Venturi Metering of Natural Gas and Other Related Hydrocarbon Fluids

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API MPMS Ch. 14.XX
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1 Scope

This standard provides a performance-based reference for engineering equations, uncertainty estimations, installation requirements, and standardized implementation recommendations for the calculation of flow rate through concentric differential-pressure-producing Venturi meters.

This standard applies to flow that remains subsonic throughout the measuring section, and where the fluid is Newtonian (the absolute viscosity remains constant for a given temperature, independent of the shear forces applied), can be considered single-phase, and in which the flow is sufficiently free from pulsation effects. It gives information for calculating the flow rate and the associated uncertainty when each of these devices is used within specified limits of beta ratio and Reynolds number.

This standard also defines the testing and reporting standards to provide users with a description of the flow metering capabilities for Venturi meters. The objectives of this standard are:

1. To ensure that the user of a Venturi flow meter knows the performance characteristics of the meter over a range of Reynolds numbers as applicable or defined by tests,
2. To provide a standardized approach for validating manufacturer's performance specifications,
3. To quantify the uncertainty of a given Venturi and define the operating and installation conditions for which the stated uncertainties apply,
4. To provide recommendations for maintenance and specify inspection and calibration requirements over the meter lifetime.

To do so, the testing protocols define test limits for operating conditions of the meter, requirements of the facility or facilities to perform the tests, the fluids to be tested, and requirements for pressure, differential pressure, temperature, secondary instrumentation, and Reynolds number. 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 Venturi meter. A description of required dimensional measurements and tolerances and the mathematical equations required to convert the differential pressure reading to a flow rate estimation are also necessary.

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.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API MPMS Ch. 4.1, Proving Systems - Introduction

API MPMS Ch. 4.2, Proving Systems – Displacement Provers
3 Terms, Definitions, and Symbols

3.1 absolute viscosity (μ)

The measure of resistance to shear per unit of time of a fluid's intermolecular cohesive force.

3.2 beta ratio (β) [Venturi]

The ratio of the Venturi meter throat internal diameter to the internal diameter of the meter tube.
3.3 calibration

A set of operations which establish, under specified conditions, the relationship between the values indicated by a measuring device and the corresponding known values indicated when using a suitable measuring standard.

3.3.1 calibration facility

A flow laboratory used to determine the discharge coefficient of individual meters provided for field use by a manufacturer.

3.3.2 individual flow calibration

Flow testing of every meter that is manufactured in order to determine its discharge coefficient under baseline conditions.

3.4 density ($\rho$)

The density of a quantity of a homogeneous substance is the ratio of its mass to its volume. The density varies as the temperature changes and is therefore generally expressed as the mass per unit of volume at a specified temperature.

3.5 differential pressure ($\Delta P$) (Venturi)

The static pressure difference typically measured between the entrance section and throat taps of a Venturi meter.

3.6 discharge coefficient ($C_d$)

The ratio of the actual flow rate through a primary device to the theoretical flow rate. The theoretical flow rate corresponds to the flow rate without any loss of energy due to friction.

3.6.1 calibrated discharge coefficient ($C_{d\text{ (Venturi)}}$)

The discharge coefficient determined at specific Reynolds numbers and configurations during a flow calibration of the meter under baseline conditions. The calibrated $C_d$ is typically presented as an equation that curve-fits the individual discharge coefficients determined during flow calibration of the
meter or as a fixed value representing the average discharge coefficient determined during flow calibration of the meter.

3.6.2

predicted discharge coefficient (Venturi)

The discharge coefficient determined according to the standard and fabrication method used to construct the Venturi meter, or for proprietary Venturi meter designs the discharge coefficient provided by the manufacturer.

3.7

expansion (expansibility) factor (Υ) (Venturi)

A multiplying factor used to correct the calculated flow rate for the reduction in fluid density that a compressible fluid experiences when it passes through a restriction as a result of the increased fluid velocity and the decreased static pressure.

3.8

flow straightener / conditioner

A length of straight pipe containing straightening vanes or the equivalent that is installed at the inlet of a flow meter to eliminate swirl from the liquid from entering the meter and causing measurement errors.

3.9

flow rate \((q_m, q_w, Q_v)\)

The quotient of a volume or mass of liquid passing a point in a line per unit of time.

3.10

isentropic exponent (κ) (Venturi)

A thermodynamic state property that establishes the relationship between an expanding fluid's pressure and density as the fluid flows through a differential pressure primary element.

3.11

metering package

Assembly which includes the upstream piping, flow straightener/conditioner if applicable, the primary flow device, and the downstream piping section.
3.11.1

**meter pipe length – downstream** (Venturi)

The downstream meter pipe length is the distance from the downstream end of the meter body to the nearest downstream piping disturbance.

3.11.2

**meter pipe length – upstream** (Venturi)

The upstream meter pipe length is the distance from the upstream end of the meter body to the nearest upstream piping disturbance.

