h}$

<u>H_2 balance on condenser:</u> $\dot{n}_4 = (0.40)(111.6\ \text{mol/h}) = 44.64\ \text{mol H}_2\text{/h}$

<u>Saturation of condenser outlet gas:</u>

$$y_{\text{H}_2\text{O}} = \frac{p_w^*(15^\circ\text{C})}{\text{p}} \Rightarrow \frac{\dot{n}_5(\text{mol H}_2\text{O/h})}{(44.64+44.64+\dot{n}_5)(\text{mol/h})} = \frac{12.788\ \text{mm Hg}}{760\ \text{mm Hg}} \Rightarrow \dot{n}_5 = 1.53\ \text{mol H}_2\text{O(v)/h}$$

<u>H_2O balance on condenser:</u> $(111.6)(0.20)\text{mol H}_2\text{O/h} = 1.53 + \dot{n}_6$

$$\Rightarrow \dot{n}_6 = 20.8\ \text{mol H}_2\text{O/h condensed} = \underline{\underline{0.374\ \text{kg/h}}}$$

9.17 (cont'd)

b. Energy balance on condenser

References: $H_2(g),\ CO_2(g)$ at 25° C, H_2O at reference point of steam tables

Substance	$\dot{n}_{\text{in}}$ mol / h	$\hat{H}_{\text{in}}$ kJ / mol	$\dot{n}_{\text{out}}$ mol / h	$\hat{H}_{\text{out}}$ kJ / mol
$CO_2(g)$	44.64	$\hat{H}_1$	44.64	$\hat{H}_4$
$H_2(g)$	44.64	$\hat{H}_2$	44.64	$\hat{H}_5$
$H_2O(v)$	22.32	$\hat{H}_3$	1.53	$\hat{H}_6$
$H_2O(l)$	–	–	20.80	$\hat{H}_7$

Enthalpies for CO_2 and H_2 from Table B.8

$$CO_2(g,500^\circ C): \hat{H}_1 = \hat{H}_{CO_2}(500^\circ C) = 21.34 \text{ kJ / mol}$$

$$H_2(g,500^\circ C): \hat{H}_2 = \hat{H}_{H_2}(500^\circ C) = 13.83 \text{ kJ / mol}$$

$$H_2O(v,500^\circ C): \hat{H}_3 = 3488\ \frac{\text{kJ}}{\text{kg}} \times \left(\frac{18 \text{ kg}}{10^3 \text{ mol}}\right) = 62.86 \text{ kJ/mol}$$

$$CO_2(g,15^\circ C): \hat{H}_4 = \hat{H}_{CO_2}(15^\circ C) = -0.552 \text{ kJ/mol}$$

$$H_2(g,15^\circ C): \hat{H}_5 = \hat{H}_{H_2}(15^\circ C) = -0.432 \text{ kJ / mol}$$

$$H_2O(v,15^\circ C): \hat{H}_6 = 2529\frac{\text{kJ}}{\text{kg}} \times \left(\frac{18.0 \text{ kg}}{10^3 \text{ mol}}\right) = 45.52 \text{ kJ/mol}$$

$$H_2O(l,15^\circ C): \hat{H}_7 = 62.9\frac{\text{kJ}}{\text{kg}} \times \left(\frac{18.0 \text{ kg}}{10^3 \text{ mol}}\right) = 1.13 \text{ kJ/mol}$$

$$\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = \frac{(49.22 - 2971.8) \text{ kJ}}{\text{h}}\left|\frac{1 \text{ h}}{3600 \text{ s}}\right|\frac{1 \text{ kW}}{1 \text{ kJ/s}} = \underline{\underline{-0.812 \text{ kW}}}$$

(heat transferred from condenser)

c. Energy balance on reactor :

References: $H_2(g),\ C(s),\ O_2(g)$ at 25°C

Substance	$\dot{n}_{\text{in}}$ (mol / h)	$\hat{H}_{\text{in}}$ (kJ / mol)	$\dot{n}_{\text{out}}$ (mol / h)	$\hat{H}_{\text{out}}$ (kJ / mol)
CO(g)	44.64	$\hat{H}_1$	–	–
$H_2O(v)$	66.96	$\hat{H}_2$	22.32	$\hat{H}_3$
$H_2(g)$	–	–	44.64	$\hat{H}_4$
$CO_2(g)$	–	–	44.64	$\hat{H}_5$

$$CO(g,25^\circ C): \hat{H}_1 = (\Delta\hat{H}_f^\circ)_{CO} \overset{\text{Table B.1}}{=} \underline{\underline{-110.52 \text{ kJ / mol}}}$$

$$H_2O(v,150^\circ C): \hat{H}_2 = (\Delta\hat{H}_f^\circ)_{H_2O(v)} + \hat{H}_{H_2O}(150^\circ C) \overset{\text{Tables B.1, B.8}}{=} \underline{\underline{-237.56 \text{ kJ/mol}}}$$

9.17 (cont'd)

$$H_2O(v,500^\circ C): \hat{H}_3 = (\Delta\hat{H}_f^\circ)_{H_2O(v)} + \hat{H}_{H_2O}(500^\circ C) \overset{\text{Tables B.1, B.8}}{=} \underline{\underline{-224.82\ \text{kJ/mol}}}$$

$$H_2(g,500^\circ C): \hat{H}_4 = \hat{H}_{H_2}(500^\circ C) \overset{\text{Table B.8}}{=} \underline{\underline{13.83\ \text{kJ / mol}}}$$

$$CO_2(g,500^\circ C): \hat{H}_5 = (\Delta\hat{H}_f^\circ)_{CO_2} + \hat{H}_{CO_2}(500^\circ C) \overset{\text{Tables B.1, B.8}}{=} \underline{\underline{-372.16\ \text{kJ / mol}}}$$

$$Q = \Delta H = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = \frac{[-21013.83-(-20839.96)]\ \text{kJ}}{\text{h}}\left|\frac{1\ \text{h}}{3600\ \text{s}}\right|\frac{1\ \text{kW}}{1\ \text{kJ/s}} = \underline{\underline{-0.0483\ \text{kW}}}$$

(heat transferred from reactor)

d. Benefits

Preheating CO ⇒ more heat transferred from reactor (possibly generate additional steam for plant)
Cooling CO ⇒ lower cooling cost in condenser.

9.18 b.

$\underline{\text{References}}$: FeO(s), CO(g), Fe(s), CO_2(g) at 25°C

Substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ / mol)
FeO	1.00	0	n_1	$\hat{H}_1$
CO	n_0	$\hat{H}_0$	n_2	$\hat{H}_2$
Fe	–	–	n_3	$\hat{H}_3$
CO_2	–	–	n_4	$\hat{H}_4$

$$Q = \xi \Delta\hat{H}_r^o + \sum n_{\text{out}}\hat{H}_{\text{out}} - \sum n_{\text{in}}\hat{H}_{\text{in}}$$

$$\Rightarrow Q = \xi \Delta\hat{H}_r^o + n_1\hat{H}_1 + n_2\hat{H}_2 + n_3\hat{H}_3 + n_4\hat{H}_4 - n_0\hat{H}_0$$

$$\underline{\text{Fractional Conversion}}: X = \frac{(1.00 - n_1)}{1.00} \Rightarrow \underline{\underline{n_1 = 1 - X}}$$

$$\underline{\text{CO consumed}}: \frac{1\text{ mol CO}}{1\text{ mol FeO consumed}}\left|\frac{(1-n_1)\text{ mol FeO consumed}}{}\right. = (1-n_1)\text{ mol CO}$$

$$\Rightarrow n_2 = n_0 - (1-n_1) = \underline{\underline{n_0 - X}}$$

$$\underline{\text{Fe produced}}: n_3 = \frac{1\text{ mol Fe}}{1\text{ mol FeO consumed}}\left|\frac{(1-n_1)\text{ mol FeO consumed}}{}\right. = (1-n_1)\text{ mol Fe} = \underline{\underline{X}}$$

$$\underline{CO_2\text{ produced}}: n_4 = \frac{1\text{ mol }CO_2}{1\text{ mol FeO consumed}}\left|\frac{(1-n_1)\text{ mol FeO consumed}}{}\right. = (1-n_1)\text{ mol }CO_2 = \underline{\underline{X}}$$

$$\underline{\text{Extent of reaction}}: \xi = \frac{|(n_{\text{CO}})_{\text{out}} - (n_{\text{CO}})_{\text{in}}|}{|\nu_{\text{CO}}|} = \frac{|n_2 - n_0|}{1} = \underline{\underline{X}}$$

$$\hat{H}_i = \int_{25}^{T} C_{pi}\,dT \qquad \text{for } i = 0,1,2,3,4$$

$$\hat{H}_0 = 0.02761\,(T_0 - 298) + 2.51\times10^{-6}(T_0^{\,2} - 298^2)$$

$$\Rightarrow \underline{\underline{\hat{H}_0 = (-8.451 + 0.02761\,T_0 + 2.51\times10^{-6}\;T_0^2)\text{ kJ / mol}}}$$

$$\hat{H}_1 = 0.0528\,(T - 298) + 3.1215\times10^{-6}(T^2 - 298^2) + 3.188\times10^2(1/T - 1/298)$$

$$\Rightarrow \underline{\underline{\hat{H}_1 = (-17.0814 + 0.0528\,T + 3.1215\times10^{-6}T^2 + 3.188\times10^2\;/\,T)\text{ kJ / mol}}}$$

$$\hat{H}_2 = (0.02761\,(T - 298) + 2.51\times10^{-6}(T^2 - 298^2)$$

$$\Rightarrow \underline{\underline{\hat{H}_2 = -8.451 + 0.02761\,T + 2.51\times10^{-6}\;T^2)\text{ kJ / mol}}}$$

$$\hat{H}_3 = 0.01728\,(T - 298) + 1.335\times10^{-5}(T^2 - 298^2)$$

$$\Rightarrow \underline{\underline{\hat{H}_3 = (-6.335 + 0.01728\,T + 1.335\times10^{-5}\;T^2)\text{ kJ / mol}}}$$

$$\hat{H}_4 = 0.04326(T - 298) + 0.573\times10^{-5}(T^2 - 298^2) + 8.18\times10^2(1/T - 1/298)$$

$$\Rightarrow \underline{\underline{\hat{H}_4 = (-16.145 + 0.04326\,T + 0.573\times10^{-5}T^2 + 8.18\times10^2\;/\,T)\text{ kJ / mol}}}$$

9.18 (cont'd)

c. $n_0 = 2.0$ mol CO, $T_0 = 350$ K, $T = 550$ K, and $X = 0.700$ mol FeO reacted/mol FeO fed

$$\Rightarrow n_1 = 1 - 0.7 = 0.3,\ n_2 = 2 - 0.7 = 1.3,\ n_3 = 0.7,\ n_4 = 0.7,\ \xi = 0.7$$

$\underline{\text{Summary}:}\ \hat{H}_0 = 1.520$ kJ/mol, $\hat{H}_1 = 13.48$ kJ/mol, $\hat{H}_2 = 7.494$ kJ/mol,

$\hat{H}_3 = 7.207$ kJ/mol, $\hat{H}_4 = 10.87$ kJ/mol

$\Delta\hat{H}_r^o = -16.48$ kJ/mol

$$Q = (0.7)(-16.48) + (0.3)(13.48) + (1.3)(7.494) + (0.7)(7.207) + (0.7)(10.87) - (2)(1.520)$$

$$\Rightarrow \underline{\underline{Q = 11.86 \text{ kJ}}}$$

d.

no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
1	400	1	298	1	0	0	1	1	2.995	0	0	0	0	-19.48
1	400	1	400	1	0	0	1	1	2.995	5.335	2.995	2.713	4.121	-12.64
1	400	1	500	1	0	0	1	1	2.995	10.737	5.982	5.643	8.553	-5.279
1	400	1	600	1	0	0	1	1	2.995	16.254	9.019	8.839	13.237	2.601
1	400	1	700	1	0	0	1	1	2.995	21.864	12.11	12.303	18.113	10.941
1	400	1	800	1	0	0	1	1	2.995	27.555	15.24	16.033	23.152	19.71
1	400	1	900	1	0	0	1	1	2.995	33.321	18.43	20.031	28.339	28.895
1	400	1	1000	1	0	0	1	1	2.995	39.159	21.67	24.295	33.663	38.483

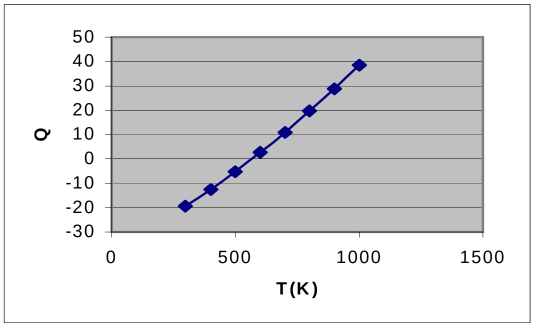
no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
1	298	1	700	1	0	0	1	1	0	21.864	12.11	12.303	18.113	13.936
1	400	1	700	1	0	0	1	1	2.995	21.864	12.11	12.303	18.113	10.941
1	500	1	700	1	0	0	1	1	5.982	21.864	12.11	12.303	18.113	7.954
1	600	1	700	1	0	0	1	1	9.019	21.864	12.11	12.303	18.113	4.917
1	700	1	700	1	0	0	1	1	12.11	21.864	12.11	12.303	18.113	1.83
1	800	1	700	1	0	0	1	1	15.24	21.864	12.11	12.303	18.113	-1.308
1	900	1	700	1	0	0	1	1	18.43	21.864	12.11	12.303	18.113	-4.495
1	1000	1	700	1	0	0	1	1	21.67	21.864	12.11	12.303	18.113	-7.733

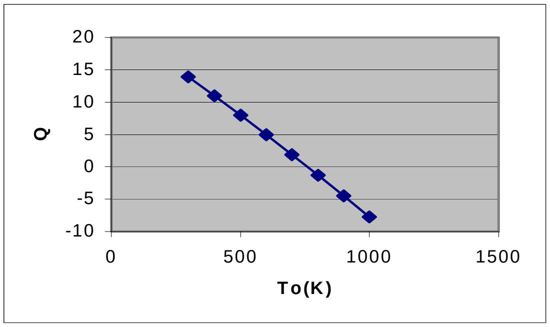
no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
1	400	0	500	0	1	1	0	0	2.995	10.737	5.55	5.643	8.533	13.72
1	400	0.1	500	0.1	0.9	0.9	0.1	0.1	2.995	10.737	5.55	5.643	8.533	11.82
1	400	0.2	500	0.2	0.8	0.8	0.2	0.2	2.995	10.737	5.55	5.643	8.533	9.92
1	400	0.3	500	0.3	0.7	0.7	0.3	0.3	2.995	10.737	5.55	5.643	8.533	8.02
1	400	0.4	500	0.4	0.6	0.6	0.4	0.4	2.995	10.737	5.55	5.643	8.533	6.12
1	400	0.5	500	0.5	0.5	0.5	0.5	0.5	2.995	10.737	5.55	5.643	8.533	4.22
1	400	0.6	500	0.6	0.4	0.4	0.6	0.6	2.995	10.737	5.55	5.643	8.533	2.32
1	400	0.7	500	0.7	0.3	0.3	0.7	0.7	2.995	10.737	5.55	5.643	8.533	0.42
1	400	0.8	500	0.8	0.2	0.2	0.8	0.8	2.995	10.737	5.55	5.643	8.533	–1.48
1	400	0.9	500	0.9	0.1	0.1	0.9	0.9	2.995	10.737	5.55	5.643	8.533	–3.38
1	400	1	500	1	0	0	1	1	2.995	10.737	5.55	5.643	8.533	–5.28

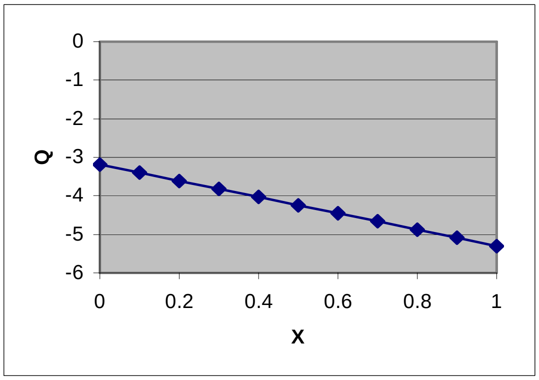
no	To	X	T	Xi	n1	n2	n3	n4	H0	H1	H2	H3	H4	Q
0.5	400	0.5	400	0.5	0.5	0.0	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
0.6	400	0.5	400	0.5	0.5	0.1	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
0.8	400	0.5	400	0.5	0.5	0.3	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.0	400	0.5	400	0.5	0.5	0.5	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653

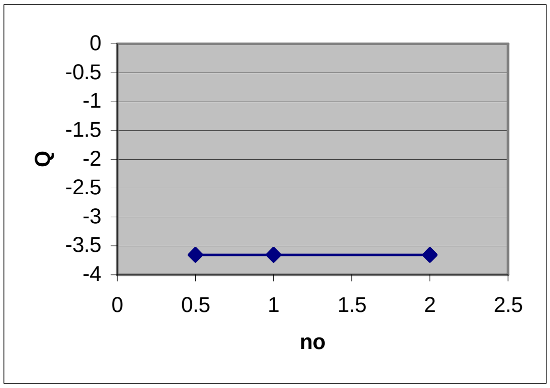
9.18 (cont'd)

1.2	400	0.5	400	0.5	0.5	0.7	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.4	400	0.5	400	0.5	0.5	0.9	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.6	400	0.5	400	0.5	0.5	1.1	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
1.8	400	0.5	400	0.5	0.5	1.3	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653
2.0	400	0.5	400	0.5	0.5	1.5	0.5	0.5	2.995	5.335	2.995	2.713	4.121	-3.653









9.19 **a.** Fermentor capacity : 550,000 gal

Solution volume : $(0.9\times 550{,}000) = 495{,}000$ gal

$$\text{Final reaction mixture}: \begin{cases} 0.071\text{ lb}_m\ C_2H_5OH/\text{lb}_m\text{ solution} \\ 0.069\text{ lb}_m\text{ (yeast, other species)}/\text{lb}_m\text{ solution} \\ 0.86\text{ lb }H_2O/\text{lb}_m\text{ solution} \end{cases}$$

$$\text{Mass of tank contents}: \frac{495{,}000\text{ gal}}{} \left| \frac{1\text{ ft}^3}{7.4805\text{ gal}} \right| \frac{65.52\text{ lb}_m}{1\text{ ft}^3} = 4335593\text{ lb}_m$$

$$\text{Mass of ethanol produced}: \frac{4.336\times 10^6\text{ lb}_m\text{ solution}}{} \left| \frac{0.071\text{ lb}_m\ C_2H_5OH}{\text{lb}_m\text{ solution}} \right. = \underline{\underline{3.078\times 10^5\text{ lb}_m\ C_2H_5}}$$

$$\Rightarrow \frac{3.078\times 10^5\text{ lb}_m\ C_2H_5OH}{} \left| \frac{1\text{ lb-mole }C_2H_5OH}{46.1\text{ lb}_m\ C_2H_5OH} \right. = 6677\text{ lb-mole }C_2H_5OH$$

$$\Rightarrow \frac{307827\text{ lb}_m\ C_2H_5OH}{} \left| \frac{1\text{ ft}^3\ C_2H_5OH}{49.67\text{ lb}_m\ C_2H_5OH} \right| \frac{7.4805\text{ gal}}{1\text{ ft}^3} = 46{,}360\text{ gal }C_2H_5OH$$

9.19 (cont'd)

$$\underline{\text{Makeup water required}}: 495{,}000\text{ gal } - \begin{array}{c|c} 46{,}360\text{ gal } C_2H_5OH & 25\text{ gal mash} \\ \hline & 2.6\text{ gal } C_2H_5OH \end{array} = \underline{\underline{4.9\times10^4\text{ gal}}}$$

b.

$$\underline{\text{Acres reqd.}}: \begin{array}{c|c|c|c|c|c} 46{,}360\text{ gal } C_2H_5OH & 1\text{ bu} & 1\text{ acre} & 1\text{ batch} & 24\text{ h} & 330\text{ days} \\ \hline 1\text{ batch} & 2.6\text{ gal } C_2H_5OH & 101\text{ bu} & 8\text{ h} & 1\text{ day} & 1\text{ year} \end{array} = \underline{\underline{1.75\times10^5\ \frac{\text{acres}}{\text{year}}}}$$

$$C_{12}H_{22}O_{11}(s) + 12O_2(g) \rightarrow 12CO_2(g) + 11H_2O(l) \qquad \Delta\hat{H}_c^o = -5649.1\text{ kJ / mol}$$

$$\Delta\hat{H}_c^o = 12\ \Delta\hat{H}_f^o(CO_2) + 11\Delta\hat{H}_f^o(H_2O) - \Delta\hat{H}_f^o(C_{12}H_{22}O_{11})$$

$$\Rightarrow \Delta\hat{H}_f^o(C_{12}H_{22}O_{11}) = -2217.14\text{ kJ / mol}$$

$$C_{12}H_{22}O_{11}(s) + H_2O(l) \rightarrow 4C_2H_5OH(l) + 4CO_2(g)$$

$$\Delta\hat{H}_r^o = 4\ \Delta\hat{H}_f^o(C_2H_5OH) + 4\ \Delta\hat{H}_f^o(CO_2) - \Delta\hat{H}_f^o(C_{12}H_{22}O_{11}) - \Delta\hat{H}_f^o(H_2O) = -184.5\text{kJ / mol}$$

c.

$$\Rightarrow \Delta\hat{H}_r^o = \begin{array}{c|c|c} -181.5\text{ kJ} & 453.6\text{ mol} & 0.9486\text{ Btu} \\ \hline 1\text{ mol} & 1\text{ lb - mole} & 1\text{ kJ} \end{array} = \underline{\underline{-7.811\times10^4\text{ Btu / lb - mole}}}$$

Moles of maltose:

$$\begin{array}{c|c|c|c} 4.336\times10^6\text{ lb}_m\text{ solution} & 0.071\text{ lb } C_2H_5OH & 1\text{ lb - mole } C_2H_5OH & 1\text{ lb - mole } C_{12}H_{22}O_{11} \\ \hline & 1\text{ lb}_m\text{ solution} & 46.1\text{ lb } C_2H_5OH & 4\text{ lb - mole } C_2H_5OH \end{array}$$

$$= 1669\text{ lb - moles } C_{12}H_{22}O_{11} \Rightarrow \xi = n_{C_{10}H_{22}O_{11}} = 1669\text{ lb - moles}$$

$$Q = \xi\Delta\hat{H}_r + mC_p(95^\circ\text{ F - }85^\circ\text{ F})$$

$$= (1669\text{ lb - moles})(-7.811\times10^4\ \frac{\text{Btu}}{\text{lb - mole}}) + (4.336\times10^6\text{lb}_m)(0.95\frac{\text{Btu}}{\text{lb -}^\circ\text{ F}})(10^\circ\text{ F})$$

d.

$$= \underline{\underline{-8.9\times10^7\text{ Btu}}} \quad \text{(heat transferred from reactor)}$$

Brazil has a shortage of natural reserves of petroleum, unlike Venezuela.

9.20 **a.**

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O,$$

$$2NH_3 + \frac{3}{2}O_2 \rightarrow N_2 + 3H_2O$$

References: $N_2(g)$, $H_2(g)$, $O_2(g)$, at 25°C

Substance	$\dot{n}_{in}$ (mol/min)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/min)	$\hat{H}_{out}$ (kJ/mol)
NH_3	100	$\hat{H}_1$	–	–
Air	900	$\hat{H}_2$	–	–
NO	–	–	90	$\hat{H}_3$
H_2O	–	–	150	$\hat{H}_4$
N_2	–	–	716	$\hat{H}_5$
O_2	–	–	69	$\hat{H}_6$

$$\hat{H}_i = \Delta\hat{H}_{fi}^o + \int_{25}^{T} C_{pi}dT$$

$$NH_3(g,\ 25^\circ C):\ \hat{H}_1 = (\Delta\hat{H}_f^o)_{NH_3} \overset{\overset{\text{Table B.1}}{\downarrow}}{=} \underline{\underline{-46.19\text{ kJ/mol}}}$$

9.20 (cont'd)

$$\text{Air(g, 150°C)}: \ \hat{H}_2 \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} \underline{\underline{3.67 \ \text{kJ/mol}}}$$

$$\text{NO(g, 700°C)}: \ \hat{H}_3 = 90.37 + \int_{25}^{700} C_p dT \overset{\substack{\text{Table B.1,Table B.2}\\ \downarrow}}{=} \underline{\underline{111.97 \ \text{kJ/mol}}}$$

$$\text{H}_2\text{O(g, 700°C)}: \ \hat{H}_4 \overset{\substack{\text{Table B.1,}\\ \text{Table B.8}\\ \downarrow}}{=} \underline{\underline{-216.91 \ \text{kJ/mol}}}$$

$$\text{N}_2\text{(g, 700°C)}: \ \hat{H}_5 \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} \underline{\underline{20.59 \ \text{kJ/mol}}}$$

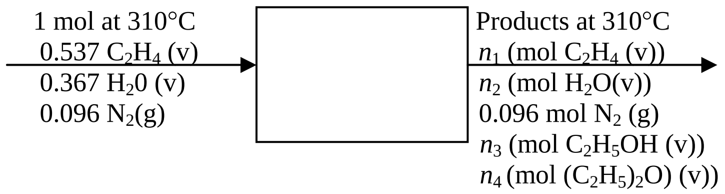
$$\text{O}_2\text{(g, 700°C)}: \ \hat{H}_6 \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} \underline{\underline{21.86 \ \text{kJ/mol}}}$$

b. $\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = -4890 \ \text{kJ/min} \times (1 \ \text{min} / 60\text{s}) = \underline{\underline{-81.5 \ \text{kW}}}$

(heat transferred from the reactor)

c. If molecular species had been chosen as references for enthalpy calculations, the extents of each reaction would have to be calculated and Equation 9.5-1b used to determine $\Delta\dot{H}$. The value of $\dot{Q}$ would remain unchanged.

9.21 **a.** Basis: 1 mol feed



$$C_2H_4(v) + H_2O(v) \Leftrightarrow C_2H_5OH(v)$$

$$2C_2H_5OH(v) \Leftrightarrow (C_2H_5)_2O(v) + H_2O(v)$$

5% ethylene conversion: $(0.537)(0.05) = 0.02685 \text{ mol } C_2H_4$ consumed

$$\Rightarrow n_1 = (0.95)(0.537) = 0.510 \text{ mol } C_2H_4$$

90% ethanol yield:

$$n_3 = \frac{0.02685 \text{ mol } C_2H_4 \text{ consumed}}{} \left| \frac{0.9 \text{ mol } C_2H_5OH}{1 \text{ mol } C_2H_4} \right. = 0.02417 \text{ mol } C_2H_5OH$$

C balance : $(2)(0.537) = (2)(0.510) + (2)(0.02417) + 4n_4 \Rightarrow n_4 = 1.415 \times 10^{-3} \text{ mol } (C_2H_5)_2O$

O balance : $0.367 = n_2 + 0.02417 + 1.415 \times 10^{-3} \Rightarrow n_2 = 0.3414 \text{ mol } H_2O$

9.21 (cont'd)

<u>References</u>: $C(s),\ H_2(g),\ O_2(g)$ at 25°C, $N_2(g)$ at 310°C

substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
C_2H_4	0.537	$\hat{H}_1$	0.510	$\hat{H}_1$
H_2O	0.367	$\hat{H}_2$	0.3414	$\hat{H}_2$
N_2	0.096	0	0.096	0
C_2H_5OH	–	–	0.02417	$\hat{H}_3$
$(C_2H_5)_2O$	–	–	1.415×10^{-3}	$\hat{H}_4$

$$\underline{C_2H_4(g,\ 310°C)}:\ \hat{H}_1 = (\Delta\hat{H}_f^o)_{C_2H_4} + \int_{25}^{310} C_p dT \underset{\substack{\text{Table B.1 for } \Delta\hat{H}_f^o \\ \text{Table B.2 for } C_p}}{\Rightarrow} (52.28+16.41) = 68.69\ \text{kJ/mol}$$

$$\underline{H_2O(g,\ 310°C)}:\ \hat{H}_2 = (\Delta\hat{H}_f^o)_{H_2O(v)} + \hat{H}_{H_2O(v)}(310°C) \underset{\substack{\text{Table B.1} \\ \text{Table B.8}}}{\Rightarrow} (-241.83+9.93) = -231.90\ \text{kJ/mol}$$

b.

$$\underline{C_2H_5OH(g,\ 310°C)}:\ \hat{H}_3 = (\Delta\hat{H}_f^o)_{C_2H_5OH(g)} + \int_{25}^{310} C_p dT \underset{\substack{\text{Table B.1} \\ \text{Table B.2}}}{\Rightarrow} (-235.31+24.16) = -211.15\ \text{kJ/mol}$$

$$\underline{(C_2H_5)_2O(g,\ 310°C)}:\ \hat{H}_4 = \left(\Delta\hat{H}_f^o\right)_{(C_2H_5)O(l)} + \Delta\hat{H}_v(25°C) + \int_{25}^{310} C_p dT = (-272.8+26.05+42.52)$$
$$= -204.2\ \text{kJ/mol}$$

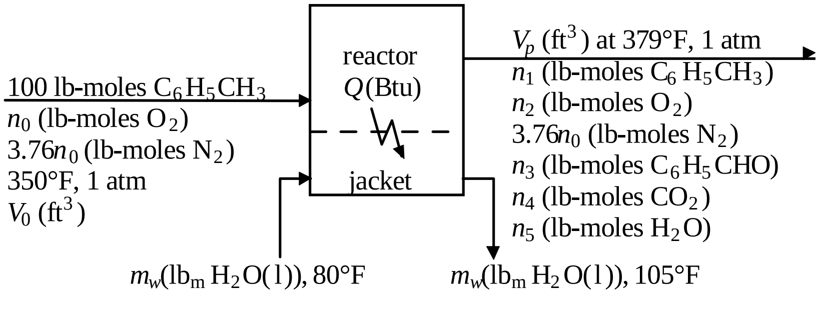
<u>Energy balance:</u> $Q = \Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = -1.3\ \text{kJ} \Rightarrow$ 1.3 kJ transferred from reactor/mol feed

To suppress the undesired side reaction. Separation of unconsumed reactants from products and recycle of ethylene.

9.22

$$C_6H_5CH_3 + O_2 \rightarrow C_6H_5CHO + H_2O$$
$$C_6H_5CH_3 + 9O_2 \rightarrow 7CO_2 + 4H_2O$$

<u>Basis</u>: 100 lb-mole of $C_6H_5CH_3$ fed to reactor.



<u>Strategy:</u>

All material and energy balances will be performed for the assumed basis of 100 lb-mole $C_6H_5CH_3$. The calculated quantities will then be scaled to the known flow rate of water in the product gas $(29.3\ \text{lb}_m/4\ \text{h})$.

9.22 (cont'd)

Plan of attack:		
	% excess air $\Rightarrow n_0$	Ideal gas equation of state $\Rightarrow V_0$
	13% C_6H_5CHO formation $\Rightarrow n_3$	Ideal gas equation of state $\Rightarrow V_p$
	0.5% CO_2 formation $\Rightarrow n_4$	E.B. on reactor $\Rightarrow Q$
	C balance $\Rightarrow n_1$	E.B. on jacket $\Rightarrow m_w$
	H balance $\Rightarrow n_5$	Scale V_0, V_p, Q, m_w by $(\dot{n}_5)$actual / (n_5)basis
	O balance $\Rightarrow n_2$	

<u>100% excess air:</u>

$$n_0 = \frac{100\text{ lb-moles }C_6H_5CH_3}{} \left| \frac{1\text{ mol }O_2\text{ reqd}}{1\text{ mole }C_6H_5CH_3} \right| \frac{(1+1)\text{mole }O_2\text{ fed}}{1\text{ mol }O_2\text{ reqd}} = 200\text{ lb-moles }O_2$$

<u>N_2 feed (& output)</u> $= 3.76(200)\text{lb-moles }N_2 = 752\text{ lb-moles }N_2$

<u>$13\% \to C_6H_5CHO$</u> $\Rightarrow n_3 = \dfrac{100\text{ lb-moles }C_6H_5CH_3}{} \left| \dfrac{0.13\text{ mole }C_6H_5CH_3\text{ react}}{1\text{ mole }C_6H_5CH_3\text{ fed}} \right| \dfrac{1\text{ mole }C_6H_5CHO\text{ formed}}{1\text{ mole }C_6H_5CH_3\text{ react}}$

$= 13\text{ lb-moles }C_6H_5CHO$

<u>$0.5\% \to CO_2$</u> $\Rightarrow n_4 = \dfrac{(100)(0.005)\text{lb-moles }C_6H_5CH_3\text{ react}}{} \left| \dfrac{7\text{ moles }CO_2}{1\text{ mole }C_6H_5CH_3} \right. = 3.5\text{ lb-moles }CO_2$

<u>C balance:</u> $(100)\overset{\substack{\text{mol C/mole }C_7H_8\\ \downarrow}}{(7)}\text{ lb-moles C} = 7n_1 + (13)(7) + (3.5)(1) \Rightarrow n_1 = 86.5\text{ lb-moles }C_6H_5CH_3$

<u>H balance:</u> $(100)(8)\text{lb-moles H} = (86.5)(8) + (13)(6) + 2n_5 \Rightarrow n_5 = 15.0\text{ lb-moles }H_2O(v)$

<u>O balance:</u> $(200)(2)\text{lb-moles O} = 2n_2 + (13)(1) + (3.5)(2) + (15)(1) \Rightarrow n_2 = 182.5\text{ lb-moles }O_2$

<u>Ideal gas law – inlet:</u>

$$V_0 = \frac{(100+200+752)\text{lb-moles}}{} \left| \frac{359\text{ ft}^3(\text{STP})}{1\text{ lb-moles}} \right| \frac{(350+460)^\circ\text{R}}{492^\circ\text{R}} = 6.218\times10^5\text{ ft}^3$$

<u>Ideal gas law – outlet:</u>

$$V_p = \frac{\left(\overset{C_7H_8}{86.5} + \overset{O_2}{182.5} + \overset{C_7H_8O}{13} + \overset{CO_2}{3.5} + \overset{H_2O}{15} + \overset{N_2}{752}\right)\text{lb-moles}}{} \left| \frac{359\text{ ft}^3}{1\text{ lb-mole}} \right| \frac{(379+460)^\circ\text{R}}{492^\circ\text{R}} = 6.443\times10^5\text{ ft}^3$$

9.22 (cont'd)

Energy balance on reactor (excluding cooling jacket)

References : C(s), $H_2(g)$, $O_2(g)$, $N_2(g)$ at $25^\circ C(77^\circ F)$

substance	n_{in} (lb-moles)	$\hat{H}_{in}$ (Btu/lb-mole)	n_{out} (lb-moles)	$\hat{H}_{out}$ (Btu/lb-mole)
$C_6H_5CH_3$	100	$\hat{H}_1$	86.5	$\hat{H}_4$
O_2	200	$\hat{H}_2$	182.5	$\hat{H}_5$
N_2	752	$\hat{H}_3$	752	$\hat{H}_6$
C_6H_5CHO	–	–	13	$\hat{H}_7$
CO_2	–	–	3.5	$\hat{H}_8$
H_2O	–	–	15	$\hat{H}_9$

Enthalpies:

$$C_6H_5CH_3(g,T):\ \hat{H}(T)=\left[\overset{\substack{\text{Table B.1}\\ \downarrow}}{\Delta\hat{H}_f^o}\,(\text{kJ/mol})\times\frac{430.28\ \text{Btu/lb-mole}}{1\ \text{kJ/mol}}+31\frac{\text{Btu}}{\text{1b-mole}\cdot{}^\circ\text{F}}(T-77)^\circ\text{F}\right]$$

$$C_6H_5CH_3(g{,}350^\circ F):\hat{H}_1=2.998\times10^4\ \text{Btu/lb-mole}$$

$$C_6H_5CH_3(g{,}379^\circ F):\hat{H}_4=3.088\times10^4\ \text{Btu/lb-mole}$$

$$C_6H_5CHO(g,T):\ \hat{H}(T)=\left[-17200+31(T-77)^\circ\text{F}\right]\ \text{Btu/lb-mole}$$

$$\Rightarrow\hat{H}_7=-7.83\times10^3\ \text{Btu/lb-mole}$$

$$O_2(g{,}350^\circ F):\ \hat{H}_2=\hat{H}_{O_2}(350^\circ F)\ \overset{\substack{\text{Table B.9}\\ \downarrow}}{=}\ 1.972\times10^3\ \text{Btu / lb – mole}$$

$$N_2(g{,}350^\circ F):\ \hat{H}_3=\hat{H}_{N_2}(350^\circ F)\ \overset{\substack{\text{Table B.9}\\ \downarrow}}{=}\ 1.911\times10^3\ \text{Btu / lb – mole}$$

$$O_2(g{,}379^\circ F):\ \hat{H}_5=\hat{H}_{O_2}(379^\circ F)\ \overset{\substack{\text{Table B.9}\\ \downarrow}}{=}\ 2.186\times10^3\ \text{Btu / lb – mole}$$

$$N_2(g{,}379^\circ F):\ \hat{H}_6=\hat{H}_{N_2}(379^\circ F)\ \overset{\substack{\text{Table B.9}\\ \downarrow}}{=}\ 2.116\times10^3\ \text{Btu / lb – mole}$$

$$CO_2(g{,}379^\circ F):\ \hat{H}_8=(\Delta\hat{H}_f^\circ)_{CO_2(g)}+\hat{H}_{CO_2}(379^\circ F)\ \overset{\substack{\text{Table B.1 and B.9}\\ \downarrow}}{=}\ -1.664\times10^5\ \text{Btu / lb – mole}$$

$$H_2O(g{,}379^\circ F):\ \hat{H}_9=(\Delta\hat{H}_f^\circ)_{H_2O(g)}+\hat{H}_{H_2O}(379^\circ F)\ \overset{\substack{\text{Table B.1 and B.9}\\ \downarrow}}{=}\ -1.016\times10^5\ \text{Btu / lb – mole}$$

Energy Balance :

$$Q=\Delta H=\sum_{\text{out}}n_i\hat{H}_i-\sum_{\text{in}}n_i\hat{H}_i=-2.376\times10^6\ \text{Btu}$$

Energy balance on cooling jacket:

$$Q=\Delta H=m_w\int_{80}^{105}\left(C_p\right)_{H_2O(l)}dT$$

$$\Downarrow\quad Q=+2.376\times10^4\ \text{Btu},\ C_p=1.0\ \text{Btu/(lb}_m\cdot{}^\circ\text{ F)}$$

$$2.376\times10^6\,\text{Btu}=m_w(\text{lb}_m)\times1.0\frac{\text{Btu}}{\text{lb}_m\cdot{}^\circ\text{F}}\times(105-80)^\circ\text{F}\ \Rightarrow\ m_w=9.504\times10^4\ \text{lb}_m\ H_2O(l)$$

9.22(cont'd)

$$\underline{\text{Scale factor}}:\ \frac{(\dot{n}_5)_{\text{actual}}}{(n_5)_{\text{basis}}}=\frac{29.3\ \text{lb}_\text{m}\ \text{H}_2\text{O}}{4\ \text{h}}\bigg|\frac{1\text{b - mole H}_2\text{O}}{18.016\ \text{lb}_\text{m}\ \text{H}_2\text{O}}\bigg|\frac{1}{15.0\ \text{lb - moles H}_2\text{O}}=0.02711\ \text{h}^{-1}$$

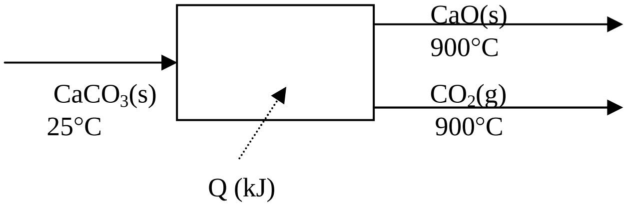
a. $V_0=\left(6.218\times10^5\ \text{ft}^3\right)\left(0.02711\ \text{h}^{-1}\right)=\underline{\underline{1.69\times10^4\ \ \text{ft}^3/\text{h}\ \ (\text{feed})}}$

$V_p=\left(6.443\times10^5\ \text{ft}^3\right)\left(0.02711\ \text{h}^{-1}\right)=\underline{\underline{1.75\times10^4\ \ \text{ft}^3/\text{h}\ \ (\text{product})}}$

b. $Q=\left(-2.376\times10^6\ \text{Btu}\right)\left(0.02711\ \text{h}^{-1}\right)=\underline{\underline{-6.44\times10^4\ \text{Btu / h}}}$

$$\dot{m}_w=\left(9.504\times10^4\ \text{Btu}\right)\left(0.02711\ \text{h}^{-1}\right)=\frac{2577\ \text{lb}_\text{m}}{\text{h}}\bigg|\frac{1\ \text{ft}^3}{62.4\ \text{lb}_\text{m}}\bigg|\frac{7.4805\ \text{gal}}{1\ \text{ft}^3}\bigg|\frac{1\ \text{h}}{60\ \text{min}}=\underline{\underline{5.15\ \text{gal}\ \ \text{H}_2\text{O}/\text{min}}}$$

9.23 **a.** $\text{CaCO}_3(\text{s})\rightarrow\text{CaO(s)}\ +\text{CO}_2(\text{g})$



$$\underline{\text{Basis}}: 1000\ \text{kg CaCO}_3=\frac{1000\ \text{kg}}{}\bigg|\frac{1\ \text{mol}}{0.100\ \text{kg}}=10.0\ \text{kmol CaCO}_3\Rightarrow\begin{array}{l}10.0\ \text{kmol CaO(s) produced}\\10.0\ \text{kmol CO}_2(\text{g})\ \text{produced}\\10.0\ \text{kmol CaCO}_3(\text{s})\ \text{fed}\end{array}$$

<u>References</u>: Ca(s), C(s), O_2(g) at 25°C

Substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ/mol)
$CaCO_3$	10^4	$\hat{H}_1$	–	–
CaO	–	–	10^4	$\hat{H}_2$
CO_2	–	–	10^4	$\hat{H}_3$

$$\text{CaCO}_3(\text{s, } 25^\text{o}\text{C}):\hat{H}_1=(\Delta\hat{H}_\text{f}^\text{o})_{\text{CaCO}_3(\text{s})}\overset{\substack{\text{Table B.1}\\\downarrow}}{=}-1206.9\ \text{kJ / mol}$$

$$\text{CaO(s, } 900^\text{o}\text{C}):\hat{H}_2=(\Delta\hat{H}_\text{f}^\text{o})_{\text{CaO(s)}}+\int_{298}^{1173}C_p\text{dT}\overset{\substack{\text{Table B.1,}\\\text{Table B.2}\\\downarrow}}{=}(-635.6+48.54)\ \text{kJ / mol}=-587.06\ \text{kJ / mol}$$

$$\text{CO}_2(\text{g, } 900^\text{o}\text{C}):\hat{H}_3=(\Delta\hat{H}_\text{f}^\text{o})_{\text{CO}_2(\text{g})}+\hat{H}_{\text{CO}_2}(900^\text{o}\text{C})\overset{\substack{\text{Table B.1,}\\\text{Table B.8}\\\downarrow}}{=}(-393.5+42.94)\ \text{kJ / mol}=-350.56\ \text{kJ / mol}$$

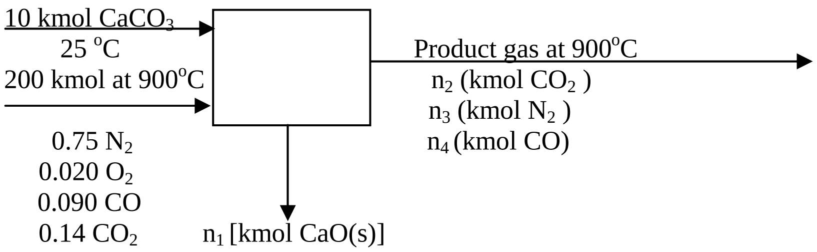
$$\underline{\text{Energy balance}}:\ \ Q=\Delta H=\left(\sum_{\text{out}}n_\text{i}\hat{H}_\text{i}-\sum_{\text{in}}n_\text{i}\hat{H}_\text{i}\right)=\ \underline{\underline{2.7\times10^6\ \text{kJ}}}$$

9.23 (cont'd)

b. Basis : 1000 kg $CaCO_3$ fed $\Rightarrow$ 10.0 kmol $CaCO_3$

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

$$2CO + O_2 \rightarrow 2CO_2$$



10 kmol $CaCO_3$ react $\Rightarrow n_1 = 10.0$ kmol CaO

$$n_2 = (0.14)(200) + \frac{10.0 \text{ kmol } CaCO_3 \text{ react}}{} \left| \frac{1 \text{ kmol } CO_2}{1 \text{ kmol } O_2} \right. + \frac{4 \text{ kmol } O_2 \text{ react}}{} \left| \frac{2 \text{ kmol } CO_2}{1 \text{ kmol } O_2} \right. = 46 \text{ kmol } CO_2$$

$$n_3 = (0.75)(200) = 150 \text{ kmol } N_2$$

C balance: $(10.0)(1) + (200)(0.09)(1) + (200)(0.14)(1) = 46(1) + n_4(1) \Rightarrow n_4 = 10.0$ kmol CO

References : Ca(s), C(s), O_2(g), N_2(g) at 25°C

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
$CaCO_3$	10.0	$\hat{H}_1$	–	–
CaO	–	–	10	–587.06
CO_2	28	–350.56	46	–350.56
CO	18	$\hat{H}_2$	10	$\hat{H}_2$
O_2	4.0	$\hat{H}_3$	–	–
N_2	150	$\hat{H}_4$	150	$\hat{H}_4$

$$CaCO_3(\text{s, }25^\circ\text{C}) : \hat{H}_1 = (\Delta\hat{H}_f^o)_{CaCO_3(s)} \overset{\text{Table B.1}}{\overset{\downarrow}{=}} -1206.9 \text{ kJ/mol}$$

$$CO(\text{g, }900^\circ\text{C}) : \hat{H}_1 = (\Delta\hat{H}_f^o)_{CO(g)} + \hat{H}_{CO}(900^\circ\text{C}) \overset{\text{Table B.1, Table B.8}}{\overset{\downarrow}{=}} (-110.52 + 27.49) \text{ kJ/mol} = -83.03 \text{ kJ/mol}$$

$$O_2(\text{g, }900^\circ\text{C}) : \hat{H}_2 = \hat{H}_{O_2}(900^\circ\text{C}) \overset{\text{Table B.8}}{\overset{\downarrow}{=}} 28.89 \text{ kJ/mol}$$

$$N_2(\text{g, }900^\circ\text{C}) : \hat{H}_3 = \hat{H}_{N_2}(900^\circ\text{C}) \overset{\text{Table B.8}}{\overset{\downarrow}{=}} 27.19 \text{ kJ/mol}$$

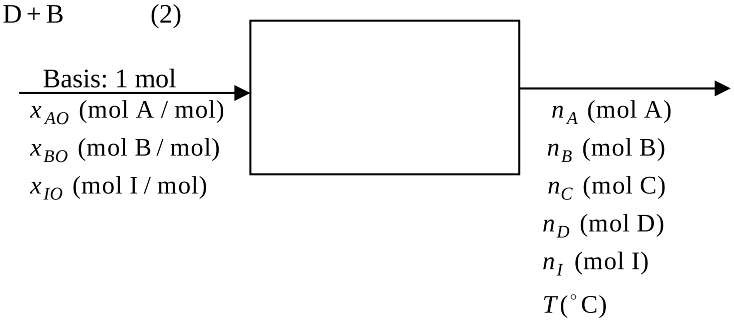
$$Q = \Delta H = \left(\sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i \right) = 0.44 \times 10^6 \text{ kJ}$$

$$\% \text{ reduction in heat requirement } = \left| \frac{2.7 \times 10^6 - 0.44 \times 10^6}{2.7 \times 10^6} \right| \times 100 = 83.8\%$$

c. The hot combustion gases raise the temperature of the limestone, so that less heat from the outside is needed to do so. Additional thermal energy is provided by the combustion of CO.

9.24 **a.** $A+B \rightarrow C$ (1)

$2C \rightarrow D+B$ (2)



Fractional conversion: $f_A = \dfrac{\text{mol A consumed}}{\text{mol A feed}} = \dfrac{x_{AO}-n_A}{x_{AO}} \Rightarrow \underline{\underline{n_A = x_{AO}(1-f_A)}}$

C generated: $n_0 = \begin{array}{c|c|c} x_{A0}(\text{mol A fed}) & f_A(\text{mol A consumed}) & Y_C(\text{mol C generated}) \\ \hline & \text{mol A fed} & \text{mol A consumed} \end{array}$

$\Rightarrow \underline{\underline{n_C = x_{AO} f_A Y_C}}$

D generated: $n_D = 0.5 \times \text{mol C consumed} = (1/2) \times (\text{mol A consumed } - \text{mol C out})$

$\Rightarrow \underline{\underline{n_D = (1/2)(x_{AO} f_A - n_C)}}$

Balance on B: mol B out = mol B in – mol B consumed in (1) + mol B generated in (2)

= mol B in – mol A consumed in (1) + mol D generated in (2)

$\Rightarrow \underline{\underline{n_B = x_{BO} - x_{AO} f_A + n_D}}$

Balance on I: mol I out = mol I in $\Rightarrow \underline{\underline{n_I = x_{IO}}}$

b.

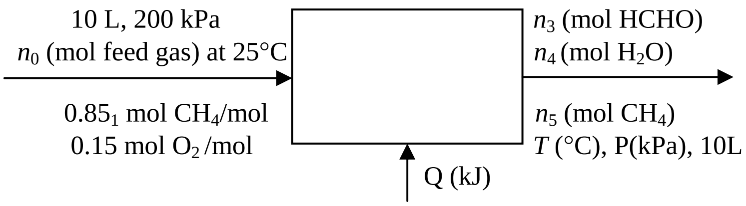
Species	**Formula**	**DHf**	**a**	**b**	**c**	**d**
A	C2H4(v)	52.28	0.04075	1.15E-04	-6.89E-08	1.77E-11
B	H2O(v)	-241.83	0.03346	6.88E-06	7.60E-09	-3.59E-12
C	C2H5OH(v)	-235.31	0.06134	1.57E-04	-8.75E-08	1.98E-11
D	C4H10)O(v	-246.75	0.08945	4.03E-04	-2.24E-07	0
I	N2(g)	0	0.02900	2.20E-05	5.72E-09	-2.87E-12

Tf	**Tp**	**xA0**	**xB0**	**xI0**	**fA**	**YC**
310	310	0.537	0.367	0.096	0.05	0.90

Species	**n(in) (mol)**	**H(in) (kJ/mol)**	**n(out) (mol)**	**H(out) (kJ/mol)**
A	0.537	68.7	0.510	68.7
B	0.367	-231.9	0.341	-231.9
C	0	-211.2	0.024	-211.2
D	0	-204.2	0.001	-204.2
I	0.096	9.4	0.096	9.4
Q(kJ) =	**-1.31**			

c. For $T_f = 125^\circ C$, $Q = \underline{\underline{7.90 \text{ kJ}}}$. Raising T_p, lowering f_A, and raising Y_C all increase Q.

9.25 **a.** $CH_4(g) + O_2(g) \rightarrow HCHO(g) + H_2O(g)$



$$\underline{\text{Basis}}: n_0 = \frac{200\text{ kPa}}{} \left| \frac{1000\text{ Pa}}{1\text{ kPa}} \right| \frac{10\text{ L}}{} \left| \frac{10^{-3}\text{ m}^3}{1\text{ L}} \right| \frac{1\text{ mol K}}{8.314\text{ m}^3\text{ Pa}} \left| \frac{}{298\text{ K}} \right.$$

$$= 0.8072\text{ mol feed gas mixture}$$

$$\underline{0.8072\text{ mol feed gas mixture}} \Rightarrow (0.85)(0.8072) = 0.6861\text{ mol }CH_4,$$

$$\Rightarrow (0.15)(0.8072) = 0.1211\text{ mol }O_2$$

$$\underline{CH_4\text{ consumed}}: \frac{1\text{ mol }CH_4}{1\text{ mol }O_2\text{ fed}} \left| \frac{0.1211\text{ mol }O_2\text{ fed}}{} \right. = 0.1211\text{ mol }CH_4$$

$$\Rightarrow n_5 = (0.6861 - 0.1211)\text{ mol }CH_4 = 0.5650\text{ mol }CH_4$$

$$\underline{\text{HCHO produced}}: n_3 = \frac{1\text{ mol HCHO}}{1\text{ mol }CH_4\text{ consumed}} \left| \frac{0.1211\text{ mol }CH_4\text{ consumed}}{} \right. = 0.1211\text{ mol HCHO}$$

$$\underline{H_2O\text{ produced}}: n_4 = \frac{1\text{ mol }H_2O}{1\text{ mol }CH_4\text{ consumed}} \left| \frac{0.1211\text{ mol }CH_4\text{ consumed}}{} \right. = 0.1211\text{ mol }H_2O$$

$$\underline{\text{Extent of reaction}}: \xi = \frac{\left|(n_{O_2})_{\text{out}} - (n_{O_2})_{\text{in}}\right|}{\left|\nu_{O_2}\right|} = \frac{|0 - 0.1211|}{|1|} = 0.1211\text{ mol}$$

$\underline{\text{References}}$: $CH_4(g)$, $O_2(g)$, HCHO(g), $H_2O(g)$, at $25^{\circ}C$

Substance	n_{in} mol	$\hat{U}_{\text{in}}$ kJ/mol	n_{out} mol	$\hat{U}_{\text{out}}$ kJ/mol
CH_4	0.6861	0	0.5650	$\hat{U}_1$
O_2	0.1211	0	–	–
HCHO	–	–	0.1211	$\hat{U}_2$
H_2O	–	–	0.1211	$\hat{U}_3$

$$\hat{U}_i = \int_{25}^{T} (C_v)_i\, dT = \int_{25}^{T} (C_p - R)_i\, dT \quad i = 1,2,3$$

Using $(C_p)_i$ from Table B.2 and $R = 8.314 \times 10^{-3}$ kJ / mol·K:

$$\hat{U}_1 = (0.02599\ T + 2.7345 \times 10^{-5}\ T^2 + 0.1220 \times 10^{-8}\ T^3 - 2.75 \times 10^{-12}\ T^4 - 0.6670)\text{ kJ / mol}$$

$$\hat{U}_2 = (0.02597\ T + 2.1340 \times 10^{-5}\ T^2 - 2.1735 \times 10^{-12}\ T^4 - 0.6623)\text{ kJ / mol}$$

$$\hat{U}_3 = (0.02515\ T + 0.3440 \times 10^{-5}\ T^2 + 0.2535 \times 10^{-8}\ T^3 - 0.8983 \times 10^{-12}\ T^4 - 0.6309)\text{ kJ / mol}$$

9.25 (cont'd)

$$Q = \begin{array}{c|c|c} 100\text{ J} & 85\text{ s} & 1\text{ kJ} \\ \hline \text{s} & & 1000\text{ J} \end{array} = 8.5\text{ kJ}$$

$$\Delta\hat{H}_r^o = (\Delta\hat{H}_f^o)_{\text{HCHO}} + (\Delta\hat{H}_f^o)_{\text{H}_2\text{O}} - (\Delta\hat{H}_f^o)_{\text{CH}_4} \overset{\text{Table B.1}}{\overset{\downarrow}{=}} \big((-115.90) + (-241.83) - (-74.85)\big)\text{ kJ / mol}$$

$$= -282.88\text{ kJ / mol}$$

$$\Delta\hat{U}_r^o = \Delta\hat{H}_r^o - RT\Big(\sum_{\substack{\text{gaseous}\\ \text{products}}} \nu_i - \sum_{\substack{\text{gaseous}\\ \text{reactants}}} \nu_i\Big)$$

$$= -282.88\text{ kJ / mol} - \begin{array}{c|c|c|c} 8.314\text{ J} & 298\text{ K} & (1+1-1-1) & 1\text{ kJ} \\ \hline \text{mol K} & & & 10^3\text{ J} \end{array} = -282.88\text{ kJ / mol}$$

$\underline{\text{Energy Balance}}$:

$$Q = \xi\Delta\hat{U}_r^o + \sum (n_i)_{\text{out}}(\hat{U}_i)_{\text{out}} - \sum (n_i)_{\text{in}}(\hat{U}_i)_{\text{in}}$$

$$= (0.1211)(-282.88\text{ kJ/mol}) + 0.5650\,\hat{U}_1 + 0.1211\,\hat{U}_2 + 0.1211\,\hat{U}_3$$

Substitute for $\hat{U}_1$ through $\hat{U}_3$ and Q

$$0 = 0.02088\,T + 1.845\times10^{-5}\,T^2 + 0.09963\times10^{-8}\,T^3 - 1.926\times10^{-12}\,T^4 - 43.29\text{ kJ / mol}$$

Solve for T using E - Z Solve $\Rightarrow T = 1091^\circ\text{C} = 1364\text{ K}$

$$\Rightarrow P = nRT/V = \begin{array}{c|c|c|c} 0.8072\text{ mol} & 8.314\text{ m}^3\cdot\text{Pa} & 1364\text{ K} & 1\text{ L} \\ \hline & \text{mol}\cdot\text{K} & 10\text{ L} & 10^{-3}\text{m}^3 \end{array} = 915\times10^3\text{ Pa} = \underline{\underline{915\text{ kPa}}}$$

b. Add heat to raise the reactants to a temperature at which the reaction rate is significant.

