PRACTICAL IMPLICATIONS OF GEOMETRIC TOLERANCES IN API MPMS CHAPTER 14.3/AGA REPORT NO. 3 − PART 2

Edgar B. Bowles, Jr.
Jacob L. Thorson

Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238 USA

Introduction

This paper describes the current contents of the United States (U.S.) orifice flow metering standard − 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] This document is also known as American Gas Association Report No. 3, Part 2.[2] As of the writing of this paper (i.e., May 2017), this standard was in its fifth edition and was last revised in March 2016.

API MPMS, Chapter 14.3, includes four parts:

- Part 1: General Equations and Uncertainty Guidelines
- Part 2: Specification and Installation Requirements
- Part 3: Natural Gas Applications
- Part 4: Background, Development Implementation Procedure

The focus of this paper is Part 2 of the standard.

As a brief history of the development of API MPMS, Chapter 14.3, Part 2, research on orifice flow meters began in the U.S. around 1904. Thomas Weymouth published an ASME paper in 1912 describing the results of a series of flow experiments dating to 1904 that he had performed on a flange tap orifice meter. Orifice meter research by what was known at the time as the National Bureau of Standards (NBS) (now known as the National Institute of Standards and Technology (NIST)) and others continued through the late 1920s. The *first* U.S. 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. This followed the publication of a preliminary report published in 1927 and revised in 1929.

AGA Report No. 2 was published in 1935. Key enhancements to Report No. 2 were improved orifice coefficients based on a larger experimental dataset and the addition of supercompressibility factors for natural gas.

AGA Report No. 3 was first published in 1955 and incorporated an even larger experimental dataset than did Report No. 2. Report No. 3 was first revised in 1969, and subsequently revised again in 1985, 1992, and 2000. The API first adopted AGA Report No. 3 as a standard in 1975, and the American National Standards Institute (ANSI) first recognized the document as a national standard in 1977.

Annex A describes much of the critical research related to the development of Part 2 of API MPMS, Chapter 14.3 and cites over 200 separate research studies performed on orifice flow meters between 1922 and 1999.

Scope of the Standard

The scope of API MPMS, Chapter 14.3, Part 2 currently includes the following:

1. Construction and Installation Requirements
2. Normative References
3. Terms, Definitions, and Symbols
4. Orifice Plate Specifications
5. Meter Tube Specifications
6. Installation Requirements

- Annexes

A − Research Projects and Tests Conducted Between 1922 and 1999
B − Orifice Meter Inspection Guidelines
C − Specific Installation Calibration Test
D − Flow Conditioner Performance Test
E − Maximum Allowable Orifice Plate Differential Pressure

The following sections describe the principal contents of API MPMS, Chapter 14.3, Part 2. Note that all section, figure, and table numbers are from the fifth edition of API MPMS, Chapter 14.3, Part 2. These numbers are not the same as in the previous versions of this standard.

Construction and Installation Requirements (Section 1.2)

This section notes that Part 2 includes the mechanical tolerances for the flow meter assembly required to ensure accurate flow measurement and the potential for measurement error associated with not maintaining the meter within the specified tolerances. This section also includes a "grandfather" clause, which essentially gives the flow meter operator/owner the discretion to decide whether or not to upgrade a given flow meter to the most current specifications whenever a new revision to Part 2 is published. If the operator chooses *not* to upgrade the meter to the latest specifications, additional flow measurement bias errors *may* result − possibly because of inadequate flow conditioning and upstream straight pipe length.

This section also provides cautionary guidance on diameter ratio (i.e., the ratio of the orifice bore diameter to the meter tube diameter, β_r) limits, and maintenance and upkeep of the flow meter to help ensure accurate flow measurement. (Diameter ratio is also sometimes referred to as beta ratio.) Specifically, this section states that the standard is based on beta ratios of 0.10 to 0.75, with the best results between 0.2 and 0.6 with orifice bore diameters greater than 0.45-inches. These are not hard limits, but diameter ratios and bore diameters outside of these limits may require special considerations.

Normative References (Section 2)

This section would list other standards that are necessary for the application of this standard, but currently none are listed.

Terms, Definitions, and Symbols (Section 3)

This section provides definitions for all of the parameters used in the equations, figures, and tables referenced in Part 2. This section also provides definitions for the key terms referenced in Part 2, such as *orifice plate*, *meter tube*, *diameter ratio*, and *flow conditioner*, among others.