3.11.3

**meter run**

The section of piping which includes the upstream flow conditioning section and the downstream flow section.

3.12

**meter tube internal diameter** (D)

The inside diameter of the upstream section of the meter tube.

3.13

**Newtonian fluid**

A fluid whose viscosity does not change with rate of flow.

3.14

**pulsations**

Irregular fluid flow in a piping system resulting from pressure variations.

3.15

**pressure loss**

The differential pressure in the flowing fluid stream (which will vary with flow rate) between the inlet and the outlet of a meter, flow straightener, valve, strainer, lengths of pipe, etc.

3.16

**pressure tap**

A hole radially drilled in the wall of the meter tube, perpendicular to the centerline of the meter tube, the inside edge of which is flush, without burrs, and as sharp as possible.
3.17
primary device
The primary device is the component of the meter that causes the fluid to accelerate or decelerate, thereby creating a measurable and predictable pressure drop in response to flow rate.

3.18
Reynolds number \((Re)\)
The ratio of the inertial forces to the viscous forces of the fluid flow. This non-dimensional parameter is defined as:

\[
Re = \frac{VDp}{\mu}
\]

3.18.1
pipe Reynolds number \((Re_D)\)
The Reynolds number within the meter pipe or meter body.

3.18.2
throat Reynolds number \((Re_d)\)
The Reynolds number within the meter throat.

3.19
secondary devices
Devices used to produce data such as, but not limited to, static pressure, temperature, differential pressure, relative density, and other variables used to calculate flow rate.

3.20
static pressure \((P_f)\)
Pressure in a fluid or system that is exerted perpendicular to the surface on which it acts. In a moving fluid, the static pressure is measured at right angles to the direction of flow.

3.21
subsonic flow
Flow which occurs at a rate lower than the speed of sound.
3.22

swirl

A qualitative term describing tangential motions of liquid flow in a pipe, tube, or tank.

3.23

thermowell

A metal protective socket installed in the well or shell of a liquid container into which the sensing element of a temperature sensing device is inserted.

3.24

throat diameter \((d)\)

The internal diameter of the throat section of a Venturi meter.

3.25

uncertainty

Describes the range of deviation between a measured value and the true value, expressed as a percentage. For example, a device with an accuracy of 2 % would have an uncertainty of ±2 %.

3.26

Venturi meter

A fluid flow measuring device which produces a differential pressure to infer flow rate. The primary element consists of a cylindrical entrance section, converging conical section, a concentric cylindrical section called the throat, and a diverging conical section. The restriction produces a pressure differential measured through taps on the upstream section and throat section.

3.26.1

Herschel (classical) Venturi meter

A Venturi meter design specified in industry standards which define the specific geometry, fabrication methods, and tolerances required to produce a Venturi meter with a specified discharge coefficient within a defined uncertainty.

3.26.2

proprietary Venturi meter

A Venturi meter design specific to a manufacturer. Proprietary Venturi meter designs may differ in geometry compared to the Herschel Venturi meter, but should be constructed using the fabrication methods and tolerances defined by Herschel Venturi meter standards.
4 Venturi Meter Principle of Operation

A Venturi meter is a fluid flow measuring device which produces a differential pressure to infer flow rate. The primary element consists of a cylindrical entrance section, converging conical section, a concentric cylindrical section called the throat, and a diverging conical section. The restriction produces a pressure differential between the upstream section and throat section. The differential pressure is measured across pressure taps located on the inlet and throat sections.

![Figure 1 - Venturi Flow Meter](image)

The Venturi meter beta ratio is defined as the ratio of the internal diameter of the throat to the internal diameter of the entrance section.

The design of a Venturi meter is intended to reduce the permanent pressure loss across the device. The gradual changes in diameter and diverging outlet section allow for significant pressure recovery downstream of the throat.

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

This standard defines the uncertainty of a Venturi meter measurement based upon a defined calibration and testing protocol, rather than empirical data dependent upon the meter design and fabrication tolerances. A Venturi meter shall be calibrated according to the procedures described in this standard in order to demonstrate it meets the specified uncertainty over the entire operating range.

The most common Venturi meter design is the Hershel or classical Venturi meter, which is specified in industry standards ASME MFC-3M and ISO 5167-4.

However, many supplier-specific variations to the Hershel Venturi meter design are possible. A proprietary Venturi meter design is considered within the scope of this standard if the following criteria are met:
• the inlet convergence section is designed as to not affect the relationship between the throat Reynolds number and discharge coefficient,
• the throat section length is appropriate to not be effected by either the convergence or divergence sections,

If calibration according to the procedures described in this standard demonstrates the Venturi meter meets the criteria above, the static throat tap prediction formula is valid.

Venturi meters may be fabricated using various methods including casting, machining, and welding. The method of construction is dependent on the Venturi meter size and metallurgy. The meter shall be fabricated to meet the regulatory or code requirements of the adjacent piping and the tolerances listed in ASME MFC-3M and ISO 5167-4.

