Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids—Concentric, Square-edged Orifice Meters

Part 3: Natural Gas Applications

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Introduction

API *MPMS* Chapter 14.3.3/AGA Report No. 3, Part 3 is organized as follows: Symbols and units are first defined, the basic flow equation is presented, then key equation components are defined, and finally the gas properties applicable to orifice metering of natural gas are developed. Factors to compensate for meter calibration and location are included in Annex A. The factor approach to orifice measurement is included in Annex B. Annex F covers derivation of constants. The user is cautioned that the symbols may be different from those used in previous orifice metering standards.

Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids—Concentric, Square-edged Orifice Meters Part 3: Natural Gas Applications

1 Scope

1.1 General

This part of API *MPMS* Ch. 14.3/AGA Report No. 3 has been developed as an application guide for the calculation of natural gas flow through a flange-tapped, concentric orifice meter, using the U.S. customary (USC) inch-pound system of units.

For applications involving international system (SI) of units, a conversion factor can be applied to the results (Q_m, Q_v, or Q_b) determined from the equations in 4.3. Intermediate conversion of units will not necessarily produce consistent results. As an alternative, the more universal approach specified in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 can be used. The meter has to be constructed and installed in accordance with API *MPMS* Ch. 14.3.2/AGA Report No. 3, Part 2.

1.2 Definition of Natural Gas

As used in this document, the term natural gas applies to fluids that for all practical purposes are considered to include both pipeline and production quality gas with single-phase flow and mole percentage ranges of components as given in Table 1 of API *MPMS* Ch. 14.2/AGA Report No. 8. For other hydrocarbon mixtures, the more universal approach specified in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 may be more applicable. Diluents or mixtures other than those stipulated in API *MPMS* Ch. 14.2/AGA Report No. 8 may increase the flow measurement uncertainty.

1.3 Basis for Equations

The computation methods used in this document are consistent with those developed in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 and include the Reader-Harris/Gallagher (RG) equation for flange-tapped orifice meter discharge coefficient. The equation has been modified to reflect the more common units of the USC inch-pound system.

1.4 Expansion Factor Application

For all existing installations, the decision as to which expansion factor equation to use is at the discretion of the parties involved. However, the parties should be cognizant of the following:

1) If the calculated difference between previous revision (1990) Buckingham and Bean expansion factor equation (refer to Annex G) and the new revised expansion factor equation (refer to 5.6) is less than or equal to 0.25 %, then the expansion factor values produced by either expansion factor equation will be within the uncertainty of the new expansion factor database and the existence of any flow bias is uncertain.

2) However, if the calculated difference between expansion factor equations exceeds 0.25 %, then a variable flow bias, which is a function of diameter ratio (β), isentropic exponent (κ), and $\Delta P / P_{f_1}$ ratio (x_1), will be experienced unless the new expansion factor equation is utilized.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API *MPMS* Ch. 14.2/AGA Report No. 8, *Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases*

API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1, *Concentric, Square-edged Orifice Meters*, Part 1—*General Equations and Uncertainty Guidelines*

GPA 2145-09 [1], *Table of Physical Properties for Hydrocarbons and Other Compounds of Interest to the Natural Gas Industry*

3 Symbols, Units, and Terminology

3.1 General

The symbols and units used are specific to API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3 and were developed based on the USC inch-pound system of units. Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 should be used for consistent results.

3.2 Symbols and Units

C_d	orifice plate coefficient of discharge
$C_d\ (FT)$	coefficient of discharge at a specified pipe Reynolds number for flange-tapped orifice meter
$C_i(CT)$	coefficient of discharge at infinite pipe Reynolds number for corner-tapped orifice meter
$C_i(FT)$	coefficient of discharge at infinite pipe Reynolds number for flange-tapped orifice meter
c_p	specific heat at constant pressure [Btu/(lbm-°F)]
c_v	specific heat at constant volume [Btu/(lbm-°F)]
D	meter tube internal diameter calculated at flowing temperature, T_f (in.)
D_r	meter tube internal diameter at reference temperature, T_r (in.)
d	orifice plate bore diameter calculated at flowing temperature, T_f (in.)
d_r	orifice plate bore diameter at reference temperature, T_r (in.)
E_v	velocity of approach factor
e	Napierian constant rounded to six significant figures (2.71828)
F_{pv}	supercompressibility factor
G	gas relative density (specific gravity)
G_i	ideal gas relative density
G_r	real gas relative density
h_w	orifice differential pressure (also see ΔP) (inches of water column at 60 °F)
Mr_{air}	molar mass (molecular weight) of air (28.9625 lbm/lb-mol)
Mr_{gas}	molar mass (molecular weight) of gas (lbm/lb-mol)
Mr_i	molar mass (molecular weight) of component (lbm/lb-mol)
m	mass (lbm)
N_4	unit conversion factor (discharge coefficient)
n	number of moles
P	pressure (psia)
P_b	base pressure (psia)

[1] Gas Processors Association, 6526 E. 60th Street, Tulsa, Oklahoma 74145, www.gasprocessors.com.

$P_{b_{air}}$	base pressure of air (psia)
$P_{b_{gas}}$	base pressure of gas (psia)
P_f	static pressure of fluid at the pressure tap (psia)
P_{f_1}	absolute static pressure at the orifice upstream differential pressure tap (psia)
P_{f_2}	absolute static pressure at the orifice downstream differential pressure tap (psia)
P_s	reference base pressure (14.73 psia)
Q_b	volume flow rate at base conditions (ft^3/hr)
Q_m	mass flow rate per hour (lbm/hr)
Q_v	volume flow rate per hour at reference base conditions (ft^3/hr)
q_m	mass flow rate per second (lbm/s)
R	universal gas constant [1,545.35 (lbf-ft)/(lb-mol-°R)]
Re_D	pipe Reynolds number
T	temperature (°R)
T_b	base temperature (°R)
$T_{b_{air}}$	base temperature of air (°R)
$T_{b_{gas}}$	base temperature of gas (°R)
T_f	temperature of fluid at flowing conditions (°R)
T_r	reference temperature of the orifice plate bore diameter and/or meter tube inside diameter (68 °F)
T_s	reference base temperature, set to U.S. standard temperature (519.67 °R)
U_{f_1}	flowing velocity at upstream tap (ft/s)
V	volume (ft^3)
V_b	volume at base conditions (ft^3)
V_{f_1}	flowing volume at upstream tap (ft^3)
w	number of the last component
x	ratio of differential pressure to absolute static pressure
x_1	ratio of differential pressure to absolute static pressure at the upstream pressure tap
x_2	ratio of differential pressure to absolute static pressure at the downstream pressure tap
x/κ	acoustic ratio
Y	expansion factor
Y_1	expansion factor based on upstream absolute static pressure
Y_2	expansion factor based on downstream absolute static pressure
Z	compressibility
Z_b	compressibility at base conditions
$Z_{b_{gas}}$	compressibility of the gas at base conditions (P_b, T_b)
Z_f	compressibility at flowing conditions (P_f, T_f)
Z_{f_1}	compressibility at upstream flowing conditions
Z_{f_2}	compressibility at downstream flowing conditions
Z_s	compressibility at reference base conditions (P_s, T_s)
$Z_{s_{air}}$	compressibility of air at 14.73 psia and 60 °F (0.999590)

°F	temperature, in degrees Fahrenheit
°R	temperature, in degrees Rankine (459.67 + °F)
α	linear coefficient of thermal expansion [in./(in.-°F)]
α_1	linear coefficient of thermal expansion of the orifice plate material [in./(in.-°F)]
α_2	linear coefficient of thermal expansion of the meter tube material [in./(in.-°F)]
β	ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f
ΔP	orifice differential pressure (see also h_w) (psi)
κ	isentropic exponent (see 5.6)
κ_i	ideal gas isentropic exponent
κ_p	perfect gas isentropic exponent
κ_r	real gas isentropic exponent
μ	absolute viscosity of flowing fluid [lbm/(ft-s)]
π	universal constant rounded to six significant figures (3.14159)
ρ_b	density of a fluid at base conditions (P_b, T_b) (lbm/ft^3)
$\rho_{b_{\text{air}}}$	density of air at base conditions (P_b, T_b) (lbm/ft^3)
$\rho_{b_{\text{gas}}}$	density of a gas at base conditions (P_b, T_b) (lbm/ft^3)
ρ_s	density of a fluid at reference base conditions (P_s, T_s) (lbm/ft^3)
$\rho_{t,p}$	density of a fluid at flowing conditions (P_f, T_f) (lbm/ft^3)
ρ_{t,p_1}	density of a fluid at flowing conditions at upstream tap position (P_{f_1}, T_f) (lbm/ft^3)
ρ_{t,p_2}	density of a fluid at flowing conditions at downstream tap position (P_{f_2}, T_f) (lbm/ft^3)
ϕ_i	mole fraction of component (mol%/100)

NOTE Factors, ratios, and coefficients are dimensionless.

3.3 Terminology

3.3.1 Pressure

One pound-force (lbf) per square inch (in.^{2}) pressure is defined as the force a one pound-mass (lbm) exerts when evenly distributed on an area of 1 in.^{2} and when acted on by the standard acceleration of free fall, 32.1740 ft/s^2.

3.3.2 Subscripts

The subscript 1 on the expansion factor (Y_1), the flowing density (ρ_{t,p_1}), the fluid flowing static pressure (P_{f_1}), and the fluid flowing compressibility (Z_{f_1}) indicates that these variables are to be measured, calculated, or otherwise determined relative to the fluid flowing at the conditions of the upstream differential tap. Variables related to the downstream differential pressure tap are identified by the subscript 2, including Y_2, ρ_{t,p_2}, P_{f_2}, and Z_{f_2}, and can be used in the equations with equal precision of the calculated flow rates (except for Y_2, which has a separate equation).

The subscript 1 is arbitrarily used in the equations in this part to emphasize the necessity of maintaining the relationship of these four variables to the chosen static pressure reference tap.

3.3.3 Temperature

The temperature of the flowing fluid (T_f) does not have a numerical subscript. This temperature is usually measured downstream of the orifice plate for minimum flow disturbance but may be measured upstream within the locations prescribed in API *MPMS* Ch. 14.3.2/AGA Report No. 3, Part 2. It is assumed that there is no difference between fluid temperatures at the two differential pressure tap locations and the measurement point, so the subscript is unnecessary.

3.3.4 Reference Base (Standard) Conditions

In this document, reference base conditions are defined as the absolute static pressure, P_s, of 14.73 psia and the absolute temperature, T_s, of 519.67 °R (60 °F). For interstate commerce, the reference base conditions for the flow measurement of natural gases are defined in the United States as a pressure of 14.73 psia (P_s) at a temperature of 60 °F or 519.67 °R (T_s). Although technically incorrect, these reference base conditions are often referred to as standard conditions and designated in symbology by the subscript "s."

Base conditions, i.e. base pressure (P_b) andd base temperature (T_b), are defined by contract or government regulation and may be different from reference base conditions.

3.3.5 Definitions

General definitions are covered in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 and API *MPMS* Ch. 14.3.2/AGA Report No. 3, Part 2. Definitions specific to API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3 are incorporated in the text.

4 Flow Measurement Equations

4.1 General

The following equations express flow in terms of mass and volume per unit time and produce equivalent results. Since this section deals exclusively with the USC inch-pound system of units, the numeric constants defined in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 have been converted to reflect these units.

The numeric constants for the basic flow equations, unit conversion values, density of water, and density of air are given in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 and in Section 6 and Annex F of this document. The tables in this part that list solutions to these equations incorporate these constants and values. Key equation components are developed in Section 5. Other physical properties are given in Section 6.

4.2 Equations for Mass Flow of Natural Gas

The equations for the mass flow of natural gas, in lbm/hr, can be developed from the density of the flowing fluid (see F.3), the ideal gas relative density, or the real gas relative density, using the following equations.

The mass flow developed from the density of the flowing fluid (ρ_{t,p_1}) is expressed as follows:

$$Q_m = 359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w} \tag{1}$$

Mass flow developed from the ideal gas relative density, G_i, is expressed as follows:

$$Q_m = 589.885 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}} \tag{2}$$

The mass flow equation developed from the real gas relative density, G_r, assumes a pressure of 14.73 psia and a temperature of 519.67 °R (60 °F) as the reference base conditions for the determination of real gas relative density. This assumption allows the base compressibility of air at 14.73 psia and 519.67 °R (60 °F) to be incorporated into the numeric constant of the flow rate equation. If the assumption about the reference base conditions is not valid, the results obtained from this flow rate equation will have an added increment of uncertainty. The mass flow equation developed from real gas relative density, G_r, is expressed as follows:

$$Q_m = 590.006 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{Z_s G_r P_{f_1} h_w}{Z_{f_1} T_f}} \tag{3}$$

where

- $C_d(FT)$ is the coefficient of discharge for flange-tapped orifice meter;
- d is the orifice plate bore diameter, in inches, calculated at flowing temperature (T_f);
- E_v is the velocity of approach factor;
- G_i is the ideal gas relative density;
- G_r is the real gas relative density;
- h_w is the orifice differential pressure, in inches of water at 60 °F;
- P_{f_1} is the flowing pressure at upstream tap, in psia;
- Q_m is the mass flow rate, in lbm/hr;
- T_f is the flowing temperature, in °R;
- Y_1 is the expansion factor (upstream tap);
- Z_s is the compressibility at reference base conditions (P_s, T_s);
- Z_{f_1} is the compressibility at upstream flowing conditions (P_{f_1}, T_f);
- ρ_{t,p_1} is the density of the fluid at upstream flowing conditions (P_{f_1}, T_f), in lbm/ft^3.