Orifice Plate Specifications (Section 4)

This section provides dimensional tolerances for the key components of an orifice flow meter assembly. This includes tolerances for the following:

- Orifice plate faces
- Orifice plate bore edges
- Orifice plate bore diameter (d_m) and roundness (d_r)
- Orifice plate bore thickness (e)
- Orifice plate thickness (E)
- Orifice plate bevel angle (θ)

Figure 1 shows the symbols for the orifice plate dimensions that were defined in Section 3. This figure is similar to the figure included in subsection 4.1 of the standard. These symbols and nomenclature are used throughout the rest of the report.

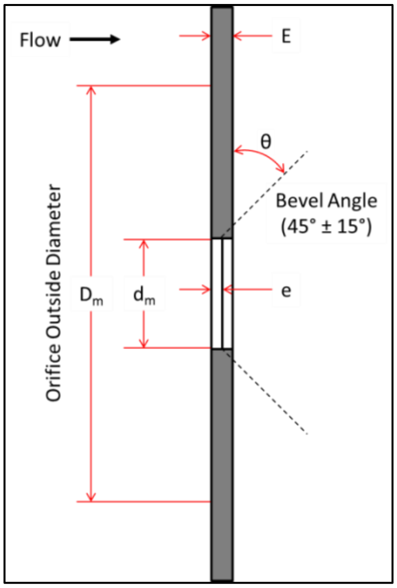

Figure 1. Symbols for Orifice Plate Dimensions

The flatness of the orifice plate is a critical parameter that influences the accuracy of the flow measurement. Allowable tolerances for the plate flatness are included in subsection 4.2, which describes the requirements for orifice plate faces. This also includes restrictions and recommendations on the plate roughness, flatness, cleanliness, and other factors. One example method of measuring this flatness is shown in Figure 2, which is similar to Figure 2a of Part 2.

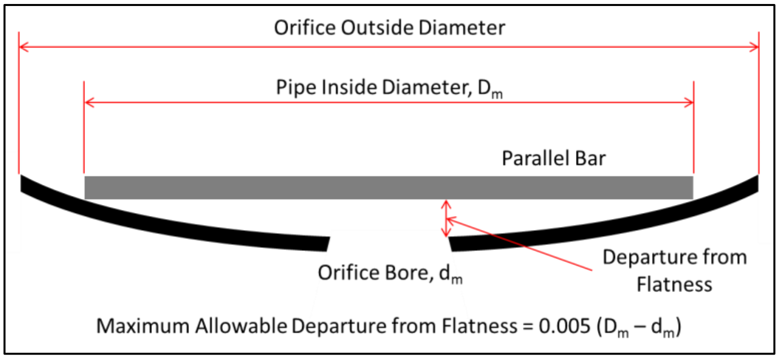

Figure 2. Orifice Plate Departure from Flatness
(Measured at the edge of orifice bore and within inside pipe diameter)

Subsection 4.3 describes methods of inspecting the edge of the orifice bore, which can critically affect measurement accuracy. The roundness of the orifice bore is described and defined in subsection 4.4, and Table 1 includes tolerances for the orifice bore roundness for different ranges of bore diameters. Subsection 4.4 also describes the methodology of accurately measuring the orifice plate bore diameter.

The next subsection describes the thickness of the orifice plate bore as defined in Section 3. Subsection 4.5 describes the geometry of the orifice plate bore and applies special considerations to this portion of the orifice plate. The standard then provides equations to determine the maximum and minimum orifice plate bore diameter thickness. The upper and lower limits on the bore thickness depend on both the bore diameter and the pipe diameter. The minimum bore thickness is plotted in Figure 3. The maximum bore thickness is plotted for two different inside pipe diameters in Figure 4. This subsection also establishes the requirement for a bevel (described later) when the orifice plate bore thickness, e, is smaller than the orifice plate thickness, E.