See ASME MFC-3M and ISO 5167-4 for recommendations related to the pressure tap size, location, circularity, and edge sharpness. Supplier-specific variations to this criteria are considered within the scope of this standard if calibration of the Venturi meter determines the performance meets the specified uncertainty over the entire operating range.

A differential pressure measurement device shall be installed across the pressure taps, typically using lengths of piping or tubing. A minimum of two upstream and two throat taps are recommended on the Venturi meter. The multiple upstream pressure taps are piped together and the multiple throat taps are piped together to achieve an average measurement. Typical configurations are referred to as “Triple-T” or piezometer rings. Additional pressure taps may be installed if required.

6 Method of Calculation

See API MPMS Chapter 14.3.1 Section 6 for fundamental equations describing the calculation of flow using a differential pressure measurement device, including the mass flow rate, volumetric flow rate, and volumetric flow at base (standard) conditions. This section includes equations used to calculate coefficients and terms in the mass flow rate equation.

The equations in API MPMS Chapter 14.3.1 Section 6 may be applied to Venturi meters. However, the expansibility factor for Venturi meters operating in compressible fluids shall be determined based on the isentropic expansion factor. Refer to ISO 5167-4 for the expansion factor equation based on the isentropic exponent.

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

The discharge coefficient of a Venturi meter is generally a function of the meter geometry and the throat Reynolds number. The relationship between the throat Reynolds number and discharge coefficient of a Venturi meter shall be determined by laboratory calibration prior to initial installation. See Section 12 of this standard for details regarding acceptable flow calibration procedures.

8 Flow Conditions

Flowing conditions can influence field accuracy, therefore certain flow condition limitations have to be followed to assure accuracy within the required uncertainty:

1) The flow shall approach steady-state mass flow conditions on fluids that are considered clean, single phase, homogeneous, Newtonian;
2) The fluid shall not undergo any change of phase as it passes through the flow meter;
3) The flow shall be subsonic through the flow meter;
4) The pipe Reynolds number shall be greater than 200,000;
5) The beta ratio shall be within the range 0.3 to 0.75;
6) No bypass of flow around the flow meter shall occur at any time.
7) The flow shall be free from pulsations as per the definition and equation in API MPMS Chapter 14.3.2 section 2.6.4

9 Installation

The installation and orientation of a Venturi meter may affect the performance, therefore the following practices should be followed to minimize these effects.

It is recommended for the diameter and schedule of the adjacent pipe to be the same nominal diameter as the Venturi meter. To avoid installation effects, see Section 10 for the recommended length of straight, interrupted piping upstream and downstream of the meter.

The meter shall also be installed so that gaskets do not protrude inside the pipe.

The meter shall be properly supported to reduce any effects of vibration and pipe stress.

For horizontal piping, the preferred orientation for the Venturi meter is with the pressure taps at the horizontal centerline. Other tap orientations are possible, however, installations with the pressure taps greater than 45 degrees below the meter centerline are not recommended as this increases potential for plugging. In liquid service, the pressure taps shall also be oriented to remain liquid-full.

The location of secondary devices such as static pressure, temperature, and density may affect the overall uncertainty of the measurement. See Section 14 for recommended installation of secondary devices.
10 Meter Run

In order to assure a Venturi meter produces a measurement within the specified uncertainty, the fluid should enter the Venturi meter with a fully developed flow profile, free from swirl or vortices. Such a condition is best achieved through the use of adequate lengths of straight pipe preceding and following the Venturi meter or a flow straightener/conditioner.

The meter run is defined as the straight and uninterrupted pipe upstream and downstream of the meter, into which the meter is mounted in the test facility and in the field. The meter run includes the flow straightener/conditioner, if used.

Flow straighteners/conditioners are devices that effectively remove or reduce the swirl component of a flow stream. Specifications for the description, installation, or uncertainty of flow straighteners/conditioners are not included in this standard. These devices should be specified as required based on calibration or sufficient performance test data provided by the manufacturer.

It recommended to calibrate a Venturi meter as an assembly including the meter run in order to determine the effect of the upstream and downstream piping configuration on performance. If it is not possible to calibrate the meter according to this method, the following applies.

For the Herschel or classical Venturi meter design, refer to the straight length requirements in ASME MFC-3M and ISO 5167-4. The meter run shall meet the requirements for surface roughness and concentricity defined in these standards. If the required straight length is not available, a flow straightener or conditioner should be considered.

For proprietary Venturi meter designs, the manufacturer’s straight length requirements should be consulted and substantiated with sufficient calibration test data to ensure the assembly meets the specified performance criteria. If manufacturer’s recommendations are not available, the straight length requirements for the Herschel Venturi meter design described in ASME MFC-3M and ISO 5167-4 may be used as a reference only. However, proprietary Venturi meter designs may not meet the specified uncertainty if the installation effects are not known or validated with sufficient testing.

