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

Part 1: General Equations and Uncertainty Guidelines

American Gas Association

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1 Introduction

1.1 Scope

This standard provides a single reference for engineering equations, uncertainty estimations, construction and installation requirements, and standardized implementation recommendations for the calculation of flow rate through concentric, square-edged, flange-tapped orifice meters. Both U.S. customary (USC), and international system of units (SI) units are included.

1.2 Organization of Standard

The standard is organized into four parts. Parts 1, 2, and 4 apply to the measurement of any Newtonian fluid in the petroleum and chemical industries. Part 3 focuses on the application of Parts 1, 2, and 4 to the measurement of natural gas.

1.2.1 Part 1—General Equations and Uncertainty Guidelines

The mass flow rate and base (or standard) volumetric flow rate equations are discussed, along with the terms required for solution of the flow equation.

The empirical equations for the coefficient of discharge and expansion factor are presented. However, the basis for the empirical equations are contained in other sections of this standard or the appropriate reference document.

In several sections of this revision of Part 1, identified errata have been changed relative to previous editions. In addition, this revision includes a change to the empirical expansion factor (Y) calculation for the flange-tapped orifice meters.

For all existing installations, the decision as to which expansion factor equation to use shall be 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 (Annex C or API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3, Annex G) and the new revised expansion factor equation 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 will be 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.

For the proper use of this standard, a discussion is presented on the prediction (or determination) of the fluid's properties at flowing conditions. The fluid's physical properties shall be determined by direct measurements, appropriate technical standards, or equations of state.

Uncertainty guidelines are presented for determining the possible error associated with the use of this standard for any fluid application. User-defined uncertainties for the fluid's physical properties and auxiliary (secondary) devices are required to solve the practical working formula for the estimated uncertainty.

1.2.2 Part 2—Specifications and Installation Requirements

Specifications are presented for orifice meters; in particular, orifice plates, orifice plate holders, sensing taps, meter tubes, and flow conditioners.

Installation requirements for orifice plates, meter tubes, thermometer wells, flow conditioners, and upstream/ downstream meter tube lengths are presented.

1.2.3 Part 3—Natural Gas Applications

The application of this standard to natural gas is presented, along with practical guidelines. Mass flow rate and base (or standard) volumetric flow rate methods are presented in conformance with North American industry practices.

1.2.4 Part 4—Background, Development, and Implementation Procedure and Subroutine Documentation

The coefficient of discharge database for flange-tapped orifice meters and its background, development, and limitations are presented.

Implementation procedures for flange-tapped orifice meters are presented, along with a set of example calculations. The examples are designed to aid in checkout procedures for any routines that are developed using the implementation procedures.

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. 12.2.1, *Calculation of Petroleum Quantities Using Dynamic Measurement Methods and Volumetric Correction Factors,* Part 1—*Introduction*

API *MPMS* Ch. 14.3.2/AGA Report No. 3, Part 2/GPA 8185, Part 2, *Concentric, Square-Edged Orifice Meters,* Part 2—*Specification and Installation Requirements* (2000 edition)

API *MPMS* Ch. 14.3.3/AGA Report No. 3, Part 3, *Concentric, Square-Edged Orifice Meters,* Part 3—*Natural Gas Applications*

API *MPMS* Ch. 14.3.4/AGA Report No. 3, Part 4, *Concentric, Square-Edged Orifice Meters,* Part 4—*Background, Development, Implementation Procedures and Subroutine Documentation*

API *MPMS* Ch. 14.6, *Continuous Density Measurement*

API *Technical Data Book—Petroleum Refining*

AGA Report No. 8 [1], *Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases*

[1] American Gas Association, 400 N. Capitol St., NW, Suite 450, Washington, DC 20001, www.aga.org.

3 Terms, Definitions, and Symbols

3.1 Terms and Definitions

This standard reflects orifice meter application to fluid flow measurement. The definitions are given to emphasize the particular meaning of the terms as used in this standard.

3.1.1 Primary Element

The primary element is defined as the orifice plate, the orifice plate holder with its associated differential pressure sensing taps, and the meter tube.

3.1.1.1
orifice plate
The orifice plate is defined as a thin plate in which a circular concentric aperture (bore) has been machined. The orifice plate is described as a thin plate with a sharp, square edge because the thickness of the plate material is small, compared with the internal diameter of the measuring aperture (bore), and because the upstream edge of the measuring aperture is sharp and square.

3.1.1.2
orifice plate bore diameter (d, d_m, d_r)
The calculated orifice plate bore diameter (d) is the internal diameter of the orifice plate measuring aperture (bore) computed at flowing temperature (T_f), as specified in 6.2. The calculated orifice plate bore diameter (d) is used in the flow equation for the determination of flow rate.

The measured orifice plate bore diameter (d_m) is the measured internal diameter of the orifice plate measuring aperture at the temperature of the orifice plate (T_m) at the time of bore diameter measurements, determined as specified in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2.

The reference orifice plate bore diameter (d_r) is the internal diameter of the orifice plate measuring aperture at reference temperature (T_r), calculated as specified in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2. The reference orifice plate bore diameter is the certified or stamped orifice plate bore diameter.

3.1.1.3
orifice plate holder
The orifice plate holder is defined as a pressure-containing piping element, such as a set of orifice flanges or an orifice fitting, used to contain and position the orifice plate in the piping system.

3.1.1.4
meter tube
The meter tube is defined as the straight sections of pipe, including all segments that are integral to the orifice plate holder, upstream and downstream of the orifice plate, as specified in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2.

3.1.1.5
meter tube internal diameter (D, D_m, D_r)
The calculated meter tube internal diameter (D) is the inside diameter of the upstream section of the meter tube computed at flowing temperature (T_f), as specified in 6.3. The calculated meter tube internal diameter (D) is used in the diameter ratio and Reynolds number equations.

The measured meter tube internal diameter (D_m) is the inside diameter of the upstream section of the meter tube at the temperature of the meter tube (T_m) at the time of internal diameter measurements, determined as specified in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2.

The reference meter tube internal diameter (D_r) is the inside diameter of the upstream section of the meter tube at the reference temperature (T_r), calculated as specified in API *MPMS* 14.3, Part 2/AGA Report No. 3, Part 2. The reference meter tube internal diameter is the certified or stamped meter tube internal diameter.

3.1.1.6
diameter ratio (β)
The diameter ratio (β) is defined as the calculated orifice plate bore diameter (d) divided by the calculated meter tube internal diameter (D).

3.1.2 Pressure Measurement

3.1.2.1
tap hole
A tap hole is a hole drilled radially in the wall of the meter tube or orifice plate holder, the inside edge of which is flush and without any burrs.

3.1.2.2
flange taps
Flange taps are a pair of tap holes positioned as follows (see Figure 1):

a) the upstream tap center is located 1 in. (25.4 mm) upstream of the nearest plate face,

b) the downstream tap center is located 1 in. (25.4 mm) downstream of the nearest plate face.

3.1.2.3
differential pressure (Δ*P*)
The differential pressure (ΔP) is the static pressure difference measured between the upstream and downstream flange taps.

3.1.2.4
static pressure (P_f)
The static pressure (P_f) is the absolute flowing fluid pressure measured at one of the flange tap holes. The absolute pressure may be measured directly or can be obtained by adding local barometric pressure to measured gauge pressure:

$$\text{absolute static pressure} = \text{gauge static pressure} + \text{local barometric pressure}$$

3.1.3 Temperature Measurement (T_f)

The temperature is the flowing fluid temperature (T_f) measured at the designated upstream or downstream location, as specified in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2.

In flow measurement applications where the fluid velocity is well below sonic, it is common practice to insert a temperature sensing device in the middle of the flowing stream to obtain the flowing temperature. For practical applications, the sensed temperature is assumed to be the static temperature of the flowing fluid.

The use of flowing temperature in this part of the standard requires the temperature to be measured in degrees Fahrenheit or degrees Celsius. However, if the flowing temperature is used in an equation of state to determine the density of the flowing fluid, it may require that the Fahrenheit or Celsius values be converted to absolute temperature values of degrees Rankine or Kelvin through the following relationships:

$$°R = °F + 459.67$$

$$K = °C + 273.15$$

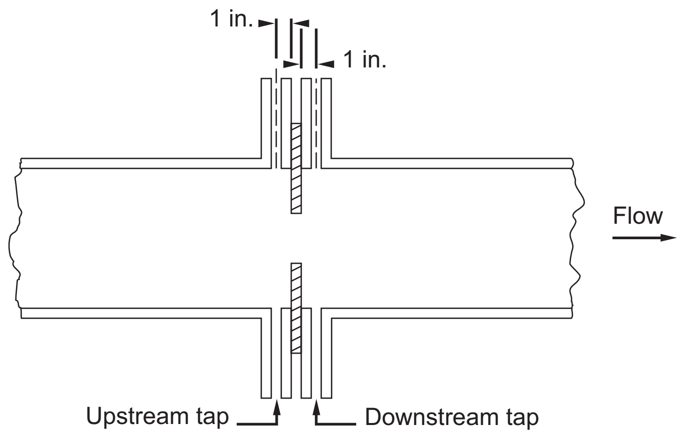

Figure 1—Orifice Tapping Location

3.1.4 Flow Rate Determination

3.1.4.1
orifice flow rate (q_m, q_v, Q_v)
The orifice flow rate is the mass or volume flow through an orifice meter per unit of time.

3.1.4.2
orifice plate coefficient of discharge (C_d)
The orifice plate coefficient of discharge (C_d) is the ratio of the actual flow to the theoretical flow and is applied to the theoretical flow equation to obtain the actual flow.

3.1.4.3
velocity of approach (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.

3.1.4.4
expansion factor (Y)
The expansion factor (Y) is an empirical expression used to correct the flow rate for the reduction in fluid density that a compressible fluid experiences when it passes through the orifice plate bore.

3.1.4.5
pipe Reynolds number (Re_D)
The pipe Reynolds number is a dimensionless ratio of forces used to correlate the variations in the orifice plate coefficient of discharge (C_d) with changes in the fluid's properties, flow rate, and orifice meter geometry.

3.1.5 Fluid Physical Properties

3.1.5.1
density ($\rho_{t,p}$, ρ_b)
The flowing fluid density ($\rho_{t,p}$) is the mass per unit volume of the fluid being measured at flowing conditions (T_f, P_f).

The base fluid density (ρ_b) is the mass per unit volume of the fluid being measured at base conditions (T_b, P_b).

3.1.5.2
absolute viscosity (μ)
The absolute viscosity (μ) is the measure of a fluid's intermolecular cohesive force's resistance to shear per unit of time.

3.1.5.3
compressibility (Z)
The compressibility (Z) is an adjustment factor used to account for the deviation from the ideal gas law.

3.1.5.4
isentropic exponent (κ)
The isentropic exponent (κ) is a thermodynamic state property that establishes the relationship between an expanding fluid's pressure and density as the fluid flows through the orifice plate bore. See 10.3 for further information on isentropic exponent as it applies to this standard.

3.1.6 Base Conditions (P_b, T_b)

Historically, the flow measurement of some fluids, such as custody transfer and process control, has been stated in volume units at base conditions of pressure and temperature. Base conditions are reference conditions of pressure and temperature for the calculation of volumes, generally defined by contract or regulation. Often base conditions are set as standard conditions and the terms are sometimes used interchangeably.

The base conditions for the flow measurement of fluids, such as crude petroleum and its liquid products, whose vapor pressure is equal to or less than atmospheric at base temperature are often designated as a pressure of 14.696 psia (101.325 kPa) at a temperature of 60.0 °F (15.56 °C) in the United States (U.S.) and 59.00 °F (15.00 °C) for ISO.

For fluids, such as liquid hydrocarbons, whose vapor pressure is greater than atmospheric pressure at base temperature, the base pressure is customarily designated as the equilibrium vapor pressure at base temperature.

Base conditions are normally defined by contract or government regulation. For interstate commerce, the base conditions for the flow measurement of natural gases are defined in the U.S. as a pressure of 14.73 psia (101.560 kPa) at a temperature of 60.0 °F (15.56 °C). Note, according to ISO, base conditions are defined as a pressure of 14.696 psia (101.325 kPa) at a temperature of 59.00 °F (15.00 °C).

For both liquid and gas applications, these base conditions can change from one country to the next, one state to the next, or one industry to the next. Therefore, it is necessary that the base conditions be identified for standard volumetric flow measurement.

3.1.7 Sensitivity Coefficient (S)

In estimating the uncertainty associated with the metering facility, a number of variables must be combined. The mathematical relationships among the variables establish the sensitivity of the metered quantities to each of these variables. As such, each variable that may influence the flow equation has a specific sensitivity coefficient. The derivation of this coefficient is based on a mathematical relationship or estimated from calculations, tables, or curves.

3.1.8 Meter Factor (MF)

The MF is a number obtained by dividing the quantity of fluid measured by the reference flow system by the quantity indicated by the orifice meter during calibration. See 9.2 for further information on meter factor as it applies to this standard.

3.1.9 In-situ Calibration

An in-situ calibration is defined as a calibration conducted under normal operating conditions, with the actual approach piping configuration, using the actual fluid with the actual orifice plate and recording system in place.

3.2 Symbols

This standard reflects orifice meter application to fluid flow measurement with symbols in general technical use.

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	coefficient of discharge at infinite pipe Reynolds number
$C_i\ (CT)$	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
c_v	specific heat at constant volume
d	orifice plate bore diameter calculated at flowing temperature, T_f
d_m	orifice plate bore diameter measured at T_m
d_r	orifice plate bore diameter at reference temperature, T_r
D	meter tube internal diameter calculated at flowing temperature, T_f
D_m	meter tube internal diameter measured at T_m
D_r	meter tube internal diameter at reference temperature, T_r
ΔP	orifice differential pressure
°C	temperature, in degrees Celsius
°F	temperature, in degrees Fahrenheit
K	temperature, in Kelvin
°R	temperature, in degrees Rankine
E_v	velocity of approach factor
g_c	dimensional conversion constant
G_i	ideal gas relative density (specific gravity)
κ	isentropic exponent
κ_i	ideal gas isentropic exponent
κ_p	perfect gas isentropic exponent
κ_r	real gas isentropic exponent
MF	calibration meter factor
Mr_{air}	molar mass of air
Mr_{gas}	molar mass of gas
N_1	unit conversion factor (orifice flow)
N_2	unit conversion factor (Reynolds number)
N_3	unit conversion factor (expansion factor)
N_4	unit conversion factor (discharge coefficient)
P	pressure
P_b	base (reference or standard) pressure
P_f	static pressure of fluid at the pressure tap
P_{f_1}	absolute static pressure at the orifice upstream differential pressure tap
P_{f_2}	absolute static pressure at the orifice downstream differential pressure tap

q_m	mass flow rate
q_{m_i}	mass flow rate indicated by the orifice meter being calibrated
q_{m_p}	mass flow rate determined by the reference flow system (or master meter)
q_v	volume flow rate at flowing (actual) conditions
q_{v_i}	volume flow rate indicated by the orifice meter being calibrated
Q_v	volume flow rate at base (standard) conditions
R	universal gas constant
R_a	roughness average value from continuously averaging meter readings
Re_D	pipe Reynolds number
T	temperature
T_b	base (reference or standard) temperature
T_f	temperature of fluid at flowing conditions
T_m	temperature of the orifice plate or meter tube at time of diameter measurements
T_r	reference temperature of orifice plate bore diameter and/or meter tube inside diameter
x	ratio of differential pressure to absolute static pressure
x_1	ratio of differential pressure to absolute static pressure at the upstream pressure tap
S	sensitivity coefficient (influence coefficient)
Y	expansion factor
Y_1	expansion factor based on upstream absolute static pressure
Y_2	expansion factor based on downstream absolute static pressure
Z	fluid compressibility
Z_f	fluid compressibility at flowing conditions
Z_{f_1}	compressibility of the fluid flowing at the upstream pressure tap location
Z_{f_2}	compressibility of the fluid flowing at the downstream pressure tap location
α	linear coefficient of thermal expansion
α_1	linear coefficient of thermal expansion of the orifice plate material
α_2	linear coefficient of thermal expansion of the meter tube material
β	ratio of orifice diameter to meter tube diameter calculated at flowing conditions
μ	absolute viscosity of fluid flowing
π	universal constant rounded to six significant figures
ρ	density of the fluid
ρ_b	density of the fluid at base conditions (P_b, T_b)
$\rho_{t,p}$	density of the fluid at flowing conditions (P_f, T_f)

4 Field of Application

4.1 Applicable Fluids

This standard applies to steady-state mass flow conditions for fluids that, for all practical purposes, are considered to be clean, single phase, homogeneous, and Newtonian and have pipe Reynolds numbers of 4,000 or greater. All gases, most liquids, and most dense phase fluids associated with the petroleum, petrochemical, and natural gas industries are usually considered Newtonian fluids.

4.2 Types of Meters

This standard provides design, construction, and installation specifications for flange-tapped, concentric, square-edged orifice meters of nominal 2-in. Schedule 160 and larger pipe diameters.

An orifice meter is a fluid flow measuring device that produces a differential pressure to infer flow rate. The meter consists of the following elements (see Figure 2):

a) a thin, concentric, square-edged orifice plate;

b) an orifice plate holder consisting of a set of orifice flanges (or an orifice fitting) equipped with the appropriate differential pressure sensing taps;

c) a meter tube consisting of the adjacent piping sections (with or without flow conditioners).

The auxiliary (secondary) devices necessary for the precise determination of flow rate are not included in the scope of this standard. These devices are usually instruments that sense the differential and static pressure, fluid temperature, and fluid density and/or relative density (specific gravity), and either mechanical recording devices or electronic calculators. A review of the publications of AGA, API, GPA, and others that address the specifications and installations of these auxiliary(secondary) devices is encouraged.