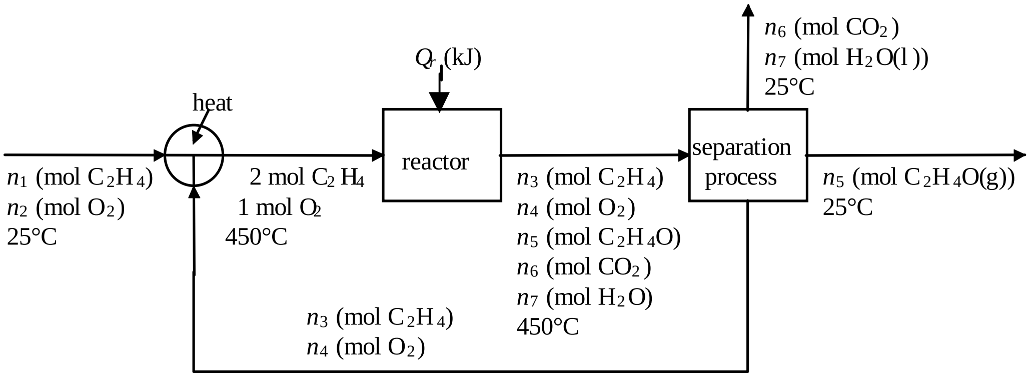
c. $\underline{\underline{\text{Side reaction}}}$: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. T would have been higher (more negative heat of reaction for combustion of methane), volume and total moles would be the same, therefore $P = nRT/V$ would be $\underline{\underline{\text{greater}}}$.

9.26 **a.**

Basis: 2 mol C_2H_4 fed to reactor

$$C_2H_4(g)+\frac{1}{2}O_2(g)\rightarrow C_2H_4O(g)$$

$$C_2H_4+3O_2\rightarrow 2CO_2+2H_2O$$



25% conversion $\Rightarrow 0.500$ mol C_2H_4 consumed $\Rightarrow n_3=\underline{\underline{1.50 \text{ mol } C_2H_4}}$

70% yield $\Rightarrow n_5=\dfrac{0.500 \text{ mol } C_2H_4 \text{ consumed}}{}\bigg|\dfrac{0.700 \text{ mol } C_2H_4O}{1 \text{ mol } C_2H_4}=\underline{\underline{0.350 \text{ mol } C_2H_4O}}$

C balance on reactor: $(2)(2)=(2)(1.50)+(2)(0.350)+n_6\Rightarrow n_6=\underline{\underline{0.300 \text{ mol } CO_2}}$

Water formed: $n_7=\dfrac{0.300 \text{ mol } CO_2}{}\bigg|\dfrac{1 \text{ mol } H_2O}{1 \text{ mol } CO_2}=\underline{\underline{0.300 \text{ mol } H_2O}}$

O balance on reactor: $(2)(1)=2n_4+0.350+(2)(0.300)+0.300\Rightarrow n_4=\underline{\underline{0.375 \text{ mol } O_2}}$

Overall C balance: $2n_1=n_6+2n_5=0.300+(2)(0.350)\Rightarrow n_1=\underline{\underline{0.500 \text{ mol } C_2H_4}}$

Overall O balance: $2n_2=2n_6+n_7+n_5=(2)(0.300)+(0.300)+(0.350)\Rightarrow n_2=\underline{\underline{0.625 \text{ mol } O_2}}$

Feed stream: 44.4% C_2H_4, 55.6% O_2 Reactor inlet: 66.7% C_2H_4, 33.3% O_2

Recycle stream: 80.0% C_2H_4, 20.0% O_2

Reactor outlet: 53.1% C_2H_4, 13.3% O_2, 12.4% C_2H_4O, 10.6% CO_2, 10.6% H_2O

Mass of ethylene oxide $=\dfrac{0.350 \text{ mol } C_2H_4O}{}\bigg|\dfrac{44.05 \text{ g}}{1 \text{ mol}}\bigg|\dfrac{1 \text{ kg}}{10^3 \text{ g}}=0.0154$ kg

b. References for enthalpy calculations: $C(s)$, $H_2(g)$, $O_2(g)$ at 25° C

$$\hat{H}_i(T)=\Delta\hat{H}_{fi}^o+\int_{25}^{T}C_p dT \text{ for } C_2H_4$$

$$=\Delta\hat{H}_f^0+\int_{298}^{T+273}C_p dT \text{ for } C_2H_4O$$

$$\left.\begin{array}{l}=\Delta\hat{H}_{fi}^o+\hat{H}_i(\text{table B.8})\\ =\Delta\hat{H}_f^o \text{ for } H_2O(l)\end{array}\right. \text{ for } O_2,\ CO_2,\ H_2O(g)$$

9.26 (cont'd)

Overall Process

Substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ / mol)
C_2H_4	0.500	52.28	–	–
O_2	0.625	0	–	–
C_2H_4O	–	–	0.350	–51.00
CO_2	–	–	0.300	–393.5
$H_2O(l)$	–	–	0.300	–285.84

Reactor

substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ / mol)
C_2H_4	2	79.26	1.50	79.26
O_2	1	13.37	0.375	13.37
C_2H_4O	–	–	0.350	–19.99
CO_2	–	–	0.300	–374.66
$H_2O(g)$	–	–	0.300	–226.72

Energy balance on process: $Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = \underline{\underline{-248 \text{ kJ}}}$

Energy balance on reactor: $Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = \underline{\underline{-236 \text{ kJ}}}$

c. Scale to 1500 kg C_2H_4O/day:

C_2H_4O production for initial basis $= (0.350 \text{ mol})\left(\frac{44.05 \text{ kg}}{10^3 \text{ mol}}\right) = 0.01542 \text{ kg } C_2H_4O$

$$\Rightarrow \text{Scale factor} = \frac{1500 \text{ kg/day}}{0.01542 \text{ kg}} = 9.73 \times 10^4 \text{ day}^{-1}$$

In initial basis, fresh feed contains
0.500 mol C_2H_4
0.625 mol O_2

$$\overline{M} = (0.500)(28.05 \text{ g } C_2H_4/\text{mol}) + (0.625)(32.0 \text{ g } O_2/\text{mol}) = 34.025 \times 10^{-3} \text{ kg}$$

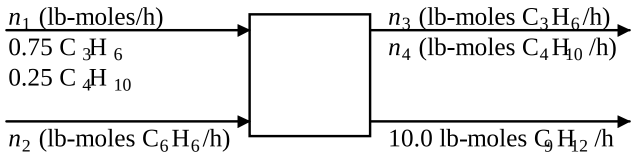
Fresh feed rate $= (34.025 \times 10^{-3} \text{ kg})(9.73 \times 10^4 \text{ day}^{-1}) = \underline{\underline{3310 \text{ kg/day } (44.4\% \ C_2H_4,\ 55.6\% \ O_2)}}$

$$Q_{\text{process}} = \frac{(-248 \text{ kJ})(9.73 \times 10^4 \text{ day}^{-1})}{} \left| \frac{1 \text{ day}}{24 \text{ hr}} \right| \frac{1 \text{ hr}}{3600 \text{ s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right. = \underline{\underline{-279 \text{ kW}}}$$

$$Q_{\text{reactor}} = \frac{(-236 \text{ kJ})(9.73 \times 10^4 \text{ day}^{-1})}{} \left| \frac{1 \text{ day}}{24 \text{ hr}} \right| \frac{1 \text{ hr}}{3600 \text{ s}} \left| \frac{1 \text{ kW}}{1 \text{ kJ/s}} \right. = \underline{\underline{-265 \text{ kW}}}$$

9.27 **a.** $$\underline{\text{Basis}}:\ \frac{1200\ \text{lb}_\text{m}\ \text{C}_9\text{H}_{12}}{\text{h}}\bigg|\frac{1\ \text{lb-mole}}{120\ \text{lb}_\text{m}} = 10.0\ \text{lb-moles cumene produced/h}$$

<u>Overall process :</u>



$$\text{C}_3\text{H}_6(\text{l})+\text{C}_6\text{H}_6(\text{l})\rightarrow \text{C}_9\text{H}_{12}(\text{l}),\qquad \Delta\hat{H}_\text{r}(77°\,\text{F}) = -39520\ \text{Btu/lb-mole}$$

$$\underset{(\text{input=consumption})}{\underline{\text{Benzene balance:}}}\ \dot{n}_2 = \frac{10.0\ \text{lb-moles C}_9\text{H}_{12}\ \text{produced}}{\text{h}}\bigg|\frac{1\ \text{mole C}_6\text{H}_6\ \text{consumed}}{1\ \text{mole C}_9\text{H}_{12}\,\text{produced}}$$

$$= \frac{10.0\ \text{lb-moles C}_6\text{H}_6}{\text{h}}\bigg|\frac{78.1\ \text{lb}_\text{m}\ \text{C}_6\text{H}_6}{1\ \text{lb-mole}} = \underline{\underline{781\ \text{lb}_\text{m}\ \text{C}_6\text{H}_6/\text{h}}}$$

$$\underset{(\text{input=output+consumption})}{\underline{\text{Propylene balance:}}}\ 0.75\dot{n}_1 = \dot{n}_3 + \frac{10.0\ \text{lb-moles C}_9\text{H}_{12}}{\text{h}}\bigg|\frac{1\ \text{mole C}_3\text{H}_6}{1\ \text{mole C}_9\text{H}_{12}}$$

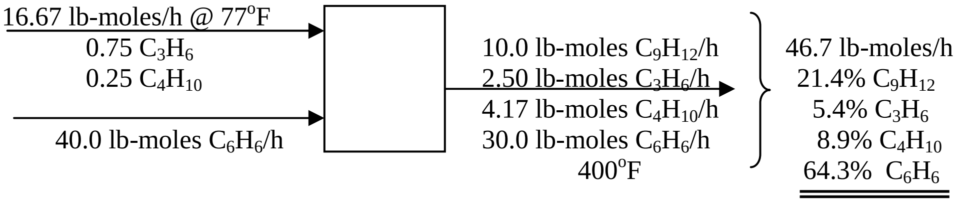
$$\left.\begin{array}{r}\Rightarrow 0.75\dot{n}_1 = \dot{n}_3 + 10\\ \underline{20\%\ \text{C}_3\text{H}_6\ \text{unreacted}}\Rightarrow \dot{n}_3 = 0.20(0.75\dot{n}_1)\end{array}\right\}\Rightarrow\quad \begin{array}{l}\dot{n}_1 = 16.67\ \text{lb-moles/h}\\ \dot{n}_3 = 2.50\ \text{lb-moles C}_3\text{H}_6/\text{h}\end{array}$$

$$\underline{\text{Mass flow rate of C}_3\text{H}_6\ /\ \text{C}_4\text{H}_{10}\ \text{feed}} = \frac{(0.75)(16.67)\text{lb-moles C}_3\text{H}_6}{\text{h}}\bigg|\frac{42.08\ \text{lb}_\text{m}\ \text{C}_3\text{H}_6}{1\ \text{lb-mole}}$$

$$+\frac{(0.25)(16.67)\text{lb-moles C}_4\text{H}_{10}}{\text{h}}\bigg|\frac{58.12\ \text{lb}_\text{m}\ \text{C}_4\text{H}_{10}}{1\ \text{lb-mole}} = \underline{\underline{768\ \text{lb}_\text{m}/\text{h}}}$$

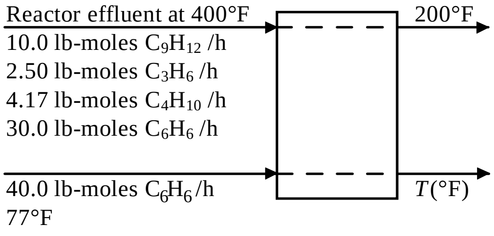
<u>Reactor :</u>

$$\underline{\text{Benzene feed rate}} = \frac{10.0\ \text{lb-moles fresh feed}}{\text{h}}\bigg|\frac{(3+1)\text{moles fed to reactor}}{1\ \text{mole fresh feed}} = 40\ \text{lb-moles C}_6\text{H}_6/\text{h}$$



$$\underline{\text{Overhead from T1}} \Rightarrow \left.\begin{array}{r}2.50\ \text{lb-moles C}_3\text{H}_6/\text{h}\\ 4.17\ \text{lb-moles C}_4\text{H}_{10}/\text{h}\end{array}\right\}\Rightarrow \begin{array}{l}\underline{\underline{6.67\ \text{lb-moles/h}}}\\ \underline{\underline{37.5\%\ \text{C}_3\text{H}_6}}\\ \underline{\underline{62.5\%\ \text{C}_4\text{H}_{10}}}\end{array}$$

b. <u>Heat exchanger :</u>



9.27 (cont'd)

Energy balance: $\Delta H = 0 \Rightarrow \sum n_i\left(\hat{H}_{i,\text{ out}} - \hat{H}_{i,\text{ in}}\right) = \sum n_i C_{pi}\left(T_{\text{out}} - T_{\text{in}}\right)_i = 0$

(Assume adiabatic)

$$\left[\frac{10\text{ lb-moles C}_9\text{H}_{12}}{\text{h}}\left|\frac{120\text{ lb}_\text{m}}{1\text{ lb-mole}}\right|\frac{0.40\text{ Btu}}{1\text{b}_\text{m}\cdot{}^\circ\text{ F}}\right]\left(200^\circ\text{ F}-400^\circ\text{ F}\right)+\overset{\overset{\text{C}_3\text{H}_6}{\downarrow}}{(2.50)}(42.08)(0.57)\left(200^\circ\text{ F}-40\right.$$

$$+\overset{\overset{\text{C}_4\text{H}_{10}}{\downarrow}}{(4.17)}(58.12)(0.55)\left(200^\circ\text{ F}-400^\circ\text{ F}\right)+\underset{\underset{\text{C}_6\text{H}_6\text{ in effluent}}{\uparrow}}{(30.0)}(78.11)(0.45)\left(200^\circ\text{ F}-400^\circ\text{ F}\right)$$

$$+\underset{\underset{\text{C}_6\text{H}_6\text{ fed to reactor}}{\uparrow}}{(40.0)}(78.11)(0.45)\left(T-77^\circ\text{ F}\right)=0\Rightarrow \underline{\underline{T = 323^\circ\text{ F}}}$$

(Refer to flow chart of Part b: $T = 323^\circ$ F)

References : $C_3H_6(l)$, $C_4H_{10}(l)$, $C_6H_6(l)$, $C_9H_{12}(l)$ at 77° F

$\hat{H}_i(\text{Btu/lb-mole}) = C_{pi}(\text{Btu/lb}_\text{m}\cdot{}^\circ\text{F})M_i(\text{lb}_\text{m}/\text{lb-mole})(T-77)({}^\circ\text{ F})$

Substance	$\dot{n}_{\text{in}}$ (lb-mole / h)	$\hat{H}_{\text{in}}$ (Btu / lb-mole)	$\dot{n}_{\text{out}}$ (lb-mole / h)	$\hat{H}_{\text{out}}$ (Btu / lb-mole)
C_3H_6	12.0	0	2.50	7750
C_4H_{10}	4.17	0	4.17	10330
C_6H_6	40.0	8650	30.0	11350
C_9H_{12}	–	–	10.0	15530

Energy balance on reactor :

$$Q = \Delta H = \frac{\dot{n}_{C_9H_{12}}\Delta\hat{H}_\text{r}^\text{o}}{\nu_{C_9H_{12}}} + \sum_{\text{out}}\dot{n}_i\hat{H}_i - \sum_{\text{in}}\dot{n}_i\hat{H}_i$$

$$= \frac{(10.0)(-39520)}{(1)} + (2.50)(7750) + (4.17)(10330) + (30.0)(11350) + (10.0)(15530)$$

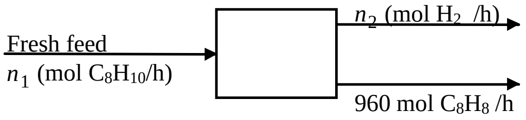
$$-(40.0)(8650) = \underline{\underline{-183000\text{ Btu/h}}}\ (\text{heat removal})$$

9.28

Basis : $\frac{100\text{ kg C}_8\text{H}_8}{\text{h}}\left|\frac{10^3\text{ g}}{1\text{ kg}}\right|\frac{1\text{ mol}}{104.15\text{ g}} = 960\text{ mol/h}$ styrene produced

a. $C_8H_{10}(g) \rightarrow C_8H_8(g) + H_2(g)$

Overall system



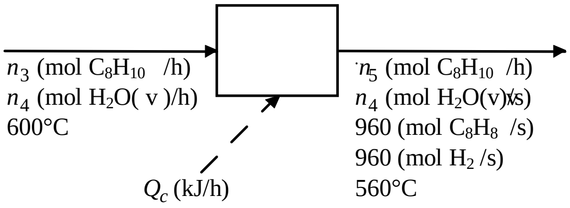
Fresh feed rate: $\dot{n}_1 = \frac{960\text{ mol C}_8\text{H}_8}{\text{h}}\left|\frac{1\text{ mol C}_8\text{H}_{10}}{1\text{ mol C}_8\text{H}_8}\right. = \underline{\underline{960\text{ mol C}_8\text{H}_{10}/\text{h}}}$ fresh feed

(C_8H_{10} balance)

H_2 balance : $\dot{n}_2 = \frac{960\text{ mol C}_8\text{H}_{10}}{\text{h}}\left|\frac{1\text{ mol H}_2}{1\text{ mol C}_8\text{H}_{10}}\right. = 960\text{ mol H}_2/\text{h}$

9.28 (cont'd)

Reactor :

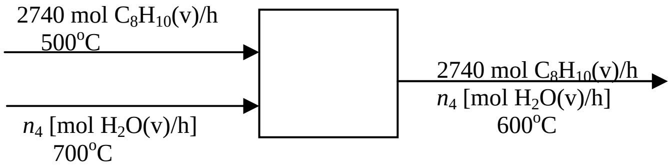


$$\underline{\text{35\% 1-pass conversion}} \Rightarrow \frac{0.35 n_3 (\text{mol } C_8H_{10} \text{ react})}{\text{h}} \left| \frac{1 \text{ mol } C_8H_8}{1 \text{ mol } C_8H_{10}} \right. = 960 \text{ mol } C_8H_8/\text{h}$$

$$\Rightarrow \dot{n}_3 = 2740 \text{ mol } C_8H_{10}/\text{h fed to reactor}$$

$$\Rightarrow \underline{\text{Recycle rate}} = (2740 - 960) = \underline{\underline{1780 \text{ mol } C_8H_{10}/\text{h recycled}}}$$

Reactor feed mixing point



Energy balance: $\Delta H = 2740 \Delta \hat{H}_{C_8H_{10}} + \dot{n}_4 \Delta \hat{H}_{H_2O} = 0 (\text{kJ/h})$

(Neglect Q, ΔE_k)

$$\Delta \hat{H}_{C_8H_{10}} = \left[\int_{500}^{600} \underbrace{(118 + 0.30T)}_{C_p} dT \right] \frac{\text{J}}{\text{mol} \cdot {}^\circ\text{C}} \times \frac{1 \text{ kJ}}{10^3 \text{ J}} = 28.3 \text{ kJ/mol}$$

$$\Delta \hat{H}_{H_2O} \overset{\text{Table B.8}}{\underset{P=1 \text{ bar}}{\Rightarrow}} = -3.9 \text{ kJ/mol}$$

$$(2740)(28.3) + \dot{n}_4(-3.9) = 0 \Rightarrow \dot{n}_4 = \underline{\underline{1.99 \times 10^4 \text{ mol } H_2O / \text{h}}}$$

b. Ethylbenzene preheater (A) :

$$\frac{960 \text{ mol fresh feed}}{\text{h}} + \frac{1780 \text{ mol recycled}}{\text{h}} = \frac{2740 \text{ mol EB(l)}}{\text{h}} \text{ at } 25^\circ\text{C}$$

$$\Rightarrow \frac{2740 \text{ mol EB(v)}}{\text{h}} \text{ at } 500^\circ\text{C}$$

$$\Delta \hat{H} = \int_{25}^{136} C_{pl} dT + \Delta \hat{H}_v (136^\circ \text{C}) + \int_{136}^{500} C_{pv} dT = (20.2 + 36.0 + 77.7) \text{kJ/mol} = 133.9 \text{ kJ/mol}$$

$$\dot{Q}_A = \Delta \dot{H} = \frac{2740 \text{ mol } C_8H_{10}}{\text{h}} \left| \frac{133.9 \text{ kJ}}{\text{mol } C_8H_{10}} \right. = \underline{\underline{3.67 \times 10^5 \text{ kJ/h}}} \text{ (preheater)}$$

Steam generator (F) :

$$19400 \text{ mol/h } H_2O(\text{l}, 25^\circ\text{C}) \rightarrow 19400 \text{ mol/h } H_2O(\text{v}, 700^\circ\text{C}, 1 \text{ atm})$$

$$\text{Table B.5} \Rightarrow \hat{H}(\text{l}, 25^\circ\text{C}) = 104.8 \text{ kJ/kg};$$

$$\text{Table B.7} \Rightarrow \hat{H}(\text{v}, 700^\circ\text{C}, 1 \text{ atm} \approx 1 \text{ bar}) = 3928 \text{ kJ/kg}$$

9.28 (cont'd)

$$\dot{Q}_F = \Delta\dot{H} = \frac{19400 \text{ mol } H_2O}{\text{h}}\left|\frac{18.0 \text{ g}}{1 \text{ mol}}\right|\frac{1 \text{ kg}}{10^3 \text{ g}}\left|\frac{(3928-104.8)\text{kJ}}{\text{kg}}\right.$$

$$= \underline{\underline{1.34\times10^6 \text{ kJ/h}}} \text{ (steam generator)}$$

Reactor (C) :

References: $C_8H_8(v)$, $C_8H_{10}(v)$, $H_2(g)$, $H_2O(v)$ at 600°C

$$\hat{H}_i(560^\circ\text{C}) = \int_{600}^{560}(C_{pv})_i dT \text{ for } C_8H_{10},\ C_8H_8$$

$$\approx \hat{H}(T) \text{ for } H_2, H_2O \text{ (interpolating from Table B.8)}$$

Substance	$\dot{n}_{\text{in}}$ (mol/h)	$\hat{H}_{\text{in}}$ (kJ/mol)	$\dot{n}_{\text{out}}$ (mol/h)	$\hat{H}_{\text{out}}$ (kJ/mol)
C_8H_{10}	2740	0	1780	−11.68
H_2O	19900	0	19900	−1.56
C_8H_8	–	–	960	−10.86
H_2	–	–	960	−1.19

Energy balance :

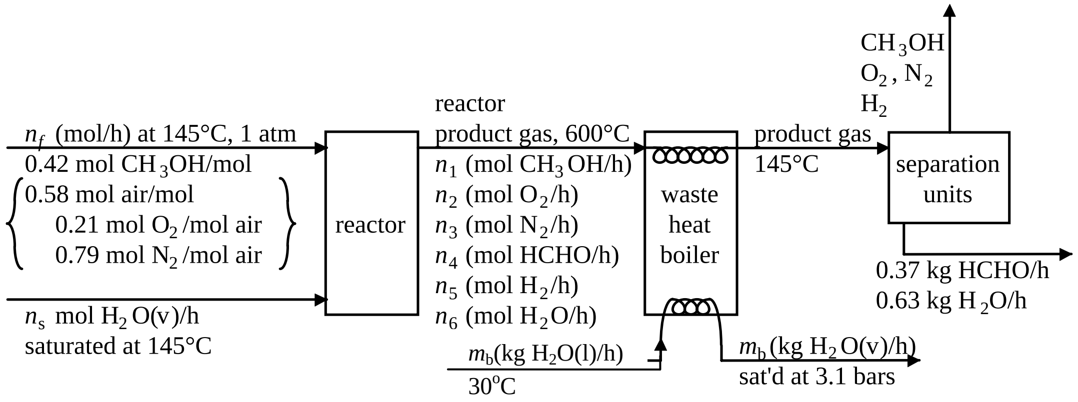
$$\dot{Q}_c = \Delta\dot{H} = \frac{960 \text{ mol } C_8H_8 \text{ produced}}{\text{h}}\left|\frac{124.5 \text{ kJ}}{1 \text{ mol } C_8H_8}\right. + \sum_{\text{out}}\dot{n}_i\hat{H}_i - \sum_{\text{in}}\dot{n}_i\hat{H}_i$$

$$= \underline{\underline{5.61\times10^4 \text{ kJ/h}}} \text{ (reactor)}$$

c. This is a poorly designed process as shown. The reactor effluents are cooled to 25°C, and then all but the hydrogen are reheated after separation. Probably less cooling is needed, and in any case provisions for heat exchange should be included in the design.

9.29 $CH_3OH \rightarrow HCHO + H_2,\quad H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

a.



b. In the absence of data to the contrary, we assume that the separation of methanol from formaldehyde is complete.

Methanol vaporizer:

The product stream, which contains 42 mole % $CH_3OH(v)$, is saturated at $T_m(^\circ C)$ and 1 atm.

9.29 (cont'd)

$$y_m P = p_m^*(T_m) \Rightarrow (0.42)(760 \text{ mmHg}) = 319.2 \text{ mmHg} = p_m^*(T_m)$$

$$\xrightarrow{\text{Antoine equation}} p_m^* = 319.2 \text{ mmHg} \;\Rightarrow\; T_m = \underline{\underline{44.1^\circ\text{C}}}$$

c. <u>Moles HCHO formed :</u>

$$= \begin{array}{c|c|c|c} 36\times 10^6 \text{ kg solution} & 0.37 \text{ kg HCHO} & 1 \text{ kmol} & 1 \text{ day} \\ \hline 350 \text{ days} & 1 \text{ kg solution} & 30.03 \text{ kg HCHO} & 24 \text{ h} \end{array} = 52.80 \frac{\text{kmol HCHO}}{\text{h}}$$

but if all the HCHO is recovered, then this equals $\dot{n}_4$, or $\dot{n}_4 = 52.80 \text{ kmol HCHO/h}$

<u>70% conversion :</u>

$$\begin{array}{c|c|c|c} 52.80 \text{ kmol HCHO} & 1 \text{ kmol CH}_3\text{OH react} & 1 \text{ kmol CH}_3\text{OH fed} & 1 \text{ kmol feed gas} \\ \hline \text{h} & 1 \text{ kmol HCHO formed} & 0.70 \text{ kmol CH}_3\text{OH react} & 0.42 \text{ kmol CH}_3\text{OH} \end{array} = \dot{n}_f$$

$$\Rightarrow \dot{n}_f = 179.59 \text{ kmol/h}$$

<u>Methanol unreacted:</u>

$$\dot{n}_1 = \begin{array}{c|c} (0.42)(179.59)\text{kmol CH}_3\text{OH fed} & (1-0.70) \text{ kmol CH}_3\text{OH fed} \\ \hline \text{h} & 1 \text{ kmol CH}_3\text{OH fed} \end{array} = 22.63 \frac{\text{kmol CH}_3\text{OH}}{\text{h}}$$

<u>N_2 balance:</u> $\dot{n}_3 = (179.6 \text{ kmol/h})(0.58)(0.79) = 82.29 \text{ kmol } N_2/\text{h}$

Four reactor stream variables remain unknown — $\dot{n}_s$, $\dot{n}_2$, $\dot{n}_5$, and $\dot{n}_6$ — and four relations are available — H and O balances, the given H_2 content of the product gas (5%), and the energy balance. The solution is tedious but straightforward.

<u>H balance:</u> $(179.6)(0.42)(4) + 2n_s = (22.63)(4) + (52.8)(2) + 2\dot{n}_5 + 2\dot{n}_6$

$$\Rightarrow \; \dot{n}_s = \dot{n}_5 + \dot{n}_6 - 52.80 \qquad (1)$$

<u>O balance:</u> $(179.6)(0.42)(1) + (179.6)(0.58)(0.21)(2) + \dot{n}_s = (22.63)(1) + 2\dot{n}_2 + (52.80)(1) + \dot{n}_6$

$$\Rightarrow \dot{n}_s = 2\dot{n}_2 + \dot{n}_6 - 43.75 \qquad (2)$$

<u>H_2 content:</u> $$\frac{\dot{n}_5}{22.63 + \dot{n}_2 + 82.29 + 52.89 + \dot{n}_5 + \dot{n}_6} = 0.05 \Rightarrow 19\dot{n}_5 - \dot{n}_2 - \dot{n}_6 = 157.72 \qquad (3)$$

<u>References</u> : $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C

$$H = \Delta\hat{H}_f^o + \int_{25}^{T} \overset{\overset{\text{Table B.2}}{\downarrow}}{C_p} dT$$

or Table B.8 for O_2, N_2 and H_2

9.29 (cont'd)

substance	$\dot{n}_{\text{in}}$ kmol / h	$\hat{H}_{\text{in}}$ kJ / kmol	$\dot{n}_{\text{out}}$ kmol / h	$\hat{H}_{\text{out}}$ kJ / kmol
CH_3OH	75.43	−195220	22.63	−163200
O_2	21.88	3620	n_2	18410
N_2	82.29	3510	82.29	17390
H_2O	n_s	−237740	n_6	−220920
HCHO	–	–	52.80	−88800
H_2	–	–	n_5	16810

Energy Balance :

$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0 \Rightarrow 18410 n_2 + 16810 n_5 - 220920 n_6 + 237704 n_s = -7.406 \times 10^6 \qquad (4)$$

We now have four equations in four unknowns. Solve using E-Z Solve.

$$\dot{n}_s = \frac{58.8 \text{ kmol } H_2O(v)}{\text{h}} \left| \frac{18.02 \text{ kg}}{1 \text{ kmol}} \right. = \underline{\underline{1060 \text{ kg steam fed/h}}}$$

$$\dot{n}_2 = 2.26 \text{ kmol } O_2/\text{h}, \ \dot{n}_5 = 13.58 \text{ kmol } H_2/\text{h}, \ \dot{n}_6 = 98.00 \text{ kmol } H_2O/\text{h}$$

Summarizing, the product gas component flow rates are 22.63 kmol CH_3OH/h, 2.26 kmol O_2/h, 82.29 kmol N_2/h, 52.80 kmol HCHO/h, 13.58 kmol H_2/h, and 98.02 kmol H_2O/h

$$\Rightarrow \begin{array}{l} \underline{\underline{272 \text{ kmol/h product gas}}} \\ \underline{\underline{8\% \ CH_3OH, \ 0.8\% \ O_2, \ 30\% \ N_2, \ 19\% \text{ HCHO}, \ 5\% \ H_2, \ 37\% \ H_2O}} \end{array}$$

d. Energy balance on waste heat boiler. Since we have already calculated specific enthalpies of all components of the product gas at the boiler inlet (at 600°C), and for all but two of them at the boiler outlet (at 145°C), we will use the same reference states for the boiler calculation

Reference States: $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C for reactor gas

$H_2O(l)$ at triple point for boiler water

Substance	$\dot{n}_{\text{in}}$ kmol/h	$\hat{H}_{\text{in}}$ kJ/kmol	$\dot{n}_{\text{out}}$ mol	$\hat{H}_{\text{out}}$ kJ/mol
CH_3OH	22.63	−163200	22.63	−195220
O_2	2.26	18410	2.26	3620
N_2	82.29	17390	82.29	3510
H_2O	98.02	−220920	98.02	−237730
HCHO	52.80	−88800	52.80	−111350
H_2	13.58	16810	13.58	3550
H_2O	m_b (kg/h)	125.7 (kJ/kg)	m_b (kg/h)	2726.1 (kJ/kg)

9.29 (cont'd)

Energy Balance :

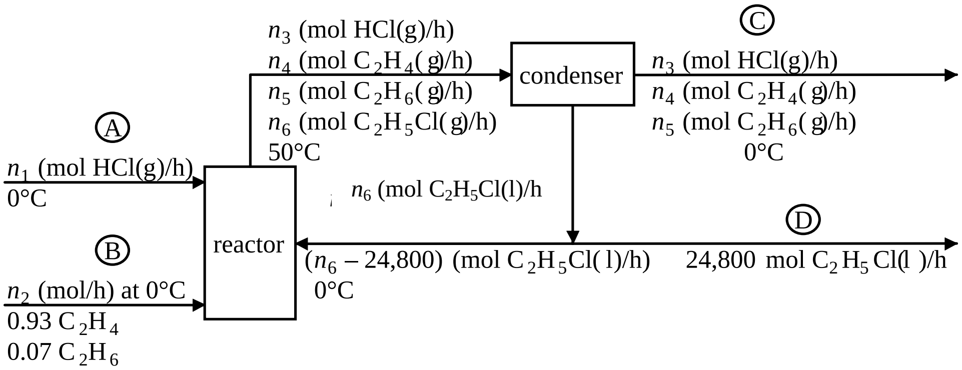
$$\Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0$$

$$\Rightarrow m_b(2726.1 - 125.7) - 4.92 \times 10^6 = 0$$

$$\Rightarrow \underline{\underline{m_b = 1892 \text{ kg steam/h}}}$$

9.30 **a.** $C_2H_4 + HCl \rightarrow C_2H_5Cl$

Basis: $\dfrac{1600 \text{ kg } C_2H_5Cl(l)}{\text{h}} \left| \dfrac{10^3 \text{ g}}{1 \text{ kg}} \right| \dfrac{1 \text{ mol}}{64.52 \text{ g}} = 24800 \text{ mol/h } C_2H_5Cl$



Product composition data:

$$n_3 = 0.015 n_1 \qquad (1)$$

$$n_4 = 0.015(0.93 n_2) = 0.01395 n_2 \qquad (2)$$

$$n_5 = 0.07 n_2 \qquad (3)$$

Overall Cl balance :

$$\frac{n_1(\text{mol HCl/h})}{} \left| \frac{1 \text{ mol Cl}}{1 \text{ mol HCl}} \right. = (n_3)(1) + (24800)(1) \qquad (4)$$

Solve (4) simultaneously with (1) $\Rightarrow n_1 = 25180$ mol/h = $\underline{\underline{\text{25.18 kmol HCl fed / h}}}$

$$n_3 = 378 \text{ mol HCl(g)/h}$$

Overall C balance :

$$n_2(0.93)(2) + n_2(0.07)(2) = 2n_4 + 2n_5 + (2)(24800)$$

From Eqs. (2) and (3) $\Rightarrow 2n_2\left[0.93 + 0.07 - 0.0139 - 0.07\right] = (2)(24800)$

$n_2 = 27070$ mol fed/h = $\underline{\underline{27.07 \text{ kmol/h of Feed B}}}$

b.

$$\left.\begin{array}{l} n_3 = 378 \text{ mol HCl/h} \\ n_4 = 0.01395(27070) = 378 \text{ mol } C_2H_4/\text{h} \\ n_5 = 0.07(27070) = 1895 \text{ mol } C_2H_6/\text{h} \end{array}\right\} \begin{array}{l} \underline{2.65 \text{ kmol / h of Product C}} \\ \underline{\underline{14.3\% \text{ HCl}, 14.3\% \ C_2H_4, 71.4\% \ C_2H_6}} \end{array}$$

9.30 (cont'd)

c.

References : $C_2H_4(g),\ C_2H_6(g),\ C_2H_5Cl(g),\ HCl(g)$ at $0^\circ C$

$$C_2H_4(g,\ 50^\circ C):\ \hat{H} = \int_0^{50} C_p dT \overset{\text{Table B.2}}{\Rightarrow} 2.181\ \text{kJ/mol}$$

$$C_2H_6(g,\ 50^\circ C):\ \hat{H} = \int_0^{50} C_p dT \overset{\text{Table B.2}}{\Rightarrow} 2.512\ \text{kJ/mol}$$

$$HCl(g,\ 50^\circ C):\ \hat{H} = \int_0^{50} C_p dT \overset{\text{Table B.2}}{\Rightarrow} 1.456\ \text{kJ/mol}$$

$$C_2H_5Cl(l,\ 0^\circ C):\ \hat{H} = -\Delta\hat{H}_v(0^\circ C) = -24.7\ \text{kJ/mol}$$

$$C_2H_5Cl(g,\ 50^\circ C):\ \hat{H} = \int_0^{50} C_{pv} dT = 2.709\ \text{kJ/mol}$$

substance	n_{in} mol	$\hat{H}_{in}$ kJ / mol	n_{out} mol	$\hat{H}_{out}$ kJ / mol
HCl	25180	0	378	1.456
C_2H_4	25175	0	378	2.181
C_2H_6	1895	0	1895	2.512
C_2H_5Cl	$n_6 - 24800$	−24.7	n_6	2.709

Energy balance:

$$\Delta H = 0 \Rightarrow \frac{n_A \Delta\hat{H}_r(0^\circ C)}{\nu_A} + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 0$$

$$\Rightarrow \frac{(25180-378)\text{mol HCl react}}{\text{h}} \left| \frac{-64.5\text{ kJ}}{1\text{ mol HCl}} \right. + (378)(1.456) + (378)(2.181) + (1895)(2.512)$$

$$+2.709n_6 - (n_6 - 24800)(-24.7) = 0 \Rightarrow n_6 = 80490\text{ mol } C_2H_5Cl/\text{h} \text{ in reactor effluent}$$

$$\underline{C_2H_5Cl\text{ recycled}} = \frac{80490\text{ mol condensed}}{\text{h}} - \frac{24800\text{ mol product}}{\text{h}} = 55690\frac{\text{mol}}{\text{h}}$$

$$= \underline{\underline{55.7\frac{\text{kmol recycled}}{\text{h}}}}$$

d.

C_p is a linear function of temperature.

$\Delta\hat{H}_v$ is independent of temperature.

100% condensation of ethylbenzene in the heat exchanger is assumed.

Heat of mixing and influence of pressure on enthalpy is neglected.

Reactor is adiabatic.

No C_2H_4 or C_2H_6 is absorbed in the ethyl chloride product.

9.31 **a.** $4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$ $\Delta\hat{H}_r^o = -904.7$ kJ / mol

Basis : 10 mol/s Feed gas

9.31 (cont'd)

$$\underline{\text{O}_2 \text{ consumed}}: \ \frac{5 \text{ mol O}_2}{4 \text{ mol NH}_3}\left|\frac{4 \text{ mol NH}_3 \text{ fed}}{\text{s}}\right. = 5 \text{ mol/s} \ \Rightarrow \dot{n}_3 = (6-1) \text{ mol O}_2\text{/s} \ = \underline{\underline{1 \text{ mol O}_2 \text{/}}}$$

$$\underline{\text{NO produced}}: \ \dot{n}_4 = \frac{4 \text{ mol NO produced}}{4 \text{ mol NH}_3}\left|\frac{4 \text{ mol NH}_3 \text{ fed}}{\text{s}}\right. = \underline{\underline{4 \text{ mol NO/s}}}$$

$$\underline{\text{H}_2\text{O produced}}: \dot{n}_5 = \frac{6 \text{ mol H}_2\text{O produced}}{4 \text{ mol NH}_3}\left|\frac{4 \text{ mol NH}_3 \text{ fed}}{\text{s}}\right. = \underline{\underline{6 \text{ mol H}_2\text{O/s}}}$$

$$\underline{\text{Extent of reaction}}: \dot{\xi} = \frac{\left|(\dot{n}_{\text{NH}_3})_{\text{out}} - (\dot{n}_{\text{NH}_3})_{\text{in}}\right|}{\left|\nu_{\text{NH}_3}\right|} = \frac{|0-4|}{|4|} = \underline{\underline{1 \text{ mol/s}}}$$

b. Well-insulated reactor, so no heat loss
No absorption of heat by container wall
Neglect kinetic and potential energy changes;
No shaft work
No side reactions.

c. $\underline{\text{References:}}\ \text{NH}_3\text{(g), O}_2\text{(g), NO(g), H}_2\text{O(g) at } 25^\circ\text{C, 1atm}$

Substance	$\dot{n}_{\text{in}}$ (mol/s)	$\hat{H}_{\text{in}}$ (kJ/mol)	$\dot{n}_{\text{out}}$ (mol/s)	$\hat{H}_{\text{out}}$ (kJ/mol)
NH_3(g)	4.00	$\hat{H}_1$	–	–
O_2(g)	6.00	$\hat{H}_2$	1.00	$\hat{H}_3$
NO(g)	–	–	4.00	$\hat{H}_4$
H_2O(g)	–	–	6.00	$\hat{H}_5$

$$\hat{H}_1 = \int_{25}^{200} (C_p)_{\text{NH}_3} dT \overset{\substack{\text{Table B.2} \\ \downarrow}}{=} 6.74 \text{ kJ/mol}, \quad \hat{H}_2 = \hat{H}_{\text{O}_2}(200^\circ\text{C}) \overset{\substack{\text{Table B.8} \\ \downarrow}}{=} 5.31 \text{ kJ/mol}$$

Using $(C_p)_i$ from Table B.2 :

$$\hat{H}_3 = (0.0291\, T_{\text{out}} + 0.5790\times10^{-5}\, T_{\text{out}}^{\ 2} - 0.2025\times10^{-8}\, T_{\text{out}}^{\ 3} + 0.3278\times10^{-12}\, T_{\text{out}}^{\ 4} - 0.7311) \text{ kJ/mol}$$

$$\hat{H}_4 = (0.0295\, T_{\text{out}} + 0.4094\times10^{-5}\, T_{\text{out}}^{\ 2} - 0.0975\times10^{-8}\, T_{\text{out}}^{\ 3} + 0.0913\times10^{-12}\, T_{\text{out}}^{\ 4} - 0.7400) \text{ kJ/mol}$$

$$\hat{H}_5 = (0.03346\, T_{\text{out}} + 0.3440\times10^{-5}\, T_{\text{out}}^{\ 2} + 0.2535\times10^{-8}\, T_{\text{out}}^{\ 3} - 0.8983\times10^{-12}\, T_{\text{out}}^{\ 4} - 0.8387) \text{ kJ/mol}$$

$\underline{\text{Energy Balance:}}\ \Delta\dot{H} = 0$

$$\Delta\dot{H} = \dot{\xi}\Delta\hat{H}_{\text{r}}^{\text{o}} + \sum_{i=3}^{5} (n_i)_{\text{out}} (\hat{H}_i)_{\text{out}} - \sum_{i=1}^{2} (n_i)_{\text{in}} (\hat{H}_i)_{\text{in}}$$

9-31 (cont'd)

$$\Rightarrow \Delta\dot{H} = \dot{\xi}\Delta\hat{H}_{\rm r}^{\rm o} + (1.00)\hat{H}_3 + (4.00)\hat{H}_4 + (6.00)\hat{H}_5 - (4.00)\hat{H}_1 - (6.00)\hat{H}_2$$

$\Downarrow$ Substitute for $\dot{\xi}$, $\Delta\hat{H}_{\rm r}^{\rm o}$, and $\hat{H}_1$ through $\hat{H}_6$

$$\Delta\dot{H} = (0.3479\ T_{\rm out} + 4.28\times10^{-5}\ T_{\rm out}{}^2 + 0.9285\times10^{-8}\ T_{\rm out}{}^3 - 4.697\times10^{-12}\ T_{\rm out}{}^4) - 972.24\ \text{kJ/mol} = 0$$

E-Z Solve $\Rightarrow$ $\underline{\underline{T_{\rm out} = 2223\ ^{\rm o}\text{C}}}$

d. If only the first term from Table B.2 is used, $\hat{H}_i = \int_{25}^{T}(C_{pi})dT = C_{pi}(T-25)$

$\hat{H}_1 = 0.03515(200-25) = 6.15\ \text{kJ / mol},\ \hat{H}_2 = 5.31\ \text{kJ / mol},\ \hat{H}_3 = 0.0291(T_{\rm out}-25),$

$\hat{H}_4 = 0.0295(T_{\rm out}-25),\ \hat{H}_5 = 0.03346(T_{\rm out}-25)$

<u>E.B.</u> $\Delta\dot{H} = \dot{\xi}\Delta\hat{H}_{\rm r}^{\rm o} + (1.00)\hat{H}_3 + (4.00)\hat{H}_4 + (6.00)\hat{H}_5 - (4.00)\hat{H}_1 - (6.00)\hat{H}_2 = 0$

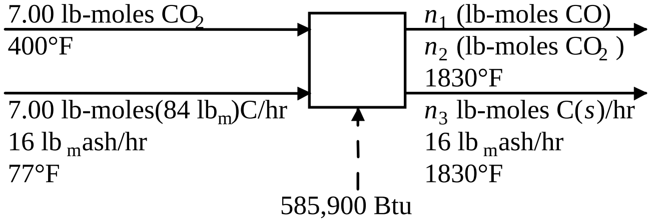
$\Downarrow$ Substitute for $\dot{\xi}$ (=1 mol/s), $\Delta\hat{H}_{\rm r}^{\rm o}$ (= −904.7 kJ/mol) and $\hat{H}_1$ through $\hat{H}_6$

$$0 = 0.3479\ T_{\rm out} - 969.86\ \Rightarrow \underline{\underline{T_{\rm out} = 2788\ ^{\rm o}\text{C}}}\ \Rightarrow\ \%\ \text{error} = \frac{2788^{\rm o}\text{C} - 2223^{\rm o}\text{C}}{2223\ ^{\rm o}\text{C}}\times100 = \underline{\underline{25\%}}$$

e. If the higher temperature were used as the basis, the reactor design would be <u>safer</u> (but more expensive).

9.32 <u>Basis</u> : 100 lb_m coke fed

$\Rightarrow 84\ \text{lb}_\text{m}\ \text{C} \Rightarrow 7.00\ \text{lb-moles C fed} \Rightarrow 7.00\ \text{lb-moles CO}_2\ \text{fed}$



a. $\text{C(s)} + \text{CO}_2\text{(g)} \rightarrow 2\text{CO(g)}$,

$$\Delta\hat{H}_{\rm r}^{\rm o}\underset{=25^\circ\text{C}}{\left(77^\circ\text{F}\right)} = \left(\Delta\hat{H}_{\rm c}^{\rm o}\right)_{\text{CO}_2(\text{g})} - 2\left(\Delta\hat{H}_{\rm c}^{\rm o}\right)_{\text{CO(g)}}$$

$$= \frac{[-393.50-(2)(-282.99)]\ \text{kJ}}{\text{mol}}\left|\frac{0.9486\ \text{Btu}}{1\ \text{kJ}}\right|\frac{453.6\ \text{mols}}{1\ \text{lb-mole}} = 74{,}210\ \ \text{Btu/lb-mole}$$

Let $x =$ fractional conversion of C and CO_2 :

$\Downarrow$

$$n_1 = \frac{7.00x(\text{lb-moles C reacted})}{}\left|\frac{2\ \text{lb-moles CO formed}}{1\ \text{lb-mole C reacted}}\right. = 14.0x\ \text{lb-moles CO}$$

$n_2 = 7.00(1-x)\ \text{lb-moles CO}_2$

$n_3 = 7.00(1-x)\ \text{lb-moles C(s)}$

<u>References for enthalpy calculations</u>: $\text{C(s), CO}_2\text{(g), CO(g), ash at } 77^\circ\text{F}$

9.32 (cont'd)

$\underline{CO_2(g, 400°F)}$: $\hat{H} = \hat{H}_{CO_2}(400°F) \overset{\text{Table B.9}}{\Rightarrow} 3130 \text{ Btu/lb-mole}$

$\underline{CO_2(g, 1830°F)}$: $\hat{H} = \hat{H}_{CO_2}(1830°F) \overset{\text{Table B.9}}{\Rightarrow} 20{,}880 \text{ Btu/lb-mole}$

$\underline{CO(g, 1830°F)}$: $\hat{H} = \hat{H}_{CO}(1830°F) \overset{\text{Table B.9}}{\Rightarrow} 13{,}280 \text{ Btu/lb-mole}$

Solid $(1830°F)$: $\hat{H} = \dfrac{0.24 \text{ Btu}}{\text{lb}_m \cdot °F} \Bigg| \dfrac{(1830 - 77)°F}{} = 420 \text{ Btu/lb}_m$

Mass of solids (emerging)

$$= \frac{7.00(1-x) \text{ lb-moles C}}{} \Bigg| \frac{12.0 \text{ lb}_m}{1 \text{ lb-mole}} + 16 \text{ lb}_m = (100 - 84x) \text{ lb}_m$$

substance	n_{in} (lb – moles)	$\hat{H}_{in}$ (Btu/lb-mole)	n_{out} (lb – moles)	$\hat{H}_{out}$ (Btu/lb-mole)
CO_2	7.00	3130	$7.00(1-x)$	20,890
CO	–	–	$14.0x$	13,280
	(lb_m)	(Btu/lb_m)	(lb_m)	(Btu/lb_m)
solid	100	0	$100 - 84x$	420

$\underline{\text{Extent of reaction}}$: $n_{CO} = (n_{CO})_o + \nu_{CO}\xi \Rightarrow 14.0x = 2\xi \Rightarrow \xi(\text{lb-moles}) = 7.0x$

Energy balance:

$$Q = \Delta H = \xi\, \Delta\hat{H}_r^o + \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

$$585{,}900 \text{ Btu} = \frac{7.0x \text{ (lb-moles)}}{} \Bigg| \frac{74{,}210 \text{ Btu}}{\text{lb-mole}} + 7.00(1-x)(20{,}880)$$

$$+(14.0x)(13{,}280) + (100 - 84x)(420) - (7.00)(3130)$$

$$\Downarrow$$

$$x = 0.801 \Rightarrow \underline{\underline{80.1\% \text{ conversion}}}$$

b.

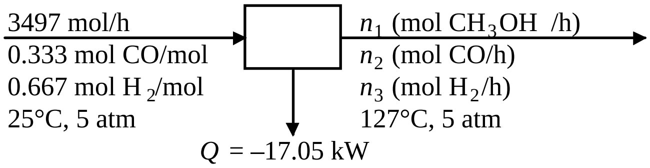
Advantages of CO. Gases are easier to store and transport than solids, and the product of the combustion is CO_2, which is a much lower environmental hazard than are the products of coke combustion.

Disadvantages of CO. It is highly toxic and dangerous if it leaks or is not completely burned, and it has a lower heating value than coke. Also, it costs something to produce it from coke.

9.33 $\underline{\text{Basis}}: \dfrac{17.1\ \text{m}^3}{\text{h}} \left| \dfrac{10^3\ \text{L}}{1\ \text{m}^3} \right| \dfrac{273\ \text{K}}{298\ \text{K}} \left| \dfrac{5.00\ \text{atm}}{1.00\ \text{atm}} \right| \dfrac{1\ \text{mol}}{22.4\ \text{L(STP)}} = 3497\ \text{mol/h feed}$

$CO(g) + 2H_2(g) \rightarrow CH_3OH(g)$,

$\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o\right)_{CH_3OH(g)} - \left(\Delta\hat{H}_f^o\right)_{CO(g)} = -90.68\ \text{kJ/mol}$



Let f = fractional conversion of CO (which also equals the fractional conversion of H_2, since CO and H_2 are fed in stoichiometric proportion).

$\underline{\text{CO reacted}}: = \dfrac{(3497)(0.333)\ \text{mol CO feed}}{} \left| \dfrac{f\ (\text{mol react})}{\text{mol feed}} \right. = 1166 f\ (\text{mol CO react})$

$\underline{CH_3OH\ \text{produced}}: \ \dot{n}_1 = \dfrac{1166 f\ \text{mol CO react}}{} \left| \dfrac{1\ \text{mol}\ CH_3OH}{1\ \text{mol CO}} \right. = 1166 f\ \text{mol}\ CH_3OH/\text{h}$

$\underline{\text{CO remaining}}: \ \dot{n}_2 = 1166(1-f)\ \text{mol CO/h}$

$\underline{H_2\ \text{remaining}}: \ \dot{n}_3 = (3497)(0.667)\ \text{mol}\ H_2\ \text{fed} - \dfrac{1166 f\ \text{mol CO react}}{} \left| \dfrac{2\ \text{mol}\ H_2\ \text{react}}{1\ \text{mol CO react}} \right.$

$= 2332(1-f)\ \text{mol}\ H_2/\text{h}$

$\underline{\text{Reference states}}$**:** CO(g), $H_2(g)$**,** $CH_3OH(g)$ at 25°C

Substance	$\dot{n}_{in}$ (mol/h)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/h)	$\hat{H}_{out}$ (kJ/mol)
CO	1166	0	$1166(1-f)$	$\hat{H}_1$
H_2	2332	0	$2332(1-f)$	$\hat{H}_2$
CH_3OH	–	–	$1166 f$	$\hat{H}_3$

$CO(g, 127^\circ C): \ \hat{H}_1 = \hat{H}_{CO}(127^\circ C) \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} 2.99\ \text{kJ/mol}$

$H_2(g, 127^\circ C): \ \hat{H}_2 = \hat{H}_{H_2}(127^\circ C) \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} 2.943\ \text{kJ/mol}$

$CH_3OH(g, 127^\circ C): \ \hat{H}_3 = \int_{25}^{122} C_p dT \overset{\substack{\text{Table B.2}\\ \downarrow}}{=} 5.009\ \text{kJ / mol}$

$\underline{\text{Energy balance}}: \ \dot{Q} = \Delta\dot{H} = \dot{\xi}\Delta\hat{H}_r^o + \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i$

$\Rightarrow \dfrac{-17.05\ \text{kJ}}{\text{s}} \left| \dfrac{3600\ \text{s}}{1\ \text{h}} \right. = (1166 f)(-90.68)\ \dfrac{\text{kJ}}{\text{h}} + \left[1166(1-f)\right](2.99)$

$+ \left[2332(1-f)\right](2.993) + \left[1166 f(5.009)\right](\text{kJ/h})$

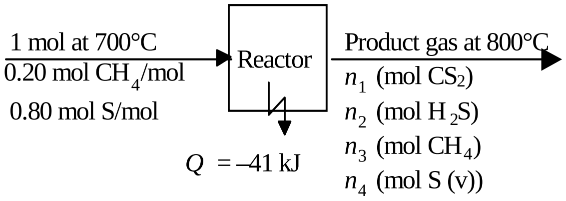
$\Rightarrow 1.102 \times 10^5 f = 7.173 \times 10^4 \Rightarrow \underline{\underline{f = 0.651\ \text{mol CO(or}\ H_2)\ \text{converted/mol fed}}}$

9.33 (cont'd)

$$\dot{n}_1 = 1166(0.651) = 759.1 \text{ mol/h}$$
$$\dot{n}_2 = 1166(1-0.651) = 406.9 \text{ mol/h}$$
$$\dot{n}_3 = 2332(1-0.651) = 813.9 \text{ mol/h}$$
$$\Downarrow$$
$$\dot{n}_{\text{tot}} = 1980\frac{\text{mol}}{\text{h}} \Rightarrow V_{\text{out}} = \frac{1980 \text{ mol}}{\text{h}}\left|\frac{22.4 \text{ L(STP)}}{1 \text{ mol}}\right|\frac{400 \text{ K}}{273 \text{ K}}\left|\frac{1.00 \text{ atm}}{5.00 \text{ atm}}\right|\frac{1 \text{ m}^3}{10^3 \text{ L}} = \underline{\underline{13.0 \text{ m}^3/\text{h}}}$$

9.34 **a.** $CH_4(g) + 4S(g) \rightarrow CS_2(g) + 2H_2S(g)$, $\Delta\hat{H}_r(700°C) = -274$ kJ/mol

Basis : 1 mol of feed



Let f = fractional conversion of CH_4 (which also equals fractional conversion of S, since the species are fed in stoichiometric proportion)

Moles CH_4 reacted $= 0.20f$, Extent of reaction = ξ(mol) = $0.20f$

$$n_3 = 0.20(1-f) \text{ mol } CH_4$$

$$n_4 = 0.80 \text{ mol S fed} - \frac{0.20f(\text{mol } CH_4 \text{ react})}{}\left|\frac{4 \text{ mol S react}}{1 \text{ mol } CH_4 \text{ react}}\right. = 0.80(1-f) \text{ mol S}$$

$$n_1 = \frac{0.20f \text{ mol } CH_4 \text{ react}}{}\left|\frac{1 \text{ mol } CS_2}{1 \text{ mol } CH_4}\right. = 0.20f \text{ mol } CS_2$$

$$n_2 = \frac{0.20f \text{ mol } CH_4 \text{ react}}{}\left|\frac{2 \text{ mol } H_2S}{1 \text{ mol } CH_4}\right. = 0.40f \text{ mol } H_2S$$

References: $CH_4(g), S(g), CS_2(g), H_2S(g)$ at 700°C (temperature at which $\Delta\hat{H}_r$ is known)

substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ/mol)
CH_4	0.20	0	$0.20(1-f)$	$\hat{H}_1$
S	0.80	0	$0.80(1-f)$	$\hat{H}_2$
CS_2	–	–	$0.20f$	$\hat{H}_3$
H_2S	–	–	$0.40f$	$\hat{H}_4$

$$\hat{H}_{\text{out}} = C_{pi}(800-700) \Rightarrow \begin{cases} CH_4(\text{g, } 800°\text{C})\text{: } \hat{H}_1 = 7.14 \text{ kJ / mol} \\ S(\text{g, } 800°\text{C})\text{: } \hat{H}_2 = 3.64 \text{ kJ / mol} \\ CS_2(\text{g, } 800°\text{C})\text{: } \hat{H}_3 = 3.18 \text{ kJ / mol} \\ H_2S(\text{g, } 800°\text{C})\text{: } \hat{H}_4 = 4.48 \text{ kJ / mol} \end{cases}$$

9.34 (cont'd)

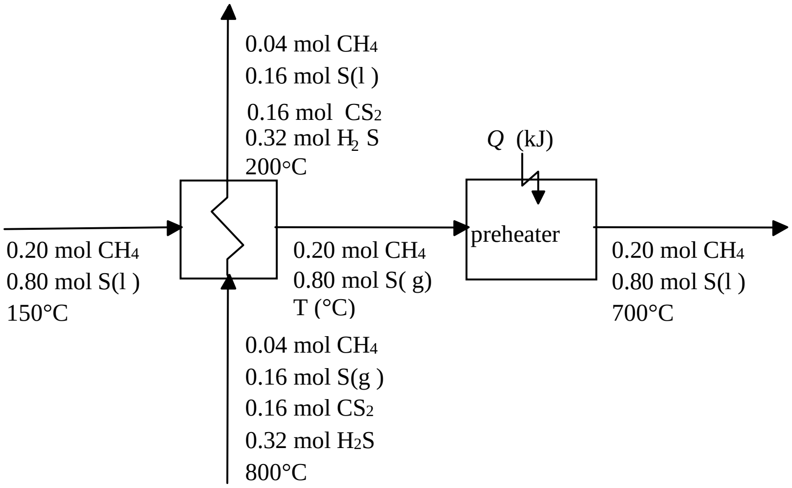
Energy balance on reactor:

$$\dot{Q} = \Delta\dot{H} = \dot{\xi}\Delta\hat{H}_r + \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = 41\frac{\text{kJ}}{\text{s}}$$

$$= \frac{(0.20f)(-274.0)}{(1)} + \left[0.20(1-f)(7.140) + 0.80(1-f)(3.640) + 0.20f(3.180) + 0.40f(4.480)\right]$$

$$\Rightarrow \underline{\underline{f = 0.800}}$$

b.



