Manual of Petroleum Measurement Standards Chapter 22—Testing Protocol

Section 2—Differential Pressure Flow Measurement Devices

FIRST EDITION, AUGUST 2005

REAFFIRMED, AUGUST 2012

energy **API**

AMERICAN PETROLEUM INSTITUTE

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Measurement Coordination

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Suggested revisions are invited and should be submitted to API, Standards department, 1220 L Street, NW, Washington, DC 20005.

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Chapter 22—Testing Protocol

Section 2—Differential Pressure Flow Measurement Devices

1.0 Introduction

This document defines the testing and reporting protocols for flow measurement devices based on the detection of a pressure differential that is created by the device in a flowing stream. This protocol is designed to supply industry with a comparable description of the capabilities of these devices for the measurement of single-phase fluid flow when they are used under similar operating conditions. The objectives of this Testing Protocol are to:

1. Ensure that the user of any differential pressure flow meter knows the performance characteristics of the meter over a range of Reynolds numbers as applicable or defined by tests,

2. Facilitate both the understanding and the introduction of new technologies,

3. Provide a standardized vehicle for validating manufacturer's performance specifications,

4. Provide information about relative performance characteristics of the primary elements of the differential pressure metering devices under standardized testing protocol.

5. Quantify the uncertainty of these devices and define the operating and installation conditions for which the stated uncertainties apply.

To accomplish these objectives, the testing protocol defines the test limits for operating conditions of the meter, the requirements of the facility or facilities to perform the tests, the fluids to be tested, and the ranges for pressure, differential pressure, temperature, secondary instrumentation, and Reynolds number.

Examples of flow meters covered in this standard include, but are not limited to orifice plates, Venturis, nozzles, V-Cones, wedge meters, and multiport averaging Pitot tubes. Reporting and testing protocols for test facilities are included to ensure that the performance characteristics of each meter are compared with identical conditions as set forth in this standard. These protocols require descriptions of the test fluids to be used, the mechanical configuration of piping, effects of fluid flow profile, and spatial orientation of the meter. A description of required dimensional measurements and tolerances and the mathematical equations required to convert the differential pressure reading to a flow rate prediction is also necessary. This document primarily addresses testing protocol for differential pressure flow meters that operate under the flowing condition that is in the turbulent flow regime. Differential pressure flow measurement devices that operate on the principle of physical laws of laminar flow require a special testing protocol, which is addressed in Section 5.

1.1 SCOPE

The testing protocol is limited to single-phase Newtonian fluid flow, and no consideration is given to pulsation effects. Further revisions of this document may include the testing of such meters in wet gas or multi-phase service and the effects of pulsation. This standard does not address testing protocols of those devices that operate on the principle of critical or choked flow condition of fluids.

The testing protocol covers any flow meter operating on the principle of a local change in flow velocity, caused by the meter geometry, giving a corresponding change of pressure between two reference locations. There are several types of differential pressure meters available to industry. It is the purpose of this standard to illustrate the range of applications of each meter and not to endorse any specific meter. The basic principle of operation of the flow measuring devices follows the physical laws relating to the conservation of energy and mass for the fluid flows through the device.

Any existing or later developed API *MPMS* document addressing a specific type or design of differential pressure flow measuring device will supersede the requirements of this document. An example of one such existing standard is API *Manual of Petroleum Measurement Standards*, Chapter 14.3 "Concentric, Square-Edged Orifice Meters."

1.2 DIFFERENTIAL PRESSURE OR HEAD-TYPE FLOW METERS

The operating principle of a differential pressure flow meter is based on two physical laws - the conservation of energy and conservation of mass, where changes in flow cross-sectional area and/or flow path produce a differential pressure, which is a function of the flow velocity, fluid path, and fluid properties. The following diagrams are presented as examples of some of the possible differential pressure devices. Other variations of meter designs are available and possible.

It is the intention of this Testing Protocol that no differential pressure meter should be excluded. Therefore, the examples presented are of eligible meters and the document is not limited to these meter types alone.
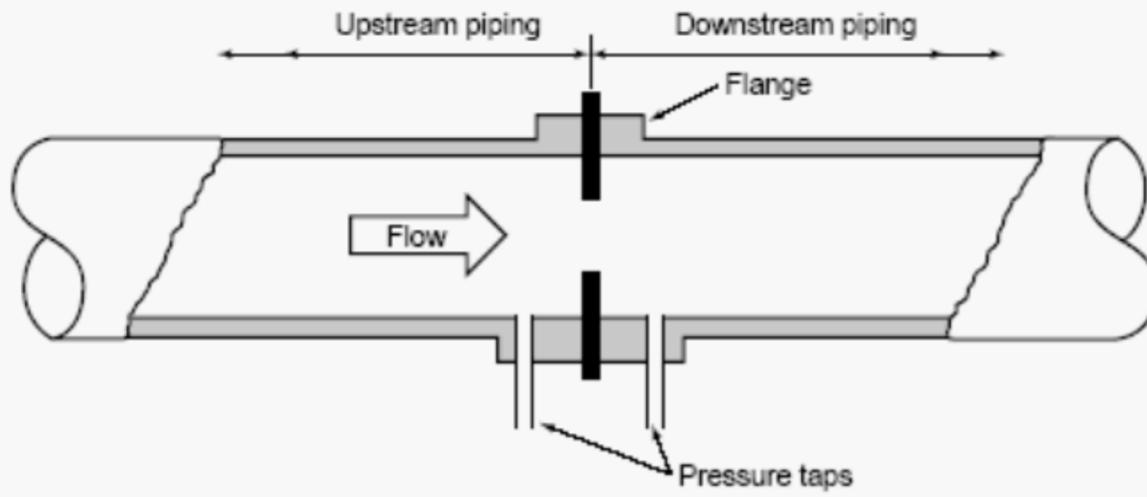
Figure 1—Concentric Orifice Flow Meter
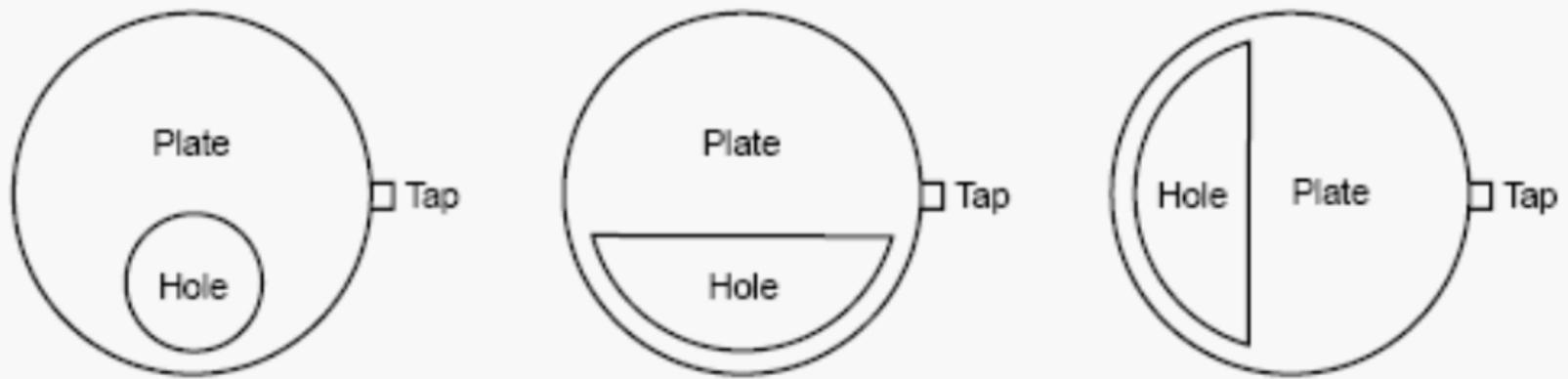
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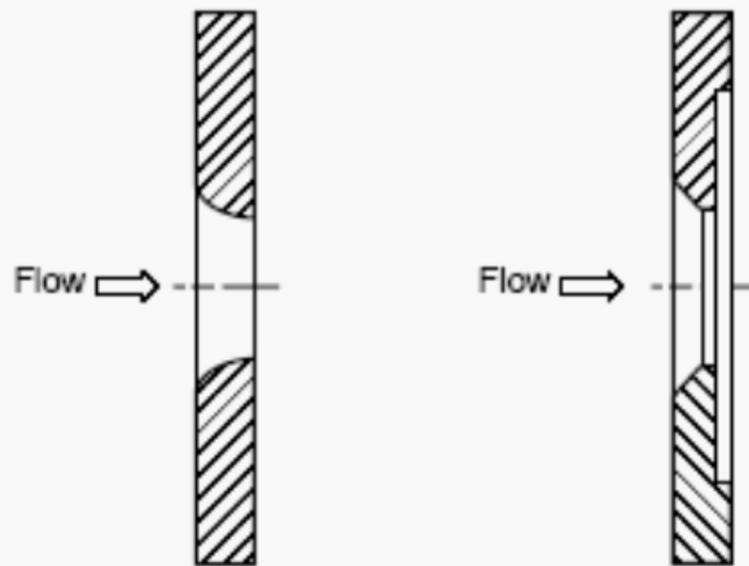
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Upstream piping   Downstream piping

Flow

Pressure taps
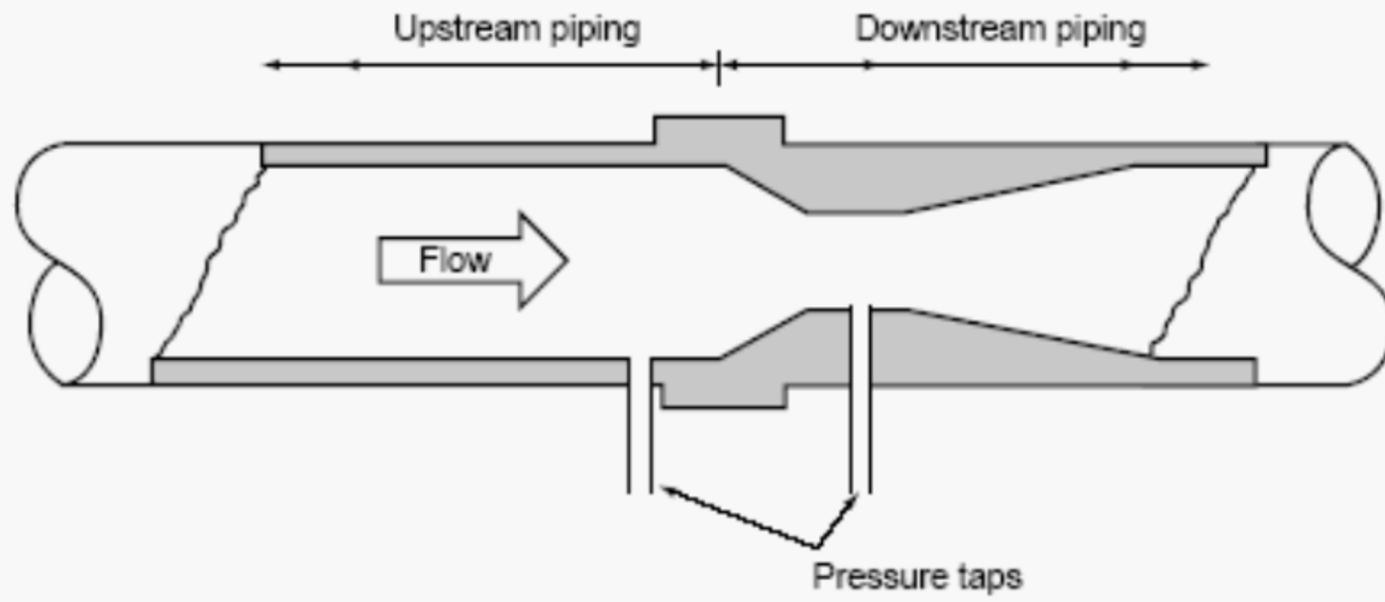
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Upstream piping   Downstream piping

