Review of API MPMS 14.3 / AGA Report Nos.3, Part 2 and 3

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ABSTRACT

In the natural gas industry, standards are established to provide uniformity of information and action with the objective to improve efficiency and avoid differences in applications and metering. Research on orifice flow meters began around 1904. The *first* . metering standard was produced by the American Gas Association in 1930,AGA Report No. 1 which later evolved into API MPMS, Chapter 14.3 or AGA Report No. 3. AGA Report No. 3 published in 1955, revised in 1969, 1985, 1992, 2000, 2013 and 2016.This AGA report applies to clean, single-phase, homogenous and Newtonian fluids measured using concentric, square edged, flange-tapped orifice meters. With refined data generated, out of coordinated research programs, during 1993 - 1999, AGA Report 3 underwent revision and resulted in publication during April of 2000 and subsequently during 2013/March 2016.

This paper discusses the latest revisions of American Petroleum Institute (API) Manual of Petroleum Measurement Standards (MPMS) Chapter 14.3, "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids," Part 2, "Specification and Installation Requirements.", Fifth Edition ,2016 and Part 3 ,Natural Gas Applications, November 2013.

Coverage of the current revision of the two standards are discussed. They cover Orifice Plates, Meter Tubes, Flow Conditioners, Meter Tube Lengths with and without flow conditioners. Orifice plate eccentricity, applications to pulsations environments are also discussed. Changes in specifications of thermometer wells are deliberated. Revised AGA 3 Part 3 presents updated flow rate equations for Natural Gas applications. This updated revision presents most comprehensive data and adherence to it will improve the measurement accuracy in the order of 0.05-0.2 % in measured volume depending on the range of input process parameters. However the decision to implement is left to the discretion of the parties.

KEYWORDS

Orifice, Standards, API, AGA, Natural Gas, Expansion Factor, Thermowell

1. INTRDUCTION

In the natural gas industry, standards are established to provide uniformity of information and action with the objective to improve efficiency and avoid differences in applications and metering. Research on orifice flow meters began in the U.S. around 1904. The *first.* metering standard was produced by the American Gas Association in 1930.AGA Report No. 1 which later evolved into API MPMS, Chapter 14.3 or AGA Report No. 3 for orifice flow meters. AGA Report No. 3 was first published in 1955 revised in 1969, 1985, 1992, 2000, 2013 and 2016. With refined data generated, out of coordinated research programs, during 1993 - 1999, Part 2 of API MPMS 14.3 or AGA Report No 3 underwent revision and resulted in publication during April 2000 with revisions to the specification and installation requirements for orifice meters and subsequently during March 2016.

This paper discusses the latest orifice flow metering standards - American Petroleum Institute (API) Manual of Petroleum Measurement Standards (MPMS) Chapter 14.3, "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids," Part 2, "Specification and Installation Requirements." [1] and Part 3 " Natural Gas Applications [2]. These standards are also referred as American Gas Association (AGA) Report No. 3, Part 2 and Part 3

More than 200 research papers of 30 research programs during 1922-1999 is briefly described Annex A of Part 2. This report applies to fluids that are considered to be clean, single-phase, homogenous and Newtonian measured using concentric, square edged, flange-tapped orifice meters. The requirements for orifice metering, flow rate calculations, as defined in this publication, will be discussed in greater detail throughout this paper. Many authors have reviewed the earlier version of the standards published during 2000 in detail [3-5]

Coverage of Part 2 incudes

Construction and Installation requirements
Normative references
Terms, Definitions, symbols
Orifice Plate Specifications
Meter Tube Specifications
Installation Requirements
Annex A Research Projects and Tests
Annex B Orifice Meter Inspection Guideline
Annex C Specific Installation Calibration Test
Annex D Flow Conditioner Performance Test
Annex E Maximum Allowable Orifice Plate Differential Pressure
Figures 1 - 6
Tables 1- 8

and Part 3 covers

Normative References
Symbols, Units, and Terminology
Flow Measurement Equations
Flow Equation Components Requiring Additional Computation
Gas Properties
Annex A Adjustments for Instrument Calibration
Annex B Factors Approach
Annex C Flow Calculation Examples
Annex D Pipe Tap Orifice Metering
Annex E SI Conversions
Annex F Development of Constants for Flow Equations
Annex G Buckingham and Bean Empirical Expansion Factor *(Y)* for Flange-tapped Orifice Meters

For existing installations, the decision to upgrade to meet the requirements of updated standards is left to the discretion of the parties involved. The parties must be aware that if a meter installation is not upgraded, measurement bias errors may exist. Use of the calculation procedures and techniques of API MPMS Ch.14.3.3/AGA Report No. 3, Part 3, with existing equipment is recommended, since these represent significant improvements over the previous methods. The uncertainty levels for flow measurement using existing equipment may be different from those quoted in earlier versions. This updated revision presents comprehensive data and adherence to it will improve the computational accuracy in measured volume depending on the range of input process parameters. The impact of revised expansion factor equation on flow rates for set of process conditions is evaluated. Flow rates calculated results in positive bias. Orifice Plates, Meter Tubes, Flow Conditioners, Meter Tube Lengths with and without flow conditioners etc. are discussed. Orifice plate eccentricity, applications to pulsations environments are also discussed. Specifications of thermometer wells are deliberated.

2. CONSTRUCTION AND INSTALLATION REQUIREMENTS (PART 3, SECTION 2)

This section outlines the various design parameters for designing metering facilities using orifice meters. The specified mechanical tolerances encompass a wide range of orifice diameter ratios for which experimental results are available. Use of the calculation procedures and techniques of API *MPMS* Ch.14.3.3/AGA Report No. 3, Part 3, with existing equipment is recommended, since these represent significant improvements over the previous methods. The uncertainty levels may be different from earlier versions. Though the standard covers the diameter ratios (beta) 0.1 - 0.75, , minimum uncertainty is achieved for 0.2 - 0.6 with orifice diameters more than 11.43 mm. It is advised to avoid extreme beta ratio. Mid-diameter ratio (around 0.4) have the highest probability of producing the best measurement. A beta ratio of.75 could be used as the design criteria for new orifice meter installations. Achieving the best level of measurement uncertainty depends on proper design, application of the metering system, maintenance of the meters and adoption of latest equations.

3. TERMS, DEFINITIONS AND SYMBOLS (PART 2, SECTION 3)

The definitions are given to emphasize the particular meaning of the terms as used in Part 2 such as diameter ratio, differential pressure, flow conditioner, meter tubes, orifice plate etc. Symbols and nomenclature used in the standards are furnished.

4. ORIFICE PLATE SPECIFICATIONS (PART 2 SECTION 4)

This section provides dimensional tolerances for the orifice plate design and the key components of an orifice plate. Section covers

- Orifice plate faces
- Orifice plate bore edge
- Orifice plate bore diameter (dm) and roundness (dr)
- Orifice plate bore thickness (e)
- Orifice plate thickness (E)
- Permanent Pressure Drop
- Orifice plate bevel angle (θ)

The symbols for orifice plate dimensions are shown in Fig.1. Fig.2 illustrates the allowable departure. Deviations from flatness shall be < 1 % of dam height $(D_m - d_m)/2$ i.e 0.010 in/in of dam height under no-flow conditions. Maximum allowable departure is 0.005$(D_m - d_m)$ and illustrated in Figs 2a-2c. The surfaces at upstream and downstream faces shall have no abrasions, scratches visible to the naked eye that exceed 50 $\mu in \quad R_a$ and may be verified by using an electronic-averaging-type / other type surface roughness instrument with a cutoff value of not less than 0.03 inch.