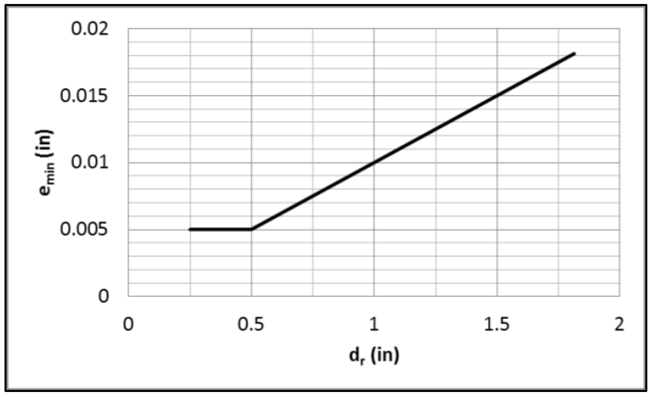

Figure 3. Relationship between Minimum Bore Thickness and Bore Diameter

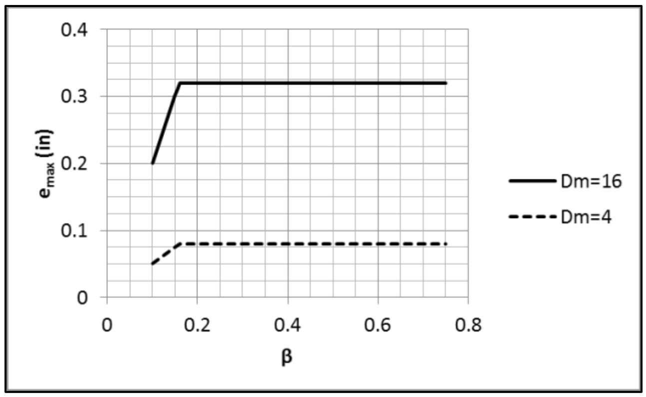

Figure 4. Relationship between Maximum Bore Thickness and Beta Ratio for Two Pipe Sizes

Next, subsection 4.6 describes the thickness of the orifice plate itself when using Type 304 or 316 stainless steel orifice plates and operating temperatures less than 150°F. The minimum, maximum, and recommended values for orifice plate thickness, E, and allowable range of differential pressure across the orifice plate are provided in Table 3. Note that the maximum allowable differential pressure is limited to 1,000 inches of water column, which is the limit of the coefficient of discharge database. The maximum allowable differential pressure for the recommended orifice plate thicknesses shown in Table 3 are for a maximum operating temperature of 150ºF. Additional guidance regarding allowable differential pressure across the orifice plate is provided in Annex E of Part 2. An equation is provided in subsection 4.6.2 that allows the reader to estimate the permanent pressure loss across an orifice plate as a function of beta ratio. This equation is plotted in Figure 5.

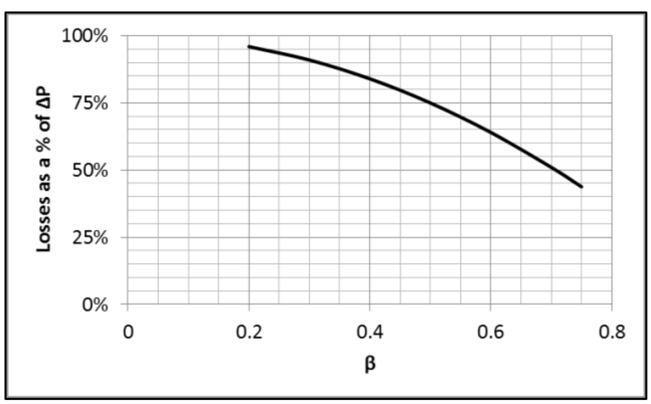

Figure 5. Relationship between Beta Ratio and Permanent Pressure Loss

If required, the orifice plate bevel is described in subsection 4.7. The allowable tolerance for the orifice plate bevel angle, θ, (i.e., the angle between the bevel and the downstream face of the orifice plate) is 45º ±15º. If a bevel is required, its minimum dimension, E minus e, measured along the axis of the bore, shall not be less than 0.0625 inch.

Meter Tube Specifications (Section 5)

The meter tube is defined as the straight length of pipe upstream of the orifice plate (of the same diameter), including the flow straightener/conditioner, if used; the orifice plate holder; and the similar downstream pipe beyond the orifice plate. The *upstream* section of the meter tube is defined as the length of straight pipe extending from the upstream face of the orifice plate to the nearest upstream change in the cross-sectional area (not including flange fittings allowed by this standard) or change in axis of the pipe centerline. Guidance is given regarding avoiding upstream and downstream flow disturbances in the meter tube, especially regarding the location of the connections and the gaskets relative to the orifice plate.