System: Heat exchanger-preheater combination. Assume the heat exchanger is adiabatic, so that the only heat transferred to the system from its surroundings is Q for the preheater.

References : CH_4(g), S(l), CS_2(g), H_2S(g) at 200°C

Substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ/mol)
$(CH_4)_{150°,700°}$	0.20	$\hat{H}_1$	0.20	$\hat{H}_7$
$(CH_4)_{800°,200°}$	0.04	$\hat{H}_2$	0.04	0
S(l)	0.80	$\hat{H}_3$	0.16	0
S(g)	0.16	$\hat{H}_4$	0.80	$\hat{H}_8$
CS_2	0.16	$\hat{H}_5$	0.16	0
H_2S	0.32	$\hat{H}_6$	0.32	0

$$\hat{H}_i = C_{pi}(T-200) \text{ for all substances but S}$$

$$= (C_p)_{\text{S(l)}}(T-200) \text{ for S(l)}$$

$$= (C_p)_{\text{S(l)}}\left(\underbrace{444.6}_{T_b} - 200\right) + \underbrace{\Delta\hat{H}_v}_{=83.7\,\text{kJ/mol}}(T_b) + (C_p)_{\text{S(g)}}(T-444.6) \text{ for S(g)}$$

9.34 (cont'd)

$\mathrm{CH_4(g,\ 150°C)}$: $\hat{H}_1 = -3.57$ kJ / mol

$\mathrm{CH_4(g,\ 800°C)}$: $\hat{H}_2 = 42.84$ kJ / mol

$\mathrm{S(l,\ 150°C)}$: $\hat{H}_3 = -1.47$ kJ / mol

$\mathrm{S(g,\ 800°C)}$: $\hat{H}_4 = 103.83$ kJ / mol

$\mathrm{CS_2(g,\ 800°C)}$: $\hat{H}_5 = 19.08$ kJ / mol

$\mathrm{H_2S(g,\ 800°C)}$: $\hat{H}_6 = 26.88$ kJ / mol

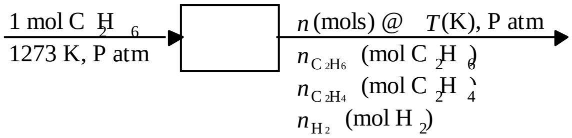
$\mathrm{CH_4(g,\ 700°C)}$: $\hat{H}_7 = 35.7$ kJ / mol

$\mathrm{S(g,\ 700°C)}$: $\hat{H}_8 = 100.19$ kJ / mol

<u>Energy balance:</u> $$Q(\mathrm{kJ}) = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i \Rightarrow Q = 59.2\ \mathrm{kJ} \Rightarrow \underline{\underline{59.2\ \mathrm{kJ/mol\ feed}}}$$

c. The energy economy might be improved by insulating the reactor better. The reactor effluent will emerge at a higher temperature and transfer more heat to the fresh feed in the first preheater, lowering (and possibly eliminating) the heat requirement in the second preheater.

9.35 Basis: 1 mol C_2H_6 fed to reactor



a. $C_2H_6 \Leftrightarrow C_2H_4 + H_2$, $K_p = \dfrac{x_{C_2H_4} x_{H_2}}{x_{C_2H_6}} P = 7.28 \times 10^6 \exp[-17{,}000 / T(K)]$ (1)

Fractional conversion = f (mols C_2H_6 react/mol fed)

$$\left.\begin{array}{l} \xi(\text{mol}) = f \\ n_{C_2H_6} = (1-f)(\text{mol } C_2H_6) \\ n_{C_2H_4} = f(\text{mol } C_2H_4) \\ n_{H_2} = f(\text{mol } H_2) \\ \hline n = 1 + f(\text{mols}) \end{array}\right\} \Rightarrow \begin{array}{l} x_{C_2H_6} = \dfrac{1-f}{1+f} \dfrac{\text{mol } C_2H_6}{\text{mol}} \\ x_{C_2H_4} = \dfrac{f}{1+f} \dfrac{\text{mol } C_2H_4}{\text{mol}} \\ x_{H_2} = \dfrac{f}{1+f} \dfrac{\text{mol } H_2}{\text{mol}} \end{array}$$

$$K_p = \frac{x_{C_2H_4} x_{H_2}}{x_{C_2H_4}} \text{P} \Rightarrow K_p = \frac{\frac{f^2}{(1+f)^2}\text{P}}{\frac{(1-f)}{(1+f)}} = \frac{f^2 \text{ P}}{(1-f)(1+f)} = \frac{f^2}{1-f^2}\text{P}$$

$$\left(1-f^2\right)K_p = f^2\text{P} \Rightarrow \underline{\underline{f = \left(\frac{K_p}{\text{P}+K_p}\right)^{1/2}}} \quad (2)$$

b. References: $C_2H_6(g)$, $C_2H_4(g)$, $H_2(g)$ at 1273 K

Energy balance:

$$\Delta H = 0 \Rightarrow \xi \Delta \hat{H}_r(1273 \text{ K}) + \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

$\left(\hat{H}_i\right)_{\text{in}} = 0$ (inlet temperature = reference temperature)

$$\left(\hat{H}_i\right)_{\text{out}} = \int_{1273}^{T} C_{pi}\, dT$$

$\Downarrow$ energy balance

$$f \Delta \hat{H}_r(1273 \text{ K})\text{kJ} + (1-f)\int_{1273}^{T} \left(C_p\right)_{C_2H_6} dT + f\int_{1273}^{T} \left(C_p\right)_{C_2H_4} dT + f\int_{1273}^{T} \left(C_p\right)_{H_2} dT = 0$$

$\Downarrow$ rearrange, reverse limits and change signs of integrals

$$\frac{1-f}{f} = \underbrace{\frac{\Delta \hat{H}_r(1273K) - \int_T^{1273} \left(C_p\right)_{C_2H_4} dT - \int_T^{1273} \left(C_p\right)_{H_2} dT}{\int_T^{1273} \left(C_p\right)_{C_2H_6} dT}}_{\phi(T)} \quad (3)$$

$$\frac{1-f}{f} = \phi(T) \Rightarrow 1-f = f\phi(T) \Rightarrow f = \frac{1}{1+\phi(T)} \quad (4)$$

9.35 (cont'd)

$$\phi(T) = \frac{145600 - \int_T^{1273} (9.419 + 0.1147T)dT - \int_T^{1273} \left(26.90 + 4.167 \times 10^{-3} T\right)dT}{\int_T^{1273} (11.35 + 0.1392T)dT}$$

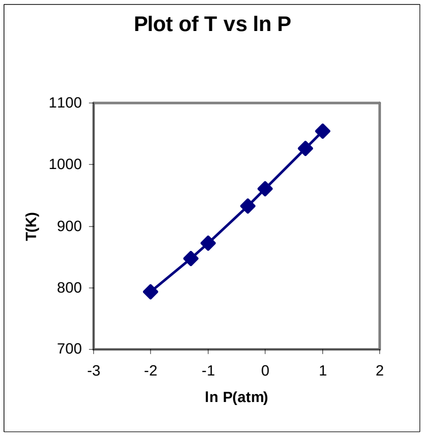
$$\Rightarrow \underline{\underline{\phi(T) = \frac{3052 + 36.2T + 0.05943T^2}{127240 - 11.3T - 0.0696T^2}}}$$

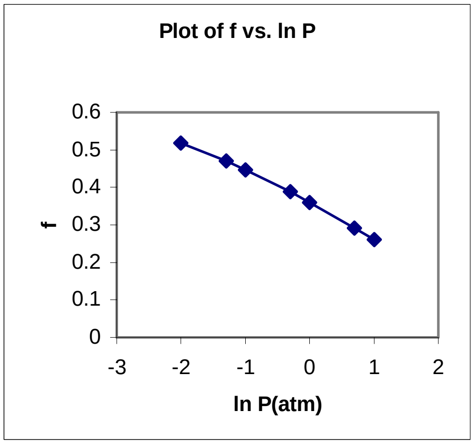
c. $$\left(\frac{K_p}{1+K_p}\right)^{1/2} = \frac{1}{1+\phi(T)} \Rightarrow \underline{\underline{\left(\frac{K_p}{1+K_p}\right)^{1/2} - \frac{1}{1+\phi(T)} = \psi(T) = 0}}$$

$\phi(T)$ given by expression of Part b. $K_p(T)$ given by Eq. (1)

d.

P (atm)	T (K)	f	Kp (atm)	Phi	Psi
0.01	794	0.518	0.0037	0.93152	-0.0001115
0.05	847.4	0.47	0.0141	1.12964	-0.0002618
0.1	872.3	0.446	0.025	1.24028	0.00097743
0.5	932.8	0.388	0.0886	1.57826	3.41E-05
1	960.3	0.36	0.1492	1.77566	4.69E-05
5	1026	0.292	0.4646	2.42913	-2.57E-05
10	1055	0.261	0.7283	2.83692	-7.54E-05


Plot of T vs ln P


Plot of f vs. ln P

e.

```
C   **PROGRAM FOR PROBLEM 9-35
      WRITE (5, 1)
 1    FORMAT ('1', 20X, 'SOLUTION TO PROBLEM 9-35'//)
      T = 1200.0
      TLAST = 0.0
      PSIL = 0.0
```

9.35 (cont'd)

```
 C   **DECREMENT BY 50 DEG. AND LOOK FOR A SIGN IN PSI
         DO 10I =1, 20
         CALL PSICAL (T, PHI, PSI)
         IF ((PSIL*PSI).LT.0.0) GO TO 40
         TLAST = T
         PSIL = PSI
         T = T – 50.
 10      CONTINUE
 40      IF (T.GE.0.0) GO TO 45
         WRITE (3, 2)
  2      FORMAT (1X, 'T LESS THAN ZERO -- ERROR')
         STOP
 C   **APPLY REGULA-FALSI
 45      DO 50 I = 1, 20
         IF (I.NE.1) T2L = T2
         T2 = (T*PSIL-TLAST*PSI)/(PSIL-PSI)
         IF (ABS(T2-T2L).LT.0.01) GO TO 99
         CALL PSICAL (T2, PHIT, PSIT)
         IF (PSIT.EQ.0) GO TO 99
         IF ((PBIT*PBIL).GT.0.0) PSIL = PSIT
         IF ((PSIT*PSIL).GT.0.0) TLAST = T2
         IF ((PSIT*PSI).GT.0.0) PSI = PSIT
         IF ((PSIT*PSI).GT.0.0) T = T2
 50      CONTINUE
         IF (I.EQ.20) WRITE (3, 3)
  3      FORMAT ('0', 'REGULA-FALSI DID NOT CONVERGE IN 20 ITERATIONS')
 93      STOP
         END
         SUBROUTINE PSICAL (T, PHI, PSI)
         REAL KF
         PHI = (3052 + 36.2*T + 36.2*T + 0.05943*T**2)/(127240. – 11.35*T
       * – 0.0636*T**2)
         KP = 7.28E6*EXP(-17000./T)
         FBI = SQRT((KP/(1. + KP)) – 1./12. + PHI)
         WRITE (3, 1) T, PSI
  1      FORMAT (6X, 'T =', F6.2, 4X, 'PSI =', E11,4)
         RETURN
         END
```

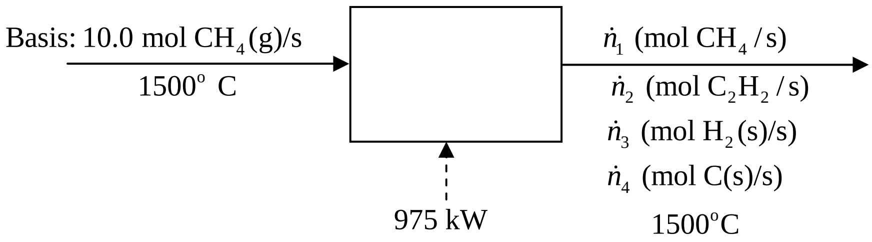
OUTPUT:

```
SOLUTION TO PROBLEM 9-35
T = 1200.00    PSI = 0.8226E + 00
T = 1150.00    PSI = 0.7048E + 00
T = 1100.00    PSI = 0.5551E + 00
T = 1050.00    PSI = 0.3696E + 00
T = 1000.00    PSI = 0.1619E + 00
T = 950.00     PSI = –0.3950E – 01
T = 959.80     PSI = –0.1824E – 02
T = 960.25     PSI = –0.7671E – 04
T = 960.27     PSI = –0.3278E – 05
```

Solution: $T = 960.3$ K, $f = 0.360$ mol C_2H_6 reacted/mol fed

9.36

$$2CH_4 \rightarrow C_2H_2 + 3H_2$$
$$C_2H_2 \rightarrow 2C(s) + H_2$$



a.

<u>60% conversion</u> $\Rightarrow \dot{n}_1 = 10(1-0.600) = \underline{\underline{4.00 \text{ mol } CH_4/s}}$

<u>C balance:</u> $10(1) = 4(1) + 2\dot{n}_2 + \dot{n}_4 \Rightarrow 2\dot{n}_2 + \dot{n}_4 = 6$ (1)

<u>H balance:</u> $10(4) = 4(4) + 2\dot{n}_2 + 2\dot{n}_3 \Rightarrow 2\dot{n}_2 + 2\dot{n}_3 = 24$ (2)

<u>References for enthalpy calculations</u> : C(s), $H_2(g)$ at 25°C

$$H_i = \left(\Delta\hat{H}_f^o\right)_i + C_{pi}(1500-25),\ i = CH_4, C_2H_2, C, H_2$$

Substance	$\dot{n}_{in}$ (mol/s)	$\hat{H}_{in}$ (kJ/mol)	$\dot{n}_{out}$ (mol/s)	$\hat{H}_{out}$ (kJ/mol)
$CH_4(g)$	10	41.68	4	41.68
$C_2H_2(g)$	–	–	$\dot{n}_2$	303.45
$H_2(g)$	–	–	$\dot{n}_3$	45.72
C(s)	–	–	$\dot{n}_4$	32.45

<u>Energy Balance</u>: $Q = \Delta H \Rightarrow 975 \text{ kJ/s} = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i$ (3)

$$\text{Solve (1) - (3) simultaneously} \Rightarrow \begin{cases} \dot{n}_2 = \underline{\underline{2.50 \text{ mol } C_2H_2/s}} \\ \dot{n}_3 = \underline{\underline{9.50 \text{ mol } H_2/s}} \\ \dot{n}_4 = \underline{\underline{1.00 \text{ mol C/s}}} \end{cases}$$

<u>Yield of acetylene</u> $= \dfrac{2.50 \text{ mol } C_2H_2/s}{6.00 \text{ mol } CH_4 \text{ consumed}/s} = \underline{\underline{0.417 \text{ mol } C_2H_2/\text{mol } CH_4 \text{ consumed}}}$

b.

If no side reaction,

$\dot{n}_1 = 10.0(1-0.600) = \underline{\underline{4.00 \text{ mol } CH_4/s}}$

$\dot{n}_3 = 0 \Rightarrow \dot{n}_2 = \underline{\underline{3.00 \text{ mol } C_2H_2/s}},\ \dot{n}_4 = \underline{\underline{9.00 \text{ mol } H_2/s}}$

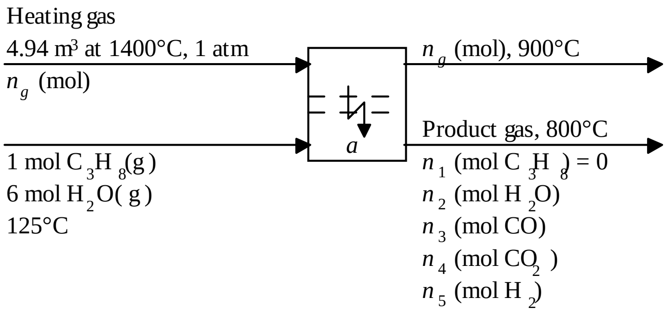
<u>Yield of acetylene</u> $= \dfrac{3.00 \text{ mol } C_2H_2/s}{6.00 \text{ mol } CH_4 \text{ consumed}/s} = \underline{\underline{0.500 \text{ mol } C_2H_2/\text{mol } CH_4 \text{ consumed}}}$

<u>Reactor Efficiency</u> $= \dfrac{0.417}{0.500} = \underline{\underline{0.834}}$

9.37 $C_3H_8(g) + 3H_2O(v) \rightarrow 3CO(g) + 7H_2(g)$

$CO(g) + H_2O(v) \rightarrow CO_2(g) + H_2(g)$

<u>Basis</u>: 1 mol C_3H_8 fed



$$n_g = \frac{4.94\text{ m}^3}{} \left| \frac{10^3\text{ L}}{1\text{ m}^3} \right| \frac{273\text{ K}}{1673\text{ K}} \left| \frac{1\text{ mol}}{22.4\text{ L}} \right. = 35.99\text{ mol heating gas}$$

Let ξ_1 and ξ_2 be the extents of the two reactions.

$$n_1 = 1 - \xi_1 \overset{n_1=0}{\Rightarrow} \xi_1 = 1\text{ mol} \qquad n_4 = \xi_2$$

$$n_2 = 6 - 3\xi_1 - \xi_2 \overset{\xi_1=1}{\Rightarrow} n_2 = 3 - \xi_2 \qquad n_5 = 7\xi_1 + \xi_2 \overset{\xi_1=1}{\Rightarrow} n_5 = 7 + \xi_2$$

$$n_3 = 3\xi_1 - \xi_2 \overset{\xi_1=1}{\Rightarrow} n_3 = 3 - \xi_2$$

<u>References</u>: C(s), $H_2(g), O_2(g)$ at 25°C, heating gas at 900°C

$$\hat{H}_i = \Delta\hat{H}^o_{fi} + \int_{25}^{T} C_{pi}\,dT \qquad \text{for } C_3H_8$$

$$= \text{Table B.8 for } CO_2, H_2, H_2O, CO$$

$$= \int_{900}^{T} C_p\,dT = C_p(T - 900) \text{ for heating gas}$$

Substance	n_{in} mol	$\hat{H}_{\text{in}}$ kJ / mol	n_{out} mol	$\hat{H}_{\text{out}}$ kJ / mol
C_3H_8	1	–95.39	0	–
H_2O	6	–238.43	$3-\xi_2$	–212.78
CO	–	–	$3-\xi_2$	–86.39
CO_2	–	–	ξ_2	–356.15
H_2	–	–	$7+\xi_2$	22.85
heating gas	35.99	200.00	35.99	0

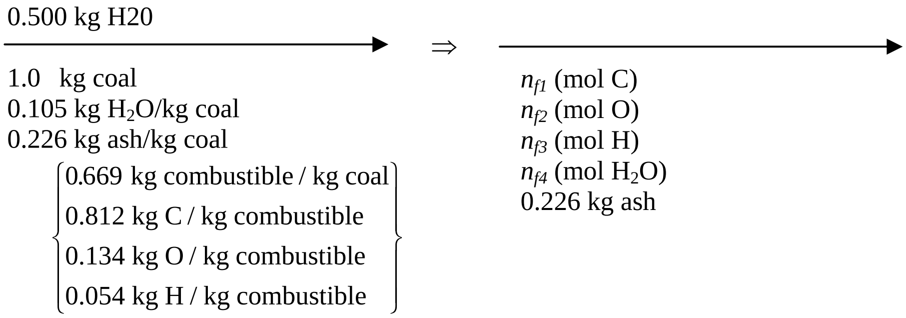
<u>Energy Balance</u>:

$$\sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = 0 \Rightarrow \xi_2 = 2.00\text{ mol} \Rightarrow n_2 = 1\text{ mol } H_2O,\ n_3 = 1\text{ mol CO},$$

$$n_4 = 1\text{ mol } CO_2, n_5 = 9\text{ mol } H_2 \Rightarrow \underline{\underline{7.7\text{ mol \% } H_2O,\ 7.7\%\text{ CO},\ 15.4\%\ CO_2,\ 69.2\%\ H_2}}$$

9.38 **a.** Any C consumed in reaction (2) is lost to reaction (1). Without the energy released by reaction (2) to compensate for the energy consumed by reaction (1), the temperature in the adiabatic reactor and hence the reaction rate would drop.

b. Basis : 1.00 kg coal fed (+0.500 kg H_20)

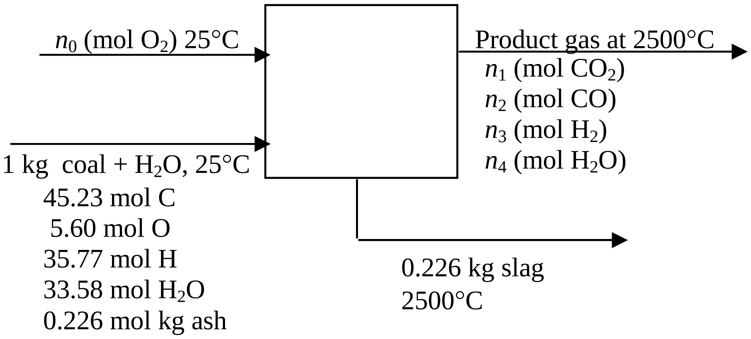


$$n_{f1} = [\,(1.00)(0.669)(0.812)\text{ kg C}][1\text{ mol C}/12.01\times10^{-3}\text{ kg}] = 45.23\text{ mol C}$$

$$n_{f2} = (1.00)(0.669)(0.134)\ /16.0\times10^{-3} = 5.6\text{ mol O}$$

$$n_{f3} = (1.00)(0.669)(0.054)\ /1.01\times10^{-3} = 35.77\text{ mol H}$$

$$n_{f4} = [\,(0.500+0.105)\text{ kg}][1\text{ mol }H_2O/18.016\times10^{-3}\text{ kg}] = 33.58\text{ mol }H_2O$$



$$\underline{\text{Reactive oxygen (O) available}} = (2n_0+5.60)\text{ mol O}$$

$$\underline{\text{Oxygen consumed by H}}\ \ (2\text{H+O}\rightarrow H_2O):\ \frac{35.77\text{ mol H}}{}\left|\frac{1\text{ mol O}}{2\text{ mol H}}\right.=17.88\text{ mol O}$$

$$\Rightarrow\ \text{Reactive O remaining} = (2n_0+5.60)-17.88 = (2n_0-12.28)\text{ mol O}$$

$$\underline{CO_2\text{ formed}}\ \ (\text{C+2O}\rightarrow CO_2):n_1 = \frac{(2n_0-12.28)\text{ mol O}}{}\left|\frac{1\text{ mol }CO_2}{2\text{ mol O}}\right.=\underline{\underline{(n_0-6.14)\text{ mol }CO_2}}$$

$$\underline{\text{C balance}}: 45.23 = n_1+n_2 \overset{n_1=n_0-6.14}{\Longrightarrow} n_2 = \underline{\underline{(51.37-n_0)\text{ mol CO}}}$$

$$\underline{\text{O balance}}: 2n_0+5.60+33.58 = 2n_1+n_2+n_4 \underset{n_2=51.37-n_0}{\overset{n_1=n_0-6.14}{\Longrightarrow}} n_4 = \underline{\underline{(n_0+0.06)\text{ mol }H_2O}}$$

$$\underline{\text{H balance}}: 35.77+2(33.58) = 2n_3+2n_4 \overset{n_4=n_0+0.06}{\Longrightarrow} n_3 = \underline{\underline{(51.37-n_0)\text{ mol }H_2}}$$

9.38 (cont'd)

c. 1 kg coal contains 45.23 mol C and 35.77 mol H

$\Rightarrow$ 1 kg coal $+ \text{nO}_2 \rightarrow 45.23\ \text{CO}_2 + (35.77/2)$ mol H_2O (l)

$\Delta\hat{H}_r = -21{,}400\ \text{kJ} = 45.23(\Delta\hat{H}_\text{f}^\text{o})_{\text{CO}_2} + (35.77/2)(\Delta\hat{H}_\text{f}^\text{o})_{\text{H}_2\text{O(l)}} - (\Delta\hat{H}_\text{f}^\text{o})_{\text{coal}}$

$\Rightarrow \underline{\underline{(\Delta\hat{H}_\text{f}^\text{o})_{\text{coal}} = -1510\ \text{kJ/kg}}}$

References : C(s), O_2(g), H_2(g), ash(s) at 25°C

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
CO_2	–	–	$n_0 - 6.14$	$\hat{H}_1$
CO	–	–	$51.37 - n_0$	$\hat{H}_2$
H_2	–	–	$51.37 - n_0$	$\hat{H}_3$
H_2O	33.58	$\hat{H}_0$	$n_0 + 0.06$	$\hat{H}_4$
Coal	1 kg	–1510 kJ/kg	–	–
Ash(slag)	(in coal)	0	0.266 kg	$\hat{H}_5$(kJ/kg)

$\hat{H}_i = \Delta\hat{H}_{fi}^\text{o} + C_{pi}(2500 - 25),\ i = 1,3$

$\hat{H}_1 = -393.5 + 0.0508(2475) = -267.8$ kJ/mol CO_2

$\hat{H}_2 = -110.52 + 0.0332(2475) = -28.35$ kJ/mol CO

$\hat{H}_3 = 0.0300(2475) = 74.25$ kJ/mol H_2

$\hat{H}_4 = -241.83 + 0.0395(2475) = -144.07$ kJ/mol H_2O

$\hat{H}_5 = (\Delta\hat{H}_\text{m})_{\text{ash}} + 1.4(2475) = 710 + 1.4(2475) = 4175$ kJ/kg ash

Energy Balance

$\Delta H = \sum n_{out}\hat{H}_{out} - \sum n_{in}\hat{H}_{in} = 0 \Rightarrow n_0 = \underline{\underline{35.4\ \text{mol O}_2}}$

9.39

$$\underline{\text{Mass of } H_2SO_4} = \begin{array}{c|c|c|}3\text{ m}^3 & 10^3\text{ L} & 1\text{ mol } H_2SO_4 \\ \hline & 1\text{ m}^3 & \text{L}\end{array} = 3000\text{ mol } H_2SO_4\left(\frac{98.02\text{ g}}{1\text{ mol}}\right) = 2.941\times10^5\text{ g } H_2SO_4$$

$$\underline{\text{Mass of solution}} = \begin{array}{c|c|c|c}3\text{ m}^3 & 10^3\text{ L} & 10^3\text{ mL} & 1.064\text{ g} \\ \hline & 1\text{ m}^3 & \text{L} & 1\text{ mL}\end{array} = 3.192\times10^6\text{ g solution}$$

$$\Rightarrow \underline{\text{Moles of } H_2O} = (3.192\times10^6 - 2.941\times10^5)\text{g } H_2O\left(\frac{1\text{ mol}}{18.02\text{ g}}\right) = 1.61\times10^5\text{ mol } H_2O$$

$$n\left(\frac{\text{mol } H_2O}{\text{mol } H_2SO_4}\right) = \frac{1.61\times10^5\text{ mol } H_2O}{3000\text{ mol } H_2SO_4} = 53.6\text{ mol } H_2O/\text{mol } H_2SO_4$$

$$\left(\Delta\hat{H}_\text{f}\right)_{H_2SO_4(\text{aq., r=53.6})} = \underset{\underset{\text{Table B.1}}{\uparrow}}{\left(\Delta\hat{H}_\text{f}^\text{o}\right)_{H_2SO_4(\text{l})}} + \underset{\underset{\text{Table B.11}}{\uparrow}}{\left(\Delta\hat{H}_\text{s}\right)_{H_2SO_4(\text{aq., r=53.6})}} = \left(-811.32-73.39\right)\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-884.7\text{ kJ/mol}}}$$

$$H = (3000\text{ mol } H_2SO_4)(\text{-}884.7\text{ kJ / mol } H_2SO_4) = \underline{\underline{\text{-}2.65\times10^6\text{ kJ}}}$$

9.40

$$\underline{\text{HCl (aq):}}\ \ \Delta\hat{H}_\text{f}^\text{o} = \left(\Delta\hat{H}_\text{f}^\text{o}\right)_{\text{HCl(g)}} + \left(\Delta\hat{H}_\text{s}^\text{o}\right)_\infty \overset{\text{Tables B.1, B11}}{=} -92.31-75.14 = -167.45\text{ kJ/mol}$$

$$\underline{\text{NaOH (aq):}}\ \ \Delta\hat{H}_\text{f}^\text{o} = \left(\Delta\hat{H}_\text{f}^\text{o}\right)_{\text{NaOH(s)}} + \left(\Delta\hat{H}_\text{s}^\text{o}\right)_\infty \overset{\overset{\text{Tables B1, B.11}}{\downarrow}}{=} -426.6-42.89 = -469.49\text{ kJ/mol}$$

$$\underline{\text{NaCl (aq):}}\ \ \Delta\hat{H}_\text{f}^\text{o} = \left(\Delta\hat{H}_\text{f}^\text{o}\right)_{\text{NaCl(s)}} + \left(\Delta\hat{H}_\text{s}^\text{o}\right)_\infty = \overset{\overset{\text{Table B.1}}{\downarrow}}{-411.0} + \overset{\overset{\text{Given}}{\downarrow}}{4.87} = -406.1\text{ kJ/mol}$$

$$\text{HCl(aq)} + \text{NaOH(aq)} \rightarrow \text{NaCl(aq)} + H_2O(\text{l})$$

$$\Delta\hat{H}_\text{r}^\text{o} = \left[-406.1-285.84-(-167.45)-(-469.49)\right] = \underline{\underline{-55.0\text{ kJ/mol}}}$$

$$\text{HCl(g)} + \text{NaOH(s)} \rightarrow \text{NaCl(s)} + H_2O(\text{l})$$

$$\Delta\hat{H}_\text{r}^\text{o} = \sum_{\text{products}} v_i\Delta\hat{H}_\text{f}^\text{o} - \sum_{\text{reactants}} v_i\Delta\hat{H}_\text{f}^\text{o}$$

$$= \left[-411.0-285.84-(-92.31)-(-426.6)\right]\text{ kJ/mol} = \underline{\underline{-177.9\text{ kJ/mol}}}$$

The difference between the two calculated values equals

$$\left\{\left(\Delta\hat{H}_\text{s}\right)_\text{NaCl} - \left(\Delta\hat{H}_\text{s}\right)_\text{HCl} - \left(\Delta\hat{H}_\text{s}\right)_\text{NaOH}\right\}.$$

9.41 **a.**

$$H_2SO_4(\text{aq}) + 2\text{NaOH(aq)} \rightarrow Na_2SO_4(\text{aq}) + 2H_2O(\text{l})$$

$$\underline{\text{Basis}}\text{: } 1\text{ mol } H_2SO_4\text{ soln} \Rightarrow \left.\begin{array}{l}0.10\text{ mol } H_2SO_4\times(98.08\text{ g/mol}) = 9.808\text{ g } H_2SO_4 \\ 0.90\text{ mol } H_2O\times(18.02\text{ g/mol}) = 16.22\text{ g } H_2O\end{array}\right\}$$

$$\Rightarrow \begin{array}{c|c}26.03\text{ g soln} & 1\text{ cm}^3 \\ \hline & 1.27\text{ g}\end{array} = 20.49\text{ cm}^3$$

$$\Rightarrow \begin{array}{c|c|c|c}0.10\text{ mol } H_2SO_4 & 2\text{ mol NaOH} & 1\text{ liter caustic soln} & 10^3\text{ cm}^3 \\ \hline & 1\text{ mol } H_2SO_4 & 3\text{ mol NaOH} & 1\text{ L}\end{array} = 66.67\text{ cm}^3\text{ NaOH(aq)}$$

9.41 (cont'd)

$$\underline{\text{Volume ratio}} = \frac{66.67\ \text{cm}^3\ \text{NaOH(aq)}}{20.49\ \text{cm}^3\ \text{H}_2\text{SO}_4\text{(aq)}} = \underline{\underline{3.25\ \text{cm}^3 \text{caustic solution / cm}^3\ \text{acid solution}}}$$

b. $\underline{H_2SO_4(aq)}$: $r = 9 \text{ mol } H_2O / 1 \text{ mol } H_2SO_4$

$$\left(\Delta\hat{H}_f^o\right)_{soln} = \left(\Delta\hat{H}_f^o\right)_{H_2SO_4(l)} + \left(\Delta\hat{H}_f^o\right)_{H_2SO_4(aq.,\, r=9)} = (-811.32 - 65.23)\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-877\ \text{kJ/mol H}_2\text{SO}_4}}$$

$\underline{\text{NaOH(aq)}}$: The solution fed contains $\left(66.67\ \text{cm}^3\right)\left(1.13\ \text{g/cm}^3\right) = 75.34$ g , and

$(0.2 \text{ mol NaOH})(40.00\ \text{g/mol}) = 8.00 \text{ g NaOH}$

$\Rightarrow (75.34 - 8.00) \text{ g } H_2O \Rightarrow (67.39 \text{ g } H_2O)(1 \text{ mol}/18.02 \text{ g}) = 3.74 \text{ mol } H_2O$

$\Rightarrow r = 3.74 \text{ mol } H_2O/0.20 \text{ mol NaOH} = 18.7 \text{ mol } H_2O / \text{mol NaOH}$

$$\left(\Delta\hat{H}_f^o\right)_{soln} = \left(\Delta\hat{H}_f^o\right)_{NaOH(s)} + \left(\Delta\hat{H}_s^o\right)_{NaOH(s)(aq.,\, r=18.7)} = (-426.6 - 42.8)\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-469.4\ \text{kJ/mol NaOH}}}$$

$\underline{Na_2SO_4(aq)}$:

$$\left(\Delta\hat{H}_f^o\right)_{soln} = \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(s)} + \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(aq)} = (-1384.5 - 1.17)\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-1385.7\ \text{kJ/mol Na}_2\text{SO}_4}}$$

$\underline{\text{Extent of reaction}}$: $(n_{H_2SO_4})_{final} = (n_{H_2SO_4})_{fed} + \nu_{H_2SO_4}\xi \Rightarrow 0 = 0.10\text{mol} - (1)\xi \Rightarrow \xi = 0.10 \text{ mol}$

$\underline{\text{Energy Balance}}$:

$$Q = \Delta H = \xi\Delta\hat{H}_r^o = \xi\left[(\Delta\hat{H}_f^o)_{Na_2SO_4(aq)} + 2(\Delta\hat{H}_f^o)_{H_2O(l)} - (\Delta\hat{H}_f^o)_{H_2SO_4(aq)} - 2(\Delta\hat{H}_f^o)_{NaOH(aq)}\right]$$

$$= (0.10 \text{ mol})\left[-1385.7 + 2(-285.84) - (-876.55) - (2)(-469.4)\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{-14.2\ \text{kJ}}}$$

9.42 **a.**

$$\underline{\text{NaCl(aq)}}:\ \Delta\hat{H}_f^o = \left(\Delta\hat{H}_f^o\right)_{NaCl(s)} + \left(\Delta\hat{H}_s^o\right)_\infty \overset{\substack{\text{Table B.1,}\\ \text{given}\\ \downarrow}}{=} (-411.0 + 4.87)\text{kJ / mol} = \underline{\underline{-406.1\ \text{kJ/mol}}}$$

$\underline{\text{NaOH(aq)}}$:

$$\Delta\hat{H}_f^o = \left(\Delta\hat{H}_f^o\right)_{NaOH(s)} + \left(\Delta\hat{H}_s^o\right)_\infty \overset{\substack{\text{Table B.1}\\ \downarrow}}{=} (-426.6 - 42.89)\text{kJ / mol} = \underline{\underline{-469.5\ \text{kJ/mol}}}$$

$$NaCl(aq) + H_2O(l) \rightarrow \frac{1}{2}H_2(g) + \frac{1}{2}Cl_2(g) + NaOH(aq)$$

$$\Delta\hat{H}_r^o = \left[-469.5 - (-406.1) - (-285.84)\right]\text{kJ/mol} = \underline{\underline{222.44\ \text{kJ/mol}}}$$

b.

$$\frac{8500 \text{ ktonne } Cl_2}{\text{yr}}\left|\frac{10^3 \text{ tonne}}{1 \text{ ktonne}}\right|\frac{10^3 \text{ kg}}{1 \text{ tonne}}\left|\frac{10^3 \text{ g}}{1 \text{ kg}}\right|\frac{1 \text{ mol } Cl_2}{70.91 \text{ g } Cl_2}\left|\frac{222.44 \text{ kJ}}{0.5 \text{ mol } Cl_2}\right|$$

$$\frac{10^3 \text{ J}}{1 \text{ kJ}}\left|\frac{2.778\times10^{-7}\text{kW}\cdot\text{h}}{1 \text{ J}}\right|\frac{1 \text{ MW}\cdot\text{h}}{10^3 \text{ kW}\cdot\text{h}}\Bigg| = \underline{\underline{1.48\times10^7\ \text{MW}\cdot\text{h / yr}}}$$

9.43 **a.**

$$\mathrm{CaCl_2(s)+10H_2O(l)\rightarrow CaCl_2(aq,\ r=10)} \qquad (1) \quad \Delta\hat{H}^{\mathrm{o}}_{\mathrm{r1}}=-64.85\ \mathrm{kJ/mol}$$

$$\mathrm{CaCl_2\cdot 6H_2O(s)+4H_2O(l)\rightarrow CaCl_2(aq,\ r=10)} \qquad (2) \quad \Delta\hat{H}^{\mathrm{o}}_{\mathrm{r2}}=+32.41\ \mathrm{kJ/mol}$$

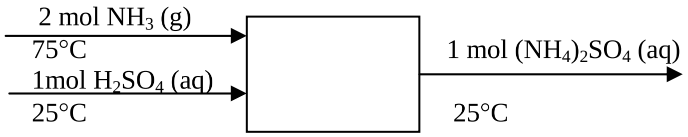
$$(1)-(2)\Rightarrow \mathrm{CaCl_2(s)+6H_2O(l)\rightarrow CaCl_2\cdot 6H_2O(s)} \qquad (3)$$

$$\Rightarrow \Delta\hat{H}^{\mathrm{o}}_{\mathrm{r3}}=\Delta\hat{H}^{\mathrm{o}}_{\mathrm{r1}}-\Delta\hat{H}^{\mathrm{o}}_{\mathrm{r2}}\ (\text{Hess's law})=\underline{\underline{-97.26\ \mathrm{kJ/mol}}}$$

b. From (1), $\Delta\hat{H}^{\mathrm{o}}_{\mathrm{r1}}=\left(\Delta\hat{H}^{\mathrm{o}}_{\mathrm{f}}\right)_{\mathrm{CaCl_2(aq,\ r=10)}}-\left(\Delta\hat{H}^{\mathrm{o}}_{\mathrm{f}}\right)_{\mathrm{CaCl_2(s)}}$

$$\Rightarrow\left(\Delta\hat{H}^{\mathrm{o}}_{\mathrm{f}}\right)_{\mathrm{CaCl_2(aq,\ r=10)}}=(-64.85-794.96)\ \mathrm{kJ/mol}=\underline{\underline{-859.81\ \mathrm{kJ/mol}}}$$

9.44 Basis: 1 mol $\mathrm{(NH_4)_2SO_4}$ produced



$$\mathrm{2NH_3(g)+H_2SO_4(aq)\rightarrow(NH_4)_2SO_4(aq)}$$

a. References : Elements at 25°C

$$\underline{\mathrm{NH_3(g,\ 75^\circ C)}}:\ \hat{H}=\Delta\hat{H}^{\mathrm{o}}_{\mathrm{f}}+\int_{25}^{75}C_p\,dT=\left(-46.19+1.83\right)\mathrm{kJ\,/\,mol}=-44.36\ \mathrm{kJ/mol}\ \ (\text{Table B.1, B.2})$$

$$\underline{\mathrm{H_2SO_4(aq,\ 25^\circ C)}}:\ \hat{H}=\left(\Delta\hat{H}^{\mathrm{o}}_{\mathrm{f}}\right)_{\mathrm{H_2SO_4(aq)}}=-907.51\ \mathrm{kJ/mol\ H_2SO_4}\ \ (\text{Ta.ble B.1})$$

$$\underline{\mathrm{(NH_4)_2SO_4(aq,\ 25^\circ C)}}:\ \hat{H}=\left(\Delta\hat{H}^{\mathrm{o}}_{\mathrm{f}}\right)_{\mathrm{(NH_4)_2SO_4(aq)}}=-1173.1\ \mathrm{kJ/mol\ (NH_4)_2SO_4}\ \ (\text{Table B.1})$$

Energy balance:

$$Q=\Delta H=\sum_{\text{out}}n_i\hat{H}_i-\sum_{\text{in}}n_i\hat{H}_i=(1)(-1173.1)-(2)(-44.36)-(1)(-907.51)\ \mathrm{kJ}$$

$$=-177\ \mathrm{kJ}\Rightarrow\underline{\underline{177\ \frac{\text{kJ withdrawn}}{\text{mol }\mathrm{(NH_4)_2SO_4}\text{ produced}}}}$$

b. 1 mole % $\mathrm{(NH_4)_2SO_4}$ solution $\Rightarrow \dfrac{1\ \mathrm{mol\ (NH_4)_2SO_4}\ \big|\ 132\ \mathrm{g}}{\big|\ \mathrm{mol}}=132\ \mathrm{g\ (NH_4)_2SO_4}$

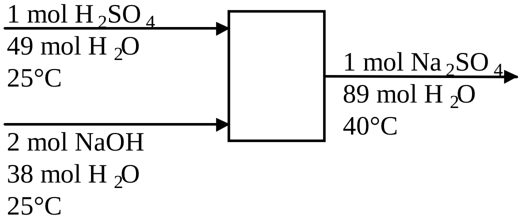
$$\frac{99\ \mathrm{mol\ H_2O}\ \big|\ 18\ \mathrm{g}}{\big|\ \mathrm{mol}}=\frac{1782\ \mathrm{g\ H_2O}}{1914\ \text{g solution}}$$

The heat transferred from the reactor in part (a) now goes to heat the product solution from

$$25^\circ\mathrm{C}\ \text{to}\ T_{\text{final}}\ \Rightarrow 177\ \mathrm{kJ}=\frac{1.914\mathrm{g}\ \big|\ 1\ \mathrm{kg}\ \big|\ 4.184\ \mathrm{kJ}\ \big|\ (T-25)^\circ\mathrm{C}}{\big|\ 10^3\ \mathrm{g}\ \big|\ \mathrm{kg}^\circ\mathrm{C}\ \big|}\ \Rightarrow T_{\text{final}}=\underline{\underline{47.1^\circ\mathrm{C}}}$$

c. In a real reactor, the final solution temperature will be less than the value calculated in part b, due to heat loss to the surroundings. The final temperature will therefore be <u>less</u> than 47.1°C.

9.45 **a.** $H_2SO_4(aq)+2NaOH(aq)\rightarrow Na_2SO_4(aq)+2H_2O(aq)$ $\quad$ Basis: 1 mol H_2SO_4 fed



Reference states: $Na(s), H_2(g), S(s), O_2(g)$ at 25°C

$H_2SO_4(aq, r=49, 25^\circ C)$:

$$n\hat{H}=(1\text{ mol }H_2SO_4)\left[\left(\Delta\hat{H}_f^o\right)_{H_2SO_4(l)}+\Delta\hat{H}_s^o(r=49)\right](\text{kJ/mol})+49\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$$=(1)[-811.3-73.3]=-884.6\text{ kJ}+49\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$NaOH(aq, r=19, 25^\circ C)$:

$$n\hat{H}=(2\text{ mol NaOH})\left[\left(\Delta\hat{H}_f^o\right)_{NaOH(s)}+\Delta\hat{H}_s^o(r=19)\right](\text{kJ/mol})+38\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$$=(2)[-426.6-42.8]=-938.8\text{ kJ}+38\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$Na_2SO_4(aq, r=89, 40^\circ C)$:

$$\frac{1\text{ kmol }Na_2SO_4}{}\left|\frac{142.0\text{ kg}}{1\text{ kmol}}\right.=0.142\text{ kg},\quad \frac{89\text{ kmol }H_2O}{}\left|\frac{18.02\text{ kg}}{1\text{ kmol}}\right.=1.604\text{ kg}\Rightarrow 1.746\text{ kg}$$

$$n\hat{H}=(1\text{ mol }Na_2SO_4)\left[\left(\Delta\hat{H}_f^o\right)_{Na_2SO_4}+\left(\Delta\hat{H}_s^o\right)_{Na_2SO_4}\right]+89\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}+mC_p(40-25)$$

$$\Big\Downarrow\ \begin{array}{l}\Delta\hat{H}_f^o=-1384.5\text{ kJ/mol(Table B.1)}\\ \Delta\hat{H}_s^o=-1.2\text{ kJ/mol}\\ m=1.746\text{ kg},\ C_p\approx\left(C_p\right)_{H_2O(l)}=4.814\text{ kJ/(kg}\cdot^\circ\text{C)}\end{array}$$

$$n\hat{H}=-1276\text{ kJ}+89\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

Energy balance: $Q=\Delta H=\sum\limits_{out}n_i\hat{H}_i-\sum\limits_{in}n_i\hat{H}_i=547.4+2\overset{-285.84\text{ kJ/mol}}{\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}}=-24.3\text{ kJ}$

Mass of acid fed

$$\frac{1\text{ mol }H_2SO_4}{}\left|\frac{98.08\text{ g }H_2SO_4}{1\text{ mol}}\right.+\frac{49\text{ mol }H_2O}{}\left|\frac{18.02\text{ g }H_2O}{1\text{ mol}}\right.=981\text{ g}=0.981\text{ kg}$$

$$\Rightarrow\frac{Q}{M_{acid}}=\frac{-24.3\text{ kJ}}{0.981\text{ kg acid}}\Rightarrow \underline{\underline{24.8\text{ kJ / kg acid transferred from reactor contents}}}$$

b. If the reactor is adiabatic, the heat transferred from the reactor of Part(a) instead goes to heat the product solution from 40°C to T_f

$$\Rightarrow 24.3\times10^3\text{ J}=\frac{1.746\text{ kg}}{}\left|\frac{4.184\text{ kJ}}{\text{kg}\cdot^\circ\text{C}}\right|\frac{(T_f-40)^\circ\text{C}}{}\Rightarrow T_f=\underline{\underline{43^\circ\text{C}}}$$

9.46 **a.** $H_2SO_4(aq) + 2NaOH(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(l)$

$\underline{H_2SO_4\text{ solution:}}$:

$$75\text{ ml of 4M }H_2SO_4\text{ solution} \Rightarrow \frac{4\text{ mol }H_2SO_4}{1\text{ L acid soln}}\bigg|\frac{1\text{ L}}{10^3\text{ mL}}\bigg|\frac{75\text{ mL}}{} = 0.30\text{ mol }H_2SO_4$$

$$(75\text{ mL})(1.23\text{ g/mL}) = 92.25\text{ g},\quad (0.3\text{ mol }H_2SO_4)(98.08\text{ g/mol}) = 29.42\text{ g }H_2SO_4$$

$$\Rightarrow (92.25-29.42)\text{ g }H_2O \Rightarrow (62.83\text{ g }H_2O)(1\text{ mol/18.02 g}) = 3.49\text{ mol }H_2O$$

$$\Rightarrow r = 3.49\text{ mol }H_2O/0.30\text{ mol }H_2SO_4 = 11.63\text{ mol }H_2O/\text{mol }H_2SO_4$$

$$\left(\Delta\hat{H}_f^o\right)_{soln} = \left(\Delta\hat{H}_f^o\right)_{H_2SO_4(l)} + \left(\Delta\hat{H}_f^o\right)_{H_2SO_4(aq.,\, r=11.63)} \overset{\substack{\text{Table B.1,}\\ \text{Table B.11}\\ \downarrow}}{=} (-811.32-67.42)\frac{\text{kJ}}{\text{mol}}$$

$$= -878.74\text{ kJ/mol }H_2SO_4$$

<u>NaOH solution required:</u>

$$\frac{0.30\text{ mol }H_2SO_4}{}\bigg|\frac{2\text{ mol NaOH}}{1\text{ mol }H_2SO_4}\bigg|\frac{1\text{ L NaOH(aq)}}{12\text{ mol NaOH}}\bigg|\frac{10^3\text{ mL}}{1\text{ L}} = \underline{\underline{50.00\text{ mL NaOH(aq)}}}$$

$$(50.00\text{ mL})(1.37\text{ g/mL}) = 68.5\text{ g}$$

$$\frac{12\text{ mol NaOH}}{1\text{ L NaOH(aq)}}\bigg|\frac{1\text{ L}}{10^3\text{ mL}}\bigg|\frac{50\text{ mL}}{}\bigg| = 0.60\text{ mol NaOH} \overset{40\text{ g/mol NaOH}}{\Longrightarrow} 24.00\text{ g NaOH}$$

$$\Rightarrow (68.5-24.00)\text{ g }H_2O \Rightarrow (44.5\text{ g }H_2O)(1\text{ mol/18.02 g}) = 2.47\text{ mol }H_2O$$

$$\Rightarrow r = 2.47\text{ mol }H_2O/0.6\text{ mol NaOH} = \frac{4.12\text{ mol }H_2O}{\text{mol NaOH}}$$

$$\left(\Delta\hat{H}_f^o\right)_{soln} = \left(\Delta\hat{H}_f^o\right)_{NaOH(s)} + \left(\Delta\hat{H}_s^o\right)_{NaOH(s)(aq.,\, r=4.12)} = (-426.6-35.10)\frac{\text{kJ}}{\text{mol}}$$

$$= -461.70\text{ kJ/mol NaOH}$$

$\underline{Na_2SO_4(aq)}$:

$$\left(\Delta\hat{H}_f^o\right)_{soln} = \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(s)} + \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(aq)} = (-1384.5-1.17)\frac{\text{kJ}}{\text{mol}} = -1385.7\text{ kJ/mol }Na_2SO_4$$

m_{total} = total mass of reactants or products = (92.25g H_2SO_4 soln + 68.5g NaOH) = 160.75g = 0.161 kg

<u>Extent of reaction</u>: $(n_{H_2SO_4})_{final} = (n_{H_2SO_4})_{fed} + \nu_{H_2SO_4}\xi \Rightarrow 0 = 0.30\text{ mol} - (1)\xi \Rightarrow \xi = 0.30\text{ mol}$

<u>Standard heat of reaction</u>

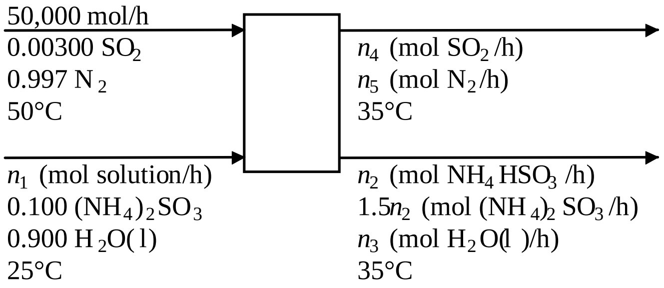
$$\Delta\hat{H}_r^o = \left(\Delta\hat{H}_f^o\right)_{Na_2SO_4(aq)} + 2\left(\Delta\hat{H}_f^o\right)_{H_2O(l)} - \left(\Delta\hat{H}_f^o\right)_{H_2SO_4(aq)} - 2\left(\Delta\hat{H}_f^o\right)_{NaOH(aq)}$$

<u>Energy Balance</u>: $Q = \Delta H = \xi\Delta\hat{H}_r^o + m_{total}C_p(T-25)^\circ\text{C}$

$$= (0.30\text{ mol})(155.2\text{ kJ/mol}) + (0.161\text{ kg})\left(4.184\ \frac{\text{kJ}}{\text{kg }^\circ\text{C}}\right)(T-25)^\circ\text{C} = 0 \Rightarrow T = \underline{\underline{94^\circ\text{C}}}$$

b. Volumes are additive.
Heat transferred to and through the container wall is negligible.