4.3 Equations for Volume Flow of Natural Gas

The volume flow rate of natural gas, in ft^3/hr at base conditions, can be developed from the densities of the fluid at flowing and base conditions and the ideal gas relative density or real gas relative density using the following equations.

The volume flow rate at base conditions, Q_b, developed from the density of the fluid at flowing conditions (ρ_{t,p_1}) and base conditions (ρ_b) is expressed as follows:

$$Q_b = \frac{359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b} \tag{4}$$

The volume flow rate at base conditions, developed from ideal gas relative density, G_i, is expressed as follows:

$$Q_b = 218.573 C_d(FT) E_v Y_1 d^2 \frac{T_b Z_b}{P_b} \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \tag{5}$$

To correctly apply the real gas relative density to the flow calculation, the reference base conditions for the determination of real gas relative density and the base conditions for the flow calculation have to be the same. Therefore, the volume flow rate at base conditions, developed from real gas relative density, G_r, is expressed as follows:

$$Q_b = 218.573 C_d(FT) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{P_{f_1} Z_b Z_{b_{\text{air}}} h_w}{G_r Z_{f_1} T_f}} \tag{6}$$

If reference base conditions are substituted for base conditions in Equation (4), Equation (5), and Equation (6), then

$P_b = P_s = 14.73$ psia,

$T_b = T_s = 519.67$ °R (60 °F), and

$Z_{b_{\text{air}}} = Z_{s_{\text{air}}} = 0.999590$.

The volume flow rate at reference base conditions, Q_v, can then be determined using the following equations.

The volume flow rate at reference base conditions, developed from the density of the fluid at flowing conditions (ρ_{t,p_1}) and reference base conditions (ρ_s), is expressed as follows:

$$Q_v = \frac{359.072 C_d(FT) E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_s} \tag{7}$$

The volume flow rate at reference base conditions, developed from ideal gas relative density, G_i, is expressed as follows:

$$Q_v = 7711.19 C_d(FT) E_v Y_1 d^2 Z_s \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}} \tag{8}$$

The volume flow rate equation at reference base conditions, Q_v, developed from the real gas relative density, requires the reference base conditions for G_r and incorporates $Z_{b_{\text{air}}}$ at reference base conditions of 14.73 psia and 519.67 °R (60 °F) in its numeric constant. Therefore, the volume flow rate at reference base conditions, developed from real gas relative density, G_r, is expressed as follows:

$$Q_v = 7709.61 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \tag{9}$$

where

$C_d(FT)$ is the coefficient of discharge for flange-tapped orifice meter;

d is the orifice plate bore diameter calculated at flowing temperature (T_f), in inches;

E_v is the velocity of approach factor;

G_i is the ideal gas relative density;

G_r is the real gas relative density;

h_w is the orifice differential pressure, in inches of water at 60 °F;

P_b is the base pressure, in psia;

P_{f_1} is the flowing pressure (upstream tap), in psia;

P_s is the reference base pressure = 14.73 psia;

Q_b is the volume flow rate per hour at base conditions, in ft^3/hr;

Q_v is the volume flow rate per hour at reference base conditions, in ft^3/hr;

T_b is the base temperature, in °R;

T_f is the flowing temperature, in °R;

T_s is the reference base temperature = 519.67 °R (60 °F);

Y_1 is the expansion factor (upstream tap);

Z_b is the compressibility at base conditions (P_b, T_b);

$Z_{b_{air}}$ is the compressibility of air at base conditions (P_b, T_b);

Z_{f_1} is the compressibility at upstream flowing conditions (P_{f_1}, T_f);

Z_s is the compressibility at reference base conditions (P_s, T_s);

$Z_{s_{air}}$ is the compressibility of air at reference base conditions (P_s, T_s);

ρ_b is the density of the flowing fluid at base conditions (P_b, T_b), in lbm/ft^3;

ρ_s is the density of the flowing fluid at reference base conditions (P_s, T_s), in lbm/ft^3;

ρ_{t,p_1} is the density of the fluid at upstream flowing conditions (P_{f_1}, T_f), in lbm/ft^3.

4.4 Volume Conversion from Reference Base to Base Conditions

For the purposes of this document, reference base and base conditions are assumed to be the same. However, if base conditions are different from reference base conditions, the volume flow rate calculated at reference base conditions can be converted to the volume flow rate at base conditions through the following relationship:

$$Q_b = Q_v \left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right) \tag{10}$$

where

P_b is the base pressure, in psia;

P_s is the reference base pressure, in psia;

Q_b is the base volume flow rate, in ft^3/hr;

Q_v is the reference base volume flow rate, in ft^3/hr;

T_b is the base temperature, in °R;

T_s is the reference base temperature, in °R;

Z_b is the compressibility at base conditions (P_b, T_b);

Z_s is the compressibility at reference base conditions (P_s, T_s).

5 Flow Equation Components Requiring Additional Computation

5.1 General

Some of the terms in Equation (1) through Equation (9) require additional computation and are developed in this section.

5.2 Diameter Ratio (β)

The diameter ratio (β), also known as beta ratio, which is used in determining the orifice plate coefficient of discharge (C_d), the velocity of approach factor (E_v), and the expansion factor (Y), is the ratio of the orifice bore diameter (d) to the internal diameter of the meter tube (D). For the most precise results, the actual dimensions should be used, as determined in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 and/or API *MPMS* Ch. 14.3.2/AGA Report No. 3, Part 2.

$$\beta = d/D \tag{11}$$

where

$$d = d_r\,[1 + \alpha_1 (T_f - T_r)] \tag{12}$$

and

$$D = D_r[1 + \alpha_2(T_f - T_r)] \tag{13}$$

where

- D is the meter tube internal diameter calculated at flowing temperature, T_f;
- D_r is the reference meter tube internal diameter calculated at reference temperature, T_r;
- d is the orifice plate bore diameter calculated at flowing temperature, T_f;
- d_r is the reference orifice plate bore diameter calculated at reference temperature, T_r;
- T_f is the temperature of the fluid at flowing conditions;
- T_r is the reference temperature for the orifice plate bore diameter and/or the meter tube internal diameter;
- α_1 is the linear coefficient of thermal expansion of the orifice plate material (see Table 1);
- α_2 is the linear coefficient of thermal expansion of the meter tube material (see Table 1);
- β is the diameter ratio.

NOTE α, T_f, and T_r have to be in consistent units. For the purpose of this standard, T_r is assumed to be 68 °F.

The orifice plate bore diameter, d_r, and the meter tube internal diameter, D_r, calculated at T_r are the diameters determined in accordance with API *MPMS* Ch. 14.3.2/AGA Report No. 3, Part 2.

5.3 Coefficient of Discharge for Flange-tapped Orifice Meter [$C_d\,(FT)$]

The coefficient of discharge for a flange-tapped orifice meter (C_d) has been determined from test data. It has been correlated as a function of diameter ratio (β), tube diameter, and pipe Reynolds number. In this document, the equation for the flange-tapped orifice meter coefficient of discharge developed in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 has been adapted to the USC inch-pound system of units.

Table 1—Linear Coefficient of Thermal Expansion

Material	Linear Coefficient of Thermal Expansion (*α*)	
	USC (in./in.-°F)	**SI (mm/mm-°C)**
Type 304 stainless steel [a]	0.00000961	0.0000173
Type 316 stainless steel [a]	0.00000889	0.0000160
Type 304/316 stainless steel [c]	0.00000925	0.0000167
Monel 400 [a]	0.00000772	0.0000139
Carbon steel [b]	0.00000620	0.0000112

NOTE For flowing temperature limits or other materials, refer to ASM International's *Metals Handbook, Engineering Properties of Steel* and *Handbook of Stainless Steels.*

[a] For flowing conditions between +32 °F and +212 °F for stainless steels and +68 °F and +212 °F for Monel.

[b] For flowing conditions between –7 °F and +154 °F, refer to API *MPMS* Ch. 12.2.1.

[c] Type 304/316 stainless steel linear coefficient of thermal expansion is the average of the Type 304 and Type 316 stainless steel coefficients and is recommended when the orifice plate is stainless steel but the grade is unknown.

NOTE Over a temperature range from 32 °F to 130 °F the maximum difference in calculated flow between use of the 304/316 average coefficient and either the 304 or 316 coefficient is less than 0.005 % (50 ppm).

The equation for the concentric, square-edged flange-tapped orifice meter coefficient of discharge, $C_d(FT)$, developed by RG, is structured into distinct linkage terms. The equation is applicable to nominal pipe sizes of 2 in. and larger; diameter ratios (β) of 0.1 to 0.75, provided the orifice plate bore diameter, d_r, is greater than 0.45 in.; and pipe Reynolds numbers (Re_D) greater than or equal to 4,000. For orifice diameters, diameter ratios, and pipe Reynolds numbers outside the stated limits, the uncertainty statement increases. For guidance, refer to API *MPMS* Ch. 14.3.1/ AGA Report No. 3, Part 1, Section 12.4.1 (September 2012).

The RG equation is defined as follows:

$$C_d(FT) = C_i(FT) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049\,A)\beta^4 C \tag{14}$$

$$C_i(FT) = C_i(CT) + \text{tap term} \tag{15}$$

$$C_i(CT) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1 \tag{16}$$

$$\text{tap term} = \text{upstrm} + \text{dnstrm} \tag{17}$$

$$\text{upstrm} = (0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1})(1 - 0.23A)B \tag{18}$$

$$\text{dnstrm} = -0.0116(M_2 - 0.52\,M_2^{1.3})\beta^{1.1}(1 - 0.14A) \tag{19}$$

also

$$B = \frac{\beta^4}{1-\beta^4} \tag{20}$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4},\, 0.0\right) \tag{21}$$

$$M_2 = \frac{2L_2}{1-\beta} \tag{22}$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \tag{23}$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \tag{24}$$

where

$C_d(FT)$ is the coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter;

$C_i(CT)$ is the coefficient of discharge at an infinite pipe Reynolds number for a corner-tapped orifice meter;

$C_i(FT)$ is the coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter;

D is the meter tube internal diameter calculated at T_f, in inches;

d is the orifice plate bore diameter calculated at T_f, in inches;

e is the Napierian constant = 2.71828;

L_1 = L_2 = dimensionless correction for tap location = N_4/D for flange taps;

N_4 = 1.0 when D is in inches;

Re_D is the pipe Reynolds number;

β is the diameter ratio = d/D.

5.4 Velocity of Approach Factor (E_v)

The velocity of approach factor (E_v) is a mathematical expression that relates the velocity of the flowing fluid in the orifice meter approach section (upstream meter tube) to the fluid velocity in the orifice plate bore.

The velocity of approach factor, E_v, is calculated as follows:

$$E_v = \frac{1}{\sqrt{1-\beta^4}} \tag{25}$$

where

E_v is the velocity of approach factor;

β is the diameter ratio = d/D.

5.5 Reynolds Number (Re_D)

The pipe Reynolds number (Re_D) is used as a correlation parameter to represent the change in the orifice plate coefficient of discharge with reference to the meter tube diameter, the fluid flow rate, the fluid density, and the fluid viscosity. The Reynolds number is a dimensionless ratio when consistent units are used and is expressed as follows:

$$Re_D = \frac{U_{f_1} D \rho_{t,p_1}}{12\mu} \tag{26}$$

or

$$Re_D = \frac{48 q_m}{\pi \mu D} \tag{27}$$

NOTE The constant, 12, in the denominator of Equation (26) is required by the use of D in inches.