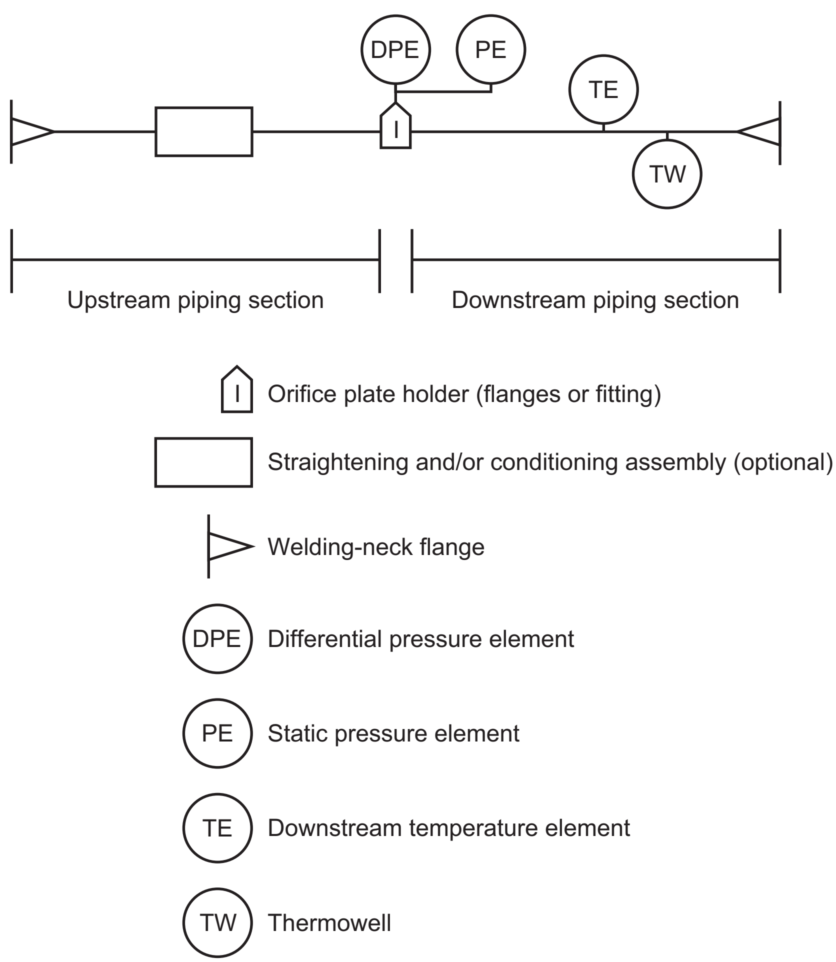

Figure 2—Orifice Meter Elements

4.3 Uncertainty of Measurement

Many factors influence the overall measurement uncertainty associated with a metering application. Major contributors include construction tolerances in the meter components, tolerances of empirical coefficient of discharge databases or in-situ flow calibrations, predictability of and variations in the fluid's physical properties, and uncertainties associated with the auxiliary (secondary and tertiary) devices.

Using the guidelines contained in this standard and other relevant industry standards in combination with the associated uncertainty tolerances for the fluid's physical properties, in-situ calibrations, or coefficient of discharge databases, and the appropriate auxiliary (secondary and tertiary) devices, the user can estimate the overall measurement uncertainty associated with a properly designed, installed, and maintained thin plate, concentric, square-edged orifice metering application.

5 Method of Calculation

This standard provides recommended standardized calculation implementation methods for the quantification of fluid flow under defined conditions, regardless of the point of origin or destination or the units of measure required by governmental customs or statute. The recommended implementation procedures provided in API *MPMS* Ch. 14.3, Part 4/AGA Report No. 3, Part 4 allow different entities using various computer languages on different computing hardware to arrive at nearly identical results using the same standardized input data.

The following two recommended implementation procedures have been prepared to illustrate the standardized set of mathematical expressions and sequencing, including iteration/rounding techniques:

a) mass flow rate,

b) standard volumetric flow rate.

The procedures presented address only the solution of the flow rate equation and require specific inputs (fixed and variable). Typical fixed inputs include meter tube internal diameter, orifice plate bore diameter, and linear coefficient of expansion for steels (pipe and orifice plate). Typical variable inputs may include differential and static pressure, temperature, fluid density, isentropic exponent for compressible fluids, and fluid viscosity.

The fluid's physical properties shall be determined by direct measurements, appropriate technical standards, or equations of state. If multiple parties are involved in the measurement, the appropriate technical method selected for determining the fluid's physical properties shall be mutually agreed upon.

6 Orifice Flow Equation

The accepted one-dimensional equation for mass flow through a concentric, square-edged orifice meter is stated in Equation (1) or Equation (2). The derivation is based on conservation of mass and energy, one-dimensional fluid dynamics, and empirical functions such as equations of state and thermodynamic process statements. Any derivation is accurate when all the assumptions used to develop it are valid. As a result, an empirical orifice plate coefficient of discharge is applied to the theoretical equation to adjust for multidimensional viscous fluid dynamic effects. In addition, an empirical expansion factor is applied to the theoretical equation to adjust for the reduction in fluid density that a compressible fluid experiences when it passes through an orifice plate.

The fundamental orifice meter mass flow equation is as follows:

$$q_m = C_d E_v Y (\pi/4) d^2 \sqrt{2 g_c \rho_{t,p} \Delta P} \quad (1)$$

where

C_d is the orifice plate coefficient of discharge;

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

ΔP is the orifice differential pressure;

E_v is the velocity of approach factor;

g_c is the dimensional conversion constant;

π is the universal constant = 3.14159;

q_m is the mass flow rate;

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

Y is the expansion factor.

The practical orifice meter flow equation used in this standard is a simplified form that combines the numerical constants and unit conversion constants in a unit conversion factor (N_1):

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

where

C_d is the orifice plate coefficient of discharge;

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

ΔP is the orifice differential pressure;

E_v is the velocity of approach factor;

N_1 is the unit conversion factor;

q_m is the mass flow rate;

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

Y is the expansion factor.

The expansion factor, Y, is included in Equation (1) and Equation (2) because it is applicable to all single-phase, homogeneous Newtonian fluids. For incompressible fluids, such as water at 60 °F (15.56 °C) and atmospheric pressure, the empirical expansion factor is defined as 1.0000.

The orifice plate coefficient of discharge, C_d, and the expansion factor, Y, are empirical functions derived from experimental data.

The orifice meter is a mass meter from which a differential pressure signal is developed as a function of the velocity of the fluid as it passes through the orifice plate bore. Manipulation of the density variable in the equation permits calculation of flow rate in either mass or volume units. The volumetric flow rate at flowing (actual) conditions can be calculated using the following equation:

$$q_v = q_m / \rho_{t,p} \tag{3}$$

The volumetric flow rate at base (standard) conditions can be calculated using the following equation:

$$Q_v = q_m / \rho_b \tag{4}$$

The mass flow rate (q_m) can be converted to a volumetric flow rate at base (standard) conditions (Q_v) if the fluid density at the base conditions (ρ_b) can be determined or is specified.

The unit conversion factor (N_1), is defined and presented in 11.1.

6.1 Velocity of Approach Factor (E_v)

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

$$E_v = \frac{1}{\sqrt{1-\beta^4}} \tag{5}$$

and

$$\beta = d/D \tag{6}$$

where

- d is the orifice plate bore diameter calculated at flowing temperature (T_f);
- D is the meter tube internal diameter calculated at flowing temperature (T_f).

6.2 Orifice Plate Bore Diameter (d)

The orifice plate bore diameter (d) is defined as the diameter at flowing conditions and can be calculated using the following equation:

$$d = d_r [1 + \alpha_1 (T_f - T_r)] \tag{7}$$

where

- α_1 is the linear coefficient of thermal expansion for the orifice plate material (see Table 1);
- d is the orifice plate bore diameter calculated at flowing temperature (T_f);
- d_r is the reference orifice plate bore diameter at reference temperature (T_r);
- T_f is the temperature of the fluid at flowing conditions;
- T_r is the reference temperature of the orifice plate bore diameter.

NOTE α, T_f, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68 °F (20 °C).

The orifice plate bore diameter (d_r) calculated at T_r is the diameter determined in accordance with the requirements contained in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2.

6.3 Meter Tube Internal Diameter (D)

The meter tube internal diameter (D) is defined as the diameter at flowing conditions and can be calculated using the following equation:

$$D = D_r [1 + \alpha_2 (T_f - T_r)] \tag{8}$$

where

α_2 is the linear coefficient of thermal expansion for the meter tube material (see Table 1);

D is the meter tube internal diameter calculated at flowing temperature (T_f);

D_r is the reference meter tube internal diameter at T_r;

T_f is the temperature of the fluid at flowing conditions;

T_r is the reference temperature of the meter tube internal diameter.

NOTE α, T_f, and T_r must be in consistent units. For the purpose of this standard, T_r is assumed to be 68 °F (20 °C).

The meter tube internal diameter (D_r) calculated at T_r is the diameter determined in accordance with the requirements contained in API *MPMS* 14.3, Part 2/AGA Report No. 3, Part 2.

Table 1—Linear Coefficient of Thermal Expansion

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

NOTE For flowing temperature limits or other materials, refer to the American Society for Metals (ASM) *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.

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).

7 Empirical Coefficient of Discharge

Empirical coefficients of discharge for flange-tapped orifice meters have been determined from experimental data by comparing the measured and theoretical flow rates. A major factor in the definition of the experimental patterns for this orifice research was dynamic similarity. Using Reynolds' Law of Similarity, experimental correlations can be applied to dynamically similar meters.

To accurately predict the coefficient of discharge, $C_d\ (FT)$, for a flange-tapped orifice meter manufactured to the specifications of this standard, certain parameters concerning the orifice meter and the fluid must be known. The relationships between these functions can be simplified for application to commercial use. In fact, the coefficient of discharge can be shown to depend on a number of parameters, the major ones being the Reynolds number (Re_D), sensing tap location, meter tube diameter (D), and β ratio:

$$C_d = f\,(Re_D, \text{ Sensing tap location}, D, \beta)$$

In 1978, Jean Stolz presented an equation form that correlates the near vicinity taps for orifice meters based on the near field static wall pressure gradient. A complete discussion of the bases of the equation is beyond the scope of this standard. However, the Bibliography will allow the reader to further explore this technical discussion.

7.1 Regression Database

Working jointly, a group of technical experts from the U.S., Europe, Canada, Norway, and Japan developed an equation using the Stolz linkage form that fits the regression data set more accurately than previously published equations. The current equation was developed from a significantly larger database than was previously used for discharge coefficient equation development.

The regression data set consists of data taken on four fluids (oil, water, natural gas, and air) from different sources, 11 different laboratories, on 12 different meter tubes of differing origins and more than 100 orifice plates of differing origins. The data provided a pipe Reynolds number range from accepted turbulent flow of 4,000 to 36,000,000 on which to select the best model. The orifice configurations included flange, corner, and radius taps. Nominal pipe sizes investigated were 2 in., 3 in., 4 in., 6 in., and 10 in., in compliance with AGA Report No. 3 specifications. Nominal β ratios used in the equation determination were 0.100, 0.200, 0.375, 0.500, 0.575, 0.660, and 0.750.

The bivariate data (C_d, Re_D) were measured in a manner appropriate for the test fluid and laboratory. The method of determining mass flow rate, expansion factor, fluid density, and fluid viscosity varied with the laboratory apparatus and test fluid.

Rather than including possibly erroneous data in the equation regression, the API/GPA/AGA technical experts envisioned two classes of data sets for orifice research regression and comparison. At a meeting of interested international orifice metering experts in November 1988, it was mutually agreed that the regression data set be defined as follows:

The regression data set shall consist of those data points contained in the API/GPA and EC [2] discharge coefficient experiments that were performed on orifice plates whose diameter was greater than 0.45 in. (11.4 mm) and if the pipe Reynolds number was equal to or greater than 4,000 (turbulent flow regime).

Data that do not satisfy these criteria shall not be included in the comparison data set.

Although it does not mean that other data are of inferior quality, it is known that insufficient information exists to determine whether the independent variables were controlled and quantified. Some examples of comparison quality data are the Ohio State University Database (303 flange-tapped points), the 1983 NBS [3] Boulder Experiments, the Foxboro-Columbus-Daniel 1,000-Point Database, and the Japanese Water Database.

The exclusion for orifice bore diameters less than 0.45 in. (11.4 mm) was due to the increased uncertainty associated with the relative sharpness of the orifice plate upstream edge.

The regression data set, as defined above, consists of data generated on orifice meters equipped with corner, radius, and flange tappings. The number of regression data points are summarized as follows:

Tapping	No. of Points
Flange	5,734
Corner	2,298
Radius	2,160
Total	10,192

2 European Commission, ec.europa.eu.
3 National Bureau of Standards [now known as National Institute of Standards and Technology (NIST)], 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899, www.nist.gov.

The empirical data associated with the API/GPA Database and the EC Database were the highest quality and largest quantity available when the equation was developed.

Detailed information on the experiments, regression data, statistical fit and other pertinent information may be found in API *MPMS* Ch. 14.3, Part 4/AGA Report No. 3, Part 4, or the references contained in the Bibliography.

7.2 Empirical Coefficient of Discharge Equation for Flange-tapped Orifice Meters

The concentric, square-edged, flange-tapped orifice meter coefficient of discharge, $C_d\,(FT)$, equation, developed by Reader-Harris/Gallagher (RG), is structured into distinct linkage terms and is considered to best represent the current regression database. The equation is applicable to nominal pipe sizes of 2 in. (50 mm) 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. (11.4 mm); and pipe Reynolds numbers (Re_D) greater than or equal to 4,000. For diameter ratios and pipe Reynolds numbers below the limit stated, refer to 12.4.1. The RG coefficient of discharge equation for an orifice meter equipped with flange taps is defined as follows:

$$C_d\,(FT) = C_i\,(FT) + 0.000511\left[\frac{10^6\beta}{Re_D}\right]^{0.7} + (0.0210 + 0.0049\,A)\beta^4 C \tag{9}$$

$$C_i\,(FT) = C_i\,(CT) + \text{tap term} \tag{10}$$

$$C_i\,(CT) = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1 \tag{11}$$

$$\text{tap term} = \text{upstrm} + \text{dnstrm} \tag{12}$$

$$\text{upstrm} = [0.0433 + 0.0712e^{-8.5L_1} - 0.1145e^{-6.0L_1}](1 - 0.23A)B \tag{13}$$

$$\text{dnstrm} = -0.0116[M_2 - 0.52\,M_2^{1.3}]\beta^{1.1}(1 - 0.14A) \tag{14}$$

also,

$$B = \frac{\beta^4}{1-\beta^4} \tag{15}$$

$$M_1 = \max\left[\left(2.8 - \frac{D_r}{N_4}\right)\text{or } 0.0\right] \tag{16}$$

$$M_2 = \frac{2L_2}{1-\beta} \tag{17}$$

$$A = \left[\frac{19{,}000\beta}{Re_D}\right]^{0.8} \tag{18}$$

$$C = \left[\frac{10^6}{Re_D}\right]^{0.35} \tag{19}$$

where

β is the diameter ratio;

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

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

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

d is the orifice plate bore diameter calculated at T_f;

D is the meter tube internal diameter calculated at T_f;

D_r is the meter tube internal diameter calculated at T_r;

e is the Napierian constant = 2.71828;

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

N_4 is 1.0 when D is in inches or 25.4 when D is in millimeters;

Re_D is the pipe Reynolds number.

7.3 Reynolds Number (Re_D)

The RG equation uses pipe Reynolds number as the correlating parameter to represent the change in the orifice plate coefficient of discharge (C_d) with reference to the fluid's mass flow rate (its velocity through the orifice), the fluid density, and the fluid viscosity.

The pipe Reynolds number can be calculated using the following equation:

$$Re_D = \frac{4q_m}{\pi\mu D} \tag{20}$$

The pipe Reynolds number equation used in this standard is in a simplified form that combines the numerical constants and unit conversion constants:

$$Re_D = \frac{N_2 q_m}{\mu D} \tag{21}$$

For the Reynolds number equations presented above, the symbols are described as follows:

D is the meter tube internal diameter calculated at flowing temperature (T_f);

μ is the absolute viscosity of fluid;

N_2 is the unit conversion factor;

π is the universal constant = 3.14159;

q_m is the mass flow rate;

Re_D is the pipe Reynolds number.

The unit conversion factor (N_2) for the Reynolds number equations is defined and presented in 11.2.

7.4 Flow Conditions

7.4.1 General

The condition of the meter tube, the mating of the piping sections, the ΔP sensing tap holes, the straight lengths of pipe preceding and following the primary element, and so forth, are factors that influence the flowing conditions.

Although some factors may be considered insignificant for commercial purposes, flowing conditions can influence field accuracy.

To assure accuracy within the uncertainty stated, certain flow condition limitations must be followed:

a) the flow shall approach steady-state mass flow conditions on fluids that are considered clean, single phase, homogeneous, and Newtonian;

b) the fluid shall not undergo any change of phase as it passes through the orifice;

c) the flow shall be subsonic through the orifice and the meter tube;

d) the Reynolds number shall be within the specified limitations of the empirical coefficients;

e) no bypass of flow around the orifice shall occur at any time.

7.4.2 Law of Similarity

The empirical coefficients calculated from the equations in this standard are valid if dynamic similarity exists between the metering installation and the experimental database. Technically, this approach is termed the Law of Similarity.

Dynamic similarity is the underlying principle for present-day theoretical and experimental fluid mechanics. The principle states that two geometrically similar meters with identical initial flow directions shall display geometrically similar streamlines.

The mechanical specifications for the meter tube, the orifice plate, the orifice flanges or fitting, the differential pressure sensing taps, the upstream and downstream piping requirements, the flow conditioner (if applicable), and the thermowell must be adhered to, as stated in the standard, to assure geometric similarity.

Geometric similarity requires that the experimental flow system be a scale model of the field installations. The experimental pattern's design identifies sensitive dimensional regions to explore, measure, and empirically fit. A proper experimental pattern for orifice meters allows the user to extrapolate to larger meter tube diameters without increasing the uncertainty.