9.47 Basis : 50,000 mol flue gas/h



90% SO_2 removal: $\dot{n}_4 = 0.100(0.00300)(50{,}000 \text{ mol/h}) = 15.0 \text{ mol } SO_2/\text{h}$

N_2 balance: $\dot{n}_5 = (0.997)(50{,}000 \text{ mol/h}) = 49{,}850 \text{ mol } N_2/\text{h}$

NH_4^+ balance: $(2)(0.100)(\dot{n}_1) = \dot{n}_2 + (1.5)(2)\dot{n}_2 \Rightarrow \dot{n}_1 = 20\dot{n}_2$

S balance: $0.100\dot{n}_1 + (0.00300)(50{,}000) = 15.0 + \dot{n}_2 + 1.5\dot{n}_2$

$$\Rightarrow \dot{n}_1 = 5400 \text{ mol/h}, \quad \dot{n}_2 = 270 \text{ mol } NH_4HSO_3/\text{h}$$

H_2O balance: $\dot{n}_3 = (0.900)(5400) - \dfrac{270 \text{ mol } NH_4HSO_3 \text{ produced}}{\text{h}} \left| \dfrac{1 \text{ mol } H_2O \text{ consumed}}{2 \text{ mol } NH_4HSO_3 \text{ produced}} \right.$

$= 4725 \text{ mol } H_2O(l)/\text{h}$

Heat of reaction:

$$\Delta\hat{H}_r^o = 2\left(\Delta\hat{H}_f^o\right)_{NH_4HSO_4(aq)} - \left(\Delta\hat{H}_f^o\right)_{(NH_4)_2SO_3(aq)} - \left(\Delta\hat{H}_f^o\right)_{SO_2(g)} - \left(\Delta\hat{H}_f^o\right)_{H_2O(l)}$$

$$= 2(-760) - (-890) - (-296.90) - (-285.84) \text{ kJ/mol} = -47.3 \text{ kJ/mol}$$

References : $N_2(g)$, $SO_2(g)$, $(NH_4)_2SO_3(aq)$, $NH_4HSO_3(aq)$, $H_2O(l)$ at 25°C

$SO_2(g, 50^\circ C)$: $\hat{H} = \int_{25}^{50} (C_p)_{SO_2}\, dT = 1.01 \text{ kJ/mol}$ (C_p from Table B.2)

$SO_2(g, 35^\circ C)$: $\hat{H} = \int_{25}^{35} (C_p)_{SO_2}\, dT = 0.40 \text{ kJ/mol}$

$N_2(g, 50^\circ C)$: $\hat{H} = 0.73 \text{ kJ/mol}$ (Table B.8)

$N_2(g, 35^\circ C)$: $\hat{H} = 0.292 \text{ kJ/mol}$

Entering solution: $\hat{H} = 0$

Effluent solution at 35°C

$$\dot{m}(\text{g/h}) = \frac{270 \text{ mol } NH_4HSO_3}{\text{h}} \left| \frac{99 \text{ g}}{\text{mol}} \right.$$

$$+ \frac{1.5 \times 270 \text{ mol } (NH_4)_2SO_3}{\text{h}} \left| \frac{116 \text{ g}}{\text{mol}} \right. + \frac{4725 \text{ mol } H_2O}{\text{h}} \left| \frac{18 \text{ g}}{1 \text{ mol}} \right. = 159{,}000 \frac{\text{g}}{\text{h}}$$

$$\dot{n}\hat{H} = mC_p\Delta T = \frac{159{,}000 \text{ g}}{\text{h}} \left| \frac{4 \text{ J}}{\text{g}\cdot{}^\circ\text{C}} \right| \frac{(35-25)^\circ\text{C}}{} \left| \frac{1 \text{ kJ}}{10^3 \text{ J}} \right. = 6360 \text{ kJ / h}$$

Extent of reaction:

$$(\dot{n}_{NH_4HSO_3})_{out} = (\dot{n}_{NH_4HSO_3})_{in} + \nu_{NH_4HSO_3}\dot{\xi} \Rightarrow 270 \text{ mol / h} = 0 + 2\dot{\xi} \Rightarrow \dot{\xi} = 135 \text{ mol / h}$$

9.47 (cont'd)

Energy balance: $\dot{Q} = \Delta\dot{H} = \dot{\xi}\Delta\hat{H}_r^o + \sum_{\text{out}}\dot{n}_i\hat{H}_i - \sum_{\text{in}}\dot{n}_i\hat{H}_i$

$$Q = \begin{array}{c|c} 135\text{ mol} & -47.3\text{ kJ} \\ \hline \text{h} & \text{mol} \end{array} + \overset{\text{SO}_2\text{ out}}{(15)(0.40)} + \overset{\text{N}_2\text{ out}}{(49{,}850)(0.292)}$$

$$+ \overset{\text{effluent solution}}{6360} - (50{,}000)(0.003)(1.01) - (49{,}850)(0.73) = \begin{array}{c|c|c} -22{,}000\text{ kJ} & 1\text{ h} & 1\text{ kW} \\ \hline \text{h} & 3600\text{ s} & 1\text{ kJ/s} \end{array} = \underline{\underline{-6.11\text{ kW}}}$$

9.48 **a.** $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(v)$

$$HHV = 890.36\text{ kJ / mol},\ LHV = \overset{\text{Table B.1 HHV}}{\overset{\downarrow}{-\Delta\hat{H}_c^o}} - 2\overset{\text{at 25°C}}{\overset{\downarrow}{\left(\Delta\hat{H}_v\right)_{H_2O}}} = \left[890.36 - 2(44.01)\right]\text{kJ/mol}$$

$$= 802.34\ \text{kJ/mol}\ CH_4$$

$$C_2H_4(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(v)$$

$$HHV = 1559.9\text{ kJ / mol},\ LHV = \left[1559.9 - 3(44.01)\right]\text{kJ/mol} = 1427.87\ \text{kJ/mol}\ C_2H_6$$

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(v)$$

$$HHV = 2220.0\text{ kJ / mol},\ LHV = \left[2220.0 - 4(44.01)\right]\text{kJ/mol} = 2043.96\ \text{kJ/mol}\ C_3H_8$$

$$(HHV)_{\text{natural gas}} = (0.875)(890.36\ \text{kJ/mol}) + (0.070)(1559.9\ \text{kJ/mol}) + (0.020)(2200.00\ \text{kJ/mol})$$
$$= \underline{\underline{933\ \text{kJ/mol}}}$$

$$(LHV)_{\text{natural gas}} = (0.875)(802.34\ \text{kJ/mol}) + (0.070)(1427.87\ \text{kJ/mol}) + (0.020)(2043.96\ \text{kJ/mol})$$
$$= \underline{\underline{843\ \text{kJ/mol}}}$$

b. $1\text{ mol natural gas} \Rightarrow [(0.875\text{ mol }CH_4)\left(16.04\frac{\text{g}}{\text{mol}}\right) + (0.070\text{ mol }C_2H_6)\left(30.07\frac{\text{g}}{\text{mol}}\right)$

$$+ (0.020\text{ mol }C_3H_8)\left(44.09\frac{\text{g}}{\text{mol}}\right) + (0.035\text{ mol }N_2)\left(28.02\frac{\text{g}}{\text{mol}}\right)] \times \frac{1\text{ kg}}{10^3\text{ g}} = 0.01800\text{ kg}$$

$$\Rightarrow \begin{array}{c|c} 843\text{ kJ} & 1\text{ mol} \\ \hline \text{mol} & 0.01800\text{ kg} \end{array} = \underline{\underline{46800\ \text{kJ/kg}}}$$

c. The enthalpy change when 1 kg of the natural gas at 25^{o}C is burned completely with oxygen at 25^{o}C and the products CO_2(g) and H_2O(v) are brought back to 25^{o}C.

9.49

$$C(s) + O_2(g) \rightarrow CO_2(g),\ \Delta\hat{H}_c^o = \overset{\text{Table B.1}}{\overset{\downarrow}{\left(\Delta\hat{H}_f^o\right)_{CO_2(g)}}} = \begin{array}{c|c|c} -393.5\text{ kJ} & 1\text{ mol} & 10^3\text{ g} \\ \hline \text{mol} & 12.01\text{ g} & 1\text{ kg} \end{array} = -32{,}764\ \text{kJ/kg C}$$

$$S(s) + O_2(g) \rightarrow SO_2(g),\ \Delta\hat{H}_c^o = \overset{\text{Table B.1}}{\overset{\downarrow}{\left(\Delta\hat{H}_f^o\right)_{SO_2}}} = -296.90\ \text{kJ/mol}\ \overset{M_{SO_2}=32.064}{\overset{\downarrow}{\Rightarrow}}\ -9261\text{ kJ / kg S}$$

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l),\ \Delta\hat{H}_c^o = \overset{\text{Table B.1}}{\overset{\downarrow}{\left(\Delta\hat{H}_f^o\right)_{H_2O(l)}}} = -285.84\ \text{kJ/mol}\ H_2\ \overset{M_{H_2}=1.008}{\overset{\downarrow}{\Rightarrow}}\ -141{,}790\ \text{kJ/kg H}$$

9.49 (cont'd)

a.

H available for combustion = total H – H in H_2O; latter is $\left.\frac{x_0\ (\text{kg O})}{\text{kg coal}}\right|\frac{2\ \text{kg H}}{\underset{\underset{\text{in water}}{\uparrow}}{16\ \text{kg O}}}$

Eq. (9.6-3) $\Rightarrow$ $\underline{\underline{HHV = 32{,}764\text{C} + 141{,}790\left(\text{H} - \frac{\text{O}}{8}\right) + 9261\text{S}}}$

This formula does not take into account the heats of formation of the chemical constituents of coal.

b. $\text{C} = 0.758,\ \text{H} = 0.051,\ \text{O} = 0.082,\ \text{S} = 0.016 \Rightarrow (HHV)_{\text{Dulong}} = 31{,}646\ \text{kJ/kg coal}$

$$1\ \text{kg coal} \Rightarrow \left.\frac{0.016\ \text{kg S}}{}\right|\frac{64.07\ \text{kg SO}_2\ \text{formed}}{32.06\ \text{kg S burned}} = 0.0320\ \text{kg SO}_2/\text{kg coal}$$

$$\phi = \frac{0.0320\ \text{kg SO}_2/\text{kg coal}}{31{,}646\ \text{kJ/kg coal}} = \underline{\underline{1.01\times10^{-6}\ \text{kg SO}_2/\text{kJ}}}$$

c. Diluting the stack gas lowers the mole fraction of SO_2, but does not reduce SO_2 emission rates. The dilution does not affect the kg SO_2/kJ ratio, so there is nothing to be gained by it.

9.50

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O(l),\ HHV = -\Delta\hat{H}_c^o = 890.36\ \text{kJ/mol}\ \ (\text{Table B.1})$$

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O(l),\ HHV = 1559.9\ \text{kJ/mol}$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2,\ HHV = 282.99\ \text{kJ/mol}$$

$$\underset{\text{(Assume ideal gas)}}{\underline{\text{Initial moles charged:}}}\ \left.\frac{2.000\ \text{L}}{}\right|\left.\frac{273.2\text{K}}{(25+273.2)\text{K}}\right|\left.\frac{2323\ \text{mm Hg}}{760\ \text{mm Hg}}\right|\frac{1\ \text{mol}}{22.4\ \text{L(STP)}} = 0.25\ \text{mol}$$

<u>Average mol. wt.:</u> (4.929 g)/(0.25 mol) = 19.72 g / mol

Let x_1 = mol CH_4/mol gas, x_2 = mol C_2H_6/mol gas $(\Rightarrow (1-x_1-x_2)\text{mol CO(mol gas)})$

$$\overline{MW} = 19.72 \Rightarrow x_1(16.04\ \text{g/mol CH}_4) + x_2(30.07) + (1-x_1-x_2)(28.01) = 19.72 \quad (1)$$

$$\overline{HHV} = 963.7\ \text{kJ/mol} \Rightarrow x_1(890.36) + x_2(1559.9) + (1-x_1-x_2)(282.99) = 963.7 \quad (2)$$

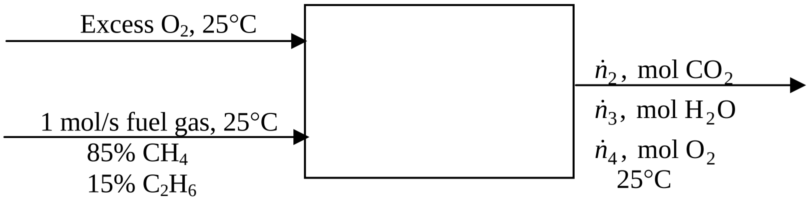
Solving (1) & (2) simultaneously yields

$$x_1 = \underline{\underline{0.725\ \text{mol CH}_4/\text{mol}}},\ x_2 = \underline{\underline{0.188\ \text{mol C}_2\text{H}_6/\text{mol}}},\ 1-x_1-x_2 = \underline{\underline{0.087\ \text{mol CO/mol}}}$$

9.51 **a.** <u>Basis</u> : 1mol/s fuel gas

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(v),\quad \Delta\hat{H}_c^o = -890.36\ \text{kJ / mol}$$

$$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(v),\ \Delta\hat{H}_c^o = -1559.9\ \text{kJ / mol}$$



9.51 (cont'd)

$\underline{1\ \text{mol/s fuel gas}} \Rightarrow 0.85\ \text{mol}\ CH_4\ /\text{s}\ ,\ 0.15\ \text{mol}\ C_2H_6\ /\text{s}$

$$\underline{\text{Theoretical oxygen}} = \frac{2\ \text{mol}\ O_2}{1\ \text{mol}\ CH_4}\bigg|\frac{0.85\ \text{mol}\ CH_4}{\text{s}} + \frac{3.5\ \text{mol}\ O_2}{1\ \text{mol}\ C_2H_6}\bigg|\frac{0.15\ \text{mol}\ C_2H_6}{\text{s}} = 2.225\ \text{mol}\ O_2\ /\text{s}$$

$\underline{\text{Assume 10\% excess}\ O_2} \Rightarrow O_2\ \text{fed} = 1.1 \times 2.225 = 2.448\ \text{mol}\ O_2\ /\text{s}$

$\underline{\text{C balance}}: \dot{n}_2 = (0.85)(1) + (0.15)(2) \Rightarrow \dot{n}_2 = 1.15\ \text{mol}\ CO_2\ /\text{s}$

$\underline{\text{H balance}}: 2\dot{n}_3 = (0.85)(4) + (0.15)(6) \Rightarrow \dot{n}_3 = 2.15\ \text{mol}\ H_2O/\text{s}$

$\underline{10\%\ \text{excess}\ O_2} \Rightarrow \dot{n}_4 = (0.1)(2.225)\ \text{mol}\ O_2\ /\text{s} = 0.223\ \text{mol}\ O_2\ /\text{s}$

$\underline{\text{Extents of reaction}}: \dot{\xi}_1 = \dot{n}_{CH_4} = 0.85\ \text{mol/s},\ \dot{\xi}_2 = \dot{n}_{C_2H_6} = 0.15\ \text{mol/s}$

$\underline{\text{Reference states:}}\ CH_4(g),\ C_2H_6(g),\ N_2(g),\ O_2(g),\ H_2O(l),\ CO_2(g)$ at 25° C

(We will use the values of $\Delta\hat{H}_c^o$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water)

Substance	$\dot{n}_{\text{in}}$ mol	$\hat{H}_{\text{in}}$ kJ/mol	$\dot{n}_{\text{out}}$ mol	$\hat{H}_{\text{out}}$ kJ/mol
CH_4	0.85	0	–	–
C_2H_6	0.15	0	–	–
O_2	2.225	0	0.223	0
CO_2	–	–	1.15	0
$H_2O(v)$	–	–	2.15	H_1

$\hat{H}_1 = \Delta\hat{H}_v(25^o C) = 44.01\ \text{kJ/mol}$

Energy Balance :

$$\dot{Q} = \dot{n}_{CH_4}\left(\Delta\hat{H}_c^o\right)_{CH_4} + \dot{n}_{C_2H_6}\left(\Delta\hat{H}_c^o\right)_{C_2H_6} + \sum_{\text{out}}\dot{n}_i\hat{H}_i - \sum_{\text{in}}\dot{n}_i\hat{H}_i$$

$$= (0.85\ \text{mol/s}\ CH_4)(-890.36\ \text{kJ/mol}) + (0.15\ \text{mol/s}\ C_2H_6)(-1559.9\ \text{kJ/mol})$$

$$+ (2.15\ \text{mol/s}\ H_2O)(44.01\ \text{kJ/mol}) = -896\ \text{kW}$$

$\Rightarrow \underline{\underline{-\dot{Q} = 896\ \text{kW}}}$ (transferred from reactor)

b. Constant Volume Process. The flowchart and stoichiometry and material balance calculations are the same as in part (a), except that amounts replace flow rates (mol instead of mol/s, etc.)

$1\ \text{mol fuel gas} \Rightarrow 0.85\ \text{mol}\ CH_4,\ 0.15\ \text{mol}\ C_2H_6$

$\text{Theoretical oxygen} = 2.225\ \text{mol}\ O_2$

$\underline{\text{Assume 10\% excess}\ O_2} \Rightarrow O_2\ \text{fed} = 1.1 \times 2.225 = 2.448\ \text{mol}\ O_2$

$\underline{\text{C balance}}: n_2 = (0.85)(1) + (0.15)(2) \Rightarrow n_2 = 1.15\ \text{mol}\ CO_2$

$\underline{\text{H balance}}: 2n_3 = (0.85)(4) + (0.15)(6) \Rightarrow n_3 = 2.15\ \text{mol}\ H_2O$

$\underline{10\%\ \text{excess}\ O_2} \Rightarrow n_4 = (0.1)(2.225)\ \text{mol}\ O_2 = 0.223\ \text{mol}\ O_2$

9.51 (cont'd)

<u>Reference states:</u> $CH_4(g)$, $C_2H_6(g)$, $N_2(g)$, $O_2(g)$, $H_2O(l)$, $CO_2(g)$ at $25^\circ C$

For a constant volume process the heat released or absorbed is determined by the internal energy of reaction.

Substance	n_{in} mol	$\hat{U}_{in}$ kJ/mol	n_{out} mol	$\hat{U}_{out}$ kJ/mol
CH_4	0.85	0	–	–
C_2H_6	0.15	0	–	–
O_2	2.225	0	0.223	0
CO_2	–	–	1.15	0
$H_2O(v)$	–	–	2.15	$\hat{U}_1$

$$\hat{U}_1 = \Delta\hat{U}_v\left(25^\circ C\right) = \Delta\hat{H}_v\left(25^\circ C\right) - RT = 44.01\ \text{kJ / mol} - \begin{array}{c|c|c} 8.314\ \text{J} & 1\ \text{kJ} & 298\ \text{K} \\ \hline \text{mol K} & 1000\ \text{J} & \end{array} = 41.53\ \frac{\text{kJ}}{\text{mol}}$$

$$\text{Eq. (9.1-5)} \Rightarrow\ \Delta\hat{U}_c^o = \Delta\hat{H}_c^o - RT\Big(\sum_{\substack{\text{gaseous}\\ \text{products}}} \nu_i - \sum_{\substack{\text{gaseous}\\ \text{reactants}}} \nu_i\Big)$$

$$\Rightarrow \left(\Delta\hat{U}_c^o\right)_{CH_4} = \left(-890.36\ \text{kJ/mol}\right) - \begin{array}{c|c|c|c} 8.314\ \text{J} & 298\ \text{K} & (1+2-1-2) & 1\ \text{kJ} \\ \hline \text{mol K} & & & 10^3\ \text{J} \end{array} = -890.36\ \frac{\text{kJ}}{\text{mol}}$$

$$\left(\Delta\hat{U}_c^o\right)_{C_2H_6} = \left(-1559.9\ \text{kJ/mol}\right) - \begin{array}{c|c|c|c} 8.314\ \text{J} & 298\ \text{K} & (3+2-3.5-1) & 1\ \text{kJ} \\ \hline \text{mol K} & & & 10^3\ \text{J} \end{array} = -1561.14\ \frac{\text{kJ}}{\text{mol}}$$

<u>Energy balance</u>:

$$Q = \Delta U = n_{CH_4}\left(\Delta\hat{U}_c^o\right)_{CH_4} + n_{C_2H_6}\left(\Delta\hat{U}_c^o\right)_{C_2H_6} + \sum_{\text{out}} n_i\hat{U}_i - \sum_{\text{in}} \dot{n}_i\hat{U}_i$$

$$= \left(0.85\ \text{mol / s}\ \ CH_4\right)\left(-890.36\ \text{kJ/mol}\right) + \left(0.15\ \text{mol / s}\ \ C_2H_6\right)\left(-1561.14\ \text{kJ/mol}\right)$$

$$+\left(2.15\ \text{mol / s}\ H_2O\right)\left(41.53\ \text{kJ / mol}\right) = -902\ \text{kJ}$$

$$\Rightarrow \underline{\underline{-Q = 902\ \text{kJ}}}\ \text{(transferred from reactor)}$$

c. Since the O_2 (and N_2 if air were used) are at 25°C at both the inlet and outlet of this process, their specific enthalpies or internal energies are zero and their amounts therefore have no effect on the calculated values of $\Delta\dot{H}$ and ΔU.

9.52 **a.** $\dot{n}_{fuel}(-\Delta\hat{H}_c^o) = \dot{W}_s - \dot{Q}_l$ (Rate of heat release due to combustion = shaft work + rate of heat loss)

$$\begin{array}{c|c|c|c|c} \dot{V}\,(\text{gal}) & 28.317\ \text{L} & 0.700\ \text{kg} & 10^3\ \text{g} & 49\ \text{kJ} \\ \hline \text{h} & 7.4805\ \text{gal} & \text{L} & 1\ \text{kg} & \text{g} \end{array}$$

$$= \begin{array}{c|c|c|c} 100\ \text{hp} & 1\ \text{J / s} & 1\ \text{kJ} & 3600\ \text{s} \\ \hline & 1.341\times10^{-3}\ \text{hp} & 10^3\ \text{J} & \text{h} \end{array} + \frac{15\times10^6\ \text{kJ}}{298\quad \text{h}} \ \Rightarrow\ \underline{\underline{\dot{V} = 2.5\ \text{gal / h}}}$$

b. The work delivered would be less since more of the energy released by combustion would go into heating the exhaust gas.

c. Heat loss increases as T_a decreases.
Lubricating oil becomes thicker, so more energy goes to overcoming friction.

9.53 **a.** Energy balance: $\Delta U = 0 \Rightarrow \dfrac{n(\text{lb}_\text{m}\ \text{fuel burned})}{} \left| \dfrac{\Delta \hat{U}_\text{c}^\text{o}\ (\text{Btu})}{\text{lb}_\text{m}} \right. + mC_v(T_\text{out} - 77°\text{F}) = 0$

$$\Rightarrow (0.00215)\Delta\hat{U}_\text{c}^\text{o} + (4.62\ \text{lb}_\text{m})(0.900\ \text{Btu/lb}_\text{m}\cdot°\text{F})(87.06°\text{F} - 77.00°\text{F}) = 0$$

$$\Rightarrow \Delta\hat{U}_\text{c}^\text{o} = \underline{\underline{-19500\ \text{Btu/lb}_\text{m}}}$$

b. The reaction for which we determined $\Delta\hat{U}_\text{c}^\text{o}$ is

$$1\ \text{lb}_\text{m}\ \text{oil} + a\text{O}_2(\text{g}) \rightarrow b\text{CO}_2(\text{g}) + c\text{H}_2\text{O(v)} \qquad (1)$$

The higher heating value is $\Delta\hat{H}_\text{r}$ for the reaction

$$1\ \text{lb}_\text{m}\ \text{oil} + a\text{O}_2(\text{g}) \rightarrow b\text{CO}_2(\text{g}) + c\text{H}_2\text{O(l)} \qquad (2)$$

Eq. (9.1-5) on p. 441 $\Rightarrow \Delta\hat{H}_\text{c1}^\text{o} = \Delta\hat{U}_\text{c1}^\text{o} + RT(b + c - a)$

Eq. (9.6-1) on p. 462 $\Rightarrow \underset{(HHV)}{-\Delta\hat{H}_\text{c2}^\text{o}} = \underset{(LHV)}{-\Delta\hat{H}_\text{c1}^\text{o}} + c\Delta\hat{H}_\text{v}(\text{H}_2\text{O},\ 77°\text{F})$

To calculate the higher heating value, we therefore need

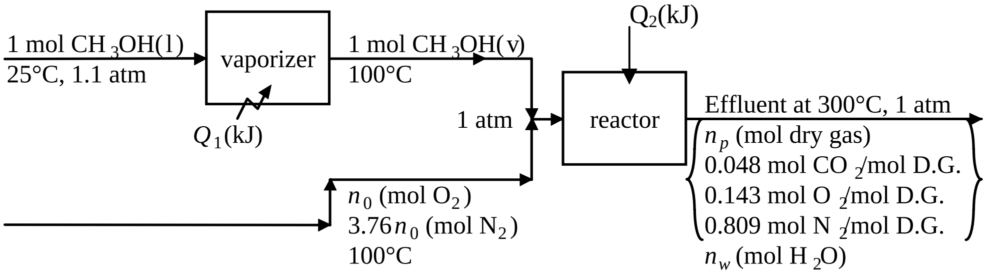
$\underline{\underline{a = \text{lb-moles of O}_2 \text{ that react with 1 lb}_\text{m} \text{ fuel oil}}}$

$\underline{\underline{b = \text{lb-moles of CO}_2 \text{ formed when 1 lb}_\text{m} \text{ fuel oil is burned}}}$

$\underline{\underline{c = \text{lb-moles of H}_2\text{O formed when 1 lb}_\text{m} \text{ fuel oil is burned}}}$

9.54 **a.** $\text{CH}_3\text{OH(v)} + \frac{3}{2}\text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) + 2\text{H}_2\text{O(l)} \qquad \Delta\hat{H}_\text{r}^\text{o} = \left(\Delta\hat{H}_\text{c}^\text{o}\right)_{\text{CH}_3\text{OH(v)}} = -764.0\dfrac{\text{kJ}}{\text{mol}}$

Basis: 1 mol CH_3OH fed and burned



Overall C balance: $\dfrac{1\ \text{mol CH}_3\text{OH}}{} \left| \dfrac{1\ \text{mol C}}{1\ \text{mol CH}_3\text{OH}} \right. = n_p(0.048)(1) \Rightarrow n_p = 20.83\ \text{mol dry gas}$

N$_2$ balance: $3.76n_0 = (20.83)(0.809) \Rightarrow n_0 = 4.482\ \text{mol O}_2$

Theoretical O$_2$: $(1\ \text{mol CH}_3\text{OH})(1.5\ \text{mol O}_2/\text{mol CH}_3\text{OH}) = 1.5\ \text{mol O}_2$

% excess air $= \dfrac{(4.482 - 1.5)\ \text{mol O}_2}{1.5\ \text{mol O}_2} \times 100\% = \underline{\underline{200\%\ \text{excess air}}}$

H balance: $(1\ \text{mol CH}_3\text{OH})(4\ \text{mol H}/1\ \text{mol CH}_3\text{OH}) = n_w(2) \Rightarrow n_w = 2\ \text{mol H}_2\text{O}$

(An atomic O balance $\Rightarrow$ 9.96 mol O = 9.96 mol O , so that the results are consistent.)

$$p_w^* = \frac{n_w}{n_w + n_p} \times P = \frac{2\ \text{mol H}_2\text{O}}{(2 + 20.83)\text{mol}} \times 760\ \text{mm Hg} = 66.58\ \text{mm Hg} = p_w^*(T_{dp}) \overset{\text{Table B.3}}{\Rightarrow} \underline{\underline{T_{dp} = 44.1°\text{C}}}$$

9.54 (cont'd)

b. Energy balance on vaporizer:

$$Q_1 = \Delta H = n\Delta\hat{H} = 1\text{ mol}\left[\int_{25}^{64.7} \underset{\substack{\uparrow\\ \text{Table B.2}}}{C_{pl}}\, dT + \underset{\substack{\uparrow\\ \text{Table B.1}}}{\Delta\hat{H}_v} + \int_{64.7}^{100} \underset{\substack{\uparrow\\ \text{Table B.2}}}{C_{pv}}\, dT\right]\frac{\text{kJ}}{\text{mol}} = \underline{\underline{40.33\text{ kJ}}}$$

References : $CH_3OH(v)$, $N_2(g)$, $O_2(g)$, $CO_2(g)$, $H_2O(l)$ at 25°C

Substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ / mol)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ / mol)
CH_3OH	1.00	3.603	–	–
N_2	16.85	2.187	16.85	8.118
O_2	4.482	2.235	2.98	8.470
CO_2	–	–	1.00	11.578
H_2O	–	–	2.00	53.58

$\hat{H}(T) = \hat{H}_i$ for N_2, O_2, CO_2 (Table B.8)

$= \Delta\hat{H}_v(25^\circ\text{C}) + \hat{H}_i$ for $H_2O(v)$ (Eq. 9.6-2a on p. 462, Table B.8)

$= \int_{25}^{T} C_p dT$ for $CH_3OH(v)$ (Table B.2)

(Note: $H_2O(l)$ was chosen as the reference state since the given value of $\Delta\hat{H}_c^o$ presumes liquid water as the product.)

Extent of reaction: $(n_{CH_3OH})_{out} = (n_{CH_3OH})_{in} + \nu_{CH_3OH}\xi \Rightarrow 0 = 1\text{ mol} - \xi \Rightarrow \xi = 1\text{ mol}$

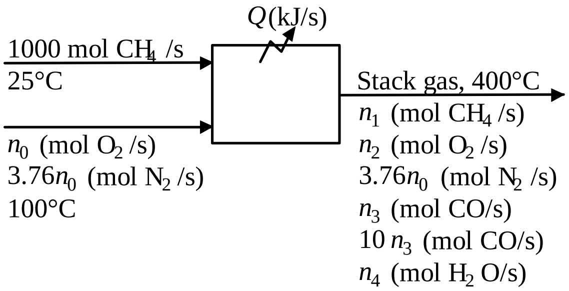
Energy balance on reactor: $Q_2 = \xi\Delta\hat{H}_c^o + \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i$

$= (1)\underset{\text{(Table B.1)}}{(-764.0)} + \left[(16.85)(8.118) + \ldots - (4.482)(2.235)\right]\text{kJ}$

$= -534\text{ kJ} \Rightarrow \underline{\underline{534\text{ kJ}}}$ transferred from reactor

9.55 a. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ $\qquad$ $CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O$

Basis : 1000 mol CH_4/h fed



90% combustion $\Rightarrow \dot{n}_1 = 0.10(1000) = 100\text{ mol } CH_4/\text{s}$

Theoretical O_2 required = 2000 mol/s

9.55 (cont'd)

10% excess O_2 $\Rightarrow O_2$ fed=1.1(2000 mol/s)=2200 mol/s

C balance:

$$(1000 \text{ mol CH}_4/\text{s})(1 \text{ mol C/mol CH}_4) = (100)(1) + \dot{n}_3(1) + 10\dot{n}_3(1) \Rightarrow \dot{n}_3 = 81.8 \text{ mol CO/s}$$

$$\Rightarrow 10\dot{n}_3 = 818 \text{ mol CO}_2/\text{s}$$

H balance: $(1000)(4) = (100)(4) + 2\dot{n}_4 \Rightarrow \dot{n}_4 = 1800 \text{ mol H}_2\text{O/s}$

O balance: $(2200)(2) = 2\dot{n}_2 + (81.8)(1) + (818)(2) + (1800)(1) \Rightarrow \dot{n}_2 = 441 \text{ mol O}_2/\text{s}$

References: C(s), $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C

Substance	$\dot{n}_\text{in}$ (mol/s)	$\hat{H}_\text{in}$ (kJ/mol)	$\dot{n}_\text{out}$ (mol/s)	$\hat{H}_\text{out}$ (kJ/mol)
CH_4	1000	–74.85	100	–57.62
O_2	2200	2.24	441	11.72
N_2	8272	2.19	8272	11.15
CO	–	–	81.8	–99.27
CO_2	–	–	818	–377.2
H_2O	–	–	1800	–228.63

$$\hat{H} = \overset{\text{Table B.1}}{\overset{\downarrow}{\Delta\hat{H}_f^o}} + \int_{25}^{T} \overset{\text{Table B.2}}{\overset{\downarrow}{C_p}}\, dT \text{ for CH}_4$$

$$= \Delta\hat{H}_f^o + \overset{\text{Table B.8}}{\overset{\downarrow}{\hat{H}_i(T)}} \text{ for others}$$

Energy balance: $\dot{Q} = \Delta\dot{H} = \sum_{\text{out}} \dot{n}_i\hat{H}_i - \sum_{\text{in}} \dot{n}_i\hat{H}_i = \underline{\underline{-5.85\times10^5 \text{ kJ/s (kW)}}}$

b.

(i) $T_{air}\uparrow$ (increases) $\Rightarrow -\dot{Q}\uparrow$

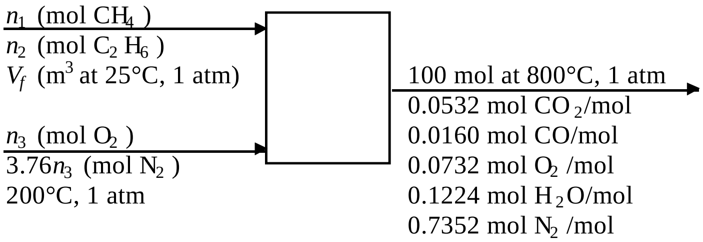
(ii) %XS $\uparrow \Rightarrow -\dot{Q}\downarrow$ (more energy required to heat additional O_2 and N_2 to 400°C, therefore less energy transferred.)

(iii) $S_{CO_2/CO}\uparrow \Rightarrow -\dot{Q}\uparrow$ (reaction to form CO2 has a greater heat of combustion and so releases more thermal energy)

(iv) $T_{stack}\uparrow \Rightarrow -\dot{Q}\downarrow$ (more energy required to heat combustion products)

9.56 $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O,\ C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$

Basis : 100 mol stack gas. Assume ideal gas behavior.



a.

N_2 balance: $3.76n_3 = (100)(0.7352)\text{mol } N_2 \Rightarrow n_3 = 19.55 \text{ mol } O_2 \text{ fed}$

$$\left.\begin{array}{l}\text{C balance: } n_1(1) + n_2(2) = (100)(0.0532)(1) + (100)(0.0160)(1) \\ \text{H balance: } n_1(4) + n_2(6) = (100)(0.1224)(2)\end{array}\right\} \Rightarrow \begin{array}{l} n_1 = 3.72 \text{ mol } CH_4 \\ n_2 = 1.60 \text{ mol } C_2H_6\end{array}$$

$$V_f = \frac{(3.72 + 1.60)\text{mol fuel gas}}{} \left| \frac{22.4 \text{ L(STP)}}{1 \text{ mol}} \right| \frac{298.2 \text{ K}}{273.2 \text{ K}} \left| \frac{1 \text{ m}^3}{10^3 \text{ L}} \right. = 0.130 \text{ m}^3$$

$$\underline{\text{Theoretical } O_2} = \frac{3.72 \text{ mol } CH_4}{} \left| \frac{2 \text{ mol } O_2}{1 \text{ mol } CH_4} \right. + \frac{1.60 \text{ mol } C_2H_6}{} \left| \frac{3.5 \text{ mol } O_2}{1 \text{ mol } C_2H_6} \right. = 13.04 \text{ mol } O_2$$

$$\underline{\text{Fuel composition:}} \quad \left.\begin{array}{l} 3.72 \text{ mol } CH_4 \\ 1.60 \text{ mol } C_2H_6 \end{array}\right\} \Rightarrow \begin{array}{l} \underline{\underline{69.9 \text{ mole\% } CH_4}} \\ \underline{\underline{30.1 \text{ mole\% } C_2H_6}} \end{array}$$

$$\underline{\text{\% Excess air:}} \quad \frac{(19.55 - 13.04)\text{mol } O_2 \text{ in excess}}{13.04 \text{ mol } O_2 \text{ required}} \times 100\% = \underline{\underline{50\% \text{ excess air}}}$$

b.

References : C(s), H_2(g), O_2(g), N_2(g) at 25°C

Substance	n_{in} mol	$\hat{H}_{in}$ kJ / mol	n_{out} mol	$\hat{H}_{out}$ kJ / mol
CH_4	3.72	–74.85	–	–
C_2H_6	1.60	–84.67	–	–
O_2	19.55	5.31	7.32	25.35
N_2	73.52	5.13	73.52	23.86
CO	–	–	1.60	–86.39
CO_2	–	–	5.32	–356.1
H_2O	–	–	12.24	–212.78

$$\hat{H} = \overset{\substack{\text{Table B.1}\\ \downarrow}}{\Delta\hat{H}_f^o} + \int_{25}^{T} \overset{\substack{\text{Table B.2, for}\\ \text{CH}_4,\ \text{C}_2\text{H}_6\\ \downarrow}}{C_p}\ dT$$

$$= \Delta\hat{H}_f^o + \overset{\substack{\text{Table B.8}\\ \downarrow}}{\hat{H}_i}(\text{T})\ \text{ for } O_2,\ N_2,\ CO,\ CO_2,\ H_2O(v)$$

<u>Energy balance:</u>

$$Q = \Delta H = \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = \frac{-2764\ \text{kJ}}{0.130\ \text{m}^3\ \text{fuel}} = \underline{\underline{-2.13\times 10^4\ \ \text{kJ}/\text{m}^3\ \ \text{fuel}}}$$

9.57

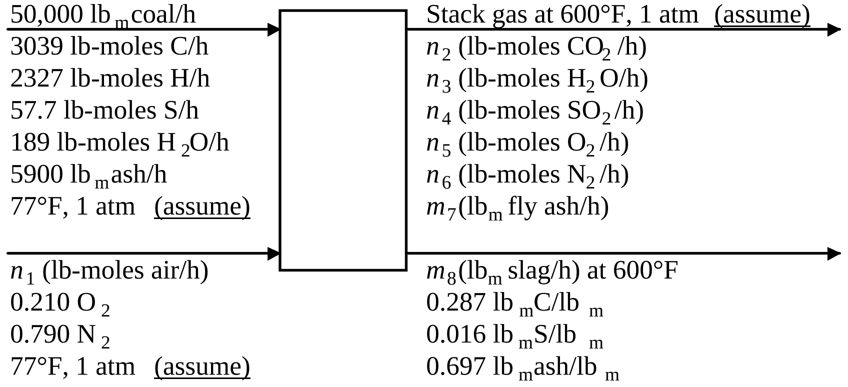
$$\underline{\text{Basis}}:\ 50000\ \text{lb}_\text{m}\ \text{coal fed/h}\ \Rightarrow\ \frac{(0.730)(50000)\text{lb}_\text{m}\text{C}}{\text{h}}\left|\frac{\text{1b - mole C}}{12.01\ \text{lb}_\text{m}}\right. = 3039\ \text{1b - mole C/h}$$

$(0.047)(50000)/1.01 = 2327\ \text{lb - moles H/h}$ (does not include H in water)

$(0.037)(50000)/32.07 = 57.7\ \text{lb - moles S/h}$

$(0.068)(50000)/18.02 = 189\ \text{lb - moles}\ H_2O/\text{h}$

$(0.118)(50000) = 5900\ \text{lb}_\text{m}\ \text{ash/h}$



a. Feed rate of air :

$$\underline{O_2\ \text{required to oxidize carbon}}\ (C + O_2 \rightarrow CO_2) = \frac{3039\ \text{lb - moles C}}{\text{h}}\left|\frac{1\ \text{lb - mole}\ O_2}{1\ \text{lb - mole C}}\right.$$

$$= 3039\ \text{lb - moles}\ O_2/\text{h}$$

$$\underline{\text{Air fed:}}\ \dot{n}_1 = \frac{1.5\times 3039\ \text{lb - moles}\ O_2\ \text{fed}}{\text{h}}\left|\frac{1\ \text{mole air}}{0.210\ \text{mole}\ O_2}\right. = 21710\ \text{lb - moles air/h}$$

$\underline{\text{30\% ash in coal emerges in slag}} \Rightarrow 0.697\dot{m}_8 = 0.30(5900\ \text{lb}_\text{m}/\text{h}) \Rightarrow \dot{m}_8 = 2540\ \text{lb}_\text{m}\ \text{slag / h}$

$\Rightarrow \dot{m}_7 = 0.700(5900) = 4130\ \text{lb}_\text{m}\ \text{fly ash/h}$

$\underline{\text{C balance:}}\ 3039(\text{lb - moles C/h}) = \dot{n}_2 + (0.287)(2540)/12.01$

$\Rightarrow \dot{n}_2 = 2978\ \text{lb - moles}\ CO_2/\text{h} \xrightarrow{M_{CO_2}=44.01} 1.31\times 10^5\ \text{lb}_\text{m}\ CO_2/\text{h}$

$\underline{\text{H balance:}}\ 2327(\text{lb - moles H/h}) + (189)(2) = 2\dot{n}_3$

$\Rightarrow \dot{n}_3 = 1352.5\ \text{lb - moles}\ H_2O/\text{h} \xrightarrow{M_{H_2O}=18.02} 2.44\times 10^4\ \text{lb}_\text{m}\ H_2O/\text{h}$

$\underline{N_2\ \text{balance:}}\ \dot{n}_6 = (0.790)21710\ \text{lb - moles/h} = 17150\ \text{lb - moles}\ N_2/\text{h} \xrightarrow{M_{N_2}=28.02} 4.81\times 10^5\ \text{lb}_\text{m}\ N_2/\text{h}$

$\underline{\text{S balance:}}\ 57.7(\text{lb - moles S/h}) = (1)\dot{n}_4 + 0.016(2540)/32.06$

$\Rightarrow \dot{n}_4 = 56.4\ \text{lb - moles}\ SO_2/\text{h} \xrightarrow{M_{SO_2}=64.2} 3620\ \text{lb}_\text{m}\ SO_2/\text{h}$

$$\underline{\text{O balance:}}\ \underset{(\text{coal})}{(189)(1)} + \underset{(\text{air})}{(0.21)(21710)(2)} = \underset{(CO_2)}{(2978)(2)} + \underset{(H_2O)}{(1352.5)(1)} + \underset{(SO_2)}{(56.4)(2)} + \underset{(O_2)}{2\dot{n}_5}$$

$\Rightarrow \dot{n}_5 = 943\ \text{lb - moles}\ O_2/\text{h} \Rightarrow 30200\ \text{lb}_\text{m}\ O_2/\text{h}$

9.57 (cont'd)

Summary of component mass flow rates

$$\left.\begin{array}{ll}\underline{\text{Stack gas at } 600^\circ\text{ F, 1 atm}} & \\ 2978 \text{ lb-moles } CO_2/\text{h} \Rightarrow & \underline{\underline{131000 \text{ lb}_m \text{ } CO_2/\text{h}}} \\ 1352.5 \text{ lb-moles } H_2O/\text{h} \Rightarrow & \underline{\underline{24400 \text{ lb}_m \text{ } H_2O/\text{h}}} \\ 56.4 \text{ lb-moles } SO_2/\text{h} \Rightarrow & \underline{\underline{3620 \text{ lb}_m \text{ } SO_2/\text{h}}} \\ 943 \text{ lb-moles } O_2/\text{h} \Rightarrow & \underline{\underline{30200 \text{ lb}_m \text{ } O_2/\text{h}}} \\ 17150 \text{ lb-moles } N_2/\text{h} \Rightarrow & \underline{\underline{48100 \text{ lb}_m \text{ } N_2/\text{h}}} \\ & \underline{\underline{4130 \text{ lb}_m \text{ fly ash/h}}} \end{array}\right\} 674{,}350 \text{ lb}_m \text{ stack gas/h}$$

Check: $[50000 + (21710)(29)]_{\text{in}} \Leftrightarrow [674350 + 2540]_{\text{out}}$

$\Rightarrow \quad (679600)_{\text{in}} \Leftrightarrow (676900)_{\text{out}}$ (0.4% roundoff error)

Total molar flow rate $= 22480$ lb-moles/h at 600° F, 1 atm (excluding fly ash)

$$\Rightarrow V = \frac{22480 \text{ lb-moles}}{\text{h}} \Bigg| \frac{359 \text{ ft}^3(\text{STP})}{1 \text{ lb-mole}} \Bigg| \frac{1060^\circ \text{R}}{492^\circ \text{R}} = \underline{\underline{1.74 \times 10^7 \text{ ft}^3/\text{h}}}$$

b. References: Coal components, air at 77°F $\Rightarrow \sum_{\text{in}} n_i \hat{H}_i = 0$

Stack gas: $$n\hat{H} = \frac{674350 \text{ lb}_m}{\text{h}} \Bigg| \frac{7.063 \text{ Btu}}{\text{lb-mole}\cdot^\circ \text{F}} \Bigg| \frac{1 \text{ lb-mole}}{28.02 \text{ lb}_m} \Bigg| \frac{(600-77)^\circ \text{F}}{} = 8.90 \times 10^7 \text{ Btu/h}$$

Slag: $$n\hat{H} = \frac{2540 \text{ lb}_m}{\text{h}} \Bigg| \frac{0.22 \text{ Btu}}{\text{lb}_m\cdot^\circ \text{F}} \Bigg| \frac{(600-77)^\circ \text{F}}{} = 2.92 \times 10^5 \text{ Btu/h}$$

Energy balance: $$Q = \Delta H = n_{\text{coal burned}} \Delta\hat{H}_c^o(77^\circ \text{F}) + \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

$$= \frac{5 \times 10^4 \text{ lb}_m}{\text{h}} \Bigg| \frac{-1.8 \times 10^4 \text{ Btu}}{\text{lb}_m} + \left(8.90 \times 10^7 + 2.92 \times 10^5\right) \text{ Btu/h}$$

$$= -8.11 \times 10^8 \text{ Btu/h}$$

Power generated $$= \frac{(0.35)\left(8.11 \times 10^8\right) \text{Btu}}{\text{h}} \Bigg| \frac{1 \text{ hr}}{3600 \text{ s}} \Bigg| \frac{1 \text{ W}}{9.486 \times 10^{-4} \text{ Btu/s}} \Bigg| \frac{1 \text{ MW}}{10^6 \text{ W}} = \underline{\underline{83.1 \text{ MW}}}$$

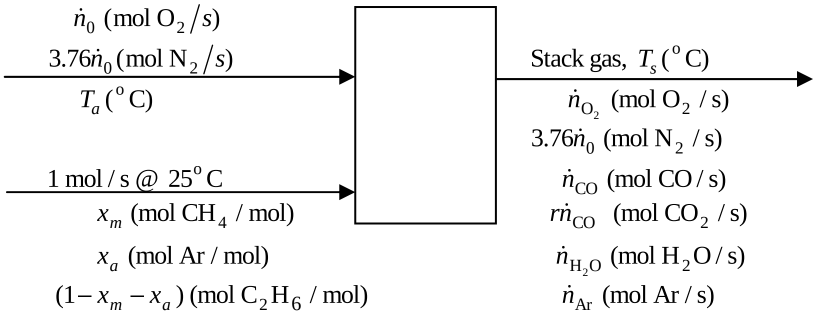
c. $\hat{Q} = \left(-8.11 \times 10^8 \text{ Btu/h}\right) \Big/ \left(5000 \text{ lb}_m \text{ coal/h}\right) = -1.62 \times 10^4 \text{ Btu/lb}_m$ coal

$$\Rightarrow \frac{-\hat{Q}}{HHV} = \frac{1.62 \times 10^4 \text{ Btu/lb}_m}{1.80 \times 10^4 \text{ Btu/lb}_m} = \underline{\underline{0.901}}$$

Some of the heat of combustion goes to vaporize water and heat the stack gas.

d. $-\hat{Q}/HHV$ would be closer to 1. Use heat exchange between the entering air and the stack gas.

9.58 **b.** Basis : 1 mol fuel gas/s



$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$C_2H_6 + \frac{7}{2} O_2 \rightarrow 2CO_2 + 3H_2O$$

Percent excess air: $\dot{n}_0 = (1+\frac{P_{xs}}{100})\left[2x_m + 3.5(1-x_m-x_a)\right]$

C balance: $x_m + 2(1-x_m-x_a) = (1+r)\dot{n}_{CO} \Rightarrow \dot{n}_{CO} = \dfrac{x_m + 2(1-x_m-x_a)}{(1+r)}$

H balance: $4x_m + 6(1-x_m-x_a) = 2\dot{n}_{H_2O} \Rightarrow \dot{n}_{H_2O} = 2x_m + 3(1-x_m-x_a)$

O balance: $2\dot{n}_0 = 2\dot{n}_{O_2} + \dot{n}_{CO} + 2\, r\, \dot{n}_{CO} + \dot{n}_{H_2O} \Rightarrow \dot{n}_{O_2} = \dot{n}_0 - \dot{n}_{CO}(1+2r)/2 - \dot{n}_{H_2O}/2$

References : C(s), H_2(g), O_2(g), N_2(g) at 25°C

Substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$
CH_4	x_m	0	–	–
C_2H_6	$(1-x_m-x_A)$	0	–	–
A	x_A	0	x_A	$\hat{H}_3$
O_2	n_o	$\hat{H}_1$	n_{O_2}	$\hat{H}_4$
N_2	$3.76n_o$	$\hat{H}_2$	$3.76n_o$	$\hat{H}_5$
CO	–	–	n_{CO}	$\hat{H}_6$
CO_2	–	–	$r\, n_{CO}$	$\hat{H}_7$
H_2O	–	–	n_{H_2O}	$\hat{H}_8$

c.

$$\hat{H}_i = (\Delta\hat{H}_f)_i + \int_{25}^{T_a \text{ or } T_s} \overset{\substack{\text{Table B.2}\\ \downarrow}}{C_{p,i}}\; dT$$

Given : $x_m = 0.85,\ x_a = 0.05,\ Px_s = 5\%,\ r = 10.0,\ T_a = 150^\circ\text{C},\ T_s = 700^\circ\text{C}$

$\Rightarrow n_o = 2.153,\ n_{CO} = 0.0955,\ n_{H_2O} = 2.00,\ n_{O_2} = 0.1500$

$\hat{H}_1(\text{kJ/mol}) = 8.091,\ \hat{H}_2 = 29.588,\ \hat{H}_3 = 0.702,\ \hat{H}_4 = 3.279,$

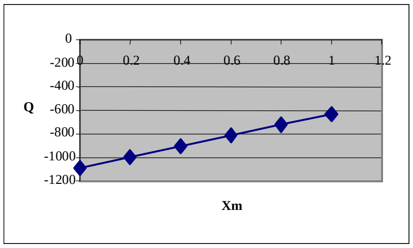
$\hat{H}_5 = 166.72,\ \hat{H}_6 = -8.567,\ \hat{H}_7 = -345.35,\ \hat{H}_8 = -433.82$

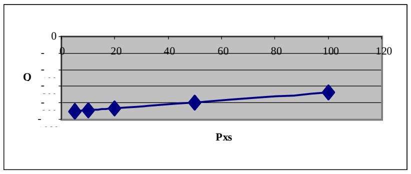
Energy balance: $\dot{Q} = \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in} = \underline{\underline{-655\text{ kW}}}$

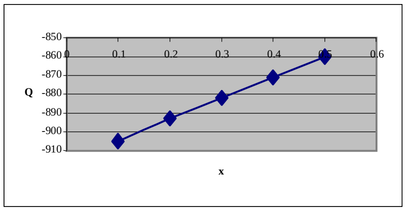
9.58 (cont'd)

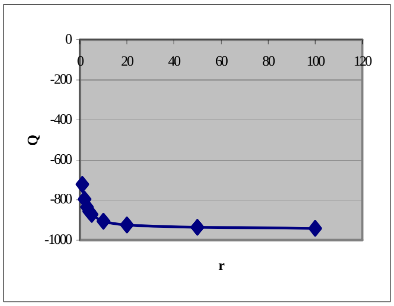
d.

