Manual of Petroleum Measurement Standards Chapter 5.8

Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters

THIRD EDITION, XXXX

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Introduction

This standard is intended to describe methods to achieve custody transfer measurement requirements, including accuracy, when an ultrasonic meter is used to measure liquid hydrocarbons. Ultrasonic meters measure flow rate. It is recognized that meters other than the types described in this document are used to meter liquid hydrocarbons.

This publication does not endorse or advocate the preferential use of an ultrasonic meter nor does it intend to restrict the development of other types of meters. Those who use other types of meters may find sections of this publication useful.

1.0 Scope

1.1 Equipment

This document describes the application, performance, and operation of multipath ultrasonic transit-time flow meters (UFM) used for the measurement of liquid hydrocarbons. Multipath ultrasonic meters have at least two independent pairs of measuring transducers (acoustic paths). Applications may include, but not limited to, the dynamic measurement of liquid hydrocarbons flow through production facilities, transmission pipelines, storage facilities, distribution systems and by end-use customers.

1.2 Field of Application

The field of application of this standard is the dynamic measurement of single-phase liquid hydrocarbons. While this document is specifically written for custody transfer measurement, other acceptable applications may include allocation measurement, check meter measurement, and leak detection measurement. This document only pertains to spool type, multi-path ultrasonic flow meters with permanently affixed acoustic transducer assemblies.

2.0 Normative References

There are no reference documents that are indispensable for the application of this document.

3.0 Terms and Definitions

For the purposes of this document, the following definitions apply. Terms of more general use may be found in the API *MPMS* Chapter 1 Online Terms and Definitions Database.

3.1 Accuracy
The closeness of agreement between a measured quantity value and a true quantity value of a measurand.

3.2 Ultrasonic path
The path that the acoustic signals follow as they propagate through the measurement section between the acoustic transducer elements.

3.3 Ultrasonic transducer
A component that produces either an acoustic output in response to an electric stimulus and/or an electric output in response to an acoustic stimulus.

3.4 As-left Verification

An As-left verification is performed at multiple flow rate points at the calibration lab after the meter has been repaired and / or adjusted, against the lab reference standard.

3.5 Axial flow velocity

The component of liquid flow velocity at a point in the measurement section that is parallel to the measurement section's axis and in the direction of the flow being measured.

3.6 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.

3.7 Calibration Coefficients

Calibration Coefficients, also known as Calibration Factors, are corrections applied in the meter electronics to obtain a meter output matching that of the reference standard.

3.8 Flow-conditioning element

A device for reducing swirl and velocity distortions.

3.9 Error

Measured quantity value minus a reference quantity value.

NOTE Since a true value cannot be determined, in practice, a conventional true (or reference) value is used.

3.10   Flow meter body

The pressure-containing section of the meter where the liquid velocity flow measurement is determined.

3.11   K Factor

The number of pulses generated by the meter per gross unit volume.

3.12   Uncertainty

Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

3.13   Meter run

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

3.14   Pulse scaling

Scaling performed in the SPU so that the meter produces a set number of pulses proportional to volume.

3.15   Repeatability

Measurement precision under a set of repeatable conditions of measurement.

3.16   Reproducibility

Measurement precision under a set of reproducible conditions of measurement.

3.17   Resolution

The smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

3.18   Transit time

Measurement of the time interval associated with transmission and reception of an acoustic signal between transducers.

3.19   True value

Quantity value consistent with the definition of a quantity.

3.20   Velocity sampling interval

The time interval between two successive fluid velocity measurements by the full set of transducers or acoustic paths.

4.0 Units and Abbreviations

Units used in this document are listed below.

Parameter	US Customary Units	SI Units
Pressure	psi	bar
Velocity	ft/s	m/s

Abbreviations used in this document are listed below.

Acronym	Expansion
ELM	Electronic Liquid Measurement
FAT	Factory Acceptance Test
NIST	National Institute of Standards and Technology
PSI	Pressure Pounds Per Square Inch
PSIA	Pressure Pounds Per Square Inch Absolute (Gauge + Atmospheric Pressure)
PSIG	Pressure Per Square Inch Gauge
SOS	Speed-of-Sound
SPU	Signal Processing Unit
UFM	Ultrasonic Flow Meter
UPS	Uninterruptible Power Supply

5.0 Principle of Measurement

5.1 General Principle

Transit-time multipath ultrasonic meters are inferential meters that derive the liquid flow rate by measuring the transit times of high-frequency sound pulses. Sound pulse transit times are measured between pairs of transducers. Pulses transmitted along the acoustic path in the direction of the liquid flow have a greater average velocity relative to pulses transmitted against the liquid flow. The difference in the sound pulse transit times is related to the average liquid flow velocity along that specific acoustic

path. Numerical calculation techniques are used to compute the average axial liquid flow velocity and the liquid volume flow rate at line conditions through the meter by combining the measurements of all active acoustic paths.

6.0 UFM Design Requirements, Considerations and Capabilities

The UFM should be designed and constructed of materials suitable for the service conditions for which the meter is to be applied. UFMs should be installed in accordance with any codes and regulations applicable to each specific meter installation. Refer to API *MPMS* Chapter 6.3A [6] for specific system design considerations.

The following provides guidance for UFM requirements, considerations, and capabilities.

6.1 Quality Assurance

The UFM manufacturer shall establish and follow a written comprehensive quality management program for the production, assembly and testing of the meter, transducers, and electronic operating system. For more information, refer to ISO 9001 [12]. A written description of the manufacturer's quality management program should be made available upon request.

6.2 UFM Body

6.2.1 Maximum Operating Pressure

The meter shall operate within the manufacturer's design minimum and maximum operating pressures, determined by the operating temperature range.

6.2.2 Minimum and Maximum Operating Temperature Ranges

The manufacturer should state the flowing liquid and ambient air temperature specifications for the UFM. The meter should operate within the manufacturer's design temperature ranges for ambient, and the meter body with and without liquid flow (such as in storage or initial field construction). The manufacturer field-mounted electronics, ultrasonic transducers, cabling, etc., minimum and maximum temperature ranges shall be stated. If the meter and the associated electronics are in direct sunlight, the temperature limits stated could not be adequate.

6.2.3 Corrosion Resistance

All internal and external surfaces of the meter should be manufactured of materials compatible with the related liquid and suitable for use in atmospheres typically found in hydrocarbon industry and/or as specified by the designer.

6.2.4 UFM Body Length

The meter body length (face to face) should be published by the meter manufacturer inclusive of the measurement section for each pressure class and pipe schedule diameter.

6.2.5 UFM Body Dimensional Measurements

a) The flow meter body measurement section shall be of constant diameter to within 0.5 % of the average internal diameter.

b) The average inside diameter shall be calculated using a minimum of 12 internal diameter measurements to determine the average internal diameter in the meter's measurement section. This average shall be used in the flow meter calculation. These measurements are as follows:

    i. Four ID measurements (one in the vertical plane, another in the horizontal plane and two in planes approximately 45 degrees from the vertical plane) should be made at three cross-sectional areas of the meter measurement section:

        a. Near the set of upstream transducers

        b. Near the set of downstream transducers

        c. Near the center of the meter body between the upstream and downstream transducers.

c) Additionally, the length of each acoustic path between transducer faces and the angle of each acoustic path shall be measured or calculated.

d) All measurements shall be made using instruments with a valid calibration traceable to a national standard body, e.g., National Institute of Standards and Technology (NIST) or an equivalent national standard body.

e) All measurements and calculations shall be documented along with the model number, serial number, flow meter body temperature at the time the measurements were made, date and time, and the individual who made the measurements identified.

6.2.6 UFM Internal Transducer Ports

UFM internal transducer ports should be designed in such a way that reduces the accumulation of any foreign material. The user needs to be aware that pipeline pigging operations can cause an interruption in meter function. Measurement inaccuracies can occur for a period after pigging operations and until the transducer ports are cleaned. If the meter is installed where pipeline pigging operations can occur through the meter, consult the meter manufacturer on the possible impact to measurement.

6.2.7 UFM Body Markings

a) The manufacturer's nameplate should denote the following:

    i. Meter manufacturer, model, serial number

    ii. Minimum and maximum operating flowrates, pressure, and temperature

    iii. Nominal meter size, flange class, schedule, and total weight

    iv. Meter inside diameter (measurement section)

    v. Minimum and maximum storage temperatures

    vi. Design code

    vii. Meter body and flange material

    viii. Direction of primary flow.

b) The nameplate and markings should be made of a material that will not deteriorate or fade when the meter is in the outdoor environment in which it will be operating.

c) Each transducer port shall be permanently marked to denote a unique designation for ease of reference.

6.2.8   Hydrotest

UFMs shall be hydrotested by the manufacturer after final assembly and prior to shipment. The hydrotest should be performed per the design code or per the users requirements including the test pressure and hold time. The hydrotest records should be provided upon request to the user. All test records should be retained by the manufacturer for a specified number of years.

6.3 Ultrasonic Transducers

6.3.1   Viscosity/Density Range Consideration

Transducers can have a different drive frequency specification appropriate for the viscosity and density range of the liquid being measured over the operating temperature.

6.3.2   Pressure Change

The transducer operating characteristics over the meter's designed pressure range shall not impact the meter measurement performance.

6.3.3   Transducer Testing

a) All ultrasonic transducers shall be individually tested by the manufacturer prior to their installation into the flow meter body. The tests conducted will ensure the ultrasonic transducers are functioning to the internal specifications that the manufacturer sets, therefore delivering optimal performance of the flow meter.

b) Transducer tests can include, but are not limited to, signal shape and signal quality tests, peak-to-peak voltage measurements, internal ring-down measurements, and static SOS measurement tests (utilizing a medium with a known SOS).

c) Results shall be maintained by the manufacturer and linked to individual transducers through unique serial numbers. Only transducers that pass all internal manufacturer test criteria should be used in the flow meter body.

6.3.4   Factory Static Setup and SOS Verification Test

Accuracy in transit time between transducer faces correlates to the velocity determination inside the meter. The electronics, transducer cables, and transducers are part of calculating the transit time.

a) During the final assembly of the flow meter, the manufacturer shall perform a static (no-flow) setup and verify the SOS calculated by the meter electronics. OEM corrections account for time delays in the electronics, cabling, and transducer buffers. These adjustments are needed to bring the meter field performance into specification. This should be a documented process followed by the manufacturer for each flow meter assembled.

b) The meter body is filled with a reference liquid (i.e., clean water). Once the liquid temperature has stabilized, the meter reading should be checked for static (no-flow) measurements from each transducer path, as well as SOS readings from each path, which are compared against the value of the liquid at the current temperature. For pure liquids such as clean water, the liquid SOS versus temperature is well known and documented. If a different reference liquid is used,

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the manufacturer should be able to provide documentation regarding the sound speed characteristic of the liquid, if requested.

NOTE There are many published references existing for graphs and tables of the SOS for pure liquids.

c) Adjustments made by the manufacturer to the programming parameters of the meter are common and necessary during this phase of meter assembly. After final programming and adjustments, the manufacturer shall ensure that all diagnostic parameters are within nominal ranges.
d) Upon completion of the static flow setup and verification, the manufacturer shall record and make available to the end user the following:
    i. Flow cell serial number
    ii. Electronics serial number (if different from the flow cell)
    iii. Ultrasonic transducer serial numbers and their locations in the flow meter body
    iv. All meter programming parameters, typically in a form that can be uploaded to the meter in the event of memory corruption.
e) The manufacturer should note if the constants are dependent on specific transducer pairs. The zero-flow verification test shall meet the following requirements:
    i. The individual path liquid velocity no greater than ± 0.02 ft/sec (0.0060 m/sec) or a difference in transit time tolerance of ± 0.10 nanoseconds
    ii. The SOS per path within ± 0.2 % of the theoretical value
    iii. Percentage of accepted signals for each acoustic path are 100 %
    iv. All gain levels are within the nominal limits provided by the manufacturer
    v. Maximum SOS path to path spread not greater than 3 ft/s (1 m/s).

6.3.5   Signal Processing Unit (SPU)

The SPU shall meet the following requirements:

a) Be designed and installed to meet the applicable hazardous area classifications.
b) Operate over its entire specified environmental conditions within the meter performance requirements.
c) Calculate a flow rate and determines an appropriate pulse frequency output rate to represent that flow rate. The relationship between the pulse frequency output rate and the flow rate is configurable in the SPU. The pulse frequency output shall be designed to provide appropriate fidelity and security. More information on fidelity and security of flow measurement pulsed data transmission systems can be found in API *MPMS* Chapter 5.5 [4].
d) Be resistant to Electromagnetic Interference (EMI).
e) Contain a monitoring function to assure automatic restart of the SPU in the event of a program fault or lock-up.

6.3.6   Output Signal Requirements

The SPU shall be equipped with the following outputs:

a) A minimum of two programmable frequency outputs representing flowrate
b) Discrete digital health status indicator
c) Serial data interface (e.g., RS-232, RS-485, or equivalent)

The SPU can be equipped with the following additional outputs:

a) Analog (4-20 mA DC)
b) Ethernet
c) Read only serial port
d) Additional frequency outputs
e) Additional digital status outputs

6.3.7   SPU Considerations

a) An analog current loop (4-20 mA, DC) output shall not be used for custody transfer due to possibility of increased uncertainty.
b) Since the electrical signals of UFMs are at relatively low power levels, care should be taken to avoid interference generated from nearby electrical equipment and wiring.
c) UFMs employ various materials and methods to provide shielding against EMI.
d) Cable jackets, rubber, plastic, and other exposed parts should be resistant to ultraviolet light, oil, and grease.
e) Poorly designed cathodic protection and grounding systems can be sources of potential interference with the UFM signals.
f) A regulated UPS should be considered to provide continuous meter operation.
g) The SPU can be housed in one or more enclosures mounted locally or remotely to the meter.

