API MPMS CHAPTER 22.2 – TESTING PROTOCOL FOR DIFFERENTIAL PRESSURE FLOW MEASUREMENT DEVICES

Class # 7180.1

Dr. Zaki Hussain
Senior Staff Engineer
Chevron Corporation
1400 Smith Street
Houston, Texas 77002, USA

Introduction

The Manuals of Petroleum Measurement Standards (MPMS) by API (American Petroleum Institute) are developed for the devices and systems installed for the measurement of oil, gas, and merchandisable petrochemical products by the oil and gas industry. Historically the API flowmeter standards are developed for devices that are accepted and installed by the industry to achieve precise and repeatable measurement for fiscal, material balance, and/or process control applications. The operating principal of field accepted installed flowmeters are based on laws of physics, where the sensors or transducers are designed to monitor the response of flow to the presence of the primary element in the flow stream or the response of the primary element or transmitted signal to the flow. Some common flowmeters that monitor response of the primary element to the flowing fluid are displacement meters, turbine meter, Coriolis meters, etc. and response of the signal to the flow are ultrasonic flowmeter, Magnetic flowmeter, thermal mass meter, etc.

Examples of flowmeters that cause the fluid flow to respond to the presence of a primary element in its flow path include orifice meters, vortex meters, nozzles and venturi meters, etc. There are also flowmeters that work on the principle of sensing the fluid velocity through the pipe, thereby inferring the average flow rate. Again there are flowmeters that work on a combination of different laws of physics and signal processing techniques to infer the flow rate through the conduit at the measuring section.

There are many flow measuring devices, working on the principle of laws of physics, that are available to the industry, but due to certain unique features and design of the flowmeter, meters may have patent protection and offered by only one manufacturer. As the patent protection expires or if an alternate design can be developed without infringing upon the patent rights of the original invention, variations of similar flowmeters are often available from other vendors. Examples of flowmeters with variations in design or sensing element but with same operating principal or laws of physics are displacement, turbine, Coriolis, and Vortex flowmeters. These flowmeters vary in design, technique of monitoring response of the flow or primary element, utilize different signal processing logic, etc.

The oil, gas, and chemical industry typically select and install flowmeters that have published industry standards by API, ISO (International Standards Organization), ASME (American Society of Mechanical Engineers), or AGA (American Gas Association). Any flowmeter can be installed to measure flow, provided all involved parties and applicable regulatory agencies agree and specify its use in the terms of the contract defined and agreed by parties involved. Yet to avoid any future dispute, only meters with published industry standard are typically selected for custody transfer application. In the oil and gas industry it has primarily been limited to the industry standards of API, AGA, and ISO. Until recently, API and AGA only published flowmeter standards for devices with a proven performance record and offered by several vendors.

API standards were not developed for a flowmeter that is offered by one vendor with proprietary design protection or meters with measurement uncertainty higher than industry accepted limits for custody transfer application. It was observed that several flowmeters of proprietary design offered certain operational advantage or more precise measurement for specific applications than flowmeters that have published API or AGA standard. It was also recognized that by not developing industry standards for better performing flowmeters with proprietary design, it stifled the entrepreneurial efforts of relatively small companies or individuals and retarded innovative designs and improvements in the measurement of oil and gas.

Precise, reliable, and repeatable flow rate measurement are the desired performance characteristics of meters for custody transfer and process control applications. Hence, members of the API Committee of Petroleum Measurement (COPM) initiated an effort to develop performance based standards for devices with operating principles based on the laws of physics. Development of the first performance-based standard by API for devices with operating principle based on the physical laws of Conservation of mass and Conservation of energy, which is the basis for Bernoulli's Equation. Meters working on this principle are known as Differential Pressure (DP) type flowmeters or head type flowmeters.