Dynamic similarity implies a correspondence of fluid forces between the two metering systems. The Reynolds number is a measure of the ratio of the inertial to viscous forces. For the orifice meter, the inertial to viscous forces are the forces considered significant within the application limitations of this standard. As a result the Reynolds number is the term that correlates dynamic similarity in all empirical coefficient of discharge equations. In fact, the Reynolds number correlation provides a rational basis for extrapolation of the empirical equation, provided the physics of the fluid does not change. For instance, the physics associated with subsonic flow is not similar to that associated with sonic flow.

For the empirical database, undisturbed flow conditions (flow pattern and fully developed velocity profile) were achieved through the use of straight lengths of meter tube both upstream and downstream from the orifice and the use of flow conditioning. For both the API/GPA and EC experiments, an undisturbed flow condition was defined as the equivalent of a symmetrical, approximately swirl-free velocity profile located approximately 45 pipe diameters downstream of a Sprenkle flow conditioner, in circular pipes with an average internal surface wall roughness, R_a, of approximately 150 microinches (µin.).

7.5 Pulsating Flow

Reliable measurements of flow cannot be obtained with an orifice meter when appreciable pulsations are present at the point of measurement. Currently, no satisfactory theoretical or empirical adjustment for orifice measurement in pulsating flow applications exists that, when applied to custody transfer measurement, will maintain the measurement accuracy predicted by this standard.

7.5.1 Sources

Pulsations in a pipeline, originating from a reciprocating device, a rotary device, valve actions, piping configuration, or another similar source, consist of sudden changes in the velocity, pressure, and density of the fluid flowing. The most common sources of pulsation are the following:

a) reciprocating compressors, engines, or impeller-type boosters;

b) pumping or improperly sized pressure regulators and loose or worn valves;

c) irregular movement of quantities of water or oil condensates in the line;

d) intermitters on wells, automatic drips, or separator dumps;

e) dead-ended piping tee junctions and similar cavities.

7.5.2 Pulsation Reduction

To obtain reliable measurements, it is necessary to suppress pulsation. In general, the following practices have been effective in diminishing pulsation and/or its effect on orifice flow measurement:

a) locating the meter tube in a more favorable location with regard to the source of the pulsation, such as the inlet side of regulators, or increasing the distance from the source of the pulsation;

b) inserting capacity tanks (volume), flow restrictions, or specially designed filters in the line between the source of pulsation and the meter tube to reduce the amplitude of the pulsation;

c) using short-coupled impulse tubing and/or manifolds of approximately the same size as the pressure taps to the differential pressure measurement instrument;

d) operating at differentials as high as is practicable by replacing the orifice plate in use with a smaller orifice bore plate or by concentrating flow in a multiple meter tube installation through a limited number of tubes;

e) using smaller sized meter tubes and keeping essentially the same orifice diameter while maintaining the highest practical limit of the differential pressure.

Considerable study and experimentation have been conducted to evaluate the requirements and methods necessary to achieve pulsation reduction. This material is outside the scope of this standard and may be found in many publications that are readily available. For further discussion regarding pulsation reduction see API *MPMS* Ch. 14.3 Part 2/AGA Report No. 3, Part 2, Section 2.6.4.

7.5.3 Pulsation Instruments

Instruments, both mechanical and electronic, have been developed that indicate the presence of pulsation. These devices are used to determine the effectiveness of pulsation suppression practices.

8 Empirical Expansion Factor (Y) for Flange-tapped Orifice Meters

Previous expansibility research on water, air, steam, and natural gas using orifice meters equipped with various sensing taps was the basis for the Buckingham and Bean expansion factor equation (see API *MPMS* Ch. 14.3 Part 3/ AGA Report No. 3, Part 3). The previous empirical research compared the flow for an incompressible fluid with that of several compressible fluids.

The empirical expansion factor equations for orifice meters equipped with flange sensing taps have been derived based on the following correlation:

$$Y = f(\beta, \kappa, x)$$

where

- β is the diameter ratio;
- 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 polytropic, 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 nominal isentropic exponent is reasonable for most 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.

In 2004, new expansion factor research, funded by API, GPA, GTI [4], and PRCI [5], and carried out at CEESI [6] and SWRI [7] laboratories developed a new expansion factor database using air and natural gas. This new database was then regressed to provide the revised equation for expansibility.

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. If this assumption is unacceptable then appropriate steps should be taken to either measure the temperature upstream of the orifice plate or to calculate the upstream temperature from downstream measurements.

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

$$0.0 < \frac{\Delta P}{N_3 P_{f_1}} < 0.25$$

or

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

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4 Gas Technology Institute, 1700 South Mount Prospect Rd., Des Plaines, IL 60018, www.gastechnology.org.
5 Pipeline Research Council International, 3141 Fairview Park Dr., Suite 525, Falls Church, Virginia, 22042, www.prci.org.
6 Colorado Engineering Experiment Station, Inc., 54043 County Rd. 37, Nunn, Colorado 80648, www.ceesi.com.
7 Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78238-5100, www.swri.org

where

ΔP is the orifice differential pressure;

N_3 is the unit conversion factor;

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.

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.

8.1 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:

$$Y_1 = 1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - \left[\frac{P_{f_2}}{P_{f_1}}\right]^{1/\kappa}\right\} \quad (22)$$

or

$$Y_1 = 1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - [1 - x_1]^{1/\kappa}\right\} \quad (23)$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \quad (24)$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \quad (25)$$

where

β is the diameter ratio*;*

ΔP is the orifice differential pressure;

κ is the isentropic exponent;

N_3 is the unit conversion factor;

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.

Equation (22) and Equation (23) and the previous revision (1990) Buckingham and Bean expansion factor equation converge when x_1 is equal to zero. As x_1 increases, the difference between the two equations increases. Both equations are dependent on β and κ.

8.2 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:

$$Y_2 = Y_1 \sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{26}$$

or

$$Y_2 = \left[1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - \left[\frac{P_{f_2}}{P_{f_1}}\right]^{1/\kappa}\right\}\right]\sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{27}$$

or

$$Y_2 = \left[1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - [1 - x_1]^{1/\kappa}\right\}\right]\sqrt{\frac{P_{f_1} Z_{f_2}}{P_{f_2} Z_{f_1}}} \tag{28}$$

where

β is the diameter ratio;

κ is the isentropic exponent;

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.

9 In-situ Calibration

9.1 General

The statement of the uncertainty of the empirical coefficient of discharge (C_d) for concentric square-edged orifice meters, is predicated on compliance with the requirements of this standard.

For accurate measurement applications, the flowmeter and adjacent piping should meet the requirements of the relevant, preferably the most stringent, specification of the standard. Deviations from the standard's specifications (e.g. eccentricity, steps between adjacent sections of pipe, pre-run lengths with or without a flow conditioner, post-run lengths, and pipe wall roughness) will invalidate the uncertainty statement.

To assure the accuracy of such flow measurements, the user may wish to calibrate the meter in-situ. This is particularly suggested for orifice meters under 2 in. (50 mm) nominal pipe size.

Calibration of an orifice meter in-situ requires the use of a reference flow system. This reference flow system may be portable or permanently installed. A master meter that has been calibrated with a reference flow standard can also be used for in-situ calibration.

The in-situ calibration should be performed with a reference flow system (or master meter) with an overall uncertainty less than the overall uncertainty of q_m of the meter being calibrated. Refer to the working uncertainty equation given in Section 12.

To perform an in-situ calibration, the reference flow system (or master meter) should be installed either upstream or downstream of the pipe fitting nearest to the meter tube or meter tube manifold so that it provides a calibration of the meter in its normal flowing configuration (that is, velocity profile). In-situ calibration should be performed at the normal flow rate, temperature, and pressure of the meter station. Additionally, in-situ calibration may be performed over the range of flow rates, temperatures, and pressures to assure a higher confidence level over the complete range of flowing conditions.

9.2 Meter Factor (*MF*)

The in-situ calibration can provide an MF that may be used to correct the calculated mass flow rate as determined by Equation (1), if agreed upon by the parties. The MF is defined as follows:

$$MF = \frac{q_{m_p}}{q_{m_i}} = \frac{q_{m_p}}{q_{v_i}\rho_{t,p}} \tag{29}$$

where

q_{m_p} is the mass flow rate determined by the reference flow system (or master meter);

q_{m_i} is the mass flow rate indicated by the orifice meter being calibrated;

q_{v_i} is the volumetric flow rate indicated by the orifice meter being calibrated;

$\rho_{t,p}$ is the density (mass) of fluid at the meter at flowing conditions.

Alternatively, the results may be used to identify installations that exceed the uncertainty estimated using Section 12. If the MF falls outside the $0.9 \leq MF \leq 1.1$ limits, the system should be investigated until the physical cause for the deviation has been identified and corrected.

When the MFs are determined over a range of operating conditions, several values of MF may result. A plot of MF vs pipe Reynolds number (Re_D) should provide a single curve that may be used for determining MF corrections.

If the MF is applied to the metered quantities for custody transfer purposes, then in-situ calibration should be periodically repeated to ensure accurate measurement. Additional in-situ calibrations should be performed when physical changes to the metering system or significantly different operating conditions are encountered.

10 Fluid Physical Properties

Certain fluid physical properties are required to solve the orifice flow equation.

For the mass flow equation, the following fluid properties are required:

a) the viscosity at flowing conditions (μ);

b) the fluid density at flowing conditions ($\rho_{t,p}$);

c) the isentropic exponent (κ), for compressible fluids.

For the standard volumetric flow equation, the density at base conditions, (ρ_b), is required for solution.

10.1 Viscosity (μ)

The absolute (or dynamic) viscosity of the fluid at flowing conditions is required to compute the pipe Reynolds number. Fluid viscosities may be measured experimentally or computed from empirical equations.

For high Reynolds number applications, viscosity variations are usually ignored, since a sensitivity analysis indicates negligible effect in the flow computation. For low Reynolds number applications, accurate viscosity values and their variation with composition, temperature, and pressure may have a significant effect on the flow computation.

10.2 Density ($\rho_{t,p}$, ρ_b)

Appropriate values for the density of the fluid, $\rho_{t,p}$ and ρ_b, can be obtained using one of the two following methods.

a) Empirical density correlation. The empirical density value may be calculated by an equation of state or another technically qualified expression.

b) On-line density meters. An on-line density meter can measure the fluid density at operating conditions (or base conditions).

For on-line density meter applications where the density at flowing conditions (or base conditions) is greater than 0.30 g/cm^3, refer to API *MPMS* Ch.14.6 for the installation, operation, and calibration of these devices.

For on-line density meter applications where the density at flowing conditions (or base conditions) is less than 0.30 g/cm^3, refer to the manufacturers' recommendations for the installation, operation, and calibration of these devices. The manufacturer should be able to demonstrate that operation of the on-line density measurement device will not interfere with the basic operation of the orifice meter.

From a practical standpoint, the fluid temperature differences between the upstream sensing tap, the downstream sensing tap, and the temperature sensing device are assumed to be insignificant when the temperature device is installed as required in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2. For fluids whose density changes rapidly with changes in flowing temperature, for low fluid velocities, and/or to minimize ambient temperature and heat transfer effects, the user may wish to thermally insulate the meter tube between the primary element and the temperature device.

10.3 Isentropic Exponent (κ)

The isentropic exponent (κ), is required in the solution of the empirical expansion factor (Y) equation.

As a compressible fluid flows through the reduced area of an orifice plate bore, it undergoes a contraction and then an expansion. The expansion, which results in a change in the static pressure, is assumed to follow a polytropic path expressed by the following relationship:

$$\frac{P_f}{[\rho_{t,p}]^n} = \text{Constant} \tag{30}$$

where

P_f is the absolute static pressure;

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

n is the polytropic exponent.

However, if the expansion is assumed to be relatively rapid (that is, short in length) and the pressure change relatively small in magnitude, the polytropic relationship can be replaced by an idealized (reversible and adiabatic) one-dimensional isentropic expansion relationship of the following form:

$$\frac{P_f}{[\rho_{t,p}]^\kappa} = \text{Constant} \tag{31}$$

where

P_f is the absolute static pressure;

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

κ is the isentropic exponent.

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 its specific heats (c_p/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). 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 equations.

11 Unit Conversion Factors

11.1 Orifice Flow Equation

The values for the unit conversion factor (N_1), for the orifice flow rate equation are summarized in Table 2. The table contains common engineering units, along with their corresponding conversion factor value.

11.2 Reynolds Number Equation

The values for the unit conversion factor (N_2), for the Reynolds number equation are summarized in Table 3. The table contains common engineering units, along with their corresponding conversion factor value.

11.3 Expansion Factor Equation

The values for the unit conversion factor (N_3), for the expansion factor equation are summarized in Table 4. The table contains common engineering units, along with their corresponding conversion factor value.

11.4 Flow Rate per Unit of Time Conversion

To convert the mass or volume flow rate per unit of time to another unit of time, the following multiplication factors are applicable:

From	To	Multiplying Factor
Units per second	Units per minute	60
Units per second	Units per hour	3,600
Units per second	Units per day	86,400

Table 2—Orifice Flow Rate Equation: Unit Conversion Factor (N_1)

Mass Rate

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

Volumetric Rate at Flowing (Actual) Conditions

$$q_v = \frac{q_m}{\rho_{t,p}} = \frac{N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}}{\rho_{t,p}}$$

Volumetric Rate at Base Conditions

$$Q_v = \frac{q_m}{\rho_b} = \frac{N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p} \Delta P}}{\rho_b}$$

where

	USC Units	SI Units	
π	3.14159	3.14159	Universal constant
g_c	32.1740	NA	lbm-ft/(lbf-s^2)
g_c	NA	1.0000	kg · m/(N · s^2)
d	ft	m	
ΔP	lbf/ft^2	Pa	
$\rho_{t,p}$	lbm/ft^3	kg/m^3	
ρ_b	lbm/ft^3	kg/m^3	
q_m	lbm/s	kg/s	
q_v	ft^3/s	m^3/s	
Q_v	Sft^3/s	m^3/s	
N_1	6.30025	1.11072	

	USC Units	USC Units	USC Units	SI Units	SI Units	
π	3.14159	3.14159	3.14159	3.14159	3.14159	Universal Constant
g_c	32.1740	32.1740	32.1740	NA	NA	lbm-ft/ (lbf-s^2)
g_c	NA	NA	NA	1.0000	1.0000	kg · m/(N · s^2)
D	in.	in.	in.	mm	mm	
ΔP	lbf/in.^{2}	in. H_2O_{60}	in. H_2O_{68}	millibar	kPa	
$\rho_{t,p}$	lbm/ft^3	lbm/ft^3	lbm/ft^3	kg/m^3	kg/m^3	
ρ_b	lbm/ft^3	lbm/ft^3	lbm/ft^3	kg/m^3	kg/m^3	
q_m	lbm/s	lbm/s	lbm/s	kg/s	kg/s	
q_v	ft^3/s	ft^3/s	ft^3/s	m^3/s	m^3/s	
Q_v	Sft^3/s	Sft^3/s	Sft^3/s	m^3/s	m^3/s	
N_1	0.525021	0.0997424	0.0997019	0.0000111072	0.0000351241	

Table 3—Reynolds Number Equation: Unit Conversion Factor (N_2)

$$Re_D = \frac{4q_m}{\pi\mu D} \text{ or } Re_D = \frac{N_2 q_m}{\mu D}$$

where

		USC Units	SI Units	
	q_m	lbm/s	kg/s	Universal constant
	π	3.14159	3.14159	SI Unit equal to Pa-s
	μ	lbm/ft-s	kg/m-s	
	D	ft	m	
	N_2	1.27324	1.27324	

	USC Units	USC Units	SI Units	SI Units	
q_m	lbm/s	lbm/s	kg/s	kg/s	Universal Constant
π	3.14159	3.14159	3.14159	3.14159	
μ	centipoise	poise	centipoise	poise	
D	in.	in.	mm	mm	
N_2	22,737.5	227.375	1,273,240	12,732.4	

Table 4—Empirical Expansion Factor Equation: Unit Conversion Factor (N_3)

$$x = \frac{\Delta P}{N_3 P}$$

		USC Units	SI Units
	ΔP	lbf/ft^2	Pa
	P	lbf/ft^2	Pa
	N_3	1.00000	1.00000

	USC Units	USC Units	USC Units
ΔP	lb/in.^{2}	in. H_2O_{60}	in. H_2O_{68}
P	lb/in.^{2}	lb/in.^{2}	lb/in.^{2}
N_3	1.00000	27.7072	27.7297

	SI Units	SI Units	SI Units
ΔP	kPa-	mbar	mbar
P	MPa	bar	MPa
N_3	1000.00	1000.00	0.010000

12 Practical Uncertainty Guidelines

The most important assumption underlying the calculation of the orifice discharge coefficient equation is that laboratories' systematic equipment biases are randomized within the database. This means that there is no bias in the equation's ability to represent reality due to equipment variety in the various laboratories. Such an assumption of randomization has precedent in ISO 5168, established in 1978, and a 1939 paper by Rossini and Deming. This allows the use of results from the world's finest laboratories without requiring that experimental equipment be identical.

Every effort has been made to remove residual bias from the representation of the experimental data by the equation for mass flow. Consequently, the subsequent precision statements are valid for an individual orifice meter installation for which physical characteristics and measurements of these characteristics are maintained within the precision that is used to determine the contributions to imprecision in mass flow measurement caused by various factors.

In accordance with prudent statistical and engineering practice, the estimated orifice flow rate uncertainty shall be calculated at the 95 % confidence level.

12.1 General

Many factors associated with an orifice installation influence the overall error in flow measurement. These errors are due to uncertainties about the following:

a) representation of reality by the mass flow equation;

b) uncertainty about actual physical properties of the fluid being measured;

c) imprecision in the measurement of important installation parameters (such as orifice diameter and β ratio).

Examples of the calculations of the overall uncertainty as it depends on these major categories are given below. For ease of understanding, graphical summaries are presented where feasible.

12.2 Uncertainty Over a Flow Range

From a practical standpoint, the accuracy envelope for an orifice meter is usually estimated using the uncertainty assigned to the differential pressure-sensing device. This technique realistically estimates the uncertainty associated with the designer's flow range.