The standard recommends the plate shall be clean, free from accumulation of dirt, ice, grit, grease, oil, free liquid, and other extraneous materials. The upstream and downstream edges of the orifice plate bore shall be free from defects visible to the naked eye, such as flat spots, feathered texture, roughness, burrs, bumps, nicks, and notches. The surface of the plate bevel shall have no defects visible to naked eye, such as grooves, ridges, pits, or lumps. Regular inspection schedule depending on the service conditions shall be practiced. The upstream edge of the orifice plate bore shall be square and sharp. An estimation of suitable sharpness can be made by comparing the orifice plate bore edge with the bore edge of a properly sharp reference orifice plate of the same nominal diameter. The orifice plate bore edge being evaluated should feel and look the same as the edge of the reference orifice plate.

The measured orifice bore diameter d_m is the mean of four or more evenly spaced diameter measurements at the inlet edge. The roundness tolerances are given in Table 1. During measurement, the temperature should be within ± 1 °F (± 0.5 °C). The orifice plate bore diameter at reference temperature is defined as $d_r = d_m[1 + \alpha_t(T_r - T_m)]$.Linear coefficient of thermal expansion for orifice plate material are given in Table 2. This edition has revised the coefficients. For SS 304 and 316 , separate values are given. The value for Monel 400 has been revised (3 %) . Metric Conversions has been added in the table. The applicable range of temperature have been lowered to 32 – 212 ºF from -100 ºF - 300 ºF for stainless steel and for Monel, 68 ºF – 212 ºF. Maximum error is 0.005 % in flow for SS over the temperature range between old and new coefficients.

The minimum *allowable* bore thickness is specified as $e \geq 0.01 d_r$ or $e >$ 0.005” whichever is larger. The *maximum* allowable bore thickness is specified as $e \leq 0.02 D_r$ or $e \leq 0.125\, d_r$ whichever is smaller; but e shall not be greater than the maximum allowable orifice plate thickness, E. When the orifice plate thickness *(E)* exceeds the orifice bore thickness *(e),* a bevel is required on the downstream side of the orifice bore.Orifice plate bores that demonstrate any convergence from inlet to outlet are unacceptable.

Allowable differential pressure limits varies and are function of beta ratio, pipe sizes, plate thickness, plate material, mechanical strength, acceptable expansion factor, uncertainty. Maximum acceptable permanent pressure loss and allowable differential pressures are as high as 1000 “ WC.

The minimum, maximum, and recommended values of orifice plate thickness *(E)* for Types 304 and 316 SS orifice plates are given in Table 3. The maximum allowable differential pressure is in the range of 180 - 1,000 inches of water column depending on pipe size . Maximum allowable differential pressures for the recommended orifice plate thicknesses in Table 3 are for operating temperatures not exceeding 150°F. The use of an orifice plate thickness other than the recommended thickness is acceptable in either new or existing orifice plate holding devices as long as the thickness is within the maximum and minimum range; and the orifice plate eccentricity, bore thickness, differential pressure tap hole, and expansion-factor pressure-ratio tolerances and limits are satisfied.Additional guidance on allowable differential pressure across the orifice plate is provided in Annex E. Guidance is also provided for estimating the permanent pressure loss across an orifice plate. Permanent pressure loss is approximated to $\Delta P(1 - \beta^2)$. It ranges from 96-44 % for beta ratios of 0.2 - 0.75 for listed maximum differential pressures of Table 3

The allowable tolerance for the orifice plate bevel angle,θ, is 45°±15°. If a bevel is required, its minimum dimension, E-e, measured along the axis of the bore, shall not be less than 0.0625 inch.

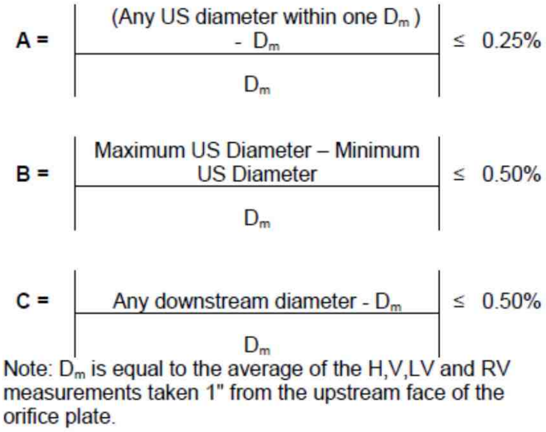
5. METER TUBE SPECIFICATIONS (PART 2 SECTION 5)

The meter tube consists the straight length of pipe upstream of the orifice of the same diameter, including the flow straightener/conditioner, the orifice plate holder and the similar downstream pipe beyond the orifice plate. Allowable tolerances are provided for the meter tube surface roughness. Guidance is also provided on where to measure surface roughness along the meter tube. Meter tube surfaces that are too hydrodynamically "smooth" or "rough" will result in a flow measurement bias error.

Proper meter tube inside surface roughness is required to assure accurate measurement. The surface roughness requirement for meter tubes of 12” or less is 300 μin Ra when βr < 0.6, 250 μin Ra when βr≥0.6 and Minimum Ra is 0.34 μin.The surface roughness requirement for greater than 12 “ pipe is 600 μin Ra when β_r < 0.6, 500 μin Ra when β_r≥0.6 and Minimum Ra is 0.34 μin. Irregularities such as grooves, scoring, or ridges resulting from seams, welding distortion, offsets, and the like that affect the tolerance in excess of that allowed are not permitted. The existence of pits in the surface of the meter tube, although undesirable, are allowed provided their individual measurements do not exceed the surface roughness and/or diameter tolerance requirements of the meter tube and do not compromise the meter tube’s pressure integrity. When these tolerances are exceeded, the irregularities must be corrected. The increase in the meter tube surface wall roughness requirement should not be interpreted as reducing the need to maintain clean meter tubes. Due care shall be exercised to keep the meter tube interior clean and free from accumulation of dirt, ice, grit, grease, oil, free liquid and other extraneous materials, to the extent feasible. Damage and/or accumulation of extraneous materials in the meter tube may result in a greater uncertainty for the orifice plate coefficient of discharge, Cd(FT).

Readily available cold drawn seamless pipe used in the construction of meter tubes generally falls within 75 to 150 micro inches. When other types of commercial pipe are used, honing to achieve the desired finish is required. Digital profilometers are commonly used to accurately determine this measurement

Procedures are provided for measuring the meter tube diameter, D_m for both metering and check measurements. For metering, measurement must be made at 1” upstream plane of orifice and check measurements must be made at 1” downstream and 2Di from orifice face. The measured diameter D_m is the mean of four or more evenly spaced diameter measurements . Typical calculation of tolerances are given in Table 4. During measurement, the temperature should be within ± 5 °F (± 2.5 °C). The diameter at reference temperature is defined as $D_r = D_m[1+\alpha_2(T_r - T_m)]$.Linear coefficient of thermal expansion is in Table 2. Allowable tolerances are provided for both meter tube diameter and roundness - both upstream and downstream of the orifice plate.



$$A = \left| \frac{(\text{Any US diameter within one } D_m) - D_m}{D_m} \right| \le 0.25\%$$

$$B = \left| \frac{\text{Maximum US Diameter} - \text{Minimum US Diameter}}{D_m} \right| \le 0.50\%$$

$$C = \left| \frac{\text{Any downstream diameter} - D_m}{D_m} \right| \le 0.50\%$$

Note: D_m is equal to the average of the H,V,LV and RV measurements taken 1" from the upstream face of the orifice plate.

		Roundness Tolerances		
Nominal Pipe Diameter (")	Internal Pipe Diameter, mm (Sch 40 Pipe)	Up Stream A	B mm	Down stream C mm
2	52.550	0.131	0.263	0.263
3	77.900	0.195	0.390	0.390
4	102.300	0.256	0.512	0.512
6	154.100	0.385	0.771	0.771
8	202.700	0.507	1.014	1.014
10	254.550	0.636	1.273	1.273
12	303.250	0.758	1.516	1.516
14	333.300	0.833	1.667	1.667
16	381.000	0.953	1.905	1.905

Tables 4 and 5 provide example meter tube internal diameter roundness tolerances.