11 Flow Calibration

The relationship between the throat Reynolds number and discharge coefficient of a Venturi meter shall be determined prior to initial installation by calibration in a flow testing or calibration facility.

The flow testing or calibration facility shall be certified to the appropriate standards, and be traceable to recognized national metrology standards. If the flow calibration facility is owned and operated by the manufacturer rather than an independent, unaffiliated facility, it should be independently verified according to the protocol described in API MPMS Chapter 22.2
A meter shall be calibrated with the same phase fluid (liquid or gas) that corresponds with its intended use. Typically water, air, or natural gas is utilized as the calibration fluid. Calibration with an alternative fluid is acceptable where transferability to the process fluid has been demonstrated.

Refer to API MPMS Chapter 22.2 Section 6 for acceptable laboratory calibration methods.

In order to accurately determine the performance of a Venturi meter, it is recommended to perform a baseline calibration in a flow lab with a piping configuration replicating the field installation, including the associated metering package as applicable. If it is not practical to reproduce the piping configuration in the field in the calibration facility, additional installation effects testing may be necessary. See API MPMS Chapter 22.2 Section 6.5 for recommended installation effects testing procedures.

Venturi meters shall be calibrated over the full operating Reynolds number range of the application. In some cases it may not be practical to calibrate a Venturi meter over the entire operating range of Reynolds numbers due to limitations of available calibration facilities such as line size, flow rate, or process fluid conditions. The decision to use the meter beyond the calibrated range may be considered. However, the uncertainty of the measurement can significantly increase depending on the size and condition of the meter, as well as the extent the Reynolds number range is extrapolated past the calibrated range.

Refer to ASME PTC 19.5 for an example procedure to extrapolate meter performance beyond the calibrated range. Using this method, the dependence of the discharge coefficient on the throat Reynolds number is determined within the range the meter was calibrated, and the data is characterized using a linear regression. If the 95% confidence interval of the slope is greater than the absolute value of the slope, the calibration data may be accepted for extrapolation. The uncertainty of the extrapolation is heavily dependent on the calibrated range, so this range should be as large as feasible to reduce the uncertainty.

The calibration data shall be compared to the expected discharge coefficient as described in ASME MFC-3M and ISO 5167-4, or the discharge coefficient specified by the supplier for proprietary Venturi meter designs. Any significant deviations beyond three standard deviations between the designed and calibrated discharge coefficient shall be investigated to identify potential sources of error.

Records should be provided which include the method used to individually calibrate each meter, the uncertainty of the calibration facility, the calibration fluid, the procedure used to determine the discharge coefficient, the range of throat Reynolds numbers and other conditions (e.g. temperature, pressure, and density at each flow rate), a description of the installation configuration(s), the serial number of the meter, and the name and location of the calibration facility.

Refer to Annex B for a sample test report form.
12 Uncertainty of Measurement

Many factors influence the overall measurement uncertainty associated with a metering application. Major contributors include uncertainty of flow calibration, predictability of and variations in the fluid’s physical properties, and uncertainties associated with the secondary devices.

Using the guidelines contained in this standard and other relevant industry standards in combination with the associated uncertainty tolerances for the fluid’s physical properties, the discharge coefficient as determined by calibration, and the appropriate secondary devices, the user can define the overall measurement uncertainty associated with the Venturi meter assembly.

See Section 9 of this standard for limitations placed on the flow conditions in order to ensure the Venturi meter assembly meets the specified uncertainty. It is recommended to limit application of this standard to Venturi meters with beta ratios in the range of 0.30 to 0.75 and pipe Reynolds numbers greater than 200,000, based on ASME MFC-3M and ISO 5167. The measurement uncertainty increases for pipe Reynolds numbers less than 200,000, however the uncertainty may be acceptable for the application and should be determined by calibration.

The flow calibration data shall be evaluated to determine the uncertainty, which includes the calibration facility uncertainty and uncertainty associated with the method used to determine the meter discharge coefficient. A statistically significant data set of at least 20 data points shall be collected in order to determine the uncertainty of the Venturi meter discharge coefficient. The data shall be analyzed to determine the deviation at each point between the meter performance and reference value. See PTC 19.5 Appendix 1 for a sample procedure used to evaluate the uncertainty of a flow calibration data set and deviation of the linear regression fit. Other methods of determining meter uncertainty may also be acceptable. The uncertainty calculation procedure, if different from the sample calculation method, shall be clearly described in the test report.

The confidence interval of the deviations at the 95 % confidence interval should not exceed 0.03 % for a typical well-constructed meter and qualified flow laboratory. If this confidence level is not achieved with 20 calibration points, it may be possible to achieve the requirement by collecting additional calibration points.

See Annex A for a sample analysis of Venturi meter calibration data and uncertainty.

13 Differential Pressure Device

Performance specifications for the differential pressure device shall be provided by the manufacturer. The user shall select a device based on its performance specifications and the required uncertainty. When considering the uncertainty, care should be taken to take into account the effects of ambient temperature, humidity, static pressure, driving mechanism, and response time of the user selected device.
14 Secondary Devices

Refer to API MPMS Chapter 21.1 or 21.2 as appropriate for procedures regarding the use of secondary devices in order to accurately calculate the mass flow rate through the Venturi meter.