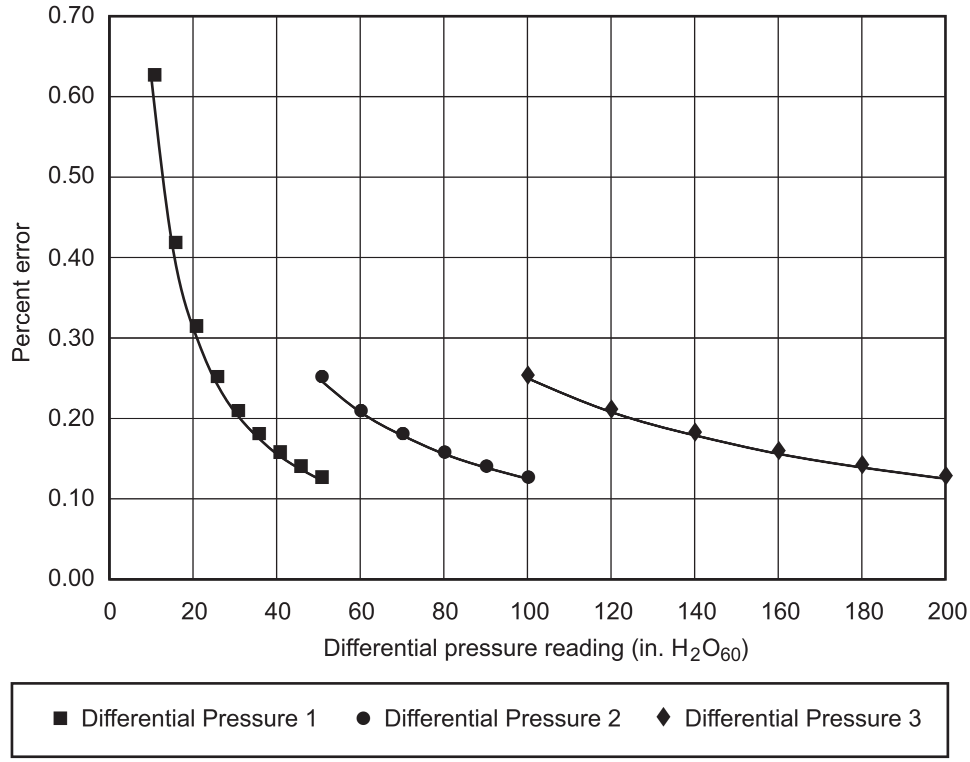
An accuracy envelope incorporates the influence quantities associated with the ΔP sensing device. The significant quantities include ambient temperature effects, static pressure effects, long-term drift, hysteresis, linearity, repeatability, and the calibration standard's uncertainty.

For some applications, parallel orifice meters are required to meet the user's desired uncertainty and rangeability. In addition, the designer may choose to install stacked ΔP devices calibrated for different ranges to minimize uncertainty while maximizing rangeability for a given orifice plate, as shown in Figure 3.

12.3 Uncertainty of Flow Rate

The overall uncertainty is the quadrature sum (square root of the sum of the squares) of the uncertainties associated with the pertinent variables:

$$q_m = f(C_d, Y, \Delta P, d, D, \rho_{t,p})$$



NOTE The precision of the differential pressure device used in this example is ±0.25 % of full scale.

Figure 3—Contribution to Flow Error Due to Differential Pressure Instrumentation

For practical considerations, the pertinent variables are assumed to be independent to provide a simpler uncertainty calculation. In fact, no significant change in the uncertainty estimate will occur if the user applies the simplified uncertainty equations presented below.

The total uncertainty of the flow rate through an orifice meter may be calculated by one of two methods:

a) empirical coefficient of discharge using flange-tapped orifice meters;

b) in-situ calibration using orifice meters.

12.3.1 Uncertainty Using Empirical Coefficient of Discharge for Flange-tapped Orifice Meter

The basic flow Equation (1) used is as follows:

$$q_m = C_d E_v Y(\pi/4) d^2 \sqrt{2 g_c p_{t,p} \Delta P}$$

where

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

E_v is the velocity of approach factor;

β is the diameter ratio.

Using differentiation, it can be shown that:

$$(\delta q_m/q_m) = SC_d\ (\delta C_d/C_d) + SE_v(\delta E_v/E_v) + S_Y(\delta Y/Y) + S_d(\delta d/d) + S\rho_{t,p}(\delta\rho_{t,p}/\rho_{t,p}) + S_{\Delta P}(\delta\Delta P/\Delta P) \quad (32)$$

where

S is the sensitivity coefficient of the particular variable.

Therefore,

$SE_v\ SC_d$ and $S_Y = 1.0$

and

$$S_d = 2$$
$$S_{\rho_{t,p}} = 1/2$$
$$S_{\Delta P} = 1/2$$

By continuing this process to put $\delta E_v/E_v$ in terms of $\delta d/d$ and $\delta D/D$, it can be shown that:

$$(\delta E_v/E_v) = \frac{2\beta^4}{1-\beta^4}[(\delta d/d) - (\delta D/D)] \quad (33)$$

Assuming that independent estimates are available for $\delta C_d/C_d$, $\delta Y/Y$, $\delta d/d$, and $\delta D/D$ and substituting for $\delta E_v/E_v$ gives us the following working equation for the uncertainty of the mass flow rate:

$$\frac{\delta q_m}{q_m} = \left\{\left(\frac{\delta C_d}{C_d}\right)^2 + \left(\frac{\delta Y}{Y}\right)^2 + \left[\frac{2\beta^4}{1-\beta^4}\right]^2\left(\frac{\delta d}{d}\right)^2 + 4\left(\frac{\delta d}{d}\right)^2 + \left[\frac{-2\beta^4}{1-\beta^4}\right]^2\left(\frac{\delta D}{D}\right)^2 + \frac{1}{4}\left(\frac{\delta\rho_{t,p}}{\rho_{t,p}}\right)^2 + \frac{1}{4}\left(\frac{\delta\Delta P}{\Delta P}\right)^2\right\}^{0.5} \quad (34)$$

12.3.2 Uncertainty Using an In-situ Calibration

When the orifice meter has been calibrated in-situ, the practical working formula for the uncertainty of the mass flow rate can be expressed as follows:

$$(\delta q_m/q_m) = [(\delta MF/MF)^2 + 1/4(\delta\Delta P/\Delta P)^2 + 1/4(\delta\rho_{t,p}/\rho_{t,p})^2]^{0.5} \quad (35)$$

The MF term is estimated from the combination of the reference flow uncertainty, the master meter uncertainty, and the precision of the orifice meter calibration. Note that the MF determined for the orifice plate and tube is a combination of several possible errors. No additional uncertainty is necessary for installation conditions or expansion factor.

12.4 Typical Uncertainties

For precise metering applications, such as custody transfer, the flowmeter and adjacent piping should meet the requirements of the relevant, preferably the most stringent, specification of the standard. In the following sections, the typical uncertainties expressed can be obtained only through compliance with the specifications of the standard.

12.4.1 Empirical Coefficient of Discharge

The estimated uncertainty of the empirical coefficient of discharge for concentric, square-edged, flange-tapped orifice meters that are in compliance with this standard is a function of the Reynolds number and the diameter ratio (β). At very high Reynolds numbers the uncertainty is only a function of the diameter ratio (β). This uncertainty estimate is shown graphically in Figure 4. As the Reynolds number decreases, the uncertainty of the orifice plate coefficient of discharge increases. The ratio of the uncertainty at a given Reynolds number to the uncertainty at infinite Reynolds number is shown graphically in Figure 5. The overall uncertainty of the empirical coefficient of discharge is the product of the value read from Figure 4 and the value read from Figure 5. The values for Figure 4, expressed in percentage, may be approximated by the following:

For $\beta > 0.175$,

$$\delta C_i\,(FT)/C_d\,(FT) = 0.5600 - 0.2550\beta + 1.9316\beta^8 \tag{36}$$

For $\beta \le 0.175$,

$$\delta C_i\,(FT)/C_d\,(FT) = 0.7000 - 1.0550\beta \tag{37}$$

The values for Figure 5 may be approximated by the following:

$$\delta C_d\,(FT)/\delta C_i\,(FT) = 1 + 0.7895\left(\frac{4,000}{Re_D}\right)^{0.8} \tag{38}$$

These estimates for the uncertainty were developed using the regression database discussed in 7.1. Orifice plates with bore diameters less than 0.45 in. (11.4 mm), installed according to API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2 may have coefficient of discharge [$C_d\,(FT)$] uncertainties as great as 3.0 %. This large uncertainty is due to problems with edge sharpness. These types of problems are discussed further in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2. Deviations from the installation specifications in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2 will invalidate this uncertainty statement.

12.4.2 Empirical Expansion Factor for Flange-tapped Orifice Meters

The values of Y computed by the empirical equations are subject to a tolerance varying from 0, when $x_1 = 0$, to ±0.5 %, when $x_1 = 0.2$. For larger values of x_1, a larger uncertainty may be expected.

An alternative approach for determining the uncertainty for the expansion factor stipulates that when β, ΔP, P_f, and κ are assumed to be known without error, the percentage uncertainty of the value of Y is estimated by:

$$\pm 2.6\left[\frac{\Delta P}{N_3 P_f}\right]$$

This value comes from a detailed analysis of the data used in the regression. A white paper on this analysis was written and is referenced in the Bibliography. For fluids that are not compressible, the expansion factor equals 1.000 by definition, and the estimated uncertainty is zero.

12.4.3 Installation Conditions

To assure accurate flow measurement, the fluid should enter the orifice plate with a fully developed flow profile, free from swirl or vortices. Such a condition is best achieved through the use of flow conditioners and adequate lengths of straight pipe preceding and following the orifice plate.

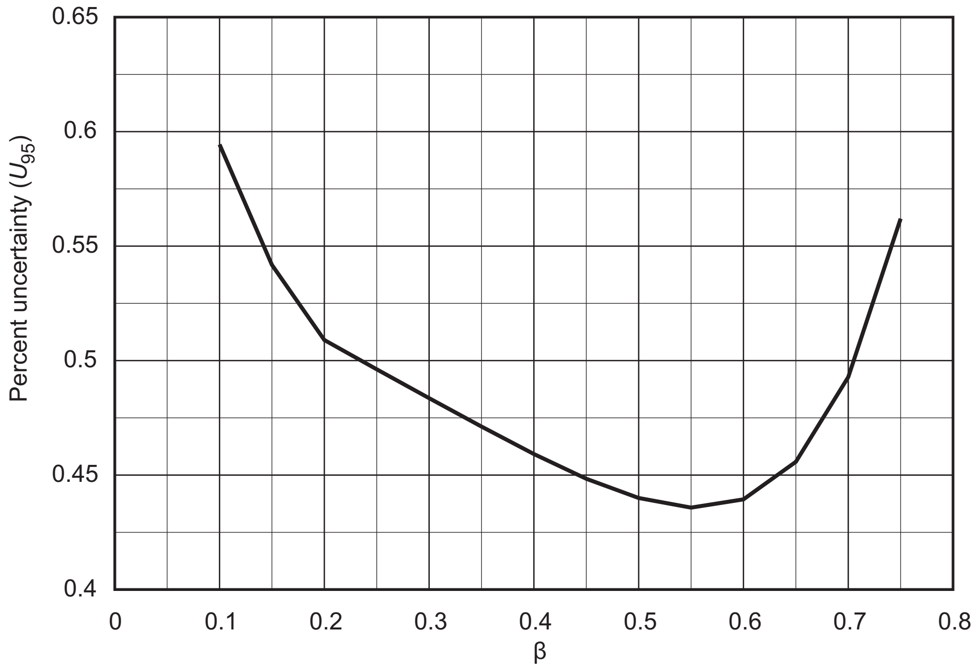


Figure 4—Empirical Coefficient of Discharge: Uncertainty at Infinite Reynolds Number

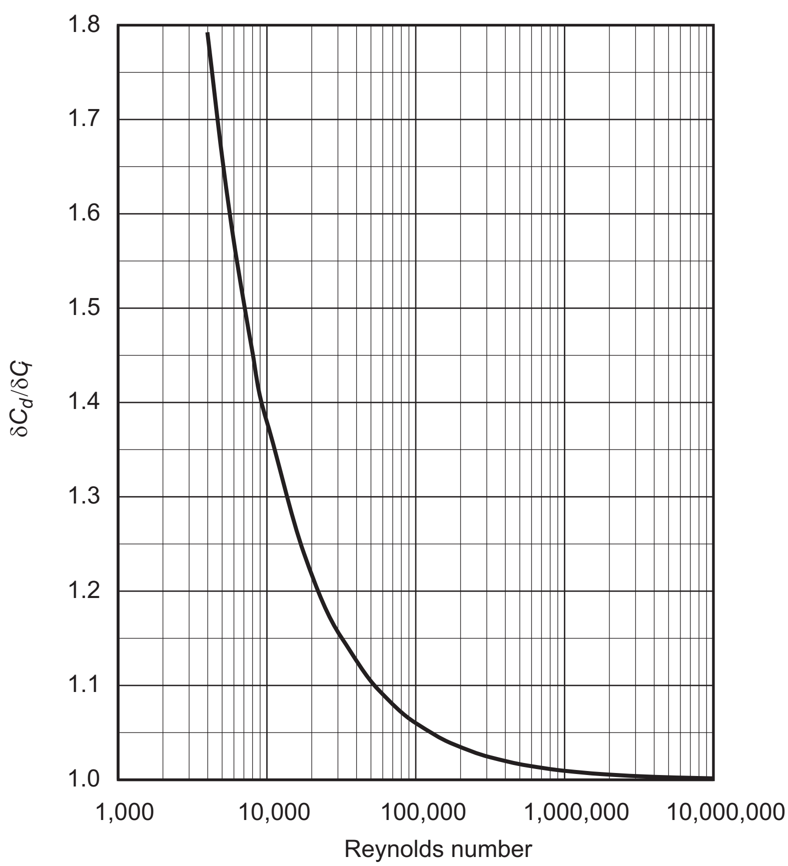


Figure 5—Relative Change in Uncertainty: Dependence on Reynolds Number

Table 5—Uncertainty Statement for Empirical Expansion Factor

Common USC Units										
ΔP	ΔP	Expansion Factor Uncertainty (%) When P_f (psia) Equals								
in. H_2O_{60}	psid	25	50	100	250	500	750	1,000	1,250	1,500
10	0.36	0.04	0.02	0.01	0	0	0	0	0	0
50	1.80	0.19	0.09	0.05	0.02	0.01	0.01	0	0	0
100	3.61	0.38	0.19	0.09	0.04	0.02	0.01	0.01	0.01	0.01
150	5.41	0.56	0.28	0.14	0.06	0.03	0.02	0.01	0.01	0.01
200	7.22	NA	0.38	0.19	0.08	0.04	0.03	0.02	0.02	0.01
250	9.02	NA	0.47	0.23	0.09	0.05	0.03	0.02	0.02	0.02
300	10.83	NA	0.56	0.28	0.11	0.06	0.04	0.03	0.02	0.02
350	12.63	NA	NA	0.33	0.13	0.07	0.04	0.03	0.03	0.02
400	14.44	NA	NA	0.38	0.15	0.08	0.05	0.04	0.03	0.03
450	16.24	NA	NA	0.42	0.17	0.08	0.06	0.04	0.03	0.03
500	18.05	NA	NA	0.47	0.19	0.09	0.06	0.05	0.04	0.03
Common SI Units										
ΔP	ΔP	Expansion Factor Uncertainty (%) When P_f (MPa) Equals								
In. H_2O_{60}	kPa	0.17	0.3	0.7	1.7	3.4	5.2	6.9	8.6	10.3
10	2.49	0.04	0.02	0.01	0	0	0	0	0	0
50	12.44	0.19	0.09	0.05	0.02	0.01	0.01	0	0	0
100	24.88	0.38	0.19	0.09	0.04	0.02	0.01	0.01	0.01	0.01
150	37.33	0.56	0.28	0.14	0.06	0.03	0.02	0.01	0.01	0.01
200	49.77	NA	0.38	0.19	0.08	0.04	0.03	0.02	0.02	0.01
250	62.21	NA	0.47	0.23	0.09	0.05	0.03	0.02	0.02	0.02
300	74.65	NA	0.56	0.28	0.11	0.06	0.04	0.03	0.02	0.02
350	87.15	NA	NA	0.33	0.13	0.07	0.04	0.03	0.03	0.02
400	99.60	NA	NA	0.38	0.15	0.08	0.05	0.04	0.03	0.03
450	112.05	NA	NA	0.42	0.17	0.08	0.06	0.04	0.03	0.03
500	124.50	NA	NA	0.47	0.19	0.09	0.06	0.05	0.04	0.03

NOTE 1 Orifice plates having bore diameters less than 0.45 in. (11.4 mm), installed according to API *MPMS* Ch. 14.3, Part 2/ AGA Report No. 3, Part 2, may have coefficient of discharge (Cd) uncertainties as great as 3.0 %. This large uncertainty is due to problems with edge sharpness.

NOTE 2 The relative uncertainty level depicted in Figure 6 assumes a symmetric swirl-free inlet velocity profile.