Guidance is provided on the proper location and configuration (e.g., geometry) of pressure taps adjacent to the orifice plate. Meter tubes using flange taps shall have the the center of the upstream tap hole placed one inch from the upstream face of the orifice plate. The center of the downstream pressure tap shall be one inch from the downstream face of the orifice plate. There are allowable deviations specified in Fig.3. The recommendation is to use a Beta ratio of 0.75 to determine the allowable tolerance. All Tolerances Listed are at 0.75 beta ratio

Nominal Pipe Size	Tolerance Fig.3	Minimum Diameter	Maximum Diameter
2" & 3"	1" ±0.015"	0.985"	1.015"
≥4"	1" ± 0.035"	0.965"	1.035"

The tap holes shall be drilled radially to the meter tube. The centerline of the tap hole shall intersect and form a right angle with the axis of the meter tube. All pressure tap holes must be round to a tolerance of ± 0.004 inch throughout their length. The diameter and diameter tolerances are contained in the following table:

Pipe Diameter	Pressure tap hole diameter	Diameter	
Nominal		Minimum	Maximum
2" & 3"	0.375" ± 0.016"	0.359"	0.391"
4" or Larger	0.500" ±.016"	0.484"	0.516"

To avoid any resonance in the gauge line, the length of the gauge line should be as short as possible or should have lengths (/) specified according to the highest frequency (/) of concern from one of the following formulas.

$0 \leq l1 \leq 0.25c/(2\pi f)$

$l2 = 2.5c/(2\pi f)$

$l3 = 5.5c/(2\pi f)$

$l4 = 8.5c/(2\pi f)$

$l5 = 11.5c/(2\pi f)$

c is the speed of sound in gas

A flow conditioner is a device placed upstream of the orifice plate that attempts to correct or eliminate flow field distortions created by the upstream piping configuration. Flow *straighteners* are effective at reducing or eliminating swirl from the flow stream. However, they may not be capable of creating a flow condition (i.e., velocity profile) similar to that achieved for the flow experiments run to create the orifice plate coefficient of discharge dataset. If the flow field at an orifice inlet is substantially different than that for the flow experiments performed to create the orifice plate coefficient of discharge dataset, flow measurement bias errors can result. An example of a flow *straightener* is provided in Fig 4 . *Isolating* flow conditioners are those that attempt to "isolate" the orifice plate from any adverse effects of flow distortions created by the upstream piping configuration. Isolating flow conditioners attempt to produce a fully- developed, axi-symmetric, swirl-free, turbulent velocity profile immediately upstream of the orifice plate. Isolating flow conditioners typically use a perforated plate or grid configuration, and associated pressure drop, to redistribute the flow into the desired velocity profile downstream of the conditioner. Standard includes flow conditioner performance criteria and Annex D includes a test protocol to verify performance of "other" flow conditioner types besides flow straighteners. Performance tests shall be conducted under the following conditions

i. Good Flow Conditions with 75 Di
ii. Two adjoining out of plane 90^{o} Elbows
iii. 50 % closed valve
iv. High swirl Generator (Out of Plane Elbows)
v.

6. INSTALLATION REQUIREMENTS (PART 2 SECTION 6)

Section 6 includes specifications for orifice plate bore eccentricity, ϵ orifice plate perpendicularity and measurements. The orifice plate bore must be concentric with both the upstream and the downstream inside bore of the orifice plate holder Eccentricity parallel to the axis of the differential pressure taps, ε_x shall be less than or equal to the tolerance defined by the following equation.

$$\varepsilon_x \leq \frac{0.0025D_m}{0.1 + 2.3\beta_m^4}$$

Eccentricity perpendicular to the axis ε_y of the differential pressure taps may be four times the amount calculated using the equation. Fig 5 shows a sample method for measuring the eccentricity. Parallel to differential pressure taps: (X-X')/2 and Perpendicular to the Differential Pressure Taps: (Y-Y')/2 .Table 6 shows the maximum tolerances for orifice plate bore eccentricity.

Standard provides guidance on the minimum length of straight pipe required upstream and downstream of the orifice plate. The upstream piping configuration shall produce an axi-symmetric, swirl-free, fully-developed, turbulent velocity profile at the inlet to the orifice plate in order to produce the most accurate flow measurement. Standard includes specifications for the minimum length of straight pipe required upstream of the plate - both with and without the inclusion of a flow conditioner. The recommended minimum upstream meter tube length varies depending on the orifice diameter ratio, and the configuration of the piping element(s) immediately upstream of the meter tube. Fig 6 shows the orifice meter tube layout for flanged or welded inlet. This figure includes the critical length dimensions for the meter tube. The research data segments the meter tube lengths into the following three categories:

i. Meter tube lengths without 19 tube concentric tube bundles (Bare meter tubes).
ii. Meter tubes lengths with 19 tube concentric tube bundles $17D_i \leq UL > 29D_i$
iii. UL≥29Di

The 1998 Uniform Concentric 19-Tube bundle is considered a flow straightener. The individual tubes must be of uniform smoothness, outer diameter and wall thickness. Commercially available seamless carbon steel tubing is most commonly used. The individual wall thickness of the tubes shall be less than or equal to 2.5% of Di.The required length of the tube bundles must be 3 X NPS for 2”, 2.5 X NPS for 3” & 4”,2 X NPS for 6” and above.The tubes must be arranged in a cylindrical pattern and the individual tube outer walls must come in direct contact with each other. The outside diameter of the tube bundle must be a minimum of 95% of the published internal diameter of the meter tube.

Table 7 presents the orifice meter length requirements for meter tubes without a flow conditioner and Tables 8a and 8b present the length requirements for meter tubes with a 1998 uniform concentric 19-tube bundle flow straightener. In many instances it might be difficult to control upstream piping configurations. In all but two of the applications identified in Table 7, a UL length of 44D at a beta ratio of .75 meets minimum requirements. The exceptions are Two 90°elbows in perpendicular planes where S<5D*i* and any other configuration (catch all category).

For two 90° elbows in perpendicular planes, the recommendation is 95 Di for beta ratios of 0.50 - 0.75. For configurations not specifically addressed in Table 7, 145

Di are recommended for beta ratios 0.40 - 0.75 without flow conditioner. A piping segment upstream of the meter tube in between the elbows "S" will control the straight length requirements to 44Di. With flow straighteners or conditioners, the UL requirements fall drastically to 5-14.5 Depending on beta ratio. With increasing beta, UL increases.

For 1998 19-Tube Bundle, there are multiple configurations that are not allowed at the higher beta ratios (0.6-0.75). This means that it is not possible to find an acceptable location .For Example single 90° tee used as an elbow but not as a header element for beta ratios of .67 and higher and partially closed valves (at least 50% open) for beta ratios of .60 and higher.

Flow conditioners not meeting the requirements of the 1998 Uniform Concentric Tube Bundle are considered as Other Flow Conditioners. For other flow conditioners, use is based on technical performance data obtained from performance test(s). The standard provides a uniform criterion for evaluation of installation and/or flow conditioner performance (perturbation) test or tests. Details of the performance test are given in Annex D. The performance test(s) will confirm the orifice meter diameter ratio, meter tube length, and flow conditioner location for which acceptable performance is obtainable. Significant research and numerous flow studies have been conducted since 1991 to test various flow conditioner designs with repeatable and acceptable results. Many companies have now changed their engineering standards to accommodate other types of one and two piece flow conditioners such as those produced by Gallagher, Canadian Pipeline Accessories and Daniel.

Section 6 also discusses operation of orifice flow meters under pulsating flow conditions. Part 2 states that a pulsating differential pressure across the orifice plate, $\Delta P_{rms}/\Delta P_{avg}$, of up to 10% root mean square . This applies to single frequency flow pulsations with or without several harmonics and to broad-band flow pulsations/noise. Part 2 also states. "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. Arbitrary application of any correcting formula may even *increase* the flow measurement error under pulsating flow conditions. The user should make every practical effort to eliminate pulsations at the source to avoid increased uncertainty in measurements."