6.4 Influences on Accuracy

The accuracy of an ultrasonic liquid meter depends on many factors, such as:

a) Precisely measured dimensions of the flow meter body and ultrasonic transducer locations
b) The velocity integration technique inherent in the design of the meter
c) The shape of the velocity profile of the flowing liquid stream at the meter
d) Stability of the flowing liquid stream
e) Dimensional integrity of the flow meter body over time (e.g., erosion, corrosion, and dirt build up on internal meter surfaces, etc.)
f) Flow calibration
g) The accuracy of transit-time measurements which depends on several factors, including:
    1. The electronic clock accuracy and stability
    2. Accurate and consistent detection of sound pulse transit times
    3. Proper compensation for signal delays of electronic components and transducers

Ultrasonic flow meter (UFM) accuracy is dependent on these fundamental factors and their continued integrity over time. Emphasis on UFM diagnostic data collection and interpretation in this document is made to impress upon users the need to monitor UFM integrity so that accuracy is maintained. Refer to Annex A for more information on UFM measurement principals.

6.5 Flow Fluctuations

Steady State fully developed pipe flow can take many different forms. In the most basic description; laminar, transitional, and turbulent flows normally have some dynamic behavior at varied intensities and scales based on the fluid Reynolds number and pipe roughness.

When typical metering pipe fittings such as; tees, elbows, valves, reducers (expanders), dead ends, or blind flanges etc. are present, they can add to or contribute to flow fluctuations. These fluctuations can manifest into greater intensities and scales due to the fluid dynamic response to these installation effects. The operator should be aware that the liquid UFM responds to these dynamic behaviors, and this can be observed in the output which is inherent to the meter. The operator should consult the manufacturer to ensure that the result is not biased by the flow fluctuations.

7.0 UFM User Interface Software and Firmware

7.1.1   User Interface Software

UFMs shall be supplied with a user interface software capable of allowing on site or remote configuring of the SPU, and for monitoring and displaying the meter's diagnostics, alarms, and audit logs.

7.1.2   Firmware

a) The firmware is the program/computer code that controls and operates the meter. The firmware and all the calculations and operator parameters shall be stored in non-volatile memory.
b) The UFM manufacturer should document and provide the ability to identify primary UFM configuration parameters and settings that affect the flow meter's output.
c) The manufacturer shall maintain and publish all software and firmware revisions including:
    i.   Revision number
    ii.   Date of revision
    iii. Firmware modifications, additions, and the reason for any changes
    iv.   Provide any information on metrological effects
    v.   Meter model that is affected by a firmware change
    vi.   Circuit board revisions affected by a firmware change
d) The manufacturer shall provide a means of viewing or displaying the firmware revision number, revision date, serial number, and checksum(s). This information can be displayed by an operator software interface, flow computer, or a local display on the SPU.
e) The meter's firmware/software configuration should be documented and tracked for validation purposes over the lifetime of the SPU. A change in checksum, for example, would indicate a change in meter configuration and can affect meter performance. On initial installation, the meter's firmware/software configuration should be documented and tracked for validation

purposes. A change in checksum, for example, would indicate a change in meter configuration and can affect meter performance.

8.0 UFM Configuration Parameters and Settings

a) The UFM manufacturer shall provide the ability to identify primary UFM components and document the meter's configuration parameters and settings that affect the flow meter's output.
b) A UFM shall provide an audit trail of the meter's configuration parameters and settings that affect the meter's output(s).

9.0 Alarms and Event Logs

a) The UFM shall provide output signal generation which can be a voltage, current, or frequency pulse or can be digitally communicated to indicate an alarm and/or event.
b) Additionally, UFM alarms and event logs shall be viewable through the UFM software interface.

10.0   UFM Security and Access

Configuration parameters and settings shall be secured against tampering, unauthorized changes, or undocumented changes. This can be achieved by using passwords and/or tamper-proof seals or locks. Refer to API *MPMS* Chapter 21.2 [10] for more information.

11.0   Auditing and Reporting Requirements

a) A UFM shall provide an audit trail of the meter's configuration parameters and settings that affect the meter's output(s) during operation.
b) Any and all programmable parameters, flow, and volume calculations shall be auditable.
c) The audit trail, meter configuration parameters, metrological flow calculation, calibration factors, firmware revision number, revision date, serial number, checksums, meter dimensions, velocity sampling rate, etc., shall be made available to view and print.
d) API *MPMS* Chapter 21.2 [10] fully addresses the auditing and reporting requirements of a generic Electronic Liquid Measurement (ELM) system. The audit requirements of an ELM system using an UFM are similar, except for the addition of specific configuration and setup parameters contained in the SPU which shall be auditable and securable.

12.0   Meter Diagnostics

The UFM's Hardware and Software shall be capable of monitoring certain parameters based on the specific application. Many of these parameters are monitored in the UFM, and when these parameters fall outside the preset limits a diagnostic alarm will be generated. In most cases, the troubleshooting process requires the evaluation of more than one of the parameters below.

Using various methods such as trending plots can help to clarify the performance status of the UFM over time and how these parameters compare to the original factory setup and the onsite start-up

conditions. The complete troubleshooting process, however, requires evaluating these diagnostics parameters and process operating conditions combined. The parameters below are typical of those that can be accessed via a data interface or other means.

12.1 Gain

Gain is a measure of the amount of amplification required to achieve the desired signal amplitude for processing. High gain indicates greater attenuation of the signal. High gain can be caused by the presence of solids or gas in the liquid, high viscosity, water/oil mixtures, or a weakening acoustic transducer for example[1]. When the gain reaches maximum amplification (saturation) it is an indication of a weak signal or path failure, and a diagnostic alarm should be generated.

12.2 Signal to Noise Ratio (SNR)

SNR is the ratio of useful signal to noise in the signal waveform as seen on each acoustic transducer of a UFM. High SNR is beneficial to good measurement. A low SNR can indicate a potential acoustic transducer problem or process condition.

A low SNR could be a normal signal strength and high noise possibly caused by improper grounding or electrical interference. Alternatively, a low SNR could be a low signal strength caused by the presence of solids or gas in the liquid, high viscosity, or water/oil mixtures.

12.3 Speed-of-Sound Velocity Along Each Acoustic Path

By knowing the SOS and comparing to what is determined by the meter, the SOS on each path should be similar indicating a consistent homogeneous product stream. A change in SOS can indicate a change of product in the stream or a path to path SOS variation from top to bottom of the meter could indicate a density or temperature gradient. Differences in the SOS across the acoustic paths can indicate a nonuniform liquid medium (i.e., water, vapor, or liquid interface).

The distance between the acoustic transducers is known (path length), and with the transit time of the signal, a SOS measurement can be made. The approximate SOS ranges for some liquids are shown below:

Air = 1100 ft/sec at sea level (as a reference point to vapor)

Ethanol = 3810 ft/sec

Benzene = 4325 ft/sec

Gasoline = 4330 ft/sec

Diesel = 4580 ft/sec

Water = 4850 ft/sec

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[1] The examples provided are for illustration purposes only. Each company should develop its own approach. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

Seawater = 4995 ft/sec

Propane = 2000 ft/sec to 2500 ft/sec

Refined products = 2000 ft/sec to 4600 ft/sec (includes NGLs)

Isobutane = 2200 ft/sec to 2800 ft/sec

Normal butane = 3100 ft/sec to 3700 ft/sec

Crude oil (Condensate) = 4400 ft/sec

Asphaltic crude = 5050 ft/sec

Brine = 5740 ft/sec to 6000 ft/sec

12.4   Flow Stream Path Turbulence (Standard Deviation of Individual Path Velocities)

This is the standard deviation of the individual path velocities over a time period. The stability of the flow velocity along each path is an indication of the turbulence intensity within the flow stream. Some turbulence is normal due to friction effects or boundary layer effects (typically 2 % to 4 %). Higher turbulence levels can indicate partial blockages of upstream flow conditioners, changes in pipe wall internal roughness, throttled or partially open valves, reduced bore valves, or gasket protrusions for example[2].

12.5   Accepted Measurements for Each Acoustic Path

A series of checks are performed for each acoustic path to determine if it is suitable for transit time measurement. The number of parameters can vary by manufacturer. The results are reported as the percentage of measurements accepted over a given interval.

12.6   Path Velocity Ratio

This is the ratio of an individual path velocity to the average axial flow velocity. By comparing these path velocity ratios, changes in the flow profile can be determined.

Ultrasonic flow meter path velocity ratios change in the presence of swirl or asymmetrical flow profiles. Individual path velocities are combined in various ways to report flow diagnostics as dimensionless ratios, such as asymmetry or flatness. This gives users insight into the condition of the flow passing through the meter. For example [3], asymmetric profiles can be an indication of flow disturbances such as debris in the strainer or in the flow conditioner.

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[2] The examples provided are for illustration purposes only. Each company should develop its own approach. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

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13.0   Associated Flow Computer

API *MPMS* Chapter 21.2 [10] addresses the flow computer as a flow calculation device which could utilize other primary and/or tertiary equipment in addition to the primary measuring device. Additionally, auditing and reporting requirements of a generic ELM system is covered.

14.0   Component Replacement

a) Transducers, transducer cables, electronic parts, and firmware shall have the ability to be replaced. The replacement of such components shall not cause a change in the meter's performance greater than the manufacturer's published uncertainty, repeatability, and linearity.
b) Any component replacement shall require deenergizing all appropriate power sources. Follow all safety, lockout, and tagout procedures.
c) Some UFMs are designed whereas the transducers are exposed to process liquids and can be under pressure. Safety considerations should be observed during the replacement of transducers. Replacement of the transducers can require a system shutdown and draining the pipe of all liquid. Consult the manufacturer for transducer replacement procedures.
d) After component replacement, using the manufacturer's diagnostic software, check that the meter operational parameters are within acceptable performance specifications.

15.0   Metering System Design Criteria

15.1   General

The following criteria should be considered for metering system design:

a) A typical UFM metering system for pipeline and marine loading/unloading measuring system; refer to API *MPMS* Chapter 6.3A [6].
b) The meter run design should consider the user's minimum and maximum flow rates, Reynolds number, temperatures, and pressures.
c) The meter run design should consider the following physical properties: viscosity, relative density, vapor pressure, and corrosiveness.
d) Operate the meter within the linear flow range based on the specific application.
e) The flow rate limits that can be measured by the UFM are determined by the velocity of the flowing liquid. The designer of the metering system should determine the expected flow rate and size the meter accordingly. The designer should also consider the maximum velocity for piping and equipment.
f) The class and type of piping connections and materials, and the dimensions of the equipment to be used, the space required for the installation of the metering and proving system should be considered.
g) Though most UFMs have minimal, or no pressure drop, consideration should be given to the pressure drop created by the flow conditioning element.

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h) Metallurgy, elastomers, coatings, and other components should be compatible with the process liquid fluid.

i) The effects of erosive and or corrosive contaminants on the meter and the quantity and size of foreign matter, including abrasive particles, which can be carried in the flow stream.

j) Possible depositions such as wax, asphaltenes, or other precipitants that can affect the performance of the UFM.

k) The size and type of prover and method of proving. Unidirectional piston pipe provers with external detector switches (small volume prover) require special consideration to achieve repeatability. See Annex B. Maintenance, costs, and spare parts that are needed.

l) Requirements and suitability for security sealing, auditing, and/or reporting.

m) Interface requirements for communicating meter pulses, diagnostics, and alarms to other electronic devices as needed.

n) Power requirements.

o) Steps need to be taken to minimize the amount of water in the fluid being measured. Depending on the flow regime, the acoustic properties of the oil, the water droplet size and distribution, and the amount of water, UFMs can become less accurate because paths can become inoperable. Consult the UFM manufacturer for guidance on a water content limit. The meter diagnostics can be useful in understanding the performance of the meter. See section 12.

p) The flowing stream should be analyzed for solids, contaminates, corrosive materials, and for the presence of vapor. Deposits due to normal pipeline conditions (e.g., sludge, mill-scale, dirt, sand, water, and sediment) can affect the meter's accuracy by reducing the meter's cross-sectional area.

q) Deposits within the meter can also attenuate or obstruct the ultrasonic sound waves emitted from, and received by, the ultrasonic transducers or reflected by the internal wall of the meter.

15.2   Pressure Limitations

a) Meters shall be adequately protected from excessive pressure through the proper use of pressure relief devices. This kind of protection can require the installation of surge tanks, expansion chambers, pressure-limiting valves, pressure relief valves, and/or other protective devices.

b) The meter shall operate within the manufacturer's design minimum and maximum operating pressures.

15.3   Backpressure

a) The operating pressure in the meter run shall be maintained above vapor pressure.

b) Users should consult the manufacturer for a minimum backpressure. In the absence of a manufacturer's recommendation, the numerical value of the minimum back pressure at the outlet of the meter to prevent cavitation can be calculated with the following expression.

c) Equation 1 can be used to calculate the minimum backpressure. For liquids with vapor pressure greater than atmospheric pressure, a backpressure above the liquid vapor pressure at operating conditions can be sufficient and should be verified.

d) In order to prevent cavitation API *MPMS* Chapter 5.3 [3] recommends a minimum backpressure. Consult the meter manufacturer for maximum pressure drop to determine the total backpressure required in 0.
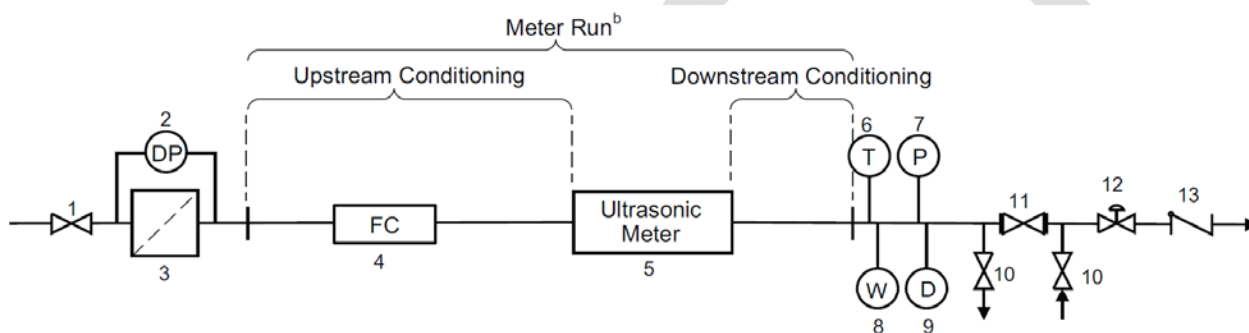
19

$$P_b = 2\Delta p + 1.25 p_e \qquad (1)$$

Where;

P_b = the minimum back pressure, PSIG

Δp = the pressure drop through the meter run components such as those in Figure 1. Other components can need consideration depending on the meter system design. Pressure drop is determined at maximum operating flow rate for the liquid being measured, PSI

p_e = equilibrium vapor pressure of the liquid at the operating temperature, PSIA.

e) For liquids with vapor pressure greater than atmospheric pressure, a backpressure above the liquid vapor pressure at operating conditions can be sufficient and should be verified.