For various technical reasons, the uncertainty associated with installation conditions is difficult to quantify. Therefore, Figure 6 has been provided as a general guide. This figure represents a combined practical uncertainty level attributed to the following parameters:

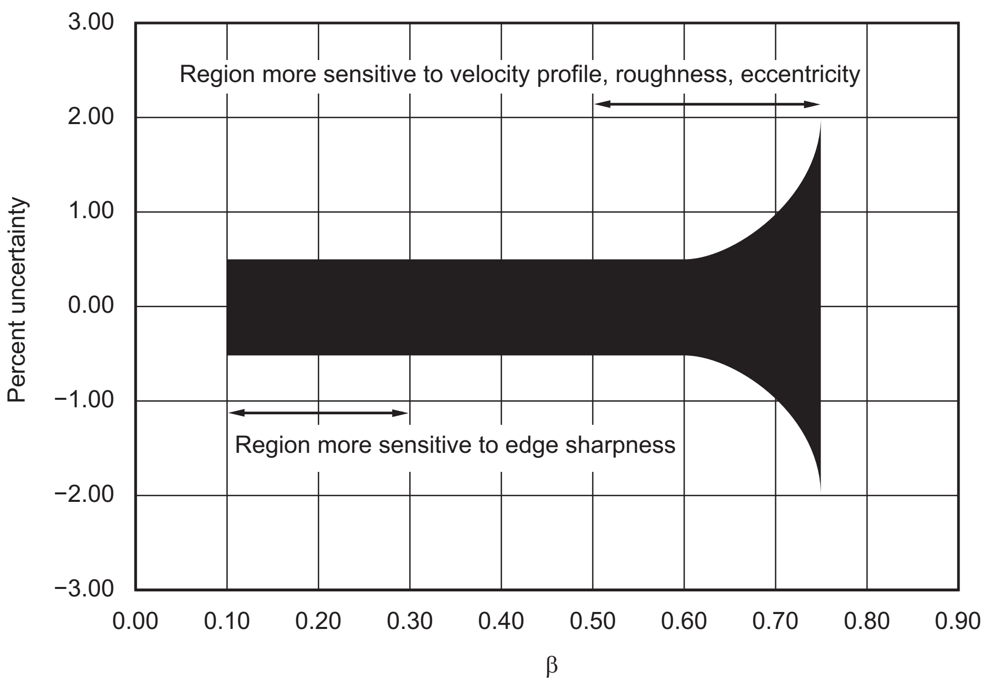
a) empirical coefficient of discharge;

b) installation conditions, such as velocity profile and swirl;

c) mechanical specifications, such as pipe wall roughness, plate eccentricity, and orifice plate bore edge sharpness.

Figure 6 depicts the prospective combined uncertainty level as a function of diameter ratio (β). It is apparent from the figure that the lowest relative combined uncertainty levels occur over a diameter ratio range of 0.10 to 0.60.

The approach length (upstream meter tube), piping configuration, and flow conditioning recommendations presented in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2 include changes to the installation requirements (meter tube lengths). These changes reduce the uncertainty attributable to installation effects to a magnitude smaller (one half or less) than the uncertainty of the database supporting the RG equation and, therefore, constitute no need for additional measurement uncertainty. Substantial research programs in support of these changes were conducted by API, EC, and GRI.



NOTE 1 Orifice plates whose bore diameters are less than 0.45 in. (11.4 mm), installed according to, API *MPMS* Ch. 14.3 Part 2/AGA Report No. 3, Part 2, may have coefficient of discharge uncertainties as great as 3.0 %. This large uncertainty is due to problems with edge sharpness.

NOTE 2 The relative uncertainty level shown in the figure assumes a symmetric swirl-free inlet velocity profile.

Figure 6—Practical Uncertainty Levels

12.4.4 Orifice Plate Bore Diameter

The plate diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2.

If the dimensional measurements are available, the plate diameter uncertainty is equated to the root mean square (rms) of the differences between each reading and the mean value.

For example [8], if the four measurements for d_m are 20.005, 20.002, 19.995, and 19.998, then the mean value is 20.000.

The deviations from the mean are +0.005, +0.002, –0.005, and –0.002, so:

$$\delta d_m = \left[\frac{\sum_{i=1}^{n}(\delta d_{m_i})^2}{n-1}\right]^{0.5}$$

$$= \pm\left[\frac{(0.005)^2 + (0.002)^2 + (-0.005)^2 + (-0.002)^2}{3}\right]^{0.5}$$

$$= \pm\, 0.0044$$

$$\frac{\delta d_m}{d_m} = \pm\frac{0.0044}{20.00}$$

$$= \pm 0.00022 \times 100$$

$$= \pm 0.022\ \%$$

12.4.5 Meter Tube Internal Diameter

The meter tube diameter uncertainty may be determined from dimensional measurements or, alternatively, from the roundness specifications presented in API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2.

If the dimensional measurements are available, the meter tube diameter uncertainty is equated to the rms of the differences between each reading and the mean value.

For example [9], if the four measurements for D_m are 20.050, 20.020, 19.950, and 19.980, then the mean value is 20.000.

The deviations from the mean are +0.05, +0.02, –0.05, and –0.02, so:

$$\delta D_m = \left[\frac{\sum_{i=1}^{n}(\delta D_{m_i})^2}{n-1}\right]^{0.5}$$

$$= \pm\frac{(0.05)^2 + (0.02)^2 + (-0.05)^2 + (-0.02)^2}{3}$$

$$= \pm 0.044$$

[8] These examples are merely for illustration purposes only. Each company should develop its own approach. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

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$$\frac{\delta D_m}{D_m} = \pm\frac{0.044}{20.00}$$

$$= \pm 0.0022 \times 100$$

$$= \pm 0.22\ \%$$

12.4.6 Differential Pressure Device

Performance specifications for the differential pressure device must be provided by the manufacturer. The user selects a device based on its performance specifications and the desired uncertainty associated with the application.

When considering the uncertainty, care should be taken to take into account the effects of ambient temperature, humidity, static pressure, driving mechanism, and response time on the user-selected device.

12.4.7 Fluid Density

When an empirical correlation is used to predict a liquid density, the uncertainty should be estimated based on the stated uncertainty of the correlation and the estimated uncertainty of the variables required to calculate the density. The following example for proplyene, calculated using the method of API *MPMS* Ch. 11.3.3.2, demonstrates this procedure.

Proplyene is being metered at 60 °F and 800 psia. The stated uncertainty of the API *MPMS* Ch. 11.3.3.2 method for calculating the density of proplyene is ±0.24 %. The stated uncertainty of the temperature measurement is ±0.5 °F. The stated uncertainty of the pressure measurement is ±4 psia. The uncertainty in the density is calculated according to the following formula:

$$(\delta\rho_{t,p}/\rho_{t,p}) = \left\{(\delta\rho_{t,p}/\rho_{t,p})^2 + \left[\frac{\partial\rho_{t,p}}{\partial T_f}\right]^2_{P_f}(\delta T_f/\rho_{t,p})^2 + \left[\frac{\partial\rho_{t,p}}{\partial P_f}\right]^2_{T_f}(\delta P_f/\rho_{t,p})^2\right\}^{0.5} \tag{39}$$

Using this method, the following calculated values can be used to estimate $\left(\partial\rho_{t,p} / \partial T_f\right)_{P_f}$ and $\left(\partial\rho_{t,p}/\partial P_f\right)_{T_f}$

T_f (°F)	P_f (psia)	Density (lb/ft³)
60	800	33.3413
60	780	33.3215
60	820	33.3611
58	800	33.4445
62	800	33.2376

$$\left[\frac{\delta\rho_{t,p}}{\delta T_f}\right]_{P_f} \cong (33.2376 - 33.4445)/4 = -0.052$$

$$\left[\frac{\delta\rho_{t,p}}{\delta P_f}\right]_{T_f} \cong (33.3611 - 33.3215)/40 = -0.00099$$

then

$$\delta\rho_{t,p}/\rho_{t,p} \cong \pm\left[(0.0024)^2 + (-0.052)^2\left(\frac{0.5}{33.3413}\right)^2 + (0.00099)^2\left(\frac{4}{33.3413}\right)^2\right]^{0.5}$$

$$= \pm\left[(0.0024)^2 + (0.0008)^2 + (0.0001)^2\right]^{0.5}$$

$$= \pm 0.0025 \text{ or } \pm 0.25\%$$

Therefore, the estimated overall uncertainty in the proplyene density is ±0.25 %.

When on-line density meters are used, the uncertainty should be estimated based on the calibration technique, density differences between the orifice and density meter locations, and the density meter manufacturer's recommendations.

12.5 Example Uncertainty Calculations

Example uncertainty calculations for liquid and gas flows are presented in 12.5.1 and 12.5.2.

12.5.1 Example Uncertainty Estimate for Liquid Flow Calculation

An example of the effect of uncertainties is provided in Table 6, using Equation (1):

$$q_m = C_d E_V Y(\pi/4)d^2\sqrt{2g_c\rho_{t,p}\Delta P}$$

The following assumptions and conditions were selected for the calculation.

a) The fluid flowing is proplyene. The liquid density will be calculated using the API *MPMS* Ch. 11.3.3.2 method. The viscosity will be estimated using Procedure 11A5.1 from the API *Technical Data Book—Petroleum Refining*. The expansion factor will be assumed to be 1.0.

b) A 4-in. meter with a β ratio of 0.5, a static pressure of 800 psia, a flowing temperature of 60 °F, and a differential pressure of 50 in. of water (60 °F) is selected for the calculation.

c) For each variable, the uncertainty listed represents random error only.

d) For ease of use, the sensitivity terms of both of the orifice diameter expressions, $\frac{\delta d}{d}$, of equation 34 have been combined and simplified to form a single sensitivity coefficient for the orifice diameter, d. For additional details, see Part 4.

As a result of the first two assumptions, the estimated values of the required physical properties are as follows:

$\rho_{t,p}$ = 33.3413 lb_m/ft^3

$\delta\rho_{t,p}/\rho_{t,p}$ = 0.25 % (as shown in liquid density sensitivity section)

μ = 0.0956 centipoise = 0.0000643 lbm / ft - s

Table 6—Example Uncertainty Estimate for Liquid Flow Calculation

		Uncertainty, U_{95}(%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Discharge coefficient	0.45	1.0	0.2025
d	Orifice diameter [a]	0.05	$2/(1-\beta^4)$	0.00114
D	Pipe diameter [b]	0.25	$-2\beta^4/(1-\beta^4)$	0.0011
ΔP	Differential pressure	0.50	0.5	0.0625
ρ	Density	0.45	0.5	0.0506
Sum of squares				0.3281
Square root of sum of squares				0.5728

NOTE As the table shows, the overall liquid flow measurement uncertainty at a 95 % confidence level is ±0.57 %.

[a] API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2, Table 2-1

[b] API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2, Section 2.5.1.3

As a result of the calculations for the flow rate,

$$C_d(\text{FT}) = 0.603659$$

$$q_m = 10.148 \text{ lbm / s}$$

$$Re_D = 603{,}400$$

$$\delta C_i(\text{FT})/C_d(\text{FT}) = \pm 0.44\% \text{ (from Figure 4)}$$

$$\delta C_d(\text{FT})/\delta C_i(\text{FT}) = 1.02 \text{ (from Figure 5)}$$

this gives:

$$\delta C_d(\text{FT})/C_d(\text{FT}) = 1.02 \times \pm 0.44 = \pm 0.45\%$$

12.5.2 Example Uncertainty Estimate for Natural Gas Flow Calculation

For natural gas flow, fluid density is defined as follow:

$$\rho_{t,p} = \frac{G_i Mr_{\text{air}} P_f}{Z_f R T_f} \quad (40)$$

where

- G_i is the ideal gas relative density (specific gravity) of the gas ($Mr_{\text{gas}}/Mr_{\text{air}}$);
- Mr_{air} is the molar mass of air;
- Mr_{gas} is the molar mass of the gas;
- P_f is the static pressure of fluid;
- R is the universal gas constant;
- T_f is the temperature of the fluid at flowing conditions;
- Z_f is the fluid compressibility at flowing conditions.

The fluid density uncertainty term, $^1/_4(\delta\rho_{t,p}/\rho_{t,p})^2$ in Equation (34) is replaced by the following terms for natural gas application:

$$\left[\frac{1}{2}\left(\frac{\delta G_i}{G_i}\right)\right]^2+\left[\frac{1}{2}\left(\frac{\delta P_f}{P_f}\right)\right]^2+\left[-\frac{1}{2}\left(\frac{\delta Z_f}{Z_f}\right)\right]^2+\left[-\frac{1}{2}\left(\frac{\delta T_f}{T_f}\right)\right]^2$$

An example of the effect of uncertainties is provided in Table 7, using the following gas flow equation:

$$q_m = C_d E_V Y(\pi/4)d^2\sqrt{2g_c\frac{G_i Mr_{\text{air}}P_f}{Z_f R T_f}\Delta P} \tag{41}$$

The following assumptions and conditions were selected for the calculation:

a) for each variable, the uncertainty listed represents random error only;

b) a 4-in. meter with a β ratio of 0.5 and static and differential pressures equal to 250 psia and 50 in. of water, respectively, was selected for the calculation.

c) For ease of use, the sensitivity terms of both of the orifice diameter expressions, $\frac{\delta d}{d}$, of equation 34 have been combined and simplified to form a single sensitivity coefficient for the orifice diameter, d. For additional details, see Part 4.

NOTE The precision of the ΔP device used in this example was ±0.25 % of full scale.

Table 7—Example Uncertainty Estimate for Natural Gas Flow Calculation

		Uncertainty U_{95} (%)	Sensitivity Coefficient, S	$(U_{95}S)^2$
C_d	Discharge (Figure 4)	0.44	1	0.1936
Y	Expansion factor (Table 5)	0.02	1	0.0004
d	Orifice diameter [a]	0.05	$2/(1-\beta^4)$	0.0114
D	Pipe diameter [b]	0.25	$-2\beta^4/(1-\beta^4)$	0.0011
ΔP	Differential pressure	0.50	0.5	0.0625
P	Static pressure	0.50	0.5	0.0625
Z	Compressibility factor [c]	0.1	–0.5	0.0025
T	Temperature	0.25	–0.5	0.0156
G	Relative density	0.60	0.5	0.0900
Sum of squares				0.4396
Square root of sum of squares				0.6630

NOTE As the table shows, the overall gas flow measurement uncertainty at a 95 % confidence level is ±0.66 %.

a API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2/GPA 8185, Part 2–2000, Table 2-1.

b API *MPMS* Ch. 14.3, Part 2/AGA Report No. 3, Part 2/GPA 8185, Part 2–2000, Section 2.5.1.3.

c AGA Report No. 8.

Annex A
(informative)

Discharge Coefficients for Flange-tapped Orifice Meters

Table A.1—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 2-in. (50-mm) Meter [D = 1.939 in. (49.25 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.60014	0.59940	0.59883	0.59873	0.59862	0.59860	0.59858	0.59857	0.59857	0.59857
0.04	0.60102	0.59981	0.59890	0.59873	0.59854	0.59851	0.59847	0.59847	0.59846	0.59846
0.06	0.60178	0.60016	0.59895	0.59872	0.59848	0.59844	0.59839	0.59838	0.59837	0.59837
0.08	0.60248	0.60050	0.59901	0.59873	0.59843	0.59838	0.59832	0.59831	0.59830	0.59829
0.10	0.60315	0.60083	0.59908	0.59875	0.59840	0.59834	0.59827	0.59826	0.59824	0.59824
0.12	0.60381	0.60116	0.59916	0.59879	0.59839	0.59832	0.59824	0.59823	0.59821	0.59821
0.14	0.60448	0.60150	0.59927	0.59886	0.59841	0.59832	0.59823	0.59821	0.59820	0.59819
0.16	0.60515	0.60187	0.59940	0.59894	0.59844	0.59835	0.59825	0.59823	0.59820	0.59820
0.18	0.60586	0.60226	0.59955	0.59905	0.59850	0.59840	0.59828	0.59826	0.59824	0.59823
0.20	0.60660	0.60269	0.59974	0.59919	0.59859	0.59848	0.59835	0.59832	0.59829	0.59829
0.22	0.60738	0.60315	0.59996	0.59936	0.59871	0.59858	0.59844	0.59841	0.59838	0.59837
0.24	0.60823	0.60367	0.60022	0.59957	0.59886	0.59872	0.59856	0.59853	0.59849	0.59848
0.26	0.60914	0.60423	0.60052	0.59982	0.59904	0.59889	0.59871	0.59867	0.59863	0.59862
0.28	0.61014	0.60487	0.60087	0.60011	0.59926	0.59909	0.59889	0.59885	0.59880	0.59878
0.30	0.61123	0.60557	0.60127	0.60045	0.59952	0.59933	0.59911	0.59906	0.59900	0.59898
0.32	0.61243	0.60635	0.60173	0.60084	0.59982	0.59962	0.59936	0.59931	0.59923	0.59921
0.34	0.61375	0.60722	0.60224	0.60128	0.60017	0.59994	0.59965	0.59959	0.59950	0.59948
0.36	0.61522	0.60818	0.60282	0.60178	0.60056	0.60030	0.59998	0.59990	0.59980	0.59978
0.38	0.61683	0.60926	0.60347	0.60234	0.60100	0.60071	0.60034	0.60026	0.60014	0.60011
0.40	0.61862	0.61044	0.60419	0.60296	0.60149	0.60117	0.60075	0.60065	0.60051	0.60047
0.42	0.62059	0.61175	0.60499	0.60365	0.60202	0.60167	0.60119	0.60108	0.60091	0.60087
0.44	0.62276	0.61319	0.60586	0.60440	0.60261	0.60221	0.60167	0.60154	0.60134	0.60129
0.46	0.62515	0.61476	0.60682	0.60522	0.60324	0.60279	0.60218	0.60203	0.60180	0.60174
0.48	0.62777	0.61647	0.60784	0.60610	0.60391	0.60341	0.60271	0.60254	0.60228	0.60221
0.50	0.63063	0.61833	0.60895	0.60703	0.60462	0.60406	0.60327	0.60307	0.60278	0.60270
0.52	0.63374	0.62034	0.61012	0.60803	0.60536	0.60473	0.60384	0.60361	0.60327	0.60318
0.54	0.63712	0.62249	0.61136	0.60906	0.60612	0.60541	0.60441	0.60415	0.60376	0.60366
0.56	0.64077	0.62479	0.61265	0.61014	0.60688	0.60609	0.60497	0.60467	0.60423	0.60411
0.58	0.64470	0.62722	0.61399	0.61123	0.60763	0.60675	0.60549	0.60516	0.60465	0.60451
0.60	0.64890	0.62979	0.61535	0.61233	0.60836	0.60738	0.60596	0.60558	0.60501	0.60486
0.62	0.65337	0.63246	0.61671	0.61341	0.60903	0.60794	0.60636	0.60593	0.60529	0.60511
0.64	0.65811	0.63524	0.61806	0.61445	0.60963	0.60842	0.60665	0.60617	0.60545	0.60525
0.66	0.66309	0.63809	0.61937	0.61542	0.61012	0.60878	0.60681	0.60628	0.60546	0.60523
0.68	0.66829	0.64098	0.62061	0.61629	0.61047	0.60899	0.60680	0.60621	0.60529	0.60504
0.70	0.67369	0.64389	0.62174	0.61703	0.61066	0.60902	0.60660	0.60593	0.60491	0.60463
0.72	0.67925	0.64679	0.62274	0.61762	0.61064	0.60884	0.60615	0.60542	0.60428	0.60396
0.74	0.68494	0.64964	0.62358	0.61802	0.61040	0.60842	0.60546	0.60464	0.60338	0.60303
0.75	0.68781	0.65103	0.62394	0.61815	0.61019	0.60812	0.60501	0.60415	0.60282	0.60245