Differential Pressure Type Flowmeters

The physical laws of conservation of mass and energy state that for steady flow in a closed conduit (e.g. pipe, duct, etc.), if no energy and mass is created, destroyed, stored, or leave or enter between two points of measurement in the flow stream, the total energy and mass measured at those two points remain unchanged. In a flow stream, two main forms of energy are the flow velocity (kinetic energy) and the pressure (potential energy). If flow cross-sectional area of a pipe changes between two points, the flow velocity or flow profile will change, resulting in changes to the kinetic energy of the flow. As the total energy must be conserved, the change in the kinetic energy would cause the potential energy or the pressure to change between the two locations. For a steady state flow in a pipe, assuming all other forms of energy remaining unchanged or have negligible change, if the downstream flow cross-sectional area is restricted, the flow velocity will increase, therefore the static pressure (potential energy) must decrease to adjust for the increase in kinetic energy.

From Bernoulli's Equation it can be derived that the differential pressure between two specified points of a flow stream undergoing change in cross-sectional area is proportional to the square of the velocity. Hence, flow rate through the pipe can be expressed as a function of specific physical dimensions restricting the flow, properties of the flowing fluid, and an experimentally established parameter known as the discharge coefficient for the device that is function of the shape and size of the primary element. The discharge coefficient accounts for frictional loss, location of the pressure taps in relation to the vena contracta, and other non-ideal properties of the meter.

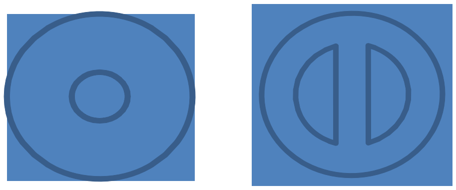

Figure 1: Change in Flow Area

Two possible arbitrary restrictions in a pipe are shown in Figure 1. The flow restriction may be abrupt or with a gradual increase and decrease of cross-sectional area for the flowing fluid. A sudden change in the cross-sectional area typically generates a high differential pressure between the upstream and downstream points across the restriction, while a gradual change causes lower differential pressure for the same blockage and flow rate; i.e., meters with gradual change typically have lower permanent pressure loss compared to the meter with abrupt change. Restriction shown on the left in Figure 1 is a hole in a flat plate that is concentric to the pipe and is the orifice plate, widely used in the natural gas industry.

Figure 2 shows three concentric reductions of cross-sectional area of a pipe for the end view shown on the left in Figure 1. The three flowmeters in Figure 2 are orifice, nozzle, and venturi flow meters. The operating principle of all three meters is based on the laws of conservation of energy and mass, but the precision of measurement, range of operation, and discharge coefficients of each meter differ significantly. All three meters have internationally accepted industry standards, but only the orifice meter has API, ISO, and AGA standards. Nozzle and Venturi flowmeters have ISO and ASME standards. Typically, orifice meters are installed for fiscal measurement, while nozzles and venturis are not, primarily because of their relatively high measurement uncertainty, precision of measurement, high initial capital cost, and changing the area ratio to cover a wide range of flow rate is not easy and often not cost effective.