Key

1. block valve[a]	8. temperature test well
2. differential device[a]	9. densitometer[a]
3. strainer and/or air eliminator[a]	10. prover take-off valve
4. flow conditioning element[a]	11. double block and vent valve
5. ultrasonic flow meter	12. flow control valve[a]
6. temperature measurement device	13. check valve[a]
7. pressure measurement device	

[a] Element(s) not always required.
[b] See Section 15.9 on Flow Conditioning.

NOTE This simplified figure indicates components for a typical single meter pipeline measurement system but is not intended to indicate preferred locations. All sections of the system that can be isolated should have provisions for pressure relief (preferably not to be installed between the meter and prover).

Figure 1: Typical meter run with prover connections

15.4   Meter Run Configuration

The following figures[4] show different options for unidirectional and bidirectional meter run configurations. A meter run consists of the upstream and downstream sections as shown in **Error! Reference source not found.** and **Error! Reference source not found.**. The UFM manufacturer can be consulted for recommended meter run configuration with or without a specified flow conditioner.
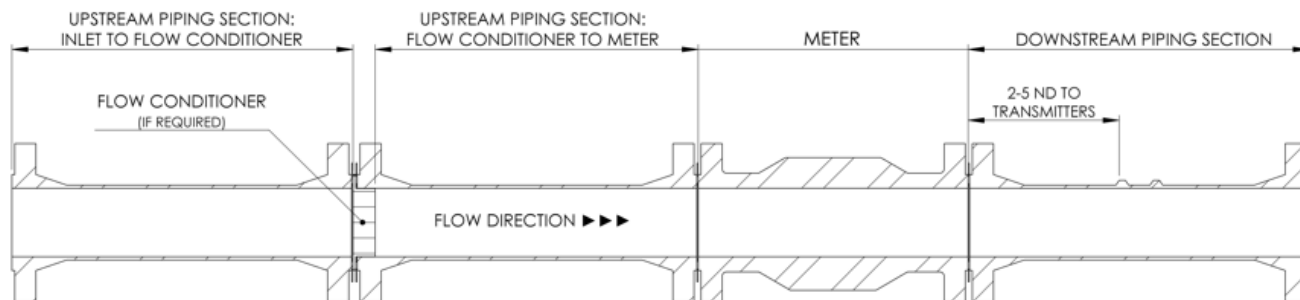
Figure 2: Unidirectional meter run configuration

15.5   Bidirectional Flow

UFMs have the inherent capability of measuring flow in either direction with equal accuracy. The designer shall specify if bidirectional measurement is required so that the manufacturer can properly configure the SPU parameters.

a) If the meter is utilized in bidirectional flow, both inlets of the meter shall conform to the upstream requirements, a meter factor shall be determined for each direction.
b) If a meter is utilized more often in one flow direction than the other; temperature, pressure, and/or density instrumentation shall be located downstream of the meter run relative to this direction.
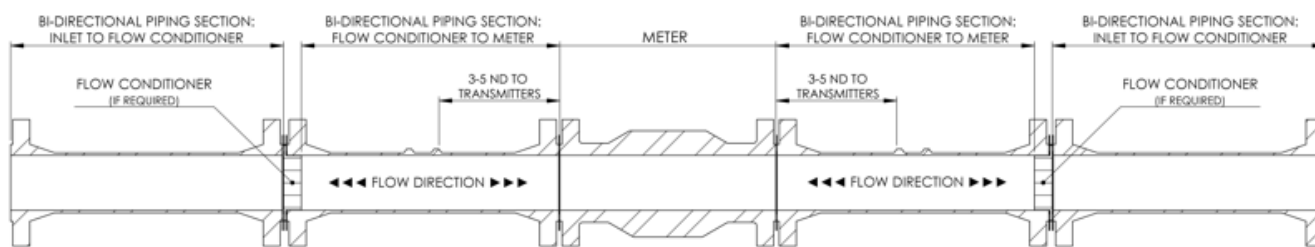
Figure 3: Bidirectional meter run configuration

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[4] The following figures are merely examples for illustration purposes only. Each company should develop its own approach. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

15.6   Protrusions and Alignment

a) The inside diameter of the meter run piping schedule and tolerances shall be the same as the inlet-outlet of meter.
   i.   Welds shall be internally ground smooth, and all gaskets shall be installed to not protrude into the pipe.
   ii. Methods to ensure proper internal alignment are recommended to prevent any steps inside the meter run.
b) The effects of different piping configurations or flow-conditioning elements on the flow-conditioning installation requirements has not been fully evaluated; therefore, consult the manufacturer for design considerations.
c) Meter proving repeatability, as well as the derived meter factor, can be affected by the flow-conditioning design, including the type and location of the flow-conditioning elements. For example, in cases where the meter cannot be proved immediately after meter run servicing, the original rotational position of the flow-conditioning element shall be maintained. The rotational position of the flow-conditioning element can affect meter performance (i.e., meter factor).

15.7   Pressure, Temperature, and Density measuring devices

a) Temperature sensing devices, temperature test thermowells, pressure, and density sensing devices shall be installed to accurately represent the actual metering conditions. Immediately downstream of the UFM and the downstream flow conditioning section of the meter run (see Figure 1). Secondary devices such as pressure, temperature, density, and other process variable sensing transmitters shall not be located within the downstream flow conditioning section of the meter run. Refer to Figures 2 and 3 for correct placement of secondary devices with ample spacing, to ensure measurement is representative relative to the flow element. Refer to API *MPMS* Chapter 21.2 [10] for more information on secondary devices.
b) The temperature sensing thermowell and the test thermowell should be selected to conform to code and user installation practices. Thermowells are typically threaded, welded, or flange mounted. The immersion length of the thermowell should be sufficient to put the sensing portion of the device within the center one-third of the pipe diameter or provide immersion of 0.3 m (1 ft.) unless limited by fluid velocity considerations. The thermowell should be installed in as near to a vertical position as practical to allow it to be filled with an appropriate thermal-conducting material to cover the sensor.
c) Temperature measurement of liquid hydrocarbons for volume correction is an important aspect of measurement. Keeping the temperature measuring device as close as possible to the liquid ultrasonic meter without impacting the flow conditioning or profile within the measurement section of the meter is best practice. The thermowell and temperature transmitter are commonly depicted as the first elements in the outlet side of the meter relative to the test temperature well and pressure transmitter. In some cases, these devices can be transposable in sequence however the meter manufacturer should be consulted to determine any impact to the meter performance. Refer to the appropriate section of API *MPMS* Chapter 6 [5] for more information in system considerations.
d) In bidirectional flowing applications, a primary and secondary flow direction should be identified. Primary flow direction would be that with the most volume accumulation direction as per the

system operation design and secondary flow would be the opposite flow direction. The best practice for thermowell and temperature probe installation is downstream of the flow conditioning section of the meter run in the primary flow direction. Refer to Figure 3.

15.8   Sample Probes

Sample probes can be required to withdraw a representative sample from the flowing stream. The sample probe shall not be installed in the upstream and/or downstream flow conditioning sections. Depending on the application, refer to API *MPMS* Chapter 8.2 [7] for guidance on the design, installation, and location of a sample probe. Refer to Figure 1.

15.9   Flow Conditioning

a) Ultrasonic flow meters benefit from a symmetrical, non-swirling flow profile for optimum flow measurement performance. Individual path velocities are combined in various manners to report flow diagnostics as dimensionless ratios to give users insight into the condition of the flow passing through the meter.

b) Various combinations of upstream fittings and valves can produce velocity profile distortions at the meter that can result in measurement errors. The amount of meter error will depend on the type and severity of the velocity profile distortion produced by the upstream piping configuration and the meter's sensitivity to these distortions and will vary by meter design. Research has demonstrated that asymmetric velocity profiles can persist for 50 pipe diameters or more downstream from the initiation point while swirling velocity profiles can persist for more than 200 pipe diameters.

c) Although mitigation of distorted velocity profiles is commonly provided using flow conditioners, some meter designs could not require the use of flow conditioning.

d) The user should ask for manufacturer test data generated by an accredited flow-calibration laboratory that verifies meter performance without a flow conditioner. However, because flow conditioners are designed to produce an exit velocity profile that reduces the effects of most upstream flow disturbances, the use of flow conditioning is recommended to provide the basis for a repeatable and stable metering package.

e) Flow conditioning element(s) shall be properly installed per the manufacturer's instructions. The ability to confidently transfer the results of the calibration facility to a field installation is greatly increased by using a properly qualified and installed flow conditioner.

f) Research results have shown that this effect is dependent on the meter design, as well as the type and severity of the flow profile distortion produced at the meter. Although a substantial amount of data is available on the effects of upstream piping, the full range of field piping installation configurations has not been studied in detail.

g) Meter station designers/operators can gain insight into expected meter performance for given upstream piping installation configurations by soliciting available test results from meter manufacturers or by reviewing test data found in the open literature. Alternatively, if the user requires confirmation of the meter performance characteristics for a particular piping installation configuration, flow calibration of the metering package with the same upstream piping configuration can be necessary.

h) The design shall ensure appropriate flow conditioning upstream and downstream of the meter in accordance to the manufacturer's recommendations.

i) Special attention should be given to the length of piping upstream of the flow meter, if a flow conditioning element is not used.

j) Headers, tees, and bends out-of-plane with 90-degree turns located upstream of the meter run can induce swirl which can impact the performance of the UFM based on the meter design and the degree in which these conditions are present.

15.10 Orientation of Meters

Orientation refers to vertical, horizontal, and rotational position of the meter. If the meter is installed vertically, liquids should flow upward through the meter. The meter manufacturer should be consulted in determining the proper meter orientation.

15.11 Series Metering

a) Meters can be installed in series to provide check or redundant measurement. The meters can be of different design such as number of transducers, path configuration, and/or from different manufacturers to reduce common mode errors. Consideration should be given to the meter bore diameters and transducer ports or protrusions to prevent flow disturbances that can influence the downstream meter.

b) Consideration should be given to the transducer frequencies and excitation methodology to avoid interference with signal detection of adjacent meter(s) and the flow measurement result.

c) Each meter should be managed independently of the other with respect to power, input/output signals, output frequencies, and data transmission.

d) The complete custody transfer metering assemblies, including the upstream and downstream flow conditioning sections as well as the meters, should be calibrated together and installed in the meter and piping arrangement as calibrated.

15.12 Handling the Meter

15.12.1   Shipment Preparation and Packaging

a) The meter and/or the complete meter run should be assembled prior to calibration either at the manufacturing facility or the calibration lab. The meter or the entire meter run should be prepared and packaged to avoid marring of the internal and external finishes as well as physical damage from lifting and moving equipment.

b) After calibration, the following should be considered:
   i.   shipping the meter fully assembled, including, if practical, the electronic enclosure and all transducers.
   ii.   flange covers or other sealing mechanisms should be used to protect the internal surfaces.
   iii. securing the meter to prevent it from rolling and shifting in transit.
   iv.   if supplied as an entire meter run for calibration, the assembly remains intact for shipment when practical. If not practical, prior to packaging, all piping components shall be labelled, indexed, and referenced to ensure proper reassembly and alignment to match the calibrated meter run.

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    v.   preservation and packaging requirements that ensures the meter or the meter run is protected from potential damaging effects including rust and corrosion.

15.12.2   Lifting and Supports

a) Proper lift points should be engineered and identified on the meter by the manufacturer, or by the designer on the components of an assembled metering package and lifting instruction should be part of the documentation provided upon delivery of the metering package. Care should be taken to ensure that lifting is carried out in a safe and proper manner per industry guidelines. Lift points for the meter are not designed for lifting the entire assembled metering package.

b) Anti-roll mechanisms installed on UFMs are designed to stabilize the flow-meter body only and are not sufficient to prevent rotational movement of the metering package in storage and during shipment. Blocking and support during transport of the metering package to the destination needs to be carefully considered and installed based on transportation methodology to prevent excessive movement.

c) To prevent damage to transducers and SPU when the UFM is being transported or set on a flat surface during installation or maintenance activities, the meter body shall have a means to prevent rolling.

15.12.3   Long Term Storage

a) The UFM shall be stored in a secure and enclosed location which does not exceed the equipment's rated storage temperature and humidity. Air quality should not contain excessive dust, grease, or corrosive gases which will cause degradation to the equipment. The UFM should also be stored such that is not in a high traffic area which could potentially expose it to shock from other equipment or personnel.

b) If the ultrasonic flow meter is likely to come into contact with chemically aggressive or physically abrasive substances, precautions that prevent it from being damaged should be used. A means to ensure the type of protection employed is not compromised should be used.

c) Equipment packaging or crating should consider the recommendations under section 15.12.1. Sufficient labelling from an identification and handling perspective should also be considered.

d) It can be necessary to store an ultrasonic flow meter for an extended period of time. If installed, the meter should be pulled from the piping, cleaned, a light coat of oil applied to the internal meter body, and end caps inserted into each end of the meter. If the meter is new, and will require storage, the meter should have a light coat of oil applied to the internal meter body and end caps inserted into each end of the meter.

e) The electronics, control modules, and transducers should be tightly sealed with a means to prevent moisture entering the transducer and/or the electronics housing.

f) The meter and auxiliary equipment should be stored in a location that is protected from ambient conditions.