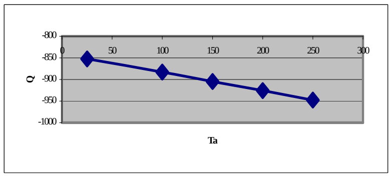
Xa	Pxs	r	Ta	Ts	Q
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.0	5	10	150	700	-
0.1	5	10	150	700	-
0.1	10	10	150	700	-
0.1	20	10	150	700	-
0.1	50	10	150	700	-
0.1	100	10	150	700	-
0.1	5	10	150	700	-
0.2	5	10	150	700	-
0.3	5	10	150	700	-
0.4	5	10	150	700	-
0.5	5	10	150	700	-
0.1	5	1	150	700	-722
0.1	5	2	150	700	-796
0.1	5	3	150	700	-834
0.1	5	4	150	700	-856
0.1	5	5	150	700	-871
0.1	5	10	150	700	-905
0.1	5	20	150	700	-924
0.1	5	50	150	700	-936
0.1	5	100	150	700	-941
0.1	5	10	25	700	-852
0.1	5	10	100	700	-883
0.1	5	10	150	700	-905
0.1	5	10	200	700	-926
0.1	5	10	250	700	-948
0.1	5	10	150	500	-1014
0.1	5	10	150	600	-960
0.1	5	10	150	700	-905
0.1	5	10	150	800	-848
0.1	5	10	150	900	-790
0.1	5	10	150	1000	-731

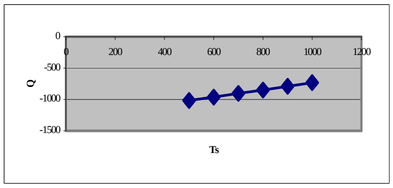






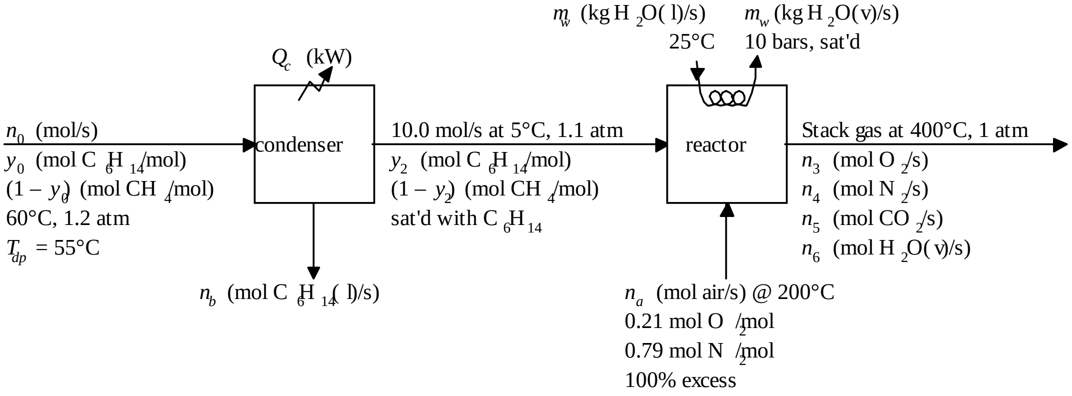






9.59 **a.** Basis:
$$\begin{array}{c|c|c|c}207.4\text{ liters} & 273.2\text{ K} & 1.1\text{ atm} & 1\text{ mol}\\ \hline \text{s} & 278.2\text{ K} & 1.0\text{ atm} & 22.4\text{ liters(STP)}\end{array} = 10.0\ \text{mols/s fuel gas to furnace}$$

$H = C_6H_{14}$; $M = CH_4$



$$T_{dp} = 55^\circ\text{C} \Rightarrow y_0 P = p_H^{\alpha}(55^\circ\text{C}) \overset{\substack{\text{Antoine Eq.}\\ \downarrow}}{=} 483.3\ \text{mm Hg}$$

$$\Rightarrow y_0 = \frac{483.3\ \text{mm Hg}}{1.2\times 760\ \text{mm Hg}} = \underline{\underline{0.530\ \text{mol}\ C_6H_{14}/\text{mol}}} \Rightarrow 0.470\ \text{mol}\ CH_4/\text{mol}$$

Saturation at condenser outlet:

$$y_2 = \frac{p_H^*(5^\circ\text{C})}{\text{P}} = \frac{58.89\ \text{mm Hg}}{1.1\times 760\ \text{mm Hg}} = \underline{\underline{0.070\ \text{mol}\ C_6H_{14}/\text{mol}}} = 0.93\%\ \text{mol}\ CH_4/\text{mol}$$

Methane balance on condenser: $\dot{n}_0(1-y_0) = 10.0(1-y_2) \underset{y_2=0.070}{\overset{y_0=0.530}{\Rightarrow}} \dot{n}_0 = 19.78\ \text{mol/s}$

Hexane balance on condenser: $\dot{n}_0 y_0 = \dot{n}_\text{b} + 10.0y_2 \underset{\substack{\dot{n}_0=19.78\\ y_0=0.530\\ y_2=0.070}}{\Rightarrow} \dot{n}_\text{b} = 9.78\ \text{mol}\ C_6H_{14}/\text{s condensed}$

$$\text{Volume of condensate} = \begin{array}{c|c|c|c|c}9.78\ \text{mol}\ C_6H_{14}(\text{l}) & 86.17\ \text{g} & \text{cm}^3 & 1\text{L} & 3600\ \text{s}\\ \hline \text{s} & \underset{\text{Table B.1}}{\overset{}{\text{mol}\atop\uparrow}} & \underset{\text{Table B.1}}{0.659\ \text{g}\atop\uparrow} & 10^3\ \text{cm}^3 & 1\ \text{h}\end{array}$$

$$= \underline{\underline{4600\ \text{L}\ C_6H_{14}(l)/\text{h}}}$$

b. References: $CH_4(\text{g},\ 5^\circ\text{C})$, $C_6H_{14}(\text{l},\ 5^\circ\text{C})$

Substance	$\dot{n}_\text{in}$ (mol / s)	$\hat{H}_\text{in}$ (kJ / mol)	$\dot{n}_\text{out}$ (mol / s)	$\hat{H}_\text{out}$ (kJ / mol)
CH_4	9.30	1.985	9.30	0
$C_6H_{14}(\text{v})$	10.48	41.212	0.70	32.940
$C_6H_{14}(\text{l})$	–	–	9.78	0

$\underline{CH_4(\text{g})}$: $\hat{H} = \int_5^T \overset{\substack{\text{Table B.2}\\ \downarrow}}{C_p}\, dT$ $\underline{C_6H_{14}(\text{v})}$: $\hat{H} = \int_5^{T_b} \overset{\substack{\text{Table B.1}\\ \downarrow}}{C_{pR}}\, dT + \overset{\substack{\text{Table B.1}\\ \downarrow}}{\Delta\hat{H}_v} + \int_{T_b}^{T} C_{pv} dT$

Condenser energy balance: $\dot{Q}_c = \Delta\dot{H} = \sum_\text{out} \dot{n}_i\hat{H}_i - \sum_\text{in} \dot{n}_i\hat{H}_i = \underline{\underline{-427\ \text{kW}}}$

9.59 (cont'd)

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\,,\ C_6H_{14} + \frac{19}{2}O_2 \rightarrow 6CO_2 + 7H_2O$$

$$\underline{\text{Theoretical } O_2\text{:}}\ \frac{9.30\text{ mol CH}_4}{\text{s}}\left|\frac{2\text{ mol O}_2}{1\text{ mol CH}_4}\right. + \frac{0.70\text{ mol C}_6\text{H}_{14}}{\text{s}}\left|\frac{9.5\text{ mol O}_2}{1\text{ mol C}_6\text{H}_{14}}\right. = 25.3\text{ mol O}_2/\text{s}$$

$$\underline{100\%\text{ excess}} \Rightarrow (O_2)_{\text{fed}} = 2\times(O_2)_{\text{theor.}} \Rightarrow 0.21\dot{n}_a = 2\times 25.3 \Rightarrow \dot{n}_a = 240.95\text{ mol air/s}$$

$$\underline{N_2\text{ balance:}}\ 0.79(240.95) = \dot{n}_4 \Rightarrow \dot{n}_4 = 190.35\text{ mol N}_2/\text{s}$$

<u>C balance:</u>

$$\frac{9.30\text{ mol CH}_4}{\text{s}}\left|\frac{1\text{ mol C}}{1\text{ mol CH}_4}\right. + \frac{0.70\text{ mol C}_6\text{H}_{14}}{}\left|\frac{6\text{ mol C}}{1\text{ mol C}_6\text{H}_{14}}\right. = \frac{n_5(\text{mol CO}_2)}{}\left|\frac{1\text{ mol C}}{1\text{ mol CO}_2}\right.$$

$$\Rightarrow \dot{n}_5 = 13.5\text{ mol CO}_2/\text{s}$$

<u>H balance:</u>

$$(9.30\text{ mol CH}_4/\text{s})(4\text{ mol H/mol CH}_4) + (0.70)(14) = \dot{n}_6(2) \Rightarrow \dot{n}_6 = 23.5\text{ mol H}_2\text{O}$$

Since combustion is complete, $(O_2)_{\text{remaining}} = (O_2)_{\text{excess}} = \frac{1}{2}(O_2)_{\text{fed}} \Rightarrow \dot{n}_3 = 25.3\text{ mol O}_2/\text{s}$

<u>References</u>: $C(s)$, $H_2(g)$, $O_2(g)$, $N_2(g)$ at 25°C for reactor side, $H_2O(l)$ at triple point for steam side (reference state for steam tables)

Substance	$\dot{n}_{\text{in}}$ mol / s	$\hat{H}_{\text{in}}$ kJ / mol	$\dot{n}_{\text{out}}$ mol / s	$\hat{H}_{\text{out}}$ kJ / mol
CH_4	9.30	–75.553	–	–
$C_6H_{14}(v)$	0.70	–170.07	–	–
O_2	50.6	5.31	25.3	11.72
N_2	190.35	5.13	190.35	11.15
CO_2	–	–	13.5	–377.15
$H_2O(v)$	–	–	23.5	–228.60
H_2O(boiler water)	$\dot{m}_w$ (kg / s)	104.8	$\dot{m}_w$ (kg / s)	2776.2

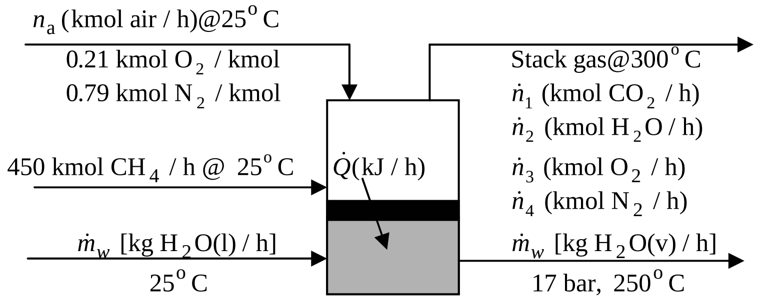
$$\hat{H}(T) \overset{\substack{\text{Table B.1 and B.2}\\ \downarrow}}{=} \Delta\hat{H}_f^o + \int_{25}^{T} C_p dT \quad \text{for CH}_4,\ \text{C}_6\text{H}_{14}$$

$$\overset{\substack{\text{Table B.1 and B.8}\\ \downarrow}}{=} \Delta\hat{H}_f^o + \hat{H}_i(T) \text{ for O}_2, \text{N}_2, \text{CO}_2, \text{H}_2\text{O(v)}$$

<u>Energy balance on reactor</u> (assume adiabatic):

$$\Delta\dot{H} = \sum_{\text{out}}\dot{n}_i\hat{H}_i - \sum_{\text{in}}\dot{n}_i\hat{H}_i = 0 \Rightarrow -8468 + \dot{m}_w(2776.2 - 104.8) = 0 \ \Rightarrow \dot{m}_w = \underline{\underline{3.2\text{ kg steam/s}}}$$

9.60 **a.** Basis: 450 kmol CH_4 fed/h $\qquad CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$



Air fed: $\dot{n}_a = \dfrac{450 \text{ kmol } CH_4}{h} \left| \dfrac{2 \text{ kmol } O_2 \text{ req'd}}{1 \text{ kmol } CH_4} \right| \dfrac{1.2 \text{ kmol } O_2 \text{ fed}}{1 \text{ kmol } O_2 \text{ req'd}} \left| \dfrac{1 \text{ kmol air}}{0.21 \text{ kmol } O_2} \right.$

$= 5143 \text{ kmol air/h}$

$450 \text{ kmol/h } CH_4 \text{ react} \Rightarrow \dot{n}_1 = 450 \text{ kmol } CO_2/\text{h}, \; \dot{n}_2 = 900 \text{ kmol } H_2O/\text{h}$

N_2 balance: $\dot{n}_4 = (0.79)\left(5.143\times10^6 \text{ mol/h}\right) = 4060 \text{ kmol } N_2/\text{h}$

Molecular O_2 balance:

$$\dot{n}_3 = (0.21)(5143)\frac{\text{mol } O_2 \text{ fed}}{\text{h}} - \frac{450 \text{ kmol } CH_4 \text{ react}}{\text{h}} \left| \frac{2 \text{ mol } O_2}{1 \text{ mol } CH_4} \right. = 180 \text{ kmol } O_2/\text{h}$$

$$\left.\begin{array}{l} 450 \text{ kmol } CO_2/\text{h} \\ 900 \text{ kmol } H_2O/\text{h} \\ 4060 \text{ kmol } N_2/\text{h} \\ \underline{180 \text{ kmol } O_2/\text{h}} \end{array}\right\} \Rightarrow \begin{array}{l} \underline{\underline{y_{CO_2} = 0.0805}} \\ \underline{\underline{y_{H_2O} = 0.161}} \\ \underline{\underline{y_{N_2} = 0.726}} \\ \underline{\underline{y_{O_2} = 0.0322}} \end{array}$$

5590 kmol / h

Mean heat capacity of stack gas

$$\overline{C}_p = \sum y_i C_{pi} = (0.0805)(0.0423) + (0.161)(0.0343) + (0.726)(0.0297) + (0.0322)(0.0312)$$

$$= \underline{\underline{0.0315 \text{ kJ/mol}\cdot^\circ \text{C}}}$$

Energy balance on furnace (combustion side only)

References: $CH_4(g)$, $CO_2(g)$, $O_2(g)$, $N_2(g)$, $H_2O(l)$ at 25°C

Substance	$\dot{n}_{in}$ (kmol / h)	$\hat{H}_{in}$ (kJ / kmol)	$\dot{n}_{out}\hat{H}_{out}$ (kJ / h)
CH_4	450	0	–
Air	5143	0	–
Stack gas	–	–	$\dot{H}_p$

Extent of reaction:

$$\dot{\xi} = \dot{n}_{CH_4} = 450 \text{ kmol / h}$$

9.60 (cont'd)

$$\dot{H}_p = \dot{n}_2(\Delta\hat{H}_v)_{\mathrm{H_2O(25^\circ C)}} + \dot{n}_{\text{stack gas}}(\bar{C}_p)_{\text{stack gas}}(T_{\text{stack gas}} - 25^\circ\mathrm{C})$$

$$= \frac{180\text{ kmol H}_2\text{O}}{\text{h}}\bigg|\frac{10^3\text{ mol}}{1\text{ kmol}}\bigg|\frac{44.01\text{ kJ}}{\text{mol}} + \frac{5590\text{ kmol}}{\text{h}}\bigg|\frac{10^3\text{ mol}}{1\text{ kmol}}\bigg|\frac{0.0315\text{ kJ}}{\text{mol}\cdot^\circ\text{C}}\bigg|\frac{(300-25)^\circ\text{C}}{}\bigg|$$

$$= \underline{\underline{5.63\times10^7\text{ kJ/h}}}$$

$$\dot{Q} = \Delta\dot{H} = \dot{\xi}(\Delta\hat{H}_c^\circ)_{\mathrm{CH_4}} + \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i$$

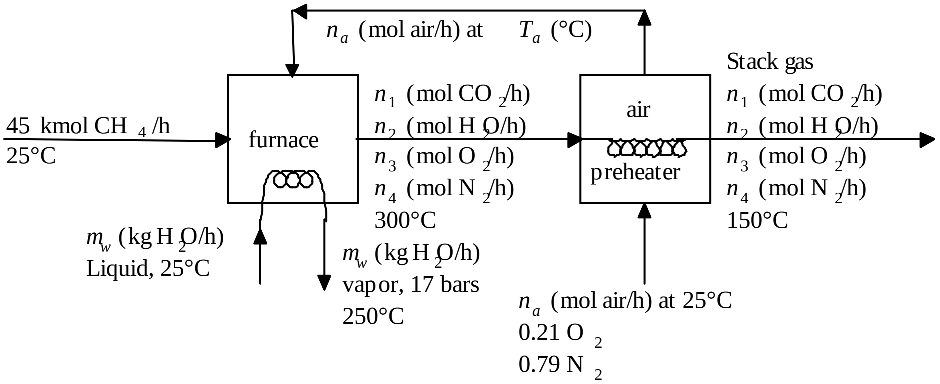
$$= \left(450\ \frac{\text{kmol}}{\text{h}}\right)\left(1000\frac{\text{mol}}{\text{kmol}}\right)\left(-890.36\frac{\text{kJ}}{\text{mol}}\right) + 5.63\times10^7\ \frac{\text{kJ}}{\text{h}} = \underline{\underline{-3.44\times10^8\ \frac{\text{kJ}}{\text{h}}}}$$

Energy balance on steam boiler

$$\dot{Q} = \dot{m}_w\Delta\hat{H}_w \Rightarrow\ +3.44\times10^8\ \frac{\text{kJ}}{\text{h}} = \left[\dot{m}_w\left(\frac{\text{kg}}{\text{h}}\right)\right]\left[\left(\overset{\text{Table B.7}}{2914} - \overset{\text{Table B.6}}{105}\right)\frac{\text{kJ}}{\text{kg}}\right]$$

$$\Rightarrow\ \dot{m}_w = \underline{\underline{1.23\times10^5\text{ kg steam/h}}}$$

b.



E.B. on overall process: The material balances and the energy balance are identical to those of part (a), except that the stack gas exits at 150°C instead of 300°C.

References: $\mathrm{CH_4(g), CO_2(g), O_2(g), N_2(g), H_2O(l)}$ at 25°C (furnace side)

$\mathrm{H_2O(l)}$ at triple point (steam table reference) (steam tube side)

Substance	$\dot{n}_{\text{in}}$ (kmol / h)	$\hat{H}_{\text{in}}$ (kJ / kmol)	$\dot{n}_{\text{out}}\hat{H}_{\text{out}}$ (kJ / h)
$\mathrm{CH_4}$	450	0	–
Air	5143	0	–
Stack gas	–	–	$\dot{H}_p$
$\mathrm{H_2O}$	$\dot{m}_w$ (kg / h)	105 kJ / kg	$\dot{m}_w$ (kg / h) 2914 kJ / kg

$$\dot{H}_p = \dot{n}_2(\Delta\hat{H}_v)_{\mathrm{H_2O(25^\circ C)}} + \dot{n}_{\text{stack gas}}(\bar{C}_p)_{\text{stack gas}}(T_{\text{stack gas}} - 25^\circ\mathrm{C})$$

$$= \frac{180\text{ kmol H}_2\text{O}}{\text{h}}\bigg|\frac{10^3\text{ mol}}{1\text{ kmol}}\bigg|\frac{44.01\text{ kJ}}{\text{mol}} + \frac{5590\text{ kmol}}{\text{h}}\bigg|\frac{10^3\text{ mol}}{1\text{ kmol}}\bigg|\frac{0.0315\text{ kJ}}{\text{mol}\cdot^\circ\text{C}}\bigg|\frac{(150-25)^\circ\text{C}}{}\bigg|$$

$$= \underline{\underline{2.99\times10^7\text{ kJ/h}}}$$

9.60 (cont'd)

$$\Delta\dot{H} = \dot{\xi}(\Delta\hat{H}_c^o)_{CH_4} + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 0$$

$$\Rightarrow \left(450\ \frac{\text{kmol}}{\text{h}}\right)\left(1000\frac{\text{mol}}{\text{kmol}}\right)\left(-890.36\frac{\text{kJ}}{\text{mol}}\right) + 2.99\times10^7\ \frac{\text{kJ}}{\text{h}}$$

$$+\left[\dot{m}_w\left(\frac{\text{kg}}{\text{h}}\right)\right]\left[(2914-105)\frac{\text{kJ}}{\text{kg}}\right] = 0 \ \Rightarrow\ m_w = \underline{\underline{1.32\times10^5\ \text{kg steam/h}}}$$

Energy balance on preheater: $\Delta\dot{H} = \left(\Delta\dot{H}\right)_{\text{stack gas}} + \left(\Delta\dot{H}\right)_{\text{air}} = 0$

$$\left(\Delta H\right)_{\text{stack gas}} = n\overline{C}_p\Delta T = \begin{array}{c|c|c} 5590\ \text{kmol} & 10^3\,\text{mol} & 0.0315\ \text{kJ}\quad (150-300)^\circ\text{C} \\ \hline \text{h} & 1\ \text{kmol} & \text{mol}\cdot{}^\circ\text{C} \end{array} = -2.64\times10^7\ \frac{\text{kJ}}{\text{h}}$$

$$\left(-\Delta H\right)_{\text{stack gas}} = \left(\Delta H\right)_{\text{air}} = n_a\hat{H}_{\text{air}}(T_a) \Rightarrow \hat{H}_{\text{air}}(T_a) = \begin{array}{c|c} 2.64\times10^7\ \text{kJ/h} & 1\ \text{kmol} \\ \hline 5143\ \text{kmol/h} & 10^3\ \text{mol} \end{array} = 5.133\ \frac{\text{kJ}}{\text{mol}}$$

$$\hat{H}_{\text{air}} = 5.133\ \text{kJ/mol} \xrightarrow{\text{Table B.8}} \underline{\underline{T_a = 199^o\,\text{C}}}$$

c. The energy balance on the furnace includes the term $-\sum n_{\text{in}}\hat{H}_{\text{in}}$. If the air is preheated and the stack gas temperature remains the same, this term and hence $\dot{Q}$ become more negative, meaning that more heat is transferred to the boiler water and more steam is produced. The stack gas is a logical heating medium since it is available at a high temperature and costs nothing.

9.61

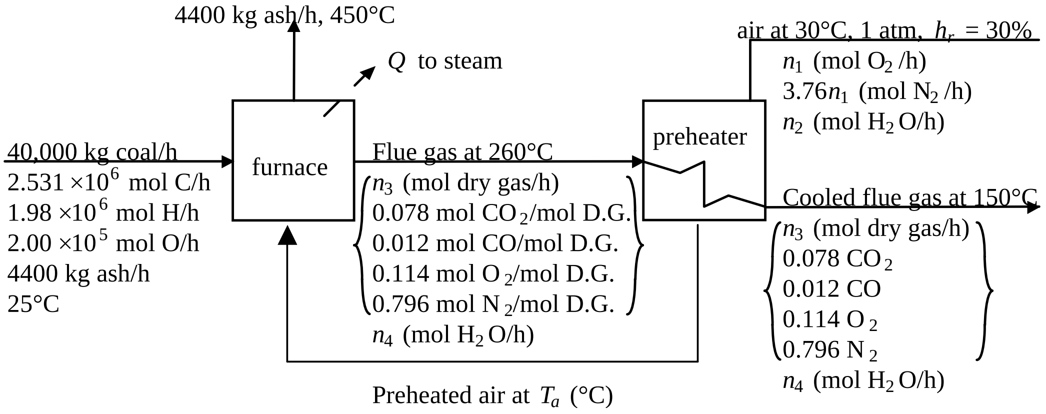
$$\underline{\text{Basis: } 40000\ \text{kg coal/h}} \Rightarrow \begin{array}{c|c|c} (0.76\times40000)\text{kg C} & 10^3\text{g} & 1\ \text{mol C} \\ \hline \text{h} & 1\ \text{kg} & 12.01\ \text{g} \end{array} = 2.531\times10^6\ \text{mol C/h}$$

Assume coal enters at 25°C

$$\left[(0.05\times4000)\text{kg H/h}\right]\left(10^3/1.01\right) = 1.98\times10^6\ \text{mol H/h}$$

$$\left[(0.08\times4000)\text{kg O/h}\right]\left(10^3/16.0\right) = 2.00\times10^5\ \text{mol O/h}$$

$$(0.11\times40000) = 4400\ \text{kg ash/h}$$



a. Overall system balances

C balance: $2.531\times10^6 = 0.078n_3 + 0.012n_3 \Rightarrow n_3 = 2.812\times10^7$ mol/h dry flue gas

$\underline{N_2\text{ balance}}$: $3.76n_1 = (0.796)(2.812\times10^7) \Rightarrow n_1 = 5.95\times10^6$ mol O_2/h $(3.76)(5.95\times10^6)$

$= 224\times10^7$ mol N_2/h

9.61 (cont'd)

30% relative humidity (inlet air):

$$y_{H_2O}P = 0.30p^*_{H_2O}(30^\circ\text{C}) \Rightarrow \frac{\dot{n}_2}{5.95\times10^6 + 2.24\times10^7 + n_2}(760\text{ mm Hg}) = 0.300(\overset{\substack{\text{Table B.3}\\ \downarrow}}{31.824}\text{ mm Hg})$$

$$\Rightarrow \dot{n}_2 = 3.61\times10^5 \text{ mol } H_2O/h$$

Volumetric flow rate of inlet air:

$$\dot{V} = \frac{(5.95\times10^6 + 224\times10^7 + 3.61\times10^5)\text{mol}}{\text{h}}\left|\frac{22.4\text{ liters(STP)}}{1\text{ mol}}\right|\frac{1\text{ m}^3}{10^3\text{ liters}} = 6.43\times10^5\text{SCMH}$$

Air/fuel ratio: $\dfrac{6.43\times10^5\text{ m}^3\text{ air/h}}{40000\text{ kg coal/h}} = \underline{\underline{16.1\text{ SCM air/kg coal}}}$

H balance: $\underbrace{1.98\times10^6\text{ mol H/h}}_{\text{H in coal}} + \underbrace{2(3.61\times10^5)\text{mol H/h}}_{\text{H in water vapor}} = 2\dot{n}_4 \Rightarrow \dot{n}_4 = 1.351\times10^6\text{ mol } H_2O/h$

$$\underline{H_2O\text{ content of stack gas}} = \frac{1.357\times10^6\text{ mol } H_2O/h}{(1.357\times10^6 + 2.812\times10^7)\text{ mol/h}}\times100\% = \underline{\underline{4.6\%\ H_2O}}$$

b. Energy balance on stack gas in preheater

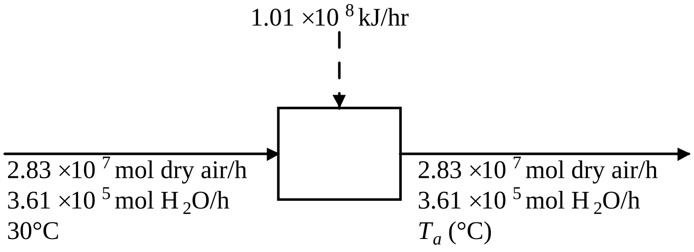
References: CO_2, CO, O_2, N_2, $H_2O(v)$ at 25° C

Substance	n_{in} mol/h	$\hat{H}_{\text{in}}$ kJ/mol	n_{out} mol/h	$\hat{H}_{\text{out}}$ kJ/mol
CO_2	2.193×10^6	4.942	2.193×10^6	9.738
CO	0.337×10^6	3669	0.337×10^6	6.961
O_2	3.706×10^6	3758	3.206×10^6	7.193
N_2	22.38×10^6	3655	72.38×10^6	6.918
H_2O	1.357×10^6	4266	1.351×10^6	8135

$\hat{H}_i(T)$ from Table B.8 for inlet $\qquad \hat{H}_i(T) = \int \overset{\substack{\text{Table B.2}\\ \downarrow}}{C_p}\ dT$ for outlet

$$Q = \sum_{\text{out}} n_i\hat{H}_i - \sum_{\text{in}} n_i\hat{H}_i = \underline{\underline{-1.01\times10^8\text{ kJ/h}}}\ (\text{Heat transferred from stack gas})$$

Air preheating



(We assume preheater is adiabatic, so that $Q_{\text{stack gas}} = -Q_{\text{air}}$)

Energy balance on air:

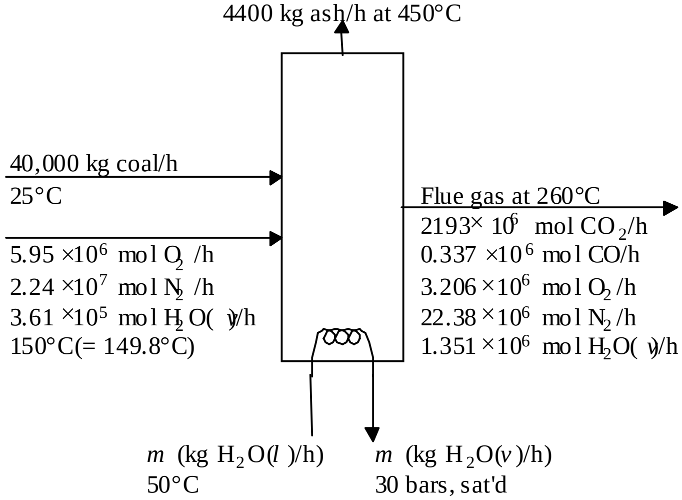
$$Q = \Delta H \Rightarrow 1.01\times10^8\text{ kJ/hr} = \sum\int_{30}^{T_a} n_i(C_p)_i\,dT = \int_{30}^{T_a} n_{dry\,air}\,\overset{\substack{\text{Table B.2}\\ \downarrow}}{(C_p)_{dry\,air}}\,dT + \int_{30}^{T_a} n_{H_2O}\,\overset{\substack{\text{Table B.2}\\ \downarrow}}{(C_p)_{H_2O}}\,dT$$

9.61 (cont'd)

$$\Rightarrow 1.01\times 10^8 = 8.31\times 10^5 (T_a - 30) + 59.92(T_a^2 - 30^2) + 0.031(T_a^3 - 30^3) - 1.42\times 10^{-5}(T_a^4 - 30^4)$$

$$\Rightarrow \underline{\underline{T_a = 150^\circ \text{C}}}$$

c.



<u>References for energy balance on furnace</u>: CO_2, CO, O_2, N_2, $H_2O(l)$, coal at 25° C

(Must choose $H_2O(l)$ since we are given the higher heating value of the coal.)

substance	n_{in}	$\hat{H}_{in}$	n_{out}	$\hat{H}_{out}$	
Coal	40000	0	–	–	$n(\text{kg/h})$
Ash	–	–	4400	412.25	$\hat{H}(\text{kJ/kg})$
O_2	5.95×10^6	3.758	3.206×10^6	7.193	
N_2	2.24×10^6	3.655	2.24×10^7	6.918	$n(\text{mol/h})$
CO_2	–	–	2.193×10^6	9.738	$\hat{H}(\text{kJ/mol})$
CO	–	–	0.337×10^6	6.961	
H_2O	3.61×10^5	48.28	1.351×10^6	52.14	

(Furnace only — exclude boiler water)

<u>Heat transferred from furnace</u>

$$Q = n_{\text{coal}} \Delta \hat{H}_{\text{i}}^{\text{o}} + \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i$$

$$= \left(4\times 10^4 \frac{\text{kg}}{\text{h}}\right)\left(-2.5\times 10^4 \frac{\text{kJ}}{\text{kg}}\right) + \left(2.74\times 10^3 - \underset{\substack{\uparrow \\ \hat{H} \text{ of preheated air}}}{1.22\times 10^8}\right)\frac{\text{kJ}}{\text{kg}}$$

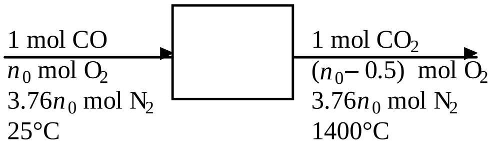
$$= -8.76\times 10^8 \text{ kJ/h}$$

<u>Heat transferred to boiler water</u>: 0.60(8.76x10^8 kJ/h) = 5.25x10^8 kJ/h

<u>Energy balance on boiler:</u> $\dot{Q}(\text{kJ/h}) = \dot{m}\left(\frac{\text{kg}}{\text{h}}\right)\left[\hat{H}(H_2O(l),\ 30b,\ \text{sat'd}) - \hat{H}(H_2O(l),\ 50^\circ \text{C})\right]$

$$\Rightarrow 5.25\times 10^8 \text{ kJ/h} = \dot{m}\left[\underset{\substack{\uparrow \\ \text{Table B.6}}}{2802.3} - \underset{\substack{\uparrow \\ \text{Table B.5}}}{209.3}\right]\frac{\text{kJ}}{\text{kg}} \Rightarrow \underline{\underline{\dot{m} = 2.02\times 10^5 \text{ kg steam/h}}}$$

9.62 Basis : 1 mol CO burned. $CO+\frac{1}{2}O_2 \rightarrow CO_2,\ \Delta\hat{H}_c^o = -282.99\ \text{kJ/mol}$



a. Oxygen in product gas: $n_1 = n_0(\text{mol } O_2 \text{ fed}) - \frac{1\text{ mol CO react} \mid 0.5\text{ mol } O_2}{\mid 1\text{ mol CO}} = n_0 - 0.5$

References: CO, CO_2, O_2, N_2 at 25°C

Substance	n_{in} (mol)	$\hat{H}_{in}$ (kJ/mol)	n_{out} (mol)	$\hat{H}_{out}$ (kJ/mol)
CO	1	0	–	–
O_2	n_0	0	$n_0 - 0.5$	$\hat{H}_1$
N_2	$3.76n_0$	0	$3.76n_0$	$\hat{H}_2$
CO_2	–	–	1	$\hat{H}_3$

$$O_2(g,1400^\circ C):\ \hat{H}_1 = \hat{H}_{O_2}(1400^\circ C) \overset{\text{Table B.8}}{\overset{\downarrow}{=}} 47.07\ \text{kJ/mol}$$

$$N_2(g,1400^\circ C):\ \hat{H}_2 = \hat{H}_{N_2}(1400^\circ C) \overset{\text{Table B.8}}{\overset{\downarrow}{=}} 44.51\ \text{kJ/mol}$$

$$CO_2(g,1400^\circ C):\ \hat{H}_3 = \hat{H}_{CO_2}(1400^\circ C) \overset{\text{Table B.8}}{\overset{\downarrow}{=}} 71.89\ \text{kJ/mol}$$

E.B.:

$$\Delta H = n_{CO}\Delta\hat{H}_c^o + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = -282.99 + 47.07(n_0 - 0.5) + 44.51(3.76n_0) + 71.89 = 0$$

$$\Rightarrow n_0 = 1.094\ \text{mol } O_2$$

Theoretical O_2 $= (1\text{ mol CO})(0.5\text{ mol } O_2/\text{mol CO}) = 0.500\text{ mol } O_2$

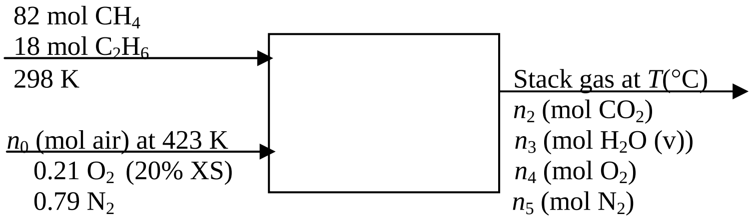
Excess oxygen: $\frac{1.094\text{ mol fed} - 0.500\text{ mol reqd.}}{0.500\text{ mol}} \times 100\% = \underline{\underline{119\%\text{ excess oxygen}}}$

b. Increase %XS air ⇒ T_{ad} would decrease, since the heat liberated by combustion would go into heating a larger quantity of gas (i.e., the additional N_2 and unconsumed O_2).

9.63 **a.** Basis : 100 mol natural gas ⇒ 82 mol CH_4, 18 mol C_2H_6

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(v),\quad \Delta\hat{H}_c^o = -890.36\text{ kJ / mol}$$

$$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(v),\ \Delta\hat{H}_c^o = -1559.9\text{ kJ / mol}$$



9.63 (cont'd)

Theoretical oxygen $= \dfrac{2 \text{ mol } O_2}{1 \text{ mol } CH_4}\Big|\dfrac{82 \text{ mol } CH_4}{} + \dfrac{3.5 \text{ mol } O_2}{1 \text{ mol } C_2H_6}\Big|\dfrac{18 \text{ mol } C_2H_6}{} = 227 \text{ mol } O_2$

Air fed : $n_1 = \dfrac{1.2 \times 227 \text{ mol } O_2}{}\Big|\dfrac{1 \text{ mol air}}{0.21 \text{ mol } O_2} = 1297.14 \text{ mol air}$

C balance : $n_2 = (82.00)(1) + (18.00)(2) \Rightarrow n_2 = 118.00 \text{ mol } CO_2$

H balance : $2n_3 = (82.00)(4) + (18.00)(6) \Rightarrow n_3 = 218.00 \text{ mol } H_2O$

20% excess air, complete combustion $\Rightarrow n_4 = (0.2)(227) \text{ mol } O_2 = 45.40 \text{ mol } O_2$

N_2 balance : $n_5 = (0.79)(1297.14) = 1024.63 \text{ mol } N_2$

Extents of reaction: $\xi_1 = n_{CH_4} = 82 \text{ mol}, \ \ \xi_1 = n_{C_2H_6} = 18 \text{ mol}$

Reference states: $CH_4(g),\ C_2H_6(g),\ N_2(g),\ O_2(g),\ H_2O(l)$ at 298 K

(We will use the values of $\Delta\hat{H}_c^o$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water.)

$$\hat{H}_i(T) = C_{pi}(T - 298 \text{ K}) \text{ for all species but water}$$
$$= \Delta\hat{H}_{v,H_2O}(298 \text{ K}) + C_{p,H_2O}(T - 298 \text{ K}) \text{ for water}$$

Substance	n_{in} mol	$\hat{H}_{in}$ kJ/mol	n_{out} mol	$\hat{H}_{out}$ kJ/mol
CH_4	82.00		–	–
C_2H_6	18.00	0	–	–
O_2	272.40	4.14	45.40	$0.0331(T-298)$
N_2	1024.63	3.91	1024.63	$0.0313(T-298)$
CO_2	–	–	118.00	$0.0500(T-298)$
$H_2O(v)$	–	–	218.00	$44.013 + 0.0385(T-298)$

Energy balance : $\Delta H = 0$

$$\xi_1\left(\Delta\hat{H}_c^o\right)_{CH_4} + \xi_2\left(\Delta\hat{H}_c^o\right)_{C_2H_6} + \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i = 0$$

$$\Rightarrow (82.00 \text{ mol } CH_4)(-890.36 \text{ kJ/mol}) + (18.00 \text{ mol } C_2H_6)(-1559.90 \text{ kJ/mol})$$
$$+\big[(45.40)(0.0331) + (1024.63)(0.0313) + (118.00)(0.0500) + (218.00)(0.0385)\big](T-298)$$
$$+(218.00)(44.01) - (272.40)(4.14) - (1024.63)(3.91) = 0$$

b. Solving for T using E-Z Solve $\Rightarrow \underline{\underline{T = 2317 \text{ K}}}$

Increase % excess air $\Rightarrow$ $\underline{\underline{T_{out} \text{ decreases}}}$. (Heat of combustion has more gas to heat)

% methane increases $\Rightarrow T_{out}$ might decrease. (lower heat of combustion, but heat released goes into heating fewer moles of gas.)

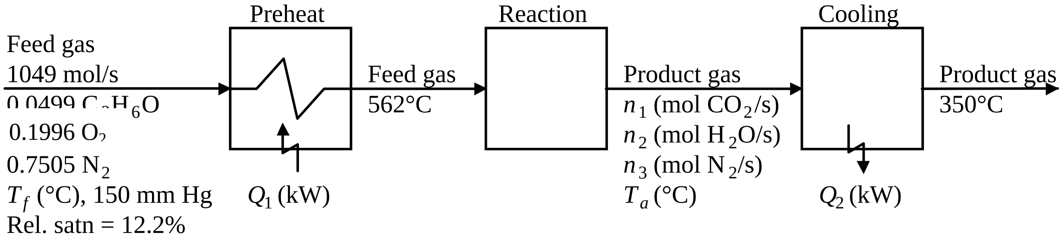
9.64 $C_3H_6O(g)+4O_2(g)\rightarrow 3CO_2(g)+3H_2O(l),\ \Delta\hat{H}_i^o=-1821.4\ \text{kJ/mol}$

$$\underline{\text{Basis}}:\ \frac{1410\ \text{m}^3(\text{STP})\ \text{feed gas}}{\text{min}}\left|\frac{10^3\ \text{mol}}{22.4\ \text{m}^3(\text{STP})}\right|\frac{1\ \text{min}}{60\ \text{s}}=1049\ \text{mol/s feed gas}$$

Stochiometric proportion:

$$1\ \text{mol}\ C_3H_6O\Rightarrow 4\ \text{mol}\ O_2\Rightarrow 4\times 3.76=15.04\ \text{mol}\ N_2\Rightarrow(1+4+15.04)=20.04\ \text{mol}$$

$$y_{C_3H_6O}=\frac{1\ \text{mol}\ C_3H_6O}{20.04\ \text{mol}}=0.0499\frac{\text{mol}\ C_3H_6O}{\text{mol}},\ y_{O_2}=\frac{4}{20.04}=0.1996\ \text{mol}\ O_2/\text{mol}$$



a. Relative saturation $=12.2\%\Rightarrow y_{C_3H_6O}P=0.122\,p^*_{C_3H_6O}(T_f)$

$$\Rightarrow p^*=\frac{(0.0499)(1500\ \text{mm Hg})}{0.122}=613.52\ \text{mm Hg}\ \xrightarrow{\text{Table B.4}}\ \underline{\underline{T_f=50.0^o\text{C}}}$$

b. Feed contains $(1049\ \text{mol/s})(0.0499\ C_3H_6O/\text{mol})=52.34\ \text{mol}\ C_3H_6O/\text{s}$

$(1049)(0.1996)=209.4\ \text{mol}\ O_2/\text{s}$

$(1049)(0.7505)=787.3\ \text{mol}\ N_2/\text{s}$

$$\Rightarrow\text{Product contains}\left.\begin{array}{l}n_1=(52.34)(3)=157.0\ \text{mol}\ CO_2/\text{s}\\ n_2=(52.34)(3)=157.0\ \text{mol}\ H_2O/\text{s}\\ n_3=787.3\ \text{mol}\ N_2/\text{s}\end{array}\right\}\Rightarrow\begin{array}{l}\underline{\underline{14.25\ \text{mole\%}\ CO_2}}\\ \underline{\underline{14.25\%\ H_2O}}\\ \underline{\underline{71.5\%\ N_2}}\end{array}$$

$\underline{\text{References}}$: $C_3H_6O(g),\ O_2,\ N_2,\ H_2O(l),\ CO_2$ at 25°C

Substance	$\dot{n}_{\text{in}}$ (mols)	$\hat{H}_{\text{in}}$ (kJ/mol) (562°C)	$\dot{n}_{\text{out}}$ (mols)	$\hat{H}_{\text{out}}$ (kJ/mol) T_a
C_3H_6O	52.34	67.66	–	–
O_2	209.4	17.72	–	–
N_2	787.3	17.18	787.3	$0.032(T_a-25)$
CO_2	–	–	157.0	$0.052(T_a-25)$
H_2O	–	–	157.0	$44.013+0.040(T_a-25)$

Energy balance on reactor:

$$\Delta H=n_{C_3H_6O}\Delta\hat{H}_c^o+\sum_{\text{out}}n_i\hat{H}_i-\sum_{\text{in}}n_i\hat{H}_i=0\ (\text{kJ/s})$$

$$\Rightarrow(5234\ \text{mol/s})\left(-1821.1\frac{\text{kJ}}{\text{mol}}\right)+39.638(T_a-25)+157.0(44.013)-2.078\times10^4=0\Rightarrow\underline{\underline{T_a=2780°\text{C}}}$$

9.64 (cont'd)

c.

Preheating step: References: $C_3H_6(g)$, O_2, N_2 at 25°C

Substance	$\dot{n}_{\text{in}}$ (mol / s)	$\hat{H}_{\text{in}}$ (kJ / mol) (50° C)	$\dot{n}_{\text{out}}$ (mol / s)	$\hat{H}_{\text{out}}$ (kJ / mol) (562° C)
C_3H_6O	52.34	3.15	52.34	67.66
O_2	209.4	0.826	209.4	17.72
N_2	787.3	0.775	787.3	16.65

E.B. $\Rightarrow \dot{Q}_1 = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = \underline{\underline{1.94 \times 10^4 \text{ kW}}}$

Cooling step. References: $CO_2(g)$, $H_2O(v)$, $N_2(g)$ at 25°C

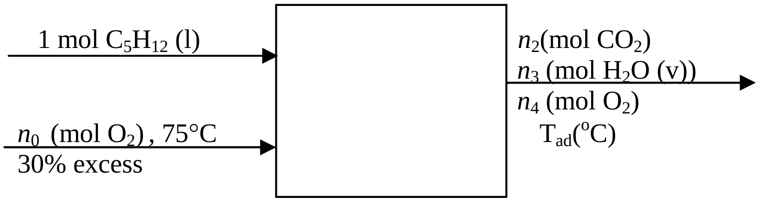
Substance	n_{in} (mol)	$\hat{H}_{\text{in}}$ (kJ / mol) (2871°C)	n_{out} (mol)	$\hat{H}_{\text{out}}$ (kJ / mol) (350°C)
CO_2	157.0	142.3	157.0	16.25
H_2O	157.0	108.15	157.0	12.35
N_2	787.3	88.23	787.3	10.08

E.B. $\Rightarrow Q_2 = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = \underline{\underline{-9.64 \times 10^4 \text{ kW}}}$

Exchange heat between the reactor feed and product gases.

9.65 **a.** Basis : 1 mol C_5H_{12} (l)

$$C_5H_{12}(l) + 8O_2(g) \rightarrow 5CO_2(g) + 6H_2O(v), \qquad \Delta\hat{H}_c^o = -3509.5 \text{ kJ / mol}$$



$\underline{\underline{\text{Theoretical oxygen}}} = \dfrac{1 \text{ mol } C_5H_{12} \;\big|\; 8 \text{ mol } O_2}{\big|\; 1 \text{ mol } C_5H_{12}} = 8 \text{ mol } O_2$

30% excess $\Rightarrow n_0 = 1.3 \times 8 = 10.4 \text{ mol } O_2$

C balance: $n_2 = (1)(5) \Rightarrow n_2 = 5 \text{ mol } CO_2$

H balance: $2n_3 = (1)(12) \Rightarrow n_3 = 6 \text{ mol } H_2O$

30% excess O_2, complete combustion $\Rightarrow n_4 = (0.3)(8) \text{ mol } O_2 = 2.4 \text{ mol } O_2$

Reference states: $C_5H_{12}(l)$, $O_2(g)$, $H_2O(l)$, $CO_2(g)$ at 25°C

(We will use the values of $\Delta\hat{H}_c^0$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water)

9.65 (cont'd)

substance	n_{in} mol	$\hat{H}_{\text{in}}$ kJ/mol	n_{out} mol	$\hat{H}_{\text{out}}$ kJ/mol
C_5H_{12}	1.00	0	–	–
O_2	10.40	$\hat{H}_1$	2.40	$\hat{H}_2$
CO_2	–	–	5.00	$\hat{H}_3$
H_2O	–	–	6.00	$\hat{H}_4$

$$\hat{H}_i = \int_{25}^{T} (C_p)_i \, dT \qquad i = 2,3$$

$$= \Delta\hat{H}_v\left(25^\circ \text{C}\right) + \int_{25}^{T} (C_p)_{\text{H}_2\text{O(v)}} dT \;\; \text{for H}_2\text{O(v)}$$

$$\hat{H}_1 = \hat{H}_{\text{O}_2}(75^\circ \text{C}) \overset{\substack{\text{Table B.8}\\ \downarrow}}{=} 1.48 \text{ kJ / mol}$$

Substituting $(C_p)_i$ from Table B.2 :

$$\hat{H}_2 = (0.0291\, T_{ad} + 0.579\times10^{-5}\, T_{ad}{}^2 - 0.2025\times10^{-8}\, T_{ad}{}^3 + 0.3278\times10^{-12}\, T_{ad}{}^4 - 0.7311)\ \frac{\text{kJ}}{\text{mol}}$$

$$\hat{H}_3 = (0.03611\, T_{ad} + 2.1165\times10^{-5}\, T_{ad}{}^2 - 0.9623\times10^{-8}\, T_{ad}{}^3 + 1.866\times10^{-12}\, T_{ad}{}^4 - 0.9158)\ \frac{\text{kJ}}{\text{mol}}$$

$$\hat{H}_4 = 44.01 + (0.03346\, T_{ad} + 0.3440\times10^{-5}\, T_{ad}{}^2 + 0.2535\times10^{-8}\, T_{ad}{}^3 - 0.8983\times10^{-12}\, T_{ad}{}^4 - 0.838)\ \frac{\text{kJ}}{\text{mol}}$$

$$\Rightarrow \hat{H}_4 = 43.17 + (0.03346\, T_{ad} + 0.3440\times10^{-5}\, T_{ad}{}^2 + 0.2535\times10^{-8}\, T_{ad}{}^3 - 0.8983\times10^{-12}\, T_{ad}{}^4)\ \frac{\text{kJ}}{\text{mol}}$$

<u>Energy balance</u> : $\Delta H = 0$

$$n_{\text{C}_5\text{H}_{12}}\left(\Delta\hat{H}_c^{\text{o}}\right)_{\text{C}_5\text{H}_{12}\text{(l)}} + \sum_{\text{out}} n_i \hat{H}_i - \sum_{\text{in}} n_i \hat{H}_i = 0$$

$$(1 \text{ mol C}_5\text{H}_{12})(-3509.5 \text{ kJ / mol}) + (2.40)\ \hat{H}_2 + (5.00)\ \hat{H}_3 + (6.00)\ \hat{H}_4 - (10.40)(\hat{H}_1) = 0$$

$$\Big\Downarrow\ \text{Substitute for } \hat{H}_1 \text{ through } \hat{H}_4$$

$$\Delta\dot{H} = (0.4512\, T_{\text{ad}} + 14.036\times10^{-5}\, T_{\text{ad}}{}^2 - 3.777\times10^{-8}\, T_{\text{ad}}{}^3 + 4.727\times10^{-12}\, T_{\text{ad}}{}^4) - 3272.20 \text{ kJ / mol} = 0$$

$$\Rightarrow f(T_{\text{ad}}) = -3272.20 + 0.4512\, T_{\text{ad}} + 14.036\times10^{-5}\, T_{\text{ad}}{}^2 - 3.777\times10^{-8}\, T_{\text{ad}}{}^3 + 4.727\times10^{-12}\, T_{\text{ad}}{}^4 = 0$$

<u>Check</u> : $\dfrac{-3272.20}{4.727\times10^{-12}} = -6.922\times10^{14}$

Solving for T_{ad} using E-Z Solve $\Rightarrow$ $\underline{\underline{T_{\text{ad}} = 4414^\circ \text{C}}}$

b.

Terms	T_{ad}	% Error
1	7252	64.3%
2	3481	–21.1%
3	3938	–10.8%

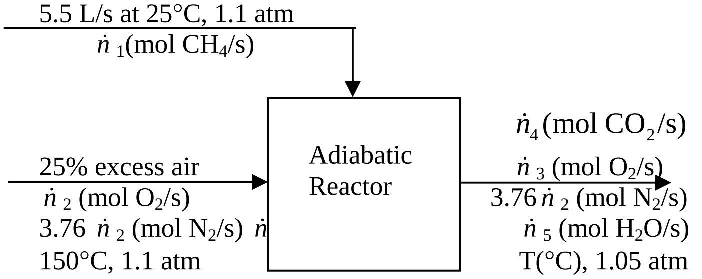
9.65 (cont'd)

c.

T	f(T)	f'(T)	Tnew
7252	6.05E+03	3.74	5634
5634	1.73E+03	1.82	4680
4680	3.10E+02	1.22	4426
4426	1.41E+01	1.11	4414
4414	3.11E-02	1.11	4414

d. The polynomial formulas are only applicable for T ≤ 1500°C

9.66



$$2CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

<u>Fuel feed rate :</u> $= \frac{5.50\text{ L}}{\text{s}}\left|\frac{273\text{ K}}{298\text{ K}}\right|\frac{1.1\text{ atm}}{1.0\text{ atm}}\left|\frac{\text{mol}}{22.4\text{ L(STP)}}\right. = 0.247\text{mol CH}_4/\text{s}$

<u>Theoretical O_2</u> $= 2\times 0.247 = 0.494$ mol O_2 / s

<u>25% excess air</u> $\Rightarrow \dot{n}_2 = 1.25(0.494) = 0.6175$ mol O_2 / s ,
$\Rightarrow 3.76\times 0.6175 = 2.32$ mol N_2 / s

<u>Complete combustion</u> $\Rightarrow \dot{\xi} = n_1 = 0.247$ mol / s, $\dot{n}_4 = 0.247$ mol CO_2 / s, $\dot{n}_5 = 0.494$ mol H_2O / s

$\dot{n}_3 = 0.6175$ mol O_2 fed / s − 0.494 mol consumed / s
$= 0.124$ mol O_2 / s

<u>References</u>: $CH_4, O_2, N_2, CO_2, H_2O$ at 25^o C

Substance	$\dot{n}_{in}$ (mol / s)	$\hat{H}_{in}$ (kJ / mol)	$\dot{n}_{out}$ (mol / s)	$\hat{H}_{out}$ (kJ / mol)
CH_4	0.247	0	−	−
O_2	0.6175	$\hat{H}_1$	0.124	$\hat{H}_3$
N_2	2.32	$\hat{H}_2$	2.32	$\hat{H}_4$
CO_2	−	−	0.247	$\hat{H}_5$
H_2O	−	−	0.497	$\hat{H}_6$

$$\hat{H}_1 = \hat{H}(O_{2,}150^oC) \xrightarrow{\text{Table B.8}} 3.78\text{ kJ/mol}$$

$$\hat{H}_2 = \hat{H}(N_{2,}150^oC) \xrightarrow{\text{Table B.8}} 3.66\text{ kJ/mol}$$

$$(\Delta\hat{H}_c^o)_{CH_4} = -890.36\text{ kJ/mol}$$

$$\hat{H}_i = \int_{25}^{T} C_{pi}dT,\quad i = 3-5$$

9.66 (cont'd)

$$\hat{H}_b = (\Delta\hat{H}_v)_{H_2O(25^\circ C)} + \int_{25}^{T} (C_p)_{H_2O(v)}\, dT$$

a. Energy Balance

$$\Delta\dot{H} = \dot{\xi}(\Delta\hat{H}_c^o)_{CH_4} + \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in} = 0$$

Table B.2 for $C_{pi}(T)$, $(\Delta\hat{H}_v)_{H_2O}$ = 44.01 kJ/mol

$$0.247(-890.36) + 0.494(44.01) + 0.0963(T-25) + 1.02\times10^{-5}(T^2-25^2) + 0.305\times10^{-8}(T^3-25^3)$$
$$-1.61\times10^{-12}(T^4-25^4) - 0.6175(3.78) - 2.32(3.66) = 0$$

$$\Rightarrow -211.4 + 0.0963T_{ad} + 1.02\times10^{-5}T_{ad}{}^2 + 0.305\times10^{-8}T_{ad}{}^3 - 1.61\times10^{-12}T_{ad}{}^4 = 0 \Rightarrow \underline{\underline{T = 1832^o C}}$$

b. In product gas,

$T = 1832^o$C, $P = 1.05\times760 = 798$ mmHg

$$y_{H_2O} = \frac{0.494 \text{ mol/s}}{(0.124+2.32+0.247+0.494) \text{ mol/s}} = 0.155 \text{ mol } H_2O\text{/mol}$$

Raoult's law: $y_{H_2O}P = p^*_{H_2O}(T_{dp}) \Rightarrow p^*_{H_2O} = (0.155)(798) = 124 \text{ mmHg} \overset{\text{Table B.3}}{\Longrightarrow} \underline{\underline{T_{dp} = 56^\circ C}}$

Degr. superheat = $1832^\circ C - 56^\circ C$ = $\underline{\underline{1776^\circ C}}$

9.67 **a.** $CH_4(l) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(v)$

Basis: 1 mol CH_4

$$\text{Theoretical oxygen} = \frac{1 \text{ mol } CH_4 \mid 2 \text{ mol } O_2}{\mid 1 \text{ mol } CH_4} = 2.00 \text{ mol } O_2$$

30 % excess air $\Rightarrow 1.30\ (2.00) = 2.60$ mol O_2 , $\Rightarrow 3.76\times2.60 = 9.78$ mol N_2

Complete combustion $\Rightarrow n_2 = 1.00$ mol CO_2, $n_3 = 2.00$ mol H_2O

2.00 mol O_2 consumed $\Rightarrow n_4 = (2.60 - 2.00)$ mol O_2 $= 0.60$ mol O_2

Internal energy of reaction: Eq. (9.1-5) $\Rightarrow$ $\Delta\hat{U}_c^o = \Delta\hat{H}_c^o - RT\left(\sum_{\substack{\text{gaseous}\\\text{products}}}\nu_i - \sum_{\substack{\text{gaseous}\\\text{reactants}}}\nu_i\right)$

$$\Rightarrow \left(\Delta\hat{U}_c^o\right)_{CH_4} = \left(-890.36\ \frac{kJ}{mol}\right) - \frac{8.314 \text{ J} \mid 298 \text{ K} \mid (1+2-1-2) \mid 1 \text{ kJ}}{\text{mol K} \mid \mid \mid 10^3 \text{ J}} = -890.36\ \frac{kJ}{mol}$$

$$\hat{U} = \int_{25}^{T}(C_v)dT \overset{\text{Ideal Gas}}{\Longrightarrow} \int_{25}^{T}(C_p - R_g)dT$$

If C_p is independent of $T \Rightarrow \hat{U} = (C_p - R_g)(T - 25^o C)$

9.67 (cont'd)

b. Reference states: $CH_4(g),\ N_2(g),\ O_2(g),\ H_2O(l),\ CO_2(g)$ at $25^o C$

(We will use the values of $\Delta\hat{H}_c^0$ given in Table B.1, which are based on $H_2O(l)$ as a combustion product, and so must choose the liquid as a reference state for water.)

Substance	n_{in} mol	$\hat{U}_{in}$ kJ/mol	n_{out} mol	$\hat{U}_{out}$ kJ/mol
CH_4	1.00	0	–	–
O_2	2.60	0	0.60	$\hat{U}_1$
N_2	9.78	0	9.78	$\hat{U}_2$
CO_2	–	–	1.00	$\hat{U}_3$
$H_2O(v)$	–	–	2.00	$\hat{U}_4$

$$\hat{U}_i \overset{\overset{\text{Part a}}{\downarrow}}{=} (C_p - R_g)(T-25) \quad \text{for all species except } H_2O(v)$$

$$= \Delta\hat{U}_v\left(25^o C\right) + (C_p - R_g)(T-25) = \left[\Delta\hat{H}_v\left(25^o C\right) - R_g T_{ref}\right] + (C_p - R_g)(T-25) \ \text{ for } H_2O(v)$$

Substituting given values of $(C_p)_i$ and $R_g = 8.314\times10^{-3}$ kJ / mol yields

$$\hat{U}_1 = (0.033 - 8.314\times10^{-3})(T-25) \text{ kJ / mol} = (0.02469T - 0.6172) \text{ kJ / mol}$$

$$\hat{U}_2 = (0.032 - 8.314\times10^{-3})(T-25) \text{ kJ / mol} = (0.02369T - 0.5922) \text{ kJ / mol}$$

$$\hat{U}_3 = (0.052 - 8.314\times10^{-3})(T-25) \text{ kJ / mol} = (0.04369T - 1.0922) \text{ kJ / mol}$$

$$\hat{U}_4 = \left[44.01\ \frac{\text{kJ}}{\text{mol}} - \left(8.314\times10^{-3}\ \frac{\text{kJ}}{\text{mol}\cdot\text{K}}\right)(298\text{ K})\right] + \ (0.040 - 8.314\times10^{-3})(T-25)\ \frac{\text{kJ}}{\text{mol}}$$

$$\Rightarrow \hat{U}_4 = 41.53\ \frac{\text{kJ}}{\text{mol}} + \ (0.052 - 8.314\times10^{-3})(T-25)\ \frac{\text{kJ}}{\text{mol}} = (0.03167T - 40.74)\ \frac{\text{kJ}}{\text{mol}}$$

Energy Balance

$$Q = n_{CH_4}\left(\Delta\hat{U}_c^o\right)_{CH_4} + \sum_{out} n_i\hat{U}_i - \sum_{in} n_i\hat{U}_i = 0$$

$$\Rightarrow Q = (1.00)(-890.36 \text{ kJ / mol}) + (0.60)\hat{U}_1 + (9.87)\hat{U}_2 + (1.00)\hat{U}_3 + (2.00)\hat{U}_4 = 0$$

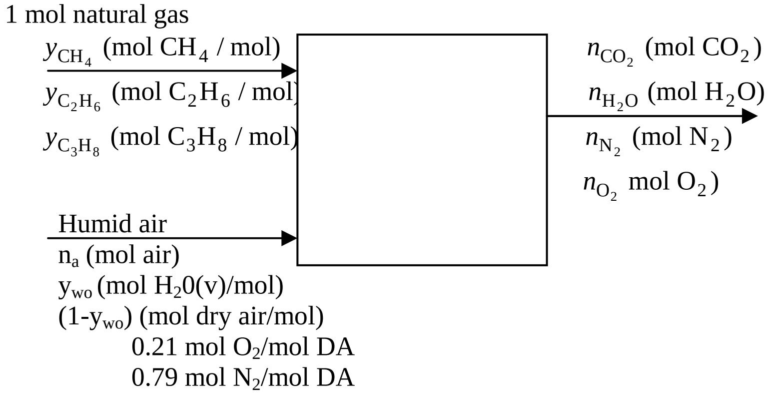
Substituting $\hat{U}_1$ through $\hat{U}_4$

$$0.3557\ T - 816.19 = 0 \Rightarrow \underline{\underline{T = 2295^o C}}$$

Ideal Gas Equation of State $\Rightarrow \dfrac{P_f}{P_i} = \dfrac{T_f}{T_i} \Rightarrow P_f = \left(\dfrac{(2295+273)\text{ K}}{(25+273)\text{ K}}\right)\times 4.00 \text{ atm} = \underline{\underline{34.5 \text{ atm}}}$

c.
– Heat loss to and through reactor wall
– Tank would expand at high temperatures and pressures

9.68 **b.**



Basis : 1 g-mole natural gas

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + H_2O(v)$$

$$C_2H_6(g) + \frac{7}{2}O_2(g) \rightarrow 2CO_2(g) + 3H_2O(v)$$

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(v)$$

Theoretical oxygen :

$$\frac{2\text{ mol }O_2}{1\text{ mol }CH_4}\Bigg|\, y_{CH_4}\text{ (mol }CH_4) + \frac{3.5\text{ mol }O_2}{1\text{ mol }C_2H_6}\Bigg|\, y_{C_2H_6}\text{ (mol }C_2H_6) + \frac{5\text{ mol }O_2}{1\text{ mol }C_3H_8}\Bigg|\, y_{C_3H_8}\text{ (mol }C_3H_8)$$

$$= (\,2y_{CH_4} + 3.5y_{C_2H_6} + 5\,y_{C_3H_8})$$

Excess oxygen: $0.21n_a(1-y_{wo}) = \left(1+\frac{P_{xs}}{100}\right)(\,2y_{CH_4} + 3.5y_{C_2H_6} + 5\,y_{C_3H_8})$ mol O_2

$$\Rightarrow\ n_a \ = \left(1+\frac{P_{xs}}{100}\right)(\,2y_{CH_4} + 3.5y_{C_2H_6} + 5\,y_{C_3H_8})\ \frac{1}{0.21(1-y_{w0})}\ \text{mol air}$$

Feed components

$$(n_{O_2})_{in} = 0.21n_a(1-y_{wo}),\ (n_{N_2})_{in} = 0.79n_a(1-y_{wo}),\ (n_{H_2O})_{in} = n_a y_{wo}$$

N_2 in product gas: $n_{N_2} = (n_{N_2})_{in}$ mol N_2

CO_2 in product gas :

$$n_{CO_2} = \frac{1\text{ mol }CO_2}{1\text{ mol }CH_4}\Bigg|\, n_{CH_4}\text{ (mol }CH_4) + \frac{2\text{ mol }CO_2}{1\text{ mol }C_2H_6}\Bigg|\, n_{C_2H_6}\text{ (mol }C_2H_6) + \frac{3\text{ mol }CO_2}{1\text{ mol }C_3H_8}\Bigg|\, n_{C_3H_8}\text{ (mol }C_3H_8)$$

$$= (n_{CH_4} + 2n_{C_2H_6} + 3n_{C_3H_8})\text{ mol }CO_2$$

H_2O in product gas :

$$n_{H_2O} = \frac{1\text{ mol }H_2O}{1\text{ mol }CH_4}\Bigg|\, n_{CH_4}\text{ (mol }CH_4) + \frac{3\text{ mol }H_2O}{1\text{ mol }C_2H_6}\Bigg|\, n_{C_2H_6}\text{ (mol }C_2H_6) + \frac{4\text{ mol }O_2}{1\text{ mol }C_3H_8}\Bigg|\, n_{C_3H_8}\text{ (mol }C_3H_8)$$

$$= \ [2n_{CH_4} + 3n_{C_2H_6} + 4n_{C_3H_8} + n_a(1\text{-}y_{wo})]\text{ mol }H_2O$$

O_2 in product gas : $n_{O_2} = \frac{P_{xs}}{100}(\,2n_{CH_4} + 3.5n_{C_2H_6} + 5\,n_{C_3H_8})$ mol O_2

9.68 (cont'd)

c. References: C(s), H_2(g) at 25°C

$$\hat{H}_{CH_4}(T) = (\Delta \hat{H}_f^o)_{CH_4} + \int_{25}^{T} (C_p)_{CH_4}\, dT$$

Using $(\Delta H_f^o)_{CH_4}$ from Table B.1 and $(C_p)_{CH_4}$ from Table B.2

$$\hat{H}_{CH_4}(T) = -74.85 \text{ kJ/mol} + \left(\int_{25}^{T} (0.03431 + 5.469\times10^{-5}T + 0.3661\times10^{-8}T^2 - 11.00\times10^{-12}T^3)\, dT \right) \text{kJ/mol}$$

$$\Rightarrow \hat{H}_{CH_4}(T) = [-75.72 + 3.431\times10^{-2}T + 2.734\times10^{-5}T^2 + 0.122\times10^{-8}T^3 - 2.75\times10^{-12}T^4] \text{ kJ/mol}$$

Substance	n_{in} mol	$\hat{H}_{in}$ kJ/mol	n_{out} mol	$\hat{H}_{out}$ kJ/mol
CH_4	n_1	$\hat{H}_1$	–	–
C_2H_6	n_2	$\hat{H}_2$	–	–
C_3H_8	n_3	$\hat{H}_3$	–	–
O_2	n_4	$\hat{H}_4$	n_7	$\hat{H}_7$
N_2	n_5	$\hat{H}_5$	n_8	$\hat{H}_8$
CO_2	n_6	–	n_9	$\hat{H}_9$
H_2O	–	–	n_{10}	$\hat{H}_{10}$

$$\Delta H = \sum_{i=4}^{7}(n_i)_{out}(H_i)_{out} - \sum_{i=1}^{6}(n_i)_{in}(H_i)_{in}$$

$$\hat{H}_i = a_i + b_i T + c_i T^2 + d_i T^3 + e_i T^4$$

$$\sum_{i=1}^{6}(n_i)_{in}(H_i)_{in} = \sum_{i=1}^{3}(n_i)_{in}\hat{H}_i(T_f) + \sum_{i=4}^{6}(n_i)_{in}\hat{H}_i(T_a)$$

$$\Rightarrow \Delta H = \sum_{i=4}^{7}(n_i)_{out}(a_i + b_i T + c_i T^2 + d_i T^3 + e_i T^4)_{out} - \sum_{i=1}^{3}(n_i)_{in}\hat{H}_i(T_f) - \sum_{i=4}^{6}(n_i)_{in}\hat{H}_i(T_a)$$

$$\Rightarrow \Delta H = \sum_{i=1}^{7}(n_i)_{out}a_i + \sum_{i=4}^{7}(n_i)_{out}b_i T + \sum_{i=1}^{7}(n_i)_{out}c_i T^2 + \sum_{i=1}^{7}(n_i)_{out}d_i T^3 + \sum_{i=1}^{7}(n_i)_{out}e_i T^4$$

$$- \sum_{i=1}^{3}(n_i)_{in}\hat{H}_i(T_f) - \sum_{i=4}^{6}(n_i)_{in}\hat{H}_i(T_a)$$

$$= \alpha_0 + \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3 + \alpha_4 T^4$$

where $\alpha_0 = \sum_{i=1}^{7}(n_i)_{out}a_i - \sum_{i=1}^{3}(n_i)_{in}\hat{H}_i(T_f) - \sum_{i=4}^{6}(n_i)_{in}\hat{H}_i(T_a)$

$$\alpha_1 = \sum_{i=1}^{7}(n_i)_{out}b_i \qquad \alpha_2 = \sum_{i=1}^{7}(n_i)_{out}c_i$$

$$\alpha_3 = \sum_{i=1}^{7}(n_i)_{out}d_i \qquad \alpha_4 = \sum_{i=1}^{7}(n_i)_{out}e_i$$

.