Flange

Flow

Pressure taps
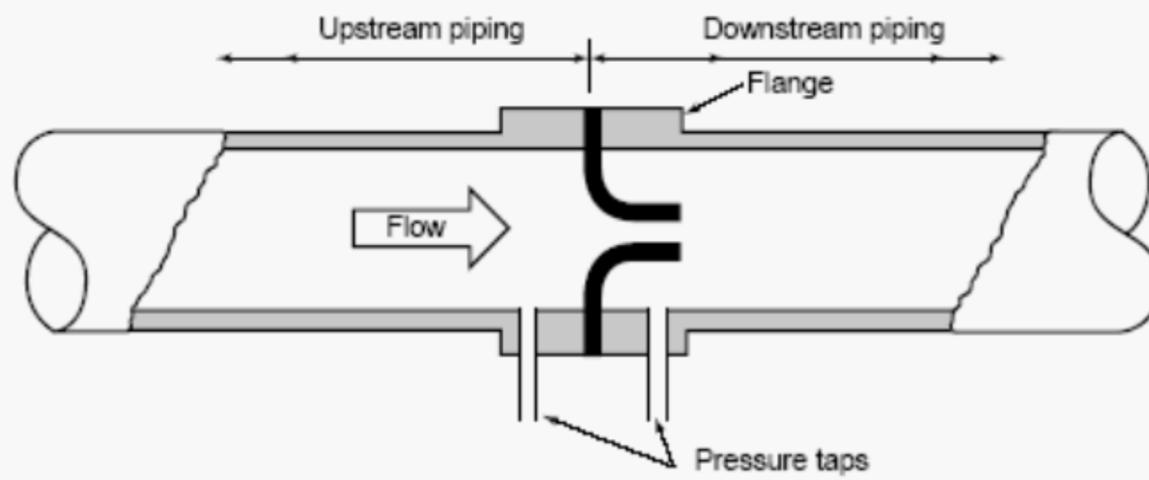
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Flow

H

L
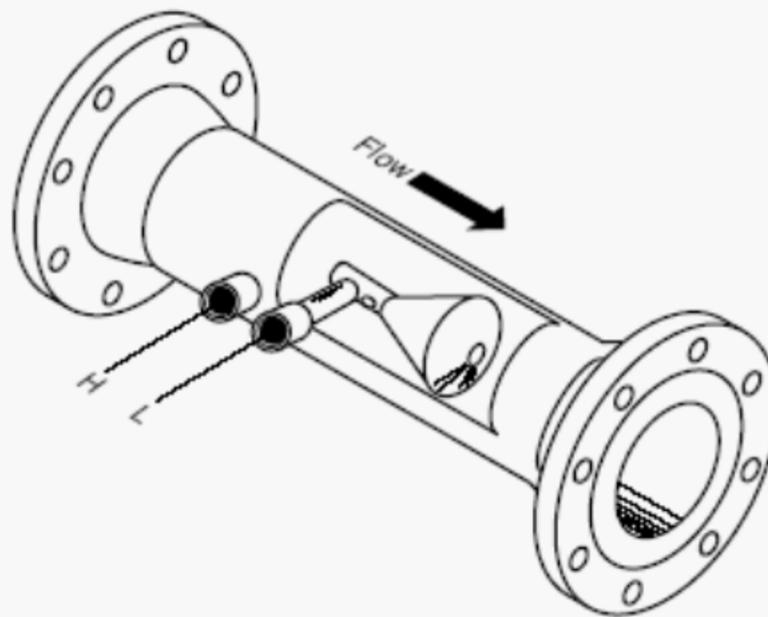
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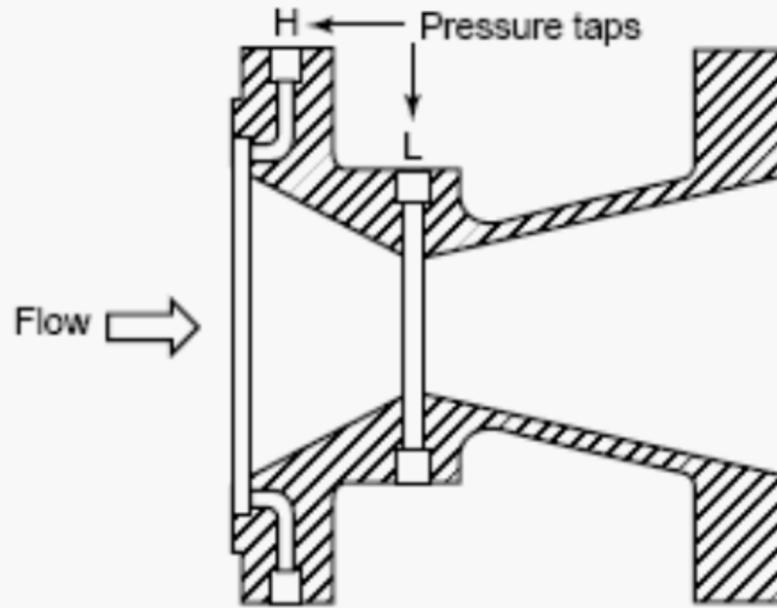
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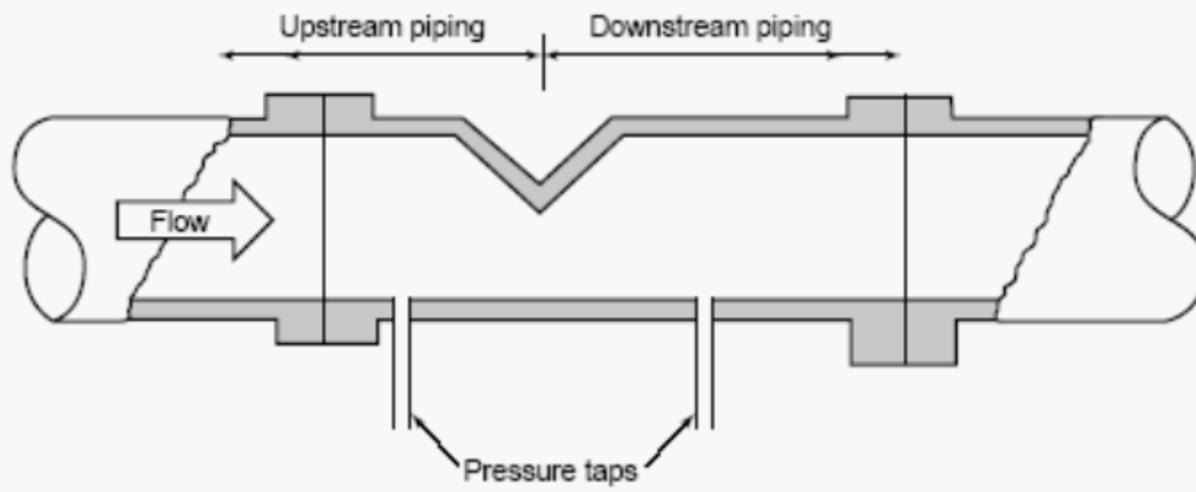
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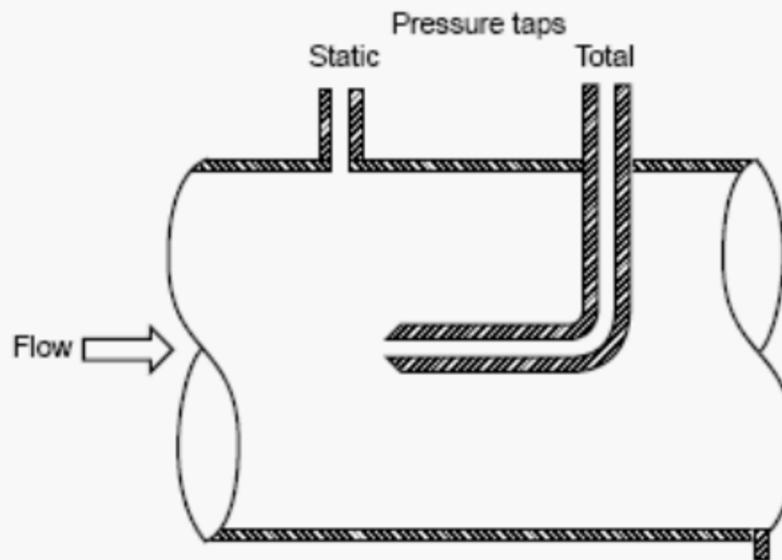
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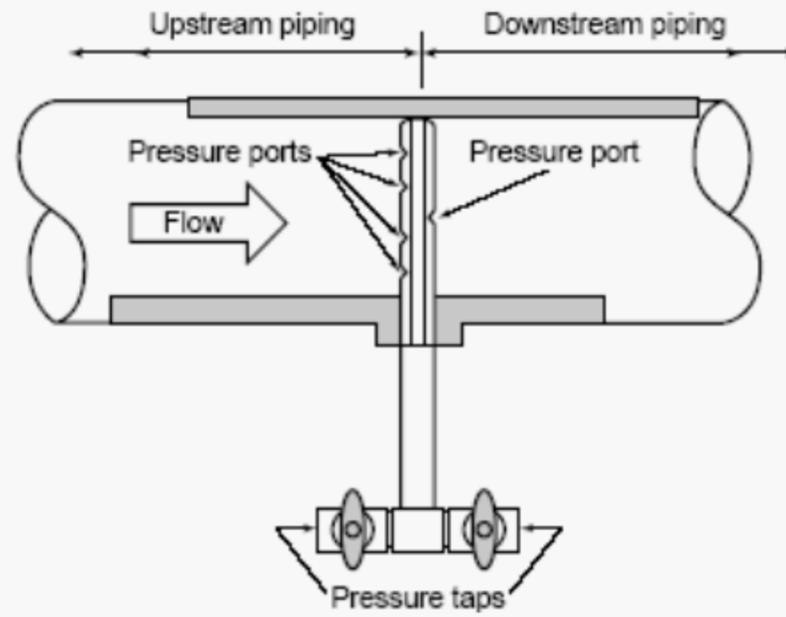
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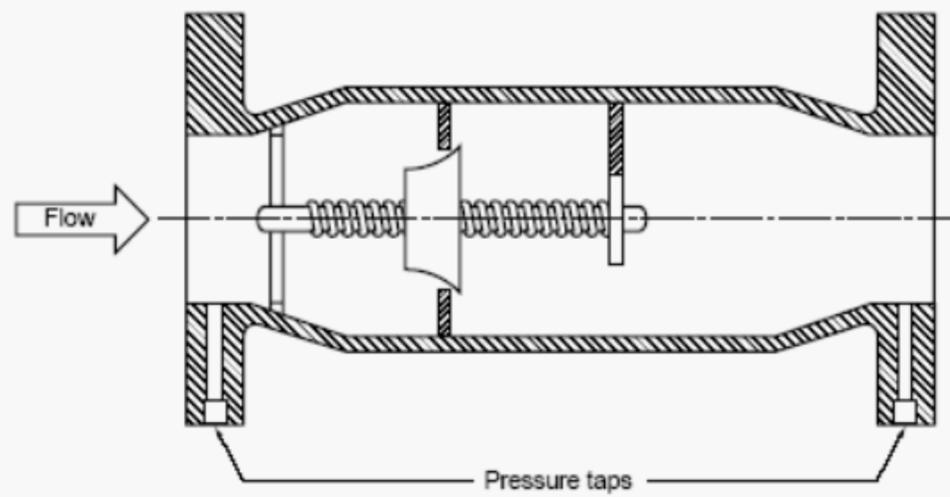
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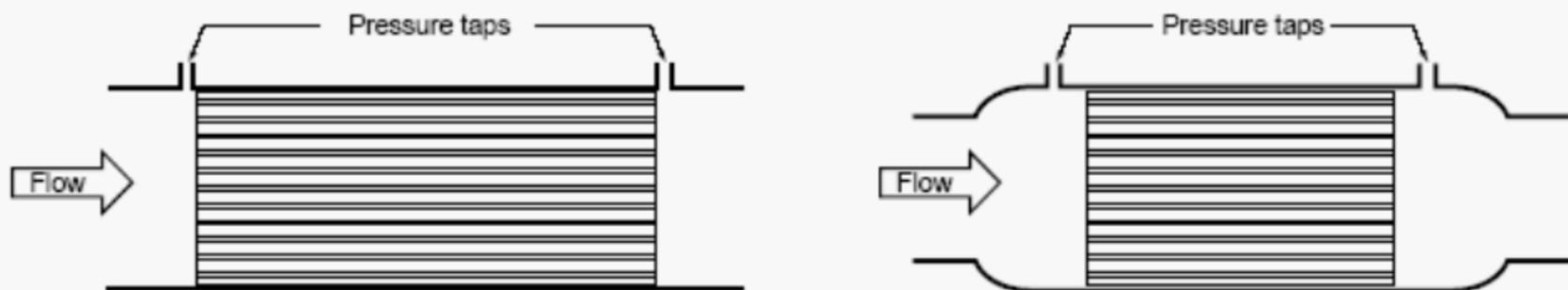
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2.0 Definitions and Specific Terms