The fluid velocity, in ft/s, can be obtained in terms of the hourly volumetric flow rate at base conditions from the following relationship:

$$U_{f_1} = \left(\frac{Q_b \rho_b}{D^2 \rho_{t,p_1}}\right)\left[\frac{(4)(144)}{3600\pi}\right] = 0.0509296\left(\frac{Q_b \rho_b}{D^2 \rho_{t,p_1}}\right) \tag{28}$$

Substituting Equation (28) into Equation (26) results in the following relationship:

$$Re_D = \left(\frac{0.0509296}{12}\right)\left(\frac{Q_b \rho_b}{\mu D}\right)\left(\frac{D \rho_{t,p_1}}{D \rho_{t,p_1}}\right) = 0.00424413\left(\frac{Q_b \rho_b}{\mu D}\right) \tag{29}$$

The Reynolds number for natural gas can be approximated by substituting the following relationship for ρ_b (see 6.5.3 for equation development) into Equation (29):

$$\rho_b = \frac{2.69881 P_b}{T_b Z_{b_{\text{gas}}}}\left(G_r \frac{Z_{b_{\text{gas}}}}{Z_{b_{\text{air}}}}\right) \tag{30}$$

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{\text{air}}}}\right) \tag{31}$$

By using an average value of 0.0000069 lbm/ft-s for μ and substituting the reference base conditions of 519.67 °R, 14.73 psi, and 0.999590 for T_b, P_b, and $Z_{b_{\text{air}}}$ Equation (31) reduces to the following:

$$Re_D = 47.0723\left(\frac{Q_v G_r}{D}\right) \tag{32}$$

where

- D is the meter tube internal diameter calculated at the flowing temperature (T_f), in inches;
- G_r is the real gas relative density;
- P_b is the base pressure;
- Q_b is the volume flow rate at base conditions, in ft^3/hr;
- Q_v is the volume flow rate at reference base conditions, in ft^3/hr;
- q_m is the mass flow rate, in lbm/s;

Re_D is the pipe Reynolds number;

T_b is the base temperature, in °R;

U_{f_1} is the velocity of the flowing fluid at the upstream tap location, in ft/s;

$Z_{b_{air}}$ is the compressibility of air at 14.73 psia and 60 °F;

$Z_{b_{gas}}$ is the compressibility of the gas at base conditions (P_b, T_b);

μ is the absolute (dynamic) viscosity, in lbm/ft-s;

π = 3.14159;

ρ_b is the density of the flowing fluid at base conditions (P_b, T_b), in lbm/ft^3;

ρ_{t,p_1} is the density of the fluid at upstream flowing conditions (P_{f_1}, T_f), in lbm/ft^3.

Viscosity is a variable that is a function of temperature, relative density, and pressure. An average viscosity of 0.0000069 lbm/ft-s is typically used in natural gas measurement. Temperature in the range of 30 °F to 90 °F and relative density in the range of 0.55 to 0.75 should result in viscosity values in the range of 0.0000059 to 0.0000079 lbm/ft-s. Viscosity has an influence on the calculated discharge coefficient. If the measured fluid has a viscosity, temperature, or real gas relative density different from those shown above, the use of the average viscosity of 0.0000069 lbm/ft-s may not be applicable.

When the flow rate is not known, the Reynolds number can be developed through iteration, assuming an initial value of 0.60 for the coefficient of discharge for a flange-tapped orifice meter, $C_d\,(FT)$, and using the volume computed to estimate the Reynolds number.

5.6 Expansion Factor (Y)

5.6.1 General

When a gas flows through an orifice, the change in fluid velocity and static pressure is accompanied by a change in the density, and a factor has to be applied to the coefficient to adjust for this change. The expansion factor (Y) is a function of diameter ratio (β), the ratio of differential pressure to static pressure at the designated tap, and the isentropic exponent (κ).

The real compressible fluid isentropic exponent, κ_r, is a function of the fluid and the pressure and temperature. For an ideal gas, the isentropic exponent, κ_i, is equal to the ratio of the specific heats (c_p/c_v) of the gas at constant pressure (c_p) and constant volume (c_v) and is independent of pressure. A perfect gas is an ideal gas that has constant specific heats. The perfect gas isentropic exponent, κ_p, is equal to κ_i evaluated at base conditions.

It has been found that for many applications, the value of κ_r is nearly identical to the value of κ_i, which is nearly identical to κ_p. From a practical standpoint, the flow equation is not sensitive to small variations in the isentropic exponent. Therefore, the perfect gas isentropic exponent, κ_p, is often used in the flow equation. Accepted practice for natural gas applications is to use $\kappa_p = \kappa = 1.3$. Under certain conditions, such as variation in composition or significant changes in pressure or temperature, the user may choose to calculate an explicit fixed value or a live value for the isentropic exponent.

The application of the expansion factor is valid as long as the following dimensionless criterion for pressure ratio is followed:

$$0 < \frac{\Delta P}{N_3 P_{f_1}} < 0.25 \tag{33}$$

or

$$0.75 < \frac{P_{f_2}}{P_{f_1}} < 1.0 \tag{34}$$

where

N_3 is the unit conversion factor (refer to API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—2012, Table 4);

P_f is the absolute static pressure at the pressure tap;

P_{f_1} is the absolute static pressure at the upstream pressure tap;

P_{f_2} is the absolute static pressure at the downstream pressure tap;

ΔP is the orifice differential pressure.

The expansion factor equation for flange taps may be used for a range of diameter ratios from 0.10 to 0.75. For diameter ratios (β) outside the stated limits, increased uncertainty will occur.

5.6.2 Expansion Factor Referenced to Upstream Static Pressure (Y_1)

If the absolute static pressure is taken at the upstream differential pressure tap, the value of the expansion factor, Y_1, can be calculated using the following equation:

$$Y_1 = 1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - \left[\frac{P_{f_2}}{P_{f_1}}\right]^{\frac{1}{\kappa}}\right\} \tag{35}$$

or

$$Y_1 = 1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - [1 - x_1]^{\frac{1}{\kappa}}\right\} \tag{36}$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \tag{37}$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \tag{38}$$

where

N_3 is the unit conversion factor (refer to API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—2012, Table 4);

P_{f_1} is the absolute static pressure at the upstream tap, in psia;

P_{f_2} is the absolute static pressure at the downstream tap, in psia;

x_1 is the ratio of differential pressure to absolute static pressure at the upstream tap;

Y_1 is the expansion factor based on the absolute static pressure measured at the upstream tap;

β is the diameter ratio = d/D;

ΔP is the orifice differential pressure;

κ is the isentropic exponent (see 5.6.1).

5.6.3 Expansion Factor Referenced to Downstream Static Pressure (Y_2)

If the absolute static pressure is taken at the downstream differential tap (P_{f_2}), it is recommended that the value of the upstream pressure (P_{f_1}) be calculated by adding the measured differential pressure (ΔP) to the measured downstream static pressure (P_{f_2}) with appropriate unit conversion.

If the user chooses to not to determine Y_1, then the downstream expansion factor Y_2 shall be determined. The downstream expansion factor requires determination of the downstream static pressure, the upstream static pressure, the downstream compressibility factor, the upstream compressibility factor, the diameter ratio, and the isentropic exponent. The value of the downstream expansion factor, Y_2, shall be calculated using the following equation:

$$Y_2 = Y_1\sqrt{\frac{P_{f_1}Z_{f_2}}{P_{f_2}Z_{f_1}}} \tag{39}$$

or

$$Y_2 = \left[1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - \left[\frac{P_{f_2}}{P_{f_1}}\right]^{\frac{1}{\kappa}}\right\}\right]\sqrt{\frac{P_{f_1}Z_{f_2}}{P_{f_2}Z_{f_1}}} \tag{40}$$

or

$$Y_2 = \left[1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - [1 - x_1]^{\frac{1}{\kappa}}\right\}\right]\sqrt{\frac{P_{f_1}Z_{f_2}}{P_{f_2}Z_{f_1}}} \tag{41}$$

where

P_{f_1} is the absolute static pressure at the upstream pressure tap;

P_{f_2} is the absolute static pressure at the downstream pressure tap;

x_1 is the ratio of differential pressure to absolute static pressure at the upstream tap;

Y_1 is the expansion factor based on the absolute static pressure measured at the upstream tap;

Y_2 is the expansion factor based on the absolute static pressure measured at the downstream tap;

Z_{f_1} is the fluid compressibility at the upstream pressure tap;

Z_{f_2} is the fluid compressibility at the downstream pressure tap;

κ is the isentropic exponent.

6 Gas Properties

6.1 General

The measurement of gaseous flow rate in volumetric units generally requires conversion for pressure, temperature, and the deviation of the measured volume from the ideal gas laws (compressibility). Energy measurement also requires determination of the gas heating value (energy content). The reference base conditions used in this document are 14.73 psia and 519.67 °R (60 °F, U.S. standard temperature).

As a mixture of compounds, natural gas complicates the calculation of some of these conversion factors. The factors that cannot be determined by simple calculations can be derived from gas composition and/or other measurements. In addition to this section, refer to Annex F and API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—2012. Certain factors can be measured in the field, using instruments calibrated against standard gas samples. Either approach will produce equivalent results when rigorous methods are applied.

The determination of energy is the product of volume and heating value per unit volume or the product of mass and the heating value per unit mass. For determination of heating value including or excluding water vapor, refer to API *MPMS* Ch. 14.5/GPA 2172 or AGA Report No. 5.

6.2 Physical Properties

The physical properties shall be taken from the latest edition of GPA 2145.

The compressibility of air at reference base conditions ($Z_{s_{\mathrm{air}}}$) is 0.999590.

6.3 Compressibility

6.3.1 Ideal and Real Gas

The terms ideal gas and real gas are used to define calculation or interpretation methods. An ideal gas is one that conforms to the thermodynamic laws of Boyle and Charles (ideal gas laws), such that the following is true:

$$144PV = nRT \tag{42}$$

If subscript 1 represents a gas volume measured at one set of temperature–pressure conditions and subscript 2 represents the same volume measured at a second set of temperature–pressure conditions, then

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \tag{43}$$

The numerical constant in Equation (42) is required to convert P, in psia, to units that are consistent with the value of R given in 3.2.

All gases deviate from the ideal gas laws to some extent. This deviation is known as compressibility and is denoted by the symbol Z. Additional discussion of compressibility and the method for determining the value of Z for natural gas are developed in detail in API *MPMS* Ch. 14.2/AGA Report No. 8. The method used in that report is included as a part of this standard.

The application of Z changes the ideal relationship in Equation (42) to the following real relationship:

$$144PV = nZRT \tag{44}$$

As modified by Z, Equation (43) allows the volume at the upstream flowing conditions to be converted to the volume at base conditions by use of the following equation:

$$V_b = V_{f_1}\left(\frac{P_{f_1}}{P_b}\right)\left(\frac{Z_b}{Z_{f_1}}\right)\left(\frac{T_b}{T_f}\right) \tag{45}$$

where

n is the number of pound-moles of a gas;

P is the absolute static pressure of a gas, in psia;

P_b is the absolute static pressure of a gas at base conditions, in psia;

P_{f_1} is the absolute static pressure of a gas at the upstream tap, in psia;

R is the universal gas constant = 1,545.35 (lbf-ft)/(lb-mol-°R);

T is the absolute temperature of a gas, in °R;

T_b is the absolute temperature of a gas at base conditions, in °R;

T_f is the absolute temperature of a flowing gas, in °R;

V is the volume of a gas, in ft^3;

V_b is the volume of a gas at base conditions (P_b, T_b), in ft^3;

V_{f_1} is the volume of a gas at flowing conditions (P_{f_1} , T_f), in ft^3;

Z is the compressibility of a gas at P and T;

Z_b is the compressibility of a gas at base conditions (P_b, T_b);

Z_{f_1} is the compressibility of a gas at flowing conditions (P_{f_1}, T_f).

6.3.2 Compressibility at Base Conditions

The value of Z at base conditions (Z_b) is required and shall be calculated from the procedures in API *MPMS* Ch. 14.2/AGA Report No. 8 for volume determination. API *MPMS* Ch. 14.5/GPA 2172 or AGA Report No. 5 provide methods to determine Z_b for use in heating value per real unit volume and real relative density at base conditions. The differences in Z_b resulting from these methods is within the experimental uncertainty of the property data that, as stated in API *MPMS* Ch. 14.5/GPA 2172, derive from experimental data that, in general, are accurate to no better than 1 part in 1000.

6.3.3 Supercompressibility

In orifice measurement, Z_b and Z_{f_1} appear as a ratio to the 0.5 power. This relationship is termed the supercompressibility factor and may be calculated from the following equation:

$$F_{pv} = \sqrt{\frac{Z_b}{Z_{f_1}}} \tag{46}$$

or

$$Z_{f_1} = \frac{Z_b}{F_{pv}^{\;2}} \tag{47}$$

where

F_{pv} is the supercompressibility factor;

Z_b is the compressibility of the gas at base conditions (P_b, T_b);

Z_{f_1} is the compressibility of the gas at flowing conditions (P_{f_1} , T_f).

6.4 Relative Density

6.4.1 General

Relative density, G, is a component in several of the flow equations. The relative density is defined as a dimensionless number that expresses the ratio of the density of the flowing fluid to the density of a reference gas at the same reference conditions of temperature and pressure. The gas industry has historically referred to the relative density as either ideal or real and has designated the reference gas as air and the reference base conditions as a pressure of 14.73 psia and a temperature of 519.67 °R (60 °F). The value for relative density may be determined by measurement or by calculation from the gas composition.