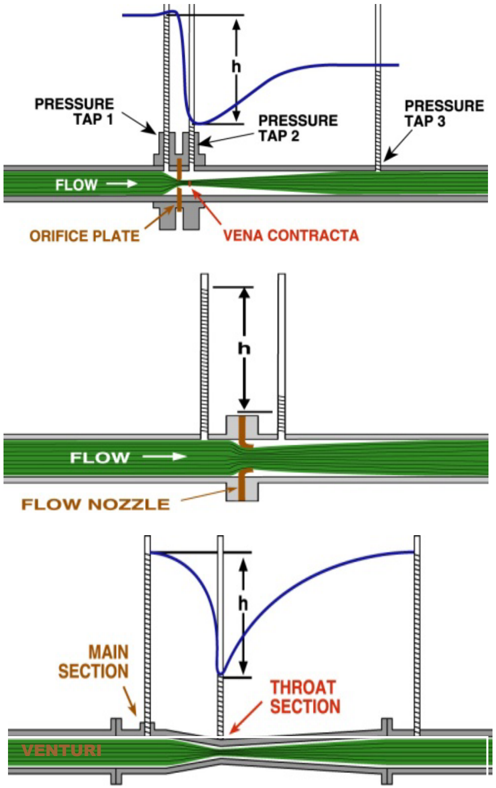

Figure 2: Different Area Change

There are many design variations of differential pressure type flowmeters and test results of several of those flowmeters demonstrated that the precision of measurement were within acceptable limits of fiscal measurements. It was also observed that for certain applications, some of the other differential pressure type flowmeters can offer certain advantage in performance and maintenance with higher precision in measurement than that can be achieved by an orifice meter. As there was no API or AGA standard for those devices, because API did not develop standard for meters with proprietary design, those meters with similar or better level of performance characteristics were not selected for fiscal applications.

Chapter 22.2, a performance based standard, was developed for flowmeters with an operating principle utilizing the laws of conservation of mass and energy. This standard defines the set of requirements and a uniform or standardized testing protocol for any differential pressure type device for which there is no existing API or AGA standard. As this standard is applicable to meters for which no API standard exists, this standard does not apply to orifice flowmeters.

Background History, Scope, and Purpose of Chapter 22.2

The goal of performance based standards was to allow the industry to use devices that have proprietary design protection or have no applicable industry standard. First performance based standard developed for DP devices was published under API Chapter 5, which is the chapter for flowmeters, as Chapter 5 Section 7 (Chapter 5.7). It was then brought to the attention of COPM that API Chapter 5 is for liquid flowmeters only, while differential pressure type flowmeters were primarily used in gas flow applications. To avert this inconsistency, API COPM assigned a new chapter (Chapter 22) for standards defining verifiable performance characteristics of devices for the petrochemical industry through standardized testing protocol. Most API MPMS Chapters with multiple sections have Section 1 as the Introduction Section for the Chapter, which typically is the guideline for developing other Sections under that Chapter. So, Chapter 5.7 was withdrawn and published as Chapter 22.2 and the guideline for developing performance based standard (Chapter 22.1) has since been published.

Sections of API MPMS Chapter 22 are developed with a list of minimum necessary requirements and a standardized testing protocol for a specific type of device that measures or monitors certain process variables. Conforming to standardized testing protocol, experimental results are to be presented in public domain to facilitate users to make quantitative and qualitative evaluation of performance characteristics of different measuring or monitoring devices for the application of interest by the user. Based on performance characteristics, a device may be selected for fiscal application, irrespective of whether the device has proprietary design protection.

There were two major factors that mandated immediate revision of Chapter 22.2. When Chapter 22.1 was published, it was observed that the format and layout of Chapter 22.2 were inconsistent with the guideline defined Section 1. More importantly, immediately following the publication of Chapter 22.2, several proprietary DP meters were tested in conformance with the requirements defined in Chapter 22.2 and it became evident that there were several areas in the requirements and specifications of the standardized testing protocol that failed to adequately capture or address certain possible shortcomings in performance characteristics of all different designs of DP devices. The revised Chapter 22.2 with major rewrite with additional requirements was balloted reviewed by users and vendors. The revised draft has since been balloted once and it is expected that the second edition of Chapter 22.2 be approved for publication in 2012.

This paper presents the general overview of Chapter 22.2, including expected changes to the next published edition of the standard. Paper also describes overall goal, necessary requirements, and the test format for DP type flow meters detailed in API MPMS Chapter 22.2 and some of the additional requirements that are addressed in the revised draft.