The definitions are given to emphasize and clarify the particular meaning of terms as used in this document.

2.1   meter: A meter is the assembly of a primary element, a differential producer holder with the upstream and downstream meter tubes that will generate a differential pressure when placed in a flow stream. The differential pressure is monitored by secondary device(s) (section 2.6) to derive the flow rate.

2.1.1   meter asymmetry: Meter asymmetry refers to the orientation of specific items in the meter in this document. For example, it may refer to the position of the differential tap holes, or the orientation of supports within the meter which are not symmetrically placed throughout the diameter.

2.2   primary element or differential producer: The primary element is defined as the differential producer when placed in a flowing stream.

2.3   differential producer holder: The differential producer holder is defined as a pressure containing piping element used to contain and position the differential producer and its associated differential pressure sensing taps in the piping system. An orifice fitting would be an example of such a device.

2.4   meter tube: The meter tube is defined as the straight sections of pipe, including all segments that are integral to the differential producer holder, upstream and downstream of the differential producer and the flow conditioner, if required.

2.5   meter tube internal diameter, D, D_i, D_m, or D_r: In this document it has been assumed that the meter tube is circular. If the meter is used in a non-circular cross-sectional flow line or a non-circular device is installed in a circular flow line, the manufacturer of the device must explain how the critical dimensions of the primary element would be defined and calculated. In addition, other necessary or critical upstream and downstream flow conduit geometry and dimensions for the non-circular differential pressure producing flow measuring device must be defined by the manufacturer.

The published meter tube internal diameter (D_i) is the inside diameter as published in standard piping handbooks. This internal diameter is used for determining the required meter run length (e.g., for orifice meters as stated in Tables 2–7 and 2–8 of API *MPMS* Chapter 14.3 Part 2, "Specification and Installation Requirements").

The measured meter tube diameter (D_m) is the average inside diameter of the upstream section of the meter tube measured at a distance from the primary element as defined by either a published standard or by the meter's design and at the temperature of the meter tube (T_m) at the time of the internal diameter measurements. For example, an orifice diameter is measured at one inch upstream of the orifice plate. The

meter manufacturer must define how D_m is obtained and utilized to calculate the flow rate for that meter.

The calculated meter tube internal diameter (D), if used, is the inside diameter of the upstream section of the meter tube computed at flowing fluid temperature (T_f). The calculated meter tube internal diameter, D, is used to determine the diameter ratio or ß, if applicable, and in the Reynolds Number calculations.

The reference meter tube internal diameter (D_r) is the inside diameter of the upstream section of the meter tube calculated at the reference temperature (T_r). The reference diameter, D_r, is the certified meter tube internal diameter, as described in the orifice meter document API *MPMS* Chapter 14.3 Part 2.

2.5.1   area (m) and/or diameter ratio, ß: The area ratio, m, is the minimum unrestricted area at the primary element divided by the cross-sectional area of the meter tube.

The area ratio has been simplified to a diameter ratio (ß) for orifice and Venturi meters where the bore diameter of the primary element is simply divided by the meter tube internal diameter and is the square root of the actual area ratio.

2.6   secondary devices: Secondary devices required for determining the flow through the primary element, which typically includes monitoring differential pressure and the sensors defining the flowing conditions and fluid properties (pressure, temperature, density, etc.). Differential pressure transmitters are sensitive to mounting position orientation. To minimize the effects of orientation, the transmitter must be zeroed after installation.

2.6.1   pressure measurement: The static pressure and differential pressure are measured using either a digital or an analog transmitter. Static pressure transmitters measure either the absolute or gage pressure of the fluid. Differential pressure transmitters measure the differential pressure developed between two points of measurement, caused by the primary element. A multivariable transmitter measures both static and differential pressure and may also accept a temperature sensor input. Analog transmitters provide an analog output proportional to the measured variable. The output of digital transmitters can be analog or digital.

2.6.2   static and differential pressure measurement, P_1, P_2, and ΔP: The static pressure of the process is usually measured upstream of the differential producer by a tap normal to the flow velocity. The static pressure can be used (in conjunction with the temperature and composition) to determine the density of the flowing fluid. The line pressure can also be monitored at the pressure tap downstream of the differential producer. Vendor must specify the location of the static pressure for the calculation of the flow rate.

In all differential producing flow meter designs there are high and low pressure taps. Subscripts 1 and 2 refer to two

pressures, where 1 is the high pressure and 2 is the low pressure. In many designs these pressures are the static pressures upstream and downstream of the differential producer. In other designs the high pressure may be as high as the upstream total pressure and the low pressure is a function of the design of the differential producer and the location and orientation of the pressure tap.

To minimize the effects of the static pressure on the differential pressure reading, an isolation manifold should be used to apply the operating line pressure to both sides of the differential pressure transmitter. The transmitter should then be zeroed at the elevated static pressure.

The differential pressure (ΔP) is the difference between the high and the low pressures (P_1 - P_2). Other definitions of differential pressure are permitted provided the definition is specified for the meter. The instantaneous differential pressure (ΔP_t) is a single measurement of ΔP at any instant. The average differential pressure (ΔP_{ave}) is a time mean of the particular meter's individual differential pressure measurements.

The root mean square fluctuating component of the differential pressure (ΔP_{rms}) is the square root of the mean of the squares of the difference between the instantaneous differential pressure ΔP_t and time mean differential ΔP_{ave}.

$$\Delta P_{rms} = \sqrt{\frac{\sum_{i=1}^{n} (\Delta P_{t,i} - \Delta P_{\text{ave}})^2}{n}} \quad (2.1)$$

where

n = the number of samples,

i = the i-th data of n-number of sample points,

$\Delta P_{t,i}$ = the instantaneous differential pressure at time, i

ΔP_{ave} = the average of n samples of ΔP_t values.

2.6.3 temperature measurement, T_f: The fluid temperature (T_f) is the temperature of the flowing fluid measured at the manufacturer's designated location. If the flow Mach number (ratio of the average flow velocity of the fluid to the speed of propagation of sound in that fluid under those local conditions) is greater than 0.25, dynamic effects on the temperature measurement should be taken into account. Care must be taken to ensure that the temperature sensing elements are coupled to the flowing fluid and not to the material of the meter tube. The sensed temperature with any necessary cor-

rections is assumed to be the static temperature of the flowing fluid.

2.6.4 density determination: The density of the fluids used may be determined by direct measurement, by measurement and calculations based on an equation of state, or by appropriate and generally recognized industry standards.

2.7 roughness average, R_a: The roughness average (R_a) used in this standard is that given in ANSI B46.1 and is "the arithmetic average of the absolute values of the measured profile height deviation taken within the sampling length and measured from the graphical centerline" of the surface.

2.8 discharge coefficient, C_d: The discharge coefficient (C_d) is the ratio of the actual flow rate to the theoretical flow rate. The theoretical flow rate corresponds to the flow rate without any loss of energy (assume expansibility factor is 1).

2.9 expansibility factor, ε or Y: The expansibility factor (ε or Y) is the ratio of the flow rate for a compressible fluid to its flow rate as an incompressible fluid, for the same Reynolds number and geometry.

2.10 Reynolds number, Re: The Reynolds number (Re) is the ratio of the inertial forces to the viscous forces of the fluid flow. This non-dimensional parameter is defined as:

$$Re = \frac{V\rho D}{\mu} \quad (2.2)$$

where

V = the average axial velocity

ρ = the density of the fluid

μ = the absolute viscosity of the fluid

D = a characteristic length, which in most applications is the calculated meter tube diameter for Re_D or bore diameter for Re_d.

2.11 flow conditioner: A device installed upstream of the primary element, designed to minimize the effect of flow profile distortions on the discharge coefficient.

2.12 swirl: Swirl is a condition in which the flow has a rotational (tangential) component in addition to the axial velocity component.