6.4.2 Ideal Gas Relative Density

The ideal gas relative density, G_i, is defined as the ratio of the ideal density of the gas to the ideal density of dry air at the same reference conditions of pressure and temperature. Since the ideal densities are defined at the same reference conditions of pressure and temperature, the ratio reduces to a ratio of molar masses (molecular weights).

Therefore, the ideal gas relative density is set forth in the following equation:

$$G_i = \frac{Mr_{\text{gas}}}{Mr_{\text{air}}} = \frac{Mr_{\text{gas}}}{28.9625} \tag{48}$$

where

G_i is the ideal gas relative density;

Mr_{air} is the molar mass (molecular weight) of air = 28.9625 lbm/lb-mol;

Mr_{gas} is the molar mass (molecular weight) of a gas, in lbm/lb-mol.

6.4.3 Real Gas Relative Density (Real Specific Gravity)

Real gas relative density, G_r, is defined as the ratio of the real density of the gas to the real density of dry air at the same reference conditions of pressure and temperature. To correctly apply the real gas relative density to the flow calculation, the reference conditions for the determination of the real gas relative density have to be the same as the base conditions for the flow calculation. At base conditions (P_b, T_b), real gas relative density is expressed as follows:

$$G_r = \frac{144\dfrac{P_{b_{\text{gas}}} Mr_{\text{gas}}}{Z_{b_{\text{gas}}} R T_{b_{\text{gas}}}}}{144\dfrac{P_{b_{\text{air}}} Mr_{\text{air}}}{Z_{b_{\text{air}}} R T_{b_{\text{air}}}}} \tag{49}$$

Since the pressures and temperatures are defined to be at the same designated base conditions,

$$P_{b_{\text{gas}}} = P_{b_{\text{air}}}$$

$$T_{b_{\text{gas}}} = T_{b_{\text{air}}}$$

The real gas relative density reduces to:

$$G_r = \left(\frac{Mr_{\text{gas}}}{Mr_{\text{air}}}\right)\left(\frac{Z_{b_{\text{air}}}}{Z_{b_{\text{gas}}}}\right) \tag{50}$$

Relative density is commonly calculated from composition. Refer to API *MPMS* Ch. 14.5/GPA 2172 or AGA Report No. 5 for calculation details.

The use of real gas relative density in the flow calculations has a historic basis but may add an increment of uncertainty to the calculation as a result of the limitations of gravitometer devices. When real gas relative densities are directly determined by relative density measurement equipment, the observed values have to be adjusted so that both air and gas measurements reflect the same pressure and temperature. The fact that the temperature and/or pressure are not always at base conditions results in small variations in determinations of relative density. Another source of variation is the use of atmospheric air. The composition of atmospheric air—and its molecular weight and density—varies with time and geographical location.

When recording gravitometers are used and calibration is performed with reference gases, either ideal or real gas relative density can be obtained as a recorded relative density by proper certification of the reference gas. The relationship between ideal gas relative density and real gas relative density is expressed as follows:

$$G_r = G_i \frac{Z_{b_{\text{air}}}}{Z_{b_{\text{gas}}}} \tag{51}$$

where

G_i is the ideal gas relative density;

G_r is the real gas relative density;

Mr_{air} is the molar mass (molecular weight) of air = 28.9625 lbm/lb-mol;

Mr_{gas} is the molar mass (molecular weight) of the flowing gas, in lbm/lb-mol;

$P_{b_{\text{air}}}$ is the base pressure of air, in psia;

$P_{b_{\text{gas}}}$ is the base pressure of a gas, in psia;

R is the universal gas constant = 1,545.35 (lbf-ft)/(lb-mol-°R);

$T_{b_{\text{air}}}$ is the base temperature of air, in °R;

$T_{b_{\text{gas}}}$ is the base temperature of a gas, in °R;

$Z_{b_{\text{air}}}$ is the compressibility of air at base conditions (P_b, T_b);

$Z_{b_{\text{gas}}}$ is the compressibility of a gas at base conditions (P_b, T_b).

6.5 Density of Fluid at Flowing Conditions

6.5.1 General

The flowing density ($\rho_{t,p}$) is a key component of certain flow equations. It is defined as the mass per unit volume at flowing pressure and temperature that exists at the selected static pressure tap location. The value for flowing density can be calculated from equations of state or from the relative density at the selected static pressure tap. The fluid density at flowing conditions can also be measured using commercial density meters. Most density meters, because of their physical installation requirements and design, cannot accurately measure the density at the selected pressure tap location. Therefore, the fluid density difference between the density measured and that existing at the defined pressure tap location has to be checked to determine whether changes in pressure or temperature have an impact on the flow measurement uncertainty.

6.5.2 Density Based on Gas Composition

When the composition of a gas mixture is known, the gas densities $\rho_{t,p}$ and ρ_b may be calculated from the gas law equations. The molecular weight of the gas may be determined from composition data, using mole fractions of the components and their respective molecular weights.

$$Mr_{\text{gas}} = \phi_1 Mr_1 + \phi_2 Mr_2 + \ldots + \phi_w Mr_w = \sum_{i=1}^{w} \phi_i\, Mr_i \tag{52}$$

The gas law equation, Equation (44), is rearranged to obtain density values:

$$144PV = nZRT$$

$$n = \frac{m}{Mr_{\text{gas}}} \tag{53}$$

therefore

$$144PV = \left(\frac{m}{Mr_{\text{gas}}}\right) ZRT \tag{54}$$

and

$$\rho_{t,p_1} = \frac{m}{V_{f_1}} = \frac{144P_{f_1} Mr_{\text{gas}}}{Z_{f_1} RT_f} \tag{55}$$

or

$$\rho_b = \frac{m}{V_b} = \frac{144P_b Mr_{\text{gas}}}{Z_b RT_b} \tag{56}$$

where

Mr_{gas} is the molar mass (molecular weight) of the flowing gas, in lbm/lb-mol;

Mr_i is the molar mass (molecular weight) of a component, in lbm/lb-mol;

m is the mass of a fluid, in lbm;

n is the number of moles;

P is the absolute static pressure of a gas, in psia;

P_b is the absolute static pressure of a gas at base conditions, in psia;

P_{f_1} is the absolute static pressure of a gas at the upstream tap, in psia;

R is the universal gas constant = 1,545.35 (lbf-ft)/(lb-mol-°R);

T is the absolute temperature of a gas, in °R;

T_b is the absolute temperature of a gas at base conditions, in °R;

T_f is the absolute temperature of a flowing gas, in °R;

V is the volume of a gas, in ft^3;

V_b is the volume of a gas at base conditions (P_b, T_b), in ft^3;

V_{f_1} is the volume of a gas at flowing conditions (P_{f_1}, T_f), in ft^3;

w is the number of the last component;

Z is the compressibility of a gas at P and T;

Z_b is the compressibility of a gas at base conditions (P_b, T_b);

Z_{f_1} is the compressibility of a gas at flowing conditions (P_{f_1}, T_f);

ρ_b is the density of a gas at base conditions (P_b, T_b), in lbm/ft^3;

ρ_{t,p_1} is the density of a gas at upstream flowing conditions (P_{f_1}, T_f), in lbm/ft^3;

ϕ_i is the mole fraction of a component.

6.5.3 Density Based on Ideal Gas Relative Density

The gas densities ρ_{t,p_1} and ρ_b may be calculated from the ideal gas relative density, as determined in 6.4.2. The following equations are applicable when a gas analysis is available:

$$G_i = \frac{Mr_{\text{gas}}}{Mr_{\text{air}}} = \frac{Mr_{\text{gas}}}{28.9625} \tag{57}$$

NOTE The molecular weight of dry air, from GPA 2145-09, is given as 28.9625 lbm/lb-mol (exactly).

$$Mr_{\text{gas}} = G_i \, Mr_{\text{air}} = G_i \, (28.9625) \tag{58}$$

Substituting for Mr_{gas} in Equation (55) and Equation (56), ρ_{t,p_1} and ρ_b are determined as follows:

$$\rho_{t,p_1} = \frac{P_{f_1} G_i (28.9625)(144)}{Z_{f_1} R T_f} = 2.69881 \frac{P_f G_i}{Z_{f_1} T_f} \tag{59}$$

and

$$\rho_b = \frac{P_b G_i (28.9625)(144)}{Z_b R T_b} = 2.69881 \frac{P_b G_i}{Z_b T_b} \tag{60}$$

where

G_i is the ideal gas relative density;

Mr_{air} is the molar mass (molecular weight) of air = 28.9625 lbm/lb-mol;

Mr_{gas} is the molar mass (molecular weight) of a flowing gas, in lbm/lb-mol;

P_b is the absolute static pressure of the gas at base conditions, in psia;

P_{f_1} is the absolute static pressure of a gas at the upstream tap, in psia;

R is the universal gas constant = 1,545.35 (lbf-ft)/(lb-mol-°R);

T_b is the absolute temperature of a gas at base conditions, in °R;

T_f is the absolute temperature of a flowing gas, in °R;

Z_b is the compressibility of a gas at base conditions (P_b, T_b);

Z_{f_1} is the compressibility of a gas at flowing conditions (P_{f_1}, T_f);

ρ_b is the density of a gas at base conditions (P_b, T_b, and Z_b), in lbm/ft^3;

ρ_{t,p_1} is the density of a gas at upstream flowing conditions (P_{f_1}, T_f, and Z_{f_1}), in lbm/ft^3.

6.5.4 Density Based on Real Gas Relative Density

The relationship of real gas relative density to ideal gas relative density is given by the following equation:

$$G_r = G_i \frac{Z_{b_{\text{air}}}}{Z_{b_{\text{gas}}}} \tag{61}$$

or

$$G_i = G_r \frac{Z_{b_{\text{gas}}}}{Z_{b_{\text{air}}}} \tag{62}$$

NOTE The real gas relative density of dry air at base conditions is defined as exactly 1.00000.

Substituting for G_i in Equation (59) and Equation (60) results in the following:

$$\rho_{t,p_1} = \frac{2.69881 P_{f_1} G_r Z_{b_{\text{gas}}}}{Z_{f_1} T_f Z_{b_{\text{air}}}} \tag{63}$$

$$\rho_b = \frac{2.69881 P_b G_r}{T_b Z_{b_{\text{air}}}} \tag{64}$$

To correctly apply the density equations Equation (63) and Equation (64), which were developed from the real gas relative density, to the flow equations, the base conditions used for both the relative density and within the flow calculation have to be the same. When reference base conditions (P_s, T_s) are substituted for base conditions,

$P_b = P_s = 14.73$ psia,

$T_b = T_s = 519.67$ °R (60 °F), and

$Z_{b_{\text{air}}} = Z_{s_{\text{air}}} = 0.999590.$

The gas density based on real gas relative density is given by the following equations:

$$\rho_{t,p_1} = \frac{2.69881 P_{f_1} G_r Z_{s_{gas}}}{0.999590 Z_{f_1} T_f} = 2.69992 \frac{P_{f_1} Z_{s_{gas}} G_r}{Z_{f_1} T_f} \quad (65)$$

and

$$\rho_s = \frac{(2.69881)(14.73) G_r}{(0.999590)(519.67)} = 0.0765289 G_r \quad (66)$$

where

G_i is the ideal gas relative density;

G_r is the real gas relative density;

P_b is the absolute static pressure of a gas at base conditions, in psia;

P_{f_1} is the absolute static pressure of a gas at the upstream tap, in psia;

P_s is the absolute static pressure of a gas at reference base conditions, in psia;

T_b is the absolute temperature of a gas at base conditions, in °R;

T_f is the absolute temperature of a flowing gas, in °R;

T_s is the absolute temperature of a gas at reference base conditions, in °R;

$Z_{b_{air}}$ is the compressibility of air at base conditions (P_b, T_b);

$Z_{b_{gas}}$ is the compressibility of a gas at base conditions (P_b, T_b);

Z_{f_1} is the compressibility of a gas at flowing conditions (P_{f_1}, T_f);

$Z_{s_{air}}$ is the compressibility of air at reference base conditions (P_s, T_s);

$Z_{s_{gas}}$ is the compressibility of a gas at reference base conditions (P_s, T_s);

ρ_b is the density of a gas at base conditions (P_b, T_b), in lbm/ft^3;

ρ_s is the density of a gas at reference base conditions (P_s, T_s), in lbm/ft^3;

ρ_{t,p_1} is the density of a gas at upstream flowing conditions (P_{f_1} , T_f), in lbm/ft^3.

The density equations for density at reference base conditions (ρ_s) based on the real gas relative density developed above require that G_r be determined at the same reference base conditions and incorporate $Z_{b_{air}} = Z_{s_{air}}$ at 14.73 psia and 519.67 °R in their numeric constants.

Annex A
(informative)

Adjustments for Instrument Calibration

A.1 Scope

This annex provides equations and procedures for adjusting and correcting field measurement calibrations of secondary instruments.