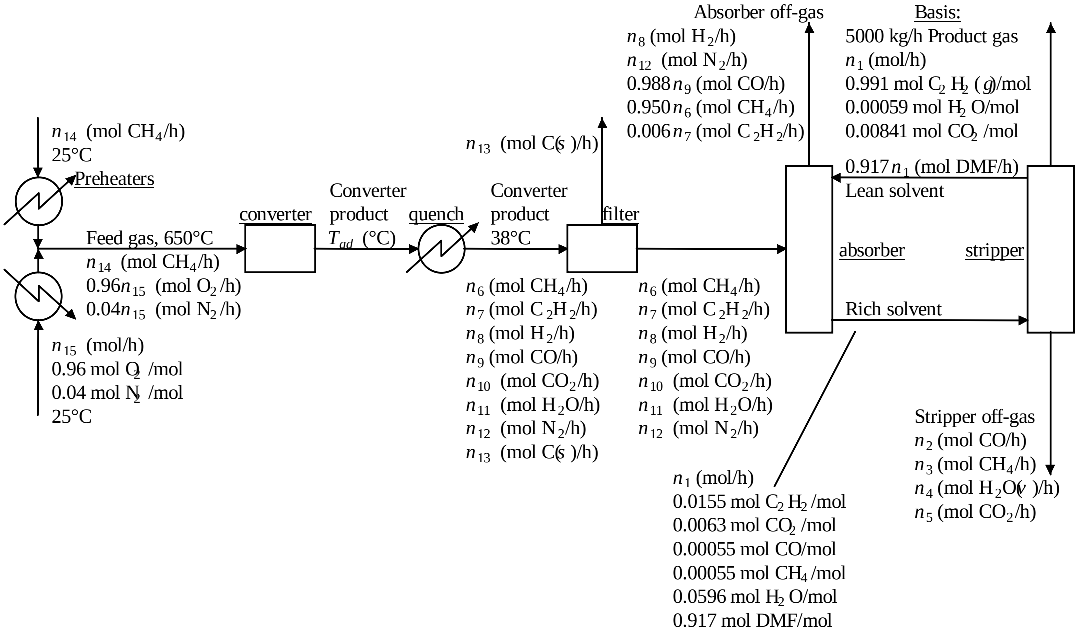
9.68 (cont'd)

d.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**
yCH4	0.75	0.86	0.75	0.75	0.75	0.75
yC2H6	0.21	0.1	0.21	0.21	0.21	0.21
yC3H8	0.04	0.04	0.04	0.04	0.04	0.04
Tf	40	40	150	40	40	40
Ta	150	150	150	250	150	150
Pxs	25	25	25	25	100	25
ywo	0.0306	0.0306	0.0306	0.0306	0.0306	0.1
nO2i	3.04	2.84	3.04	3.04	4.87	3.04
nN2	11.44	10.67	11.44	11.44	18.31	11.44
nH2Oi	0.46	0.43	0.46	0.46	0.73	1.61
HCH4	-74.3	-74.3	-70	-74.3	-74.3	-74.3
HC2H6	-83.9	-83.9	-77	-83.9	-83.9	-83.9
HC3H8	-102.7	-102.7	-93	-102.7	-102.7	-102.7
HO2i	3.6	3.6	3.6	6.6	3.6	3.6
HN2i	3.8	3.8	3.8	6.9	3.8	3.8
HH2Oi	-237.6	-237.6	-237.6	-234.1	-237.6	-237.6
nCO2	1.29	1.18	1.29	1.29	1.29	1.29
nH2O	2.75	2.61	2.75	2.75	3.02	3.9
nO2	0.61	0.57	0.61	0.61	2.44	0.61
nN2	11.44	10.67	11.44	11.44	18.31	11.44
Tad	**1743.1**	**1737.7**	**1750.7**	**1812.1**	**1237.5**	**1633.6**
alph0	-1052	-978.9	-1057	-1099	-1093	-1058
alph1	0.4892	0.4567	0.4892	0.4892	0.7512	0.5278
alph2	0.0001	1.00E-04	0.0001	0.0001	0.0001	0.0001
alph3	-3.00E-08	-3.00E-08	-3.00E-08	-3.00E-08	-4.00E-08	-2.00E-08
alph4	3.00E-12	3.00E-12	3.00E-12	3.00E-12	4.00E-12	2.00E-12
Delta H	3.00E-07	9.00E-06	-4.00E-07	-1.00E-04	-1.00E-05	6.00E-04

Species	a	b	c	d	e
		x 10^2	x 10^5	x 10^8	x 10^12
CH4	-75.72	3.431	2.734	0.122	-2.75
C2H6	-85.95	4.937	6.96	-1.939	1.82
C3H8	-105.6	6.803	11.3	-4.37	7.928
O2	-0.731	2.9	0.11	0.191	-0.718
N2	-0.728	2.91	0.579	-0.203	0.328
H20	-242.7	3.346	0.344	0.254	-0.898
CO2	-394.4	3.611	2.117	-0.962	1.866

9.69



Average M.W. of product gas:

$$\overline{M} = 0.991(26.04) + 0.00059(18.016) + 0.00841(44.01) = 26.19 \text{ g/mol}$$

Molar flow rate of product gas: $n_0 = \begin{array}{c|c|c|c} 5000\text{ kg} & 10^3\text{ g} & 1\text{ mol} & 1\text{ day} \\ \hline \text{day} & 1\text{ kg} & 26.19\text{ g} & 24\text{ h} \end{array} = 7955 \text{ mol/h}$

Material balances -- plan of attack (refer to flow chart):

Stripper balances: $C_2H_2 \Rightarrow n_1$, $CO \Rightarrow n_2$, $CH_4 \Rightarrow n_3$, $H_2O \Rightarrow n_4$, $CO_2 \Rightarrow n_5$

Absorber balances: $CH_4 \Rightarrow n_6$, $C_2H_2 \Rightarrow n_7$, $CO \Rightarrow n_9$, $CO_2 \Rightarrow n_{10}$, $H_2O \Rightarrow n_{11}$

$$\left.\begin{cases}\text{5.67\% soot formation}\\ \text{converter C balance}\end{cases}\right\} \Rightarrow n_{13}, n_{14}, \ \underline{\text{converter H balance}} \Rightarrow n_8$$

$\underline{\text{Converter O balance}} \Rightarrow n_{15}$, $\underline{\text{converter } N_2 \text{ balance}} \Rightarrow n_{12}$

Stripper balances:

C_2H_2: $0.0155n_1 = 0.991(7955 \text{ mol/h}) \Rightarrow n_1 = 5.086 \times 10^5$ mol/h

CO: $(0.00055)(5.086 \times 10^5) = n_2 \Rightarrow n_2 = 79.7$ mol CO/h

CH_4: $(0.00055)(5.086 \times 10^5) = n_3 \Rightarrow n_3 = 79.7$ mol CH_4/h

H_2O: $(0.0596)(5.086 \times 10^5) = n_4 + (0.00059)(7955) \Rightarrow n_4 = 30308$ mol H_2O/h

CO_2: $(0.0068)(5.086 \times 10^5) = n_5 + (0.00841)(7955) \Rightarrow n_5 = 3392$ mol CO_2/h

Absorber balances

CH_4: $n_6 = 0.950n_6 + (0.00055)(5.086 \times 10^5) = n_6 \Rightarrow 5595$ mol CH_4/h

9.69 (cont'd)

C_2H_2: $n_7 = (0.0155)\left(5.086\times 10^5\right) + 0.006n_7 \Rightarrow n_7 = 7931 \text{ mol } C_2H_2/\text{h}$

CO: $n_9 = 0.988n_9 + (0.00055)\left(5.086\times 10^5\right) \Rightarrow n_9 = 23311 \text{ mol CO/h}$

CO_2: $n_{10} = (0.0068)\left(5.086\times 10^5\right) = 3458 \text{ mol } CO_2/\text{h}$

H_2O: $n_{11} = (0.0596)\left(5.086\times 10^5\right) = 30313 \text{ mol } H_2O/\text{h}$

<u>Soot formation:</u> $\dfrac{n_{13} = (0.0567)n_{14}(\text{mol } CH_4)}{\text{h}}\left|\dfrac{1 \text{ mol C}}{1 \text{ mol } CH_4}\right. \Rightarrow n_{13} = 0.0567n_{14} \quad (1)$

<u>Converter C balance:</u>

$n_{14} = (5595 \text{ mol } CH_4/\text{h})(1 \text{ mol C/mol } CH_4) + (7931)(2) + (23311)(1) + (3458)(1) + n_{13}$

$\Rightarrow n_{14} = n_{13} + 48226 \quad (2)$

Solve (1) & (2) simultaneously $\Rightarrow n_{13} = 2899 \text{ mol C(s)/h},\ n_{14} = 51120 \text{ mol } CH_4/\text{h}$

<u>Converter H balance:</u> $\dfrac{51120 \text{ mol } CH_4}{\text{h}}\left|\dfrac{4 \text{ mol H}}{1 \text{ mol } Ch_4}\right. = \overset{CH_4}{(5595)(4)} + \overset{C_2H_2}{(7931)(2)} + \overset{H_2}{2n_8} + \overset{H_2O}{(30313)(2)}$

$\Rightarrow n_8 = 52816 \text{ mol } H_2/\text{h}$

<u>Converter O balance:</u> $(0.96n_{15})(2) = \dfrac{23311 \text{ mol CO}}{\text{h}}\left|\dfrac{1 \text{ mol O}}{1 \text{ mol CO}}\right. + \overset{CO_2}{(3458)(2)} + \overset{H_2O}{(30313)(1)}$

$\Rightarrow n_{15} = 31531 \text{ mol/h}$

<u>Converter N_2 balance:</u> $(0.04)(31531)n_{12} \Rightarrow n_{12} = 1261 \text{ mol } N_2/\text{h}$

a. <u>Feed stream flow rates</u>

$$V_{CH_4} = \frac{51120 \text{ mol } CH_4}{\text{h}}\left|\frac{0.0244 \text{ m}^3(\text{STP})}{1 \text{ mol}}\right. = \underline{\underline{1145 \text{ SCMH } CH_4}}$$

$$V_{O_2} = \frac{31531 \text{ mol } (O_2 + N_2)}{\text{h}}\left|\frac{0.0244 \text{ m}^3(\text{STP})}{1 \text{ mol}}\right. = \underline{\underline{706 \text{ SCMH } O_2(+N_2)}}$$

b. <u>Gas feed to absorber</u>

$$\left.\begin{array}{r} 5595 \text{ mol } CH_4/\text{h} \\ 7931 \text{ mol } C_2H_2/\text{h} \\ 23311 \text{ mol CO/h} \\ 3458 \text{ mol } CO_2/\text{h} \\ 30313 \text{ mol } H_2O/\text{h} \\ 52816 \text{ mol } H_2/\text{h} \\ \underline{1261 \text{ mol } N_2/\text{h}} \\ 1.2469\times 10^5 \text{ mol/h} \end{array}\right\} \Rightarrow \underline{\underline{125 \text{ kmol/h}}},\quad \underline{\underline{\begin{array}{l} 4.5 \text{ mole\% } CH_4,\ 6.4\ \%\ C_2H_2,\ 18.7\% \text{ CO},\\ 2.8\%\ CO_2,\ 24.3\%\ H_2O,\ 42.4\%\ H_2,\ 1.0\%\ N_2 \end{array}}}$$

<u>Absorber off-gas</u>

$$\left.\begin{array}{l} 52816 \text{ mol } H_2/\text{h} \\ 1261 \text{ mol } N_2/\text{h} \\ 23031 \text{ mol CO/h} \\ 5315 \text{ mol } CH_4/\text{h} \\ \underline{41.6 \text{ mol } C_2H_2/\text{h}} \\ 8.2471\times 10^4 \text{ mol/h} \end{array}\right\} \Rightarrow \underline{\underline{82.5 \text{ kmol/h}}},\ \underline{\underline{\begin{array}{l} 64.1 \text{ mole\% } H_2,\ 1.5\%\ N_2,\ 27.9\% \text{ CO},\\ 6.4\%\ CH_4,\ 0.06\%\ C_2H_2 \end{array}}}$$

9.69 (cont'd)

Stripper off-gas

$$\left.\begin{array}{l}279.7\text{ mol CO/h}\\279.7\text{ mol CH}_4\text{/h}\\30308\text{ mol H}_2\text{O/h}\\\underline{3392\text{ mol CO/h}}\\3.4259\times10^4\text{ mol/h}\end{array}\right\}\Rightarrow \underline{\underline{34.3\text{ kmol/h}}},\ \underline{\underline{0.82\%\text{ CO},\ 0.82\%\text{ CH}_4,\ 88.5\%\text{ H}_2\text{O},\ 9.9\%\text{ CO}_2}}$$

c. $\underline{\text{DMF recirculation rate}} = 0.917\left(5.086\times10^5\ \frac{\text{mol}}{\text{h}}\right)\left(\frac{1\text{ kmol}}{10^3\text{ mol}}\right) = \underline{\underline{466\text{ kmol DMF/h}}}$

d. $\underline{\text{Overall product yield}} = \frac{(0.991)(7955)\text{ mol C}_2\text{H}_2\text{ in product gas}}{51120\text{ mol CH}_4\text{ in feed/h}} = \underline{\underline{0.154\frac{\text{mol C}_2\text{H}_2}{\text{mol CH}_4}}}$

The theoretical maximum yield would be obtained if only the reaction $2CH_4 \rightarrow C_2H_2 + 3H_2$ occurred, the reaction went to completion, and all the C_2H_2 formed were recovered in the product gas. This yield is (1 mol C_2H_2/2 mol CH_4) = 0.500 mol C_2H_2/2 mol CH_4.

The ratio of the actual yield to the theoretical yield is 0.154/0.500 = $\underline{0.308}$.

e. Methane preheater

$$\dot{Q}_{CH_4} = \Delta\dot{H} = \dot{n}_{14}\int_{25}^{650}\overset{\substack{\text{Table B.2}\\\downarrow}}{\left(C_p\right)}_{CH_4} dT = \frac{51120\text{ mol}}{\text{h}}\left|\frac{32824\text{ J}}{\text{mol}}\right|\frac{1\text{ h}}{3601\text{ s}}\left|\frac{1\text{ kJ}}{10^3\text{ J}}\right. = \underline{\underline{466\text{ kW}}}$$

Oxygen preheater

$$\dot{Q}_{O_2} = \Delta\dot{H} = 0.96\dot{n}_{15}\ \overset{\substack{\text{Table B.8}\\\downarrow}}{\hat{H}(O_2,650^\circ C)} + 0.04\dot{n}_{15}\ \overset{\substack{\text{Table B.8}\\\downarrow}}{\hat{H}(N_2,650^\circ C)}$$

$$= \left(31531\frac{\text{mol}}{\text{h}}\right)\left[(0.96\times20.135+0.04\times18.99)\frac{\text{kJ}}{\text{mol}\cdot^\circ\text{C}}\right]\left(\frac{1\text{ h}}{3600\text{ s}}\right) = \underline{\underline{176\text{ kW}}}$$

f. $\underline{\text{References}}$: C(s), H_2(g), O_2(g), N_2(g) at 25°C

Substance	$\dot{n}_{in}$	$\hat{H}_{in}(650^\circ C)$	$\dot{n}_{out}$	$\hat{H}_{out}(T_{out})$	
CH_4	51120	–42.026	5595	$-74.85+\int_{25}^{T_a}C_p dT$	
O_2	30270	20.125	–	–	
N_2	1261	18.988	1261	$\int_{35}^{T_a}C_p dT$	
C_2H_2	–	–	7931	$+226.75\int_{25}^{T_a}C_p dT$	
H_2	–	–	52816	$\int C_p dT$	n(mol/h)
CO	–	–	23311	$-110.52+\int C_p dT$	$\hat{H}$(kJ/mol)
CO_2	–	–	3458	$-393.5+\int C_p dT$	
H_2O	–	–	30313	$-241.83+\int C_p dT$	
C(s)	–	–	2899	$\int C_p dT$	

9.69 (cont'd)

$$\hat{H}_i = \underset{\text{kJ/mol}}{\Delta\hat{H}_i^0} + \underset{\text{kJ/mol}\cdot{}^\circ\text{C}}{\int_{25}^{T} C_{pi}\,dT}$$

$$\sum_{\text{in}} \dot{n}_i \hat{H}_i = -1.575 \times 10^6 \text{ kJ/h}$$

$$\sum_{\text{out}} \dot{n}_i \hat{H}_i = -9.888 \times 10^6 \text{ kJ/h} + \int_{25}^{T_{\text{out}}} \Big[5595(C_p)_{\text{CH}_4} + 1261(C_p)_{\text{N}_2} + 7931(C_p)_{\text{C}_3\text{H}_2}$$

$$+52816(C_p)_{\text{H}_2} + 23311(C_p)_{\text{CO}} + 3458(C_p)_{\text{CO}_2} + 3013(C_p)_{\text{H}_2\text{O}(v)} \Big] \frac{1 \text{ kJ}}{10^3 \text{ J}} dT$$

$$+\int_{298}^{T_{ad}+273} (C_p)_{\text{C}(s)} \times \frac{1 \text{ kJ}}{10^3 \text{ J}} dT$$

We will apply the heat capacity formulas of Table B.2, recognizing that we will probably push at least some of them above their upper temperature limits

$$\sum_{\text{out}} \dot{n}_i \hat{H}_i = -9.888 \times 10^6 \text{ kJ/h} + \int_{25}^{T_{ad}} \left(3902 + 1.2185 - 5.9885 \times 10^{-4} T^2 - 1.0162 \times 10^{-7} T^3\right) dT$$

$$+\int_{298}^{T_{ad}+273} \left(32.411 + 0.031744T - \frac{1.4179 \times 10^6}{T^2}\right) dT$$

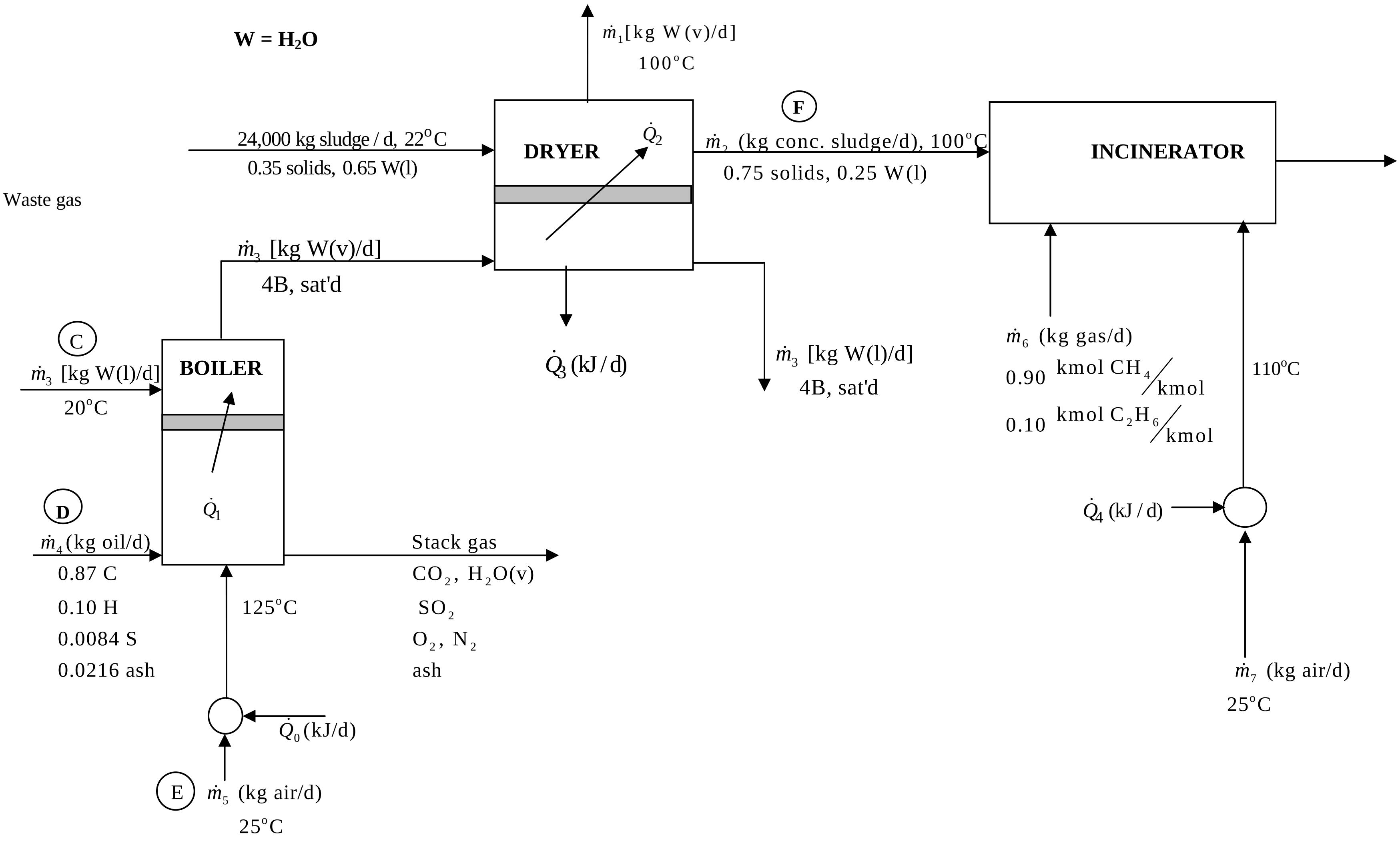
$$\sum_{\text{out}} \dot{n}_i \hat{H}_i = -1.000 \times 10^7 + 3943T_a + 0.6251T_a^2 - 1.996 \times 10^{-4} T_a^3 - 2.5405 \times 10^{-8} T_a^4 + \frac{1.418 \times 10^6}{T_a + 273}$$

<u>Energy balance:</u> $\Delta\dot{H} = \sum_{\text{out}} \dot{n}_i \hat{H}_i - \sum_{\text{in}} \dot{n}_i \hat{H}_i = 0$

$$\Rightarrow f(T_c) = -8.485 \times 10^6 + 3943T_c + 0.6251T_c^2 - 1.996 \times 10^{-4} T_c^3 - 2.5405 \times 10^{-8} T_c^4 + \frac{1.418 \times 10^6}{T_c + 273} = 0$$

$$\xRightarrow{\text{E-Z Solve}} \underline{\underline{T_c = 2032^\circ \text{C.}}}$$

9.70 a.


W = H2O
ṁ1 [kg W(v)/d]
100°C
24,000 kg sludge / d, 22°C
0.35 solids, 0.65 W(l)
DRYER
Q̇2
F
ṁ2 (kg conc. sludge/d), 100°C
0.75 solids, 0.25 W(l)
INCINERATOR
Waste gas
ṁ3 [kg W(v)/d]
4B, sat'd
Q̇3 (kJ / d)
ṁ3 [kg W(l)/d]
4B, sat'd
ṁ6 (kg gas/d)
0.90 kmol CH4/kmol
0.10 kmol C2H6/kmol
110°C
C
ṁ3 [kg W(l)/d]
20°C
BOILER
Q̇1
D
ṁ4 (kg oil/d)
0.87 C
0.10 H
0.0084 S
0.0216 ash
125°C
Stack gas
CO2, H2O(v)
SO2
O2, N2
ash
Q̇4 (kJ / d)
Q̇0 (kJ/d)
E
ṁ5 (kg air/d)
25°C
ṁ7 (kg air/d)
25°C

9.70 (cont'd)

Solids balance on dryer:

$$0.35\times 24{,}000\ \text{kg/d} = 0.75\dot{n}_2 \Rightarrow \dot{n}_2 = 11200\ \text{kg/d} \Rightarrow \underline{\underline{\ F\quad 11.2\ \text{tonnes/d}}}\ \text{(conc. sludge)}$$

Mass Balance on dryer: $24{,}000 = \dot{n}_1 + 11200 \Rightarrow \dot{n}_1 = 12{,}800\ \text{kg/d}$

Energy balance on sludge side of dryer:

References: $H_2O(l, 22^\circ C)$, Solids$(22^\circ C)$

Substance	$\dot{n}_{in}$ (kg/d)	$\hat{H}_{in}$ (kJ/kg)	$\dot{n}_{out}$ (kg/d)	$\hat{H}_{out}$ (kJ/kg)
Solids	8400	0	8400	$\hat{H}_1$
$H_2O(l)$	15600	0	2800	$\hat{H}_2$
$H_2O(v)$	–	–	12800	$\hat{H}_3$

$$\hat{H}_1 = 2.5(100-22) = 195.0\ \text{kJ/kg}$$

$$\hat{H}_2 = (419.1-92.2) = 326.9\ \text{kJ/kg}$$

$$\hat{H}_3 = (2676-92.2) = 2584\ \text{kJ/kg}$$

$(\hat{H}_{\text{water}}$ from Table B.5)

$$\dot{Q}_2 = \sum_{\text{out}} \dot{m}_i \hat{H}_i - \sum_{\text{in}} \dot{m}_i \hat{H}_i \Rightarrow \underline{\underline{\dot{Q}_2 = 3.56\times 10^7\ \text{kJ/day}}}$$

$$\dot{Q}_{\text{steam}} = \frac{3.56\times 10^7}{0.55} = 6.47\times 10^7\ \text{kJ/d} \Rightarrow \underline{\underline{\dot{Q}_3 = 2.91\times 10^7\ \text{kJ/d}}}$$

Energy balance on steam side of dryer:

$$6.47\times 10^7\ \frac{\text{kJ}}{\text{d}} = \dot{n}_3\left(\frac{\text{kg}}{\text{d}}\right)\times \overset{\substack{\Delta\hat{H}_v\ \text{for}\\ H_2O(\text{sat'd, })\\ \downarrow}}{2133}\left(\frac{\text{kJ}}{\text{kg}}\right)\left(\frac{1\ \text{tonne}}{10^3\ \text{kg}}\right) \Rightarrow \underline{\underline{\dot{n}_3 = 30.3\ \text{tonnes/d}}}\ \text{(boiler feedwater)}$$

Energy balance on steam side of boiler:

$$Q_1 = (30300\frac{\text{kg}}{\text{d}})(2737.6-83.9)\frac{\text{kJ}}{\text{kg}} = \underline{\underline{8.04\times 10^7\ \text{kJ/d}}}$$

62% efficiency $\Rightarrow$ Fuel heating value needed $= \dfrac{8.04\times 10^7}{0.62} = 1.3\times 10^8\ \text{kJ/d}$

$$\Rightarrow \dot{n}_4 = \frac{1.30\times 10^8\ \text{kJ/d}}{3.75\times 10^4\ \text{kJ/kg}} = \underline{\underline{3458\ \text{kg/d}}} \Rightarrow \underline{\underline{\text{D} = 3.5\ \text{tonnes/day}}}\ \text{(fuel oil)}$$

Air feed to boiler furnace: $C + O_2 \rightarrow CO_2$, $4H + O_2 \rightarrow 2H_2O$, $S + O_2 \rightarrow SO_2$

$$(n_{O_2})_{\text{theo}} = 3458\frac{\text{kg}}{\text{d}}\left[(0.87\frac{\text{kgC}}{\text{kg}})(\frac{1\ \text{kmol C}}{12\ \text{kg}})(\frac{1\ \text{kmol}\ O_2}{1\ \text{kmol C}}) + (0.10)(\frac{1}{1})(\frac{1}{4}) + (0.0084)(\frac{1}{32})(\frac{1}{1})\right]$$

$$= 338\ \text{kmol}\ O_2/\text{d}$$

9.70 (cont'd)

$$\text{Air fed (25\% excess)} = 1.25\left(4.76\frac{\text{kmol air}}{\text{kmol O}_2}\right)\left(338\frac{\text{kmol O}_2}{\text{d}}\right) = 2011\frac{\text{kmol air}}{\text{d}}$$

$$\Rightarrow \begin{array}{c|c|c} 2011\text{ kmol} & 29\text{ kg} & 1\text{ tonne} \\ \hline \text{d} & \text{kmol} & 10^3\text{ kg} \end{array} \Rightarrow \underline{\underline{\dot{E} = 58.3\text{ tonnes/d}}}\text{ (air to boiler)}$$

Energy balance on boiler air preheater:

$$\text{Table B.8} \Rightarrow \hat{H}_{air}(125^\circ\text{C}) = 2.93\frac{\text{kJ}}{\text{mol}} \Rightarrow \dot{Q}_0 = \begin{array}{c|c|c} 2011\text{ kmol} & 10^3\text{ mol} & 2.93\text{ kJ} \\ \hline \text{d} & 1\text{ kmol} & \text{mol} \end{array} = \underline{\underline{5.89\times10^6\text{ kJ/d}}}$$

Supplementary fuel for incinerator:

$$\dot{n}_6 = \begin{array}{c|c|c} 11.2\text{ tonne sludge} & 195\text{ SCM} & 1\text{ kmol} \\ \hline \text{d} & \text{tonne} & 22.4\text{ SCM} \end{array} = 97.5\,\text{kmol/d}$$

$$\overline{MW}_{gas} = 0.90\,\overline{MW}_{\text{CH}_4} + 0.10\,\overline{MW}_{\text{C}_2\text{H}_6} = (0.90)(16) + (0.10)(30) = 17.4\ \text{kg/kmol}$$

$$M_{gas} = (97.5)(17.4) \Rightarrow \underline{\underline{\dot{G} = 1.7\text{ tonne/d}}}\ \text{(natural gas)}$$

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O},\ \text{C}_2\text{H}_6 + \frac{7}{2}\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O}$$

Air feed to incinerator:

$$(\text{air})_{th,sludge}: \begin{array}{c|c|c|c|c} 11200\text{ kg sludge} & 0.75\text{ kg sol} & 19000\text{ kJ} & 2.5\text{ m}^3\text{(STP) air} & 1\text{ kmol} \\ \hline \text{d} & \text{kg sludge} & 1\text{ kg sol} & 10^4\text{ kJ} & 22.4\text{ m}^3\text{(STP)} \end{array} = 1781\ \frac{\text{kmol air}}{\text{d}}$$

$$(\text{air})_{th,gas}: 97.5\frac{\text{kmol}}{\text{d}}\left[0.90\frac{\text{kmol CH}_4}{\text{kmol}}\times\frac{2\text{ kmol O}_2}{\text{kmol CH}_4} + (0.10)(3.5)\right]\left(\frac{4.76\text{ kmol air}}{1\text{ kmol O}_2}\right) = 998\ \frac{\text{kmol air}}{\text{d}}$$

$$\text{100\% excess air: } \dot{n}_7 = 2(1781 + 998)\frac{\text{kmol air}}{\text{d}} = 5558\text{ kmol air/d}$$

$$\Rightarrow \begin{array}{c|c|c} 5558\text{ kmol air} & 29.0\text{ kg air} & 1\text{ tonne} \\ \hline \text{d} & 1\text{ kmol air} & 10^3\text{ kg} \end{array} = \underline{\underline{161\text{ tonne air/d}}}\ \text{(incinerator air)}$$

Energy balance on air preheater :

$$\text{Table B.8} \Rightarrow \hat{H}_{air}(110^\circ\text{C}) = 2.486\ \frac{\text{kJ}}{\text{mol}} \Rightarrow \dot{Q}_4 = \begin{array}{c|c|c} 5558\text{ kmol} & 10^3\text{ mol} & 2.486\text{ kJ} \\ \hline \text{d} & 1\text{ kmol} & \text{mol} \end{array} = \underline{\underline{1.38\times10^7\ \frac{\text{kJ}}{\text{d}}}}$$

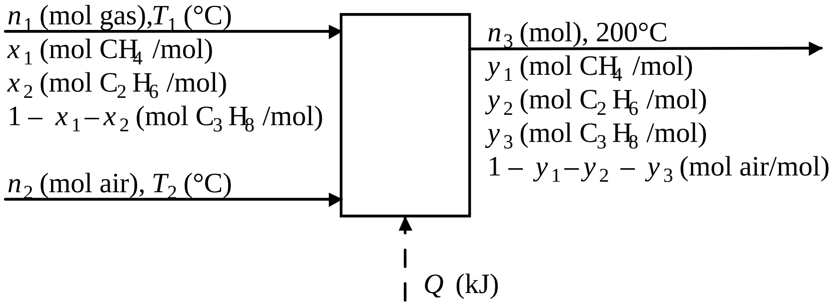
b. Cost of fuel oil, natural gas, fuel oil and air preheating, pumping and compression, piping, utilities, operating personnel, instrumentation and control, environmental monitoring. Lowering environmental hazard might justify lack of profit.

c. Put hot product gases from boiler and/or incinerator through heat exchangers to preheat both air streams. Make use of steam from dryer.

d. Sulfur dioxide, possibly NO_2, fly ash in boiler stack gas, volatile toxic and odorous compounds in gas effluents from dryer and incinerator.

CHAPTER TEN

10.1 **b**. Assume no combustion



11 variables	$(n_1, n_2, n_3, x_1, x_2, y_1, y_2, y_3, T_1, T_2, Q)$
–5 relations	(4 material balances and 1 energy balance)
6 degrees of freedom	

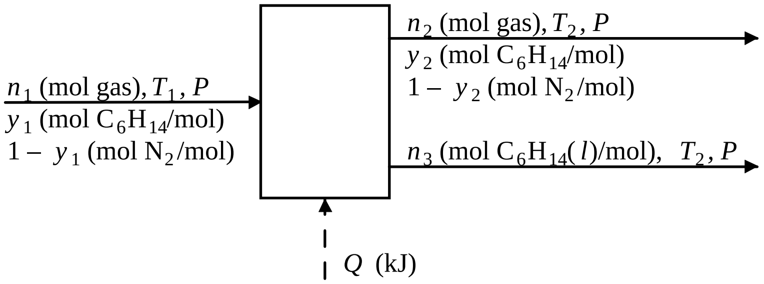
A feasible set of design variables: $\underline{\underline{\{n_1,\ n_2,\ x_1,\ x_2,\ T_1,\ T_2\}}}$

Calculate n_3 from total mole balance, y_1, y_2, and y_3 from component balances, Q from energy balance.

An infeasible set: $\underline{\underline{\{n_1,\ n_2,\ n_3,\ x_1,\ x_2,\ T_1\}}}$

Specifying n_1 and n_2 determines n_3 (from a total mole balance)

c.



9 variables	$(n_1, n_2, n_3, y_1, y_2, T_1, T_2, Q, P)$
–4 relations	(2 material, 1 energy, and 1 equilibrium: $y_2 P = P^*_{C_6H_{14}}(T_2)$)
5 degrees of freedom	

A feasible set: $\underline{\underline{\{n,\ y_1,\ T_1,\ P,\ n_3\}}}$

Calculate n_2 from total balance, y_2 from C_6H_{14} balance, T_2 from Raoult's law: [$y_2 P = P^*_{C_6H_4}(T_2)$], Q from energy balance

An infeasible set: $\underline{\underline{\{n_2,\ y_2,\ n_3,\ P,\ T_2\}}}$

Once y_2 and P are specified, T_2 is determined from Raoult's law

10.2 10 variables $(n_1, n_2, n_3, n_4, x_1, x_2, x_3, x_4, T, P)$

–2 material balances

–2 equilibrium relations: $[x_3 P = x_4 P_B^*(T),\ (1-x_3)P = (1-x_4)P_C^*(T)]$

6 degrees of freedom

a. A straightforward set: $\underline{\underline{\{n_1,\ n_3,\ n_4,\ x_1,\ x_4,\ T\}}}$

Calculate n_2 from total material balance, P from sum of Raoult's laws:

$$P = x_4 p_B^*(T) + (1-x_4)P_c^*(T)$$

x_3 from Raoult's law, x_2 from B balance

b. An iterative set: $\underline{\underline{\{n_1,\ n_2,\ n_3,\ x_1,\ x_2,\ x_3\}}}$

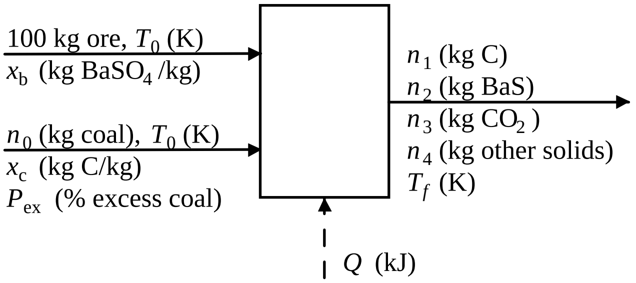
Calculate n_4 from total mole balance, x_4 from B balance.
Guess P, calculate T from Raoult's law for B, P from Raoult's law for C, iterate until pressure checks.

c. An impossible set: $\underline{\underline{\{n_1,\ n_2,\ n_3,\ n_4,\ T,\ P\}}}$

Once n_1, n_2, and n_3 are specified, a total mole balance determines n_4.

10.3 $2\mathrm{BaSO_4(s)} + 4\mathrm{C(s)} \rightarrow 2\mathrm{BaS(s)} + 4\mathrm{CO_2(g)}$

a.



11 variables $(n_0, n_1, n_2, n_3, n_4, x_b, x_c, T_0, T_f, Q, P_{ex})$

-5 material balances $(\mathrm{C},\ \mathrm{BaS},\ \mathrm{CO_2},\ \mathrm{BaSO_4},\ \text{other solids})$

-1 energy balance

$+1$ reaction

-1 relation defining P_{ex} in terms of n_0, x_b, and x_c

$\underline{\underline{5}}$ degrees of freedom

b. Design set: $\underline{\underline{\{x_b,\ x_c,\ T_0,\ T_f,\ P_{ex}\}}}$

Calculate n_0 from x_b, x_c, and P_{ex}; n_1 through n_4 from material balances,
Q from energy balance

10.3 (cont'd)

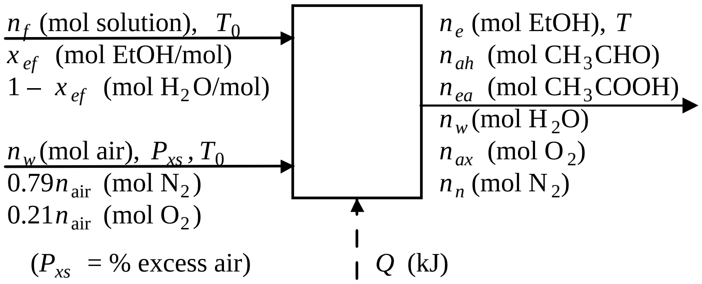
c. <u>Design set:</u> $\underline{\underline{\{x_B,\ x_c,\ T_0,\ n_2,\ Q\}}}$

Specifying x_B determines $n_2 \Rightarrow$ impossible design set.

d. <u>Design set</u>: $\underline{\underline{\{x_B,\ x_c,\ T_0,\ P_{ex},\ Q\}}}$

Calculate n_2 from x_B, n_3 from x_B
n_0 from x_B, x_c and P_{ex}
n_1 from C material balance, n_4 from total material balance
T_f from energy balance (trial-and-error probably required)

10.4 $2C_2H_5OH + O_2 \rightarrow 2CH_3CHO + 2H_2O$
$2CH_3COH + O_2 \rightarrow 2CH_3CHOOH$



a. 13 variables $\left(n_f, n_{aw}, n_e, n_{eh}, n_{ea}, n_w, n_{ex}, n_0, x_{ef}, T_0, T, Q, P_{xs}\right)$
-6 material balances
-1 energy balance
-1 relation between P_{xs}, n_f, x_{ef}, and n_{air}
$+2$ reactions

$\underline{\underline{7}}$ degrees of freedom

b. <u>Design set</u>: $\underline{\underline{\{n_f,\ x_{ef},\ P_{xs},\ n_e,\ n_{ah},\ T_0,\ T\}}}$

Calculate n_{air} from n_f, x_{ef} and P_{xs}; n_n from N_2 balance;
n_{aa} and n_w from n_f, x_{ef}, n_e, n_{ah} and material balances;
n_{ex} from O atomic balance; Q from energy balance

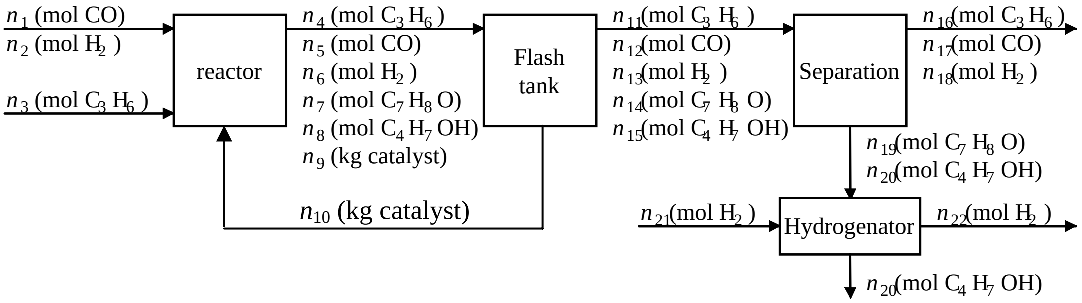
c. <u>Design set:</u> $\underline{\underline{\{n_f,\ x_{ef},\ T_0,\ n_{air},\ Q,\ n_e,\ n_w\}}}$

Calculate P_{xs} from n_f, x_{ef} and n_{air}; n's from material balances; T from energy balance (generally nonlinear in T)

d. <u>Design set</u>: $\underline{\underline{\{n_{air},\ n_n,\ \ldots\}}}$. Once n_{air} is specified, an N_2 balance fixes n_n

10.5

a.



<u>Reactor:</u>

10 variables $(n_1 - n_{16})$
−6 material balances
+2 reactions
$\underline{\underline{6}}$ degrees of freedom

<u>Flash Tank:</u>

12 variables $(n_4 - n_{15})$
−6 material balances
$\underline{\underline{6}}$ degrees of freedom

<u>Separation:</u>

10 variables $(n_{11} - n_{20})$
−5 material balances
$\underline{\underline{5}}$ degrees of freedom

<u>Hydrogenator:</u>

5 variables $(n_{19} - n_{23})$
−3 material balances
+1 reaction
$\underline{\underline{3}}$ degrees of freedom

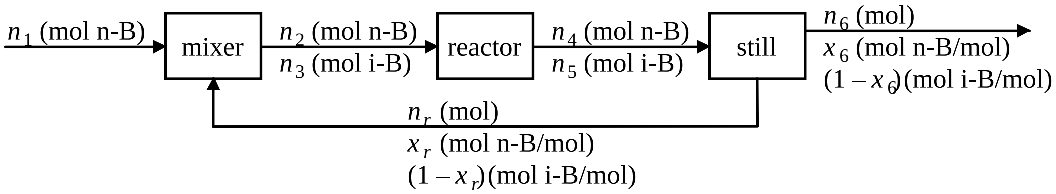
<u>Process:</u>

20 Local degrees of freedom
−14 ties
$\underline{\underline{6}}$ overall degrees of freedom

The last answer is what one gets by observing that 14 variables were counted two times each in summing the local degrees of freedom. However, one <u>relation</u> also was counted twice: the catalyst material balances on the reactor and flash tank are each $n_9 = n_{10}$. We must therefore <u>add</u> one degree of freedom to compensate for having subtracted the same relation twice, to finally obtain $\underline{\underline{\text{7 overall degrees of freedom}}}$ (A student who gets this one has done very well indeed!)

b. The catalyst circulation rate is not included in any equations other than the catalyst balance ($n_9 = n_{10}$). It may therefore not be determined unless either n_9 or n_{10} is specified.

10.6 $n-\mathrm{C_4H_{10}} \rightarrow i-\mathrm{C_4H_{10}} \quad (n-B = i-B)$



a. Mixer:

$$\begin{array}{l} 5 \text{ variables } (n_1, n_2, n_3, n_r, x_r) \\ -2 \text{ material balances} \\ \hline \underline{\underline{3}} \text{ degrees of freedom} \end{array}$$

Reactor:

$$\begin{array}{l} 4 \text{ variables } (n_2, n_3, n_3, n_5) \\ -2 \text{ material balances} \\ +1 \text{ reaction} \\ \hline \underline{\underline{3}} \text{ degrees of freedom} \end{array}$$

Still:

$$\begin{array}{l} 6 \text{ variables } (n_4, n_5, n_6, x_6, n_r, x_r) \\ -2 \text{ material balances} \\ \hline \underline{\underline{4}} \text{ degrees of freedom} \end{array}$$

Process:

$$\begin{array}{l} 10 \text{ Local degrees of freedom} \\ -6 \text{ ties} \\ \hline \underline{\underline{4}} \text{ overall degrees of freedom} \end{array}$$

b. $n_1 = 100 \text{ mol } n-\mathrm{C_4H_{10}}, \; x_6 = 0.115 \text{ mol } \; n-\mathrm{C_4H_{10}}/\text{mol}, \; x_r = 0.85 \text{ mol } \; n-\mathrm{C_4H_{10}}/\text{mol}$

Overall C balance: $(100)(4) = n_6[(0.115)(4) + (0.885)(4)]\text{mol C} \Rightarrow \underline{\underline{n_6 = 100 \text{ mol overhead}}}$

Overall conversion $= \dfrac{100 \text{ mol } n\text{ - }B \text{ fed} - (100)(0.115)\text{mol } n\text{ - }B \text{ unreacted}}{100 \text{ mol } n\text{ - }B \text{ fed}} \times 100\% = \underline{\underline{88.5\%}}$

Mixer *n-B* balance: $100 + 0.85 n_T = n_2 \quad (1)$

35% S.P. conversion: $n_4 = 0.65 n_2 \overset{(1)}{\Rightarrow} n_4 = 65 + 0.5525 n_r \quad (2)$

Still $n-B$ balance:

$$n_4 = n_6 x_6 + n_r x_r \overset{(2)}{\Rightarrow} 65 + 0.5525 n_r = (0.115)(100) + 0.85 n_r \Rightarrow n_r = 179.83 \text{ mol}$$

Recycle ratio $= (179.83 \text{ mol recycle})/(100 \text{ mol fresh feed}) = \underline{\underline{1.79 \dfrac{\text{mol recycle}}{\text{mol fresh feed}}}}$

10.6 (cont'd)

c.

	$k=1$	$k=2$	$k=3$
n_r	100.0	132.3	151.5
$n_2=100+0.85n_r$	185.0	212.5	228.8
$n_3=n_r(1-0.85)$	15.0	19.85	22.73
$n_4=0.65n_2$	120.25	138.1	148.7
$n_5=n_2+n_3-n_4$	79.75	94.21	102.8
$\left.\begin{array}{l} n_4+n_5=n_6+n_r \\ n_4=0.115n_6+0.85n_r \end{array}\right\}\Rightarrow$ $n_6=$	67.69	80.76	88.55
$n_r=$	132.3	151.5	163.0

$$\underline{\text{Error}}:\ \frac{179.83-163.0}{179.83}\times 100=\underline{\underline{9.3\%\ \text{error}}}$$

d. $$w=\frac{151.5-132.3}{132.3-100.0}=0.595$$

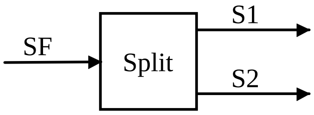
$$q=\frac{0.595}{0.595-1}=-1.470$$

$$n_r^{(3)}=-1.470(132.3)+(1-(-1.470))(151.5)=179.8$$

$$\underline{\text{Error:}}\ \frac{179.8-179.8}{179.8}\times 100=\underline{\underline{<0.1\%\ \text{error}}}$$

e. Successive substitution, Iteration 32: n_r = 179.8319 → n_r = 179.8319
Wegstein, Iteration 3: n_r = 179.8319 → n_r = 179.8319

10.7



a.

	A	B	C	D
1	X1 =	0.6		
2		Molar flow rates (mol/h)		
3		SF	S1	S2
4	nA	85.5	51.3	34.2
5	nB	52.5	31.5	21.0
6	nC	12.0	7.2	4.8
7	nD	0.0	0.0	0.0
8	T(deg.C)	315	315	315

Formula in C4: = \$B\$1*B4
Formula in D4: = B4-C4

10.7 (cont’d)

b.

```
C     **CHAPTER 10 -- PROBLEM 7
        DIMENSION SF(8), S1(8), S2(8)
        FLOW = 150.
        N = 3
        SF(1) = 0.35*FLOW
        SF(2) = 0.57*FLOW
        SF(3) = 0.08*FLOW
        SF(8) = 315.
        X1 = 0.60
        CALL SPLIT (SF, S1, S2, X1, N)
        WRITE (6, 900)' STREAM 1', S1(1), S1(2), S1(3), S1(B)
        WRITE (6, 900)' STREAM 2', S2(1), S2(2), S2(3), S2(B)
  900   FORMAT (A10, F8.2,' mols/h n-octane', /,
       *10X, F8.2,' mols/h iso-octane', /,
       *10X, F8.2,' mols/h inerts', /,
       *10X, F8.2,' K')
        END

   C
   C    SUBROUTINE SPLIT
   C
        SUBROUTINE SPLIT (SF, S1, S2, X1, N)
        DIMENSION SF(8), S1(8), S2(8)
        D0 100 J = 1, N
        S1(J) = X1*SF(J)
  100   S2(J) = SF(J) – S1(J)
        S1(8) = SF (8)
        S2(8) = SF (8)
        RETURN
        END
```

```
Program Output:  Stream 1  31.50  mols/h  n-octane
                           51.30  mols/h  iso-octane
                            7.20  mols/h  inerts
                            315.00 K
                 Stream 2  21.00  mols/h  n-octane
                           34.20  mols/h  iso-octane
                            4.80  mols/h  inerts
                           315.00 K
```

10.8

a. Let Bz = benzene, Tl = toluene

Antoine equations: $\underline{\underline{p^*_{Bz}}} = 10^{6.89272-1211.033/(T+220.790)}$ (=1350.491)

$\underline{\underline{p^*_{Tl}}} = 10^{6.95805-1346.773/(T+219.693)}$ (=556.3212)

Raoult's law: $\underline{\underline{x_{Bz}}} = (P - p^*_{Tl})/(p^*_{Bz} - p^*_{Tl})$ (=0.307) , $\underline{\underline{y_{Bz}}} = x_{Bz} p^*_{Bz} / P$ (= 0.518)

$$\left.\begin{array}{ll} \text{Total mole balance: } & 100 = n_v + n_l \\ \text{Benzene balance: } & 40 = y_{Bz} n_v + x_{Bz} n_l \end{array}\right\}$$

$$\Rightarrow \underline{\underline{n_v}} = \frac{40 - 100 x_{Bz}}{y_{Bz} - x_{Bz}} \text{ (=44.13)}, \ \underline{\underline{n_l}} = 100 - n_v \text{ (=55.87)}$$

Fractional benzene vaporization: $\underline{\underline{f_B}} = n_v y_{Bz} / 40$ (=0.571)

Fractional toluene vaporization: $\underline{\underline{f_T}} = n_v (1 - y_{Bz}) / 60$ (=0.354)

The specific enthalpies are calculated by integrating heat capacities and (for vapors) adding the heat of vaporization.