2.13 swirl angle: The swirl angle, in degrees, is obtained from the ratio of the tangential to the axial velocity components at any point in the flow field.
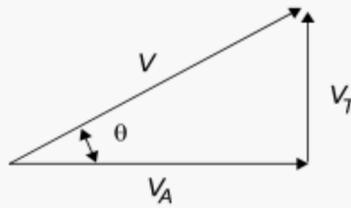
where

$$\tan\theta = V_T/V_A$$

θ = swirl angle

V_A = axial component of velocity

V_T = tangential component of velocity

2.14 geometrically similar: Refer to API *MPMS* Chapter 14.3 Part 1 and Appendix C for further information.

A meter of a particular size is said to be geometrically similar to a meter of a different size if all meter dimensions for both sizes can be expressed as the same constant function of published pipe diameter, D_i as follows:

meter dimension $X_1 = C_1 \times D_i$;
meter dimension $X_2 = C_2 \times D_i$;
meter dimension $X_3 = C_3 \times D_i$;

•

•

•

meter dimension $X_n = C_n \times D_i$;

where X is any specific dimension of the meter and C is the ratio of the actual dimension X to published pipe diameter, D_i.

For example, for a 4-in. (100 mm) meter which has a flow element of dimension X that is 1-in. (25 mm) long, the C dimension in this case is 0.250. For an 8-in. (200 mm) meter to be geometrically similar, the same X dimension must be 0.250 × 8 in. (200 mm) = 2 in. (50 mm). This relationship must repeat for all the key flow elements in the meter to provide geometric similarity. See Appendix C for additional information on prototype and model tests with fluid dynamic similitude.

With a flange-tapped orifice, the tap locations are fixed at 1 in. (25 mm) upstream and downstream of the respective orifice plate faces. This 1-in. (25 mm) dimension is irrespective of line size and consequently the flanged-tapped orifice meters of different line sizes are not geometrically similar.

3.0 Installation and Test Facility Requirements

3.1 ACCEPTABLE TEST FACILITIES

Test facility measurement systems for mass, length, time, temperature, and pressure must be traceable to the NIST Primary Standards or an equivalent National or International Standard.

It is essential that the test facility notes the pressure rating for all the items being tested and ensures that in no instance is the metering device and associated equipment overstressed (as a guideline test pressure should not exceed 90% of the design pressure of the meter).

The test facility must be able to determine values of the orifice Discharge Coefficient for orifice metering systems that meet the requirements of API *MPMS* Chapter 14.3, within the 95% confidence interval of the Reader-Harris Gallagher (R-G) equation. The orifice metering system will be tested over at least a 3:1 Reynolds number range. The upper and lower limits of the orifice test will include the Reynolds number range over which the primary element will be tested. For flow meters with rangeability of less than 3:1, the Reynolds number range of the orifice meter test must cover the entire flow rate range of the meter being tested. The line size of the orifice meter(s) used to verify the facility must allow these conditions to be met, but may otherwise be of any line size similar to the primary elements under test. The facility may be verified using historical orifice meter data taken within the previous 1 year of testing.

3.2 REQUIRED METER DIMENSIONS

Differential pressure meters must be manufactured to certain dimensional tolerances to enable a flow uncertainty to be determined. The internal dimensions/geometry of the meter must be known to establish the cross-sectional area to determine a volume flow rate.

For orifice meters the dimensional tolerances are specified in API *MPMS* Chapter 14.3 Part 2. The ISO 5167 standard provides the tolerances for orifice, Venturi, and nozzle meters. The differential pressure devices not covered by these standards shall have the dimensional tolerances specified by the manufacturer. The tolerance requirement need not apply to individually flow calibrated meters.

3.3 REQUIRED PIPING CONSIDERATIONS UPSTREAM AND DOWNSTREAM OF THE METER

It is known that some differential pressure meters are sensitive to the shape of the velocity profile. As the roughness of pipe wall, R_a, is known to affect the shape of the fully developed velocity profile, it is a requirement that all test facilities should have a similar pipe roughness in the minimum required straight length pipe section upstream of the meter, specified by the manufacturer. The test facility upstream pipe shall conform to the following:

For pipe diameter 12 in. (300 mm) or smaller:
R_a = 40 µin. (1 µm) to 250 µin. (6 µm)
For pipe diameter greater than 12 in. (300 mm):
R_a = 40 µin. (1 µm) to 500 µin. (12 µm)

Application of the meter with pipe wall roughness outside these limits should be demonstrated by actual tests.

In this test protocol upstream and downstream lengths are defined as straight lengths of pipe with no tees, branches, drain holes or any obstructions.

Spirally welded pipes are not permissible as upstream and downstream meter tube for the performance verification tests.

4.0 Meter Tests

4.1 METERS TO BE TESTED

Meters are normally tested in the horizontal orientation. In general, testing meters in the vertical orientation may be difficult. However, the meter should be tested in the orientation in which it is to be used. For meters installed vertically, differential pressure readings may need to be corrected as defined by the manufacturer for the relative elevation of the pressure taps.

Two nominal line sizes are required for these tests. The smaller line size should be equal to 4 in. (100 mm) and the larger line size should be equal to or greater than 8 in. (200 mm). However, the actual sizes will be governed by the size range covered by the meter manufacturer and the flow range capability of the test facilities.

It may be appropriate to test meters smaller than 4 in. (100 mm) diameter. The minimum 2:1 ratio between the sizes tested should be maintained.

For meters that are geometrically similar, test results for meters 4 in. (100 mm) and greater in size may be scaled up to larger line sizes without introducing additional uncertainty. However, test results should not be scaled down to meters less than 4 inches (100 mm) in diameter because of increased sensitivity to manufacturing tolerances.

For meters that have geometries designed to produce area ratios, tests shall be performed with two area ratios on either of the line sizes. The larger of the two required line sizes shall have the largest area ratio applicable for the meter to achieve a relatively low differential pressure. The smaller line size shall have the smallest area ratio applicable for the meter to achieve a relatively high differential pressure.

All of the tests shall include at least ten different Reynolds number values spread evenly from the minimum value (±5%) to the maximum value (± 5%). The manufacturer will define the minimum practical flow rate for the meter. The ratio of the maximum to the minimum flow rate should be 3:1 or greater or as per specification claimed by the manufacturer, specifically when the claim of the meter rangeability (turndown) is less than 3:1. A further 8 intermediate flow rates will be selected to produce evenly spaced rates for the test. Each Reynolds number tested must have at least five data points to assure ± 0.5% repeatability is being achieved. The test results are valid within this Reynolds number range but not beyond. The test meter's performance shall be compared with the primary standard or reference meter in the approved test facility (see Section 3.1).

Note: The laboratory should provide Reproducibility for the test stand over the range of Re values tested. This should be included in Section 8.1 "Uncertainty of the Test Facility".

These test results will verify whether the meter conforms to the uncertainty tolerance specified by the manufacturer. Acceptance of meter uncertainty for custody transfer is left to the terms and conditions of the contract between the parties involved.

4.2 ACCEPTABLE TEST FLUIDS

Testing of differential pressure flow meters can be conducted with various fluids provided that during the test following conditions are met:

- The fluid is and will remain homogenous and in single phase during the test; i.e., gas shall not undergo condensation and liquid shall not cavitate. Liquid flows shall have no gas present (e.g., entrained air) in the test meter or any part of the test facility.
- Only Newtonian fluids are permitted.
- All physical properties of the fluid used shall be determined by direct measurements, by measurement and calculations based on an equation of state, or by appropriate and generally recognized industry standard. Fluids shall be characterized by the following properties: density, viscosity (dynamic or kinematic), temperature, isentropic exponent of compressible fluid, and composition.

Meter manufacturers that wish to test meters for liquid or gas applications only, may do so by choosing to use either an incompressible fluid (liquid) or a compressible fluid (gas) only. In such cases, this restriction shall be explicitly stated in the results.

If a meter is to be tested in both liquid and gas flows then as long as the fluid type conforms to the Standard (Section 4.2) a combination of liquid and gas flow tests can be performed in different accepted facilities with different relevant fluids in order to achieve the required Re range.

4.3 LIQUID FLOW TESTS

For the liquid flow tests, two meter sizes and two area ratios must be tested as defined in Section 4.1 at one pressure. The maximum recommended velocity for liquid testing is typically 30 ft/s (10 m/s), but may be alternatively defined by the manufacturer.

4.4 GAS FLOW TESTS

The gas flow test matrix must include at least two line pressures and the ratio of the absolute pressures must be at least 5:1 on either line size. If the meter is offered for ANSI 600 # flange rating or more, the high pressure test should be at least 800 psi (5.5 MPa).

For meters that have geometries designed to produce area ratios, tests at multiple line pressures may be performed with only one area ratio for a given line size.

The manufacturer will define the minimum practical velocity. The maximum velocity should be 90 ft/s (30 m/s) or as defined by the manufacturer.

If the test matrix has a maximum Re less than 3,000,000 then that is the maximum Re covered by the Primary Element. The minimum Re is to be chosen by the manufacturer. The tests results are valid within this Re range.

If the Re tested reaches beyond 3,000,000, then the results can be extrapolated to a higher Re, with added uncertainty. The added uncertainty at the required Re would be determined from the discharge coefficient to Re graph.

4.4.1 Expansibility Factor

It is the responsibility of the meter manufacturer to supply a gas expansion factor equation for the flow meter. This factor must have been independently produced and a report from the independent facility must be available for review.

For the tests required by this standard, the $\Delta P/P$ must be recorded and these values should lie within the limits used to develop the gas expansion factor.

In reporting the flow rates and discharge coefficients for the tests, the results must be corrected by using the expansibility equation defined by the manufacturer.

4.5 TESTING LIMITS

It is the responsibility of the manufacturer to specify the allowable range of differential pressures to be used with specific fluids, based on the thermodynamic properties of fluids and mechanical and fluid dynamic constraints. In no case shall the differential pressures in these tests exceed the limits imposed by mechanical and fluid dynamic constraints. The effect of static pressure on differential pressure transmitters is a separate technical issue and is addressed in 2.6.2.

In typical industrial flow rates, the maximum liquid velocity is at 30 ft/s (10 m/s) and gas velocity is at 90 ft/s (30 m/s). For some meters the associated differential pressure may be excessively high at these stated velocities. In such a case, the maximum fluid velocities shall be lower than those given above and shall not produce a differential pressure which exceeds the manufacturer's maximum allowable limit. The test report must state the maximum velocities and differential pressures observed during the tests. For compressible fluid flows and the low-pressure test, if the manufacturer specifies a limit on the maximum value of $\Delta P/P_1$, the maximum velocity for the test must be limited to account for the allowable limit of $\Delta P/P_1$ for the meter. The limit shall be documented in the test report (Section 7).