A.2 General

Field practices for secondary instrument calibrations and calibration standard applications contribute to the overall uncertainty of flow measurement.

Calibration standards for differential pressure and static pressure instruments are sometimes used in the field without local gravitational force adjustment or correction of the values indicated by the calibrating standards. It is usually more convenient and accurate to incorporate these adjustments in the flow computation than to apply these small corrections during the calibration process. Therefore, additional factors are added to the flow equation for the purpose of including the appropriate calibration standard corrections in the flow computation either by the flow calculation procedure in the office or by the meter technician in the field, but not to both.

Four factors are provided that may be used individually or in combination, depending on the calibration device and the calibration procedure used:

F_{am} is the correction for air over the water in the water manometer during the differential instrument calibration;

F_{pwl} is the local gravitational correction for the deadweight tester static pressure standard;

F_{wl} is the local gravitational correction for the water column calibration standard;

F_{wt} is the water density correction (temperature or composition) for the water column calibration standard.

These factors expand the base volume flow equation to the following:

$$Q'_v = Q_v F_{am} F_{wl} F_{wt} F_{pwl} \tag{A.1}$$

All of the flow factors that are pertinent to gas flow and are defined in this standard are included in Equation (A.1). Some of the factors are not applicable to all measurement systems and can therefore be considered equal to 1 or ignored, as preferred by the user. For other applications, particularly those involving mass flow calculation, specific factors may be included in the selected equation as appropriate for the system, the calibration of the instrumentation, and particular operating procedures.

A.3 Symbols, Units, and Terminology

A.3.1 General

The symbols and units used are specific to this annex and were developed based on the USC inch-pound system of units. Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 should be used for consistent results.

A.3.2 Symbols and Units

F_{am}	correction for air over the water in the water manometer
F_{pwl}	local gravitational correction for deadweight tester
F_{wl}	local gravitational correction for water column
F_{wt}	water density correction
G_i	ideal gas relative density
G_r	real gas relative density
g_l	local acceleration due to gravity (ft/s^2)
g_o	acceleration of gravity used to calibrate weights or deadweight calibrator (ft/s^2)
H	elevation above sea level (ft)
h_{wa}	differential pressure above atmospheric (inches of water column at 60 °F)
L	latitude on Earth's surface (degrees)
Mr	molar mass of gas (lbm/lb-mol)
Mr_{air}	molar mass of air (28.9625 lbm/lb-mol)
P	absolute gas pressure (psia)
P_{atm}	local atmospheric pressure (psia)
P_b	base pressure (psia)
P_f	absolute pressure of flowing gas (psia)
Q'_v	volume flow rate at reference base conditions modified for instrument calibration adjustments (ft^3/hr)
R	universal gas constant [1,545.35 (lbf-ft)/(lb-mol-°R)]
T	absolute gas temperature (°R)
T_b	base temperature (°R)
T_f	absolute temperature of a flowing gas (°R)
T_{gas_a}	gas ambient temperature (°R)
Z	compressibility of a gas at T and P
Z_a	compressibility of air at $P_{\mathrm{atm}} + h_{wa}$ and 519.67 °R
$Z_{a_{\mathrm{atm}}}$	compressibility of air at P_{atm} and 519.67 °R
Z_b	compressibility of a gas at base conditions (G_r, P_b, and T_b)
$Z_{b_{\mathrm{air}}}$	compressibility of air at reference base conditions of 14.73 psia and 519.67 °R (0.999590)
Z_f	compressibility of gas at flowing conditions (G_r, P_f, and T_f)
°F	temperature, in degrees Fahrenheit
°R	temperature, in degrees Rankine
ρ_a	density of air at pressure above atmospheric (lbm/ft^3)
ρ_{atm}	density of atmospheric air (lbm/ft^3)
ρ_g	density of gas or vapor in the differential pressure instrument (lbm/ft^3)
ρ_w	density of water in the manometer at other than 60 °F (lbm/ft^3)

A.4 Water Manometer Gas Leg Correction Factor (F_{am})

The factor F_{am} corrects for the gas leg over water when a water manometer is used to calibrate a differential pressure instrument:

$$F_{am} = \sqrt{\frac{\rho_w - \rho_a}{\rho_w}} \tag{A.2}$$

When atmospheric air is used as the medium to pressure both the differential pressure instrument and the water U-tube manometer during calibration, the density of air at atmospheric pressure and 60 °F shall be calculated using the following equation:

$$\rho = \frac{MrG_iP}{RZT} \tag{A.3}$$

Substituting local atmospheric pressure (P_{atm}) for absolute pressure (P), 519.67 °R (60 °F) for the absolute temperature (T), 28.9625 for Mr_{air}, 1.0 for the ideal relative density of air (G_i), and 1,545.35 for the universal gas constant (R) provides the following relationship:

$$\rho_{atm} = \frac{(28.9625)(1.0)P_{atm}}{\frac{1545.35}{144}Z_{a_{atm}}(519.67)} = \frac{P_{atm}}{192.556Z_{a_{atm}}} \tag{A.4}$$

The local atmospheric pressure can be determined using the following equations based on NOAA's *U.S. Standard Atmosphere* [2].

In USC units:

$$P_a = 14.6960 \times (1 - 0.00000686 \times \text{elevation})^{5.2554} \tag{A.5}$$

where

elevation is the height above mean sea level, in ft;

P_a is the atmospheric pressure at 60 °F, in psia.

In SI units:

$$P_a = 101.325 \times (1 - 0.00002256 \times \text{elevation})^{5.2554} \tag{A.6}$$

where

elevation is the height above mean sea level, in m;

P_a is the atmospheric pressure at 15 °C, in kPa.

The density of air at any given differential pressure (h_{wa}) above atmospheric pressure can then be represented by the following:

$$\rho_a = \frac{P_{atm} + \frac{h_{wa}}{27.707}}{192.477Z_a} \tag{A.7}$$

2 National Oceanic and Atmospheric Administration, *U.S. Standard Atmosphere,* U.S. Department of Commerce, National Technical Information Service, October 1976.

The density of water can be obtained from Table A.1 or calculated from the following Patterson and Morris water density equation (refer to API *MPMS* Ch. 11.4.1):

$$\rho_w = \rho_o[1 - (A\Delta t + B\Delta t^2 + C\Delta t^3 + D\Delta t^4 + E\Delta t^5)] \quad \text{(A.8)}$$

where

A = 7.0134 × 10^{-8} (°C) $^{-1}$;

B = 7.926504 × 10^{-6} (°C) $^{-2}$;

C = –7.575677 × 10^{-8} (°C) $^{-3}$;

D = 7.314894 × 10^{-10} (°C) $^{-4}$;

E = –3.596458 × 10^{-12} (°C) $^{-5}$;

G_i is the ideal gas relative density;

h_{wa} is the differential pressure above atmospheric, in inches of water at 60 °F;

Mr is the molar mass of a gas, in lbm/lb-mol;

P is the absolute gas pressure, in psia;

P_{atm} is the local atmospheric pressure, in psia;

R is the universal gas constant = 1,545.35 (lbf-ft)/(lb-mol-°R);

T is the absolute gas temperature, in °R;

T_w is the temperature of water, in °C;

T_0 = 3.9818 °C;

Z is the compressibility of a gas at P and T;

Z_a is the compressibility of air at P_{atm} + h_{wa} and 519.67 °R;

$Z_{a_{\text{atm}}}$ is the compressibility of air at P_{atm} and 519.67 °R;

Δt = $T_w - T_0$;

ρ is the density of a gas, in lbm/ft^3;

ρ_a is the density of air at pressure above atmospheric, in lbm/ft^3;

ρ_{atm} is the density of atmospheric air, in lbm/ft^3;

ρ_o is the density of water at temperature T_0, 999.97358 kg/m^3 (maximum density of water);

ρ_w is the density of water in kg/m^3.

Table A.1—Water Density Based on Patterson and Morris Equation

Temperature (°F)	Density (lbm/ft^3)	Temperature (°F)	Density (lbm/ft^3)
45	62.4213	63	62.3492
46	62.4194	64	62.3429
47	62.4173	65	62.3365
48	62.4149	66	62.3299
49	62.4123	67	62.3230
50	62.4093	68	62.3159
51	62.4062	69	62.3087
52	62.4027	70	62.3012
53	62.3990	71	62.2936
54	62.3951	72	62.2857
55	62.3909	73	62.2776
56	62.3865	74	62.2694
57	62.3819	75	62.2610
58	62.3770	76	62.2523
59	62.3719	77	62.2435
60	62.3665	78	62.2346
61	62.3610	79	62.2254
62	62.3552	80	62.2160

A.5 Water Manometer Temperature Correction Factor (F_{wt})

The factor F_{wt} corrects for variations in the density of water used in the manometer when the water is at a temperature other than 60 °F. The F_{wt} correction factor should be included in the flow measurement computation when a differential instrument is calibrated with a water manometer.

$$F_{wt} = \sqrt{\frac{\rho_w}{62.3665}} \tag{A.9}$$

where

ρ_w is the density of water in a manometer at a temperature other than 60 °F, in lbm/ft^3.

A.6 Local Gravitational Correction Factor for Water Manometers (F_{wl})

The factor F_{wl} corrects the weight of the manometer fluid for the local gravitational force. The effect on the quantity is the square root of the ratio of the local gravitational force to the standard gravitational force used in the equation derivations. This relationship is expressed as follows:

$$F_{wl} = \sqrt{\frac{g_l}{32.1740}} \tag{A.10}$$

where

g_l is the local acceleration due to gravity, in ft/s^2.

The local value of gravity at any location may be obtained from a U.S. Coast and Geodetic Survey reference to aeronautical data or from the Smithsonian Meteorological Tables. Using Equation (A.11), approximate values of g_l may be obtained from the following curve-fit equation covering latitudes from 0° to 90°:

$$g_l = 0.0328084\,(978.01855 - 0.0028247L + 0.0020299L^2 - 0.000015085L^3 - 0.000094H) \tag{A.11}$$

where

H is the elevation, in feet above sea level;

L is the latitude, in degrees.

A.7 Local Gravitational Correction Factor for Deadweight Calibrators Used to Calibrate Differential and Static Pressure Instruments (F_{pwl})

The factor F_{pwl} is used to correct for the effect of local gravity on the weights of a deadweight calibrator. The calibrator weights are usually sized for use at a standard gravitational force or at some specified gravitational force. A correction factor has to then be applied to correct the flow to the local gravitational force:

$$F_{pwl} = \sqrt{\frac{g_l}{g_o}} \tag{A.12}$$

where

g_l is the acceleration due to local gravitational force, in ft/s^2;

g_o is the acceleration of gravity used to calibrate the weights of a deadweight calibrator, in ft/s^2.

When a deadweight calibrator is used for the differential pressure and the static pressure, both have to be corrected for local gravity. This involves using F_{pwl} twice.

Annex B
(informative)

Factors Approach

B.1 Introduction

API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3 no longer contains details of the factors approach. Refer instead to API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3—1992, Appendix 3-B—Factors Approach, and Appendix 3-C—Flow Calculation Examples, which are included by reference. To use the factors approach, refer to the 1992 edition of the standard including the errata in B.3 below.

Note that in API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3—1992, the general factor equation for volume (3-B-1), the term Z_b/Z_s was missing, and Equation (3-B-2) and Equation (3-B-4) the term F_{zb} was missing. This term F_{zb} is equal to Z_b/Z_s, the compressibility at base conditions divided by the compressibility at reference base (standard) conditions. These corrections should be included to be consistent with the nonfactors approach.

B.2 Expansion Factor

When using the factor approach, refer to the expansion factor calculation in 5.6. No tables are provided for the expansion factor.

B.3 Errata

NOTE The corrections stated below refer to the 1992 edition of this part of the standard.