Most DP type flowmeters operate with acceptable performance characteristics in the turbulent flow regime. There are flowmeters that performs well in the laminar flow regime utilizing physical laws applicable to laminar flows. Chapter 22.2 primarily addresses flowmeters developed for turbulent flows and includes discussions on performance and testing of flowmeters designed for laminar flowing conditions. Note that most flows in the natural gas industry are turbulent flows. A generalized mass flow rate equation of a differential pressure type device in the turbulent flow regime can be expressed as,

$$Q_m = N_1 \times Cd \times A_f \times Y \times F_{AR} \times \sqrt{\rho_f \times DP} \qquad \text{Equation 1}$$

where,

Qm = mass flow rate per unit measure of time,

N_1 = a numerical constant for the dimensional units and other physical constants,

Cd = ratio of actual flow rate to calculated flow rate for ideal fluid and ideal flowing conditions for the device and is also referred as discharge coefficient,

A_f = dimensional constant for the flow cross-sectional area,
Y = compressibility or expansibility factor, which is unity (1) for incompressible fluids,
F_{AR} = factor for the area ratio or the factor for the change in flow area due to the primary element,
ρ_f = density of the fluid at the flowing conditions,
DP = differential pressure measured between two specified locations for the flow meter.

It is to be noted that the flow rate is a square root function of the density of the fluid at operating conditions and inaccuracy associated with defining the fluid density affect the measurement uncertainty. Flow rate in volumetric units at the base conditions is obtained by dividing Equation 1 by the density of the fluid at base conditions. The expansibility factor of compressible flows is typically function of the dimensions of the primary element, pressure tap location, ratio of the differential pressure to the line pressure, and certain fluid properties.

The discharge coefficient, Cd, is an experimentally-derived value for the primary element that is generally a function the pipe diameter, fluid properties (density and viscosity) at the flowing conditions, and average velocity through the pipe. The non-dimensional parameter for those variables is the Reynolds number,

$$Re = \frac{V \times \rho \times D}{\mu} \qquad \text{Equation 2}$$

where,

V = average velocity through the pipe,
ρ = density of the flowing fluid
μ = viscosity of the flowing fluid, and
D = diameter of the pipe.

Within the measurement uncertainty of specific design and size of a DP flowmeter, the discharge coefficient may be relatively constant over a Reynolds number range or vary as a function of flow rate and fluid properties; i.e. the variability of the discharge coefficient of a DP device with a fixed geometry and dimension can often be expressed as a function of the Reynolds number. A Venturi flowmeter demonstrates a fixed Cd value over a limited range of Reynolds numbers, while the orifice flow meter discharge coefficient is expressed, with a specified degree of uncertainty, as a function of the Reynolds number. From a significantly large database of a specific design of DP flowmeter, it may be possible to develop a generalized discharge coefficient equation as a function of line size, geometrical variations in area ratio, and Reynolds number.

Following are some of the desired goals of API MPMS Chapter 22.2:

- Make the users of a DP flowmeter aware of the performance characteristics over the range of Reynolds numbers and DP/P defined by the testing protocol.
- Facilitate the understanding of the new technology utilizing DP measurement.
- Provide a standardized method of validating manufacturer’s performance specifications.
- Provide information to the users to compare relative performance characteristics of different DP meters under a standardized testing protocol.
- Quantify measurement uncertainty of different DP designs in a similar data presentation format.

To achieve these objectives, the standard defines the test limits for the operating conditions of the meter, information to be provided to the test facility before the meter is tested, requirements of the facility performing the test, the testing fluids to be used, the range of pressure, temperature, and differential pressure, a standardized format for the documentation of the test results, system uncertainty, and secondary instrumentation, the Reynolds number range of the test, and other information..

If a DP device is tested over specified range of Reynolds number and meter sizes defined in the standard, any size of that meter 4 inches and greater having dynamic similarity of the tested meter can be installed for fiscal application. If a meter is tested over a limited range of Reynolds number or meter size, that design of flowmeter can only be installed for fiscal measurement within the range over which the meter was tested and the measurement uncertainty was established.