16.0   Installation Considerations

16.1   General

Applicable industry standards and manufacturer's recommendations shall be followed when installing the meter and metering system components.

   a)   The meter installation shall meet the performance requirements outlined in section 17.
   b)   The meter run design shall consider the user's minimum and maximum flow rates, Reynolds number, temperatures, and pressures. Additionally, the meter run design shall consider the following physical properties; viscosity, relative density, vapor pressure, and corrosiveness. Operating within the linear flow range of the UFM based on the specific application is desirable.

16.2   Valves

a)   Valves require special consideration since their location and performance can affect flow profile and thereby also measurement accuracy.

b)   The preferred location of the flow or pressure-control valves should be downstream of the meter run and prover take-off valves. Valves should be capable of smooth operation to prevent shocks and surges.

c)   Valves, particularly those between the meter and prover (e.g., the stream diversion valves, drains, and vents), require leak proof shutoff, which can be provided by a double block and bleed valve.

d)   When using isolation valves upstream and downstream of the meter or meter run, full port valves should be used versus reduced port type to prevent flow profile distortion and impact on measurement accuracy.

16.3   Environmental and Process Considerations

16.3.1 Ambient and Flowing Temperature

In applications where the metering system along with the UFM is installed in extreme ambient and/or process conditions which exceeds the manufacturer's recommended temperature range, consideration should be given to provide shelter, insulation, heating, and/or cooling of the process. Consideration should be given to protecting the SPU and any primary and/or tertiary equipment from ambient conditions.

16.3.2 External Mechanical Vibration

External vibration can cause permanent damage to electronics, tertiary equipment, wiring/cabling, and connections, all of which can affect a UFM's performance. Care shall be taken not to install a UFM in locations where vibration or frequencies might interfere with the resonant frequencies of the SPU, ancillary components, and the ultrasonic transducers.

16.3.3 Electrical Noise

The manufacturer shall design and test the UFM to ensure immunity to EMI. UFMs and their interconnecting cables are all susceptible to EMI. Since the electrical signals of UFMs are at relatively low power levels, care should be taken to avoid interference generated from nearby electrical equipment and wiring. UFMs employ various materials and methods to provide shielding against EMI.

16.3.4 Process Pulsation

Process pulsation and/or hammering created by valves opening and closing, positive displacement pumps, or repeated pipeline pressure shock should be kept to a minimum for accurate measurement. Pulsation and/or hammering can affect the ability of the UFM to measure accurately, it can also affect the meter proving process and meter repeatability, and meter factor reproducibility can be difficult to achieve.

16.3.5 Strainers and Filtration

UFMs typically do not require the use of strainers and/or filters since they have no mechanical moving parts that could be adversely affected by debris. Strainers and/or filters can be required to protect associated equipment, including meter provers or pumps, or to provide a means of keeping flow conditioners free of debris. However, if solid particles are distributed across a flowing stream, transducer acoustic deflection can occur reducing the number of transit time signals received, impacting the measurement accuracy.

16.3.6 Air Eliminators

If air or vapor is present in the flowing stream, eliminators shall be provided to minimize measurement error.

17.0   Flow Meter Calibration and Performance Requirements

17.1   General

Manufacturing variances can cause each ultrasonic flow meter to have its own unique operating characteristics or bias. To minimize UFM measurement uncertainty, the manufacturer or operator can flow calibrate the meter and then use the calibration data to correct or compensate for the meter's measurement error by multiplying the meter reading by the corresponding calibration coefficient.

The performance of an ultrasonic meter depends on the operating Reynolds number range and therefore requires special consideration for the application data as outlined in this section.

Calibrations are performed by placing the ultrasonic flow meter under test (MUT) in series with a flow standard (e.g., prover, master meter). The flow standard, used to accurately measure volume, has been calibrated using standards that are traceable to a national metrology institute such as NIST.

The objective of the ultrasonic meter calibration is to determine the linearity of the meter and ensure that the meter performs within the field flowing conditions and uncertainty requirements based upon the manufacturer's specifications. The flow calibration not only corrects bias in the meter but can

also collect useful diagnostic information. The user can use that information to assess both the quality of the flow calibration and to baseline the meter performance prior to installation in the field.

The user or entity shall provide the manufacturer or calibration facility with the application data listed in Section 15.0. Using this information, the manufacturer or calibration facility can calculate the expected minimum and maximum values for the Reynolds number relative to the field installation requirements. The calculated application Reynolds number range can be compared to the Reynolds number range capabilities of the calibration facility.

The manufacturer and end user will verify that the proposed calibration range meets the meter performance requirements of the application under field conditions. Any limitations of a calibration are likely to result from one of the following:

a) Limitations of flow rate range in the calibration facility, particularly at high and low flow rates combined with large meter sizes.
b) Difference in viscosity between the laboratory's available liquids and the viscosity of the liquids the meter will encounter when installed in the field.

When the application Reynolds numbers are outside of the capabilities of the calibration facility, the calibration cannot encompass the entire application Reynolds number range. As a result, the meter factor will be extrapolated outside of the meter's calibrated Reynolds number range increasing the meter factor uncertainty. The end user should be aware of the potential effect on the meter factor uncertainty due to the contribution of extrapolation outside the actual collected calibration data to accommodate the expected field conditions.

At higher Reynolds numbers, the meter is typically more linear. This facilitates extrapolation of the calibration results. At the lower Reynolds numbers, the linearity can degrade.

Extrapolated results can be considered for high accuracy or custody transfer applications only with the consideration of additional uncertainty from operating the meter in the field outside of a calibrated range of Reynolds number.

For the purpose of determining quality performance of the ultrasonic flow meter within the turbulent flow regime, Table 1 shows the general flow measurement performance requirements where the Reynolds number is equal to or greater than 10,000. This reduces stratification influences prior to making any calibration factor adjustments:

Table 1: Flow Performance Requirements for a Reynolds Number ≥ 10,000

As-Found: Minimum of 6 Test Points over the Application Reynolds Number Range	
Test Point	Requirement
Repeatability	User-defined uncertainty with the manufacturer and calibration facility, select: A fixed number of runs (e.g., 3 or 5 runs) with a larger repeatability criterion or Test each point to meet uncertainty repeatability Refer to API *MPMS* Chapter 4.8 [2], Table A-1
Linearity	± 1.5 % for Re ≥ 10,000
Resolution of Fluid Velocity as Meter Calculates	Minimum 3 decimal places
Velocity Sampling Interval	≤ 1 second
Maximum SOS Path Spread on all paths	≤ 3.5 ft/s (1.0 m/s)
As-Left: Repeat the Same Minimum 6 Test Points	
Test Point	Requirement
Repeatability	Refer to API *MPMS* Chapter 4.8 [2], Table A-1
Linearity	± 0.2 % for Re ≥ 10,000
Meter Factor Uncertainty	± 0.027 %
Resolution of Fluid Velocity as Meter Calculates	Minimum 3 decimal places
Velocity Sampling Interval	≤ 1 second
Maximum SOS Path Spread on all paths	≤ 3.5 ft/s (1.0 m/s)
Reference Annex C for more information on Reynolds Number Performance Curve	

17.2   Calibration Process Outline (Typical)

17.2.1 Before Flow Calibration

a) Review design requirements, considerations, and capabilities – See Section 6.0 for further description pertaining to flow range, temperature range, density/viscosity range, etc.
b) Record firmware revision.
c) Back up the meter's "As-Found" software configuration file.
d) Review the Meter Manufacturing Test and validation requirements prior to performing the FAT.

e) The manufacturer should develop the test plan and select the calibration facility based on Reynolds number range, meter size, meter run setup, application, and performance requirements. This includes flow rates, viscosity, Reynolds number, number of runs, uncertainty repeatability, and linearity as defined in Table 1 of this section.

f) Test plan should include agreement between the user, manufacturer, and calibration facility on piping used and the installation plan for calibration (e.g., pipe schedule, elbows, flow conditioning, laboratory piping, actual field piping, piping lengths). In most cases a dimensional drawing of the agreed calibration piping would provide clarity.

g) For testing criterion, refer to Table 1. The flow test facility operating Reynolds number range should be compared to the meter application Reynolds number range outlined above.

h) The flow calibration facility should be accredited to ISO/IEC 17025 [14] and traceable to national or international metrological standards with verified uncertainties.

i) It is recommended for custody transfer to use pulse output since this signal type provides better resolution and representation of the flow rate.

17.2.2 Calibration

a) Prior to calibration, perform physical inspection of the meter for shipping damage and assure all documentation is present. Setup the meter and/or meter run in the calibration facility per the test plan.

b) Check all critical test facility instrumentation for current calibrations including prover, master meter, temperature and pressure instrumentation, test fluid property instrumentation (i.e., viscosity, density), and the data acquisition system.

c) Check that there are no alarms generated in the flow meter by its internal diagnostics system.

d) Obtain the calibration diagnostic log file from the meter's software. Diagnostic logs can prove to be an important tool once the meter is put into service to troubleshoot potential problems with meter performance. Run the "as found" calibration which will consist of operating the meter over the application range without linearization correction and obtain results such as Meter Factor vs Flowrate, Meter Factor vs Reynolds number, the purpose of which is to construct "as found" performance curves.

e) Operate the meter according to test plan and collect the "as-found" calibration data for each test point.

f) At each test point, the repeatability performance shall follow the requirements in Table 1 above or as outlined in the test plan.

g) From the test points obtained in step 17.2.2.e), calibration coefficients are developed and uploaded into the meter.

h) During steps 17.2.2.e) and 17.2.2.f) observe and/or collect diagnostic data parameters and monitor the meter for alarm conditions.

i) Run the "as-left" verification points consisting of operating the meter according to the test plan and review results such as Meter Factor vs Flowrate, Meter Factor vs Reynolds number "as-left" calibration curves.

j) An "as-left" verification is performed at multiple flowing conditions at the same calibration lab, whether the meter has been repaired and / or adjusted, against the lab reference standard.

k) Operating the meter at the flow test points to verify the meter meets the performance requirements in Table 1 or as agreed upon in the test plan.

l) Repeatability at each verification point shall meet the requirements of Table 1 or the flow test plan and the flow test facility accreditation capability.

m) Additional testing iterations can be required to minimize meter bias error.

n) During steps 17.2.2.i) and 17.2.2.j) observe and/or collect diagnostic data parameters and monitor the meter for alarm conditions.

o) When the previous steps are satisfied, a calibration certificate is issued to the user, indicating the meter's performance against the test plan.

p) The manufacturer retains a copy of the meters "As-Left" software configuration file.

q) Once the calibration is complete, data should be reviewed by the user. Check the repeatability and linearity against the test plan.

r) Once the data has been accepted, the purchaser and manufacturer should ensure changes cannot be made to the software and calibration integrity is maintained.

s) Shipping instructions should be provided to the calibration facility to ensure proper and timely delivery to the end location. The meter and its associated piping should be end capped and sealed such that no debris or dirt can enter the meter and/or meter tube internal section.

t) Disconnect and prepare for shipment to customer site location.

u) For shipment preparation see Section 15.12.1.

v) Consider if long term storage is required (see Section 15.12.3).

17.2.3 Laboratory Recalibration

Recalibration can be necessary if the process variables, such as fluid velocity or viscosity, change and there should be consideration for evaluating recalibration of the meter. If there is significant change to upstream piping configurations there should be consideration for recalibration. Users should consult with the meter manufacturer.

18.0 Commissioning

18.1 System Setup

UFM configurations can be unique to specific applications.

18.1.1 Hardware

a) Before the meter is put into service, ensure that the meter is installed in the correct location / orientation and measurement application.

b) When the SPU is remote mounted or separated from the meter and multiple meters are installed, care shall be taken to match the correct SPU with the correct meter body. The SPU contains factory information unique to each meter body such as dimensional data, acoustic transducer path lengths, performance data, etc. (see Figure 4).

18.1.2 Software

a) Verify that configuration parameters and settings conform to the manufacturer's documentation.

b) Backup the configuration files before making any changes or modifications to the meter and again after all work is done and completed.

c) Take a Diagnostic log file after operating conditions have stabilized after commissioning. Some of these parameters are indicated in Section 12 of this document.

d) UFMs shall be operated within the manufacturers' specified flow range, operating conditions, and fluid properties.

e) UFM performance can be affected when operated outside of the Reynolds number calibration conditions with an increased uncertainty value unless proved in the new conditions.

18.1.3 Pulse Scaling

a) The SPU calculates a flow rate and manufactures an appropriate pulse frequency output rate to represent that flow rate. The relationship between the pulse frequency output rate and the flow rate is configurable in the SPU. Pulse scaling relates the pulses to the volume measured and can be used to equate a pulse frequency or output frequency to a given flow rate and can be used to define the number of pulses to be output by the UFM per measured volume.

b) When configuring pulse frequency output scaling, the pulse frequency output should not exceed 90% of the maximum allowable input frequency of the accessory equipment as not to overrange the receiving device.

c) An analog current loop (4-20 mA, DC) output shall not be used for custody transfer due to possibility of increased uncertainty.

d) If the pulse scaling is changed the meter shall be reproved.