Significant temperature changes may influence the performance of differential pressure flow meters through the change of critical geometrical parameters and fluid proper-

ties. Meter manufacturers have to specify corrections to be used in data processing. For flow velocities in piping in excess of Mach 0.25, a correction has to be made to the static temperature reading (see 2.6.3). It is generally impractical to change the fluid temperature in a flow laboratory; consequently, the flowing fluid temperature should simply be recorded.

4.6 BASELINE TESTS

This standard requires Baseline Tests to establish a meter's performance under fully-developed ideal flowing conditions. For differential pressure devices, this condition is achieved at a position at least $30D$ downstream of a number of different specially-designed perforated plate flow conditioner types, with the flow conditioner at a distance = $5D$ downstream from the first pipe fitting that is upstream of the primary element. A minimum of $5D$ of straight pipe must be placed downstream of the meter being tested. To ensure that fully developed flow conditions will be achieved at the test position, the test facility must conduct a flow profile check by the use of a Pitot traverse or other acceptable techniques.

The Baseline Tests must be conducted as described in Sections 4.1, and 4.3 and/or 4.4. This protocol requires the Baseline Tests at two line pressures for tests with gas, but it is optional to test the meter at two line pressures when the test fluid is incompressible.

Meters that do not have a varying area ratio for a given line size will be tested in two line sizes as defined above.

4.7 INSTALLATION EFFECTS TESTS

This standard requires the following Installation Effect Tests to evaluate a meter's performance in worst-case non-ideal flow conditions. As such, any "real-world" installation should result in meter performance as good as, or better than, the results obtained under this section.

4.7.1 Downstream Disturbance

If a manufacturer specifies that less than $5D$ of downstream piping are needed, then the effects of a downstream disturbance must be tested. Using the same upstream configuration as in the Baseline Testing, a half-moon orifice or half-open gate valve shall be placed at a location downstream of the meter as specified by the manufacturer. The Downstream Disturbance Test must then be conducted in accordance with Sections 4.1, and 4.3 and/or 4.4. However, gas testing at multiple pressures is not necessary. The maximum and minimum line sizes and Area or Beta ratios, test pressure, fluid properties, and Reynolds numbers should all correspond to the Baseline Test condition for these meters in order for a valid statistical analysis (Section 8.3) to be performed. The orientation of the half-moon plate or half-open gate valve with respect to any asymmetry of the meter shall be recorded.

4.7.2 Upstream Disturbances

Tests will be carried out for the manufacturer's meter, including upstream piping and flow conditioners as specified by the manufacturer, installed directly downstream of the following three disturbances. In each case, flow entering the disturbance must have a symmetrical flow pattern and no swirl, as in Section 4.6. The manufacturer must define the distance of the following upstream disturbances to the primary element being tested and record these distances in the test report (see Section 7). If a flow conditioner is used with the meter, it must also be explicitly stated in the test report.

The Upstream Disturbance Tests must be conducted in accordance with Section 4.1 and 4.3 and/or 4.4. However, gas testing at multiple pressures is not necessary. The maximum and minimum line sizes and Area or Beta ratios, test pressure, fluid properties, and Reynolds numbers should all correspond to the Baseline Test condition for these meters in order for a valid statistical analysis (see Section 8.3) to be performed.

4.7.2.1 Two Adjoining (Close Coupled) Out-of-plane 90° Elbows (Long Radius)

Installing these piping elements immediately upstream of the meter will generate a moderate swirl and flow profile asymmetry.

The spacing between the end of the curved portion of the first elbow and the beginning of the curved portion of the second elbow shall not exceed two pipe diameters ($2D$).

4.7.2.2 A Half-moon Orifice Plate (Asymmetric Flow Profile)

Installing this device immediately upstream of the meter will generate a strong asymmetric axial velocity profile. The orientation of the half-moon plate with respect to any asymmetry of the meter shall be recorded. A half-open gate valve is an acceptable substitute for a half-moon orifice plate.

4.7.2.3 Swirl Generator

Installing this device upstream of the meter will generate high swirl. A high swirl test is required to generate typical flow conditions as found downstream of industrial installations like headers. The swirl generator device (e.g., vanes) should produce a swirl angle across the pipe of at least 24° at the inlet to the upstream meter tube, the length of which is defined by the manufacturer. The angle of swirl must be confirmed on the test apparatus by use of a generally recognized technique (e.g., multi-hole Pitot tube, Cobra probe, etc.). The setting of the vane angle on the swirl generator is not considered to be a measure of the swirl angle at the location upstream of the meter. One direction of swirl being tested is regarded as sufficient to allow understanding of the meter's performance with swirl.

4.7.3 Combined Upstream And Downstream Disturbances

If a manufacturer specifies that less than $5D$ of downstream piping are needed, then a combined test of a downstream disturbance and an upstream disturbance must be performed. For this series of tests, the upstream disturbance will be the one which required the longest upstream length to reproduce the Baseline Test results in the upstream disturbance test (Section 4.7.2) above.

The downstream disturbance will be placed in the same location as in Section 4.7.1, above.

A single combined test may be performed using one line size and one area ratio if that line size and area ratio produced the worst results in both the upstream and downstream tests. If this is not the case, then the combined test must be performed at the maximum and minimum area ratios and line sizes. The test pressure, fluid properties, and Reynolds numbers should all correspond to the Baseline Test condition for these meters in order for a valid statistical analysis (see Section 8.3) to be performed.

4.7.4 Special Installation Tests

In addition to the required tests above, the user has the option of Special Installation Testing. This would be performed to establish the minimum upstream and downstream pipe lengths for a specific application which the user may have. For example, the piping configuration may produce more favorable velocity profiles than the "worst case" conditions required in the Installation Effect Tests. If the Special Installation Testing is done in accordance with the test matrix described in Section 4.1 and Section 4.3 and/or 4.4, then the meter performance for that specific installation is adequately characterized over the range of area ratios, line sizes, and Reynolds numbers tested. Alternatively, Special Installation Testing may be limited to a single test value (such as area ratio), in which case its use should be limited to that value. The results of Specific Installation Testing should be reported, as shown in Section 7.

4.8 ACOUSTIC NOISE TESTS

If excessive noise is encountered during any of these tests, it shall be documented in the report.

5.0 Laminar Flowmeter Tests

Meters operating in the laminar regime have been treated separately in this standard. Special testing, in lieu of the testing required in Section 4, is required for differential flow meters that measure fluid flows in the laminar flow regime by measuring the differential pressure between two defined pressure tap locations on the meter. The laminar pipe flow regime is defined here when the parabolic flow velocity profile is fully developed at a Reynolds number less than 2,300. In

many references, a conservative Reynolds number of 2,000 in pipe flows are defined as the upper limit of the laminar flow regime. The experimentally defined upper limit of Reynolds number for the laminar flow regime is 2,300 in pipe flow. Laminar flow meters operate on the principle of the physical law expressed in the Hagen-Poiseuille Equation, which defines the differential pressure between two locations on a straight length of pipe with a uniform and constant cross-sectional area. For a fluid of known density or specific gravity, the differential pressure,

$$\Delta P = \rho g h_l = \left(\frac{64}{Re} \cdot \frac{L}{D_i} \cdot \frac{\rho V^2}{2} \right) \qquad (5.1)$$

where

ΔP = differential pressure across the defined length is in ft (N/m^2 or Pasca),

ρ = fluid density in lb_f/ft^3 (kg/m^3),

h_l = differential head of liquid between the two locations on the straight pipe in ft (m),

g = local acceleration due to gravity in ft/s^2 (m/s^2),

L = distance between the pressure taps in ft (m),

D_i = internal diameter of the pipe in ft (m),

V = average velocity through the pipe cross-section in ft/s (m/s),

Re = flow Reynolds number (dimensionless).

Numerical factors are used to convert ΔP to convenient unit (e.g., kPa, MPa, psi, inches of water column, etc.) for the user. The U.S. Customary Unit for each term is in parenthesis.

Substituting for Re,

$$\Delta P = 32\mu \frac{VL}{D_i^2} \qquad (5.2)$$

where, μ =absolute viscosity of the fluid Pa.s (cP)

The volumetric flow rate equation can be found by the extension of this physical law for known pipe geometry, fluid viscosity, and pressure drop. The volumetric flow rate is:

$$Q = \frac{\pi \Delta P D_i^4}{128 \mu L} \qquad (5.3)$$

A laminar flow meter predicts a volumetric flow rate directly from the friction pressure loss across the meter, the meter geometry, and the viscosity of the fluid. The stated theory is for straight pipe laminar flow meters. However, in real-

ity laminar flow meter designs vary and Equation 5.2 can be reduced to a generic form to define the volume flow rate as,

$$Q = k\frac{\Delta P}{\mu} \qquad (5.4)$$

where, k = constant that relates to the meter geometry.

This Test Protocol requires that laminar flow meters be tested over the flow rates and fluid viscosity range defined by the manufacturer. Some laminar flow meters are so designed that although the flow through the main flow line may not be laminar, the meter cross-section and meter internals are such that the flow through the meter is laminar.

The meter manufacturer must state the value, k, to be used prior to performing the test. The laminar flow meter is to be tested at minimum of three flow rates, using a single phase Newtonian fluid and a fluid viscosity range defined by the manufacturer. The high flow rate for the test must be at, or higher than, 95% of the maximum flow rate of the meter for the test fluid at the flowing condition, but not to exceed the maximum flow rate specified by the manufacturer. The high and low flow rates for the test must be at least 10:1. At each flow rate, at least five data points must be acquired.

5.1 LAMINAR METER TEST FOR COMPRESSIBLE FLOWS

For meters used in compressible flows, if correction for the expansibility of the gas is necessary for the flow rate calculation, the meter manufacturer must state the expansibility correction equation prior to the test and the meter must be tested with a compressible fluid at two different operating pressures. The high test pressure will be at least 80% of the test meter's highest pressure rating or at least 800 psi (5.5 MPa); the lower of the two pressures will apply for the high pressure test. The low pressure test must be at less than 50 psi (0.34 MPa) or at the lowest operating pressure specified by the manufacturer. The higher of the two pressures will apply for the low pressure test.

5.2 LAMINAR METER TEST FOR TURBULENT FLOWS IN THE MAIN PIPE LINE

Laminar meters having non-laminar flow regime in the main flow line should be tested with fluids of two different viscosities. This test is to establish the viscosity effects. The ratio of the two test fluid viscosities should be at least 5:1.

6.0   Flow Rate Equation

The flow rate equation used to calculate the volume or mass flow rate from the measured differential pressure must be clearly stated with all the dimensional units (e.g., inch of mercury, mm of water, bar, Pascal, psi, inches of water, etc.). For any non-dimensional parameter (e.g., Reynolds number)

used in the flow rate equation, the variables included in the non-dimensional parameter must be defined with applicable engineering units. If any term is a function of fluid properties, (density, viscosity, etc.) or is dependent on any non-dimensional parameter, the range or limits must be provided by the manufacturer.

If the flow rate equation is limited by certain geometrical dimensions, those limits must also be stated by the manufacturer. The flow rate equation specified by the manufacturer and applicable limits, if any, must be documented when reporting the test results.