Static pressure shall be measured, and the preferred location of the pressure tap location is at the downstream flange tap of the Venturi meter. The static pressure may also be measured at a separate connection within 5 pipe diameters upstream or downstream of the Venturi meter throat pressure tap.

A temperature device should be located to sense the average temperature of the fluid at the Venturi meter. It is recommended to insert the temperature sensing device in the flowing stream within a thermowell. The preferred temperature sensing location is within 5 to 20 pipe diameters downstream of the Venturi meter throat pressure tap. The temperature sensing location shall also be at least 2 pipe diameters downstream of the Venturi meter end connection.

Care should be taken to ensure the temperature sensor indicates the fluid temperature and is not thermally coupled to the meter run pipe.

Insulation of the meter and meter run may be required in the case of extreme temperature differences between the ambient temperature and the temperature of the flowing fluid and/or fluids being metered near their critical point, where small temperature changes may result in major density changes. This can be critical at low flow rates, where heat transfer effects may cause not only distorted temperature profiles, but also a change in the mixed mean temperature values from the upstream to the downstream side of the meter run, and changes to the mean velocity profile.

15 Fluid Density

When an empirical correlation is used to predict a fluid density, the uncertainty should be estimated based on the stated uncertainty of the correlation and the estimated uncertainty of the variables required to calculate the density. If density is measured directly, the associated uncertainty is that of the device.

16 In-situ Calibration

For liquid applications, reference API MPMS Chapter 4 for acceptable in-situ calibration methods and prover systems.

For gas applications, reference API MPMS chapter 14.3.1 for an example procedure for in-situ calibration. For in-situ calibration in gas, AGA Report # 6 also includes acceptable procedures.
17 Maintenance

Achieving the specified meter performance requires regular maintenance of the Venturi meter, differential pressure transmitter, and other metering system components. Maintenance of the differential pressure transmitter and other system components is not directly covered in this standard.

Due care shall be exercised to keep the Venturi meter internals clean and free from accumulation of coating, build-up, and other extraneous materials to the extent feasible by implementing a regular inspection schedule, as determined by the service conditions. Damage or accumulation of extraneous materials inside the Venturi meter may result in a greater uncertainty for the discharge coefficient. Based upon the inspection, the Venturi meter manufacturer may be contacted to determine the potential effects on performance, and recommended procedure to clean and/or service the meter.

To allow for regular inspection of the Venturi meter internals, it is recommended to install the meter with at least one flanged connection to enable access. If a bypass is installed to enable inspection, the valves used to shut off main flow should be positive closing to ensure no leakage across the valve. Note for custody transfer or regulatory applications bypass piping may not be permitted. See Annex C for Venturi meter inspection guidelines.

If the Venturi meter is removed for cleaning or other purposes, it should be calibrated or proven in the field as soon as practical. If the Venturi meter does not perform within the specified uncertainty as determined by calibration or proving, it should be reconditioned if possible or replaced.

18 Auditing and Reporting Requirements

The metering system shall conform to the auditing and reporting requirements listed in API MPMS Chapter 21.1 or 21.2 as appropriate.
ANNEX A (Informative) — VENTURI METER CALIBRATION DATA

A representative sample of calibration data reflecting the performance of a Venturi meters in liquid and gas service has been collected by the ASME PTC 19.5 standard committee and is shared by permission with API. (Hold for reference)

The following sections compare Venturi meter measured to calibrated results and discuss typical uncertainties using the calibration procedures described in this standard. The analysis also compares measured to predicted results for Hershel or classical Venturi meters constructed according to industry standards ASME MFC-3M and ISO 5167-4.

A.1 Venturi Meter Liquid Calibrations

The calibration data for Venturi meters in liquid service is based on water calibrations from two independent certified flow calibration laboratories. These calibrations represent over 70 Venturi meters ranging in line sizes from 3” to 52”.₁ (Hold for water calibration reference)

The Venturi meters in this study were fabricated according to ASME MFC-3M and ISO 5167-4 standards for Herschel or classical Venturi meters. These standards define the discharge coefficient for Venturi meters constructed to the specified criteria. Please note, the fabrication method was not recorded for Venturi meters in this study, so the predicted discharge coefficient is based on the assumption the majority of Venturi meters were machined as typical for the size range. Also, the throat diameter was not measured, so there may be minor variations between the as-designed and as-built throat diameter.

Figure 3 compares the measured discharge coefficient to the discharge coefficient predicted by standards. The measured discharge coefficient agrees with the predicted discharge coefficient defined in ASME MFC-3M and ISO 5167-4 within the uncertainty stated in these standards with one exception. This discrepancy may be due to assumptions made regarding meter fabrication methods and throat diameter.
For the Venturi meter liquid calibrations, the relationship between the discharge coefficient and the throat Reynolds number was determined according to the linear regression fit methodology described in ASME PTC 19.5. The data has been analyzed to determine the deviation at each point between the measured discharge coefficient and discharge coefficient determined by the linear regression calibration equation.