$\underline{\underline{Q}} = \sum n_{out} \hat{H}_{out} - \sum n_{in} \hat{H}_{in}$ (= 1097.9)

b. Once the spreadsheet has been prepared, the goalseek tool can be used to determine the bubble-point temperature (find the temperature for which n_v=0) and the dew-point temperature (find the temperature for which n_l =0). The solutions are

$\underline{\underline{T_{bp} = 96.9^\circ \text{C}}}$, $\underline{\underline{T_{dp} = 103.2^\circ \text{C}}}$

c.

```
C  **CHAPTER 10 PROBLEM B
      DIMENSION SF(3), SL(3), SV(3)
      DATA A1, B1, C1/6.90565, 1211.033, 220.790/
      DATA A2, B2, C2/6.95334, 1343.943, 219.377/
      DATA CP1, CP2, HV1, HV2/ 0.160, 0.190, 30.765, 33.47/
      COMMON A1, B1, C1, A2, B2, C2, CP1, CP2, NV1, NV2
      FLOW = 1.0
      SF(1) = 0.30*FLOW
      SF(2) = 0.70*FLOW
      T = 363.0
      P = 512.0
      CALL FLASH2 (SF, SL, SV, T, P, Q)
      WRITE (6, 900) 'Liquid Stream', SL(1), SL(2), SL(3)
      WRITE (6, 900) 'Vapor Stream', SV(1), SV(2), SV(3)
900   FORMAT (A15, F7.4,' mol/s Benzene',/,
      * 15X, F7.4, mol/s Toluene',/,
      * 15X, F7.2, 'K')
      WRITE (6, 901) Q
```

10.8 (cont’d)

```
901   FORMAT ('Heat Required', F7.2,' kW')
      END
C
      SUBROUTINE FLASN2 (SF, SL, SV, T, P, Q)
      REAL NF, NL, NV
      DIMESION SF(3), SL(3), SV(3)
      COMMON A1, B1, C1, C2, CP1, CP2, NV1, NV2
C     Vapor Pressure
      PV1 = 10.**(A1 – B1/(T – 273.15 + C1))
      PV2 = 10.**(A2 – B2/(T – 273.15 + C2))
C     Product fractions
      XL1 = (P – PV2)/(PV1 – PVS)
      XV1 = XL1*PM/P
C     Feed Variables
      NF = SF(1) + SF(2)
      XF1 = SF(1)/NF
C     Product flows
      NL = NF*(XF1 – XV1)/(XL1 – XV1)
      NV = NF – NL
      SL(1) = XL1*NL
      SL(2) = NL – SL(1)
      SY(1) = XY1*NY
      SY(2) = NV – SY(1)
      SL(3) = T
      SV(3) = T
C     Energy Balance
      Q = CP1*SF(1)*SF(1) + CP2*SF(2)
      Q = Q*(T – SF(3)) + (NV1*XV1 + HV2*(1 – XV1))*NV
      RETURN
      END
```

10.9 **a**. Mass Balance: $NF = NL + NV \quad (1)$

$$XF(I) * NF = XL(I) * NL + XV(I) * NV \quad I = 1,2 \ldots n-1 \quad (2)$$

Energy Balance: $Q = (T - TF) * \sum_{I=1}^{N} CP(I) * \left(XL(I) * NL + XV(I) * NV \right)$

$$+ NV * \sum_{I=1}^{N} HV(I) * XV(1) \quad (3)$$

where: $XL(N) = 1 - \sum_{I=1}^{N-1} XL(I) \quad XV(N) = 1 - \sum_{I=1}^{N-1} XV(I)$

Raoult’s law: $P = \sum_{I=1}^{N} XL(I) * PV(I) \quad (4)$

$$XV(I) * P = XL(I) * PV(I) \quad I = 1,2, \ldots N - 1 \quad (5)$$

10.9 (cont'd)

where: $PV(I) = 10{*}{*}\left(A(I) - B(I)\big/\left(C(I)+T\right)\right) \quad I = 1,2,\ldots N-1$

$3 + 3(N-1) + N + 4$ variables $(NF,\ NL,\ NV,\ XF(I),\ XL(I),\ XV(I),\ PV(I), TF, T,\ P, Q)$
$-N$ mass balance
-1 energy balances
$-N$ equilibrium relations
$-N$ Antoine equations

$N + 3$ degrees of freedom

Design Set $\{TF,\ T,\ P,\ NF,\ XF(I)\}$
Eliminate NL form (2) using (1)
Eliminate XV(I) form (2) using (5)
Solve (2) for *XL*(*I*)

$$XL(I) = XF(I){*}\ NF\Big/\left(NF + NV{*}\left(PV(I)/P - 1\right)\right) \quad (6)$$

Sum (6) ove I to Eliminate XL(I)

$$f(NV) = -1 + NF{*}\sum_{I=1}^{N} XF(I)\Big/\left(NF + NV{*}\left(PV(I)/P - 1\right)\right) = 0 \quad (7)$$

Use Newton's Method to solve (7) for NV
Calulate NL from (1)
XL(I) from (2)
XV(I) from (5)
Q from (3)

b.

```
C  **CHAPTER 10 - - PROBLEM 9
      DIMENSION SF(8), SL(8), SV(8)
      DIMENSION A(7), B(7), C(7), CP(7), HV(7)
      COMMON A, B, C, CP, NV
      DATA A/6.85221, 6.87776, 6.402040, 0., 0., 0., 0./
      DATA B/1064.63, 1171.530, 1268.115, 0., 0., 0., 0./
      DATA C/232.00, 224.366, 216.900, 0., 0., 0., 0./
      DATA CP/0.188, 0.216, 0.213, 0., 0., 0., 0./
      DATA NV/25.77, 28.85, 31.69, 0., 0., 0., 0./
      FLOW = 1.0
      N*3
      SF(1) = 0.348*FLOW
      SF(2) = 0.300*FLOW
      SF(3) = 0.352*FLOW
      SF(4) = 363
      SL(4) = 338
      SV(4) = 338
      P*611
      CALL FLASHN (SF, SL, SV, N, P, Q)
      WRITE (6, 900)' Liquid Stream', (SL(I), I = 1, N + 1)
      WRITE (6, 900)' Vapor Stream', (SV(I), I = 1, N + 1)
```

10.9 (cont'd)

```
900   FORMAT (A15, F7.4,' mols/s n-pentane', /,
     *15X, F7.4,' mols/s n-hexane', /,
     *15X, F7.4,' mols/s n-hephane', /,
     *15X, F7.2,' K')
      WRITE (6, 901) Q
901   FORMAT ('Heat Required', F7.2, 'kW')
      END
C     SUBROUTINE FLASHIN (SF, SL, SV, N, P, Q)
      REAL NF, NL, NV, NVP
      DIMENSION SF(8), SL(8), SV(8)
      DIMENSION XF(7), XL(7), XV(7), PV(7)
      DIMENSION A(7), B(7), C(7), CP(7), HV(7)
      COMMON A, B, C, CP, HV
      TOL = 1,5 – 6
C     Feed Variables
      NF = 0.
      DO 100 I = 1, N
100   NF = NF + SF(I)
      DO 200 I = 1, N
200   XF(I) = SF(I)/NF
      TF = SF (N + 1)
      T = SL (N + 1)
      TC = T – 273.15
C     Vapor Pressures
      DO 300 I = 1, N
300   PV(I) = 10.**(A(I) – B(I)/(TC + C(I)))
C     Find NV -- Initial Guess = NF/2
      NVP = NF/2
      DO 400 ITER = 1, 10
      NV = NVP
      F = –1.
      FP = 0.
      DO 500 I = 1, N
      PPM1 = PV(I)/P – 1.
      F = F + NF*XF(I)/(NF + NV*PPM1)
500   FP = FP – PPM1*XF(I)/(NF + NV*PPM1)**2.
      NVP = NV – F/FP
      IF (ABS((NVP – NV)/NVP).LT.TOL) GOTO 600
400   CONTINUE
      WRITE (6, 900)
900   FORMAT ('FLASHN did not converge on NV')
      STOP
C     Other Variables
```

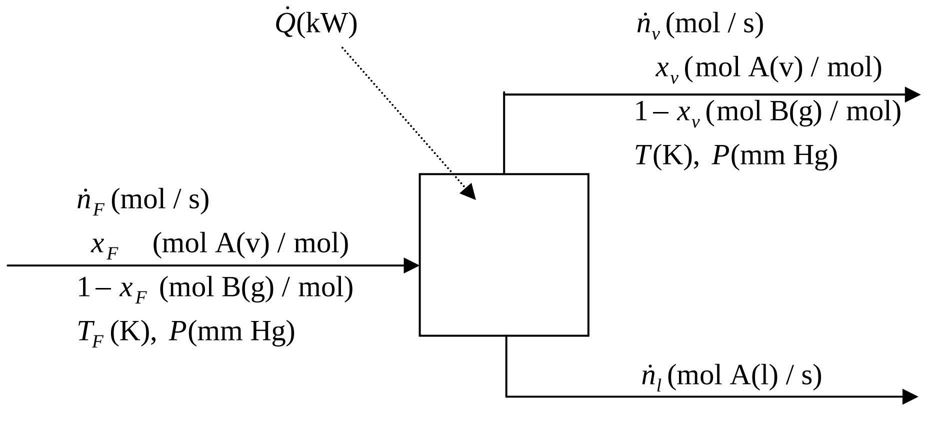
10.9 (cont’d)

```
600    NL = NF – NVP
       DO 700 I = 1, N
       XL(I) = XF(I)*NF/(NF + NV**(PV(I)/P – 1))
       SL(I) = XL(I)*NL
       XV(I) = XL(I)*PV(I)/P
700    SV(I) = SF(I) – SL(I)
       Q1 = 0.
       Q2 = 0.
       DO 800 I = 1, N
       Q1 = Q1 + CP(I)*SF(I)
800    Q2 = Q2 + HV(I)*XV(I)
       Q = Q1*(T – TF) + Q2*NVP
       RETURN
       END
```

```
Program Output:  Liquid Stream   0.0563  mols/s  n-pentane
                                 0.1000  mols/s  n-hexane
                                 0.2011  mols/s  n-heptane
                                 338.00 K
                 Vapor Stream    0.2944  mols/s  n-pentane
                                 0.2000  mols/s  n-hexane
                                 0.1509  mols/s  n-heptane
                                 338.00 K
                 Heat Required   13.01 kW
```

10.10

a.



10.10 (cont'd)

10 variables $(\dot{n}_F, x_F, T_F, P, \dot{n}_v, x_v, T, \dot{n}_l, p_A^*, \dot{Q})$
–2 material balances
–1 Antoine equation
–1 Raoult's law
–1 energy balance
5 degrees of freedom

b.

References: A(l), B(g) at 25°C

Substance	$\dot{n}_{in}$	$\hat{H}_{in}$	$\dot{n}_{out}$	$\hat{H}_{out}$
A(l)	—	—	$\dot{n}_l$	$\hat{H}_3$
A(v)	$\dot{n}_F x_F$	$\hat{H}_1$	$\dot{n}_v x_v$	$\hat{H}_4$
B(g)	$\dot{n}_F(1-x_F)$	$\hat{H}_2$	$\dot{n}_v(1-x_v)$	$\hat{H}_5$

Given $\dot{n}_F$ and x_F (or $\dot{n}_{AF}$ and $\dot{n}_{BF}$), T_F, P, y_c (fractional condensation),

Fractional condensation $\Rightarrow \underline{\underline{\dot{n}_l}} = y_c \dot{n}_F x_F$

Mole balance $\Rightarrow \underline{\underline{\dot{n}_v}} = \dot{n}_F - \dot{n}_l$

A balance $\Rightarrow \underline{\underline{x_v}} = (\dot{n}_F x_F - \dot{n}_l)/\dot{n}_v$

Raoult's law $\Rightarrow \underline{\underline{p_A^*}} = x_v P$

Antoine's equation $\Rightarrow \underline{\underline{T}} = \dfrac{B}{A - \log_{10} p_A^*} - C$

Enthalpies: $\underline{\underline{\hat{H}_1}} = \Delta\hat{H}_v + C_{pv}(T_F - 25), \underline{\underline{\hat{H}_2}} = C_{pg}(T_F - 25), \underline{\underline{\hat{H}_3}} = C_{pl}(T - 25),$

$\underline{\underline{\hat{H}_4}} = \Delta\hat{H}_v + C_{pv}(T - 25), \underline{\underline{\hat{H}_5}} = C_{pg}(T - 25)$

Energy balance: $\underline{\underline{Q}} = \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in}$

c.

nAF	nBF	nF	xF	TF	P	yc	nL
0.704	0.296	1.00	0.704	333	760	0.90	0.6336
nV	xV	A	B	C	pA*	T	Cpl
0.3664	0.1921	7.87863	1473.11	230	146.0	300.8	0.078
Cpv	Cpg	H1	H2	H3	H4	H5	Q
0.050	0.030	37.02	1.05	0.2183	35.41	0.0839	–23.7

Greater fractional methanol condensation (y_c) ⇒ lower temperature (T). ($y_c = 0.10 \Rightarrow$ T = 328°C.)

10.10 (cont’d)

e.

```
 C  **CHAPTER 10 -- PROBLEM 10
        DIMENSION SF(3), SV(3), SL(2)
        COMMON A, B, C, CPL, HV, CPV, CPG
        DATA A, B, C / 7.87863, 1473.11, 230.0/
        DATA CPL, HV, CPV, CPG,/ 0.078, 35.27, 0.050, 0.029/
        FLOW = 1.0
        SF(1) = 0.704*FLOW
        SF(2) = FLOW – SF(1)
        YC = 0.90
        P = 1.
        SF(3) = 333.
        CALL CNDNS (SF, SV, SL, P, YC, Q)
        WRITE (6, 900) SV(3)
        WRITE (6, 401) 'Vapor Stream', SV(1), SV(2)
        WRITE (6, 401) 'Liquid Stream', SL(1)
        WRITE (6, 902)Q
900     FORMAT ('Condenser Temperature', F7.2,' K')
901     FORMAT (A15, F7.3,' 'mols/s Methyl Alcohol', /,
       *15X, F7.3, 'mols/s air')
902     FORMAT ('Heat Removal Rate', F7.2,' kW')
        END
 C      SUBROUTINE CNDNS (SF, SV, SL, P, YC, Q)
        REAL NF, NL, NV
        DIMENSION SF(3), SV(3), SL(2)
        COMMON A, B, C, CPL, HV, CPV, CPG
 C      Inlet Stream Variables
        NF = SF(1) + SF(2)
        TF = SF(3)
        XF = SF(1)/NF
 C      Solve Equations
        NL = YC * XF * NF
        NV = NF - NL
        XV = (XF*NF - NL)/NV
        PV = P * XV * 760.
        T = B/(A - LOG(N)/LOG (10.)) - C
        T = T + 273.15
        Q = ((CPV * XV + CPG * (1 - XY)) * NV + CPL * NL) * (T - TF) - NL * HV
 C      Output Variables
        SL(1) = NL
        S2(2) = T
        SV(1) = XV*NV
        SV(2) = NV - SV(1)
        SV(3) = T
        RETURN
        END
```

10.11 $\eta_1 A_1 + \eta_2 A_2 + \eta_3 A_3 + \ldots \eta_m A_m = 0$

a. Extent of reaction equations:

$$\xi = -[SF(IX)*X]/NU(IX)$$

$$SP(I) = SF(I) + NU(I)*\xi \quad I = 1,2,\ldots N$$

Energy Balance: Reference states are molecular species at 298K.

$$TF = SF(N+1) \quad TP = SP(N+1)$$

$$\Delta\hat{H}_r = \sum_{I=1}^{N} HF(I)*NU(I)$$

$$Q = \xi*\Delta\hat{H}_r + (TP-298)*\sum_{I=1}^{N} SP(I)*CP(I) - (TF-298)*\sum_{I=1}^{N} SF(I)*CP(I)$$

b. $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

Subscripts: 1 = C_3H_8, 2 = O_2, 3 = N_2, 4 = CO_2, 5 = H_2O

$$\frac{270\text{ m}^3}{\text{h}}\bigg|\frac{1\text{ atm}}{273\text{K}}\bigg|\frac{\text{mol}\cdot\text{K}}{0.08206\text{ liter}\cdot\text{atm}}\bigg|\frac{1000\text{ liter}}{\text{m}^3}\bigg|\frac{\text{h}}{3600\text{ s}} = 3.348\text{ mol } C_3H_8/\text{s} \text{ [=SF(1)]}$$

$$\frac{3.348\text{ mol } C_3H_8}{\text{sec}}\bigg|\frac{1.2(5\text{ mol } O_2)}{\text{mol } C_3H_8} = 20.09\text{ mol } O_2/\text{s [= SF(2)]} \Rightarrow 75.54\text{ mol } N_2/\text{s [= SF(3)]}$$

$$X_{C_3H_8} = 0.90 \Rightarrow \dot{n}_{C_3H_8} = 0.10(3.348) = 0.3348\text{ mol } C_3H_8\text{ / s in product gas [= SP(1)]}$$

$$\xi = -[SF(IX)*X]/NU(IX) = -(3.348\text{ mol/s})(0.90)/(-1) = 3.013\text{ mol/s}$$

		1-C3H8	2-O2	3-N2	4-CO2	5-H2O(v)
Nu		-1	-5	0	3	4
nin (SF)		3.348	20.09	75.54		
X	0.90					
Xi	3.01					
nout (SP)		0.3348	5.024	75.54	9.0396	12.0528
Cp		0.1431	0.033	0.0308	0.0495	0.0375
Tin	423					
Hin		17.9	4.1	3.9	6.2	4.7
Tout	1050					
Hout		107.6	24.8	23.2	37.2	28.2
HF		-103.8	0	0	-393.5	-241.83
DHr	-2044					
Q	-4006					

For the given conditions, $\underline{\underline{Q = -4006\text{ kJ / s}}}$. As T_{stack} increases, more heat goes into the stack gas so less is transferred out of the reactor: that is, Q becomes <u>less negative</u>.

10.11 (cont’d)

```
    C  **CHAPTER 10 PROBLEM 11
         DIMENSION SF(8), SP(8), CP(7), HF(7)
         REAL NU(7)
         DATA NU/–1., –5, 0., 3., 4., 0., 0./
         DATA CP/0.1431, 0.0330, 0.0308, 0.0495, 0.0375, 0., 0./
         DATA HF/–103.8, 0., 0., –393.5, –241.83, 0., 0./
         COMMON CP, HF
         SF(1) = 3.348
         SF(2) = 20.09
         SF(3) = 75.54
         SF(4) = 0.
         SF(5) = 0.
         SF(6) = 423.
         SP(6) = 1050.
         IX = 1
         X = 0.90
         N = 5
         CALL REACTS (SF, SP, NU, N, X, IX, Q)
         WRITE (6, 900) (SP(I), I = 1, N + 1), Q
  900    FORMAT ('Product Stream', F7.3, ' mols/s propane', /,
        *15X, F7.3,' mols/s oxygen', /,
        *15X, F7.3,' mols/s nitrogen', /,
        *15X, F7.3,' mols/s carbon dioxide', /,
        *15X, F7.3,' mols/s water', /,
        *15X, F7.2,'K', /,
         Heat required', F8.2, 'kW')
         END
    C    SUBROUTINE REACTS (SF, SP, NU, N, X, IX, Q)
         DIMENSION SF(8), SP(8), CP(7), HF(7)
         REAL NU(7)
         COMMON CP, HF
    C    Extent of Reaction
         EXT = –SF(IX)*X/NU(IX)
    C    Solve Material Balances
         DO 100 I = 1, N
  100    SP(I) = SF(I) + EXT = NU(I)
    C    Heat of Reaction
         HR = 0
         DO 200 I = 1, N
  200    HR = HR + NF(I)*NU(I)
    C    Product Enthalpy (ref * inlet)
         HP = 0.
         DO 300 I = 1, N
  300    HP = HP + SP(I)*CP(I)
         HP = HP + (SP(N + 1) – SF (N + 1))
         Q = EXT * HR + HP
         RETURN
         END
```

10.12 a. Extent of reaction equations:

$$\xi = -SF(IX) * X / NU(IX)$$

$$SP(I) = SF(I) + NU(I) * \xi \quad I = 1, N$$

Energy Balance: Reference states are molecular species at feed stream temperature.

$$Q = \Delta H = \xi \Delta \hat{H}_r + \sum n_{\text{out}} \hat{H}_{\text{out}} = 0 \Rightarrow 0 = \xi \sum_{i=1}^{N} NU(I) HF(I) + \sum_{I=1}^{N} SP(I) \int_{T_{\text{feed}}}^{T} CP(I) dT$$

$\Downarrow$ CP(I) = ACP(I) + BCP(I)*T + CCP(I)*T^2 + DCP(I)*T^3

$$f(T) = \xi * \sum_{I=1}^{N} NU(I) * HF(I) + AP * (T - T_{\text{feed}}) + \frac{BP}{2} * (T^2 - T_{\text{feed}}^2)$$

$$+ \frac{CP}{3} * (T^3 - T_{\text{feed}}^3) + \frac{DP}{4} * (T^4 - T_{\text{feed}}^4) = 0$$

where: $AP = \sum_{I=1}^{N} SP(I) * ACP(I)$, and similarly for BP, CP, & DP

Use goalseek to solve $f(T) = 0$ for T [= SP(N+1)]

b. $2CO + O_2 \rightarrow 2CO_2$

Temporary basis: 2 mol CO fed

$$\frac{2 \text{ mol CO} \;\Big|\; 1.25(1 \text{ mol } O_2)}{\Big|\; 2 \text{ mol CO}} = 1.25 \text{ mol } O_2 \Rightarrow 4.70 \text{ mol } N_2$$

$\Rightarrow$ Total moles fed = (2.00 + 1.25 + 4.70) mol = 7.95 mol

Scale to given basis:

$$\frac{(23.0 \dfrac{\text{kmol}}{\text{h}})(\dfrac{1 \text{ h}}{3600 \text{ s}})(\dfrac{10^3 \text{ mol}}{1 \text{ kmol}})}{7.95 \text{ mol}} = 0.8036 \Rightarrow \begin{aligned} SF(1) &= 1.607 \text{ mol CO fed/s} \\ SF(2) &= 1.004 \text{ mol } O_2 \text{ fed/s} \\ SF(3) &= 3.777 \text{ mol } N_2 \text{ fed/s} \end{aligned}$$

10.12 (cont'd)

Solution to Problem 10.12

		1-CO	2-O2	3-N2	4-CO2
Nu		-2	-1	0	2
nin (SF)		1.607	1.004	3.777	0
X	0.45				
Xi	0.36				
nout (SP)		0.88385	0.642425	3.777	0.72315
ACP		0.02895	0.0291	0.029	0.03611
BCP		4.11E-06	1.16E-05	2.20E-06	4.23E-05
CCP		3.55E-09	-6.08E-09	5.72E-09	-2.89E-08
DCP		-2.22E-12	1.31E-12	-2.87E-12	7.46E-12
AP	0.1799				
BP	5.00E-05				
CP	-2.90E-11				
DP	-6.57E-12				
Tfeed	650				
DHF		-110.52	0	0	-393.5
DHr	-566				
T	1560				
f(T)	-4.7E-08				

The adiabatic reaction temperature is $\underline{\underline{1560^{\circ}\mathrm{C}}}$.

As *X* increases, *T* increases. (The reaction is exothermic, so more reaction means more heat released.)

d.

```
C  **CHAPTER 10 -- PROBLEM 12
      DIMENSION SF(8), SP(B), NU(7), ACP(7), BCP(7), CCP(7), DCP(7), HF(7)
      COMMON ACP, BCP, CCP, DCP, NF
      DATA NU / –2., –1., 0., 2., 0., 0., 0./
      DATA ACP/ 28.95E-3, 29.10E-3, 29.00E-3, 36.11E-3, 0., 0., 0./
      DATA BCP/ 0.4110E-5, 1.158E-5, 0.2199E-5, 4.233E-6, 0., 0., 0./
      DATA CCP/ 0.3548E-B, –0.6076E-8, 0.5723E-8, –2.887E-8, 0., 0., 0./
      DATA DCP/ –2.220 E-12, 1.311E-12, –2.871E-12, 7.464E-12, 0., 0., 0./
      DATA HF / –110.52, 0., 0., –393.5, 0., 0., 0./
      SF(1) = 1.607
      SF(2) = 1.004
      SF(3) = 3.777
      SF(4) = 0.
      SF(5) = 650.
      IX = 1
      X = 0.45
      N = 4
      CALL REACTAD (SF, SP, NU, N, X, IX)
      WRITE (6, 900) (SP(I), I = 1, N + 1)
```

10.12 (cont’d)

```
900   FORMAT ('Product Stream', F7.3, ' mols/s carbon monoxide', /,
     *15X, F7.3, 'mols/s oxygen', /.
     *15X, F7.3, 'mols/s nitrogen', /.
     *15X, F7.3, 'mols/s carbon dioxide', /,
     *15X, F7.2, 'C')
      END
  C   SUBROUTINE REACTAD (SF, SP, NU, N, X, IX)
      DIMENSION SF(8), SP(8), NU(7), ACP(7), BCP(7), CCP(7), DCP(7), HF(7)
      COMMON ACP, BCP, CCP, DCP, NF
      TOL = 1.E-6
  C   Extent of Reaction
      EXT = –SF(IX)*X/NU(IX)
  C   Solve Material Balances
      DO 100 I = 1, N
100   SP(I) = SF(I) + EXT*NU(I)
  C   Heat of Reaction
      HR = 0
      DO 200 I = 1, N
200   HR = HR + HF(I) * NU(I)
      HR = HR * EXT
  C   Product Heat Capacity
      AP = 0.
      BP = 0.
      CP = 0.
      DP = 0.
      DO 300 I = 1, N

      AP = AP + SP(I)*ACP(I)
      BP = BP + BP(I)*BCP(I)
      CP = CP + SP(I)*CCP(I)
300   DP = DP + SP(I)*DCP(I)
  C   Find T
      TIN = SF (N + 1)
      TP = TIN
      D0 400 ITER = 1, 10
      T = TP
      F = HR
      FP = 0.
      F = F +T*(AP + T*(BP/2. + T*(CP/3. + T*DP/4.)))
     *–TIN*(AP + TIN*(BP/2. + TIN*(CP/3. + TIN*DP/4.)))
      FP = FP + AP + T *(BP + T*(CP + T*DP))
      TP = T – F/FP
      IF(ABS((TP – T)/T).LT.TOL) GOTO 500
400   CONTINUE
      WRITE (6, 900)
900   FORMAT ('REACTED did not converge')
      STOP
```

10.12 (cont'd)

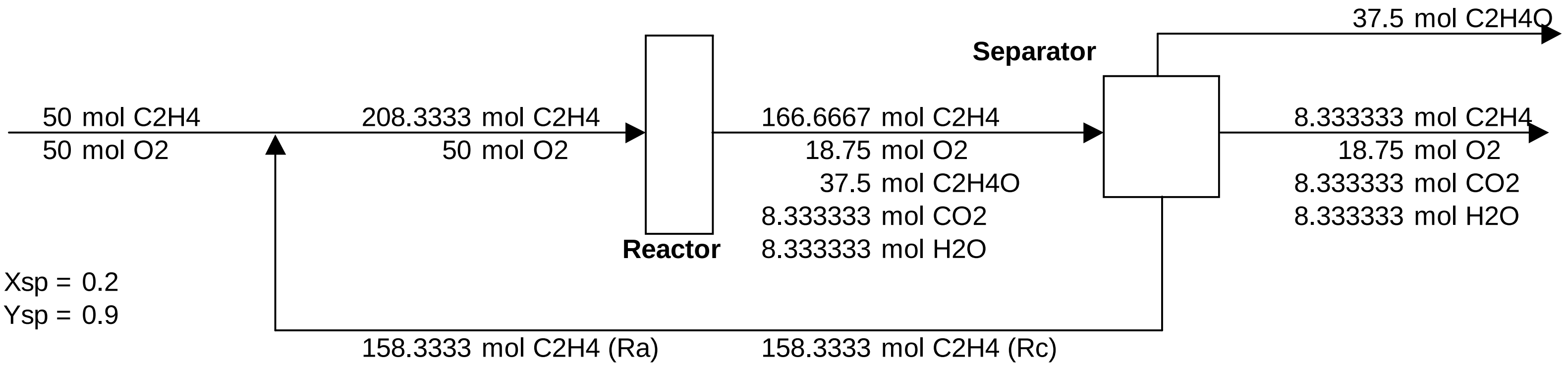
```
500    SP(N + 1) = T
       RETURN
       END
```

Program Output:

```
0.884 mol/s carbon monoxide
0.642 mol/s oxygen
3.777 mol/s nitrogen
0.723 mol/s carbon dioxide
T = 1560.43 C
```

10.13

a.



Rc-Ra = 0

<u>Procedure</u>: Assume Ra, perform balances on mixing point, then reactor, then separator. Rc is recalculated recycle rate.
Use goalseek to find the value of Ra that drives (Rc-Ra) to zero.

b.

Xsp	Ysp	Yo	no
0.2	0.72	0.6	158.33
0.2	1	0.833	158.33
0.3	0.75333	0.674	99.25
0.3	1	0.896	99.25

The second reaction consumes six times more oxygen per mole of ethylene consumed. The lower the single pass ethylene oxide yield, the more oxygen is consumed in the second reaction. At a certain yield for a specified ethylene conversion, all the oxygen in the feed is consumed. A yield lower than this value would be physically impossible.

10.14

```
C   **CHAPTER 10 -- PROBLEM 14
      DIMENSION XA(3), XC(3)
      N = 2
      EPS = 0.001
      KMAX = 20
      IPR = 1
      XA(1) = 2.0
      XA(2) = 2.0
      CALL CONVG (XA, XC, N, KMAX, EPS, IPR)
      END
C
      SUBROUTINE FUNCGEN(N, XA, XC)
      DIMENSION XA(3), XC(3)
      XC(1) = 0.5*(3. – XA(2) + (XA(1) + XA(2))**0.5
      XC(2) = 4. – 5./(XA(1) + XA(2))
      RETURN
      END
C
      SUBROUTINE CONVG (XA, XC, N, KMAX, EPS, IPR)
      DIMENSION XA(3), XC(3), XAH(3), XCM(3)
      K = 1
      CALL FUNCGEN (N, XA, XC)
      IF (IPR.EQ.1) CALL IPRNT (K, XA, XC, N)
      DO 100 I = 1, N
      XAM(I) = XA(I)
      XA(I) = XC(I)
100   XCM(I) = XC(I)
110   K = K + 1
      CALL FUNCGEN (N, XA, XC)
      IF (IPR.EQ.1) CALL IPRNT (K, XA, XC, N)
      D0 200 I = 1, N
      IF (ABS ((XA(I) - XC(I))/XC(I)).GE.EPS) GOTO 300
200   CONTINUE
C     Convergence
      RETURN
300   IF(K.EQ.KMAX) GOTO 500
      DO 400 I = 1, N
      W = (XC(I) – XCM(I))/(XA(I) – XAM(I))
      Q = W/(W – 1.)
      IF (Q.GT.0.5) Q = 0.5
      IF (Q.LT.–5) Q = –5.
      XCM(I) = XC(I)
      XAM(I) = XA(I)
400   XA(I) = Q = XAM(I) + (1. – Q)*XCM(I)
      GOTO 110
500   WRITE (6, 900)
900   FORMAT (' CONVG did not converge')
      STOP
      END
```

10.14 (cont’d)

```
  C   SUBROUTINE IPRNT (K, XA, XC, N)
      DIMENSION XA(3), XC(3)
      IF (K.EQ.1) WRITE (6, 400)
      IF (K.NE.1) WRITE (6, *)
      DO 100 I = 1, N
100   WRITE (6, 901) K, I, XA(I), XC(I)
      RETURN
900   FORMAT (' K Var Assumed Calculated')
901   FORMAT (I4, I4, 2E15.6)
      END
```

```
Program Output:   K   Var     Assumed          Calculated
                  1    1   0.200000E + 01   0.150000E + 01
                  1    2   0.200000E + 01   0.275000E + 01

                  2    1   0.150000E + 01   0.115578E + 01
                  2    2   0.275000E + 01   0.282353E + 01

                  3    1   0.395135E + 00   0.482384E + 00
                  3    2   0.283152E + 01   0.245041E + 01
                  ⋮
                  8    1   0.113575E + 01   0.113289E + 01
                  8    2   0.269023E + 01   0.269315E + 01

                  4    1   0.113199E + 01   0.113180E + 01
                  9    2   0.269186E + 01   0.269241E + 01
```

CHAPTER ELEVEN

11.1 **a.** The peroxide mass fraction in the effluent liquid equals that in the tank contents, which is:

$$x_p = \frac{M_p}{M}$$

Therefore, the leakage rate of hydrogen peroxide is $\underline{\underline{\dot{m}_1 M_p / M}}$

b. Balance on mass: Accumulation = input – output

$$\Downarrow$$

$$\underline{\underline{\frac{dM}{dt} = \dot{m}_0 - \dot{m}_1}}$$

$$\underline{\underline{t = 0,\ M = M_0}} \text{ (mass in tank when leakage begins)}$$

Balance on H_2O_2: Accumulation = input – output – consumption

$$\Downarrow$$

$$\underline{\underline{\frac{dM_p}{dt} = \dot{m}_0 x_{p0} - \dot{m}_1\left(\frac{M_p}{M}\right) - kM_p}}$$

$$\underline{\underline{t = 0,\ M_p = M_{p0}}}$$

11.2 **a.** Balance on H_3PO_4: Accumulation = input

Density of H_3PO_4: $\rho = 1.834\ \text{g / ml}$.

Molecular weight of H_3PO_4: $M = 98.00\ \text{g / mol}$.

$$\text{Accumulation} = \frac{\mathrm{dn_p}}{\mathrm{dt}}\ (\text{kmol / min})$$

$$\text{Input} = \begin{array}{c|c|c|c|c} 20.0\ \text{L} & 1000\ \text{ml} & 1.834\ \text{g} & \text{mol} & 1\ \text{kmol} \\ \hline \text{min} & \text{L} & \text{ml} & 98.00\ \text{g} & 1000\ \text{mol} \end{array} = 0.3743\ \text{kmol / min}$$

$$\Downarrow$$

$$\underline{\underline{\frac{\mathrm{dn_p}}{\mathrm{dt}} = 0.3743}}$$

$$\underline{\underline{t = 0,\ \mathrm{n_{p0}} = 150 \times 0.05 = 7.5\ \text{kmol}}}$$

b. $$\int_{7.5}^{n_p} dn_p = \int_0^t 0.3743\, dt \Rightarrow \underline{\underline{n_p = 7.5 + 0.3743t}}\ \ (\text{kmol } H_3PO_4 \text{ in tank})$$

$$\underline{\underline{x_p = \frac{n_p}{n} = \frac{n_p}{n_0 + n_p - n_{p0}} = \frac{7.5 + 0.3743t}{150 + 0.3743t}}}\ \ \frac{\text{kmol } H_3PO_4}{\text{kmol}}$$

c. $$0.15 = \frac{7.5 + 0.3743t}{150 + 0.3743t} \Rightarrow t = \underline{\underline{47.1\ \text{min}}}$$

11.3 **a.** $\dot{m}_w = a + bt \;\; \left(t=0,\, \dot{m}_w = 750\right) \;\&\; \left(t=5,\, \dot{m}_w = 1000\right) \Rightarrow \underline{\underline{\dot{m}_w(\text{kg/h}) = 750 + 50t(\text{h})}}$

Balance on methanol: Accumulation = Input – Output

M = kg CH_3OH in tank

$$\frac{dM}{dt} = \dot{m}_f - \dot{m}_w = 1200 \text{ kg/h} - (750 + 50t) \text{ kg/h}$$

$$\Downarrow$$

$$\frac{dM}{dt} = 450 - 50t(\text{kg/h})$$

$$\underline{\underline{t = 0,\; M = 750 \text{ kg}}}$$

b. $\displaystyle\int_{750}^{M} dM = \int_0^t (450 - 50t)dt$

$$\Downarrow$$

$$M - 750 = 450t - 25t^2$$

$$\Downarrow$$

$$\underline{\underline{M = 750 + 450t - 25t^2}}$$

Check the solution in two ways:

(1) $t = 0$, $M = 750$ kg $\Rightarrow$ satisfies the initial condition;

(2) $\dfrac{\text{dM}}{\text{dt}} = 450 - 50t \Rightarrow$ reproduces the mass balance.

c. $\dfrac{dM}{dt} = 0 \Rightarrow t = 450/50 = \underline{\underline{9 \text{ h}}} \Rightarrow M = 750 + 450(9) - 25(9)^2 = \underline{\underline{2775 \text{ kg}}}$ (maximum)

$$M = 0 = 750 + 450t - 25t^2$$

$$t = \frac{-450 \pm \sqrt{(450)^2 + 4(25)(750)}}{2(-25)} \Rightarrow t = \cancel{-1.54 \text{ h}},\; \underline{\underline{19.54 \text{ h}}}$$

d. $\dfrac{3.40 \text{ m}^3}{} \left|\dfrac{10^3 \text{ liter}}{1 \text{ m}^3}\right| \dfrac{0.792 \text{ kg}}{1 \text{ liter}} = 2693 \text{ kg}$ (capacity of tank)

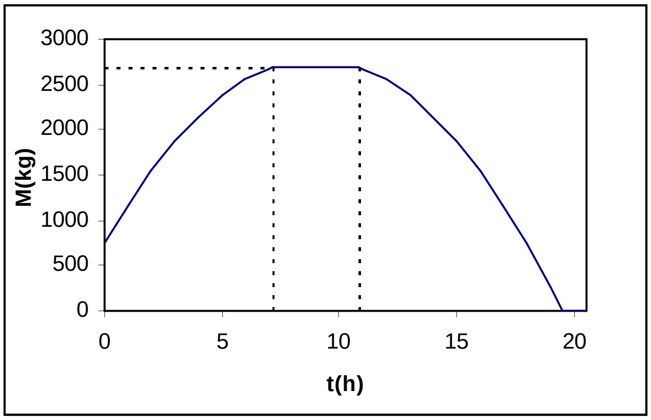
$$M = 2693 = 750 + 450t - 25t^2$$

$$t = \frac{-450 \pm \sqrt{(450)^2 + 4(25)(750 - 2693)}}{2(-25)} \Rightarrow t = 7.19 \text{ h}, 10.81 \text{ h}$$

Expressions for M(t) are:

$$\underline{\underline{\text{M(t)} = \begin{cases} 750 + 450\text{t} - 25\text{t}^2 \;\; (0 \le t \le 7.19 \text{ and } 10.81 \le t \le 19.54) & \text{(tank is filling or draining)} \\ 2693 \qquad (7.19 \le t \le 10.81) & \text{(tank is overflowing)} \\ 0 \qquad (19.54 \le t \le 20.54) & \text{(tank is empty, draining as fast as methanol is fed to it)} \end{cases}}}$$

11.3 (cont'd)



11.4 **a.** <u>Air initially in tank:</u> $N_0 = \frac{10.0\ \text{ft}^3 \mid 492°\text{R} \mid 1\ \text{lb-mole}}{\mid 532°\text{R} \mid 359\ \text{ft}^3(\text{STP})} = 0.0258\ \text{lb-mole}$

<u>Air in tank after 15 s:</u>

$$\frac{P_f V}{P_0 V} = \frac{N_f RT}{N_0 RT} \Rightarrow N_f = N_0 \frac{P_f}{P_0} = \frac{0.0258\ \text{lb-mole} \mid 114.7\ \text{psia}}{\mid 14.7\ \text{psia}} = 0.2013\ \text{lb-mole}$$

<u>Rate of addition:</u> $\dot{n} = \frac{(0.2013 - 0.0258)\ \text{lb-mole air}}{15\ \text{s}} = \underline{\underline{0.0117\ \ \text{lb-mole air/s}}}$

b. <u>Balance on air in tank:</u> Accumulation = input

$$\underline{\underline{\frac{dN}{dt}}} = 0.0117(\text{lb-moles/s});\ \underline{\underline{t = 0,\ N = 0.0258\ \text{lb-mole}}}$$

c. <u>Integrate balance:</u> $\int_{0.0258}^{N} dN = \int_0^t \dot{n}\, dt \Rightarrow \underline{\underline{N = 0.0258 + 0.0117t}}\ (\text{lb-mole air})$

<u>Check the solution in two ways:</u>

(1) $t = 0, N = 0.0258\ \ \text{lb-mole} \Rightarrow$ satisfies the initial condition

(2) $\frac{dN}{dt} = 0.0117\,\text{lb-mole air / s} \Rightarrow$ reproduces the mass balance

d. $t = 120\ \text{s} \Rightarrow N = 0.0258 + (0.0117)(120) = 1.43\ \text{lb-moles air}$

<u>O_2 in tank</u> $= 0.21(1.43) = \underline{\underline{0.30\ \text{lb-mole}\ O_2}}$

11.5 **a.** Since the temperature and pressure of the gas are constant, a volume balance on the gas is equivalent to a mole balance (conversion factors cancel).

Accumulation = Input – Output

$$\frac{dV}{dt}=\begin{array}{c|c} 540\text{ m}^3 & 1\text{ h} \\ \hline \text{h} & 60\text{ min} \end{array} -\dot{\nu}_w\left(\text{m}^3/\text{min}\right)$$

$$t=0, V=3.00\times10^3\text{ m}^3\left(t=0\text{ corresponds to 8:00 AM}\right)$$

$$\int_{3.00\times10^3}^{V} dV=\int_0^t\left(9.00-\dot{\nu}_w\right)dt\Rightarrow \underline{\underline{V\left(\text{m}^3\right)=3.00\times10^3+9.00t-\int_0^t\dot{\nu}_w dt}}\quad t\text{ in minutes}$$

b. Let $\dot{\nu}_{wi}$ = tabulated value of $\dot{\nu}_w$ at $t=10(i-1)$ $\quad i=1, 2, \ldots, 25$

$$\int_0^{240}\dot{\nu}_w dt\cong\frac{10}{3}\left[\dot{\nu}_{w1}+\dot{\nu}_{w25}+4\sum_{i=2,4,\ldots}^{24}\dot{\nu}_{wi}+2\sum_{i=3,5,\ldots}^{24}\dot{\nu}_{wi}\right]=\frac{10}{3}\left[11.4+9.8+4(124.6)+2(113.4)\right]$$

$$=2488\text{ m}^3$$

$$V=3.00\times10^3+9.00(240)-2488=\underline{\underline{2672\text{ m}^3}}$$

c. Measure the height of the float roof (proportional to volume).
The feed rate decreased, or the withdrawal rate increased between data points, or the storage tank has a leak, or Simpson's rule introduced an error.

d.

```
      REAL VW(25), T, V, V0, H
      INTEGER I
      DATA V0, H/3.0E3, 10./
      READ (5, *) (VW(I), I = 1, 25)
      V= V0
      T=0.
      WRITE (6, 1)
      WRITE (6, 2) T, V
      DO 10 I = 2, 25
            T = H * (I – 1)
            V = V + 9.00 * H – 0.5 * H * (VW(I – 1) + VW(I))
            WRITE (6, 2) T, V
   10 CONTINUE
    1 FORMAT ('TIME (MIN)  VOLUME (CUBIC METERS)')
    2 FORMAT (F8.2, 7X, F6.0)
      END
$DATA
11.4   11.9      12.1      11.8      11.5      11.3
⋮
```

Results:

```
TIME (MIN)   VOLUME (CUBIC METERS)
0.00         3000.
10.00        2974.
20.00        2944.
⋮            ⋮
230.00       2683.
240.00       2674.
```

$$V_{\text{trapezoid}}=2674\text{ m}^3;\ V_{\text{Simpson}}=2672\text{ m}^3;\ \frac{2674-2672}{2672}\times100\%=\underline{\underline{0.07\%}}$$

<u>Simpson's rule is more accurate</u>.

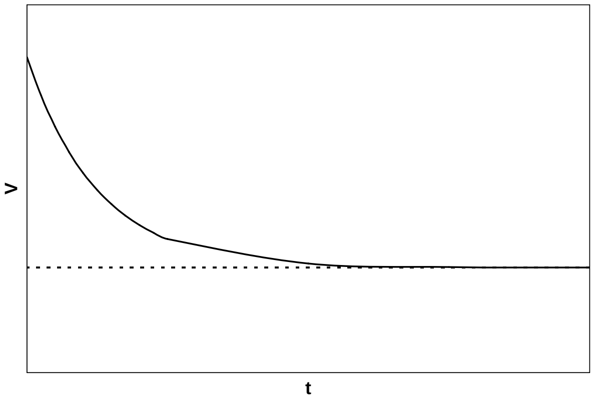
11.6 **a.** $\dot{\nu}_{out}(\text{L/min}) = kV(\text{L}) \underset{\substack{V=300\\ \dot{\nu}_{out}=60}}{\Rightarrow} \underline{\underline{\dot{\nu}_{out} = 0.200V}}$ $\dot{\nu}_{out} = 20.0\ \text{L/min} \Rightarrow \underline{\underline{V_s = 100\ \text{L}}}$

b. Balance on water: Accumulation = input – output (L/min).
(Balance volume directly since density is constant)

$$\underline{\underline{\frac{dV}{dt} = 20.0 - 0.200V}}$$
$$\underline{\underline{t = 0, V = 300}}$$

c. $\frac{dV}{dt} = 0 = 200 - 0.200V_s \Rightarrow \underline{\underline{V_s = 100\ \text{L}}}$

The plot of V vs. t begins at (t=0, V=300). When t=0, the slope (dV/dt) is $20.0 - 0.200(300) = -40.0$. As t increases, V decreases. $\Rightarrow dV/dt = 20.0 - 0.200V$ becomes less negative, approaches zero as $t \to \infty$. The curve is therefore concave up.



d. $$\int_{300}^{V} \frac{dV}{20.0 - 0.200V} = \int_0^t dt$$

$$\Rightarrow -\frac{1}{0.200}\ln\left(\frac{20.0 - 0.200V}{-40.0}\right) = t$$

$$\Rightarrow -0.5 + 0.005V = \exp(-0.200t) \Rightarrow \underline{\underline{V = 100.0 + 200.0\exp(-0.200t)}}$$

$$V = 1.01(100) = 101\ \text{L}\ (1\%\ \text{from steady state}) \Rightarrow$$

$$101 = 100 + 200\exp(-0.200t) \Rightarrow t = \frac{\ln(1/200)}{-0.200} = \underline{\underline{26.5\ \text{min}}}$$

11.7 **a.** A plot of D (log scale) vs. t (rectangular scale) yields a straight line through the points ($t=1$ week, $D=2385\ \text{kg/week}$) and ($t=6$ weeks, $D=755\ \text{kg/week}$).

$$\ln D = bt + \ln a \Leftrightarrow D = ae^{bt}$$

$$b=\frac{\ln D_2/D_1}{t_2-t_1}=\frac{\ln(755/2385)}{6-1}=-0.230$$

$$\ln a = \ln D_1 - bt_1 = \ln(2385)+(0.230)(1)=8.007 \Rightarrow a = e^{8.007}=3000$$

$$\Downarrow$$

$$\underline{\underline{D=3000e^{-0.230t}}}$$

b. Inventory balance: Accumulation = –output

$$\frac{dI}{dt}=-3000e^{-0.230t}\,(\text{kg/week})$$

$$\underline{\underline{t=0,\ I=18{,}000\text{ kg}}}$$

$$\int_{18{,}000}^{I} dI=\int_{0}^{t}-3000e^{-0.230t}dt \Rightarrow I-18{,}000=\frac{3000}{0.230}e^{-0.230t}\Big]_0^t \Rightarrow \underline{\underline{I=4957+13{,}043e^{-0.230t}}}$$

c. $t=\infty \Rightarrow \underline{\underline{I=4957\text{ kg}}}$

11.8 **a.** Total moles in room:

$$N=\begin{array}{c|c|c} 1100\text{ m}^3 & 273\text{ K} & 10^3\text{ mol} \\ \hline & 295\text{ K} & 22.4\text{ m}^3(\text{STP}) \end{array}=45{,}440\text{ mol}$$

Molar throughput rate:

$$\dot{n}=\begin{array}{c|c|c} 700\text{ m}^3 & 273\text{ K} & 10^3\text{ mol} \\ \hline \text{min} & 295\text{ K} & 22.4\text{ m}^3(\text{STP}) \end{array}=28{,}920\text{ mol/min}$$

SO_2 balance ($t=0$ is the instant after the SO_2 is released into the room):

$N(\text{mol})x(\text{mol SO}_2/\text{mol})=$ mol SO_2 in room

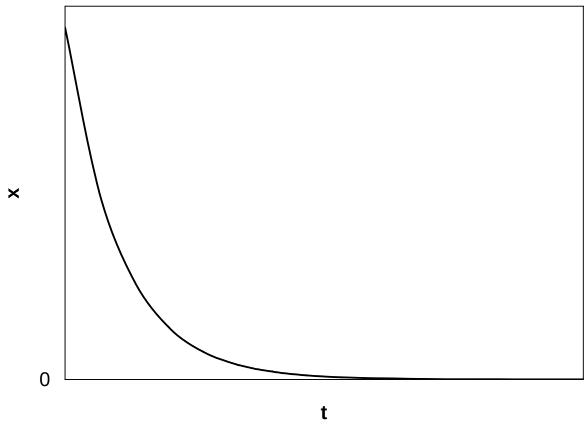
Accumulation = –output.

$$\frac{d}{dt}(Nx)=-\dot{n}x \underset{\substack{N=45{,}440\\ \dot{n}=28{,}920}}{\Rightarrow} \frac{dx}{dt}=-0.6364x$$

$$\underline{\underline{t=0,\ x=\frac{1.5\text{ mol SO}_2}{45{,}440\text{ mol}}=3.30\times10^{-5}\text{ mol SO}_2/\text{mol}}}$$

b. The plot of x vs. t begins at (t=0, x=3.30×10^{-5}). When t=0, the slope (dx/dt) is $-0.6364\times3.30\times10^{-5}=-2.10\times10^{-5}$. As t increases, x decreases.⇒ $dx/dt=-0.6364x$ becomes less negative, approaches zero as $t\to\infty$. The curve is therefore concave up.

11.8 (cont'd)



c. Separate variables and integrate the balance equation:

$$\int_{3.30\times10^{-5}}^{x} \frac{dx}{x} = \int_{0}^{t} -0.6364dt \Rightarrow \ln\frac{x}{3.30\times10^{-5}} = -0.6364t \Rightarrow \underline{\underline{x = 3.30\times10^{-5}e^{-0.6364t}}}$$

Check the solution in two ways:

(1) t = 0, $x = 3.30\times10^{-5}$ mol SO_2 / mol $\Rightarrow$ satisfies the initial condition;

(2) $\frac{dx}{dt} = -0.6364\times3.30\times10^{-5}e^{-0.6364t} = -0.6364x \Rightarrow$ reproduces the mass balance.

d. $$C_{SO_2} = \frac{45{,}440 \text{ moles}}{1100 \text{ m}^3}\left|\frac{x \text{ mol } SO_2}{\text{mol}}\right|\frac{1 \text{ m}^3}{10^3 \text{ L}} = 4.131\times10^{-2}x = \underline{\underline{1.3632\times10^{-6}e^{-0.6364t} \text{ mol } SO_2 / \text{L}}}$$

i) $t = 2 \text{ min} \Rightarrow C_{SO_2} = \underline{\underline{3.82\times10^{-7}\frac{\text{mol } SO_2}{\text{liter}}}}$

ii) $x = 10^{-6} \Rightarrow t = \frac{\ln\left(10^{-6}/3.30\times10^{-5}\right)}{-0.6364} = \underline{\underline{5.5 \text{ min}}}$

e. The room air composition may not be uniform, so the actual concentration of the SO_2 in parts of the room may still be higher than the safe level. Also, "safe" is on the average; someone would be particularly sensitive to SO_2.

11.9 **a.** Balance on CO: Accumulation=-output

$N\,(\text{mol})\ x\,(\text{mol CO / mol})$ = total moles of CO in the laboratory

Molar flow rate of entering and leaving gas: $\dot{n}\ (\frac{\text{kmol}}{\text{h}}) = \frac{P\dot{v}_p}{RT}$

Rate at which CO leaves: $\dot{n}\ (\frac{\text{kmol}}{\text{h}})\ x\left(\frac{\text{kmol CO}}{\text{kmol}}\right) = \frac{P\dot{v}_p}{RT}x$

CO balance: Accumulation = -output

$$\frac{d(Nx)}{dt} = -\frac{P\dot{v}_p}{RT}x \Rightarrow \frac{dx}{dt} = -\left(\frac{P}{NRT}\right)\dot{v}_p x$$

$$\Downarrow PV = NRT$$

$$\frac{dx}{dt} = -\frac{\dot{v}_p}{V}x$$

$$\underline{\underline{t = 0,\ x = 0.01\ \frac{\text{kmol CO}}{\text{kmol}}}}$$

b. $$\int_{0.01}^{x}\frac{dx}{x} = -\frac{\dot{v}_p}{V}\int_{0}^{t_r}dt \Rightarrow \underline{\underline{t_r = -\frac{V}{\dot{v}_p}\ln(100x)}}$$

c. $V = 350\ \text{m}^3$

$$t_r = -\frac{350}{700}\ln\left(100\times 35\times 10^{-6}\right) = \underline{\underline{2.83\ \text{hrs}}}$$

d. The room air composition may not be uniform, so the actual concentration of CO in parts of the room may still be higher than the safe level. Also, “safe” is on the average; someone could be particularly sensitive to CO.

Precautionary steps:
Purge the laboratory longer than the calculated purge time. Use a CO detector to measure the real concentration of CO in the laboratory and make sure it is lower than the safe level everywhere in the laboratory.

11.10 **a.** Total mass balance: Accumulation = input – output

$$\frac{dM}{dt} = \dot{m} - \dot{m}(\text{kg/min}) = 0 \Rightarrow \therefore\ \underline{\underline{M \text{ is a constant} = 200\ \text{kg}}}$$

b. Sodium nitrate balance: Accumulation = - output

x = mass fraction of NaNO_3

$$\frac{d(xM)}{dt} = -x\dot{m}(\text{kg/min})$$

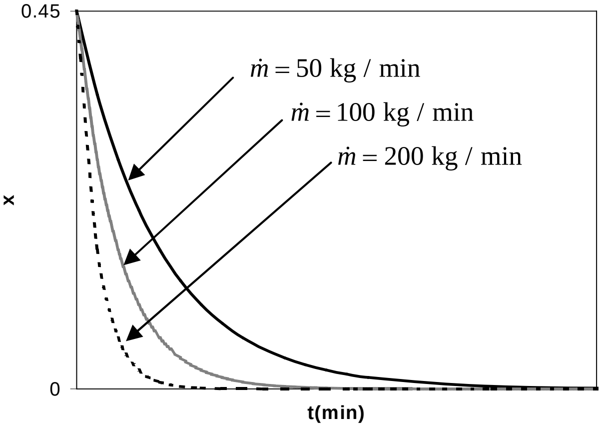
$$\Downarrow$$

$$\frac{dx}{dt} = -\frac{\dot{m}}{M}x = -\frac{\dot{m}}{200}x$$

$$\underline{\underline{t = 0,\ x = 90/200 = 0.45}}$$

11.10 (cont'd)

c.