For compressible fluids, the expansibility equation of the meter must be stated in the test results.

7.0 Procedure For Reporting Meter Performance Results

To facilitate comparison between meters, all tests must be reported in the following set format. Proof of the test facility's compliance with Section 3.1 needs to be presented in the report. The result of the tests should be reported in tabular and graphical form, including results of the Baseline Tests, Installation Effect Tests, and Special Installation Tests, if applicable.

The Test Report shall contain the following information:

7.1 TEST FACILITY INFORMATION

1. Name and location of the test facility.
2. Date and time of test.
3. Fluid(s) used.
4. Manufacturer, model number, and uncertainty of transmitters used to measure pressure, differential pressure, and temperature. Copies of the Calibration Certificates must be included for all the transmitters.
5. Surface roughness of the upstream and downstream meter tubes must be recorded.
6. If a Densitometer is used the model number, uncertainty, and Calibration Certificates must be included.

7.2 METER INFORMATION

1. Name of the meter manufacturer.
2. Type/Name/Description of the meter.

3. Meter serial number and model number.
4. Nominal size of meter and piping.
5. Meter and piping schedule with pressure rating.
6. Meter geometry and critical dimensions (drawing of the meter).
7. Manufacturer's predicted discharge coefficient; this may be a constant value or an equation.
8. All equations required to predict the flow rate for the test meter should be clearly stated in the test report, especially those that are specifically used for that type of meter design. Equations should include the expansibility equation (including the limitations for $\Delta P/P_1$), the discharge coefficient equations and the flow rate equation, when applicable.
9. Position and type of any required flow conditioner.

7.3 DESCRIPTION OF THE FULL TEST MATRIX AND RESULTS

1. Clear indication of test type (e.g., "Baseline" or "Installation Effect: high swirl" etc.) .
2. Manufacturer's required upstream and downstream piping and actual installed lengths.
3. Meter orientation (i.e., horizontal or vertical).
4. Table of results, including estimates of uncertainty in measurement parameters.
5. Test summary including the meter uncertainty determined from the Baseline Testing, all test conditions for which the stated uncertainty is valid, and the conclusions from the statistical analysis comparing the baseline tests and the installation effect tests.
6. Meter asymmetry with respect to the orientation of the upstream and downstream disturbances (see Section 2.1.1).
7. The maximum velocity, ΔP, and $\Delta P/P_1$ for each set of meter tests.
8. The laboratory should record the presence of excessive noise from the meter, if noted during the baseline testing of the meter.
9. The results of any Specific Installation Testing.

7.4 SAMPLE METER TEST REPORTING FORM

Manufacturer: Generic, Inc.

Meter Description: DP Flow Widget

Serial Number: 05-000038DD

Model#: FW-26A

Line Size: 4.026"

ANSI Rating: 600#

Pipe Schedule: 40

Test Date/Time: 1-Mar-05

Test Fluid: Natural Gas

Viscosity: 0.018cP

Density: 2.28 lb/ft³

Static Pressure: 720 psig

Fluid Temperature: 76.2°F

Test Type: High Swirl

Reynolds Number	Actual Flow Coefficient	Predicted Flow Coefficient
1,000,000	0.823	0.82480
1,200,000	0.831	0.83046
1,400,000	0.836	0.83601
1,600,000	0.843	0.84127
1,800,000	0.848	0.84611
2,000,000	0.852	0.85036
2,200,000	0.857	0.85387
2,400,000	0.858	0.85649
2,600,000	0.859	0.85807
2,800,000	0.862	0.85844

Predicted flow coefficient = function of Reynolds number

DischargeCoefficient vs. Reynolds Number
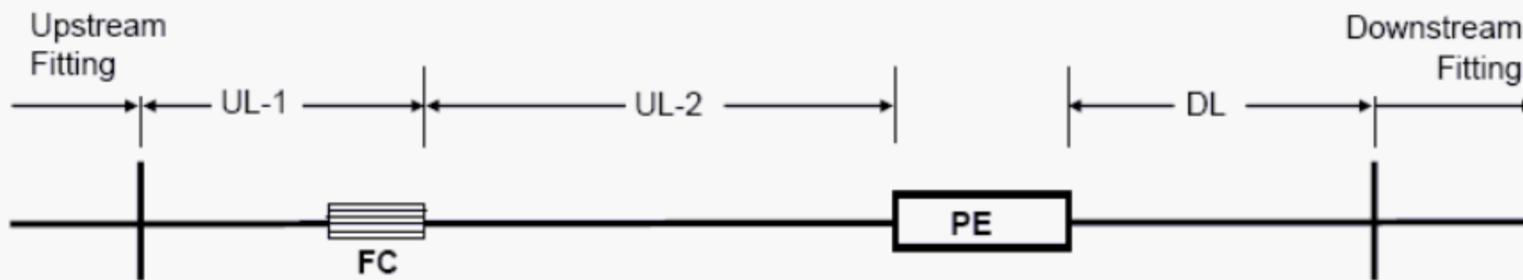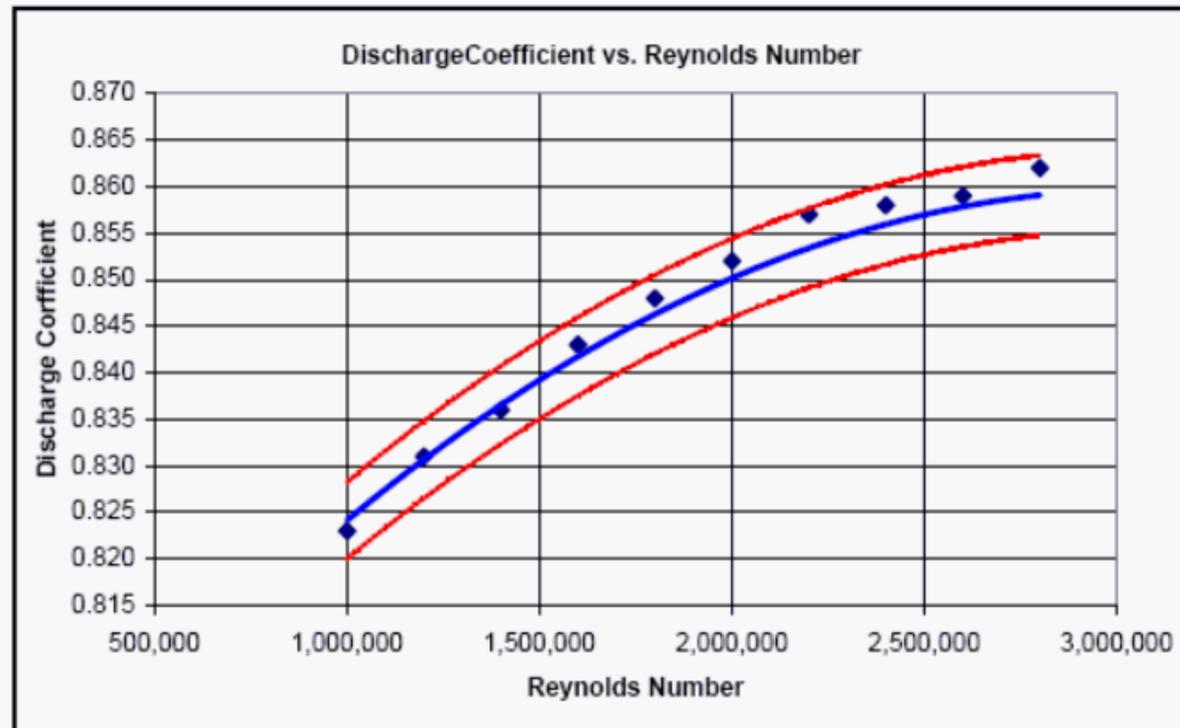
UL-1 = Straight pipe length from the end of the upstream fitting to the end of the Flow Conditioner
UL-2 = Straight pipe length from the end of the Flow Conditioner to the entrance of the test meter
FC = Flow Conditioner
PE = Primary Element and/or Test Meter
DL = Straight pipe length downstream of the Test Meter to the entrance of the downstream fitting

8.0 Uncertainty Calculations

8.1 UNCERTAINTY OF THE TEST FACILITY

The uncertainty of the test facility instrumentation, primary/secondary standard for the specific fluid being tested must be calculated and recorded. From this, the uncertainty of the flow rate (95% confidence level) must be determined in accordance with relevant uncertainty calculations (ASME MFC-2M, API *MPMS* Chapter 14.3 Part 1, or ISO 5168). The methodology and formulas used must be recorded in the test report.

Reproducibility of the Test Facility due to "turn-off-turn-on" and "day to day" considerations should be determined and included. These uncertainties are much larger (approximately 10 times) at the low flow rates.

Uncertainty of secondary instrumentation must be considered. The performance of transmitters used as secondary devices is generally stated in terms of percent of span or percent of full scale. For use in flow measurement uncertainty calculations, the instrument uncertainties expressed as a percent of span must be converted to percent of reading by the use of the following equation:

$$U_{rdg} = \pm\left(\frac{U_{span} \cdot \text{Span}}{V_{meas}}\right) \tag{8.1}$$

where

U_{rdg} = uncertainty in percent of reading,

U_{span} = specified uncertainty in percent of span,

V_{meas} = value in units measured by the instrument,

Span = calibrated span of the instrument.

Changes in the ambient temperature of the secondary instrumentation can affect their performance. Flow tests should be performed with the secondary instruments maintained at an ambient condition that has negligible effect on the secondary device. Alternatively, the increased uncertainty of the secondary device should be included in the system uncertainty.

8.2 UNCERTAINTY OF THE TEST METER DERIVED FROM THE TEST RESULTS

From the test results, the uncertainty of the test meter during the Baseline Test (Section 4.6) must be calculated and reported in the Test Report (Section 7). A sample calculation methodology is presented in Appendix B., however, other methods of determining test meter uncertainty may also be acceptable. The uncertainty calculation procedure, if different from Appendix B, must be clearly described in the Test Report.

Regardless of the method used to determine uncertainty, the following guidelines must be considered:

1. Test meter uncertainty is the variance (95% confidence) of the mean C_d determined by the test facility compared with the C_d predicted by the manufacturer at each Re tested. The mean C_d is the arithmetic average of the 5 points taken for each *Re* (see Section 4.1). The manufacturers' predicted C_d may be a constant value or an equation that is a function of *Re*, however, it must be consistent with the C_d provided to the user to determine flow rate. If meters are individually flow tested by the manufacturer, then the C_d for the specific meter being tested must be used to determine the uncertainty.

2. The statistical method used to determine the uncertainty should be appropriate for a small data set. Standard deviation is intended to be used with data sets greater than 30 points. Because Section 4.1 requires only 10 points, an alternate method must be used. Appendix B uses a "Student t-distribution". Other methods may also be acceptable.