For Appendix 3-B:

On page 30, Equation (3-B.1) should read as follows:

$$Q_v = 218.573\left(\frac{519.67}{14.73}\right)\sqrt{\frac{1}{519.67}}C_d(FT)E_vY_1d^2\left(\frac{T_b}{519.67}\right)\sqrt{0.999590}$$

$$\times\left(\frac{14.73}{P_b}\right)\left[\left(\frac{519.67}{T_f}\right)\left(\frac{1}{G_r}\right)\left(\frac{Z_b}{Z_{f_1}}\right)\right]^{0.5}\left(\frac{Z_b}{Z_s}\right)\sqrt{P_{f_1}h_w}$$

On page 30, Equation (3-B.2) should read as follows:

$$Q_v = F_n(F_c + F_{sl})Y_1F_{pb}F_{tb}F_{tf}F_{gr}F_{pv}F_{zb}\sqrt{P_{f_1}h_w}$$

On page 30, Equation (3-B.4) should read as follows:

$$C' = F_n(F_c + F_{sl})Y_1F_{pb}F_{tb}F_{tf}F_{gr}F_{pv}F_{zb}$$

On page 33, Equation (3-B.9) should read as follows:

$$F_{sl} = 0.000511\left(\frac{1,000,000\beta}{Re_D}\right)^{0.7} + \left[0.0210 + 0.0049\left(\frac{19,000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1,000,000}{Re_D}\right)^{0.35} \quad \text{(3-B.9)}$$

For Appendix 3-C:

On page 60, Equation (3-B.9) should read as follows:

$$F_{sl} = 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} + \left[0.0210 + 0.0049\left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35}$$

On page 62, the first equation should read as follows:

$$\begin{aligned}
F_c &= 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 \\
&\quad + (0.0433 + 0.0712e^{-8.5/D} - 0.1145e^{-6.0/D})\left[1 - 0.23\left(\frac{19,000\beta}{Re_D}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4} \\
&\quad - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19,000\beta}{Re_D}\right)^{0.8}\right] \\
&= 0.5961 + 0.0291(0.495597)^2 - 0.2290(0.495597)^8 \\
&\quad + (0.0433 + 0.0712e^{-8.5/8.07085} - 0.1145e^{-6.0/8.07085})[1 - 0.23(0.0137493)](0.0642005) \\
&\quad - 0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495597)^{1.1}[1 - 0.14(0.0137493)] \\
&= 0.601767
\end{aligned}$$

On page 62, Equation (3-B.9) should read as follows:

$$\begin{aligned}
F_{sl} &= 0.000511\left(\frac{1{,}000{,}000\beta}{Re_D}\right)^{0.7} + \left[0.0210 + 0.0049\left(\frac{(19{,}000)\beta}{Re_D}\right)^{0.8}\right]\beta^4\left(\frac{1{,}000{,}000}{Re_D}\right)^{0.35} \\
&= 0.000511\left[\frac{1{,}000{,}000(0.495597)}{2{,}000{,}000}\right]^{0.7} + [0.0210 + 0.0049(0.0137493)](0.495597)^4(0.784584) \\
&= 0.00118960
\end{aligned}$$

On page 64, Equation (3-B.2) should read as follows:

$$\begin{aligned}
Q_v &= F_n(F_c + F_{sl})Y_1F_{pb}F_{tb}F_{tf}F_{gr}F_{pv}F_{zb}\sqrt{P_{f_1}h_w} \\
&= 616,974
\end{aligned}$$

On page 65, the first equation should read as follows:

$$\begin{aligned}
Re_D &= 0.0114588\left(\frac{Q_vP_sG_r}{\mu DT_s}\right) \\
&= 3.32446Q_v \\
&= 3.32446(616,974) \\
&= 2{,}051{,}107 \quad \text{(second iteration)}
\end{aligned}$$

On page 65, the result of substituting the second estimate of Re_D into the applicable equations is:

Q_v = 616,962 (based on the second estimate of Re_D)

On page 65, the second equation should read as follows:

$$Re_D = 3.32446Q_v$$

$$= 3.32446(616,962)$$

$$= 2,051,065 \quad \text{(third iteration)}$$

On page 65, the third equation should read as follows:

$$Q_v = F_n(F_c + F_{sl})Y_1F_{pb}F_{tb}F_{tf}F_{gr}F_{pv}F_{zb}\sqrt{P_{f_1}h_w}$$

$$= (5581.82)(0.601767 + 0.00117736)(0.998383)(1.00000)(1.00000)$$

$$\times (0.995224)(1.32453)(1.02423)(0.999868)\sqrt{(370.00)(50.0)}$$

$$= 616{,}962 \text{ ft}^3\text{/hr}$$

On page 65, the last equation, Equation (3-7), should read as follows:

$$Q_b = Q_v\left(\frac{P_s}{P_b}\right)\left(\frac{T_b}{T_s}\right)\left(\frac{Z_b}{Z_s}\right)$$

$$= 616{,}962\left(\frac{14.73}{14.65}\right)\left(\frac{509.67}{519.67}\right)\left(\frac{0.997839}{0.997971}\right)$$

$$= 608{,}314 \text{ ft}^3\text{/hr at base conditions}$$

Annex C
(informative)

Flow Calculation Examples

C.1 General

This annex presents a method for calculating the volume flow rate of natural gas through an orifice meter equipped with flange taps using the equations presented in Section 4 through Section 6.

To assist the user in interpreting the calculation methodology, the data set given below, which is for a single orifice meter, is used consistently throughout the flow calculation examples. The volume flow rate is computed under the assumption that the measurements are absolute and without error. It should be noted that depending on the type of instrumentation used and the calibration methods employed, calibration and correction factors may need to be applied. *Values shown are rounded for display purposes only. All calculations are performed to double precision. Part 4 should be used for any implementation of the equations.*

C.2 Given Data

The orifice meter consists of a carbon steel meter tube equipped with flange taps and a Type 304 stainless steel orifice plate. Static pressure measurements are taken from the upstream tap.

D_r is the mean meter tube internal diameter at T_r of 68 °F, in inches = 8.071;

d_r is the mean orifice bore diameter at T_r of 68 °F, in inches = 4.000;

G_r is the real gas relative density = 0.570;

h_w is the average differential pressure, in inches of water at 60 °F = 50.0;

P_b is the contract base pressure, in psia= 14.65;

P_{f_1} is the average upstream absolute static pressure, in psia= 370.0;

T_b is the contract base temperature of 50 °F, in °R (50 °F + 459.67) = 509.67;

T_f is the flowing temperature of 65 °F, in °R (65 °F + 459.67) = 524.67;

α_1 is the linear coefficient of thermal expansion for a Type 304 stainless steel orifice plate, in inches per inch-°F = 0.00000961;

α_2 is the linear coefficient of thermal expansion for a carbon steel meter tube, in inches per inch-°F = 0.00000620;

κ is the isentropic exponent (c_p/c_v) = 1.3;

μ is the dynamic viscosity, in lbm/(ft/s) = 0.0000069.

C.3 Calculation Examples

C.3.1 Volume Flow Rate Calculation Based on Section 4 Through Section 6

C.3.1.1 General

API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—1992 labeled this calculation as Method 1. Using the given data set, the volume flow rate of natural gas, in ft^3/hr at reference base conditions, can be calculated using Equation (9):

$$Q_v = 7709.61 C_d(FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \tag{C.1}$$

NOTE Since the given data contain values for the contract base pressure (14.65 psia) and temperature (50 °F) that differ from the values established in API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3 as reference base conditions (14.73 psia and 60 °F), the initial calculated flow rate at reference base conditions will require conversion to the flow rate at base conditions of 14.65 psia and 50 °F.

The systematic approach to solving the volume flow rate equation above involves the calculation of the intermediate values described in C.3.1.2 through C.3.1.7.

C.3.1.2 Flange-tapped Orifice Meter Coefficient of Discharge [$C_d\,(FT)$]

The following equations are used to calculate the coefficient of discharge, $C_d\,(FT)$:

$$C_d\,(FT) = C_i(FT) + 0.000511 \left(\frac{10^6 \beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049\,A)\beta^4 C \tag{C.2}$$

$$C_i(FT) = C_i(CT) + \text{tap term} \tag{C.3}$$

$$C_i(CT) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1 \tag{C.4}$$

$$\text{tap term} = \text{upstrm} + \text{dnstrm} \tag{C.5}$$

$$\text{upstrm} = (0.0433 + 0.0712 e^{-8.5 L_1} - 0.1145 e^{-6.0 L_1})(1 - 0.23 A)B \tag{C.6}$$

$$\text{dnstrm} = -0.0116(M_2 - 0.52\,M_2^{1.3})\beta^{1.1}(1 - 0.14A) \tag{C.7}$$

also

$$B = \frac{\beta^4}{1-\beta^4} \tag{C.8}$$

$$M_1 = \max\left(2.8 - \frac{D}{N_4}, 0.0\right) \tag{C.9}$$

$$M_2 = \frac{2L_2}{1-\beta} \tag{C.10}$$

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8} \tag{C.11}$$

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35} \tag{C.12}$$

where

$C_d\,(FT)$	is the coefficient of discharge at a specified pipe Reynolds number for a flange-tapped orifice meter;
$C_i(CT)$	is the coefficient of discharge at an infinite pipe Reynolds number for corner-tapped orifice meter;
$C_i(FT)$	is the coefficient of discharge at an infinite pipe Reynolds number for a flange-tapped orifice meter;
D	is the meter tube internal diameter calculated at T_f, in inches;
d	is the orifice plate bore diameter calculated at T_f, in inches;
e	is the Napierian constant = 2.71828;
L_1	is the dimensionless correction for tap location = N_4/D for flange taps;
L_2	= L_1;
N_4	is the 1.0 when D is in inches;
Re_D	is the pipe Reynolds number;
β	is the diameter ratio = d/D.

NOTE For this example, M_1 is equal to 0.0, since the given meter tube diameter (D) is greater than or equal to 2.8 in. For meter tube diameters (D) less than 2.8 in., M_1 = 2.8 – D. The solution of the intermediate equations presented above for the flow coefficient calculation follows.

C.3.1.3 Meter Tube Diameter, Orifice Plate Bore Diameter, and Diameter Ratio (D, d, and β)

Calculate the values of d, D, and β at a flowing temperature of 65 °F from the given diameters d_r and D_r:

$$d = d_r\,[1 + \alpha_1\,(T_f - T_r)] \tag{C.13}$$

$$= 4.000[1 + 0.00000961(524.67 - 527.67)]$$

$$= 3.99988$$

and

$$D = D_r[1 + \alpha_2(T_f - T_r)] \tag{C.14}$$

$$= 8.071[1 + 0.00000620(524.67 - 527.67)]$$

$$= 8.07085$$

Substitute the given values of d and D at 65 °F into Equation (11):

$$\beta = d/D \tag{C.15}$$

$$= 3.99988/8.07085$$

$$= 0.495596$$

C.3.1.4 Velocity of Approach Factor (E_v)

The following equation is used to calculate the velocity of approach factor:

$$E_v = \frac{1}{\sqrt{1-\beta^4}} \tag{C.16}$$

$$= \frac{1}{\sqrt{1-0.495596^4}}$$

$$= 1.03160$$

C.3.1.5 Expansion Factor (Y)

The following equation is used to calculate the expansion factor:

$$Y_1 = 1-(0.3625+0.1027\beta^4+1.1320\beta^8)\left\{1-\left[\frac{P_{f_2}}{P_{f_1}}\right]^{\frac{1}{\kappa}}\right\} \tag{C.17}$$

Calculate P_{f_2} from the given values of h_w and P_{f_1}:

$$P_{f_2} = P_{f_1} - \frac{h_w}{27.707} \tag{C.18}$$

$$P_{f_2} = 370 - \frac{50}{27.707}$$

$$P_{f_2} = 368.195$$

Substitute the values for κ, β, P_{f_1}, and P_{f_2} into Equation (35):

$$Y_1 = 1-(0.3625+0.1027\beta^4+1.1320\beta^8)\left\{1-\left[\frac{P_{f_2}}{P_{f_1}}\right]^{\frac{1}{\kappa}}\right\} \tag{C.19}$$

$$= 1-0.3625+0.1027(0.495596)^4+1.1320(0.495596)^8\left\{1-\left[\frac{368.195}{370}\right]^{\frac{1}{1.3}}\right\}$$

$$= 0.998600$$

C.3.1.6 Compressibility (Z_b, Z_s, and Z_{f_1})

The derivation of the equation for compressibility is presented in API *MPMS* Ch. 14.2/AGA Report No. 8. It is not within the scope of this example to present the calculation procedures necessary for determining the compressibility at base conditions (Z_b), reference base conditions (Z_s), or flowing conditions (Z_{f_1}). The following values for gas compressibility at the conditions given in the data set were obtained from the computer program that uses the calculation given in API *MPMS* Ch. 14.2/AGA Report No. 8. At G_r = 0.57,

Z_b is 0.997839 at 14.65 psia and 509.67 °R (50 °F);

Z_s is 0.997971 at 14.73 psia and 519.67 °R (60 °F);

Z_{f_1} is 0.951308 at 370 psia and 524.67 °R (65 °F).

C.3.1.7 Reynolds Number (Re_D)

The following equation is used to calculate the pipe Reynolds number:

$$Re_D = 0.0114541\left(\frac{Q_b P_b G_r}{\mu D T_b Z_{b_{\text{air}}}}\right) \tag{C.20}$$

Substituting the calculated value for D, reference base conditions for P_b and T_b, a value of 0.999590 for $Z_{b_{\text{air}}}$, and the data set values for G_r and μ in Equation (31) produce the following:

$$\begin{aligned} Re_D &= (0.0114541)\left[\frac{Q_b(14.73)(0.570)}{(0.0000069)(8.07085)(519.67)(0.999590)}\right] \\ &= 3.32446 Q_b \end{aligned}$$

When the flow rate is not known, the Reynolds number can be developed by assuming an initial value for the flange-tapped orifice meter coefficient of discharge, C_d *(FT)*, and iterating for the correct values, as stated in 5.5. The following flow rate calculation provides the initial iteration of the Reynolds number. This initial iteration is based on an assumed value for C_d *(FT)* of 0.60. Based on experience, from three to five iterations should provide results consistent with the requirements of Part 4.