Table A.2—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 3-in. (75-mm) Meter [D = 2.900 in. (73.66 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59763	0.59688	0.59632	0.59622	0.59611	0.59609	0.59606	0.59606	0.59606	0.59605
0.04	0.59859	0.59737	0.59646	0.59629	0.59611	0.59607	0.59604	0.59603	0.59602	0.59602
0.06	0.59942	0.59780	0.59659	0.59636	0.59612	0.59607	0.59603	0.59602	0.59601	0.59601
0.08	0.60019	0.59821	0.59672	0.59645	0.59615	0.59609	0.59603	0.59602	0.59601	0.59601
0.10	0.60094	0.59861	0.59687	0.59655	0.59620	0.59613	0.59606	0.59605	0.59603	0.59603
0.12	0.60167	0.59902	0.59703	0.59666	0.59626	0.59619	0.59611	0.59609	0.59608	0.59608
0.14	0.60241	0.59944	0.59721	0.59680	0.59635	0.59627	0.59618	0.59616	0.59614	0.59614
0.16	0.60315	0.59989	0.59742	0.59697	0.59647	0.59638	0.59627	0.59625	0.59623	0.59623
0.18	0.60394	0.60036	0.59766	0.59716	0.59661	0.59650	0.59639	0.59637	0.59634	0.59634
0.20	0.60475	0.60086	0.59792	0.59737	0.59677	0.59666	0.59653	0.59651	0.59648	0.59647
0.22	0.60561	0.60140	0.59822	0.59763	0.59697	0.59684	0.59670	0.59667	0.59664	0.59663
0.24	0.60652	0.60199	0.59855	0.59791	0.59720	0.59706	0.59690	0.59687	0.59683	0.59682
0.26	0.60751	0.60263	0.59893	0.59824	0.59746	0.59730	0.59713	0.59709	0.59704	0.59703
0.28	0.60857	0.60333	0.59935	0.59860	0.59775	0.59758	0.59738	0.59734	0.59729	0.59728
0.30	0.60973	0.60410	0.59983	0.59901	0.59808	0.59790	0.59767	0.59762	0.59756	0.59755
0.32	0.61099	0.60495	0.60035	0.59947	0.59846	0.59825	0.59800	0.59794	0.59787	0.59785
0.34	0.61238	0.60589	0.60093	0.59998	0.59887	0.59864	0.59835	0.59829	0.59820	0.59818
0.36	0.61391	0.60691	0.60158	0.60054	0.59933	0.59907	0.59874	0.59867	0.59857	0.59854
0.38	0.61558	0.60804	0.60229	0.60116	0.59982	0.59954	0.59917	0.59908	0.59896	0.59893
0.40	0.61742	0.60929	0.60306	0.60184	0.60037	0.60005	0.59963	0.59953	0.59939	0.59935
0.42	0.61945	0.61064	0.60391	0.60257	0.60095	0.60059	0.60012	0.60001	0.59984	0.59980
0.44	0.62167	0.61213	0.60483	0.60337	0.60158	0.60118	0.60064	0.60051	0.60032	0.60027
0.46	0.62410	0.61374	0.60581	0.60422	0.60224	0.60179	0.60118	0.60103	0.60081	0.60075
0.48	0.62676	0.61548	0.60687	0.60512	0.60294	0.60244	0.60175	0.60157	0.60131	0.60125
0.50	0.62966	0.61737	0.60799	0.60608	0.60366	0.60310	0.60232	0.60212	0.60182	0.60174
0.52	0.63280	0.61939	0.60917	0.60707	0.60440	0.60377	0.60289	0.60266	0.60232	0.60223
0.54	0.63620	0.62155	0.61040	0.60810	0.60515	0.60444	0.60344	0.60318	0.60279	0.60269
0.56	0.63987	0.62383	0.61166	0.60914	0.60588	0.60509	0.60397	0.60367	0.60323	0.60311
0.58	0.64380	0.62625	0.61295	0.61019	0.60658	0.60570	0.60444	0.60410	0.60360	0.60346
0.60	0.64800	0.62877	0.61425	0.61121	0.60723	0.60625	0.60483	0.60445	0.60388	0.60373
0.62	0.65246	0.63138	0.61552	0.61219	0.60780	0.60671	0.60512	0.60470	0.60405	0.60387
0.64	0.65716	0.63406	0.61674	0.61310	0.60826	0.60704	0.60527	0.60479	0.60407	0.60386
0.66	0.66209	0.63679	0.61788	0.61389	0.60856	0.60722	0.60524	0.60471	0.60389	0.60366
0.68	0.66723	0.63953	0.61889	0.61453	0.60868	0.60719	0.60499	0.60439	0.60348	0.60322
0.70	0.67253	0.64223	0.61974	0.61498	0.60855	0.60691	0.60447	0.60381	0.60279	0.60250
0.72	0.67797	0.64486	0.62038	0.61519	0.60814	0.60633	0.60363	0.60289	0.60176	0.60144
0.74	0.68348	0.64736	0.62075	0.61510	0.60740	0.60541	0.60243	0.60161	0.60035	0.59999
0.75	0.68624	0.64855	0.62083	0.61494	0.60689	0.60480	0.60167	0.60081	0.59948	0.59911

Table A.3—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 4-in. (100-mm) Meter [D = 3.826 in. (97.18 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59764	0.59689	0.59633	0.59623	0.59612	0.59610	0.59607	0.59607	0.59607	0.59607
0.04	0.59861	0.59739	0.59648	0.59631	0.59613	0.59610	0.59606	0.59605	0.59605	0.59605
0.06	0.59945	0.59784	0.59662	0.59640	0.59616	0.59611	0.59606	0.59605	0.59605	0.59604
0.08	0.60024	0.59826	0.59677	0.59650	0.59620	0.59615	0.59609	0.59608	0.59606	0.59606
0.10	0.60100	0.59868	0.59693	0.59661	0.59626	0.59620	0.59613	0.59612	0.59610	0.59610
0.12	0.60175	0.59910	0.59711	0.59675	0.59635	0.59627	0.59619	0.59618	0.59616	0.59616
0.14	0.60250	0.59954	0.59731	0.59690	0.59645	0.59637	0.59628	0.59626	0.59624	0.59624
0.16	0.60326	0.60000	0.59754	0.59708	0.59658	0.59649	0.59639	0.59637	0.59635	0.59634
0.18	0.60405	0.60048	0.59779	0.59729	0.59674	0.59664	0.59652	0.59650	0.59647	0.59647
0.20	0.60488	0.60099	0.59807	0.59752	0.59692	0.59681	0.59668	0.59666	0.59663	0.59662
0.22	0.60575	0.60155	0.59838	0.59779	0.59713	0.59701	0.59686	0.59684	0.59680	0.59680
0.24	0.60667	0.60215	0.59873	0.59809	0.59737	0.59723	0.59708	0.59704	0.59701	0.59700
0.26	0.60767	0.60280	0.59912	0.59842	0.59765	0.59749	0.59732	0.59728	0.59723	0.59722
0.28	0.60874	0.60352	0.59955	0.59880	0.59795	0.59779	0.59759	0.59755	0.59749	0.59748
0.30	0.60991	0.60430	0.60004	0.59922	0.59830	0.59811	0.59789	0.59784	0.59778	0.59776
0.32	0.61118	0.60516	0.60057	0.59969	0.59868	0.59847	0.59822	0.59816	0.59809	0.59807
0.34	0.61258	0.60610	0.60116	0.60021	0.59910	0.59887	0.59858	0.59852	0.59843	0.59841
0.36	0.61410	0.60713	0.60181	0.60078	0.59956	0.59930	0.59898	0.59891	0.59880	0.59878
0.38	0.61578	0.60827	0.60252	0.60140	0.60006	0.59978	0.59941	0.59932	0.59920	0.59917
0.40	0.61763	0.60951	0.60330	0.60207	0.60060	0.60028	0.59987	0.59977	0.59963	0.59959
0.42	0.61965	0.61086	0.60414	0.60280	0.60118	0.60082	0.60035	0.60023	0.60007	0.60003
0.44	0.62187	0.61233	0.60504	0.60358	0.60180	0.60140	0.60086	0.60073	0.60054	0.60048
0.46	0.62429	0.61393	0.60601	0.60442	0.60245	0.60200	0.60139	0.60123	0.60101	0.60095
0.48	0.62694	0.61567	0.60705	0.60530	0.60312	0.60262	0.60192	0.60175	0.60149	0.60142
0.50	0.62983	0.61753	0.60814	0.60623	0.60381	0.60325	0.60246	0.60226	0.60197	0.60189
0.52	0.63296	0.61952	0.60928	0.60719	0.60451	0.60388	0.60300	0.60277	0.60243	0.60234
0.54	0.63634	0.62164	0.61047	0.60817	0.60521	0.60450	0.60350	0.60324	0.60285	0.60275
0.56	0.63999	0.62389	0.61168	0.60915	0.60588	0.60509	0.60396	0.60367	0.60323	0.60310
0.58	0.64389	0.62625	0.61290	0.61013	0.60651	0.60563	0.60436	0.60403	0.60352	0.60338
0.60	0.64806	0.62871	0.61411	0.61106	0.60707	0.60609	0.60467	0.60429	0.60372	0.60356
0.62	0.65247	0.63124	0.61528	0.61194	0.60753	0.60643	0.60484	0.60442	0.60377	0.60359
0.64	0.65713	0.63384	0.61638	0.61272	0.60785	0.60664	0.60486	0.60438	0.60365	0.60345
0.66	0.66201	0.63645	0.61737	0.61335	0.60800	0.60665	0.60467	0.60413	0.60332	0.60309
0.68	0.66708	0.63905	0.61820	0.61381	0.60792	0.60643	0.60422	0.60362	0.60271	0.60245
0.70	0.67230	0.64160	0.61884	0.61403	0.60756	0.60591	0.60347	0.60280	0.60178	0.60149
0.72	0.67764	0.64403	0.61921	0.61396	0.60686	0.60504	0.60234	0.60160	0.60046	0.60014
0.74	0.68303	0.64629	0.61926	0.61354	0.60577	0.60377	0.60078	0.59996	0.59869	0.59834
0.75	0.68573	0.64733	0.61915	0.61318	0.60505	0.60295	0.59981	0.59895	0.59762	0.59725

Table A.4—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 6-in. (150-mm) Meter [D = 5.761 in. (146.33 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59765	0.59691	0.59635	0.59624	0.59613	0.59611	0.59609	0.59608	0.59608	0.59608
0.04	0.59864	0.59742	0.59651	0.59634	0.59616	0.59613	0.59609	0.59608	0.59608	0.59607
0.06	0.59950	0.59788	0.59667	0.59644	0.59620	0.59616	0.59611	0.59610	0.59609	0.59609
0.08	0.60030	0.59832	0.59683	0.59656	0.59626	0.59621	0.59615	0.59614	0.59613	0.59612
0.10	0.60107	0.59876	0.59701	0.59669	0.59635	0.59628	0.59621	0.59620	0.59618	0.59618
0.12	0.60184	0.59920	0.59721	0.59685	0.59645	0.59637	0.59629	0.59628	0.59626	0.59626
0.14	0.60260	0.59965	0.59743	0.59702	0.59657	0.59649	0.59640	0.59638	0.59636	0.59636
0.16	0.60339	0.60013	0.59767	0.59722	0.59672	0.59663	0.59653	0.59651	0.59649	0.59648
0.18	0.60319	0.60063	0.59794	0.59744	0.59690	0.59679	0.59668	0.59666	0.59663	0.59663
0.20	0.60503	0.60116	0.59824	0.59770	0.59710	0.59698	0.59686	0.59683	0.59680	0.59680
0.22	0.60592	0.60173	0.59857	0.59798	0.59733	0.59720	0.59706	0.59703	0.59700	0.59699
0.24	0.60686	0.60235	0.59894	0.59830	0.59758	0.59745	0.59729	0.59726	0.59722	0.59721
0.26	0.60786	0.60302	0.59934	0.59865	0.59787	0.59772	0.59755	0.59751	0.59746	0.59745
0.28	0.60875	0.60374	0.59979	0.59904	0.59820	0.59803	0.59783	0.59779	0.59773	0.59772
0.30	0.61013	0.60454	0.60029	0.59948	0.59855	0.59834	0.59814	0.59810	0.59803	0.59802
0.32	0.61141	0.60540	0.60083	0.59995	0.59894	0.59874	0.59849	0.59843	0.59836	0.59834
0.34	0.61281	0.60635	0.60143	0.60048	0.59937	0.59814	0.59886	0.59879	0.59871	0.59868
0.36	0.61434	0.60739	0.60208	0.60105	0.59984	0.59958	0.59926	0.59918	0.59908	0.59905
0.38	0.61602	0.60852	0.60279	0.60167	0.60034	0.60005	0.59968	0.59960	0.59948	0.59945
0.40	0.61786	0.60976	0.60356	0.60234	0.60087	0.60055	0.60014	0.60004	0.59990	0.59986
0.42	0.61988	0.61111	0.60439	0.60306	0.60144	0.60108	0.60061	0.60049	0.60033	0.60029
0.44	0.62210	0.61257	0.60528	0.60382	0.60204	0.60164	0.60110	0.60097	0.60078	0.60073
0.46	0.62452	0.61415	0.60623	0.60464	0.60266	0.60221	0.60160	0.60145	0.60123	0.60117
0.48	0.62715	0.61586	0.60723	0.60549	0.60330	0.60280	0.60211	0.60193	0.60167	0.60161
0.50	0.63002	0.61769	0.60829	0.60637	0.60395	0.60339	0.60260	0.60240	0.60211	0.60203
0.52	0.63313	0.61965	0.60938	0.60727	0.60460	0.60396	0.60308	0.60285	0.60251	0.60242
0.54	0.63649	0.62172	0.61050	0.60819	0.60523	0.60452	0.60352	0.60326	0.60287	0.60276
0.56	0.64011	0.62391	0.61163	0.60910	0.60582	0.60502	0.60390	0.60360	0.60316	0.60303
0.58	0.64398	0.62620	0.61276	0.60997	0.60634	0.60546	0.60419	0.60385	0.60335	0.60321
0.60	0.64810	0.62858	0.61386	0.61079	0.60678	0.60579	0.60437	0.60399	0.60342	0.60326
0.62	0.65247	0.63101	0.61489	0.61153	0.60709	0.60600	0.60440	0.60398	0.60333	0.60315
0.64	0.65707	0.63349	0.61583	0.61214	0.60724	0.60602	0.60424	0.60376	0.60303	0.60283
0.66	0.66188	0.63596	0.61663	0.61258	0.60718	0.60582	0.60384	0.60330	0.60248	0.60226
0.68	0.66688	0.63839	0.61723	0.61279	0.60685	0.60535	0.60314	0.60254	0.60162	0.60137
0.70	0.67201	0.64073	0.61758	0.61272	0.60618	0.60453	0.60207	0.60140	0.60038	0.60010
0.72	0.67724	0.64291	0.61762	0.61230	0.60512	0.60329	0.60057	0.59983	0.59869	0.59837
0.74	0.68250	0.64487	0.61726	0.61144	0.60358	0.60156	0.59856	0.59773	0.59647	0.59611
0.75	0.68512	0.64575	0.61690	0.61083	0.60260	0.60048	0.59733	0.59646	0.59513	0.59476