In subsection 5.1.1, 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. Allowable tolerances for meter tube surface irregularities, such as grooves, gouges, scoring, or ridges resulting from seams, welding distortion, etc. are also provided. It also requires that the meter tube be kept clean and free from accumulation of dirt, ice, grit, grease, oil, free liquid, and other extraneous material. If these restrictions are not followed, flow measurement bias errors may result.

Procedures are provided for measuring the meter tube diameter, D_m, in subsection 5.1.2. This includes guidance on how many measurements should be taken, where they should be taken, and where the user should take check measurements for verification. Figure 6 shows an example application of the temperature correction that is provided in this subsection as applied to a nominal 16-inch, schedule XS, carbon steel meter tube.

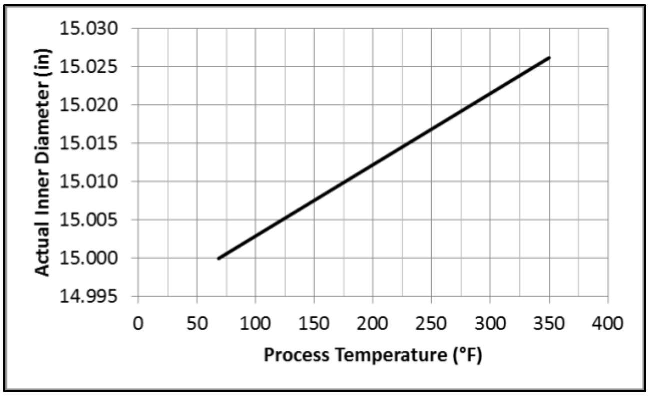

Figure 6. Predicted Inner Diameter of a 16-inch, Schedule XS, Carbon Steel Pipe as Temperature Varies

Subsection 5.1.3 provides tolerances for both meter tube diameter and roundness - both upstream and downstream of the orifice plate. Table 1 and Table 2**Error! Reference source not found.** are taken from Tables 4 and 5 of the standard, respectively. They both provide examples of the meter tube internal diameter roundness tolerances. Abrupt changes to the inside meter tube surface, such as shoulders, offsets, ridges, welding seams, etc., are generally disallowed.

	Meter Tube Internal Diameter Measurements (in)				
Position	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
% Deviation from Mean D_m	0.024%	0.092%	0.116%	0.193%	N/A

Table 1. Example Meter Tube Internal Diameter − Roundness Tolerances within the First Mean Tube Diameter Upstream of the Orifice Plate

	Meter Tube Internal Diameter Measurements (in)				
Position	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 2. Example Meter Tube Internal Diameter − Roundness Tolerances − All Upstream Meter Tube Individual Internal Diameter Measurements

Recommendations are included regarding orifice plate gasket or sealing device tolerances in subsection 5.1.4. These include the specific prohibition of protrusions into the pipe bore by gaskets or other sealing devices. This subsection also discusses the recess resulting from a gasket or sealing device and describes the effect of this recess on uncertainty for various recess geometries.

Subsections 5.2, 5.3, and 5.4 describe the various orifice configurations and pressure tap locations, respectively. Orifice *flanges* and orifice *fittings*, along with the associated inspection considerations, are discussed. Generally, it is recommended that these fittings adhere to the tolerances provided earlier in the standard. Guidance is provided on the proper location and configuration (e.g., geometry) of pressure taps adjacent to the orifice plate. For instance, Figure 7 shows the allowable variations in pressure tap hole location for flange taps and is similar to the plot shown in Figure 3 in the standard. Subsection 5.4 also provides equations and guidance for avoiding resonance in the pressure sensing lines, which can cause measurement issues and other issues.