3. If the statistical analysis shows that the manufacturer's predicted C_d results in a bias greater than the uncertainty of the test facility (determined in Section 8.1), then the manufacturer must either offer a new C_d or disclose the bias in the Test Report.

8.3 STATISTICAL ANALYSIS OF THE INSTALLATION EFFECTS TESTS

The test report shall include a statistical analysis to determine if the Installation Effect Tests are statistically similar to the corresponding Baseline Tests. If the statistical analysis concludes the results are statistically similar, the meter may be used with the upstream and downstream pipe lengths from the worst-case Installation Effect Test with no additional uncertainty or bias. If the results are not similar, the manufacturer has the option of re-running the Installation Effect Tests with longer upstream and/or downstream lengths of pipe, or quantifying the additional uncertainty and/or bias associated with the Installation Effect Test configuration.

Appendix B presents a methodology for determining statistical significance. Other methods may be used, however, a complete description of the method must be included in the test report.

APPENDIX A—TEST MATRICES FOR SECTION 4

A.1 BASELINE TESTS

Line sizes < 4 in. (100 mm) must be tested separately; extrapolation of line sizes is only valid for geometrically similar meters > 4 in. (100 mm)

A.1.1 LIQUID FLOW TESTS

Note: all tests are done at one pressure.

Test Series*	Area Ratio	Line Size
1	β_2	D_1
2	β_1	D_1
3	β_2	D_2

A.1.2 GAS FLOW TESTS:

Test Series*	Pressure	Area Ratio	Line Size
1	P_1	β_2	D_1
2	P_2	β_2	D_1
3	P_1	β_1	D_1
4	P_1	β_2	D_2

A.2 INSTALLATION EFFECT TESTS

Note: Test matrices are identical for liquid and gas testing.

A.2.1 DOWNSTREAM DISTURBANCE TEST

Note: This test is only required if < 5D downstream is specified by the manufacturer

Test Series*	Pressure	Area Ratio	Line Size
1	P_1	β_2	D_1
2	P_1	β_1	D_1
3	P_1	β_2	D_2

A.2.1.1 Upstream Disturbance Test—2 close coupled out of plane elbows

Test Series*	Pressure	Area Ratio	Line Size
1	P_1	β_2	D_1
2	P_1	β_1	D_1
3	P_1	β_2	D_2

A.2.1.2 Upstream Disturbance Test—A Half-moon Orifice Plate

Test Series*	Pressure	Area Ratio	Line Size
1	P_1	β_2	D_1
2	P_1	β_1	D_1
3	P_1	β_2	D_2

A.2.1.3 Upstream Disturbance Test—Swirl Generator

Test Series*	Pressure	Area Ratio	Line Size
1	P_1	β_2	D_1
2	P_1	β_1	D_1
3	P_1	β_2	D_2

A.2.2 COMBINED UPSTREAM AND DOWNSTREAM DISTURBANCES

Note: This test is only required if < 5D downstream is specified by the manufacturer. Use the upstream disturbance that required the longest upstream piping in 4.7.2; the downstream disturbance is the same as 4.7.1. See 4.7.3 for exceptions to the following required tests.

Test Series*	Pressure	Area Ratio	Line Size
1	P_1	β_2	D_1
2	P_1	β_1	D_1
3	P_1	β_2	D_2

A.2.3 SPECIAL INSTALLATION TESTS

Note: This test matrix will allow for complete characterization of the installation being tested between β_1 and β_2, and between D_1 and D_2. Extrapolation for line sizes > D_2 is allowable for geometrically similar meters.

Test Series*	Pressure	Area Ratio	Line Size
1	P_1	β_2	D_1
2	P_1	β_1	D_1
3	P_1	β_2	D_2

where

P_1 = low pressure,

P_2 = high pressure ($P_2 = 5 \times P_1$),

β_1 = smallest area ratio,

β_2 = largest area ratio,

D_1 = smallest line size; normally 4 in. (100 mm),

D_2 = largest line size; normally 8 in. (200 mm).

* Each Test Series includes at least 10 evenly-spaced Reynolds Numbers.

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APPENDIX B—UNCERTAINTY ESTIMATE

The most important assumption in the analysis and report of meter performance by following the procedure defined by the testing protocol is that the random and systematic biases of the laboratory or test facility instruments are randomized within the data base. This means that the variations due to the biases of different equipment of the calibration laboratory are reported as the total uncertainty of the meter. Additionally the database is limited; hence evaluation of the meter uncertainty is likely to be more conservative than the true or actual uncertainty of the meter. This allows the use of results from reported data as a qualitative and quantitative representation of the performance of the meter. When the meter is tested at a facility whose performance and random and systematic biases are documented or known with respect to other internationally recognized calibration facilities, a better understanding or assessment of the meter uncertainty is possible.

B.1　General Consideration

Many factors associated with differential-pressure flowmeter installation influence the overall error in flow measurement. These errors are due to uncertainties of the following:

a. Representation of the actual flow rate by the mass flow rate equation defined for the meter.
b. Uncertainty in defining the actual physical properties of the fluid being measured.
c. Measurement uncertainty associated with the measured physical dimensions of the metering device and the conduit that the flow equation is a function of.

Examples of some of the calculation of the overall uncertainty of some of the major parameters are given below.

B.2　Uncertainty Over A Flow Range

The accuracy of the differential pressure device is usually estimated using the uncertainty of the differential pressure sensing device. This is realistically dependent on the pressure sensing device and normally a function of the range of the transmitter and the differential pressure generated by the primary element for the applicable flow rate range of the meter for the operating conditions. The significant influence on the measured value include ambient temperature effects, static pressure effects, long term drifts, hysteresis, linearity, repeatability, and the uncertainty of the calibration or verification standards.

For some applications, parallel meters runs are installed to meet the user's desired uncertainty and rangeability requirements. It is also possible to use stacked ΔP devices to operate the meter over different flow rate ranges that minimize uncertainty in measurement and increase rangeability of the flow meter.

B.3　Uncertainty Of Flow Rate

The overall uncertainty is the root sum squares of the uncertainty associated with the pertinent variables. For practical considerations, the pertinent variables are assumed to be independent to provide simpler uncertainty calculations. Generally, dependence of any of the variables on another that affects the flow rate calculation is negligible and has no discernible uncertainty contribution; hence the assumption of independence of each variable is acceptable for the differential pressure devices. The total uncertainty of the flow rate through a differential pressure type flowmeter may be calculated by any one of the following methods:

a. Empirical coefficient of discharge flow calibration database for the device.
b. In-situ flow rate calibration of the differential pressure device.

B.3.1　UNCERTAINTY USING EMPIRICAL COEFFICIENT OF DISCHARGE FOR THE DEVICE

The basic equation for determining flow rate is typically expressed as:

$$q_m = N \frac{C_d}{\sqrt{1-\beta^4}} Y d^2 \sqrt{\rho \Delta P} \qquad (B.1)$$

where

q_m = the mass flowrate,

N = a numeric conversion factor, including the acceleration due to gravity, g,

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C_d = the coefficient of discharge for the meter, which may be a function of Reynolds Number (Reynolds Number is a function of D, ρ, q_m, and viscosity, μ),

β = the diameter ratio (for orifice and venturi meters, bore diameter, d, divided by the pipe diameter, D),

Y = the expansion factor or expansibility (for incompressible fluid = 1),

d = the characteristic length, L (bore diameter for orifice and venturi flowmeters),

ρ = the density of the flowing fluid, and

Δp = the differential pressure generated by the primary element.

It can be observed that the mass flow rate from the above equation is a function of the dimensions at the differential pressure producers of the flow element, fluid properties at the operating conditions, and can be expressed as:

$$q_m = \int (C_d, Y, D_i, L, g, \rho, \Delta p, \mu) \tag{B.2}$$

There are other parameters that can affect measurement uncertainty of a certain meter design while some of the parameters listed in the above equation may not affect the uncertainty of a specific meter design. Meter manufacturer should specify which parameters impact the meter performance and affect meter output that will allow the user to estimate the uncertainty of the measurement of a specific meter design by following uncertainty calculation procedures accepted in the industry.

B.3.2 UNCERTAINTY USING AN IN-SITU CALIBRATION

When a differential flowmeter is calibrated in situ, the practical working formula for the uncertainty of the mass flow rate can be expressed as follows:

$$\frac{\delta q_m}{q_m} = \left\{ \left(\frac{\delta Y^2}{C_d} \right)^2 + \left(\frac{\delta Y}{Y} \right)^2 + \left(E_L \cdot X_L \cdot \frac{\delta L}{L} \right)^2 + \left(E_{D_i} \cdot X_{D_i} \cdot \frac{\delta D_i}{D_i} \right)^2 + \left(E_\rho \cdot \frac{\delta \rho}{\rho} \right)^2 + \left(E_p \cdot \frac{\delta \Delta P}{\Delta P} \right)^2 \right\}^{0.5} \tag{B.3}$$

where

C_d = the coefficient of discharge for the meter,

Y = the expansion factor or expansibility (for incompressible fluid = 1),

D_i = the pipe internal diameter,

L = the characteristic length scale of the differential pressure producer,

ρ = the density of the flowing fluid at the flowing conditions,

Δp = the differential pressure monitored at the designated locations that is produced by the primary element, and

E_L = the exponent of the characteristic length scale; for orifice flowmeter, exponent (power) of the bore diameter, d, in the flow rate equation is 2,

X_L = the coefficient of the internal pipe diameter (for orifice flowmeter that value is $1/(1-\beta^4)$),

E_{Di} = the exponent of the pipe internal diameter, D_i; for orifice flowmeter, exponent (power) of the pipe ID in the flow rate equation is -2.

X_{Di} = the coefficient of the term with the pipe internal diameter (for orifice flowmeter that value is $\beta^4/(1-\beta^4)$,

E_ρ and $E_{\Delta P}$ = the respective exponents of ρ and ΔP in flow rate equation and are 0.5 (square root).

The meter factor (MF) term is estimated from the combination of the primary mass flow uncertainty, the master meter uncertainty, and the precision of the meter calibration. Note that the meter factor (MF) determined from the differential pressure device is a combination of several possible errors. No additional uncertainty is necessary for installation conditions or expansion factor.

B.4 Typical Uncertainty

For precise measurement, such as custody transfer application, the flowmeter and adjacent piping should meet the minimum requirements specified for the device by the vendor. The typical uncertainties expressed in the following sections can be obtained only through compliance with the requirements specified by the manufacturer.

B.4.1 EMPIRICAL COEFFICIENT OF DISCHARGE

The estimated uncertainty of the empirical coefficient of discharge for a differential pressure device is generally a function of the Reynolds number and the meter geometry. At high Reynolds numbers the uncertainty is generally a weak function of the Reynolds number and remains a function of the meter geometry only. The uncertainty of the discharge coefficient and the limits of the Reynolds number for the defined precision of measurement by the meter are to be specified by the manufacturer.