The intent of Chapter 22.2 is not to exclude any differential pressure type device that does not have an applicable API standard. Devices shown in Figure 3 and those discussed earlier in this paper are presented only as examples of different DP devices. The field of application for the testing protocol is limited to devices that are installed for measurement of hydrocarbon fluid in the oil, gas, and petrochemical industries.

There are many parameters that can influence or affect performance of DP type flowmeters. The influence parameters can relate to the fluid properties, flow rate, meter installation, meter design, and other dimensional and manufacturing tolerances that are specific to the meter.

- Influence parameters that relate to the flowing conditions and fluid properties include Reynolds number, fluid density, line pressure, flowing temperature, flow profile entering the meter, and fluid composition for compressibility effect.
- Influence parameters for piping configurations and meter tube dimensions affecting the meter performance are steps and gaps (misalignment) of the pipe, especially in close proximity of the primary element, out of roundness of the pipe, pipe wall roughness, length of straight tube upstream and downstream of the primary element including pipe fittings and piping configuration that may affect the flow profile at the primary element and pressure at the taps.
- Influence parameters depending on the design of the primary element and locations of the pressure sensing ports are important factors affecting the measurement uncertainty and performance of the DP device. Machining tolerances, of pressure tap location, concentricity of the primary element, surface finish are some of the factors that may affect performance of the device. Some of the devices can also be sensitive to the meter orientation.
- In addition to the design of the primary element, combination of different influence parameters may affect measurement uncertainty. Since manufacturing variances can also affect reproducibility of results under the same flowing conditions by two identical meters, additional tests may include measurement reproducibility of dimensionally similar meters by the same manufacturer.

This testing protocol is limited to single-phase Newtonian fluid flows with no significant pulsations that can influence flow rate measurement. The purpose of the standard is to establish the range of application of each design of meter and not to endorse any specific meter.

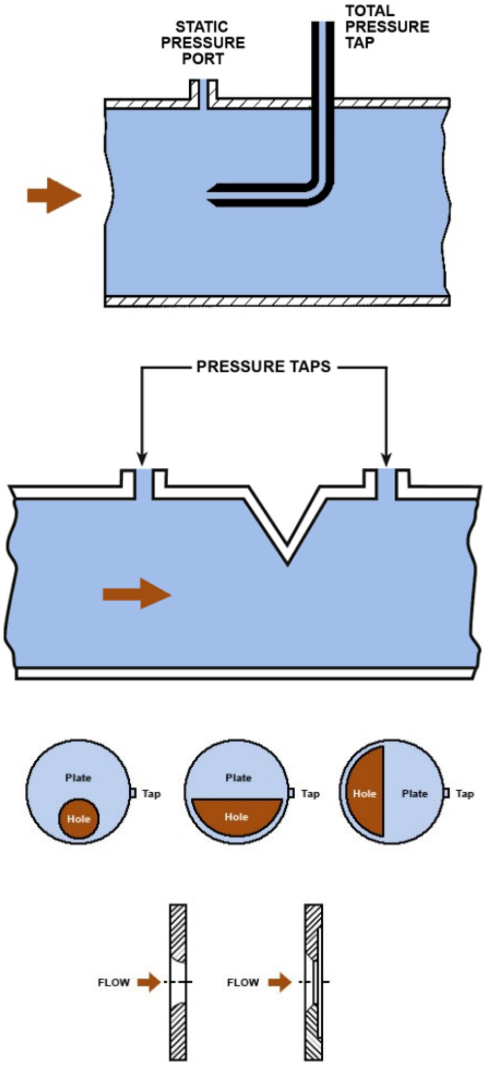

Figure 3: Examples of DP Devices

Required Information from the Meter Manufacturer

Differential pressure meters must be manufactured to certain dimensional tolerances to enable a measurement uncertainty to be determined. The internal dimension and geometry of the meter must be known to establish the area ratio to determine the flow rate. For DP devices not covered by any published standard or not individually flow calibrated, the dimensional tolerances must be specified. For meters that are not individually flow calibrated, Chapter 22.2 outlines additional testing requirements for the meter. Prior to performing the standardized flow test outlined in Chapter 22.2, the following information about the DP meter must be specified, defined, and established for the meter to be tested:

- General Specification of the Meter: Available meter sizes, available area ratios (if applicable), pressure rating (ANSI or DIN), installation method (e.g., flanged or wafer), operating temperature range, pressure tap fittings, temperature probe location, NACE and material specifications, maximum and minimum differential pressure limits, and fluid compatibility, and operating temperature limits,.

- Meter Installation Requirements: Minimum straight pipe length requirements with and without flow conditioner. If applicable, possible increase of measurement uncertainty with less than minimum recommended straight upstream and downstream lengths, tolerance to maximum misalignment of the meter with upstream-downstream piping, limits of the upstream/downstream pipe roundness and surface roughness, etc. and all of which must be established through varifiable experiments,
- Parameters Specific to the Meter: All the dimensional tolerances and limits of the meter, area ratio of the flow restriction, alignment and location of the primary element with respect to the pipe axis and pressure taps, meter orientation and alignment, surface roughness of the meter and primary element, machine finish and tolerance of critical edges, crevises, widths, lengths of the primary element, etc.
- Most importantly, the discharge coefficient and the measurement uncertainty for the meter must be specified prior to performing the standardized test, so that the performance of the meter with respect to its claims can be verified by the test. If the discharge coefficient is defined during the standardized tests at a calibration facility, the test result is applicable to that individual meter only and not for the entire class of dimensionally identical meters offered by the vendor.

A manufacturer may elect to establish and define a set of values or a curve for the dischange coefficient for a specific size and area ratio of their meter as a function of applicable variables. The vendor may also define a generalized discharge coefficient equation for the entire class of their meter as function of the area ratio, line size, Reynolds number, and other applicable parameters. The discharge coefficient and the expected measurement uncertainty must be defined by the vendor prior to performing the standardized test. If a generalized expression for the discharge coefficient value is not established for the full line of meters offered by the vendor, then the results of the standardized test shall be valid only for the size and area ratio of the meter being tested.

Requirements for the Mandatory Tests

For individually flow calibrated meters, it is a good practice to calibrate the meter installed with the upstream-downstream piping configuration of actual installation, including the flow conditioner, if used. If the upstream straight run is the minimum straight run specified by the manufacturer, calibrating the meter with the immediate upstream pipe fitting would capture the effect of possible flow profile distortion caused by the fitting. It is preferred that the meter be calibrated over the entire Re range expected during actual operation.

Meter vendor must provide the flow rate equation with all its variables clearly defined with dimensional units. For meters with one or more variables in the flow rate equation are determined through individual flow calibrations, the method of deriving the variable from calibration data must be clearly stated, including the description and measurement uncertainty of the flow facility where flow calibrations were performed. For the meter to be tested in accordance with the test protocol of Chapter 22.2, values of individually flow calibrated variables must be presented that will include the discharge coefficient of the class of meter being tested.

If the flow rate equation is limited by certain geometrical dimensions, those limits must be stated by the manufacturer and documented in the test report. Expression of the discharge coefficient and expansibility factors specified by the manufacturer must include meter geometries and influence parameters which may have been excluded from testing and that information must be appended to the test report, to allow interpolation during actual operation.

All relevant and necessary information must be provided by the manufacturer to the test facility prior to conducting the test defined by the standard. Meter calibration must be conducted by monitoring the static pressure, flowing temperature, and differential pressure at the locations specified by the meter manufacturer and must be recorded in the test report, including the properties of the test fluid defined for the operating and base conditions. If the meter is calibrated by compressible fluid, the composition and the values and method of determination of expansibility factor for the calibration fluid, must also be recorded in the test report.