Table A.5—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 8-in. (200-mm) Meter [D = 7.625 in. (193.68 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59766	0.59691	0.59635	0.59625	0.59614	0.59612	0.59610	0.59609	0.59609	0.59609
0.04	0.59865	0.59744	0.59652	0.59636	0.59617	0.59614	0.59610	0.59610	0.59609	0.59609
0.06	0.59952	0.59791	0.59669	0.59647	0.59623	0.59618	0.59613	0.59612	0.59612	0.59611
0.08	0.60033	0.59835	0.59687	0.59659	0.59630	0.59624	0.59618	0.59617	0.59616	0.59616
0.10	0.60111	0.59880	0.59706	0.59674	0.59639	0.59632	0.59625	0.59624	0.59623	0.59622
0.12	0.60189	0.59925	0.59727	0.59690	0.59650	0.59643	0.59635	0.59633	0.59632	0.59631
0.14	0.60266	0.59971	0.59749	0.59708	0.59664	0.59655	0.59646	0.59645	0.59643	0.59642
0.16	0.60345	0.60020	0.59775	0.59729	0.59680	0.59670	0.59660	0.59658	0.59656	0.59656
0.18	0.60427	0.60071	0.59803	0.59753	0.59698	0.59688	0.59677	0.59674	0.59672	0.59671
0.20	0.60511	0.60125	0.59833	0.59779	0.59719	0.59708	0.59695	0.59693	0.59690	0.59689
0.22	0.60601	0.60183	0.59867	0.59808	0.59743	0.59731	0.59717	0.59714	0.59710	0.59710
0.24	0.60695	0.60246	0.59905	0.59841	0.59770	0.59756	0.59740	0.59737	0.59733	0.59733
0.26	0.60797	0.60313	0.59947	0.59877	0.59800	0.59785	0.59767	0.59763	0.59759	0.59758
0.28	0.60906	0.60387	0.59992	0.59917	0.59833	0.59816	0.59796	0.59792	0.59787	0.59786
0.30	0.61024	0.60467	0.60042	0.59961	0.59869	0.59851	0.59828	0.59823	0.59817	0.59816
0.32	0.61153	0.60554	0.60097	0.60010	0.59909	0.59888	0.59863	0.59857	0.59850	0.59848
0.34	0.61293	0.60649	0.60157	0.60062	0.59952	0.59929	0.59901	0.59894	0.59885	0.59883
0.36	0.61447	0.60753	0.60223	0.60120	0.59999	0.59973	0.59941	0.59933	0.59923	0.59920
0.38	0.61615	0.60866	0.60294	0.60182	0.60049	0.60020	0.59983	0.59975	0.59963	0.59960
0.40	0.61799	0.60990	0.60371	0.60248	0.60102	0.60070	0.60028	0.60018	0.60004	0.60001
0.42	0.62001	0.61124	0.60453	0.60320	0.60158	0.60122	0.60075	0.60063	0.60047	0.60043
0.44	0.62222	0.61270	0.60541	0.60395	0.60217	0.60177	0.60123	0.60110	0.60091	0.60086
0.46	0.62464	0.61427	0.60635	0.60475	0.60278	0.60233	0.60172	0.60157	0.60134	0.60128
0.48	0.62727	0.61597	0.60734	0.60559	0.60340	0.60290	0.60220	0.60203	0.60177	0.60170
0.50	0.63013	0.61778	0.60837	0.60645	0.60403	0.60346	0.60268	0.60248	0.60218	0.60210
0.52	0.63323	0.61972	0.60943	0.60732	0.60464	0.60401	0.60312	0.60289	0.60255	0.60246
0.54	0.63658	0.62177	0.61052	0.60820	0.60523	0.60452	0.60352	0.60326	0.60287	0.60277
0.56	0.64018	0.62393	0.61161	0.60906	0.60578	0.60498	0.60386	0.60356	0.60312	0.60299
0.58	0.64403	0.62618	0.61269	0.60989	0.60625	0.60536	0.60410	0.60376	0.60325	0.60312
0.60	0.64814	0.62851	0.61372	0.61065	0.60662	0.60563	0.60421	0.60383	0.60326	0.60310
0.62	0.65248	0.63089	0.61468	0.61131	0.60686	0.60576	0.60416	0.60373	0.60309	0.60291
0.64	0.65706	0.63330	0.61554	0.61182	0.60691	0.60569	0.60390	0.60342	0.60270	0.60249
0.66	0.66183	0.63570	0.61623	0.61215	0.60673	0.60538	0.60339	0.60285	0.60203	0.60180
0.68	0.66679	0.63804	0.61671	0.61224	0.60627	0.60476	0.60255	0.60195	0.60103	0.60078
0.70	0.67188	0.64027	0.61691	0.61201	0.60544	0.60378	0.60132	0.60065	0.59963	0.59934
0.72	0.67705	0.64233	0.61676	0.61140	0.60418	0.60234	0.59962	0.59888	0.59774	0.59742
0.74	0.68225	0.64413	0.61619	0.61032	0.60240	0.60037	0.59736	0.59654	0.59527	0.59492
0.75	0.68484	0.64491	0.61571	0.60957	0.60128	0.59916	0.59599	0.59513	0.59379	0.59342

Table A.6—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 10-in. (250-mm) Meter [D = 9.562 in. (242.87 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59692	0.59636	0.59625	0.59614	0.59612	0.59610	0.59610	0.59609	0.59609
0.04	0.59866	0.59745	0.59653	0.59637	0.59618	0.59615	0.59611	0.59611	0.59610	0.59610
0.06	0.59953	0.59792	0.59671	0.59649	0.59624	0.59620	0.59615	0.59614	0.59613	0.59613
0.08	0.60035	0.59838	0.59689	0.59662	0.59632	0.59627	0.59621	0.59620	0.59618	0.59618
0.10	0.60114	0.59883	0.59709	0.59677	0.59642	0.59635	0.59628	0.59627	0.59626	0.59625
0.12	0.60192	0.59928	0.59730	0.59694	0.59654	0.59646	0.59638	0.59637	0.59635	0.59635
0.14	0.60270	0.59976	0.59754	0.59713	0.59668	0.59660	0.59651	0.59649	0.59647	0.59647
0.16	0.60350	0.60025	0.59780	0.59734	0.59685	0.59676	0.59665	0.59663	0.59661	0.59661
0.18	0.60432	0.60076	0.59808	0.59758	0.59704	0.59694	0.59682	0.59680	0.59678	0.59677
0.20	0.60517	0.60131	0.59840	0.59785	0.59726	0.59714	0.59702	0.59699	0.59696	0.59696
0.22	0.60607	0.60190	0.59874	0.59816	0.59750	0.59738	0.59724	0.59721	0.59718	0.59717
0.24	0.60702	0.60253	0.59913	0.59849	0.59778	0.59764	0.59748	0.59745	0.59741	0.59740
0.26	0.60804	0.60321	0.59955	0.59886	0.59808	0.59793	0.59775	0.59772	0.59767	0.59766
0.28	0.60914	0.60395	0.60001	0.59926	0.59842	0.59825	0.59805	0.59801	0.59796	0.59795
0.30	0.61032	0.60475	0.60052	0.59971	0.59879	0.59860	0.59838	0.59833	0.59827	0.59825
0.32	0.61161	0.60563	0.60107	0.60019	0.59919	0.59898	0.59873	0.59867	0.59860	0.59858
0.34	0.61302	0.60658	0.60167	0.60072	0.59962	0.59939	0.59911	0.59904	0.59896	0.59893
0.36	0.61456	0.60763	0.60233	0.60130	0.60009	0.59983	0.59951	0.59944	0.59933	0.59931
0.38	0.61624	0.60876	0.60304	0.60192	0.60059	0.60030	0.59994	0.59985	0.59973	0.59970
0.40	0.61809	0.61000	0.60381	0.60259	0.60112	0.60080	0.60038	0.60028	0.60014	0.60011
0.42	0.62010	0.61134	0.60463	0.60330	0.60168	0.60132	0.60085	0.60073	0.60057	0.60053
0.44	0.62231	0.61279	0.60551	0.60405	0.60226	0.60186	0.60132	0.60119	0.60100	0.60095
0.46	0.62473	0.61436	0.60643	0.60484	0.60286	0.60241	0.60180	0.60165	0.60143	0.60137
0.48	0.62735	0.61605	0.60741	0.60566	0.60347	0.60297	0.60228	0.60210	0.60185	0.60178
0.50	0.63021	0.61785	0.60843	0.60651	0.60409	0.60352	0.60274	0.60253	0.60224	0.60216
0.52	0.63331	0.61977	0.60947	0.60737	0.60468	0.60405	0.60316	0.60293	0.60259	0.60250
0.54	0.63665	0.62181	0.61054	0.60822	0.60525	0.60454	0.60354	0.60328	0.60289	0.60278
0.56	0.64024	0.62395	0.61161	0.60906	0.60577	0.60497	0.60384	0.60355	0.60310	0.60298
0.58	0.64408	0.62618	0.61265	0.60985	0.60621	0.60532	0.60405	0.60371	0.60321	0.60307
0.60	0.64817	0.62848	0.61365	0.61057	0.60654	0.60555	0.60412	0.60374	0.60317	0.60301
0.62	0.65250	0.63083	0.61457	0.61118	0.60672	0.60562	0.60402	0.60360	0.60295	0.60277
0.64	0.65706	0.63320	0.61536	0.61164	0.60672	0.60549	0.60371	0.60323	0.60250	0.60229
0.66	0.66182	0.63555	0.61599	0.61190	0.60647	0.60511	0.60312	0.60258	0.60176	0.60153
0.68	0.66675	0.63784	0.61639	0.61190	0.60592	0.60441	0.60219	0.60159	0.60067	0.60042
0.70	0.67181	0.64000	0.61650	0.61158	0.60499	0.60332	0.60086	0.60019	0.59916	0.59888
0.72	0.67696	0.64198	0.61624	0.61085	0.60361	0.60176	0.59903	0.59829	0.59715	0.59683
0.74	0.68212	0.64369	0.61553	0.60963	0.60167	0.59964	0.59663	0.59580	0.59453	0.59418
0.75	0.68468	0.64441	0.61497	0.60880	0.60047	0.59834	0.59517	0.59430	0.59297	0.59259

Table A.7—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 12-in. (300 mm) Meter [D = 11.374 in. (288.90 mm)]

	Pipe Reynolds Number (Re_D)								
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59692	0.59636	0.59626	0.59615	0.59613	0.59610	0.59610	0.59609	0.59609
0.04	0.59867	0.59745	0.59654	0.59637	0.59619	0.59616	0.59612	0.59611	0.59611	0.59611
0.06	0.59954	0.59793	0.59672	0.59650	0.59625	0.59621	0.59616	0.59615	0.59614	0.59614
0.08	0.60037	0.59839	0.59691	0.59663	0.59634	0.59628	0.59622	0.59621	0.59620	0.59620
0.10	0.60116	0.59885	0.59711	0.59679	0.59644	0.59637	0.59630	0.59629	0.59628	0.59627
0.12	0.60194	0.59931	0.59733	0.59696	0.59656	0.59649	0.59641	0.59639	0.59638	0.59637
0.14	0.60273	0.59978	0.59757	0.59716	0.59671	0.59663	0.59654	0.59652	0.59650	0.59650
0.16	0.60353	0.60028	0.59783	0.59738	0.59688	0.59679	0.59669	0.59667	0.59665	0.59664
0.18	0.60435	0.60080	0.59812	0.59762	0.59708	0.59698	0.59686	0.59684	0.59681	0.59681
0.20	0.60521	0.60135	0.59844	0.59790	0.59730	0.59719	0.59706	0.59704	0.59701	0.59700
0.22	0.60611	0.60194	0.59879	0.59820	0.59755	0.59743	0.59728	0.59726	0.59722	0.59722
0.24	0.60707	0.60258	0.59918	0.59854	0.59783	0.59769	0.59753	0.59750	0.59746	0.59746
0.26	0.60809	0.60326	0.59960	0.59891	0.59814	0.59799	0.59781	0.59777	0.59773	0.59772
0.28	0.60919	0.60401	0.60007	0.59932	0.59848	0.59831	0.59811	0.59807	0.59802	0.59800
0.30	0.61038	0.60481	0.60058	0.59977	0.59885	0.59866	0.59844	0.59839	0.59833	0.59832
0.32	0.61167	0.60569	0.60113	0.60026	0.59925	0.59905	0.59880	0.59874	0.59867	0.59865
0.34	0.61308	0.60665	0.60174	0.60079	0.59969	0.59946	0.59918	0.59911	0.59902	0.59900
0.36	0.61462	0.60769	0.60240	0.60137	0.60016	0.59990	0.59958	0.59951	0.59940	0.59938
0.38	0.61630	0.60883	0.60311	0.60199	0.60066	0.60037	0.60001	0.59992	0.59980	0.59977
0.40	0.61815	0.61006	0.60388	0.60265	0.60119	0.60087	0.60045	0.60035	0.60021	0.60018
0.42	0.62017	0.61140	0.60470	0.60336	0.60175	0.60139	0.60092	0.60080	0.60064	0.60059
0.44	0.62237	0.61285	0.60557	0.60411	0.60233	0.60193	0.60139	0.60126	0.60107	0.60101
0.46	0.62479	0.61442	0.60649	0.60490	0.60292	0.60247	0.60186	0.60171	0.60149	0.60143
0.48	0.62741	0.61610	0.60747	0.60572	0.60353	0.60302	0.60233	0.60216	0.60190	0.60183
0.50	0.63027	0.61790	0.60847	0.60655	0.60413	0.60357	0.60278	0.60258	0.60229	0.60221
0.52	0.63336	0.61982	0.60951	0.60740	0.60472	0.60408	0.60320	0.60297	0.60263	0.60254
0.54	0.63670	0.62184	0.61056	0.60825	0.60527	0.60456	0.60356	0.60330	0.60291	0.60280
0.56	0.64028	0.62397	0.61162	0.60907	0.60577	0.60498	0.60385	0.60355	0.60311	0.60299
0.58	0.64412	0.62619	0.61264	0.60984	0.60619	0.60530	0.60403	0.60370	0.60319	0.60305
0.60	0.64821	0.62847	0.61362	0.61053	0.60650	0.60551	0.60408	0.60370	0.60313	0.60297
0.62	0.65253	0.63080	0.61451	0.61111	0.60665	0.60555	0.60395	0.60352	0.60288	0.60270
0.64	0.65708	0.63315	0.61527	0.61154	0.60661	0.60538	0.60360	0.60312	0.60239	0.60219
0.66	0.66182	0.63548	0.61586	0.61176	0.60632	0.60496	0.60296	0.60243	0.60161	0.60138
0.68	0.66674	0.63773	0.61621	0.61171	0.60572	0.60421	0.60199	0.60139	0.60047	0.60021
0.70	0.67179	0.63985	0.61627	0.61133	0.60473	0.60306	0.60059	0.59992	0.59890	0.59861
0.72	0.67692	0.64178	0.61594	0.61053	0.60327	0.60142	0.59869	0.59795	0.59680	0.59649
0.74	0.68206	0.64343	0.61514	0.60922	0.60124	0.59921	0.59619	0.59536	0.59410	0.59374
0.75	0.68461	0.64412	0.61453	0.60834	0.59999	0.59785	0.59468	0.59381	0.59247	0.59210

Table A.8—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 16-in. (400-mm) Meter [D = 14.688 in. (373.08 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59767	0.59693	0.59637	0.59626	0.59615	0.59613	0.59611	0.59610	0.59610	0.59610
0.04	0.59868	0.59746	0.59655	0.59638	0.59620	0.59617	0.59613	0.59612	0.59612	0.59611
0.06	0.59956	0.59794	0.59673	0.59651	0.59627	0.59622	0.59617	0.59617	0.59616	0.59615
0.08	0.60038	0.59841	0.59692	0.59665	0.59635	0.59630	0.59624	0.59623	0.59622	0.59621
0.10	0.60118	0.59887	0.59713	0.59681	0.59646	0.59640	0.59633	0.59631	0.59630	0.59630
0.12	0.60197	0.59934	0.59736	0.59699	0.59659	0.59652	0.59644	0.59642	0.59641	0.59640
0.14	0.60276	0.59982	0.59760	0.59719	0.59675	0.59666	0.59657	0.59655	0.59654	0.59653
0.16	0.60356	0.60032	0.59787	0.59742	0.59692	0.59683	0.59673	0.59671	0.59669	0.59668
0.18	0.60439	0.60084	0.59817	0.59767	0.59713	0.59702	0.59691	0.59689	0.59686	0.59686
0.20	0.60526	0.60140	0.59849	0.59795	0.59735	0.59724	0.59711	0.59709	0.59706	0.59705
0.22	0.60616	0.60200	0.59885	0.59826	0.59761	0.59749	0.59734	0.59732	0.59728	0.59728
0.24	0.60712	0.60264	0.59924	0.59860	0.59789	0.59776	0.59760	0.59757	0.59753	0.59752
0.26	0.60815	0.60333	0.59967	0.59898	0.59821	0.59806	0.59788	0.59784	0.59780	0.59779
0.28	0.60925	0.60408	0.60014	0.59940	0.59855	0.59839	0.59819	0.59815	0.59809	0.59808
0.30	0.61044	0.60489	0.60066	0.59985	0.59893	0.59874	0.59852	0.59847	0.59841	0.59840
0.32	0.61174	0.60577	0.60122	0.60034	0.59934	0.59913	0.59888	0.59882	0.59875	0.59873
0.34	0.61315	0.60673	0.60183	0.60088	0.59978	0.59955	0.59926	0.59920	0.59911	0.59909
0.36	0.61469	0.60777	0.60249	0.60146	0.60025	0.59999	0.59967	0.59960	0.59949	0.59947
0.38	0.61638	0.60891	0.60320	0.60208	0.60075	0.60047	0.60010	0.60001	0.59989	0.59986
0.40	0.61823	0.61015	0.60397	0.60275	0.60128	0.60096	0.60055	0.60045	0.60031	0.60027
0.42	0.62025	0.61149	0.60479	0.60345	0.60184	0.60148	0.60101	0.60089	0.60073	0.60069
0.44	0.62246	0.61294	0.60566	0.60420	0.60242	0.60201	0.60148	0.60134	0.60115	0.60110
0.46	0.62487	0.61450	0.60658	0.60498	0.60301	0.60256	0.60195	0.60179	0.60157	0.60151
0.48	0.62749	0.61618	0.60754	0.60579	0.60361	0.60310	0.60241	0.60223	0.60198	0.60191
0.50	0.63035	0.61798	0.60854	0.60662	0.60420	0.60363	0.60285	0.60265	0.60235	0.60227
0.52	0.63343	0.61988	0.60957	0.60746	0.60478	0.60414	0.60325	0.60302	0.60269	0.60259
0.54	0.63677	0.62190	0.61061	0.60829	0.60532	0.60461	0.60360	0.60334	0.60295	0.60285
0.56	0.64035	0.62402	0.61164	0.60909	0.60580	0.60500	0.60387	0.60358	0.60313	0.60301
0.58	0.64418	0.62622	0.61265	0.60984	0.60619	0.60530	0.60403	0.60370	0.60319	0.60305
0.60	0.64826	0.62848	0.61360	0.61051	0.60647	0.60548	0.60405	0.60367	0.60310	0.60294
0.62	0.65258	0.63079	0.61446	0.61106	0.60659	0.60549	0.60389	0.60346	0.60281	0.60264
0.64	0.65711	0.63312	0.61519	0.61145	0.60651	0.60528	0.60350	0.60302	0.60229	0.60208
0.66	0.66185	0.63541	0.61573	0.61162	0.60617	0.60481	0.60281	0.60228	0.60146	0.60123
0.68	0.66675	0.63763	0.61603	0.61152	0.60551	0.60400	0.60178	0.60118	0.60026	0.60000
0.70	0.67179	0.63971	0.61602	0.61107	0.60445	0.60278	0.60031	0.59964	0.59862	0.59833
0.72	0.67690	0.64158	0.61562	0.61019	0.60291	0.60106	0.59833	0.59758	0.59644	0.59612
0.74	0.68202	0.64316	0.61473	0.60878	0.60078	0.59874	0.59572	0.59489	0.59362	0.59327
0.75	0.68456	0.64382	0.61406	0.60784	0.59947	0.59733	0.59415	0.59328	0.59194	0.59157