Figure 4 indicates the typical percent deviation between the measured discharge coefficient and calibrated discharge coefficient that can be expected for a Venturi meter calibrated in a liquid flow lab with an uncertainty of ±0.25 %. However, the uncertainty associated with the discharge coefficient for each meter should still be determined based on its individual calibration.
A.2 Venturi Meter Gas Calibrations

The calibration data for Venturi meters in gas service is based on over 70 Venturi meter calibrations conducted in air service at CEESI.

The Venturi meters in this study were fabricated according to ASME MFC-3M and ISO 5167-4 standards for Herschel or classical Venturi meters. These standards define the discharge coefficient for Venturi meters constructed to the specified criteria. Please note, the fabrication method was not recorded for Venturi meters in this study, so the predicted discharge coefficient is based on the assumption the majority of Venturi meters were machined as typical for the size range. Also, the throat diameter was not measured, so there may be minor variations between the as-designed and as-built throat diameter.

Figure 5 compares the measured discharge coefficient to the discharge coefficient predicted by standards.
In the technical paper describing the CEESI gas calibration findings\(^2\), Venturi meters were divided into four categories based on performance and agreement with the predicted discharge coefficient defined in ASME MFC-3M and ISO 5167-4. Venturi meters categorized as “Type A” agree with the predicted discharge coefficient defined in these standards within the stated uncertainty. For Venturi meters categorized as “Type B”, the majority of the measured discharge coefficients agree with the predicted discharge coefficient within the stated uncertainty. For “Type C” and “Type D”, the calibrated discharge coefficient does not match the predicted discharge coefficient within the uncertainty defined in these standards.

This discrepancy may be partially attributed to assumptions made regarding the meter fabrication method and throat diameter. To compensate for the effect of this uncertainty in the actual throat diameter, this study shifted the measured discharge coefficients to align more closely with ISO and ASME standards.

Venturi meters categorized as “Type A” and “Type B” reflect Venturi meters which may be suitable for custody transfer applications, depending on the application requirements. “Type C” and “Type D” represent Venturi meters with higher uncertainty, likely associated with less precise fabrication.

The gas calibration data demonstrates minor deviations in construction, such as pronounced weld beads and weld seams or greater internal surface roughness, have a greater impact on Venturi meter performance in gas than in liquid service. These findings also highlight the importance of calibrating
Venturi meters across the entire operating range of Reynolds numbers in order to define Venturi meter performance, especially in gas service.

Figure 6 - Venturi Meter Gas Calibrations Classified as Type A

Figure 7 - Venturi Meter Gas Calibrations Classified as Type B
The calibration data also demonstrates a phenomena specific to certain Venturi meter designs operating in gas service. For many Venturi meters, the relationship between the throat Reynolds number and discharge coefficient is linear across the entire calibrated range of Reynolds numbers. However, some Venturi meter calibration data shows a noticeable “transition hump” between the linear, transition, and
turbulent flow ranges. In these cases, the relationship between the throat Reynolds number and discharge coefficient may be described by a different linear regression equation in each flow regime. The presence of a “transition hump” is thought to be caused by the formation of a boundary layer at the Venturi meter throat which affects certain Venturi meter designs.

**Figure 10 - Venturi Meter Gas Calibration with a Large Transition Hump**

**Figure 11 - Venturi Meter Gas Calibration without a Large Transition Hump**
For the Venturi meter gas calibrations, the relationship between the discharge coefficient and the throat Reynolds number has been determined according to the linear regression fit methodology described in ASME PTC 19.5. The data has been analyzed to determine the deviation at each point between the measured discharge coefficient and discharge coefficient determined by the linear regression calibration equation.

Figure 12 indicates the typical percent deviation between the measured discharge coefficient and calibrated discharge coefficient that can be expected for a Venturi meter calibrated in a gas flow lab with an uncertainty of ±0.5 %. However, the uncertainty associated with the discharge coefficient for each meter should still be determined based on its individual calibration.

![Figure 12 - Venturi Meter Gas Percent Deviation \( C_d \) Measured / \( C_d \) Calibrated](image)

A.3 Conclusions

The collected calibration data highlights the importance of calibrating Venturi meters across the entire operating range of throat Reynolds numbers to verify performance and measurement uncertainty, rather than relying on predicted performance according to standards. The data also demonstrates the
majority of well-constructed Venturi meters calibrated at an accredited flow calibration laboratory according to the process defined in this standard are capable of producing flow measurement within an acceptable uncertainty.