Thermometer wells should be located to sense the average temperature of the fluid at the orifice plate. The wells may be placed on the downstream side of the orifice plate not closer than DL or farther than 4DL as illustrated in Tables (7-8).If a flow conditioner is used, the thermometer well may be located no closer than 36 inches upstream of the flow conditioner inlet. Thermo wells exposed to the influences of the ambient environment may result in biased measurement.

Care should be taken to ensure that the temperature sensor indicates the flowing fluid temperature and is not thermally coupled to the meter run pipe. Consideration should be given to insulating or thermally isolating adequate sections of the meter run upstream and downstream of the thermowell location to insure the indicated temperature reflects the temperature of the flowing fluid stream and not the effects of ambient conditions on the pipe surrounding the thermowell. Thermowell length shall be no longer than the length determined by the following equation and no shorter than 1/3 the pipe inner diameter and constructed of material providing adequate strength. This version specifies the probe length, defined as the distance between the probe tip and its point of attachment inside the pipe.

$$L = \left[\frac{F_m \times 4.38 \times OD \times 10}{S \times V}\left(\frac{E}{\rho}(OD^2 + ID^2)\right)^{0.5}\right]^{0.5}$$

Where

L : probe length (mm);

F : virtual mass factor for a gas, F_m = 1.0

OD : outside diameter of probe (mm);

ID : Inside diameter of probe (mm);

S : Strouhal number, 0.22.

V : Velocity of fluid (m/s);20 m/s

E : Modulus of elasticity of probe material (kg/cm^2);1978249.5 kg/cm^2

ρ : Density of probe material (kg/m^3), 7980 kg/m^3

Lengths calculated for typical applications are listed in Table 9. As the thermo wells are tapered, tip, middle and root outside diameters are used for calculations. For 12 and 10” pipe sizes, calculated lengths are less. For smaller sizes, the lengths are acceptable. Providing collars reduces the insertion length requirements

7. FLOW EQUATIONS (PART 3)

Flow equations for computing the base volumetric flow rates are presented in this section. Symbols and notations are same as given in [2]

$$Q_m = C_d(FT)E_v\pi\frac{d^2}{4}\sqrt{2\rho_f\Delta P} \quad \text{kg/s}$$

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

$$C_i(FT) = Ci(CT) + tapterm$$

$$C_i(CT) = 0.5961 + 0.029\beta^2 - 0.2290\beta^8 + 0.003(1-\beta)M_1$$

$$tapterm = upstrm + dnstrm$$

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

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

Also

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

$M_1 = \max(2.8 - \frac{D}{N_4}, 0.0)$ N_4=1 when D is in inches

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

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

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

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

$$\beta = d/D$$

$$d = d_r(1 + \alpha_1\,(T_f - T_r))$$

$$D = D_r(1 + \alpha_2\,(T_f - T_r))$$

$$Re_D = \frac{4Q_m}{\pi D\mu}$$

$$Y_1 = 1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\{1 - (1 - x_1)^{\frac{1}{k}}\}$$

$$x_1 = \frac{\Delta \mathrm{P}}{\mathrm{P_{f1}}} \quad and \ \leq 0.25$$

$$\rho_t = \frac{\mathrm{P_{f1}\,M_{rgas}}}{\mathrm{Z_{f1}RT_f}}$$

$\rho_b = \frac{\mathrm{P_b\,M_{r\,gas}}}{\mathrm{Z_bRT_b}}$ $Q_b = Q_m/\rho_b$ Initial C_d (FT) is assumed and Reynolds number and flow rate are iterated (4- 5 iterations)

While all equations are the same, significant difference is the equation for expansion factor.

Expansion Factors accounts for change in density as gas flows through an orifice. The expansion factor (Y) is a function of diameter ratio, the ratio of differential pressure to static pressure at the designated tap, and the isentropic exponent (k). The real compressible fluid isentropic exponent is a function of the fluid and the pressure and temperature. Accepted practice for natural gas applications is to use 1.3.

$$Y_1 = 1 - (0.3625 + 0.1027\beta^4 + 1.1320\beta^8)\left\{1 - (1 - x_1)^{\frac{1}{k}}\right\}$$

2013 equation (1)

$$Y_1 = 1 - (0.41 + 0.35\beta^4)(x_1/k)$$ 1992 Equation (2)

The expansion factor equation for flange taps may be used for a range of diameter ratios from 0.10 to 0.75 and x1 up to 0.2

Both equations for expansion factor converges when xi is equal to zero. As it increases, the difference between the two equations increases. The following example, Table G.1, shows the x1 value for which the percent difference between equations exceeds 0.25, or approximately half of the uncertainty associated with the discharge coefficient equation. For typical field data given below,

Orifice Diameters : 0.0135 – 0.18 m
Pipe Diameters : 50 NB- 300 NB
Beta Ratio : 0.27 – 0.62
X1 : 0.001 – 0.13

the effect of Y1 values from two equations on the volume flow rates have been compared in Fig.7. % change in base volume increases with increase in x1 linearly (up to 0.5%) depending on the Pressure Ratios. Fig.8 shows % change with beta ratio. % change decreases with increase in beta. Overall measurement uncertainty will increase by this amount unless the latest equation for Y1 is used for flow calculations.

8. CONCLUSIONS

The contents of the latest orifice flow metering standards - American Petroleum Institute (API) Manual of Petroleum Measurement Standards (MPMS) Chapter 14.3, "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids," Part 2, "Specification and Installation Requirements " and Part 3 " Natural Gas Applications" have been reviewed. Improvements up to 0.5% have been highlighted with numerical examples using practical data if new expansion factor equation is implemented in the flow rate calculations.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

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3. Tom Cathey,"A Review of the Revisions to API 14.3 / AGA 3 – Part 2",Wedge Measurement & Control, Inc. Texas 77056,USA
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5. Edgar B. Bowles, Jr A Review of API MPMS Chapter 14.3/AGA Report No. 3 - Part 2, Southwest Research Institute,TX 78238 USA

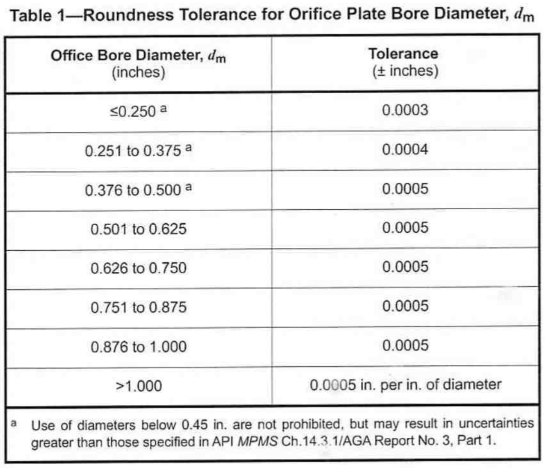


Table 1—Roundness Tolerance for Orifice Plate Bore Diameter, d_m

Office Bore Diameter, d_m (inches)	Tolerance (± inches)
≤0.250 [a]	0.0003
0.251 to 0.375 [a]	0.0004
0.376 to 0.500 [a]	0.0005
0.501 to 0.625	0.0005
0.626 to 0.750	0.0005
0.751 to 0.875	0.0005
0.876 to 1.000	0.0005
>1.000	0.0005 in. per in. of diameter

[a] Use of diameters below 0.45 in. are not prohibited, but may result in uncertainties greater than those specified in API *MPMS* Ch.14.3.1/AGA Report No. 3, Part 1.