Table A.9—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 20-in. (500-mm) Meter [D = 19.000 in. (482.60 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59626	0.59615	0.59613	0.59611	0.59611	0.59610	0.59610
0.04	0.59868	0.59747	0.59656	0.59639	0.59621	0.59617	0.59614	0.59613	0.59612	0.59612
0.06	0.59957	0.59796	0.59674	0.59652	0.59628	0.59623	0.59619	0.59618	0.59617	0.59616
0.08	0.60040	0.59842	0.59694	0.59667	0.59637	0.59631	0.59626	0.59624	0.59623	0.59623
0.10	0.60120	0.59889	0.59715	0.59683	0.59648	0.59642	0.59635	0.59633	0.59632	0.59632
0.12	0.60199	0.59936	0.59738	0.59701	0.59662	0.59654	0.59646	0.59645	0.59643	0.59643
0.14	0.60279	0.59984	0.59763	0.59722	0.59677	0.59669	0.59660	0.59658	0.59656	0.59656
0.16	0.60360	0.60035	0.59790	0.59745	0.59696	0.59686	0.59676	0.59674	0.59672	0.59672
0.18	0.60443	0.60088	0.59821	0.59771	0.59716	0.59706	0.59695	0.59693	0.59690	0.59690
0.20	0.60529	0.60144	0.59854	0.59799	0.59740	0.59729	0.59716	0.59713	0.59710	0.59710
0.22	0.60620	0.60204	0.59890	0.59831	0.59766	0.59753	0.59739	0.59737	0.59733	0.59732
0.24	0.60717	0.60269	0.59930	0.59866	0.59795	0.59781	0.59765	0.59762	0.59758	0.59757
0.26	0.60820	0.60338	0.59973	0.59904	0.59827	0.59812	0.59794	0.59790	0.59786	0.59785
0.28	0.60930	0.60413	0.60020	0.59946	0.59862	0.59845	0.59825	0.59821	0.59816	0.59814
0.30	0.61050	0.60495	0.60072	0.59992	0.59900	0.59881	0.59859	0.59854	0.59848	0.59846
0.32	0.61180	0.60583	0.60129	0.60041	0.59941	0.59920	0.59895	0.59890	0.59882	0.59880
0.34	0.61321	0.60680	0.60190	0.60095	0.59985	0.59962	0.59934	0.59927	0.59919	0.59917
0.36	0.61476	0.60784	0.60256	0.60153	0.60033	0.60007	0.59975	0.59967	0.59957	0.59955
0.38	0.61645	0.60898	0.60328	0.60216	0.60083	0.60054	0.60018	0.60009	0.59997	0.59994
0.40	0.61830	0.61022	0.60404	0.60283	0.60136	0.60104	0.60063	0.60053	0.60039	0.60035
0.42	0.62032	0.61156	0.60486	0.60353	0.60192	0.60156	0.60109	0.60097	0.60081	0.60077
0.44	0.62253	0.61301	0.60574	0.60428	0.60249	0.60209	0.60156	0.60142	0.60123	0.60118
0.46	0.62494	0.61458	0.60665	0.60506	0.60308	0.60263	0.60202	0.60187	0.60165	0.60159
0.48	0.62756	0.61625	0.60762	0.60587	0.60368	0.60317	0.60248	0.60231	0.60205	0.60198
0.50	0.63042	0.61804	0.60861	0.60669	0.60427	0.60370	0.60292	0.60272	0.60242	0.60234
0.52	0.63350	0.61995	0.60963	0.60752	0.60484	0.60420	0.60331	0.60309	0.60275	0.60265
0.54	0.63684	0.62196	0.61066	0.60834	0.60537	0.60466	0.60365	0.60339	0.60300	0.60290
0.56	0.64042	0.62407	0.61169	0.60913	0.60584	0.60504	0.60391	0.60361	0.60317	0.60305
0.58	0.64424	0.62626	0.61268	0.60987	0.60622	0.60533	0.60406	0.60372	0.60321	0.60308
0.60	0.64832	0.62851	0.61361	0.61052	0.60648	0.60548	0.60406	0.60368	0.60310	0.60295
0.62	0.65263	0.63081	0.61445	0.61105	0.60657	0.60547	0.60387	0.60344	0.60279	0.60262
0.64	0.65716	0.63311	0.61515	0.61141	0.60647	0.60524	0.60345	0.60297	0.60224	0.60204
0.66	0.66189	0.63539	0.61567	0.61155	0.60609	0.60473	0.60273	0.60219	0.60137	0.60115
0.68	0.66679	0.63758	0.61593	0.61141	0.60539	0.60388	0.60166	0.60105	0.60014	0.59988
0.70	0.67181	0.63963	0.61588	0.61091	0.60428	0.60261	0.60014	0.59947	0.59844	0.59816
0.72	0.67691	0.64146	0.61542	0.60997	0.60268	0.60083	0.59809	0.59735	0.59620	0.59589
0.74	0.68201	0.64300	0.61446	0.60850	0.60048	0.59844	0.59541	0.59459	0.59332	0.59296
0.75	0.68455	0.64363	0.61376	0.60752	0.59912	0.59698	0.59380	0.59293	0.59159	0.59122

Table A.10—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 24-in. (600-mm) Meter [D = 23.000 in. (584.20 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59627	0.59615	0.59613	0.59611	0.59611	0.59610	0.59610
0.04	0.59869	0.59747	0.59656	0.59639	0.59621	0.59618	0.59614	0.59613	0.59613	0.59613
0.06	0.59957	0.59796	0.59675	0.59653	0.59628	0.59924	0.59619	0.59618	0.59617	0.59617
0.08	0.60041	0.59843	0.59695	0.59668	0.59638	0.59632	0.59626	0.59625	0.59624	0.59624
0.10	0.60121	0.59890	0.59716	0.59684	0.59649	0.59643	0.59636	0.59635	0.59633	0.59633
0.12	0.60201	0.59937	0.59739	0.59703	0.59663	0.59656	0.59648	0.59646	0.59645	0.59644
0.14	0.60280	0.59986	0.59765	0.59724	0.59679	0.59671	0.59662	0.59660	0.59658	0.59658
0.16	0.60361	0.60037	0.59793	0.59747	0.59698	0.59689	0.59678	0.59676	0.59674	0.59674
0.18	0.60445	0.60090	0.59823	0.59773	0.59719	0.59709	0.59697	0.59695	0.59693	0.59692
0.20	0.60532	0.60147	0.59856	0.59802	0.59743	0.59731	0.59719	0.59716	0.59713	0.59713
0.22	0.60623	0.60207	0.59893	0.59834	0.59769	0.59757	0.59742	0.59740	0.59736	0.59736
0.24	0.60720	0.60272	0.59933	0.59869	0.59798	0.59785	0.59769	0.59766	0.59762	0.59761
0.26	0.60823	0.60342	0.59977	0.59908	0.59830	0.59815	0.59798	0.59794	0.59789	0.59788
0.28	0.60934	0.60417	0.60024	0.59950	0.59866	0.59849	0.59829	0.59825	0.59820	0.59818
0.30	0.61054	0.60499	0.60076	0.59996	0.59904	0.59885	0.59863	0.59858	0.59852	0.59851
0.32	0.61184	0.60587	0.60133	0.60046	0.59945	0.59925	0.59900	0.59894	0.59887	0.59885
0.34	0.61325	0.60684	0.60195	0.60100	0.59990	0.59967	0.59938	0.59932	0.59923	0.59921
0.36	0.61480	0.60789	0.60261	0.60158	0.60037	0.60012	0.59980	0.59972	0.59962	0.59959
0.38	0.61649	0.60903	0.60333	0.60221	0.60088	0.60059	0.60023	0.60014	0.60002	0.59999
0.40	0.61834	0.61027	0.60410	0.60288	0.60141	0.60109	0.60068	0.60058	0.60044	0.60040
0.42	0.62036	0.61161	0.60492	0.60358	0.60197	0.60161	0.60114	0.60102	0.60086	0.60082
0.44	0.62257	0.61306	0.60579	0.60433	0.60255	0.60215	0.60161	0.60148	0.60129	0.60123
0.46	0.62498	0.61463	0.60671	0.60511	0.60314	0.60269	0.60208	0.60192	0.60170	0.60164
0.48	0.62761	0.61630	0.60767	0.60592	0.60373	0.60323	0.60253	0.60236	0.60210	0.60203
0.50	0.63046	0.61809	0.60866	0.60674	0.60432	0.60375	0.60297	0.60276	0.60247	0.60239
0.52	0.63355	0.61999	0.60968	0.60757	0.60488	0.60425	0.60336	0.60313	0.60279	0.60270
0.54	0.63688	0.62200	0.61070	0.60838	0.60541	0.60470	0.60369	0.60343	0.60304	0.60294
0.56	0.64046	0.62411	0.61172	0.60917	0.60587	0.60507	0.60394	0.60365	0.60320	0.60308
0.58	0.64429	0.62629	0.61271	0.60989	0.60624	0.60535	0.60408	0.60375	0.60324	0.60310
0.60	0.64836	0.62854	0.61363	0.61054	0.60649	0.60550	0.60407	0.60369	0.60312	0.60296
0.62	0.65267	0.63083	0.61446	0.61105	0.60658	0.60547	0.60387	0.60345	0.60280	0.60262
0.64	0.65720	0.63313	0.61515	0.61140	0.60646	0.60523	0.60344	0.60296	0.60223	0.60202
0.66	0.66192	0.63539	0.61565	0.61153	0.60607	0.60470	0.60270	0.60216	0.60135	0.60112
0.68	0.66682	0.63757	0.61589	0.61137	0.60534	0.60383	0.60160	0.60100	0.60008	0.59983
0.70	0.67184	0.63960	0.61581	0.61084	0.60421	0.60253	0.60006	0.59939	0.59837	0.59808
0.72	0.67693	0.64142	0.61533	0.60987	0.60257	0.60072	0.59798	0.59724	0.59610	0.59578
0.74	0.68203	0.64293	0.61433	0.60836	0.60034	0.59829	0.59526	0.59444	0.59317	0.59281
0.75	0.68456	0.64355	0.61361	0.60736	0.59895	0.59681	0.59363	0.59276	0.59142	0.59105

Table A.11—Discharge Coefficients for Flange-tapped Orifice Meters: Nominal 30-in. (750-mm) Meter [D = 29.000 in. (736.60 mm)]

	Pipe Reynolds Number (Re_D)									
β	4,000	10,000	50,000	100,000	500,000	1×10^6	5×10^6	10×10^6	50×10^6	100×10^6
0.02	0.59768	0.59693	0.59637	0.59627	0.59616	0.59614	0.59611	0.59611	0.59611	0.59610
0.04	0.59869	0.59748	0.59657	0.59640	0.59622	0.59618	0.59615	0.59614	0.59613	0.59613
0.06	0.59958	0.59797	0.59676	0.59653	0.59629	0.59925	0.59620	0.59619	0.59618	0.59618
0.08	0.60041	0.59844	0.59696	0.59668	0.59639	0.59633	0.59627	0.59626	0.59625	0.59625
0.10	0.60122	0.59891	0.59717	0.59685	0.59651	0.59644	0.59637	0.59636	0.59634	0.59634
0.12	0.60202	0.59939	0.59741	0.59704	0.59665	0.59657	0.59649	0.59648	0.59646	0.59646
0.14	0.60282	0.59988	0.59767	0.59726	0.59681	0.59673	0.59664	0.59662	0.59660	0.59660
0.16	0.60363	0.60039	0.59795	0.59749	0.59700	0.59691	0.59681	0.59679	0.59676	0.59676
0.18	0.60447	0.60093	0.59825	0.59776	0.59721	0.59711	0.59700	0.59698	0.59695	0.59695
0.20	0.60534	0.60150	0.59859	0.59805	0.59745	0.59734	0.59721	0.59719	0.59716	0.59715
0.22	0.60626	0.60210	0.59896	0.59837	0.59772	0.59760	0.59746	0.59743	0.59739	0.59739
0.24	0.60723	0.60275	0.59936	0.59872	0.59802	0.59788	0.59772	0.59769	0.59765	0.59764
0.26	0.60826	0.60345	0.59980	0.59911	0.59834	0.59819	0.59801	0.59798	0.59793	0.59792
0.28	0.60937	0.60421	0.60028	0.59954	0.59870	0.59853	0.59833	0.59829	0.59824	0.59822
0.30	0.61057	0.60503	0.60081	0.60000	0.59908	0.59890	0.59867	0.59863	0.59856	0.59855
0.32	0.61188	0.60592	0.60138	0.60050	0.59950	0.59929	0.59904	0.59899	0.59891	0.59889
0.34	0.61329	0.60689	0.60199	0.60105	0.59995	0.59972	0.59943	0.59937	0.59928	0.59926
0.36	0.61484	0.60794	0.60266	0.60163	0.60043	0.60017	0.59985	0.59977	0.59967	0.59965
0.38	0.61653	0.60908	0.60338	0.60226	0.60093	0.60065	0.60028	0.60020	0.60008	0.60005
0.40	0.61838	0.61032	0.60415	0.60293	0.60147	0.60115	0.60073	0.60063	0.60049	0.60046
0.42	0.62041	0.61166	0.60497	0.60364	0.60203	0.60167	0.60120	0.60108	0.60092	0.60087
0.44	0.62262	0.61312	0.60584	0.60439	0.60260	0.60220	0.60166	0.60153	0.60134	0.60129
0.46	0.62503	0.61468	0.60676	0.60517	0.60319	0.60274	0.60213	0.60198	0.60176	0.60170
0.48	0.62766	0.61635	0.60772	0.60597	0.60379	0.60328	0.60259	0.60241	0.60216	0.60209
0.50	0.63051	0.61814	0.60871	0.60679	0.60437	0.60380	0.60302	0.60282	0.60252	0.60244
0.52	0.63360	0.62005	0.60973	0.60762	0.60493	0.60430	0.60341	0.60318	0.60284	0.60275
0.54	0.63693	0.62205	0.61075	0.60843	0.60545	0.60474	0.60374	0.60348	0.60309	0.60298
0.56	0.64051	0.62415	0.61177	0.60921	0.60591	0.60512	0.60399	0.60369	0.60325	0.60312
0.58	0.64434	0.62634	0.61275	0.60993	0.60628	0.60539	0.60412	0.60378	0.60328	0.60314
0.60	0.64841	0.62858	0.61366	0.61057	0.60652	0.60553	0.60410	0.60372	0.60315	0.60299
0.62	0.65272	0.63086	0.61448	0.61107	0.60660	0.60549	0.60389	0.60346	0.60282	0.60264
0.64	0.65724	0.63315	0.61516	0.61141	0.60646	0.60523	0.60344	0.60296	0.60223	0.60203
0.66	0.66197	0.63540	0.61564	0.61152	0.60606	0.60469	0.60269	0.60215	0.60133	0.60111
0.68	0.66686	0.63757	0.61587	0.61134	0.60531	0.60380	0.60158	0.60097	0.60006	0.59980
0.70	0.67188	0.63959	0.61577	0.61080	0.60416	0.60248	0.60001	0.59934	0.59831	0.59803
0.72	0.67697	0.64139	0.61526	0.60980	0.60249	0.60064	0.59790	0.59716	0.59601	0.59570
0.74	0.68206	0.64289	0.61424	0.60825	0.60022	0.59818	0.59515	0.59432	0.59305	0.59270
0.75	0.68459	0.64349	0.61350	0.60724	0.59882	0.59668	0.59349	0.59262	0.59128	0.59091

Annex B
(informative)

Adjustments for Instrument Calibration and Use

This annex discusses the need to consider the determination of flow rate from a holistic viewpoint. To build, operate, and maintain the facility properly, the user must have defined the desired uncertainty for the designer.

The accuracy of the metered quantities depends on a combination of the following:

a) the design, installation, and operation of the orifice metering facility;

b) the choice of measurement equipment (charts, transmitters, smart transmitters, analog/digital converters, data loggers, and so forth);

c) the means of data transmission (analog, pneumatic, digital, manual);

d) the calculation procedure and means of computation (chart integration, flow computer, mainframe, minicomputer, personal computer, and so forth);

e) the effects on the operating/calibration equipment of ambient temperature, fluid temperature and pressure, response time, local gravitational forces, atmospheric pressure, and the like;

f) the traceability chain associated with the portable field standards.

The uncertainty depends not just on the hardware but also on the hardware's performance, the software's performance, the method of calibration, the calibration equipment, the calibration procedures, and the human factor.

Annex C
(informative)

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

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:

$$Y = \frac{C_{d_1}}{C_{d_2}} \tag{C-1}$$

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:

$$Y = f(\beta, \kappa, x)$$

where

β is the diameter ratio;

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

ΔP is the orifice differential pressure;

N_3 is the unit conversion factor;

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.

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 through 0.75.

C.1 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:

$$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{x_1}{\kappa} \qquad \text{(C-2)}$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \qquad \text{(C-3)}$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \qquad \text{(C-4)}$$

where

ΔP is the orifice differential pressure;

κ is the isentropic exponent;

N_3 is the unit conversion factor;

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;

$\frac{x_1}{\kappa}$ is the upstream acoustic ratio;

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

C.2 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:

$$Y_2 = Y_1\sqrt{\frac{P_{f_1}Z_{f_2}}{P_{f_2}Z_{f_1}}} \qquad \text{(C-5)}$$

or

$$Y_2 = \left[1-(0.41+0.35\beta^4)\frac{x_1}{\kappa}\right]\sqrt{\frac{P_{f_1}Z_{f_2}}{P_{f_2}Z_{f_1}}} \qquad \text{(C-6)}$$

When the upstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_1}} \qquad \text{(C-7)}$$

When the downstream static pressure is measured,

$$x_1 = \frac{\Delta P}{N_3 P_{f_2} + \Delta P} \qquad \text{(C-8)}$$

where

ΔP is the orifice differential pressure;

κ is the isentropic exponent;

N_3 is the unit conversion factor;

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;

$\frac{x_1}{\kappa}$ 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.

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