Figure 13 compares selected Venturi meter liquid and gas calibration data (Type A and B) with discharge coefficients compensated for unknowns regarding the actual throat diameter. This analysis demonstrates Venturi meters operating in both liquid and gas service are typically linear for pipe Reynolds numbers above 200,000. Venturi meter uncertainty increases significantly below pipe Reynolds number below 200,000 based on the collected data, as well as ASME MFC-3M and ISO 5167-4 industry standards. In order to meet the requirements of this standard, it is recommended to operate above a pipe Reynolds number of 200,000. Venturi meters may be operated at lower Reynolds numbers only if calibration determines the meter meets the required uncertainty in this range.

![Figure 13 - Venturi Meter Liquid and Gas Comparison](image)

Using the methods outlined in this standard, Venturi meter performance can be accurately defined within the calibrated range and may be suitable for custody transfer of liquid or gas, depending on the application requirements. Venturi meter performance shall only be extrapolated beyond the calibrated range with caution, as the uncertainty may increase significantly depending on the size and condition of the meter, as well as the Reynolds number range.
ANNEX B (Normative) — SAMPLE CALIBRATION TEST REPORT

B.1 General

The raw data and test condition records of all tests, attested or certified by the test facility, if tests are performed at a third-party facility, shall be retained for future reference by the manufacturer of the device for verification if any of the reported results or computations is questioned at a later date. If a specific test report is not published in the public domain and is not available for verification of any claims based on that data will be deemed unverifiable.

To facilitate comparison between meters, all tests shall be reported in the following set format. Proof of the test facility’s uncertainty shall be presented in the report. The result of the tests should be reported in tabular and graphical form, including results of the baseline tests, gas expansion factor equation tests, and installation effects or special installation tests, if applicable.

The test report shall contain the following information.

B.2 Test Facility Information

- Name and location of the test facility
- Date and time of test
- Fluid(s) used
- Differential pressure, static pressure, and temperature transmitter manufacturer, model number, and uncertainty. Copies of the calibration certificates shall be included for all transmitters.
- Surface roughness of the upstream and downstream pipes shall be recorded.
- If a densitometer is used, the model number, uncertainty, and calibration certificates shall be included.

B.3 Calibration Facility Information

- Name and location of the facility performing the individual flow calibrations for each meter
- Date and time of the test
- Fluid(s) used
- Type of test performed (e.g. weigh tank, flow nozzle, master meter)
- Description and specifications of all equipment used in the flow calibration (e.g. make, model, uncertainties, calibration certificates)
- Surface roughness of the upstream and downstream meter pipes shall be recorded
- If a densitometer is used, the model number, uncertainty, and calibration certificates shall be included
- A description of how the data collected is used to establish the discharge coefficient for each meter

B.4 Meter Information

- Name of the meter manufacturer
- Type/Name/Description of the meter
- Meter serial number and model number
- Nominal size of meter and piping
- Meter and piping schedule with pressure rating
- Meter geometry and critical dimensions (drawing of meter)
- Manufacturer’s predicted discharge coefficient; this may be a constant value or an equation
- 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 expansion equation (including the limitations for DP/Pf), the discharge coefficient equations and the flow rate equation, when applicable.

B.5 Description of the Full Test Matrix and Results

- Clear indication of test type (e.g. “baseline”)
- Manufacturer’s required upstream and downstream piping and actual installed lengths
- Meter orientation (i.e. horizontal or vertical)
- Specific test conditions, including pressures, temperatures, flow rates, differential pressures, and fluid properties
- Table of results, including estimates of uncertainty in measurement parameters
- Test summary, including the meter uncertainty determined from the baseline testing, all test conditions for which the stated uncertainty is valid, and if applicable, the conclusions from the statistical analysis comparing the baseline tests and the installation effects tests
- Meter asymmetry with respect to the orientation of the upstream and downstream disturbances
- The maximum velocity, DP, and DP/Pf for each set of meter tests
- The laboratory should record the presence of excessive noise from the meter, if noted during the baseline testing of the meter
- The results of any specific installation testing, if applicable