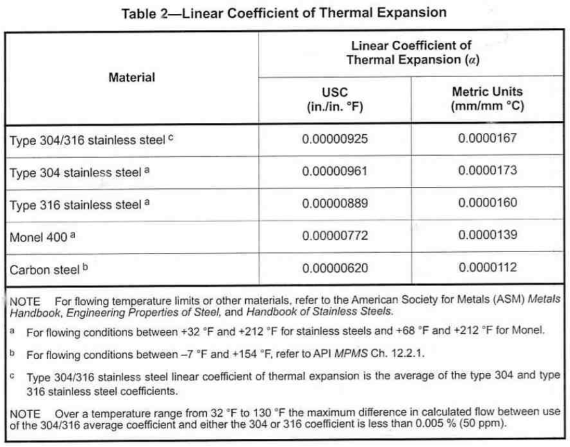


Table 2—Linear Coefficient of Thermal Expansion

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).

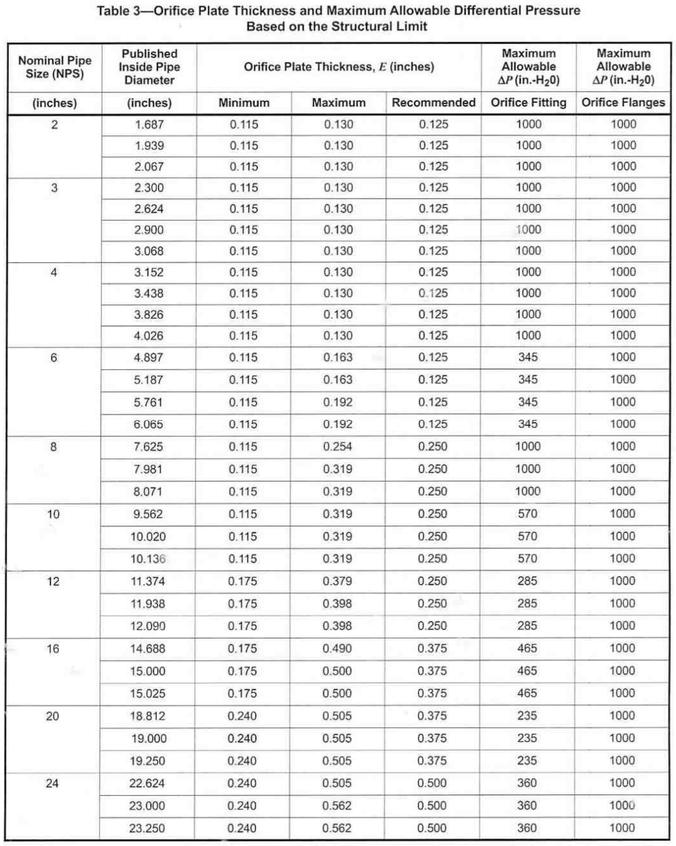


Table 3—Orifice Plate Thickness and Maximum Allowable Differential Pressure Based on the Structural Limit

Nominal Pipe Size (NPS)	Published Inside Pipe Diameter	Orifice Plate Thickness, E (inches)			Maximum Allowable ΔP (in.-H$_2$0)	Maximum Allowable ΔP (in.-H$_2$0)
(inches)	(inches)	Minimum	Maximum	Recommended	Orifice Fitting	Orifice Flanges
2	1.687	0.115	0.130	0.125	1000	1000
	1.939	0.115	0.130	0.125	1000	1000
	2.067	0.115	0.130	0.125	1000	1000
3	2.300	0.115	0.130	0.125	1000	1000
	2.624	0.115	0.130	0.125	1000	1000
	2.900	0.115	0.130	0.125	1000	1000
	3.068	0.115	0.130	0.125	1000	1000
4	3.152	0.115	0.130	0.125	1000	1000
	3.438	0.115	0.130	0.125	1000	1000
	3.826	0.115	0.130	0.125	1000	1000
	4.026	0.115	0.130	0.125	1000	1000
6	4.897	0.115	0.163	0.125	345	1000
	5.187	0.115	0.163	0.125	345	1000
	5.761	0.115	0.192	0.125	345	1000
	6.065	0.115	0.192	0.125	345	1000
8	7.625	0.115	0.254	0.250	1000	1000
	7.981	0.115	0.319	0.250	1000	1000
	8.071	0.115	0.319	0.250	1000	1000
10	9.562	0.115	0.319	0.250	570	1000
	10.020	0.115	0.319	0.250	570	1000
	10.136	0.115	0.319	0.250	570	1000
12	11.374	0.175	0.379	0.250	285	1000
	11.938	0.175	0.398	0.250	285	1000
	12.090	0.175	0.398	0.250	285	1000
16	14.688	0.175	0.490	0.375	465	1000
	15.000	0.175	0.500	0.375	465	1000
	15.025	0.175	0.500	0.375	465	1000
20	18.812	0.240	0.505	0.375	235	1000
	19.000	0.240	0.505	0.375	235	1000
	19.250	0.240	0.505	0.375	235	1000
24	22.624	0.240	0.505	0.500	360	1000
	23.000	0.240	0.562	0.500	360	1000
	23.250	0.240	0.562	0.500	360	1000

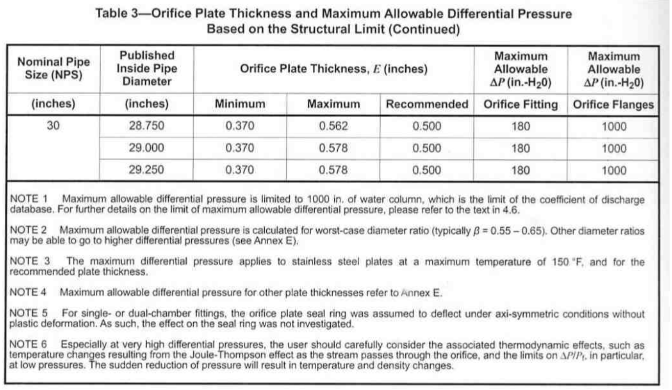


Table 3—Orifice Plate Thickness and Maximum Allowable Differential Pressure Based on the Structural Limit (Continued)

Nominal Pipe Size (NPS)	Published Inside Pipe Diameter	Orifice Plate Thickness, E (inches)			Maximum Allowable ΔP (in.-H$_2$0)	Maximum Allowable ΔP (in.-H$_2$0)
(inches)	(inches)	Minimum	Maximum	Recommended	Orifice Fitting	Orifice Flanges
30	28.750	0.370	0.562	0.500	180	1000
	29.000	0.370	0.578	0.500	180	1000
	29.250	0.370	0.578	0.500	180	1000

NOTE 1 Maximum allowable differential pressure is limited to 1000 in. of water column, which is the limit of the coefficient of discharge database. For further details on the limit of maximum allowable differential pressure, please refer to the text in 4.6.

NOTE 2 Maximum allowable differential pressure is calculated for worst-case diameter ratio (typically $\beta = 0.55 - 0.65$). Other diameter ratios may be able to go to higher differential pressures (see Annex E).

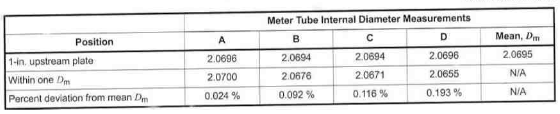
NOTE 3 The maximum differential pressure applies to stainless steel plates at a maximum temperature of 150 °F, and for the recommended plate thickness.

NOTE 4 Maximum allowable differential pressure for other plate thicknesses refer to Annex E.

NOTE 5 For single- or dual-chamber fittings, the orifice plate seal ring was assumed to deflect under axi-symmetric conditions without plastic deformation. As such, the effect on the seal ring was not investigated.

NOTE 6 Especially at very high differential pressures, the user should carefully consider the associated thermodynamic effects, such as temperature changes resulting from the Joule-Thompson effect as the stream passes through the orifice, and the limits on $\Delta P/P_f$, in particular, at low pressures. The sudden reduction of pressure will result in temperature and density changes.