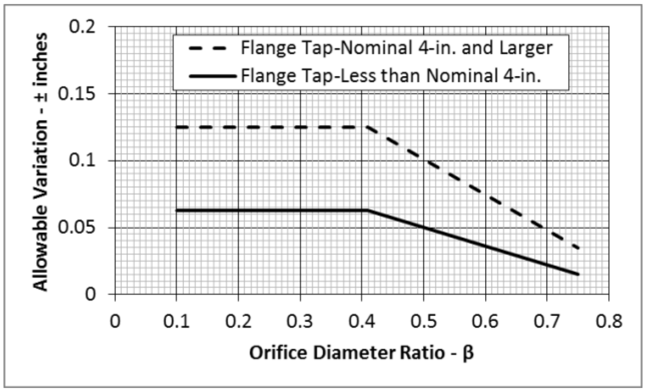

Figure 7. Allowable Variations in Pressure Tap Hole Location

Subsection 5.5 extensively discusses flow conditioners and their application to orifice flow measurement. 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 conditioners fall in one of two categories − flow *straighteners* and *isolating* flow conditioners (denoted as "*other*" flow conditioners in Section 5).

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 a 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 shown in Figure 8, which is similar to the image shown in Figure 4 in subsection 5.5.4.

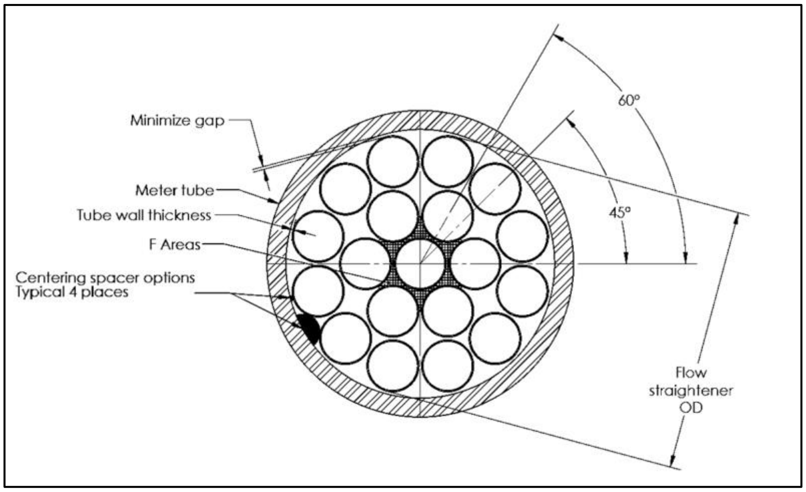

Figure 8. 1998 Uniform Concentric 19-Tube Bundle Flow Straightener

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. Subsection 5.5.5.1 includes flow conditioner performance criteria and Annex D includes a test protocol to verify performance of "other" flow conditioner types besides flow straighteners.

Installation Requirements (Section 6)

Section 6 includes specifications for orifice plate bore eccentricity, ε_x, and orifice plate perpendicularity − and how to measure these parameters. Figure 9, which is similar to Figure 5 in the standard, shows a sample method for measuring the eccentricity. This is accompanied by an equation in subsection 6.2.1, which exactly describes the allowable eccentricity. The results of this equation are plotted in Figure 10 for two different pipe sizes. This allowable eccentricity may be doubled when pressure taps 180 degrees apart are connected to attain an average pressure. Subsection 6.2.2 provides some limited guidance regarding the perpendicularity of the plane of the orifice plate relative to the meter tube axis.

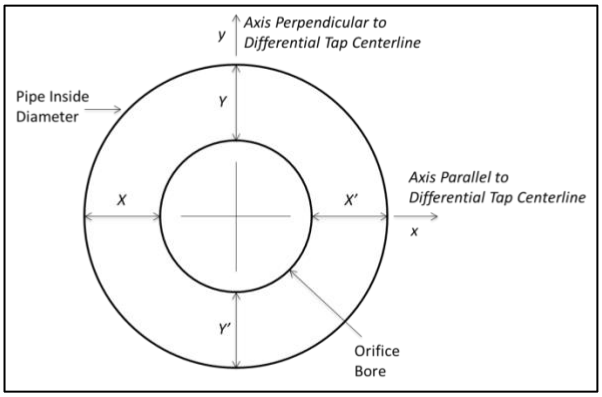

Figure 9. Eccentricity Measurements (Sample Method)