B.6 Sample Meter Test Reporting Form

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Nominal Size: 4</th>
<th>Nominal Beta Ratio: 0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Piping:</td>
<td>40D upstream with flow conditioner at 10D, 10D downstream</td>
<td></td>
</tr>
<tr>
<td>Minimum Piping per Manufacturer:</td>
<td>10D upstream, 2D downstream, No flow conditioner required</td>
<td></td>
</tr>
<tr>
<td>Orientation:</td>
<td>Horizontal</td>
<td></td>
</tr>
<tr>
<td>Test Fluid:</td>
<td>Air</td>
<td></td>
</tr>
<tr>
<td>Serial No.:</td>
<td>02181982</td>
<td></td>
</tr>
<tr>
<td>Meter type:</td>
<td>Super-meter 1000</td>
<td></td>
</tr>
<tr>
<td>Actual ID:</td>
<td>4.026</td>
<td></td>
</tr>
<tr>
<td>Actual Beta Ratio:</td>
<td>0.3502</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>Q (scf/hr)</th>
<th>DP (in H2O)</th>
<th>P (psia)</th>
<th>T (°F)</th>
<th>DP/P</th>
<th>Throat Reynolds Number</th>
<th>From Testing</th>
<th>Predicted</th>
<th>Δ</th>
<th>Δ%</th>
<th>Uncertainty (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.19</td>
<td>402</td>
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<td>0.0002</td>
<td>50,251</td>
<td>0.7451</td>
<td>0.7481</td>
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<td>-0.3993</td>
<td>±1.1411</td>
</tr>
<tr>
<td>2</td>
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<td>4.26</td>
<td>411</td>
<td>66</td>
<td>0.0037</td>
<td>250,574</td>
<td>0.7803</td>
<td>0.7803</td>
<td>0.0000</td>
<td>0.0007</td>
<td>±0.6050</td>
</tr>
<tr>
<td>3</td>
<td>38,239</td>
<td>13.50</td>
<td>398</td>
<td>64</td>
<td>0.00122</td>
<td>449,533</td>
<td>0.7998</td>
<td>0.7924</td>
<td>0.0074</td>
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<td>396</td>
<td>67</td>
<td>0.00256</td>
<td>651,015</td>
<td>0.8052</td>
<td>0.8001</td>
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<td>0.6365</td>
<td>±0.5850</td>
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<tr>
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<td>0.8057</td>
<td>-0.0056</td>
<td>-0.7022</td>
<td>±0.5845</td>
</tr>
<tr>
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<tr>
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<td>±0.5837</td>
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<tr>
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<td>0.8171</td>
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<tr>
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<td>-0.2498</td>
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</tr>
<tr>
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<td>0.8176</td>
<td>0.8223</td>
<td>-0.0047</td>
<td>-0.5753</td>
<td>±0.5814</td>
</tr>
</tbody>
</table>
ANNEX C (Informative) — VENTURI METER INSPECTION GUIDELINES

The following outline is intended to provide guidelines for preparing a Venturi meter inspection checklist. The outline is provided so that uniformity may be achieved in what is to be inspected. The format of the checklist is left to the user, according to preference. Although all the items listed may not be required at every inspection, the checklist should provide the pertinent information.

Note that the outline may not include all of a particular user’s required information. The minimal information specified in the outline provides a basis for evaluating the quality of the meter run and Venturi meter at the time of inspection.

I. Header
   a. Company name
   b. Date of inspection
   c. Meter location
   d. Flow direction
   e. Names of inspector(s) and witness(s)
   f. Any other information required

II. General Information
   a. Serial number
   b. Nominal pipe diameter
   c. Fluid measured: gas or liquid (specify name)
   d. Beta ratio limitations

III. Meter Run
   a. Manufacturer
   b. Serial number
   c. Straightening vanes? Yes or no; if yes:
      i. Type of vane
      ii. How fastened? Pinned, welded, or flanged
      iii. Dimensions
   d. Meter run type: single tube or multiple tube
   e. Nearest upstream disturbance
   f. Dimensional data:
      i. Length
      ii. Upstream and downstream diameters (at least four measurements at each location):
         1. Upstream pressure tap (also calculate the average of these values)
         2. Downstream pressure tap
         3. First pipe connection
         4. Second pipe connection
   g. Temperature of meter at time of measurement
h. Meter run quality: cleanliness and roughness upstream and downstream
i. Average tube inside diameter at 68°F, as stamped on pipe or nameplate
j. Inside tube diameter used in flow computer, for calculations and data processing

IV. Pressure Taps
   a. Orientation of primary differential pressure transducer connection (looking from inlet to outlet of meter tube)
   b. Location of static pressure transducer connection: upstream, downstream, or none
   c. Number of differential pressure connections
   d. Pressure tap size
   e. Manifold: manufactured or fabricated on site; full bore or restricted bore; three valves, five valves, or other
   f. Gauge line length

V. Other Instrumentation
   a. Measurement data on other tap connections made to the meter tube: size, location, and orientation
   b. Temperature sensor: type and location
   c. Densitometer: manufacturer and type; insertion or sample line; size; inlet or outlet location
   d. Sampler: manufacturer and type; sample line size; inlet or outlet location
   e. Composition/energy analyzers: type; sample line size; inlet or outlet location

VI. Venturi Fitting Leak Test (After Hydrostatic Testing)
   a. Measurement of seat width
   b. Measurement of seal width
   c. Difference between a and b above
   d. Results of pressure tap leak test
   e. Results of plate bypass leak test
   f. Type of seal and material of construction

VII. Venturi Meter Inspection
   a. Material of construction
   b. Manufacturer
   c. Any surface film patterning?
   d. Micrometer measurement of at least four inside diameters of the meter bore
   e. Average value of the measurements in d above
   f. Other data pertinent for identification
   g. Temperature at which meter was measured
   h. Names of inspector(s) and witness(es) and date, if not the same as for meter run
Bibliography

Venturi Meter Calibration Studies

1 Hold for reference for water calibration data