18.1.4 Calibration Coefficients and Meter Factor

a) A UFM is calibrated by the manufacturer to determine one or more calibration coefficients that are entered into the UFM SPU. These coefficients should remain unchanged. Any coefficients changed that can affect the quantities measured by the meter shall follow the audit and reporting section (refer to Section 11) of this standard.

b) There are various methods of applying the meter factor to indicate the actual quantity measured through the meter. The adjustment from indicated to actual quantity can be made by varying the meter factor or K-factor. The preferred method is to apply a meter factor in the accessory equipment because of its audit trail capability. It is important that the method selected be used consistently. If the K-factor is changed the meter shall be reproved.

c) In applications where the flow rate varies during normal operation, it can be desirable to determine meter factors over a range of flow rates. The various meter factors can then be used to linearize the output from the UFM at varying flow rates. If the meter is used to measure bidirectional flow, a meter factor should be developed for each direction.

d) The preferred method for custody transfer is to apply a meter factor in equipment that has audit trail capability sufficient to meet API *MPMS* Chapter 21.2 [10]. It is important that the method selected be used consistently.
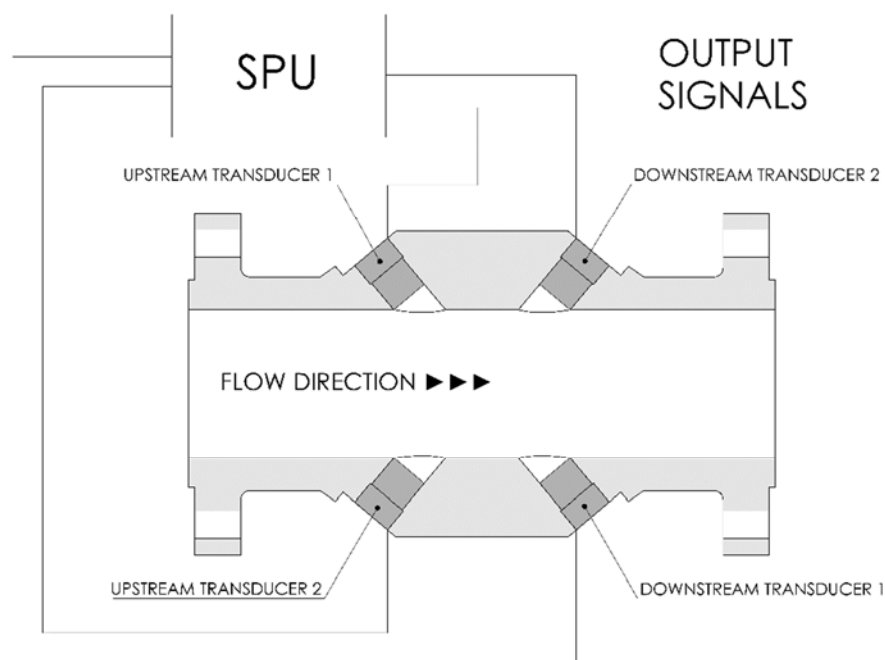
Figure 4: UFM Main Components

19.0 Meter Proving and Field Verification

19.1 Overview

a) Meter factor shall be determined by proving the meter at stable operating conditions (i.e., flow rate, density, viscosity, temperature, and pressure). API *MPMS* Chapter 4.8 [2] can be referenced for guidance in this area. Users typically determine the acceptable deviation limits of these operating conditions.

b) Proving is primarily a function of regulatory and contractual requirements and typically standard company operating procedures. Proving conditions shall be as close to the actual metering conditions as practical.

NOTE The essential purpose of proving is to confirm the meter's performance at normal operating conditions. Most UFMs provide a means of adjusting for the changes in the geometry of the meter caused by changes in body temperature. By employing this feature, reproving necessitated by temperature changes can be reduced or eliminated. Questions often arise concerning the differences between proving or calibrating a meter in a laboratory (bench) versus in-situ (field). These two locations can produce different results and cannot necessarily be interchanged without proper consideration of the installation conditions, especially the upstream flow conditioning, fluid properties, and operating conditions.

c) In-situ proving is normally preferred because it verifies the meter's accuracy under actual operating conditions.

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d) Laboratory proving is normally not preferred because laboratory conditions could not duplicate the piping and operating conditions. While there are more measurement uncertainties associated with laboratory proving, under certain conditions, it can provide the best alternative.

NOTE Operating conditions can affect a meter's accuracy and repeatability. In-situ proving at stable operating conditions compensates for variations in performance caused by flow rate, viscosity, density, temperature, pressure, as well as flow conditions, piping configurations, and contaminants.

19.2 Proving Accuracy and Repeatability Performance

a) Proving accuracy can be affected by the delay in manufactured flow pulses from a UFM. These delayed manufactured flow pulses can lead to a bias error in the calculated meter factor depending upon the magnitude of the flow rate change that occurs during the proving run and the duration of the prove run. This potential problem is explained in detail in API *MPMS* Chapter 4.8 [2] , Annex C.

b) Master meter proving of an ultrasonic flow meter as per API *MPMS* Chapter 4.5 [1] may be applied, provided the additional uncertainty typically associated with master meter proving is acceptable to the parties involved.

c) Proving run repeatability is used as an indication of whether the proving results are valid.

d) Some UFMs can produce a non-uniform pulse output, which can exhibit a wide span of repeatability when proved. Common practice has been to achieve five consecutive proving runs that agree within a repeatability of 0.05 % or better. The random uncertainty of a five-run proving at 0.05 % is estimated as ± 0.027 %. An alternative method is described in API *MPMS* Chapter 13.3 [9] to achieve the equivalent random uncertainty of ± 0.027 % by varying the repeatability requirement for the total number of runs. The repeatability limits listed in API *MPMS* Chapter 4.8 [2] Annex C maintain the same random uncertainty as five runs that repeat at 0.05 %; proving guidelines should be followed as outlined in API *MPMS* Chapter 4.8 [2] and API *MPMS* Chapter 13.2 [8].

19.3 Meter Factor Reproducibility

Meter factor reproducibility is the ability of a meter to generate consistent results over a period of time. Changes in operating conditions such as variation of pressure, temperature, flow rate, and physical properties of the liquid can affect reproducibility. Refer to API *MPMS* Chapter 4.8 [2] and API *MPMS* Chapter 13.2 [8].

20.0 Ultrasonic Meter Measurement Uncertainty Determination

API *MPMS* Chapter 13.3 [9] should be used as a reference for the determination of measurement uncertainty for installed flow meters. The in-situ measurement uncertainty of an ultrasonic meter is comprised of many elements including:

1. Uncertainty associated with the lab calibration and/or application of field proving
2. Uncertainties between operating and calibration conditions
3. Inherent uncertainties associated with the repeatability and reproducibility of the meter
4. Uncertainties associated with secondary instrumentation and corrections, including correcting volumes to standard conditions.

A complete analysis follows the procedures outlined in API *MPMS* Chapter 13.3 [9]. See also Annex D.

21.0   Field Maintenance

21.1   Ex-Situ Meter Tube Cleaning and Inspection

a) Diagnostics can indicate possible internal build-up or damage to the meter has occurred. In some cases, measurement bias can indicate a similar condition. Removing the meter tube for cleaning and inspection can be useful when determining build-up or damage to the meter tube and its transducer windows. Respectively this can result in measurement errors due to a change in internal diameter or poor chordal path signal diagnostics.
b) Procedures designed for remote meter tube cleaning and inspection should consider the collective equipment ratings and material compatibility.
c) Safe operating measures should be in place for inspection and caution should be exercised to prevent damage to the meter internals.
d) After inspection, reinstallation should be in the same direction and orientation as which they were found.
e) Meters in custody transfer shall be proved after the reinstallation. Additionally, proving before removal can be useful.

21.2   In-Situ Meter Tube Cleaning and Inspection

In-situ meter tube cleaning and inspection is not normally practical in liquid service. However, a system designed for cleaning and inspection can be useful in situations where the process can expose the internals to build-up and/or damage when dealing with large meter assemblies. This is especially true when dealing with meter assemblies which require assisted lifting or cannot be readily removed from the process.

a) Before inspection, peripheral equipment should be in place to allow for sufficient draining and cleaning.
b) System design should consider the collective equipment ratings and material compatibility.
c) Safe operating measures should be in place for inspection as well as caution should be exercised to prevent damage to the meter internals.

21.3   Evaluating Meters after Electronic Component Replacement

There are occasions when electronic components such as the SPU, transducer cables, or field-replaceable transducers need to be replaced or repaired on an installed meter. Prior to replacing or repairing such components, comparing meter diagnostics before and after to verify the new components are performing similar to the original components. The replacement of some parts and the effect on measurement performance can be covered under the type approval for the meter or by available test data and should be discussed with the manufacturer prior to any modifications or repairs.

In some cases, the manufacturer should be directly involved with the repairs and replacement of electronic components.

a) Saving of the meter configuration parameters should always be performed prior to any modifications to the hardware or firmware. Follow the manufacturer's instructions to ensure all parameters are appropriately backed up to a file or files, including the meter's calibration parameters. To obtain the meters diagnostic parameters, the pipeline should be full of liquid without vapor or gas present.

b) In some cases, a seal or lock requires removal prior to repairs and replacements of certain components. The user shall follow whatever auditing procedures are in place to ensure that seal removal does not invalidate the measurements reported by the meter.

c) If the electronics are replaced, or if the firmware is returned to its default settings, the saved parameters shall be fully uploaded to the meter before recording the second log. Checks to verify the integrity of the signals and digital data back to the flow computer and supervisory systems are recommended.

d) Finally, any seals or locks that were removed as part of the process shall be reapplied along with the proper auditing documentation. Save a final backup of the configuration parameters after all work is complete. If the manufacturer retains this information for the user, a copy can be provided to the manufacturer for future service needs.

Annex A
(Informative)
UFM Measurement Principle

Ultrasonic transit time flow meters use acoustic transducers that can send and receive high frequency acoustic signals. The acoustic transducers are located in such a way that the generated acoustic signals will travel diagonally across the pipe. Transit time methods rely on the measurement of time intervals associated with transmission of acoustic signals across the pipe in opposing directions. This methodology is not synonymous with the Doppler ultrasonic technique that relies on the measurement of frequency shift in reflected acoustic energy.

The measurement is based on the fact that the acoustic signals that travel diagonally across the pipe in the direction of flow (downstream) will take less time to cross than the one traveling in the opposite (upstream) direction under flowing conditions. The time difference between the two acoustic signals is proportional to the average flow velocity along the acoustic path. See Figure A.1.

Assuming only axial flow, the acoustic signal that travels in the direction of flow (downstream) crosses the pipe according to

$$t_{down} = \frac{L}{c + v_i \cos\theta}$$

A.1

and the acoustic signal that travels against the direction of flow (upstream) crosses the pipe according to

$$t_{up} = \frac{L}{c - v_i \cos\theta}$$

A.2

where;

t_{down} is the transit time in the downstream direction

t_{up} is the transit time in the upstream direction

L is the acoustic path length

c is the SOS in liquid

θ is the angle the acoustic path makes with the pipe axis

v_i is the individual path axial velocity

The path velocity is therefore determined by the following:

$$v_i = \frac{L}{2cos\theta}\left[\frac{t_{up} - t_{down}}{t_{up}t_{down}}\right]$$

A.3

where;

v_i is the individual path axial velocity

L is the acoustic path length

θ is the angle of the acoustic path

t_{up} is the transit time to the upstream transducer (against the flow)

t_{down} is the transit time to the downstream transducer (with the flow)

Multiple acoustic transducers can be used to create multiple acoustic paths (beams) over the cross-section of the pipe to obtain more information about the flow velocity distribution (flow profile).
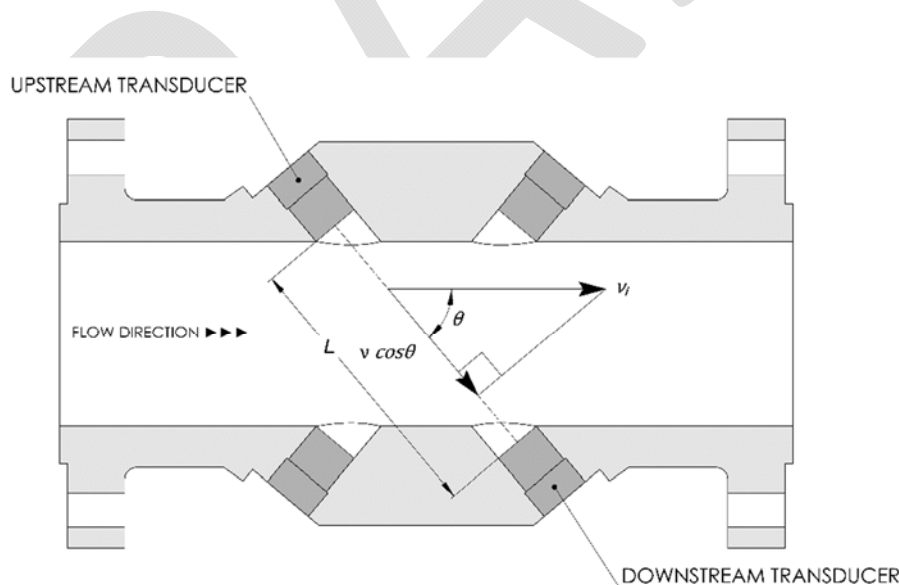

Figure A.1 UFM transit time method

Typical Sequence of Operations for a single acoustic path (see Figure A.1)

1. Emission: The SPU sends an electrical signal to the upstream transducer (piezo electric crystal) that causes the crystal to generate an acoustic signal into the fluid.
2. Reception: The acoustic signal crosses the pipe and contacts an opposing downstream acoustic transducer (piezo electric crystal) that vibrates in response to the acoustic signal, thereby generating an electrical output signal.
3. The process is then reversed to send the acoustic signal from the downstream transducer to the upstream transducer. The receiver circuit(s) in the SPU accepts these electrical signals for further processing.
4. Signal treatment: According to the manufacturer's algorithms, the SPU treats this data to obtain the t_{up} and the t_{down} values.
5. Transit time method: The SPU uses the difference between t_{up} and the t_{down} to calculate the average fluid velocity along the paths, commonly using the transit time principle described above.
6. Mass flow rate calculation: Depending on the number of paths, their geometry, and the manufacturer's algorithm, the SPU uses the average velocity values and cross-sectional area to determine the volumetric flow rate.
7. Output signals refresh: The SPU repeats the fluid velocity measurement and produces various kinds of outputs that represent the measured volumetric flow rate and other measured or inferred values. Typically, these outputs are subject to programmable scaling, averaging and smoothing functions, as these can be desirable to the user.

$$V = \sum w_i\, v_i$$

A.4

where;

V is the weighted average velocity in the pipe

w_i is the weighting factor for path i

v_i is the individual path velocity

Volumetric flowrate is then calculated as follows:

$$q = A \times V$$

A.5

where;

q is the flow rate

A is the cross-sectional area of the measurement section

V is the path axial velocity in the pipe

Solid particles, liquid bubbles, or water droplets can disturb the acoustic signal traveling through the fluid across the pipe. Typical disturbances are refraction, reflection, attenuation, and distortion. See Section 15.1. In these cases, the measurement along this path could be rejected according to the manufacturer's algorithm. Usually, low numbers of rejected measures will not impact the flow meter's accuracy. But above certain levels that are specific to each flow meter, the number of rejected measurements can have an impact on the flow meter accuracy, and in extreme cases can stop the meter's operation. Alarms can inform the user on the status of rejected measurements. See Section 12 on diagnostics.