$\frac{dx}{dt} = -\frac{\dot{m}}{200}x < 0$, x decreases when t increases

$\frac{dx}{dt}$ becomes less negative until x reaches 0;

Each curve is concave up and approaches x = 0 as t → ∞;

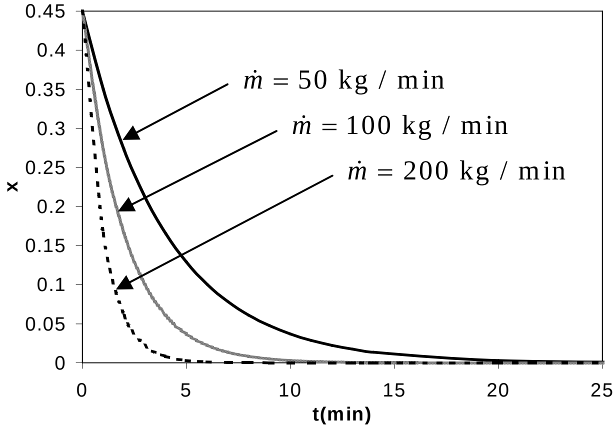
$\dot{m}$ increases $\Rightarrow$ $\frac{dx}{dt}$ becomes more negative $\Rightarrow$ x decreases faster.

d. $\int_{0.45}^{x} \frac{dx}{x} = -\int_0^t \frac{\dot{m}}{M}dt \quad \Rightarrow \quad \ln\frac{x}{0.45} = -\frac{\dot{m}}{200}t \Rightarrow \underline{\underline{x = 0.45\exp\left(-\frac{\dot{m}t}{200}\right)}}$

Check the solution:

(1) t = 0, x = 0.45 $\Rightarrow$ satisfies the initial condition;

(2) $\frac{dx}{dt} = -0.45 \times \frac{\dot{m}}{200}\exp(-\frac{\dot{m}t}{200}) = -\frac{\dot{m}}{200}x \Rightarrow$ satisfies the mass balance.



e. $\dot{m} = 100$ kg/min $\Rightarrow t = -2\ln\left(x_f/0.45\right)$

90% $\Rightarrow x_f = 0.045 \Rightarrow \underline{\underline{t = 4.6 \text{ min}}}$

99% $\Rightarrow x_f = 0.0045 \Rightarrow \underline{\underline{t = 9.2 \text{ min}}}$

99.9% $\Rightarrow x_f = 0.00045 \Rightarrow \underline{\underline{t = 13.8 \text{ min}}}$

11.11 **a.** Mass of tracer in tank: $V\left(\mathrm{m}^3\right)C\left(\mathrm{kg}/\mathrm{m}^3\right)$

Tracer balance: Accumulation = –output. If perfectly mixed, $C_{\mathrm{out}} = C_{\mathrm{tank}} = C$

$$\frac{d(VC)}{dt} = -\dot{v}C\ (\mathrm{kg/min}) \xrightarrow{\text{V is constant}} \underline{\underline{\begin{aligned} \frac{dC}{dt} &= -\frac{\dot{v}}{V}C \\ t = 0,\ C &= \frac{m_0}{V} \end{aligned}}}$$

b. $$\int_{m_0/V}^{C}\frac{dC}{C} = -\int_0^t \frac{\dot{v}}{V}\,dt \Rightarrow \ln\left(\frac{C}{m_0/V}\right) = -\frac{\dot{v}t}{V} \Rightarrow \underline{\underline{C = \frac{m_0}{V}\exp\left(-\frac{\dot{v}t}{V}\right)}}$$

c. Plot C (log scale) vs t (rect. scale) on semilog paper: Data lie on straight line (verifying assumption of perfect mixing) through $\left(t = 1, C = 0.223\times10^{-3}\right)$ & $\left(t = 2, C = 0.050\times10^{-3}\right)$.

$$-\frac{\dot{v}}{V} = \frac{\ln(0.050/0.223)}{2-1} = -1.495\ \mathrm{min}^{-1}$$

$$\Downarrow$$

$$V = \left(30\ \ \mathrm{m}^3/\mathrm{min}\right)\Big/\left(1.495\ \mathrm{min}^{-1}\right) = \underline{\underline{20.1\ \mathrm{m}^3}}$$

11.12 **a.** In tent at any time, P=14.7 psia, V=40.0 ft^3, T=68°F=528°R

$$\Rightarrow N = \frac{PV}{RT} = \mathrm{m(liquid)} = \frac{14.7\ \mathrm{psia}\ \Big|\ 40.0\ \mathrm{ft}^3}{10.73\ \dfrac{\mathrm{ft}^3\cdot\mathrm{psia}}{\mathrm{lb\text{-}mole}\cdot{}^{\mathrm{o}}\ \mathrm{R}}\ \Big|\ 528\ {}^{\mathrm{o}}\mathrm{R}} = \underline{\underline{0.1038\ \mathrm{lb\text{-}mole}}}$$

b. Molar throughout rate:

$$\dot{n}_{in} = \dot{n}_{out} = \dot{n} = \frac{60\ \mathrm{ft}^3\ \Big|\ 492^\circ\ \mathrm{R}\ \Big|\ 16.0\ \mathrm{psia}\ \Big|\ 1\ \mathrm{lb\text{-}mole}}{\mathrm{min}\ \Big|\ 528^\circ\ \mathrm{R}\ \Big|\ 14.7\ \mathrm{psia}\ \Big|\ 359\ \mathrm{ft}^3(\mathrm{STP})} = 0.1695\ \ \mathrm{lb\text{-}mole/min}$$

Moles of O$_2$ in tank$= N(\mathrm{lb\text{-}mole})\times\left(\dfrac{\mathrm{lb\text{-}mole\ O_2}}{\mathrm{lb\text{-}mole}}\right)$

Balance on O$_2$: Accumulation = input – output

$$\frac{d(Nx)}{dt} = 0.35\dot{n} - x\dot{n} \Rightarrow 0.1038\frac{dx}{dt} = 0.1695(0.35-x) \Rightarrow \underline{\underline{\begin{aligned} \frac{dx}{dt} &= 1.63(0.35-x) \\ t = 0,\ x &= 0.21 \end{aligned}}}$$

c. $$\int_{0.21}^{x}\frac{dx}{0.35-x} = \int_0^t 1.63dt \Rightarrow -\ln\frac{(0.35-x)}{(0.35-0.21)} = 1.63t$$

$$\Rightarrow \frac{0.35-x}{0.14} = e^{-1.63t} \Rightarrow \underline{\underline{x = 0.35-0.14e^{-1.63t}}}$$

$$x = 0.27 \Rightarrow t = \frac{1}{1.63}\left[-\ln\left(\frac{0.35-0.27}{0.35-0.21}\right)\right] = \underline{\underline{0.343\ \mathrm{min}}}\ (\text{or }\underline{\underline{20.6\ \mathrm{s}}})$$

11.13 a. Mass of isotope at any time $= V(\text{liters})C(\text{mg isotope/liter})$

Balance on isotope: Accumulation = –consumption

$$\frac{d}{dt}(VC) = -kC\left(\frac{\text{mg}}{\text{L}\cdot\text{s}}\right)V(\text{L}) \xRightarrow{\text{Cancel V}} \frac{dC}{dt} = -kC$$

$$\underline{\underline{t = 0,\ C = C_0}}$$

Separate variables and integrate

$$\int_{C_0}^{C}\frac{dC}{C} = \int_0^t -kdt \Rightarrow \ln\left(\frac{C}{C_0}\right) = -kt \Rightarrow t = \frac{-\ln(C/C_0)}{k}$$

$$C = 0.5C_0 \Rightarrow t_{1/2} = \frac{-\ln(0.5)}{k} \Rightarrow \underline{\underline{t_{1/2} = \frac{\ln 2}{k}}}$$

b. $t_{1/2} = 2.6 \text{ hr} \Rightarrow k = \dfrac{\ln 2}{2.6 \text{ hr}} = 0.267 \text{ hr}^{-1}$

$$C = 0.01C_0 \xRightarrow[\text{t=-ln(C/C}_0\text{)/k}]{} t = \frac{-\ln(0.01)}{0.267} = \underline{\underline{17.2 \text{ hr}}}$$

11.14 $A \rightarrow$ products

a. Mole balance on A: Accumulation = –consumption

$$\frac{d(C_AV)}{dt} = -kC_AV \qquad (V \text{ constant; cancels})$$

$$t = 0,\ C_A = C_{A0}$$

$$\Rightarrow \int_{C_{A0}}^{C_A}\frac{dC_A}{C_A} = \int_0^t -kdt \Rightarrow \ln\left(\frac{C_A}{C_{A0}}\right) = -kt \Rightarrow \underline{\underline{C_A = C_{A0}\exp(-kt)}}$$

b. Plot C_A (log scale) vs. t (rect. scale) on semilog paper. The data fall on a straight line (verifies assumption of first-order) through $(t = 21.3,\ C_A = 0.0262)$ & $(t = 120.0,\ C_A = 0.0185)$.

$$\ln C_A = -kt + \ln C_{A0}$$

$$-k = \frac{\ln(0.0185/0.0262)}{120.0 - 21.3} = -3.53\times10^{-3}\ \text{min}^{-1} \Rightarrow \underline{\underline{k = 3.5\times10^{-3}\ \text{min}^{-1}}}$$

11.15 $2A \rightarrow 2B + C$

a. Mole balance on A: Accumulation = –consumption

$$\frac{d(C_AV)}{dt} = -kC_A^2V \qquad (V \text{ constant; cancels})$$

$$t = 0,\ C_A = C_{A0}$$

$$\Rightarrow \int_{C_{A0}}^{C_A}\frac{dC_A}{C_A^2} = \int_0^t -kdt \Rightarrow -\frac{1}{C_A} + \frac{1}{C_{A0}} = -kt \Rightarrow \underline{\underline{C_A = \left[\frac{1}{C_{A0}} + kt\right]^{-1}}}$$

11.15 (cont'd)

b. $C_A = 0.5C_{A0} \Rightarrow -\frac{1}{0.5C_{A0}} + \frac{1}{C_{A0}} = -kt_{1/2} \Rightarrow t_{1/2} = \frac{1}{kC_{A0}}$; but $C_{A0} = \frac{n_{A0}}{V} = \frac{P_0}{RT} \Rightarrow t_{1/2} = \underline{\underline{\frac{RT}{kP_0}}}$

$n_A = 0.5n_{A0}$

$n_B = (0.5n_{A0} \text{ mol } A \text{ react.})(2 \text{ mol } B/2 \text{ mol } A \text{ react.}) = 0.5n_{A0}$

$n_C = (0.5n_{A0} \text{ mol } A \text{ react.})(1 \text{ mol } C/2 \text{ mol } A \text{ react.}) = 0.25n_{A0}$

$\text{total moles } = 1.25n_{A0} \Rightarrow P_{1/2} = 1.25\frac{n_{A0}RT}{V} = \underline{\underline{1.25P_0}}$

c. Plot $t_{1/2}$ vs. $1/P_0$ on rectangular paper. Data fall on straight line (verifying 2nd order decomposition) through $(t_{1/2} = 1060, 1/P_0 = 1/0.135)$ & $(t_{1/2} = 209, 1/P_0 = 1/0.683)$

Slope: $\frac{RT}{k} = \frac{1060-209}{1/0.135 - 1/0.683} = 143.2 \text{ s}\cdot\text{atm}$

$$\Rightarrow k = \frac{(1015 \text{ K})(0.08206 \text{ L}\cdot\text{atm/mol}\cdot\text{K})}{143.2 \text{ s}\cdot\text{atm}} = \underline{\underline{0.582 \text{ L/mol}\cdot\text{s}}}$$

d. $t_{1/2} = \frac{RT}{k_0 P_0}\exp\left(\frac{E}{RT}\right) \Rightarrow \ln\left(\frac{t_{1/2}P_0}{RT}\right) = \ln\frac{1}{k_0} + \frac{E}{R}\frac{1}{T}$

Plot $t_{1/2}P_0/RT$ (log scale) vs. $1/T$ (rect. scale) on semilog paper.

$\left[t_{1/2}(\text{s}),\ P_0 = 1 \text{ atm},\ R = 0.08206 \text{ L}\cdot\text{atm / (mol}\cdot\text{K), T(K)}\right]$

Data fall on straight line through $(t_{1/2}P_0/RT = 74.0, 1/T = 1/900)$ &

$(t_{1/2}P_0/RT = 0.6383, 1/T = 1/1050)$

$$\frac{E}{R} = \frac{\ln(0.6383/74.0)}{1/1050 - 1/900} = 29{,}940 \text{ K} \xrightarrow{\text{R=8.314 J/(mol·K)}} \underline{\underline{E = 2.49\times10^5 \text{ J/mol}}}$$

$$\ln\frac{1}{k_0} = \ln(0.6383) - \frac{29{,}940}{1050} = -28.96 \Rightarrow \underline{\underline{k_0 = 3.79\times10^{12} \text{ L/(mol}\cdot\text{s)}}}$$

e. $T = 980 \text{ K} \Rightarrow k = k_0 \exp\left(-\frac{E}{RT}\right) = 0.204 \text{ L/(mol}\cdot\text{s)}$

$$C_{A0} = \frac{0.70(1.20 \text{ atm})}{(0.08206 \text{ L}\cdot\text{atm/mol}\cdot\text{K})(980 \text{ K})} = 1.045\times10^{-2} \text{ mol/L}$$

$$\Big\Downarrow \text{90\% conversion}$$

$$C_A = 0.10C_{A0} \Rightarrow t = \frac{1}{k}\left[\frac{1}{C_A} - \frac{1}{C_{A0}}\right] = \frac{1}{0.204}\left[\frac{1}{1.045\times10^{-3}} - \frac{1}{1.045\times10^{-2}}\right]$$

$$= 4222 \text{ s} = \underline{\underline{70.4 \text{ min}}}$$

11.16 $A \to B$

a. <u>Mole balance on *A*:</u> Accumulation = –consumption(*V* constant)

$$\frac{dC_A}{dt} = -\frac{k_1 C_A}{1 + k_2 C_A}$$

$$t = 0,\ C_A = C_{A0}$$

$$\int_{C_{A0}}^{C_A} \frac{1 + k_2 C_A}{k_1 C_A} dC_A = \int_0^t -dt \Rightarrow \frac{1}{k_1} \ln \frac{C_A}{C_{A0}} + \frac{k_2}{k_1}\left(C_A - C_{A0}\right) = -t \Rightarrow \underline{\underline{t = \frac{k_2}{k_1}\left(C_{A0} - C_A\right) - \frac{1}{k_1} \ln \frac{C_A}{C_{A0}}}}$$

b. Plot $t/\left(C_A - C_{A0}\right)$ vs. $\ln\left(C_A / C_{A0}\right)/\left(C_{A0} - C_A\right)$ on rectangular paper:

$$\overbrace{\frac{t}{\left(C_{A0} - C_A\right)}}^{y} = \underbrace{-\frac{1}{k_1}}_{\text{slope}} \overbrace{\frac{\ln\left(C_A/C_{A0}\right)}{C_{A0} - C_A}}^{x} + \underbrace{\frac{k_2}{k_1}}_{\text{intercept}}$$

Data fall on straight line through $\left(\overset{y_1}{116.28}, \overset{x_1}{-0.2111}\right)$ & $\left(\overset{y_2}{130.01}, \overset{x_2}{-0.2496}\right)$

$$-\frac{1}{k_1} = \frac{130.01 - 116.28}{-0.2496 - (-0.2111)} = -356.62 \Rightarrow \underline{\underline{k_1 = 2.80 \times 10^{-3}\ \text{L/(mol}\cdot\text{s)}}}$$

$$\frac{k_2}{k_1} = 130.01 + 356.62(-0.2496) = 41.00 \Rightarrow \underline{\underline{k_2 = 0.115\ \text{L/mol}}}$$

11.17 $\text{CO} + \text{Cl}_2 \Rightarrow \text{COCl}_2$

a.
$$\begin{array}{l|l|l} 3.00\ \text{L} & 273\ \text{K} & 1\ \text{mol} \\ \hline & 303.8\ \text{K} & 22.4\ \text{L(STP)} \end{array} = 0.12035\ \text{mol gas}$$

$$\left.\begin{array}{l} \left(C_{\text{CO}}\right)_i = 0.60(0.12035\ \text{mol})/3.00\ \text{L} = \underline{\underline{0.02407\ \ \text{mol/L CO}}} \\ \left(C_{\text{Cl}_2}\right)_i = 0.40(0.12035\ \text{mol})/3.00\ \text{L} = \underline{\underline{0.01605\ \ \text{mol/L Cl}_2}} \end{array}\right\}\text{initial concentrations}$$

$$\left.\begin{array}{l} \underline{\underline{C_{\text{CO}}(t) = 0.02407 - C_p(t)}} \\ \underline{\underline{C_{\text{Cl}_2}(t) = 0.01605 - C_p(t)}} \end{array}\right\}\text{Since 1 mol COCl}_2\text{ formed requires 1 mol of each reactant}$$

b. Mole balance on Phosgene: Accumulation = generation

$$\frac{d\left(VC_p\right)}{dt} = \frac{8.75 C_{\text{CO}} C_{\text{Cl}_2}}{\left(1 + 58.6 C_{\text{Cl}_2} + 34.3 C_p\right)^2} \xrightarrow{\text{V=3.00 L}} \underline{\underline{\begin{array}{c} \dfrac{dC_p}{dt} = \dfrac{2.92\left(0.02407 - C_p\right)\left(0.01605 - C_p\right)}{\left(1.941 - 24.3 C_p\right)^2} \\ t = 0,\ C_p = 0 \end{array}}}$$

c. Cl_2 limiting; 75% conversion $\Rightarrow C_p = 0.75(0.01605) = 0.01204\ \ \text{mol/L}$

$$\underline{\underline{t = \frac{1}{2.92} \int_0^{0.01204} \frac{\left(1.941 - 24.3 C_p\right)^2}{\left(0.02407 - C_p\right)\left(0.01605 - C_p\right)} dC_p}}$$

11.17 (cont'd)

d.

```
          REAL F(51), SUM1, SUM2, SIMP
          INTEGER I, J, NPD(3), N, NM1, NM2
          DATA NPD/5, 21, 51/
          FN(C) = (1.441 – 24.3 * C) ** 2/(0.02407 – C)/(0.01605 – C)
          DO 10 I = 1, 3
               N = NPD(I)
               NM1 = N – 1
               NM2 = N – 2
               DO 20 J = 1, N
                    C = 0.01204 * FLOAT(J – 1)/FLOAT(NM1)
                    F(J) = FN(C)
  20           CONTINUE
               SUM1 = 0.
               DO 30 J = 2, NM1, 2
                    SUM = SUM1 + F(S)
  30           CONTINUE
               SUM2 = 0.
               DO 40 J = 3, NM2, 2
                    SUM2 = SUM2 + F(J)
  40           CONTINUE
               SIMP = 0.01204/FLOAT(NM1)/3.0 * (F(1) + F(N) + 4.0 * SUM1 + 2.0 * SUM2)
               T = SIMP/2.92
               WRITE (6, 1) N, T
  10      CONTINUE
   1      FORMAT (I4, 'POINTS —', 2X, F7.1, 'MINUTES')
          END
```

```
RESULTS
5 POINTS —   91.0 MINUTES
21 POINTS — 90.4 MINUTES
51 POINTS — 90.4 MINUTES
```

$\underline{\underline{t = 90.4 \text{ minutes}}}$

11.18 a. $\underline{\text{Moles of CO}_2 \text{ in liquid phase at any time}} = V\left(\text{cm}^3\right)C_A\left(\text{mols}/\text{cm}^3\right)$

$\underline{\text{Balance on CO}_2 \text{ in liquid phase:}}$ Accumulation = input

$$\frac{d}{dt}(VC_A) = kS\left(C_A^* - C_A\right)\left(\frac{\text{mols}}{\text{s}}\right) \underset{\div V}{\Rightarrow} \frac{dC_A}{dt} = \frac{kS}{V}\left(C_A^* - C_A\right)$$

$$\underline{\underline{t = 0,\ C_A = 0}}$$

Separate variables and integrate. Since $p_A = y_A P$ is constant, $C_A^* = p_A/H$ is also a constant.

$$\int_0^{C_A} \frac{dC_A}{C_A^* - C_A} = \int_0^t \frac{kS}{V}\,dt \Rightarrow -\ln\left(C_A^* - C_A\right)\Big]_{C_A=0}^{C_A} = \frac{kS}{V}t$$

$$\Rightarrow \ln\left[\underbrace{\frac{C_A^* - C_A}{C_A^*}}_{1-C_A/C_A^*}\right] = -\frac{kS}{V}t \overset{\exp(\ )}{\Rightarrow} 1 - \frac{C_A}{C_A^*} = e^{-kSt/V} \Rightarrow \underline{\underline{C_A = C_A^*\left(1 - e^{-kSt/V}\right)}}$$

11.18 (cont'd)

b. $t = -\dfrac{V}{kS}\ln\left[1-\dfrac{C_A}{C_A^*}\right]$

$$\Bigg\Downarrow \quad \begin{array}{l} V = 5\text{ L} = 5000\text{ cm}^3,\ k = 0.020\ \text{ cm}/\text{s},\ S = 78.5\text{ cm}^2,\ C_A = 0.62\times10^{-3}\text{ mol / cm}^3 \\ C_A^* = y_A P/H = (0.30)(20\text{ atm})\Big/\left(9230\text{ atm}\cdot\text{cm}^3/\text{mol}\right) = 0.65\times10^{-3}\ \text{ mol}/\text{cm}^3 \end{array}$$

$$t = -\frac{\left(5000\text{ cm}^3\right)}{\left(0.02\ \text{ cm}/\text{s}\right)\left(78.5\text{ cm}^2\right)}\ln\left(1-\frac{0.62\times10^{-3}}{0.65\times10^{-3}}\right) = 9800\text{ s} \Rightarrow \underline{\underline{2.7\text{ hr}}}$$

(We assume, in the absence of more information, that the gas-liquid interfacial surface area equals the cross sectional area of the tank. If the liquid is well agitated, *S* may in fact be much greater than this value, leading to a significantly lower *t* than that to be calculated)

11.19 $A \rightarrow B$

a. Total Mass Balance: Accumulation = input

$$\frac{dM}{dt} = \frac{d(\rho V)}{dt} = \rho\dot{v}$$

$$\Downarrow$$

$$\underline{\underline{\frac{dV}{dt} = \dot{v}}}$$

$$\underline{\underline{t = 0,\ V = 0}}$$

A Balance: Accumulation = input – consumption

$$\frac{dN_A}{dt} = C_{A0}\dot{v} - (kC_A)V \xRightarrow[C_A=N_A/V]{} \underline{\underline{\frac{dN_A}{dt} = C_{Ao}\dot{v} - kN_A}}$$

$$\underline{\underline{t = 0,\ N_A = 0}}$$

b. Steady State: $\dfrac{dN_A}{dt} = 0 \Rightarrow \underline{\underline{N_A = \dfrac{C_{A0}\dot{v}}{k}}}$

c. $\displaystyle\int_0^V dV = \int_0^t \dot{v}dt \Rightarrow \underline{\underline{V = \dot{v}t}}$

$$\int_0^{N_A}\frac{dN_A}{C_{A0}\dot{v} - kN_A} = \int_0^t dt$$

$$\Rightarrow -\frac{1}{k}\ln\left(\frac{C_{A0}\dot{v} - kN_A}{C_{A0}\dot{v}}\right) = t \Rightarrow \frac{C_{A0}\dot{v} - kN_A}{C_{A0}\dot{v}} = e^{-kt}$$

$$\Rightarrow \underline{\underline{N_A = \frac{C_{A0}\dot{v}}{k}\left[1-\exp(-kt)\right]}} \quad t \rightarrow \infty \Rightarrow \underline{\underline{N_A = \frac{C_{A0}\dot{v}}{k}}}$$

$$\underline{\underline{C_A = \frac{N_A}{V} = \frac{C_{A0}[1-\exp(-kt)]}{kt}}}$$

11.19 (cont'd)

When the feed rate of A equals the rate at which A reacts, N_A reaches a steady value.
N_A would never reach the steady value in a real reactor. The reasons are:
(1) In our calculation, $V = \dot{v}t \Rightarrow t \to \infty, V \to \infty$.

But in a real reactor, the volume is limited by the reactor volume;

(2) The steady value can only be reached at $t \to \infty$. In a real reactor, the reaction time is finite.

d. $\lim\limits_{t\to\infty} C_A = \lim\limits_{t\to\infty} \dfrac{C_{A0}[1-\exp(-kt)]}{kt} = \lim\limits_{t\to\infty} \dfrac{C_{A0}}{kt} = \underline{\underline{0}}$

From part c, $t \to \infty$, $\mathrm{N_A} \to$ a finite number, $\mathrm{V} \to \infty \Rightarrow \mathrm{C_A} = \dfrac{N_A}{V} \to 0$

11.20 a. $MC_v \dfrac{dT}{dt} = \dot{Q} - \dot{W}$

$$\Downarrow \quad \begin{aligned} &M = (3.00\text{ L})(1.00\text{ kg / L}) = 3.00\text{ kg} \\ &C_v = C_p = (0.0754\text{ kJ / mol}\cdot{}^\circ\text{C})(1\text{ mol / }0.018\text{ kg}) = 4.184\text{ kJ / kg}\cdot{}^\circ\text{C} \\ &\dot{W} = 0 \end{aligned}$$

$$\dfrac{dT}{dt} = 0.0797\dot{Q}\ (\text{kJ / s})$$

$$\underline{\underline{t = 0,\ T = 18^\circ\text{C}}}$$

b. $\displaystyle\int_{18^\circ\text{C}}^{100^\circ\text{C}} \mathrm{dT} = \int_0^{240\text{ s}} 0.0797\dot{Q}\,dt \Rightarrow \dot{Q} = \frac{100-18}{240\times 0.0797} = 4.287\ \frac{\text{kJ}}{\text{s}} = \underline{\underline{4.29\text{ kW}}}$

c. Stove output is much greater.
Only a small fraction of energy goes to heat the water.
Some energy heats the kettle.
Some energy is lost to the surroundings (air).

11.21 a. Energy balance: $MC_v \dfrac{dT}{dt} = \dot{Q} - \dot{W}$

$$\Downarrow \quad \begin{aligned} &M = 20.0\text{ kg} \\ &C_v \approx C_p = (0.0754\text{ kJ / mol}\cdot{}^\circ\text{C})(1\text{ mol / }0.0180\text{ kg}) = 4.184\text{ kJ / (kg}\cdot{}^\circ\text{C)} \\ &\dot{Q} = (0.97)(2.50) = 2.425\ \text{kJ/s} \\ &\dot{W} = 0 \end{aligned}$$

$$\underline{\underline{\dfrac{dT}{dt} = 0.0290\,({}^\circ\text{C/s})}}\ ,\quad \underline{\underline{t = 0,\ T = 25^\circ\text{C}}}$$

The other 3% of the energy is used to heat the vessel or is lost to the surroundings.

b. $\displaystyle\int_{25^\circ\text{C}}^{T} dT = \int_0^t 0.0290dt \Rightarrow \underline{\underline{T = 25^\circ\text{C} + 0.0290t(s)}}$

c. $T = 100^\circ\text{C} \Rightarrow t = (100-25)/0.0290 = 2585\text{ s} \Rightarrow \underline{\underline{43.1\text{ min}}}$

No, since the vessel is closed, the pressure will be greater than 1 atm (the pressure at the normal boiling point).

11.22 a. Energy balance on the bar

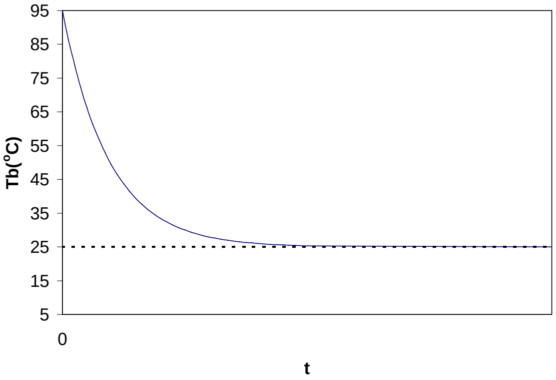
$$MC_v \frac{dT_b}{dt} = \dot{Q} - \dot{W} = -UA(T_b - T_w)$$

$$\Bigg\Downarrow \begin{array}{l} M = (60\text{ cm}^3)(\overset{\substack{\text{Table B.1}\\ \downarrow}}{7.7}\ \text{g/cm}^3) = 462\text{ g} \\ C_v = 0.46\ \text{kJ/(kg}\cdot°\text{C)},\ T_w = 25°\text{C} \\ U = 0.050\ \text{J/(min}\cdot\text{cm}^2\cdot°\text{C)} \\ A = 2[(2)(3)+(2)(10)+(3)(10)]\text{cm}^2 = 112\text{ cm}^2 \end{array}$$

$$\underline{\underline{\frac{dT_b}{dt} = -0.02635(T_b - 25)\ (°\text{C/min})}}$$

$$\underline{\underline{t = 0,\ T_b = 95°\text{C}}}$$

b. $\frac{dT_b}{dt} = 0 = -0.02635(T_{bf} - 25) \Rightarrow \underline{\underline{T_{bf} = 25°\text{C}}}$



c. $\int_{95}^{T_b} \frac{dT_b}{T_b - 25} = \int_0^t -0.02635dt$

$$\Rightarrow \ln\left(\frac{T_b - 25}{95 - 25}\right) = -0.02635t$$

$$\Rightarrow \underline{\underline{T_b(t) = 25 + 70\exp(-0.02635t)}}$$

Check the solution in three ways:

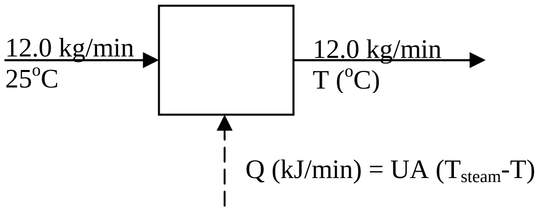
(1) t = 0, $T_b = 25 + 70 = 95^oC \Rightarrow$ satisfies the initial condition;

(2) $\frac{dT_b}{dt} = -70 \times 0.02635e^{-0.02635t} = -0.02635(T_b - 25) \Rightarrow$ reproduces the mass balance;

(3) $t \to \infty$, $T_b = 25^oC \Rightarrow$ confirms the steady state condition.

$T_b = 30°\text{C} \Rightarrow \underline{\underline{t = 100\text{ min}}}$

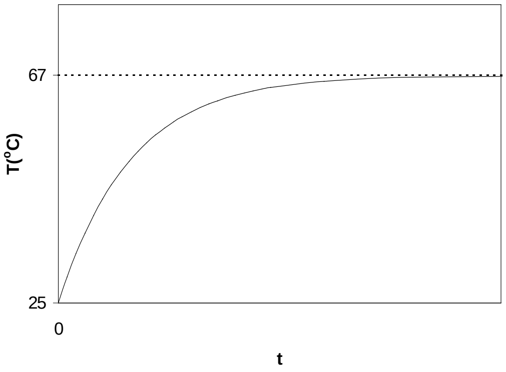
11.23



a. Energy Balance: $MC_v \dfrac{dT}{dt} = \dot{m}C_p(25-T) + UA(T_{\text{steam}} - T)$

$$\left.\begin{array}{l} M = 760 \text{ kg} \\ \dot{m} = 12.0 \text{ kg/min} \\ C_v \approx C_p = 2.30 \text{ kJ/(min}\cdot{}^\circ\text{C)} \\ UA = 11.5 \text{ kJ/(min}\cdot{}^\circ\text{C)} \\ T_{\text{steam}}(\text{sat'd; } 7.5\text{bars}) = 167.8^\circ\text{C} \end{array}\right. \Longrightarrow \underline{\underline{dT/dt = 1.50 - 0.0224T}} \; ({}^\circ\text{C/min}), \; \underline{\underline{t = 0, \; T = 25^\circ\text{C}}}$$

b. Steady State: $\dfrac{dT}{dt} = 0 = 1.50 - 0.0224T_s \Rightarrow \underline{\underline{T_s = 67^\circ\text{C}}}$



c. $$\int_{25}^{T_f} \frac{dT}{1.50 - 0.0224T} = \int_0^t dt \Rightarrow \underline{\underline{t = -\frac{1}{0.0224} \ln\left(\frac{1.50 - 0.0224T}{0.94}\right)}} \Rightarrow T = \frac{1.50 - 0.94\exp(-0.0224t)}{0.0224}$$

$t = 40$ min. $\Rightarrow \underline{\underline{T = 49.8^\circ\text{C}}}$

d. U changed. Let $x = (UA)_{new}$. The differential equation becomes:

$$\frac{dT}{dt} = 0.3947 + 0.096x - (0.01579 + 5.721x)T$$

$$\int_{25}^{55} \frac{dT}{0.3947 + 0.096x - (0.01579 + 5.721 \times 10^{-4}x)T} = \int_0^{40} dt$$

$$\Rightarrow \quad -\frac{1}{0.01579 + 5.721 \times 10^{-4}x} \ln\left[\frac{0.3947 + 0.096x - \left(0.01579 + 5.721 \times 10^{-4}x\right) \times 55}{0.3947 + 0.096x - \left(0.01579 + 5.721 \times 10^{-4}x\right) \times 25}\right] = 40$$

$$\Rightarrow x = 14.27 \text{ kJ / (min}\cdot{}^\circ\text{C)}$$

$$\frac{\Delta U}{U_{initial}} = \frac{\Delta(UA)}{(UA)_{initial}} = \frac{14.27 - 11.5}{11.5} \times 100\% = \underline{\underline{24.1\%}}$$

11.24 a. Energy balance: $MC_v\dfrac{dT}{dt}=\dot{Q}-\dot{W}$

$$\Big\Downarrow\;\begin{array}{l}\dot{W}=0,\ C_v=1.77\ \text{J/g}\cdot{}^\circ\text{C}\\ M=350\ \text{g},\ \dot{Q}=40.2W=40.2\ \text{J/s}\end{array}$$

$$\left.\begin{array}{c}\dfrac{dT}{dt}=0.0649\ ({}^\circ\text{C/s})\\ t=0,\ T=20^\circ\text{C}\end{array}\right\}\Rightarrow\begin{array}{l}T=20+0.0649t(\text{s})\\ T=40^\circ\text{C}\Rightarrow t=308\ \text{s}\Rightarrow \underline{\underline{5.1\ \text{min}}}\end{array}$$

b. The benzene temperature will continue to rise until it reaches $T_b=80.1^\circ\text{C}$; thereafter the heat input will serve to vaporize benzene isothermally.

Time to reach T_b (neglect evaporation): $t=\dfrac{80.1-20}{0.0649}=926\ \text{s}$

Time remaining: $40\ \text{minutes}\ (60\ \text{s/min})-926\ \text{s}=1474\ \text{s}$

Evaporation: $\Delta\hat{H}_v=(30.765\ \text{kJ/mol})(1\ \text{mol/78.11 g})(1000\ \text{J/kJ})=393\ \text{J/g}$

Evaporation rate $=(40.2\ \text{J/s})/(393\ \text{J/g})=0.102\ \text{g/s}$

Benzene remaining $=350\ \text{g}-(0.102\ \text{g/s})(1474\ \text{s})=\underline{\underline{200\ \text{g}}}$

c.
1. Used a dirty flask. Chemicals remaining in the flask could react with benzene. Use a clean flask.
2. Put an open flask on the burner. Benzene vaporizes⇒ toxicity, fire hazard. Use a covered container or work under a hood.
3. Left the burner unattended.
4. Looked down into the flask with the boiling chemicals. Damage eyes. Wear goggles.
5. Rubbed his eyes with his hand. Wash with water.
6. Picked up flask with bare hands. Use lab gloves.
7. Put hot flask on partner's homework. Fire hazard.

11.25 a. Moles of air in room: $n=\dfrac{60\ \text{m}^3}{}\left|\dfrac{273\ \text{K}}{283\ \text{K}}\right|\dfrac{1\ \text{kg-mole}}{22.4\ \text{m}^3(\text{STP})}=2.58\ \text{kg-moles}$

Energy balance on room air: $nC_v\dfrac{dT}{dt}=\dot{Q}-\dot{W}$

$$\Big\Downarrow\;\begin{array}{l}\dot{Q}=\dot{m}_s\Delta\hat{H}_v(\text{H}_2\text{O, 3bars, sat'd})-30.0(T-T_0)\\ \dot{W}=0\end{array}$$

$$nC_v\frac{dT}{dt}=\dot{m}_s\Delta\hat{H}_v-30.0(T-T_0)$$

$$\Bigg\Downarrow\;\begin{array}{l}N=2.58\ \text{kg-moles}\\ C_v=20.8\ \text{kJ/(kg-mole}\cdot{}^\circ\text{C)}\\ \Delta\hat{H}_v=2163\ \text{kJ/kg}\ \ (\text{from Table B.6})\\ T_0=0^\circ\text{C}\end{array}$$

$$\underline{\underline{\frac{dT}{dt}=40.3\dot{m}_s-0.559T\ ({}^\circ\text{C/hr})}}$$

$$\underline{\underline{t=0,\ T=10^\circ\text{C}}}$$

(Note: a real process of this type would involve air escaping from the room and a constant pressure being maintained. We simplify the analysis by assuming *n* is constant.)

11.25 (cont'd)

b. At steady-state, $dT/dt = 0 \Rightarrow 40.3\dot{m}_s - 0.559T = 0 \Rightarrow \dot{m}_s = \dfrac{0.559T}{40.3}$

$T = 24^\circ\text{C} \Rightarrow \underline{\underline{\dot{m}_s = 0.333 \text{ kg/hr}}}$

c. Separate variables and integrate the balance equation:

$$\int_{10}^{T_f} \frac{dT}{40.3\dot{m}_s - 0.559T} = \int_0^t dt \quad \xRightarrow[T_f = 23^\circ\text{C}]{\dot{m}_s = 0.333} \quad \int_{10}^{23} \frac{dT}{13.4 - 0.559T} = t$$

$$\Downarrow$$

$$t = -\frac{1}{0.559}\ln\left[\frac{13.4 - 0.559(23)}{13.4 - 0.559(10)}\right] = \underline{\underline{4.8 \text{ hr}}}$$

11.26 a. Integral energy balance $(t = 0 \text{ to } t = 20 \text{ min})$

$$Q = \Delta U = MC_v\Delta T = \begin{array}{c|c|c} 250 \text{ kg} & 4.00 \text{ kJ} & (60-20)^\circ\text{C} \\ \hline & \text{kg}\cdot{}^\circ\text{C} & \end{array} = 4.00 \times 10^4 \text{ kJ}$$

Required power input: $\dot{Q} = \begin{array}{c|c|c} 4.00 \times 10^4 \text{ kJ} & 1 \text{ min} & 1 \text{ kW} \\ \hline 20 \text{ min} & 60 \text{ s} & 1 \text{ kJ/s} \end{array} = \underline{\underline{33.3 \text{ kW}}}$

b. Differential energy balance: $MC_v \dfrac{dT}{dt} = \dot{Q} \xRightarrow[C_v = 4.00 \text{ kJ/kg}\cdot{}^\circ\text{C}]{M = 250 \text{ kg}} \underline{\underline{\dfrac{dT}{dt} = 0.001\dot{Q}(t)}}$

$\underline{\underline{t = 0,\ T = 20^\circ\text{C}}}$

Integrate: $\displaystyle\int_{20^\circ\text{C}}^{T} dT = \int_0^t 0.001\,\dot{Q}\,dT \Rightarrow T = 20^\circ\text{C} + \int_0^t \dot{Q}dt$

Evaluate the integral by Simpson's Rule (Appendix A.3)

$$\int_0^{600 \text{ s}} \dot{Q}dt = \frac{30}{3}\big[33 + 4(33 + 35 + 39 + 44 + 50 + 58 + 66 + 75 + 85 + 95)$$

$$+2(34 + 37 + 41 + 47 + 54 + 62 + 70 + 80 + 90) + 100\big] = 34830 \text{ kJ}$$

$$\Rightarrow T(600 \text{ s}) = 20^\circ\text{C} + (0.001\ {}^\circ\text{C/kJ})(34830 \text{ kJ}) = \underline{\underline{54.8^\circ\text{C}}}$$

c. Past 600 s, $\dot{Q} = 100 + \dfrac{10 \text{ kW}}{60 \text{ s}}(t - 600 \text{ s}) = t/6$

$$T = 20 + 0.001\int_0^t \dot{Q}dt = 20 + 0.001\left[\underbrace{\int_0^{600} \dot{Q}dt}_{34830} + \int_{600}^{t} \frac{t}{6}dt\right]$$

$$\Rightarrow T = 54.8 + \frac{0.001}{6}\left(\frac{t^2}{6} - \frac{600^2}{2}\right) \Rightarrow t(\text{s}) = \sqrt{12000(T - 24.8)}$$

$T = 85^\circ\text{C} \Rightarrow t = 850 \text{ s} = 14 \text{ min, } 10 \text{ s} \Rightarrow$ $\underline{\underline{\text{explosion at 10:14+10 s}}}$

11.27 a. Total Mass Balance:

Accumulation=Input– Output

$$\Downarrow$$

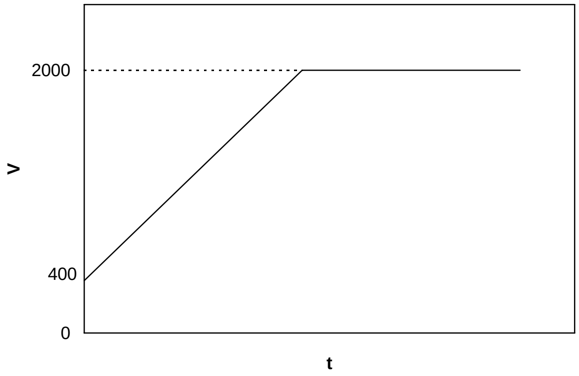
$$\frac{\mathrm{dM_{tot}}}{\mathrm{dt}} = \dot{m}_i - \dot{m}_o \Rightarrow \frac{\mathrm{d}(\rho \mathrm{V})}{\mathrm{dt}} = 8.00\rho - 4.00\rho \xrightarrow{\rho=\text{constant}} \underline{\underline{\begin{array}{l} \dfrac{dV}{dt} = 4.00 \text{ L/s} \\ t = 0,\ \mathrm{V_0} = 400 \text{ L} \end{array}}}$$

KCl Balance:

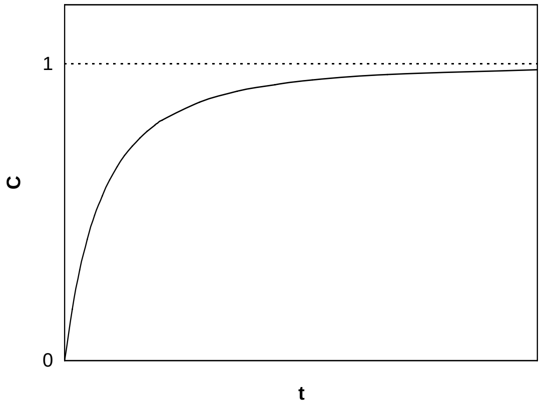
$$\text{Accumulation=Input-Output} \Rightarrow \frac{\mathrm{dM_{KCl}}}{\mathrm{dt}} = \dot{m}_{i,KCl} - \dot{m}_{o,KCl} \Rightarrow \frac{\mathrm{d}(CV)}{\mathrm{dt}} = 1.00 \times 8.00 - 4.00C$$

$$\Rightarrow V\frac{dC}{dt} + C\frac{dV}{dt} = 8 - 4C \xrightarrow{dV/dt\ =\ 4} \underline{\underline{\begin{array}{l} \dfrac{dC}{dt} = \dfrac{8-8C}{V} \\ t = 0,\ \mathrm{C_0} = 0 \text{ g/L} \end{array}}}$$

b. (i)The plot of V vs. t begins at (t=0, V=400). The slope (=dV/dt) is 4 (a positive constant). V increases linearly with increasing t until V reaches 2000. Then the tank begins to overflow and V stays constant at 2000.



(ii) The plot of C vs. t begins at (t=0, C=0). When t=0, the slope (=dC/dt) is (8-0)/400=0.02. As t increases, C increases and V increases (or stays constant)⇒ dC/dt=(8-8C)/V becomes less positive, approaches zero as t→ ∞. The curve is therefore <u>concave down.</u>



c. $\frac{dV}{dt} = 4 \Rightarrow \int_{400}^{V} dV = 4\int_0^t dt \Rightarrow \underline{\underline{V = 400 + 4t}}$

11.27 (cont'd)

$$\frac{dC}{dt}=\frac{8-8C}{V}\xRightarrow[V=400+4t]{}\frac{dC}{dt}=\frac{1-C}{50+0.5t}$$

$$\int_0^C\frac{dC}{1-C}=\int_0^t\frac{\mathrm{dt}}{50+0.5\mathrm{t}}\Rightarrow-\ln(1-C)\Big]_0^C=2\ln(50+0.5t)\Big]_0^t$$

$$\Rightarrow\ln(1\text{-}\mathrm{C})^{-1}=2\ln\frac{50+0.5t}{50}=\ln(1+0.01t)^2$$

$$\Rightarrow\frac{1}{1\text{-}\mathrm{C}}=(1+0.01t)^2\Rightarrow\underline{\underline{C=1-\frac{1}{(1+0.01t)^2}}}$$

When the tank overflows, $V=400+4t=2000\Rightarrow t=400\text{ s}$

$$\mathrm{C}=1\text{-}\frac{1}{\left(1+0.01\times400\right)^2}=\underline{\underline{0.96\text{ g / L}}}$$

11.28 a. Salt Balance on the 1st tank:

Accumulation=-Output

$$\Downarrow$$

$$\frac{\mathrm{d}(\mathrm{C}_{\mathrm{S1}}V_1)}{\mathrm{dt}}=-C_{S1}\dot{v}\Rightarrow\frac{\mathrm{dC}_{\mathrm{S1}}}{\mathrm{dt}}=-C_{S1}\frac{\dot{v}}{V_1}=-0.08C_{S1}$$

$$\underline{\underline{C_{S1}(0)=1500/500=3\text{ g / L}}}$$

Salt Balance on the 2nd tank:

Accumulation=Input-Output

$$\Downarrow$$

$$\frac{\mathrm{d}(\mathrm{C}_{\mathrm{S2}}V_2)}{dt}=C_{S1}\dot{v}-C_{S2}\dot{v}\Rightarrow\frac{\mathrm{dC}_{\mathrm{S2}}}{\mathrm{dt}}=(C_{S1}-C_{S2})\frac{\dot{v}}{V_2}=0.08(C_{S1}-C_{S2})$$

$$\underline{\underline{C_{S2}(0)=0\text{ g / L}}}$$

Salt Balance on the 3rd tank:

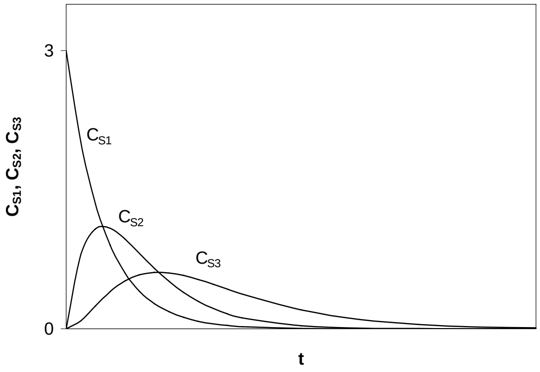
Accumulation=Input-Output

$$\Downarrow$$

$$\frac{\mathrm{d}(\mathrm{C}_{\mathrm{S3}}V_3)}{dt}=C_{S2}\dot{v}-C_{S3}\dot{v}\Rightarrow\frac{\mathrm{dC}_{\mathrm{S3}}}{\mathrm{dt}}=(C_{S2}-C_{S3})\frac{\dot{v}}{V_3}=0.04(C_{S2}-C_{S3})$$

$$\underline{\underline{C_{S3}(0)=0\text{ g / L}}}$$

b.



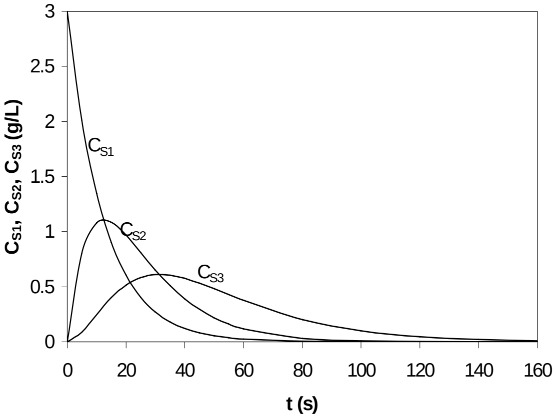
11.28 (cont'd)

The plot of C_{S1} vs. t begins at (t=0, C_{S1}=3). When t=0, the slope (=dC_{S1}/dt) is $-0.08\times 3=-0.24$. As t increases, C_{S1} decreases $\Rightarrow$ $dC_{S1}/dt=-0.08C_{S1}$ becomes less negative, approaches zero as t→ ∞. The curve is therefore concave up.

The plot of C_{S2} vs. t begins at (t=0, C_{S2}=0). When t=0, the slope (=dC_{S2}/dt) is $0.08(3-0)=0.24$. As t increases, C_{S2} increases, C_{S1} decreases ($C_{S2} < C_{S1}$)$\Rightarrow$ $dC_{S2}/dt=0.08(C_{S1}-C_{S2})$ becomes less positive until dC_{S2}/dt changes to negative ($C_{S2} > C_{S1}$). Then C_{S2} decreases with increasing t as well as C_{S1}. Finally dC_{S2}/dt approaches zero as t→∞. Therefore, C_{S2} increases until it reaches a maximum value, then it decreases.

The plot of C_{S3} vs. t begins at (t=0, C_{S3}=0). When t=0, the slope (=dC_{S3}/dt) is $0.04(0-0)=0$. As t increases, C_{S2} increases ($C_{S3} < C_{S2}$)$\Rightarrow$ $dC_{S3}/dt=0.04(C_{S2}-C_{S3})$ becomes positive $\Rightarrow$ C_{S2} increases with increasing t until dC_{S3}/dt changes to negative ($C_{S3} > C_{S1}$). Finally dC_{S3}/dt approaches zero as t→∞. Therefore, C_{S3} increases until it reaches a maximum value then it decreases.

c.



11.29 a. (i) Rate of generation of B in the 1st reaction: $r_{B1}=2r_1=\underline{\underline{0.2C_A}}$

(ii) Rate of consumption of B in the 2nd reaction: $-r_{B2}=r_2=\underline{\underline{0.2C_B^2}}$

b. Mole Balance on A:

Accumulation=-Consumption

$$\Downarrow$$

$$\frac{d(C_AV)}{dt}=-0.1C_AV\Rightarrow\frac{dC_A}{dt}=-0.1C_A$$

$$\underline{\underline{t=0,\ C_{A0}=1.00\text{ mol / L}}}$$

Mole Balance on B:

Accumulation= Generation-Consumption

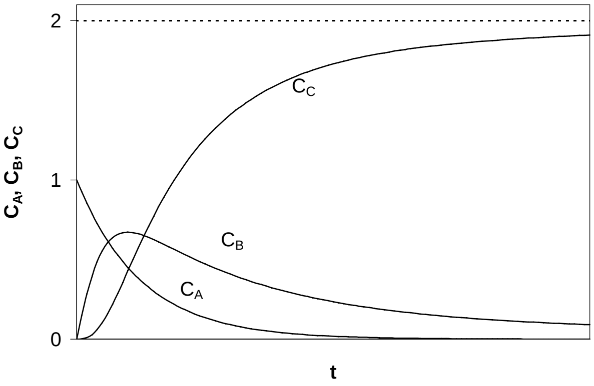
$$\Downarrow$$

$$\frac{d(C_BV)}{dt}=0.2C_AV-0.2C_B^2V\Rightarrow\frac{dC_B}{dt}=0.2C_A-0.2C_B^2$$

$$\underline{\underline{t=0,\ C_{B0}=0\text{ mol / L}}}$$

11.29 (cont'd)

c.

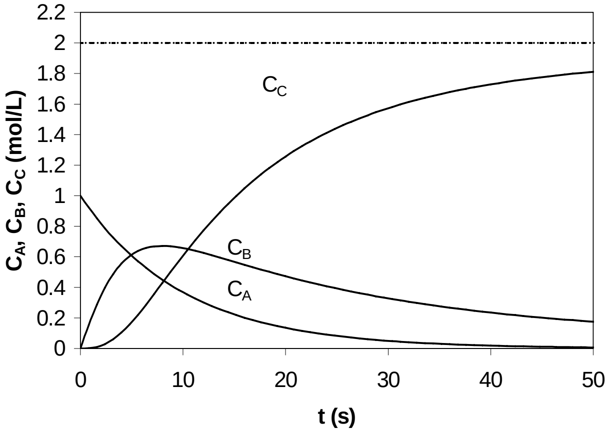


The plot of C_A vs. t begins at (t=0, C_A=1). When t=0, the slope (=dC_A/dt) is $-0.1\times 1=-0.1$. As t increases, C_A decreases ⇒ $dC_A/dt=-0.1C_A$ becomes less negative, approaches zero as t→∞. C_A→0 as t→∞. The curve is therefore <u>concave up.</u>

The plot of C_B vs. t begins at (t=0, C_B=0). When t=0, the slope (=dC_B/dt) is $0.2(1-0)=0.2$. As t increases, C_B increases, C_A decreases (C_B^2 < C_A)⇒ $dC_B/dt=0.2(C_A-C_B^2)$ becomes less positive until dC_B/dt changes to negative (C_B^2 > C_A). Then C_B decreases with increasing t as well as C_A. Finally dC_B/dt approaches zero as t→∞. Therefore, C_B increases first until it reaches a maximum value, then it decreases. C_B→0 as t→∞.

The plot of C_C vs. t begins at (t=0, C_C=0). When t=0, the slope (=dC_C/dt) is $0.2(0)=0$. As t increases, C_B increases ⇒ $dC_c/dt=0.2\,C_B^2$ becomes positive also increases with increasing t ⇒ C_C increases faster until C_B decreases with increasing t ⇒ $dC_c/dt=0.2\,C_B^2$ becomes less positive, approaches zero as t→∞ so C_C increases more slowly. Finally C_C→2 as t→∞. The curve is therefore S-<u>shaped.</u>

d.



11.30 a. When $x = 1$, $\underline{\underline{y = 1}}$.

$$y=\frac{ax}{x+b}\overset{x=1,y=1}{\Rightarrow}1=\frac{a}{1+b}\Rightarrow\underline{\underline{a=1+b}}$$

b. <u>Raoult's Law:</u> $p_{C_5H_{12}}=yP=xp^*_{C_5H_{12}}(46^{\text{o}}\text{C})\Rightarrow y=\frac{xp^*_{C_5H_{12}}(46^{\text{o}}\text{C})}{P}$

<u>Antoine Equation:</u> $p^*_{C_5H_{12}}(46^{\text{o}}\text{C})=10^{\left(6.84471-\frac{1060.793}{46+231.541}\right)}=1053\text{ mm Hg}$

$$\Rightarrow y=\frac{xp^*_{C_5H_{12}}(46^{\text{o}}\text{C})}{P}=\frac{0.7\times1053}{760}=\underline{\underline{0.970}}$$

$$\begin{cases}y=\dfrac{ax}{x+b}\xrightarrow{\text{x=0.70, y=0.970}}0.970=\dfrac{0.70a}{0.70+b}\cdots\cdots(1)\\ \text{From part (a), a}=1+\text{b}\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(2)\end{cases}\Rightarrow\begin{cases}\underline{\underline{a=1.078}}\\ \underline{\underline{b=0.078}}\end{cases}$$

c. <u>Mole Balance on Residual Liquid:</u>

Accumulation=-Output

$$\Downarrow$$

$$\frac{dN_L}{dt}=-\dot{n}_V$$

$$\underline{\underline{t=0,\ N_L=100\text{ mol}}}$$

<u>Balance on Pentane:</u>

Accumulation=-Output

$$\Downarrow$$

$$\frac{d(N_Lx)}{dt}=-\dot{n}_Vy\Rightarrow x\frac{dN_L}{dt}+N_L\frac{dx}{dt}=-\dot{n}_V\frac{ax}{x+b}$$

$$\Downarrow dN_L/dt=-\dot{n}_V$$

$$\frac{\text{dx}}{\text{dt}}=-\frac{\dot{n}_V}{N_L}\left(\frac{ax}{x+b}-x\right)$$

$$\underline{\underline{t=0,\ \text{x}=0.70}}$$

d. <u>Energy Balance:</u> Consumption=Input

$$\Downarrow$$

$$\dot{n}_V\Delta\widehat{H}_{vap}=\dot{Q}\xrightarrow{\Delta\widehat{H}_{vap}=27.0\text{ kJ/mol}}\dot{n}_V=\frac{\dot{Q}}{(27.0\text{ kJ / mol})}$$

From part (c), $\frac{dN_L}{dt}=-\dot{n}_V\xrightarrow{t=0,\ N_L=100\text{ mol}}N_L=100-\dot{n}_Vt=100-\frac{\dot{Q}t}{27.0}$

$$\frac{\dot{n}_V}{N_L}=\frac{\dot{Q}/27.0}{100-\dfrac{\dot{Q}t}{27.0}}$$

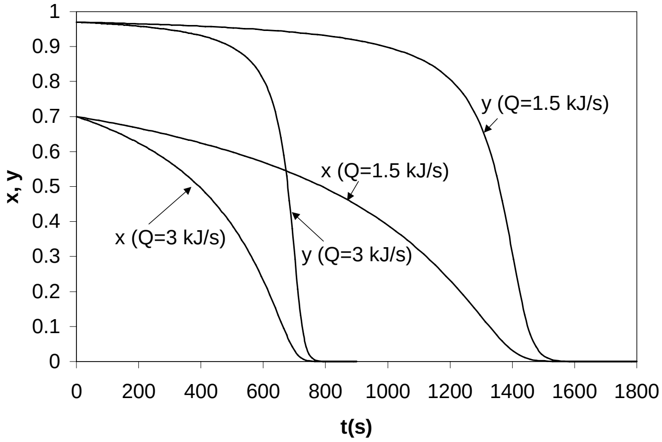
Substitute this expression into the equation for dx/dt from part (c):

11.30 (cont'd)

$$\frac{dx}{dt} = -\frac{\dot{n}_V}{N_L}\left(\frac{ax}{x+b} - x\right) = -\frac{\dot{Q}/27.0}{100 - \dfrac{\dot{Q}t}{27.0}}\left(\frac{ax}{x+b} - x\right)$$

x(0) = 0.70

e.



f. The mole fractions of pentane in the vapor product and residual liquid continuously decrease over a run. The initial and final mole fraction of pentane in the vapor are 0.970 and 0, respectively. The higher the heating rate, the faster *x* and *y* decrease.