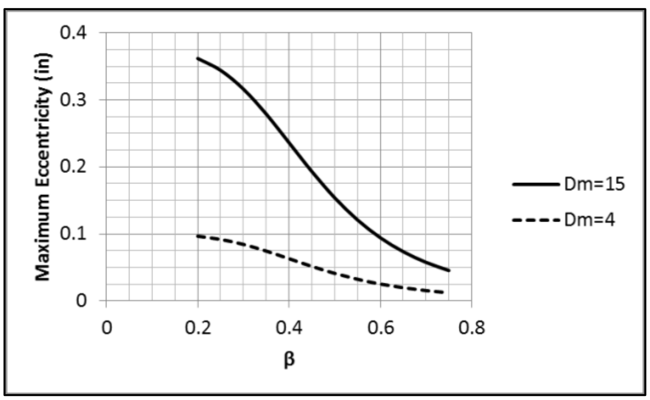

Figure 10. Maximum Eccentricity for Two Different Pipe Diameters

Section 6.3 provides extensive guidance regarding the meter tube, especially regarding the minimum length of straight pipe required upstream and downstream of the orifice plate. For the reasons previously discussed, it is critically important that the upstream piping configuration 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.

Subsection 6.3.2 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, β_r, and the configuration of the piping element(s) immediately upstream of the meter tube. Figure 11 shows the orifice meter tube layout for a flanged or a welded inlet and is similar to Figure 6 in the standard. This figure includes the critical length dimensions for the meter tube, the values of which are provided in several tables, depending on the meter tube geometry.

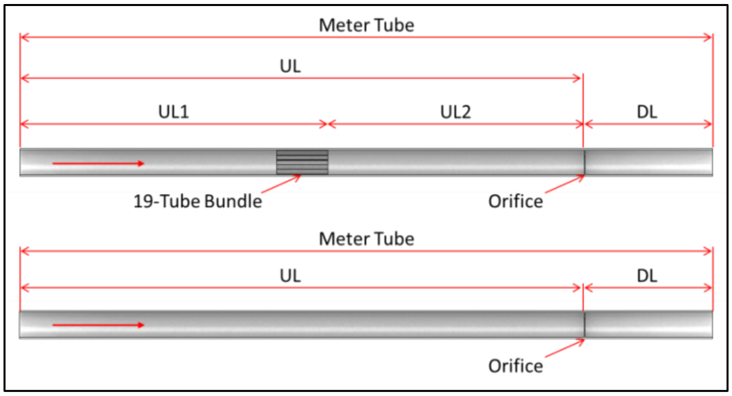

Figure 11. Orifice Meter Tube Layout for Flanged or Welded Inlet

Other flow conditioners not specifically referenced in Section 6 can be flow tested per the performance verification test included in Annex D to demonstrate their performance characteristics for orifice meter applications.

Subsection 6.4 discusses the operation of orifice flow meters under pulsating flow conditions. In this section, Part 2 states that a pulsating differential pressure across the orifice plate, ΔP, of up to 10% root mean square is acceptable. This root mean square, also known as the RMS, is a statistical measure of the magnitude of the variation in ΔP. A variation of 10% in the RMS corresponds to a square-root error (SRE) value of ~0.125%. This applies to single frequency flow pulsations with or without several harmonics and to broad-band flow pulsations/noise. Any SRE above this threshold indicates that the pulsation is adversely affecting the orifice meter accuracy.

Part 2 also states that "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."

Section 6.5 was extended in the most recent revision of Part 2 and includes guidance on the length and location of thermometer wells (thermowells) for use in orifice meter runs. Specifically, this section provides an equation that defines the maximum length of a thermowell for a given condition and geometry. The minimum length is stated as 1/3 of the inner pipe diameter.

Finally, Section 6.6 suggests that the orifice meter tube be insulated if it meets the stated criteria. These generally include conditions where temperature is likely to fluctuate or if fluctuations in temperature are likely to cause large swings in properties – for example, when the process fluid is close to the critical point.

Conclusions

This paper highlights some of the more important technical aspects of API, MPMS Chapter 14.3, Part 2, but for a complete treatment of the subject, the interested reader is strongly encouraged to refer to the standard in its entirety. Adherence to the requirements of this specification will help ensure that flow measurement accuracy using an orifice meter is optimized.

References

American Petroleum Institute, Manual of Petroleum Measurement Standards, Chapter 14.3, "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids," Part 2, "Specification and Installation Requirements," Washington, D.C., Fourth Edition, April 2000, Second Printing, June 2003.

American Gas Association Report No. 3, "Orifice Metering of Natural Gas and Other Related Hydrocarbon Fluids," Part 2, "Specification and Installation Requirements," Washington, D.C., Fourth Edition, April 2000, Second Printing, June 2003.