Annex B
(Informative)
Verification and Validation of Meter Performance

B.1 General

The turbulent flow field in a pipe is complex and contains numerous turbulent eddies and non-axial velocity components.

Turbine meters and other mechanical flow measurement devices integrate this field through mechanical convergence and are not particularly influenced by minor changes in flow stability. Fluid acceleration into the rotor combined with rotor mass produces mechanical integration of the flow field. With turbine meters for instance, the resulting meter output signal exhibits little in the way of scatter from these "instantaneous" flow effects because of the inherent inertia of the measurement element. Data scatter, or variation in repeatability, of turbine meters is usually attributable to either sustained changes in global flow or to non-linear mechanical and inertial forces that occur during proof runs.

UFMs take snapshots of the fluid velocity along one or more sample paths. Each ultrasonic path is a line of sampling that produces time differentials and subsequent velocities as snapshots equal in number to the sample frequency for the sample period. For example, at 60 Hz, 60 flow rate measurements would be computed in one second.

Variations in velocity along each path are random as the turbulent eddies and variations in local flow that produce them are entirely random. Each sample can vary from the mean velocity for a given sample period and the family of samples can be evenly distributed about the mean.

UFMs "see" not only the global axial velocity, but also all of the flow components, including the turbulent eddies resulting from fluid drag and mixing in the pipe.

Real time integration of the flow field, including both axial and non-axial components, results in a less well-behaved output and inherently more scatter. However, this scatter, because it is random, can be evenly distributed around the mean meter factor.

B.2 Meter Factor Reproducibility

Meter factor reproducibility is the ability of a meter to generate results over a period of time, where process conditions and physical properties are similar. The expected reproducibility should be determined by the operating company based on financial risk and experience with each individual meter and proving system or meter linearity.

Common practice for custody transfer applications is to accept new meter factors within 0.10 % to 0.50 % of the previous meter factor. Action and tolerance limits should be defined individually by each operating company. Guidance on action and tolerance limits is provided in API *MPMS* Chapter 13.2 [8].

Verifying the performance of a UFM is similar to verifying mechanical systems. However, because UFMs employ sampling methodology, they produce a greater degree of data scatter due to their ability to measure minute variations in velocity. UFMs can produce wider repeatability ranges for existing provers, designed in accordance with industry standards, than are typical for a mechanical device. Failure to be mindful of the evenly distributed nature of the data points about the mean meter factor will

lead to errors in evaluation. A range exceeding 0.05 % in 5 runs does not mean that a UFM is defective, or that its meter factor cannot be established with the required uncertainty.

UFM performance verification can be ascertained by conventional means and to a level consistent with API *MPMS* Chapter 4.8 [2], Table A-1. The most conservative approach to accomplishing this level of repeatability relies on determining an acceptable prover volume. For instance, turbine meters can usually be successfully proven in 5 consecutive runs to meter factors within 0.05 % span range of repeatability, which demonstrates ± 0.027 % or better meter factor repeatability uncertainty due to random effects at a 95 % confidence level. Based on field data, UFMs can require a larger prover volume to achieve this same level of meter factor uncertainty.

Given the larger prover volume that can be needed to verify a UFM to ± 0.027 % uncertainty, it follows that more than 5 proving runs can be required to verify the meter's performance. API *MPMS* Chapter 4.8 [2] , Table A-1 provides the guidance for obtaining these results. Any of the number of runs chosen from API *MPMS* Chapter 4.8 [2], Table A-1 will produce results that verify meter performance to ± 0.027 % uncertainty. There is no difference, in this regard, in a repeatability range of 0.05 % in 5 runs versus a range of 0.12 % in 10 runs—they are the same. The operator is advised to select the appropriate number of runs, and span of repeatability, suitable for the prover volume available. Alternatively, the operator may simply increase the number of proof runs incrementally until the repeatability range falls within the limits of API *MPMS* Chapter 4.8 [2], Table A-1. Experience with UFMs of several manufacturers using ball provers shows that the required meter factor accuracy can typically be achieved with fewer than 10 to 12 runs, or with a prover volume 2 to 3 times larger than current industry standards for other types of meters such as turbines. Larger numbers of runs can be necessary if small volume provers are employed. Small volume provers can generate flow disturbances and fluctuations that could cause non-repeatable proving results due to the mechanical release of the piston into the flow stream. Care should be exercised when selecting and using small volume provers including the location of the optical switches. For applications where the use of a larger prover is not viable, master meter proving of an ultrasonic meter as per API *MPMS* Chapter 4.5 [1] may be applied.

B.3 Contributors to Increased Random Uncertainty and Meter Factor Non-reproducibility

The following can lead to increased random uncertainty:

   a) Proof duration and/or volume insufficient
   b) Cavitation or void fraction in the fluid (i.e.: insufficient back pressure, etc.)
   c) Noise at frequencies that affect the transducers
   d) Temperature stratification, especially at low flow Reynolds Numbers
   e) Flowrate, density, viscosity, and/or flow profile instability
   f) Excessive time delay between the measured flow and manufactured flow pulses (See API *MPMS* Chapter 4.8 [2])
   g) Excessive flow velocity
   h) Installation issues (i.e., gasket protrusion, flange misalignment, pipe stresses, etc.)
   i) Meter alarm status (i.e., path failure, high gain, percentage of accepted measurement, etc.)
   j) Contamination that changes the cross-sectional area of the meter body

NOTE Diagnostics can help to identify this issue.

k) Corrosion or fouling
l) SPU Programming configuration changes in error

For inferred mass measurement, the random uncertainty and reproducibility of the meter factor is affected by meter performance and the method of density determination, the number of density samples or readings taken, and the density meter proving. Assessment of the meter factor should include evaluating the density uncertainty. See API *MPMS* Chapter 4.8 [2] for additional information.

Annex C
(Informative)
Reynolds Number Performance Curve

Reynolds number is a dimensionless number that quantifies the relationship between the inertial forces of the flow stream and the viscous forces of fluid flow through the pipe carrying the flow stream . Reynolds number can be mathematically represented as follows:

$$Re = \frac{DV\rho}{\mu} = \frac{DV}{\upsilon}$$

C.1

where;

D is the diameter of the pipe.

V is the average velocity of the flow stream.

ρ is the density of the fluid.

μ is the absolute (or dynamic) viscosity of the fluid.

υ is the kinematic viscosity of the fluid.

For purposes of this discussion, it is assumed that liquid petroleum typically behaves as a Newtonian fluid where the viscosity of the fluid is unaffected by the shear rate and the shear forces that exist when the fluid is in motion through a pipe are proportional to the velocity of the fluid.

When considering the velocity variations across the flow stream, it becomes apparent that the fluid velocity is zero at the inside surface of the pipe, regardless of the velocity of the flow stream. And when the velocity of the flow stream is not zero, there will be a gradient of fluid velocities between the inside surface of the pipe and the center of the pipe, with the maximum velocity being at the center, provided there are no geometrically induced hydraulic influences, i.e., elbows, reducers, etc. and that the flow profile has had sufficient time to fully develop. See Figure C.1.
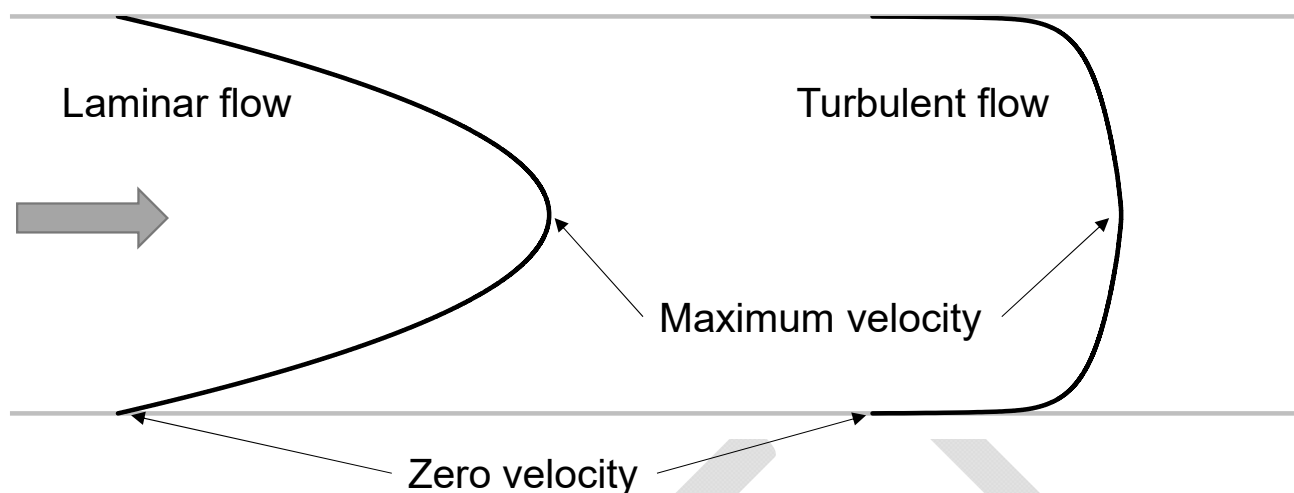
Figure C.1 Flow profile

It is well known that in fully developed flow, where flow characteristics no longer change with increased distance along the pipe, that the velocity profile shape is determined by the Reynolds number of the flow stream, along with the roughness of the pipe wall.

When the Reynolds Number is low (normally around 2,000 and below), in the laminar region, the viscous forces are dominant. If the flow is fully developed, the velocity profile in the laminar region takes the shape of a parabola (See Figure C.1).

In fully developed flow at Reynolds numbers higher than 8,000 to 10,000, the viscous forces are not sufficient to constrain the inertial forces and the flow stream becomes turbulent. At this point, the velocity gradient near the wall becomes steeper and the velocity in the center portion of the flow stream becomes flatter. In the turbulent regime the velocity gradient near the wall becomes steeper and the central area flatter as Reynolds number increases (see Figure C.2, which shows laminar and turbulent velocity profiles normalized to the maximum velocity).
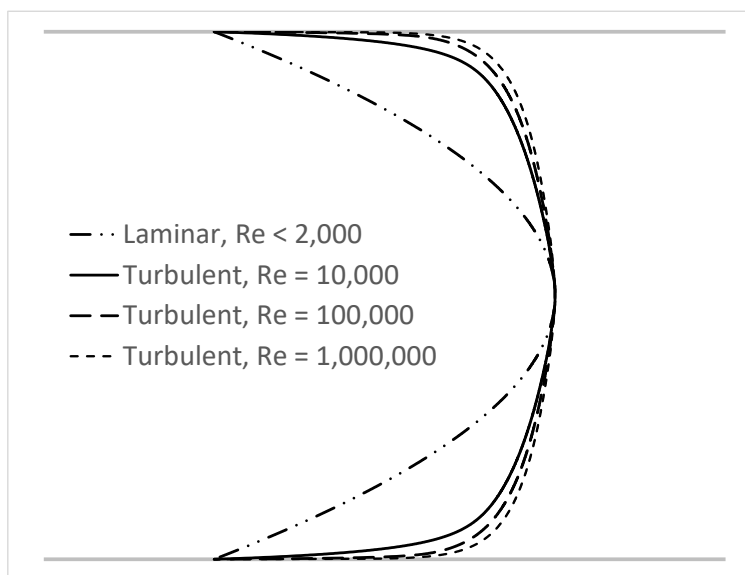
45

Figure C.2 Velocity profile shape change with Reynolds number

The part of the profile which has a steep gradient is sometimes called the boundary layer. In any case, for a given pipe with a given wall roughness, the shape of the fully developed velocity profile is determined by the Reynolds number.

As Reynolds number increases the degree of variation in the profile with Reynolds number reduces until at a critical value above which the profile shape is constant. The critical Reynolds number above which the profile does not change is a function of pipe roughness. The higher the relative roughness is the lower the critical Reynolds number will be. For more information on critical Reynolds number, reference can be made to the Moody diagram (not included here).