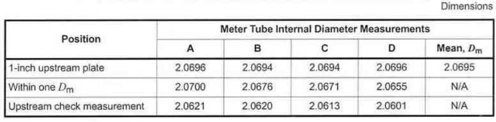
Table 4—Example Meter Tube Internal Diameter—Roundness Tolerances Within First Mean Meter Tube Diameter Upstream of Orifice Plate



Dimensions in inches

Position	Meter Tube Internal Diameter Measurements				
	A	B	C	D	Mean, D_m
1-in. upstream plate	2.0696	2.0694	2.0694	2.0696	2.0695
Within one D_m	2.0700	2.0676	2.0671	2.0655	N/A
Percent deviation from mean D_m	0.024 %	0.092 %	0.116 %	0.193 %	N/A

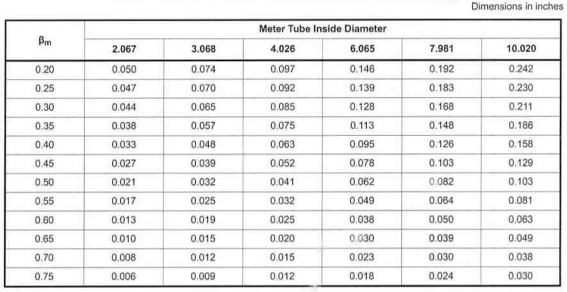
Table 5—Example Meter Tube Internal Diameter Roundness Tolerances—All Upstream Meter Tube Individual Internal Diameter Measurements



Dimensions in inches

Position	Meter Tube Internal Diameter Measurements				
	A	B	C	D	Mean, D_m
1-inch upstream plate	2.0696	2.0694	2.0694	2.0696	2.0695
Within one D_m	2.0700	2.0676	2.0671	2.0655	N/A
Upstream check measurement	2.0621	2.0620	2.0613	2.0601	N/A

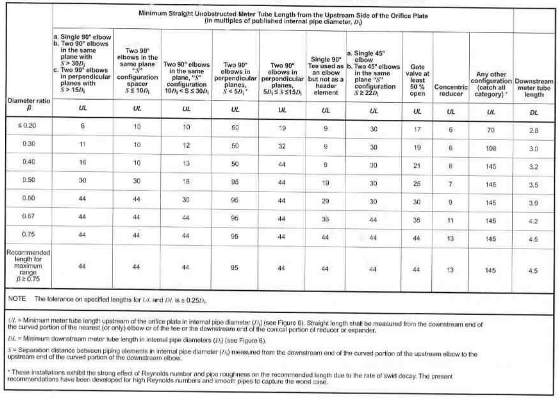
Table 6—Maximum Tolerance of Orifice Plate Bore Eccentricity (ε_x)



Dimensions in inches

β_m	Meter Tube Inside Diameter					
	2.067	3.068	4.026	6.065	7.981	10.020
0.20	0.050	0.074	0.097	0.146	0.192	0.242
0.25	0.047	0.070	0.092	0.139	0.183	0.230
0.30	0.044	0.065	0.085	0.128	0.168	0.211
0.35	0.038	0.057	0.075	0.113	0.148	0.186
0.40	0.033	0.048	0.063	0.095	0.126	0.158
0.45	0.027	0.039	0.052	0.078	0.103	0.129
0.50	0.021	0.032	0.041	0.062	0.082	0.103
0.55	0.017	0.025	0.032	0.049	0.064	0.081
0.60	0.013	0.019	0.025	0.038	0.050	0.063
0.65	0.010	0.015	0.020	0.030	0.039	0.049
0.70	0.008	0.012	0.015	0.023	0.030	0.038
0.75	0.006	0.009	0.012	0.018	0.024	0.030

Table 7—Orifice Meter Installation Requirements Without a Flow Conditioner



	Minimum Straight Unobstructed Meter Tube Length from the Upstream Side of the Orifice Plate (in multiples of published internal pipe diameter, D_i)										
	a. Single 90° elbow b. Two 90° elbows in the same plane with $S > 30D_i$ c. Two 90° elbows in perpendicular planes with $S > 15D_i$	Two 90° elbows in the same plane "S" configuration spacer $S \leq 10D_i$	Two 90° elbows in the same plane, "S" configuration $10D_i < S \leq 30D_i$	Two 90° elbows in perpendicular planes, $S < 5D_i$ *	Two 90° elbows in perpendicular planes, $5D_i \leq S \leq 15D_i$	Single 90° Tee used as an elbow but not as a header element	a. Single 45° elbow b. Two 45° elbows in the same plane "S" configuration $S \geq 22D_i$	Gate valve at least 50 % open	Concentric reducer	Any other configuration (catch all category) *	Downstream meter tube length
Diameter ratio β	UL	UL	UL	UL	UL	UL	UL	UL	UL	UL	DL
≤ 0.20	6	10	10	50	19	9	30	17	6	70	2.8
0.30	11	10	12	50	32	9	30	19	6	108	3.0
0.40	16	10	13	50	44	9	30	21	6	145	3.2
0.50	30	30	18	95	44	19	30	25	7	145	3.5
0.60	44	44	30	95	44	29	30	30	9	145	3.9
0.67	44	44	44	95	44	36	44	35	11	145	4.2
0.75	44	44	44	95	44	44	44	44	13	145	4.5
Recommended length for maximum range $\beta \geq 0.75$	44	44	44	95	44	44	44	44	13	145	4.5

NOTE The tolerance on specified lengths for UL and DL is ± $0.25D_i$.

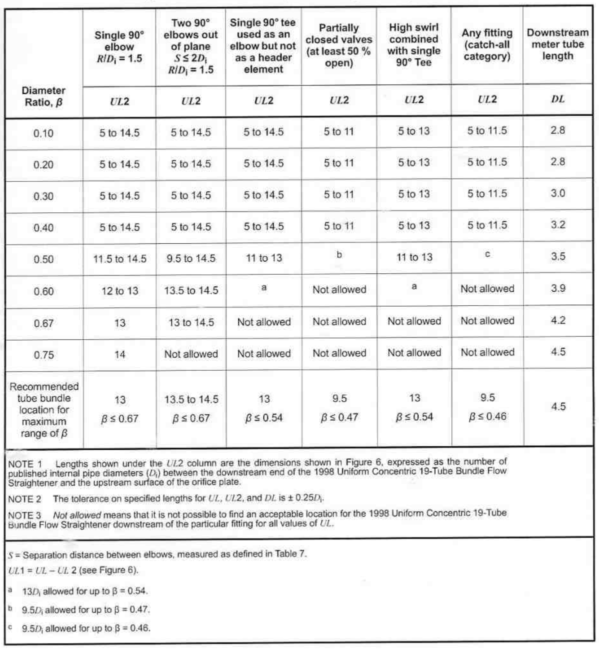
UL = Minimum meter tube length upstream of the orifice plate in internal pipe diameter (D_i) (see Figure 6). Straight length shall be measured from the downstream end of the curved portion of the nearest (or only) elbow or of the tee or the downstream end of the conical portion of reducer or expander.

DL = Minimum downstream meter tube length in internal pipe diameters (D_i) (see Figure 6).

S = Separation distance between piping elements in internal pipe diameter (D_i) measured from the downstream end of the curved portion of the upstream elbow to the upstream end of the curved portion of the downstream elbow.

* These installations exhibit the strong effect of Reynolds number and pipe roughness on the recommended length due to the rate of swirl decay. The present recommendations have been developed for high Reynolds numbers and smooth pipes to capture the worst case.