C.3.1.8 Volume Flow Rate (Q_v and Q_b)

The volume flow rate can be calculated by substituting the given parameters, the intermediate calculated values, and an assumed value of 0.60 for C_d *(FT)* in Equation (9) and iterating for the final solution:

$$Q_v = 7709.61 C_d E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}} \tag{C.21}$$

$$\begin{aligned} &= 7709.61(0.60)(1.03160)(0.998600)(3.99988)^2\sqrt{\frac{(370.0)(0.997971)(50.0)}{(0.570)(0.951308)(524.67)}} \\ &= 614{,}166 \text{ ft}^3\text{/hr at reference base conditions} \end{aligned}$$

This is an estimate of the initial flow rate based on an assumed C_d *(FT)* of 0.60.

Substitute the estimate of initial flow rate into the Reynolds number equation and calculate the estimated initial Reynolds number:

$$\begin{aligned} Re_D &= 3.32446 Q_v \\ &= 3.32446(614{,}166) \\ &= 2{,}041{,}768 \text{ (initial estimate of Reynolds number)} \end{aligned}$$

Substitute the calculated value of β into Equation (C.8) to determine B:

$$B = \frac{\beta^4}{1-\beta^4}$$

$$= \frac{0.495596^4}{1-0.495596^4}$$

$$= 0.0641999$$

Substitute the calculated values of β and D into Equation (22):

$$M_2 = \frac{2L_2}{1-\beta}$$

$$= \frac{2}{8.07085(1-0.495596)}$$

$$= 0.491284$$

Substitute the calculated values of Re_D and β into Equation (23):

$$A = \left(\frac{19{,}000\beta}{Re_D}\right)^{0.8}$$

$$= \left[\frac{19{,}000(0.495596)}{2{,}041{,}764}\right]^{0.8}$$

$$= 0.0135239$$

Substitute the calculated value of Re_D into Equation (24):

$$C = \left(\frac{10^6}{Re_D}\right)^{0.35}$$

$$= \left(\frac{10^6}{2{,}041{,}764}\right)^{0.35}$$

$$= 0.778929$$

Substitute the appropriate calculated values into Equation (16) to determine the $C_i(CT)$ term of the coefficient of discharge, $C_d\,(FT)$:

$$C_i(CT) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1$$

$$= 0.5961 + 0.0291(0.495596)^2 - 0.2290(0.495596)^8 + 0.003(1-0.495596)(0.0)$$

$$= 0.602414$$

Substitute the applicable calculated values into Equation (18) to compute the upstrm term of the coefficient of discharge, $C_d\,(FT)$:

$$\text{upstrm} = (0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1})(1 - 0.23A)B$$

$$= (0.0433 + 0.0712e^{-8.5/8.07085} - 0.1145e^{-6.0/8.07085})[1 - 0.23(0.0135239)(0.0641999)]$$

$$= 0.000876380$$

Substitute the applicable calculated values into Equation (19) to compute the dnstrm term of the coefficient of discharge, $C_d\,(FT)$:

$$\text{dnstrm} = -0.0116(M_2 - 0.52\,M_2^{1.3})\beta^{1.1}(1 - 0.14A)$$

$$= -0.0116[0.491284 - 0.52(0.491284)^{1.3}](0.495596)^{1.1}[1 - 0.14(0.0135239)]$$

$$= -0.00152379$$

Substitute the applicable calculated values into Equation (17) to compute the tap term of the coefficient of discharge, $C_d\,(FT)$:

$$\text{tap term} = \text{upstrm} + \text{dnstrm}$$

$$= 0.000876380 + (-0.00152379)$$

$$= -0.000647410$$

Substitute the applicable calculated values into Equation (15) to compute the $C_i(FT)$ term of the coefficient of discharge, $C_d\,(FT)$:

$$C_i(FT) = C_i(CT) + \text{tap term}$$

$$= 0.602414 - 0.000647410$$

$$= 0.601767$$

Substitute the value for $C_i(FT)$ and the intermediate values into Equation (14) to calculate the discharge coefficient, $C_d\,(FT)$:

$$C_d\,(FT) = C_i(FT) + 0.000511\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0210 + 0.0049A)\beta^4 C$$

$$= 0.601767 + 0.000511\left(\frac{10^6 0.495596}{2{,}041{,}764}\right)^{0.7} + [0.0210 + 0.0049(0.0135239)](0.495596)^4(0.778929)$$

$$= 0.602947 \text{ (second estimate of the coefficient of discharge)}$$

By substituting the value of $C_d\,(FT)$ into the applicable equations, the volume flow rate can be recalculated following the same process outlined in this example. The resulting volume flow rate value is as follows:

$Q_v = 617{,}180$ ft^3/hr at reference base conditions

[based on = $C_d\,(FT) = 0.602947$]

and

$Re_D = 3.32446\ Q_v = 3.32446\ (617{,}180)$

$= 2{,}051{,}790$ (second estimate of Reynolds number)

resulting in

$C_d\ (FT) = 0.602946$ (third estimate of coefficient of discharge)

Following the same calculation procedure for iteration of flow rate, the resulting volumetric flow rate is as follows:

$Q_v = 617{,}179\ \text{ft}^3/\text{hr}$ at reference base conditions

[based on = $C_d\ (FT) = 0.602946$]

and

$Re_D = 3.32446\ Q_v = 3.32446\ (617{,}179)$

$= 2{,}051{,}787$ (third estimate of Reynolds number)

resulting in

$C_d\ (FT) = 0.602946$ (fourth estimate of coefficient of discharge)

The volume flow rate calculation based on the fourth estimate of $C_d\ (FT)$ follows. As stated above, three estimates of $C_d\ (FT)$ should normally provide volume flow rate calculation results that are consistent with the requirements of Part 4.

$Q_v = 617{,}179\ \text{ft}^3/\text{hr}$ at reference base conditions

[based on = $C_d\ (FT) = 0.602946$]

Since the given data contain values for the base pressure (14.65 psia) and temperature (50 °F) that differ from the values established in this document as reference base conditions (14.73 psia and 60 °F), the initial calculated flow rate is the reference base volume flow rate. To calculate the flow rate at the given base conditions (P_b = 14.65 psia and T_b = 509.67 = °R), the reference base volume flow rate and the appropriate values for P, T, and Z are substituted into Equation (10) as follows:

$$Q_b = Q_v\left(\frac{T_b}{T_s}\right)\left(\frac{P_s}{P_b}\right)\left(\frac{Z_b}{Z_s}\right)$$

$$= 617{,}182\left(\frac{509.67}{519.67}\right)\left(\frac{14.73}{14.65}\right)\left(\frac{0.997839}{0.997971}\right)$$

$$= 608{,}528\ \text{ft}^3/\text{hr at base conditions}$$

Annex D
(informative)

Pipe Tap Orifice Metering

D.1 Introduction

API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3 no longer contains details of pipe tap orifice metering. To use pipe tap orifice metering, refer to the API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3—1992, Appendix 3-D, which is included by reference, including the errata in D.2 below.

D.2 Errata

NOTE The corrections stated below refer to the 1992 edition of this part of the standard.

On page 80, Equation (3-D.9) should read as follows (i.e. K_{pipe} should be inserted in the equation and the second line of the equation should be deleted):

$$Re_d = 220{,}858 d F_{pv} \sqrt{\rho h_w} \times (K_{\mathrm{pipe}}) \tag{D.1}$$

On page 80, Equation (3-D.9) should read as follows (i.e. K_{pipe} should be inserted in the list):

where

G is the relative density.

K_{pipe} is the values from Table 3-D.4.

Re_d is the orifice bore Reynolds number.

T_f is the absolute flowing temperature, in °R.

ρ is the specific weight of a gas at 14.7 psia and 32 °F.

Annex E
(informative)

SI Conversions

This annex contains tables of SI conversions that are pertinent to the information in this document. For additional information on SI units, refer to API *MPMS* Ch. 15.

Table E.1—Volume Reference Conditions for Custody Transfer Operations: Natural Gas Volume

Common Reference Conditions (ft^3)		To Convert from	
Pressure (psia)	**Temperature (°F)**	**ft^3 to m^3, Multiply by**	**m^3 to ft^3, Multiply by**
14.4	60	0.02769321	36.10994
14.65	60	0.02817399	35.49373
14.696	60	0.02826245	35.38263
14.7	60	0.02827015	35.37300
14.73	60	0.02832784	35.30096
14.7347	60	0.02833688	35.28970
14.735	60	0.02833746	35.28898
14.9	60	0.02865478	34.89819
15.025	60	0.02889517	34.60786

NOTE The following reference base conditions were used for USC inch-pound units—a temperature of 60 °F and a pressure of 14.73 psia. The following reference base conditions were used for SI units—a temperature of 15 °C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa. The following methodology was used to obtain the conversion factors:

$$\left(\frac{\mathrm{ft}^3}{\mathrm{m}^3}\right)\left(\frac{T_b}{T_{SI}}\right)\left(\frac{P_{SI}}{P_b}\right) = \text{factor}$$

Table E.2—Energy Reference Conditions

Unit	Used in	Definition	To Convert Btu to J, Multiply by
Btu_{IT}	International steam tables	1 Btu/lbm = 2326 J/kg	1055.056

Table E.3—Heating Value Reference Conditions

Reference Conditions (ft^3)		To Convert from Btu_{IT}/ft^3 to MJ/m^3, Multiply by
Pressure (psia)	**Temperature (°F)**	
14.4	60	0.03809801
14.65	60	0.03744787
14.696	60	0.03733066
14.7	60	0.03732050
14.73	60	0.03724449
14.7347	60	0.03723261
14.735	60	0.03723185
14.9	60	0.03681955
15.025	60	0.03651323

NOTE The following reference base conditions were used for USC inch-pound units—a temperature of 60 °F and a pressure of 14.73 psia. The following reference base conditions were used for SI units—a temperature of 15 °C and an absolute pressure of 101.325 kPa. The following values were assumed: 1 ft = 0.3048 m; 1 psi = 6.894757 kPa; 1 Btu_{IT} = 1055.056 J. The following methodology was used to obtain the conversion factors:

$$\left(\frac{\mathrm{J}}{\mathrm{Btu}}\right)\left(\frac{\mathrm{MJ}}{1\times 10^{6}\ \mathrm{J}}\right)\left(\frac{\mathrm{ft}^3}{\mathrm{m}^3}\right)\left(\frac{T_b}{T_{SI}}\right)\left(\frac{P_{SI}}{P_b}\right) = \text{factor}$$

Annex F
(informative)

Development of Constants for Flow Equations

F.1 General

The practical orifice flow equation, Equation (F.1), used in this document is Equation (2) of API *MPMS* Ch. 14.3.1/ AGA Report No. 3, Part 1:

$$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P} \tag{F.1}$$

where

C_d is the orifice plate coefficient of discharge;

d is the orifice plate bore diameter calculated at flowing temperature;

E_v is the velocity of approach factor;

q_m is the mass flow rate;

ΔP is the orifice differential pressure;

$\rho_{t,p}$ is the density of fluid at flowing conditions (P_f, T_f);

and

N_1 is the factor that incorporates the "constants" from Equation (1) and the required numeric conversions, including the following:

$\frac{3.14159}{4}$ is the constant in Equation (1).

$\sqrt{2(32.1740)}$ is the constant in Equation (1).

$\sqrt{\frac{62.3665}{12}}$ is the conversion of differential pressure (ΔP) from lbf/ft^2 to inches of water at 60 °F.

$\frac{1}{12^2}$ is the conversion of the diameter of the orifice bore (d) from feet to inches

therefore

$$N_1 = \left(\frac{3.14159}{4}\right)\sqrt{2(32.1740)}\sqrt{\frac{62.3665}{12}}\left(\frac{1}{12^2}\right)$$

$$= 0.0997424$$

(This is shown as the factor for USC units in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—2012, Table 3.)

NOTE Some numeric constants do not have absolute values (e.g. π and g_c). To express six significant digits accurately, the values were computed using double precision (16 significant digits). The results were then rounded to the values shown. In this annex, for ease of understanding, the computations are shown to only six significant digits.

Mass flow can be modified to provide volume units by dividing the mass by the density at base conditions:

$$q_v = \frac{q_m}{\rho_b}$$

where

q_m is the mass flow rate, in lbm/s;

q_v volume flow rate at base conditions, in ft^3/s;

ρ_b is the density at base conditions, in lbm/ft^3.

F.2 Symbols and Units

F.2.1 General

Regular conversion factors can be used where applicable; however, if SI units are used, the more generic equations in API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1 should be used for consistent results.