The ultrasonic flow meter measures differences in upstream and downstream acoustic signal transit times to measure the average fluid velocity along the acoustic paths. This measurement can be done with great accuracy; however, to determine the average fluid velocity across the full cross-sectional area of the meter, it is necessary to make some assumptions concerning the flow profile. For any given flow profile, once the average flow velocity has been determined, it is easy for the meter to determine flowrate if the cross-sectional area of the meter is known, or at least, is the same as when the meter was proved. Alternatively, if the velocity profile has changed significantly, the accuracy of the meter can be affected. For example, if the viscosity of the fluid changes after a meter has been proved, the flow profile will change. It is easy to see that if the flow profile is changed the relationship between path velocities and average velocity will have changed and therefore, the accuracy of the meter can change. The same can be said if the fluid velocity (flowrate) changes after the meter has been proved. However, the interesting fact is that the normalized flow profile shape will always be the same whenever the flowrate and viscosity result in the same Reynolds Number. This is illustrated in Figure C.3, which shows non-normalized velocity profiles that have identical normalized shape.

Figure C.4 shows the relationship between the meter factor and flowrate on three oils of different viscosity for a 16 inch multi-path transit time ultrasonic flowmeter.

Figure C.5 shows that the same data as in Figure C.4 correlates nicely when plotted against Reynolds Number of the flow stream.

The variation in meter factor can be at least partially explained by variations in the flow profile and the inability of the meter to exactly determine the true average flow-stream velocity from the measured path velocities.

If the meter is provided with viscosity data to allow calculation of Reynolds number or can approximate the Reynolds number of the flow stream by other means, a linearization or characterization algorithm can be employed that reduces meter factor sensitivity to variations in flowrate and viscosity within the corresponding range of Reynolds number as shown in Figure C.6.

Average velocity

200 BPH, 15 cSt   400 BPH, 30 cSt   600 BPH, 45 cSt
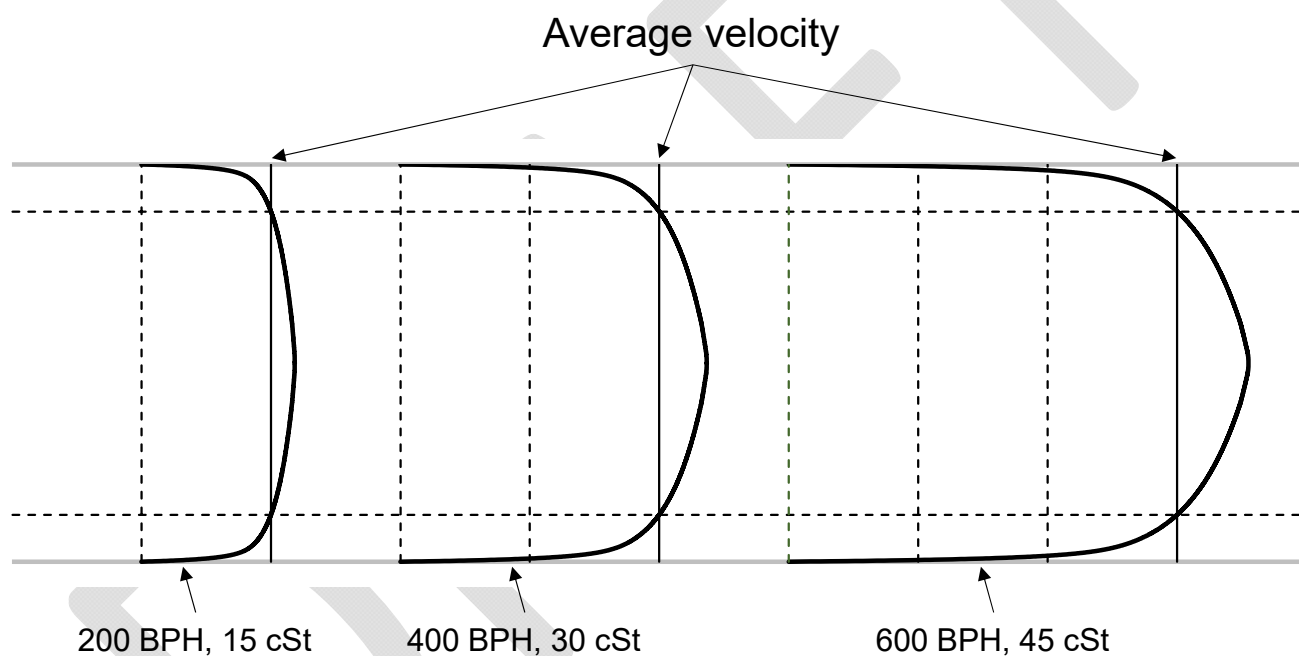
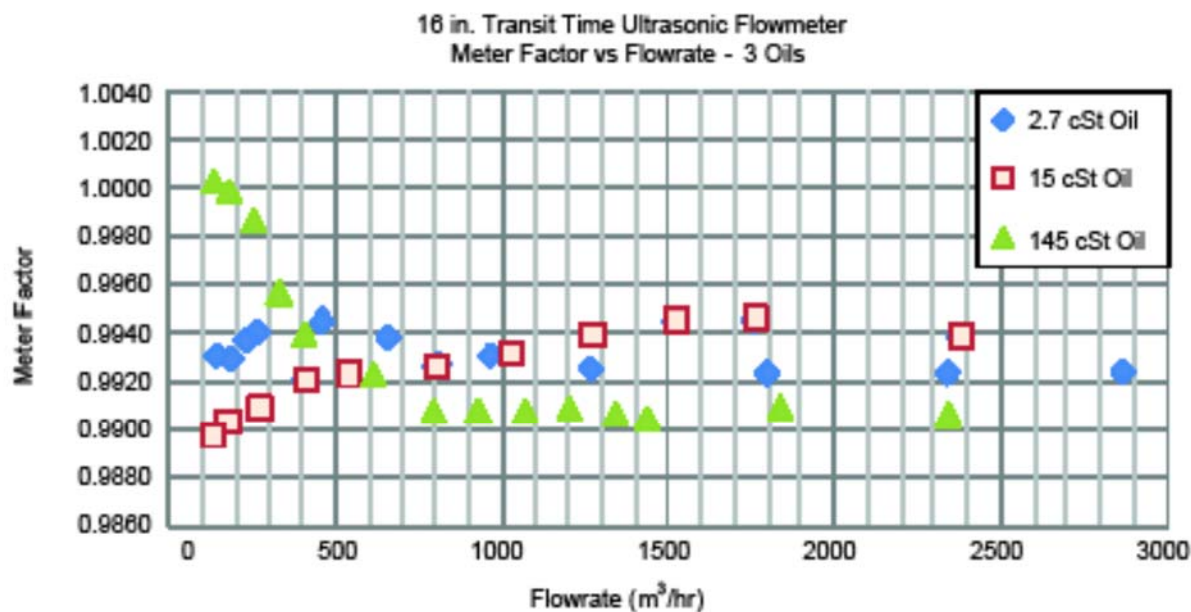**Figure C.3 Constant velocity profile shape with constant Reynolds number**

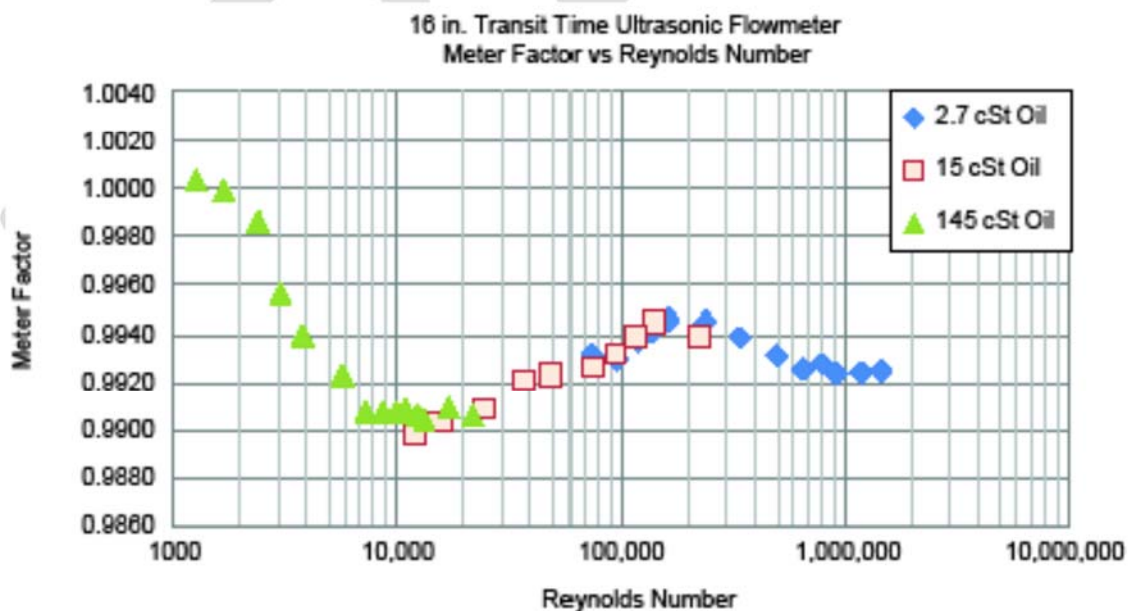**Figure C.4 Meter factor vs. flowrate – 3 oils**
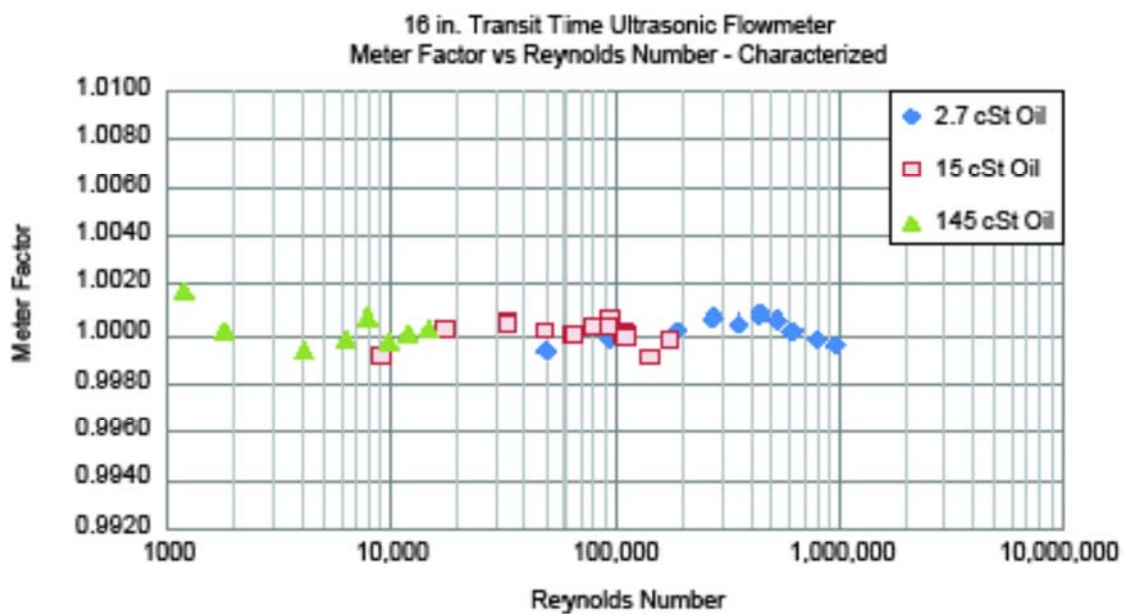

Figure C.5 Meter factor vs. Reynolds number

Figure C.6 Meter factor vs. Reynolds number – characterized

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Annex D
(Informative)
Ultrasonic Flow Measurement Uncertainty

D.1 Introduction

The uncertainty of a flow measurement using ultrasonic meters is dependent on many factors, including aspects of meter design and how the meters are calibrated and installed. This annex acts as a guide to the user who wishes to understand or evaluate measurement uncertainty when ultrasonic meters are employed.

For detail on the general methods for evaluating, combining, and reporting uncertainties the reader is referred to API *MPMS* Chapter 13.3 [9].

The volumetric flowrate at line or actual conditions measured by a multipath ultrasonic meter can be represented by the following equation:

$$q_{act} = MF \times K_C \times K_F \times A \times \sum w_i \, g_i \frac{\Delta t_i}{\left(t_{up} t_{down}\right)_i}$$

D.1

where;

q_{act} is the volumetric flowrate at actual conditions
MF is the meter factor applied externally based on the results of a calibration
K_C is the calibration coefficient applied internally based on the results of a calibration
K_F is the combination of internal correction factors applied at the meter level
A is the cross-sectional area of the measurement section
w_i is the individual path weighting factor
g_i is a path geometry factor used to convert transit times to velocity per individual path
$\Delta t_i = \left(t_{up} - t_{down}\right)_i$
t_{up} is the transit time to the upstream transducer (against the flow)
t_{down} is the transit time to the downstream transducer (with the flow)
i is the path number

See Annex A for supporting variables and formulas.

Although equation D.1 can be useful for evaluation of some specific or special cases, often it is sufficient to reduce the right-hand terms to a simple compound velocity term, *V*, i.e.

$$q_{act} = MF \times K_C \times K_F \times A \times V$$

D.2

Each of the variables in equations D.1 or D.2 above can have multiple sources of uncertainty.

In most applications, volumes will be referred to standard conditions in which case correction factors for the effect of temperature and pressure on the liquid volume, CTL_m and CPL_m, will be applied, i.e.

$$q_{std} = CTL_m \times CPL_m \times MF \times K_C \times K_F \times A \times V$$

D.3

The volume correction factors are dependent on pressure, temperature, and fluid properties, and hence the uncertainty in these terms is not specific to ultrasonic meters but should be considered when evaluating the overall uncertainty of the result.

In the following sections this standard provides information regarding the uncertainty contributions relative to equations D.1 or D.2 above.

D.2   Uncertainty Components

D.2.1   Transit time difference, Δt

The transit time difference is the variable on which the inferred velocity is most dependent. Uncertainty or errors in the transit time measurement itself are dependent on the means of signal processing used and other factors such as the signal to noise ratio. As the flow velocity tends towards zero, the relative uncertainty in the transit time difference will increase, as the transit time difference itself will become smaller.