Table 8a—Orifice Meter Installation Requirements With 1998 Uniform Concentric 19-Tube Bundle Flow Straightener for Meter Tube Upstream Length of $17D_i \leq$ UL < $29D_i$



	Single 90° elbow $R/D_i = 1.5$	Two 90° elbows out of plane $S \leq 2D_i$ $R/D_i = 1.5$	Single 90° tee used as an elbow but not as a header element	Partially closed valves (at least 50 % open)	High swirl combined with single 90° Tee	Any fitting (catch-all category)	Downstream meter tube length
Diameter Ratio, β	$UL2$	$UL2$	$UL2$	$UL2$	$UL2$	$UL2$	DL
0.10	5 to 14.5	5 to 14.5	5 to 14.5	5 to 11	5 to 13	5 to 11.5	2.8
0.20	5 to 14.5	5 to 14.5	5 to 14.5	5 to 11	5 to 13	5 to 11.5	2.8
0.30	5 to 14.5	5 to 14.5	5 to 14.5	5 to 11	5 to 13	5 to 11.5	3.0
0.40	5 to 14.5	5 to 14.5	5 to 14.5	5 to 11	5 to 13	5 to 11.5	3.2
0.50	11.5 to 14.5	9.5 to 14.5	11 to 13	b	11 to 13	c	3.5
0.60	12 to 13	13.5 to 14.5	a	Not allowed	a	Not allowed	3.9
0.67	13	13 to 14.5	Not allowed	Not allowed	Not allowed	Not allowed	4.2
0.75	14	Not allowed	Not allowed	Not allowed	Not allowed	Not allowed	4.5
Recommended tube bundle location for maximum range of β	13 $\beta \leq 0.67$	13.5 to 14.5 $\beta \leq 0.67$	13 $\beta \leq 0.54$	9.5 $\beta \leq 0.47$	13 $\beta \leq 0.54$	9.5 $\beta \leq 0.46$	4.5

NOTE 1 Lengths shown under the $UL2$ column are the dimensions shown in Figure 6, expressed as the number of published internal pipe diameters (D_i) between the downstream end of the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener and the upstream surface of the orifice plate.

NOTE 2 The tolerance on specified lengths for UL, $UL2$, and DL is ± $0.25D_i$.

NOTE 3 *Not allowed* means that it is not possible to find an acceptable location for the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener downstream of the particular fitting for all values of UL.

S = Separation distance between elbows, measured as defined in Table 7.

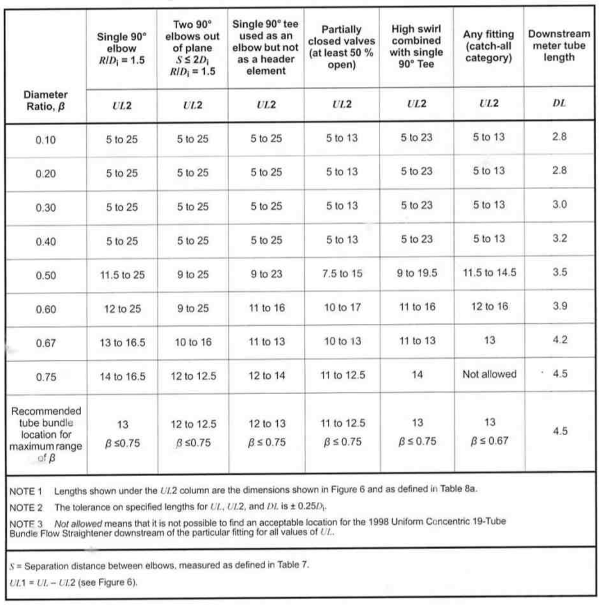
$UL1 = UL - UL\,2$ (see Figure 6).

[a] $13D_i$ allowed for up to β = 0.54.

[b] $9.5D_i$ allowed for up to β = 0.47.

[c] $9.5D_i$ allowed for up to β = 0.46.

Table 8b—Orifice Meter Installation Requirements With 1998 Uniform Concentric 19-Tube Bundle Flow Straightener for Meter Tube Upstream Length of UL ≥ $29D_i$



	Single 90° elbow $R/D_i = 1.5$	Two 90° elbows out of plane $S \leq 2D_i$ $R/D_i = 1.5$	Single 90° tee used as an elbow but not as a header element	Partially closed valves (at least 50 % open)	High swirl combined with single 90° Tee	Any fitting (catch-all category)	Downstream meter tube length
Diameter Ratio, β	$UL2$	$UL2$	$UL2$	$UL2$	$UL2$	$UL2$	DL
0.10	5 to 25	5 to 25	5 to 25	5 to 13	5 to 23	5 to 13	2.8
0.20	5 to 25	5 to 25	5 to 25	5 to 13	5 to 23	5 to 13	2.8
0.30	5 to 25	5 to 25	5 to 25	5 to 13	5 to 23	5 to 13	3.0
0.40	5 to 25	5 to 25	5 to 25	5 to 13	5 to 23	5 to 13	3.2
0.50	11.5 to 25	9 to 25	9 to 23	7.5 to 15	9 to 19.5	11.5 to 14.5	3.5
0.60	12 to 25	9 to 25	11 to 16	10 to 17	11 to 16	12 to 16	3.9
0.67	13 to 16.5	10 to 16	11 to 13	10 to 13	11 to 13	13	4.2
0.75	14 to 16.5	12 to 12.5	12 to 14	11 to 12.5	14	Not allowed	4.5
Recommended tube bundle location for maximum range of β	13 $\beta \leq 0.75$	12 to 12.5 $\beta \leq 0.75$	12 to 13 $\beta \leq 0.75$	11 to 12.5 $\beta \leq 0.75$	13 $\beta \leq 0.75$	13 $\beta \leq 0.67$	4.5

NOTE 1 Lengths shown under the $UL2$ column are the dimensions shown in Figure 6 and as defined in Table 8a.

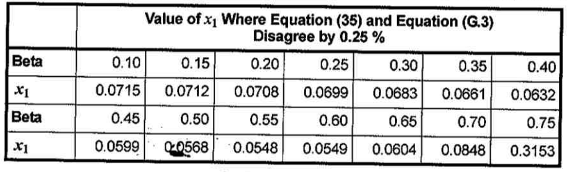
NOTE 2 The tolerance on specified lengths for UL, $UL2$, and DL is ± $0.25D_i$.

NOTE 3 *Not allowed* means that it is not possible to find an acceptable location for the 1998 Uniform Concentric 19-Tube Bundle Flow Straightener downstream of the particular fitting for all values of UL.

S = Separation distance between elbows, measured as defined in Table 7.

$UL1 = UL - UL2$ (see Figure 6).

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



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

Table 9. Thermo well Lengths

Pipe Size,"	Calculated Thermowell Length,mm	Outside Diameter, mm	Inside Diameter, mm	Actual Thermowell Length,mm		Remarks
				Without Collar	With Collar	
12	246	19	7	296		Not Acceptable
10	246	19	7	246		Acceptable
8	246	19	7	166	119	Acceptable
6	246	19	7	147	100	Acceptable
4	246	19	7	96		Acceptable
12	209	16	7	296		Not Acceptable
10	209	16	7	246		Not Acceptable
8	209	16	7	166	119	Acceptable
6	209	16	7	147	100	Acceptable
4	209	16	7	96		Acceptable
12	168	12.5	7	296		Not Acceptable
10	168	12.5	7	246		Not Acceptable
8	168	12.5	7	166	119	Acceptable
6	168	12.5	7	147	100	Acceptable
4	168	12.5	7	96		Acceptable