B.4.2 EMPIRICAL EXPANSION FACTOR, Y, FOR COMPRESSIBLE FLUIDS

The value of Y computed by the empirical equations are subject to tolerance varying from 0 to the maximum allowable differential pressure ratio ($X = \Delta P/P$) limit specified by the manufacturer. For larger values of X, relatively larger uncertainty values may be expected. Manufacturer must specify the uncertainty values for their device as a function of the differential pressure ratio, X.

B.4.3 INSTALLATION CONDITIONS

To assure accurate flow measurement, the fluid should enter the flowmeter with a fully developed flow profile, free from swirl or vortices. Such a condition is often achieved through the use of a flow conditioner and/or adequate length of straight pipe preceeding and following the flowmeter.

For various technical reasons the uncertainty associated with installation conditions is difficult to quantify. The combined practical uncertainty levels are generally contributed by the following:

- Empirical Coefficient of Discharge,
- Installation condition, velocity profile and swirl, and
- Mechanical specifications of the dimensional parameters of the meter.

The testing protocol defined in this document for different flow profiles is for qualitative evaluation of the combined uncertainty of the meter at severe flowing conditions that may be generated by different piping installations for the meter. Reported data are for the coefficient of discharge defined by the manufacturer and for the meter being tested. Test data may be used to evaluate relative performance of different meter designs and may not be the absolute uncertainty value for all the meters by the manufacturer, because the test database is limited and random and systematic uncertainty of the flow facility is embedded in the reported data.

B.4.4 DIMENSION OF THE CHARACTERISTICS LENGTH SCALE, L, OF THE PRIMARY ELEMENT

The uncertainty of the characteristic length scale, L, of the primary element may be determined from the measurements of the length dimension. If the dimensional measurements are available, the uncertainty is the root sum square (RMS) of the differences between individual reading and their mean value. For example, if five readings of the characteristic length scales are 10.005, 10.002, 9.998, 9.996, and 9.999 the mean is 10.000 and the deviations from the mean reading are + 0.005, + 0.002, – 0.002, – 0.004, and – 0.001. So,

$$\delta L = \left[\frac{\sum_{i=1}^{n} (\delta L_{mi})^2}{n-1} \right]^{0.5} = \pm \left[\frac{(0.005)^2 + (0.002)^2 + (-0.002)^2 + (-0.004)^2 + (-0.001)^2}{(5-1)} \right]^{0.5}$$

$$= \pm 0.0035$$

$$\frac{\delta L}{L_{mean}} = \pm \frac{0.00354}{10} = \pm 0.000354 \cong \pm 0.035\%$$

B.4.5   METER TUBE INTERNAL DIAMETER, D_I

The uncertainty of the pipe diameter can also be determined from the measured values of the pipe internal diameter. The pipe diameter uncertainty is similar to the example shown in Section B.4.4. If the five measured pipe internal diameters are 20.006, 19.996, 19.998, 20.003, and 19.997, then the average is 20.000 and the differences are 0.006, -0.004, -0.002, 0.003, and -0.003. So,

$$\delta D_i = \left[\frac{\sum_{i=1}^{n} (\delta D_{i-mean})^2}{n-1} \right]^{0.5} = \pm \left[\frac{(0.006)^2 + (-0.004)^2 + (-0.002)^2 + (0.003)^2 + (-0.003)^2}{(5-1)} \right]^{0.5}$$

$$= \pm 0.0043$$

$$\frac{\delta D_i}{D_{mean}} = \pm \frac{0.0043}{20} = \pm 0.000215 = \pm 0.022\%$$

B.4.6   DIFFERENTIAL PRESSURE DEVICE

Performance specification 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 must be taken to account for the effects of the ambient temperature, pressure, humidity, driving mechanism, response time on the user selected device.

B.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 calculating the density. The uncertainty calculation depends on the rate of change of density of the fluid due to changes in temperature and pressure at the operating conditions of the fluid.

B.4.8   FLUID VISCOSITY

Fluid viscosity generally affects the shape of the velocity profile and effect of viscosity on the coefficient of discharge is normally accounted for via Reynolds number effect on the discharge coefficient.

B.5   Example Of Uncertainty Calculations

Examples of uncertainty calculation for liquid and gas flows are presented below in Sections B.5.1 and B.5.2.
Assuming the mass flow rate equation of the differential pressure device is given as

$$q_m \propto C_d \cdot Y \cdot F_A \cdot \frac{d^2}{D_i^2} \cdot \sqrt{2g \cdot \rho_{t,P} \cdot \Delta P} \qquad\qquad (B.4)$$

where

$\quad C_d$ = Coefficient of Discharge,

$\quad Y$ = Coefficient of Expansion or Expansibility factor,

$\quad F_A$ = Factor for Area ratio,

$\quad d$ = Characteristic length scale,

$\quad D_i$ = Internal diameter of the pipe,

g = Acceleration due to gravity,

$\rho_{t,P}$ = Density of the flowing fluid at the operating temperature and pressure,

ΔP = Differential pressure.

B.5.1 EXAMPLE OF UNCERTAINTY ESTIMATE OF INCOMPRESSIBLE FLOW CALCULATION

An example of the effect of the uncertainties is presented in this section for the values of different parameters given in Table B.1. The value of F_A is assumed as 0.5. The expansibility factor, Y, is a constant ($Y = 1$ for incompressible fluid flows).

Table B.1—Example of Uncertainty Estimate for Liquid Flow Calculation

		Uncertainty, U_{95} (%)	Sensitivity Coefficient, S	$(U_{95}.S)^2$
C_d	Basic Discharge Coefficient	0.5	1.0	0.2500
L	Characteristic Length Scale	0.05	$2 \times F_A = 2 \times 0.5$	0.0025
D_i	Pipe Internal Diameter	0.025	$(-2) \times F_A$	0.0006
ρ	Fluid Density	0.25	0.5	0.0002
ΔP	Differential Pressure	0.45	0.5	0.0506
		Sum of the Squares		0.3039
		Square Root of the Sum of Squares		0.5513

Note: The overall uncertainty of this liquid flow example has an uncertainty of $\pm 0.55\%$.

The Area factor, F_A for D_i and L may be different which would change the corresponding F_A value in the Sensitivity Coefficient column in Table B.1.

B.5.2 EXAMPLE OF UNCERTAINTY ESTIMATE FOR COMPRESSIBLE FLOW CALCULATION

For gas flows, the fluid density may be defined as follows:

$$\rho_{t,P} = \frac{G_i \cdot M_{air} \cdot P_f}{Z_f \cdot R \cdot T_f} \tag{B.5}$$

where

G_i = Ideal gas relative density (specific gravity) of the gas (M_{gas}/M_{air}),

M_{air} = Molecular weight of air,

M_{gas} = Molecular weight of gas,

P_f = Static pressure of the fluid at flowing condition,

R = Universal gas constant,

T_f = Temperature of the fluid at the flowing condition,

Z_f = Fluid compressibility at flowing condition.

The fluid density uncertainty has a sensitivity of 0.5 for the square root value. The mass flow rate equation for the compressible flow is,

$$q_m \propto C_d \cdot Y \cdot F_A \cdot d^2 \cdot \sqrt{2g \cdot \frac{G_i \cdot M_{air} \cdot P_f}{Z_f \cdot R \cdot T_f} \cdot \Delta P} \tag{B.6}$$

where

C_d = Coefficient of Discharge,

Y = Coefficient of Expansion or Expansibility factor,

F_A = Factor for Area ratio,

d = Characteristic length scale,

D_i = Internal diameter of the pipe,

g = Acceleration due to gravity,

$\rho_{t,P}$ = Density of the flowing fluid at the operating temperature and pressure,

ΔP = Differential pressure.

Following assumptions and conditions were selected for the calculation:

- For each variable, the uncertainty listed represents the random uncertainty only.
- The uncertainty values are arbitrarily assumed for the example. Assumed values are listed in Table B.2 and the area factor, F_A is assumed to be 0.5.

The device in the example is assumed to have the same sensitivity coefficient for the internal pipe diameter and the characteristic length scale.

		Uncertainty, U_{95}(%)	Sensitivity Coefficient, S	$(U_{95}.S)^2$
Cd	Basic Discharge Coefficient	0.50	1.0	0.2500
Y	Expansibility Factor	0.03	1	0.0009
L	Characteristic Length Scale	0.05	$2 \times F_A = 2 \times 0.5$	0.0025
D_i	Pipe Internal Diameter	0.025	$(-2) \times F_A$	0.0006
ρ	Fluid Density	0.25	0.5	0.0002
P	Static Pressure	0.10	0.5	0.0025
ΔP	Differential Pressure	0.45	0.5	0.0506
Z	Compressibility factor (e.g., from AGA 8)	0.10	-0.5	0.0025
T	Flowing Temperature	0.25	-0.5	0.0156
G	Relative density	0.60	0.5	0.0900
	Sum of the Squares			0.4154
	Square Root of the Sum of Squares			0.6445

Table B.2—Example of Uncertainty Estimate for Compressible Flow Calculation

Note: The overall uncertainty of this compressible flow example has an uncertainty of ± 0.64%

The Area factor, F_A for D_i and L may be different which would change the corresponding F_A value in the Sensitivity Coefficient column in Table B.2.

APPENDIX C—DIMENSIONAL PARAMETERS FOR PROTO-TYPE TESTING

Dimensional parameters have aided significantly in the understanding of fluid-flow phenomenon. They permit limited experimental results to be applied to situations involving different physical dimensions and often different fluid properties. Thus, it is possible to conduct fewer and selective experiments to establish or determine flowmeter performance for flowing conditions for which meter has not been flow tested. The test results of an experimental investigation can also be presented in a more compact and meaningful way, so as to facilitate their use for different flowing conditions.

If accurate quantitative data are to be obtained from a model study, there must be dynamic similitude between the model and prototype. This similitude requires that (1) there be exact geometric similitude and (2) the ratio of dynamic pressures at corresponding points be constant. The second requirement may also be expressed as a kinematic similitude, i.e., the streamlines must be geometrically similar.

Geometric similitude requires that every linear dimension to have the same ratio between the model and the prototype. For the dynamic pressure to be in the same ratio at corresponding points in model and prototype, the ratios of the various types of forces must be the same at the corresponding points. Hence, for strict dynamic similitude, the Mach number, Reynolds number, Froude number, and Weber number must be the same in both model and prototype.

Strict fulfillment of these requirements is generally impossible to achieve, except in 1:1 scale ratio. Fortunately, in many situations only two of the forces are of the same magnitude.

In steady pipe flows, viscous and inertial forces are the only ones of consequence; hence when geometric similitude is observed, the same Reynolds number for model and prototype provides dynamic similitude. The various corresponding pressure coefficients are the same. For testing with fluids having same kinematic viscosity in model and prototype, the product VD, must be the same, where V is the velocity and D is the characteristics length. Frequently this requires very high velocities in small models. Therefore, extrapolation of meter performance over the range of Reynolds number at which meter has not been calibrated or tested must be used with caution and may have additional uncertainty that may not be correctly estimated.

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