After each test, the test meter and its installation must be inspected for any change from the dimensions or conditions from those measured and recorded before the test and if any change is observed, that change must be quantified and recorded in the test report.

Requirements of meter installation and precision of each instrument monitoring process variable (e.g. mass flow rate, differential pressure, flowing pressure and temperature) are specified by the standard. The upstream-downstream piping requirements and mechanical tolerances are also specified for the test.

The Base Line Test

Details of the base line test with a fully developed flow profile approaching the primary element of the meter is specified in the standard. The performance of the meter for the base line test is used as the reference to compare performance of the meter under non-ideal flowing conditions.

Non-Ideal Condition Tests

The standard requires several severe non-ideal installation effect tests to evaluate the performance of the meter for possible worst-case flowing conditions. It is assumed that any “real-world” installation is not likely to have as severe an installation effect as those of non-ideal tests defined in the standard. Hence, it is expected that for any field installation, the performance of the meter would be as good as or better than the performance of the meter for the series of non-ideal tests defined in the standard.

Details of the different non-ideal tests are outlined in the standard. Specific tests to document the meter performance with certain upstream piping and physical flow disturbances are:

- Two closed-coupled long radius out-of-plane 90^0 elbows.
- Simulated asymmetric flow profile by a half-moon orifice plate installed upstream of the meter.
- High swirl at the minimum upstream straight meter tube length specified by the manufacturer.

If the minimum downstream straight run specified by a manufacture is less than 5D, effect of downstream piping disturbance must also be tested. Performance of the meter with a half-moon orifice or half-open gate valve installed at the minimum downstream location specified by the manufacturer is to be compared against the baseline test results and recorded. Details of the requirements and variations in different parameters (e.g. pressure, dimensions of primary element, etc.) for the upstream-downstream flow disturbance tests are also specified. Meters specifying less than 5D downstream of the meter, additional tests are required that would include combined effects of upstream and downstream disturbances.

Detailed requirements of special tests and documentation of testing are specified in the standard. Tests are to be performed at a certified calibration facility traceable to national standard (e.g. NIST certified) or certified third party calibration facility. Data do not have to be published in the public domain, but must be retained for verification or if future test results refute prior claims. The range of meter sizes to be tested is determined by the manufacturer. In all cases, the test results apply to the sizes of meters that are tested.

To document the overall performance characteristics for all meter sizes, area ratios, and the specified Reynolds number range of the meter offered by a manufacturer, a standardized test matrix includes:

- Range of meter sizes to be tested
- Range of Reynolds numbers to be tested
- Range of area ratios to be tested
- Range of pressures to be tested
- Range of fluid velocities to be tested
- For compressible flows, range of the Differntial Pressure to line pressure ratio to be tested.
- Calibration fluids and limits of the test.
- Tests to determine and document measurement uncertainty for the non-ideal upstream-downstream installation effects.

The standard also defines the method of calculating the measurement uncertainty, format of the report, and required information to be included in the report. The minimum requirements for the test facility performing the standardized test including the uncertainties of the test facility and devices/instruments used to perform the test are specified. Test shall not be performed at a facility that does not meet the minimum requirements of uncertainty specified in the standard.

The method and procedure of calculating the measurement uncertainty of the meter from the recorded test data are described in the standard with examples. Standard also defines the format of the required information and test data to be recorded or included in the report. Dimensional parameters for proto-type testing of a flowmeter design is detailed in the normative Annex of the standard.

As mentioned earlier in this paper, there are differential pressure type flowmeters that work in the laminar flow regime based on physical laws of laminar flows relating to Darcy friction factor and Hagen-Pouseulle equation. The standard also addresses testing and reporting of test data for those types of devices.

The standard includes several informative annexes on uncertainty estimates, determination of significance of process variables, how to interpolate measurement uncertainty for intermediate area ratios or line diameters when test data are not available for those sizes or area ratios.

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