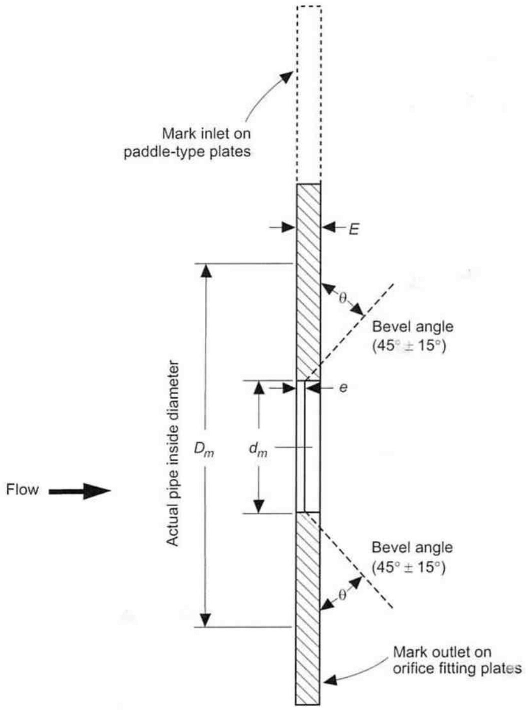


Fig.1 Symbols for Orifice Plate Dimensions

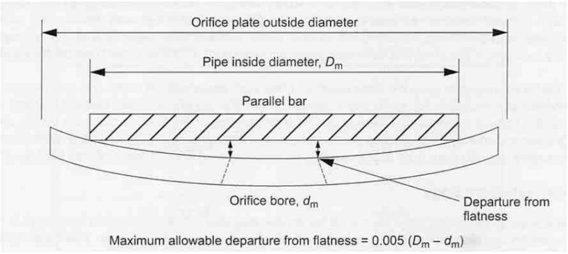


Fig 2a Orifice Plate Departure from Flatness

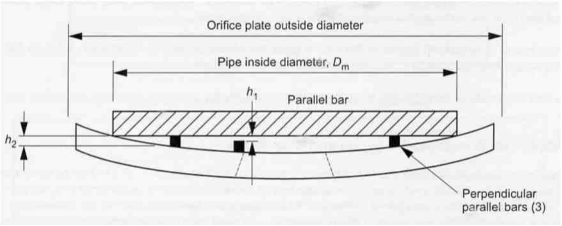


Fig 2b Alternative Method for Determination of Orifice Plate Departure from Flatness

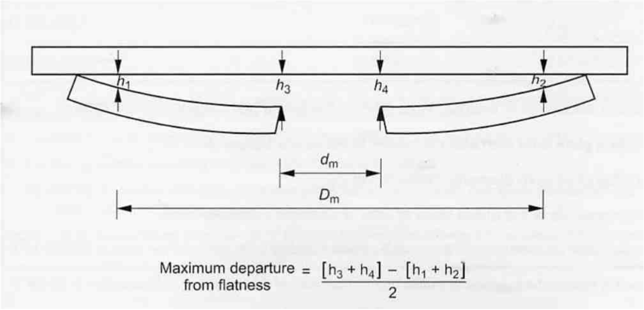


Fig 2c Maximum Orifice Plate Departure from Flatness

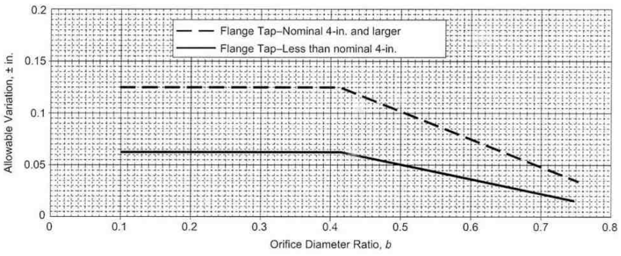


Fig 3. Allowable Variations in Pressure Tap Hole Location

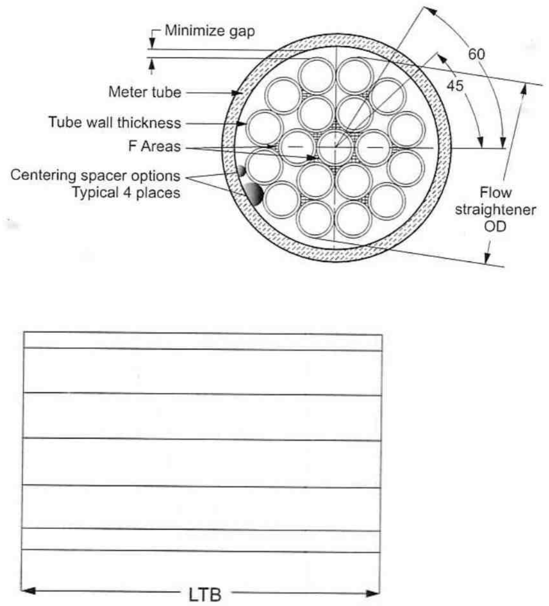


Fig.4 1998 Uniform Concentric 19-tube Bundle Flow Straightener

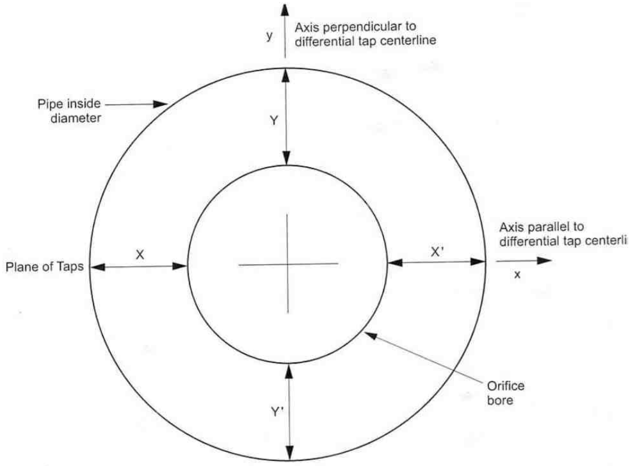


Fig.5 Eccentricity Measurements (Sample Method)

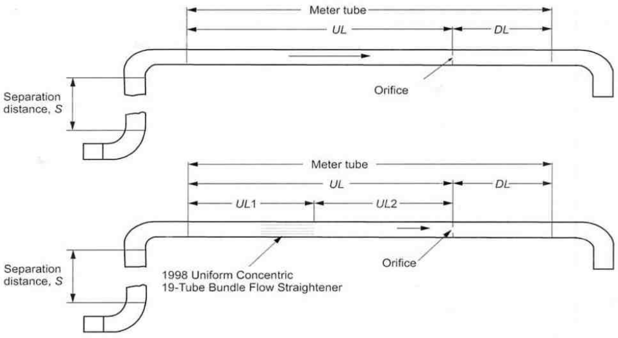


Fig.6 Orifice Meter Tube Layout

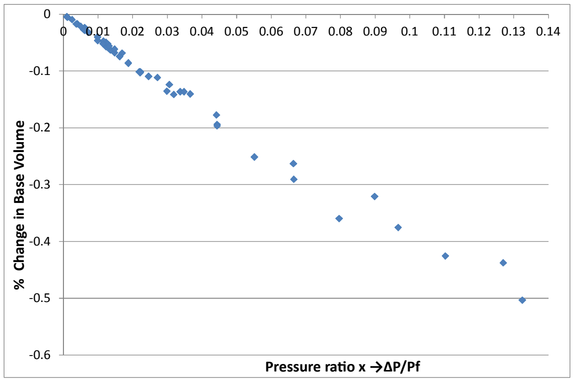


Fig.7 Effect of 2013 Expansion Factor Equation (Pressure Ratio and Flow rate

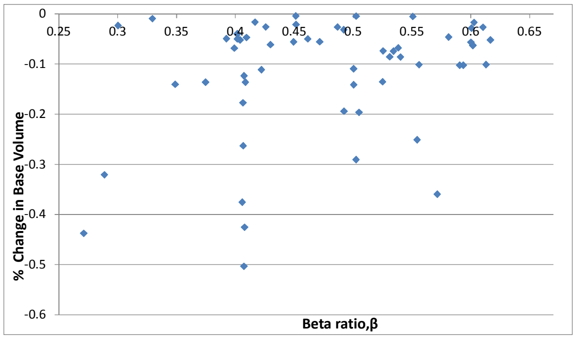


Fig.8 Effect of 2013 Expansion Factor Equation (Beta Ratio and Flow rate