F.2.2 Symbols and Units

$C_d\,(FT)$	coefficient of discharge at a specified pipe Reynolds number for flanged-tapped orifice meter
D	meter tube internal diameter calculated at flowing temperature, T_f (in.)
d	orifice plate bore diameter calculated at flowing temperature, T_f (in.)
E_v	velocity of approach factor
G_i	ideal gas relative density
G_r	real gas relative density
g_c	gravitational constant [32.1740 (lbm-ft)/(lbf-s^2)]
h_w	orifice differential pressure (inches of water column at 60 °F)
N_1	numeric conversion factor (see API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1)
P	pressure (psia)
P_b	base pressure (psia)
P_{f_1}	flowing pressure (upstream tap) (psia)
P_s	reference base pressure (14.73 psia)
Q_m	mass flow rate per hour (lbm/hr)
Q_v	volume flow rate per hour at reference base conditions (ft^3/hr)
R	universal gas constant [1,545.35 (lbf-ft)/(lb-mol-°R)]
T	temperature (°R)
T_b	base temperature (°R)
T_f	flowing temperature (°R)
T_s	reference base temperature (519.67 °R)
Y_1	expansion factor (upstream tap)
Z_b	compressibility at base conditions
$Z_{b_{\mathrm{air}}}$	compressibility of air at 14.73 psia and 60 °F (0.999590)
Z_{f_1}	compressibility at upstream flowing conditions
Z_s	compressibility at reference base conditions (P_s, T_s)

°F	temperature, in degrees Fahrenheit
°R	temperature, in degrees Rankine (459.67 + °F)
β	ratio of orifice plate bore diameter to meter tube internal diameter (d/D) calculated at flowing temperature, T_f
π	universal constant rounded to six significant figures (3.14159)
ρ_b	gas density at base conditions (P_b, T_b) (lbm/ft³)
$\rho_{b_{air}}$	density of air at base conditions (P_b, T_b) (lbm/ft³)
$\rho_{t,p}$	density at flowing conditions (P_f, T_f) (lbm/ft³)
ρ_{t,p_1}	density at upstream flowing conditions (P_{f_1}, T_f) (lbm/ft³)

F.3 General Numeric Constant for Mass Flow

Equation (1) expresses flow in lbm/hr (Q_m) rather than lbm/s (q_m) and requires an additional factor, 3600, to convert from seconds to hours.

Therefore, in Equation (1),

$$N_1 = 0.0997424\ (3600)$$

$$= 359.072$$

and

$$Q_m = 359.072 C_d(FT)E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}$$

Equation (4) is Equation (1) divided by ρ_b, as described above. The numeric constant is the same.

$$Q_b = \frac{359.072 C_d(FT)E_v Y_1 d^2 \sqrt{\rho_{t,p_1} h_w}}{\rho_b}$$

F.4 Numeric Constant for Mass Flow Developed from Ideal Gas Relative Density

Equation (2) substitutes Equation (59) for ρ_{t,p_1} in Equation (1).

$$Q_b = 359.072 C_d(FT)E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R T_f}}$$

where

28.9625 is the molecular weight of dry air;

1,545.35 is the universal gas constant (R);

144 is the factor to convert pressure from lbf/ft² to lbf/in.².

In Equation (2), therefore,

$$N_1 = 359.072 \sqrt{28.9625\left(\frac{144}{1545.35}\right)}$$

$$= 589.885$$

and

$$Q_m = 589.885 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{G_i P_{f_1} h_w}{Z_{f_1} T_f}}$$

F.5 Numeric Constant for Mass Flow Developed from Real Gas Relative Density

Equation (3) substitutes G_r for G_i in Equation (2) through the use of Equation (51):

$$Q_m = 589.885 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{Z_b G_r P_{f_1} h_w}{Z_{b_{\text{air}}} Z_{f_1} T_f}}$$

And for reference base conditions,

$$Z_{b_{\text{air}}} = Z_{s_{\text{air}}} = 0.999590 \text{ at } 14.73 \text{ psia and } 519.67\ °\text{R } (60\ °\text{F})$$

In Equation (3), therefore,

$$N_1 = \frac{589.885}{\sqrt{0.999590}}$$

$$= 590.006$$

and

$$Q_m = 590.006 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{Z_b G_r P_{f_1} h_w}{Z_{f_1} T_f}}$$

F.6 Numeric Constant for Base Volume Developed from Ideal Gas Relative Density

The constant 359.072 in Equation (4) was developed in Annex F.3. Equation (5) substitutes Equation (59) for ρ_{t, p_1} and Equation (60) for ρ_b in Equation (4).

$$Q_b = \frac{359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\rho_{t, p_1} h_w}}{\rho_b}$$

$$Q_b = 359.072 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} G_i (28.9625)(144) h_w}{Z_{f_1} R T_f}} \quad \frac{Z_b R T_b}{P_b G_i (28.9625)(144)}$$

where

1,545.35	is the universal gas constant (R);
28.9625	is the molecular weight of dry air;
144	is the factor to convert flowing pressure (P_{f_1}) from lbf/ft^2 to lbf/in.^{2};
144	is the factor to convert base pressure (P_b) from lbf/ft^2 to lbf/in.^{2}.

In Equation (5), therefore,

$$N_1 = \frac{359.072\sqrt{1545.35\left(\frac{144}{28.9625}\right)}}{144}$$

$$= 218.573$$

and

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b Z_b}{P_b} \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}}$$

For the following reference base conditions:

$P_b = P_s = 14.73$ psia

$T_b = T_s = 519.67$ °R (60 °F)

$Z_b = Z_s =$ compressibility of the gas at P_s and T_s

In Equation (8),

$$N_1 = 218.573\left(\frac{519.67}{14.73}\right)$$

$$= 7711.19$$

Therefore,

$$Q_v = 7711.19 C_d (FT) E_v Y_1 d^2 \sqrt{\frac{P_{f_1} h_w}{G_i Z_{f_1} T_f}}$$

F.7 Numeric Constant for Base Volume Developed from Real Gas Relative Density

Equation (6) substitutes G_r for G_i in Equation (5) through the use of Equation (51). The inclusion of ρ_b moves this correction to the numerator:

$$Q_b = 218.573 C_d (FT) E_v Y_1 d^2 \frac{T_b}{P_b} \sqrt{\frac{Z_b Z_{b_{\text{air}}} P_{f_1} h_w}{G_r Z_{f_1} T_f}}$$

In Equation (6), therefore,

$N_1 = 218.573$

For the following reference base conditions:

$P_b = P_s = 14.73$ psia

$T_b = T_s = 519.67$ °R (60 °F)

$Z_{b_{\text{air}}} = Z_{s_{\text{air}}} = 0.999590$

In Equation (9),

$$N_1 = 218.573\left(\frac{519.67}{14.73}\right)\sqrt{0.999590}$$

$$= 7709.61$$

$$Q_v = 7709.61 C_d(FT)E_v Y_1 d^2 \sqrt{\frac{P_{f_1} Z_s h_w}{G_r Z_{f_1} T_f}}$$

Annex G
(informative)

Buckingham and Bean Empirical Expansion Factor (Y) for Flange-tapped Orifice Meters

G.1 General

Expansibility research on water, air, steam, and natural gas using orifice meters equipped with various sensing taps is the basis for the present expansion factor equation. The empirical research compared the flow for an incompressible fluid with that of several compressible fluids.

The expansion factor, Y, was defined as follows:

$$Y = \frac{C_{d_1}}{C_{d_2}} \tag{G.1}$$

where

C_{d_1} is the coefficient of discharge from compressible fluids tests;

C_{d_2} is the coefficient of discharge from incompressible fluids tests.

Buckingham derived the empirical expansion factor equations for orifice meters equipped with various sensing taps based on the following correlation:

$$Y = f\,(\beta, \kappa, x) \tag{G.2}$$

where

β is the diameter ratio (d/D);

κ is the isentropic exponent;

x is the ratio of differential pressure to absolute static pressure.

Compressible fluids expand as they flow through a square-edged orifice. For practical applications, it is assumed that the expansion follows a polytrophic, ideal, one-dimensional path.

This assumption defines the expansion as reversible and adiabatic (no heat gain or loss). Within practical operating ranges of differential pressure, flowing pressure, and temperature, the expansion factor equation is insensitive to the value of the isentropic exponent. As a result, the assumption of a perfect or ideal isentropic exponent is reasonable for field applications. This approach was adopted by Buckingham and Bean in their correlation. They empirically developed the upstream expansion factor (Y_1) using the downstream temperature and upstream pressure.

Within the limits of this standard's application, it is assumed that the temperatures of the fluid at the upstream and downstream differential sensing taps are identical for the expansion factor calculation.

The application of the expansion factor is valid as long as the following dimensionless pressure ratio criteria are followed:

$$0 < \frac{\Delta P}{N_3 P_{f_1}} < 0.20$$

or

$$0.8 < \frac{P_{f_2}}{P_{f_1}} < 1.0$$

where

N_3 is the unit conversion factor (refer to API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—2012, Table 4);

P_f is the absolute static pressure at the pressure tap;

P_{f_1} is the absolute static pressure at the upstream pressure tap;

P_{f_2} is the absolute static pressure at the downstream pressure tap;

ΔP is the orifice differential pressure.

Although use of the upstream or downstream expansion factor equation is a matter of choice, the upstream expansion factor is recommended because of its simplicity. If the upstream expansion factor is chosen, then the determination of the flowing fluid compressibility should be based on the upstream absolute static pressure, P_{f_1}. Likewise, if the downstream expansion factor is selected, then the determination of the flowing fluid compressibility should be based on the downstream absolute static pressure, P_{f_2}.

The expansion factor equation for flange taps is applicable over a β range of 0.10 to 0.75.

G.2 Upstream Expansion Factor (Y_1)

The upstream expansion factor requires determination of the upstream static pressure, the diameter ratio, and the isentropic exponent.

If the absolute static pressure is taken at the upstream differential pressure tap, then the value of the expansion factor, Y_1, shall be calculated as follows:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{x_1}{\kappa} \tag{G.3}$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \tag{G.4}$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \tag{G.5}$$

where

N_3 is the unit conversion factor (refer to API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—2012, Table 4);

P_{f_1} is the absolute static pressure at the upstream pressure tap;

P_{f_2} is the absolute static pressure at the downstream pressure tap;

x_1 is the ratio of differential pressure to absolute static pressure at the upstream tap;

x_1/κ is the upstream acoustic ratio;

Y_1 is the expansion factor based on the absolute static pressure measured at the upstream tap;

ΔP is the orifice differential pressure;

κ is the isentropic exponent.

G.3 Downstream Expansion Factor (Y_2)

The downstream expansion factor requires determination of the downstream static pressure, the upstream static pressure, the downstream compressibility factor, the upstream compressibility factor, the diameter ratio, and the isentropic exponent. The value of the downstream expansion factor, Y_2, shall be calculated using the following equation:

$$Y_2 = Y_1 \sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{G.6}$$

or

$$Y_2 = \left[1 - (0.41 + 0.35\beta^4)\frac{x_1}{\kappa}\right] \sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{G.7}$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \tag{G.8}$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \tag{G.9}$$

where

N_3 is the unit conversion factor (refer to API *MPMS* Ch. 14.3.1/AGA Report No. 3, Part 1—2012, Table 4);

P_{f_1} is the absolute static pressure at the upstream pressure tap;

P_{f_2} is the absolute static pressure at the downstream pressure tap;

x_1 is the ratio of differential pressure to absolute static pressure at the upstream tap;

x_1/κ is the upstream acoustic ratio;

Y_1 is the expansion factor based on the absolute static pressure measured at the upstream tap;

Y_2 is the expansion factor based on the absolute static pressure measured at the downstream tap;

Z_{f_1} is the fluid compressibility at the upstream pressure tap;

Z_{f_2} is the fluid compressibility at the downstream pressure tap;

ΔP is the orifice differential pressure;

κ is the isentropic exponent.

G.4 Comparison of Expansion Factor Calculations

Equation (35) and Equation (G.3) converge when x_1 is equal to zero. As x_1 increases, the difference between the two equations increases. The two equations are dependent on β and κ. The following example, Table G.1, shows the x_1 value for which the percent difference between Equation (35) and Equation (G.3) exceeds 0.25, or approximately half of the uncertainty associated with the discharge coefficient equation. This is the same criteria adopted in API *MPMS* Ch. 14.3.2/AGA Report No. 3, Part 2 for zero installation effects uncertainty. The example in Table G.1 was developed using a nominal isentropic exponent of 1.3.

Table G.1–Comparison Between Equation (35) and Equation (G.3)

	Value of x_1 Where Equation (35) and Equation (G.3) Disagree by 0.25 %						
Beta	0.10	0.15	0.20	0.25	0.30	0.35	0.40
x_1	0.0715	0.0712	0.0708	0.0699	0.0683	0.0661	0.0632
Beta	0.45	0.50	0.55	0.60	0.65	0.70	0.75
x_1	0.0599	0.0568	0.0548	0.0549	0.0604	0.0848	0.3153

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