Although it is possible in principle to define uncertainty in the transit time difference in units of time for each path, it is often more practical to consider the influence of the transit time difference uncertainty in terms of the compound velocity as described in section D.2.5.

D.2.2   Overall transit times, t_{up} and t_{down}

The overall transit times t_{up} and t_{down} are required as inputs to the equation in order that the meter eliminates the direct influence of speed of sound. In order for this to work accurately, it is necessary that the t_{up} and t_{down} inputs to the equation be corrected for any contributions to the measured transit times that are not directly dependent on the travel time through the fluid, i.e., 'non-fluid' time delays that are incurred in cables, transducer housing windows, and as a result of the signal detection technique employed.

As with the transit time difference, although it is possible in principle to define uncertainty in the overall transit times in units of time at the path level, it is often more practical to consider their influence in terms of the compound velocity as described in section D.2.5.

D.2.3   Path geometry factor, *g*

The path geometry factor used to multiply the measured transit times and produce a velocity result for each path is typically assumed to be a constant. In its simplest form it is given by the path length divided by 2 times the cosine of the path angle as shown in Annex A.

Path angles are normally assumed to be constant. Any uncertainty between the constant value used in the electronics and the actual value would tend to be eliminated when a meter factor or calibration coefficient curve from calibration is applied. It is therefore expected that path angle changes require consideration only in special cases, for example when there is contamination on the transducer faces or if there are thermal and sound velocity gradients in a laminar boundary layer.

Path lengths are also assumed to be constant. Path length changes would only have to be considered in special cases. Contamination build-up, such as wax deposition on the face of transducer housings is akin to a path length change but is more correctly treated as an uncertainty in the transit times t_{up} and t_{down}.

Path length changes with temperature are normally treated as a simple linear expansion and is usually handled in combination with the area change using a correction factor as described in section D.2.7.

D.2.4   Weighting factor, *w*

Weighting factors are usually constant, and, in that case, they do not contribute directly to the uncertainty. In principle it is possible to have variable weightings or correction factors that are applied on a per-path basis, but this is not common.

D.2.5   Compound velocity, *V*

The terms from equation D.1 described in sections D.2.1 to D.2.4 above are replaced with a simplified velocity term *V*, in equation D.2. This can aid simplification of the uncertainty analysis when data or information with respect to those terms covered in D.2.1 to D.2.4 is not easily accessible.

Uncertainty in the compound velocity can be covered with reference to meter performance expectations. This can enable the use of calibration or test data and/or published information such as meter accuracy specifications to quantify the expected uncertainty in the compound velocity.

The terminology that we would most commonly use with respect to the uncertainty in the compound velocity are *reproducibility* and *linearity*. In other words, we are considering the deviations from a reference value that can occur when the conditions at the ultrasonic meter change. This could be for example, a change in flowrate or a change in fluid properties. In this respect it would be usual to quantify the linearity or reproducibility as a value in relative percentage terms, e.g., linearity +/- 0.15 %, which would equate to an expanded uncertainty.

In addition to a term in relative percentage terms, it can also be useful or necessary in some cases to define a reproducibility value in units of velocity. This can be considered as a 'zero stability' value and can be used to address the velocity dependent uncertainty in Δt described in section D.2.1.

One method for evaluating a component of uncertainty that is defined as reproducibility in *velocity terms* is described in D.5.2.

D.2.6   Measurement Section Cross-Sectional Area, *A*

The cross-sectional area of the meter is usually considered to be constant. Alteration of the cross-sectional area by means of corrosion or deposition can result in measurement errors and can be considered in terms of uncertainty if the magnitude of area change can be estimated.

Area changes with temperature are normally treated as a simple linear expansion in two dimensions and is usually handled in combination with the area change using a correction factor as described in section D.2.7.

D.2.7   Correction Factors, K_F

Here we are using the terminology 'correction factor' to mean a multiplying factor that is based on theory, modelling, or empirical data and that is separate from the application of calibration coefficients that are based on calibration data for the particular device.

As electronic devices, a variety of correction factors can be employed in ultrasonic meters. In principle these can be used for purposes such as the correction of temperature effects or compensation for fluid dynamic effects (e.g., a profile or swirl correction term).

Where correction terms are used for purposes such as correction of fluid dynamic effects, they can be proprietary and it will be necessary to discuss these terms with the particular meter manufacturer or to determine uncertainty related to these terms by means of testing.

For the correction of temperature effects, a correction factor, K_T in the form below is normally used to account for the combined effects of thermal expansion on path lengths and cross-sectional area:

$$K_T = 1 + 3\alpha\Delta T$$

D.4

where α is the coefficient of linear expansion for the meter body material and ΔT is the difference in temperature between the conditions of application and the temperature at which the geometry terms were determined, or the difference between operating and calibration temperature if temperature correction was not already active during calibration.

The uncertainty in the temperature correction factor can be obtained by estimation of the uncertainty in α and the uncertainty in determination of ΔT.

D.2.8 Calibration Coefficients, K_C and Meter Factors, *MF*

Due to machining tolerances, variations in component manufacturing processes, variations in the meter assembly process, and other factors, each ultrasonic meter has its own unique operating characteristics or bias. Thus, to minimize an ultrasonic flow meter measurement uncertainty, the manufacturer or operator can flow calibrate the meter and then use the calibration data to correct or compensate for the meter's measurement error by multiplying the meter reading by the corresponding calibration coefficient.

Several error correction techniques or correction methods are available depending on the meter application and the needs of the operator. This discussion of the various meter error correction techniques is beyond the scope of this document. The designer or operator should consult with the manufacturer regarding available options.

When a meter is calibrated under flowing conditions, the application of the resulting correction factor can eliminate some sources of uncertainty. Calibration correction factors can be applied either as *calibration coefficients* that are internal to the meter or as *meter factors* that are applied in a flow computer or other external device. Despite the fact that these terms are used to differentiate between how and where the correction is applied, treatment of uncertainty in K_C and *MF* terms is similar. Careful consideration should be given to any difference between the conditions under which calibration coefficients or meter factors were determined and the conditions under which those corrections are being used, as discussed in the subsections below.

D.2.8.1 Calibration Reference Uncertainty

When a meter is using calibration coefficients or meter factors determined by calibration relative to a reference standard, be that a master meter or volumetric prover, the uncertainty in the calibration reference volume becomes a component of uncertainty in the result from the flow meter.

For calibration in a laboratory with an ISO/IEC – 17025 [14] accreditation, an uncertainty analysis of the reference standards will have been performed and detailed in the laboratory's scope of accreditation. For field standards, the uncertainty will have to be evaluated. For field standards, it is important to recognize that the uncertainty in the reference volume should include all sources of uncertainty, not just the calibration of the base volume, including the effects of temperature and pressure and the uncertainty in the change of connected volume between the prover or master meter and the meter under test.

D.2.8.2 Repeatability

When calibration coefficients or meter factors are determined by calibration, the applied correction is calculated from a number of repeat runs. The uncertainty of the mean of these repeat runs is another component of uncertainty in the derived calibration coefficients or meter factors.

D.2.8.3 Fluid dynamic installation effects

Fluid dynamic installation effects is used here to describe the influence of pipeline and meter run geometry on the output from the meter.

If the conditions of operation are different from those under which the calibration coefficients or meter factors were obtained, for example if a meter was calibrated in a laboratory setting and then installed in a field location without in-situ proving, then there can be a significant component of uncertainty in the application of the correction owing to the difference in fluid dynamic installation effects.

If a meter is calibrated in-situ *at the conditions of operation* this will eliminate the uncertainty owing to fluid dynamic installation effects. However, if there is a change in operating conditions between the in-situ calibration and the conditions of use, for example a change in fluid viscosity resulting in a Reynolds number change, then there could still be some uncertainty from this source.

The evaluation of uncertainty owing to fluid dynamic installation effects is discussed further in section D.5.3.

D.2.8.4   Interpolation or Extrapolation

Often a meter is calibrated at specific conditions and then used at conditions other than those specific conditions. This could be as simple as a difference in flow rate on the same or similar fluid to that used at calibration or it could be a difference in viscosity and flow rate.

The way in which the calibration response of an ultrasonic meter varies with changing conditions is usually most strongly dependent on Reynolds number, though it can also be flowrate or velocity dependent at low flow velocities.

When using a meter at a flowrate or Reynolds number that is different from that at which the calibration was performed it is necessary to interpolate, or in some cases extrapolate, from the calibration data.

Uncertainty owing to interpolation can be evaluated from calibration data and/or linearity specifications of the meter.

Uncertainty owing to extrapolation can be more difficult to evaluate, and the meter manufacturer should be consulted to obtain information to support the proposed extrapolation and the corresponding estimation of uncertainty.

D.2.9 CTL_m and CPL_m

A detailed analysis of the uncertainty in CTL_m and CPL_m is beyond the scope of this chapter but can be evaluated following the methods outlined in API *MPMS* Chapter 13.3 [9].

D.3   Examples[5]

Two examples are provided in this section. One represents a situation where the meter is calibrated in the field using an in-situ prover. The other represents a situation where the meter is calibrated in a laboratory and installed in the field without in-situ proving.

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[5] The following examples are for illustration purposes only. Each company should develop its own approach. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

Caution – These examples are simplified. Any uncertainty analysis requires judgment as to what components to include or exclude and evaluation of the values of uncertainty to be assigned. For these reasons, the numerical results shown in these two examples should not be taken as generally applicable.

D.3.1 Ultrasonic meter that is proven in-situ against a ball prover

In this example we assume the case of an ultrasonic meter that has been proven at multiple flowrates in-situ using essentially the same fluid as is being measured, and that the meter factors derived from the proving results are recent.

Following API *MPMS* Chapter 13.3 [9]:

a) First, we determine our measurement model, which for this case will be the simplified equation D.2 above.
b) Next, we identify our elemental sources of uncertainty, which we can do with reference to the considerations of section D.2. In doing so we determine the following sources of uncertainty:

D.3.1.1 Meter Factor – Calibration Reference Uncertainty

In this simplified example, we assume the prover system has been designed to determine the volume at metering conditions, and to compute the meter factor by comparing that with the volume from the meter under test. The whole prover system has been subject to an uncertainty analysis and the expanded relative uncertainty has been determined to be 0.07 %.

D.3.1.2 Meter Factor – Repeatability

In this example proving results are accepted when the repeatability meets the acceptance criteria of 0.05 % in 5 runs. The corresponding expanded relative uncertainty in the mean MF value is 0.027 %. If we are interpolating between points, the interpolated result has an uncertainty owing to repeatability that is the combination of the two adjacent meter factors. If we assume we are mid-way between those meter factors, the expanded uncertainty in the average becomes 0.027 % divided by the square root of 2, i.e., 0.019 %.

D.3.1.3 Meter Factor – Interpolation

In this example we assume that adjacent meter factors differ by no more than 0.1 %. Considering the case we describe above, where the flowrate is in the middle between adjacent meter factors, in addition to the repeatability uncertainty there is an interpolation uncertainty. This can be thought of as a 'model' uncertainty, i.e., we are modelling the data using linear interpolation, but the change in meter factor could not follow that linear line. As the difference between meter factors is 0.1 %, we can conservatively allow an expanded uncertainty of 0.05 % for interpolation.

D.3.1.4 Meter Factor – Fluid Dynamic Installation Effects

Because this meter is being proven in-situ and we have stated our assumption that the fluid properties are the same or very similar to that during proving, it can be assumed that any influence of fluid dynamic effects is reflected in the proving results and therefore this element of uncertainty is already accounted for by the allowance for interpolation and does not need to be included separately.

D.3.1.5 Calibration Coefficients

Because this meter is being proven in-situ and we have stated our assumption that the fluid properties are the same or very similar to that during proving, it can be assumed that any influence of fluid properties on the application of internal calibration coefficients is reflected in the proving results and therefore this element of uncertainty is already accounted for by the allowance for interpolation and does not need to be included separately.

D.3.1.6 Correction Factor – Temperature

Assuming a value of 11.7×10^{-6} for the fractional change in length per degree C, and a maximum uncertainty in the delta temperature of 0.5 °C, the estimated uncertainty for the temperature correction is 0.0006 %.

D.3.1.7 Area

It is assumed that once the temperature correction above is accounted for, there is no additional uncertainty in the area term, i.e., it is assumed that other than by thermal expansion the area has not changed between proving and use.

D.3.1.8 Compound Velocity – Reproducibility

The assumptions stated above have addressed meter factor uncertainty owing to a number of different sources. However, we have not considered the reproducibility of the meter itself. If the meter has been proven multiple times at the same conditions over a period of time, a comparison of the mean values can be used to estimate the uncertainty owing to reproducibility of the meter over time with typical changes in process and environmental conditions. Here we assume this exercise has been performed and that the expanded uncertainty owing to reproducibility has been determined to be 0.08 %.

D.3.1.9 Combined Uncertainty

Now that we have identified and quantified the main uncertainty components, we can combine these to evaluate the overall uncertainty.

When performing a more complex uncertainty analysis it is necessary to consider the sensitivity of the result to the component inputs. However, as the equation we are using here is a simple multiplication of terms, then the relative sensitivity coefficient is equal to 1 for each of the inputs.

Another factor that has to be considered in some more complex cases is the existence of correlation between inputs, i.e., where a change in a variable affects more than one term in the equation. In our simple example each of the inputs and their uncertainties are considered to be uncorrelated.

Lastly, the formal process involves dividing each expanded uncertainty contribution by a coverage factor that reflects the probability distribution of the input and then combining the resulting standard uncertainties before applying a coverage factor to obtain the final result. Here we assume that all of the contributions are normally distributed. Based on these assumptions and with application of a coverage factor of $k = 2$ throughout, in this particular case the equation for the expanded uncertainty simples to the following:

$$U_{combined} = \sqrt{\sum U_i^2}$$

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where:

$U_{combined}$ is the combined and expanded uncertainty at a confidence level of approximately 95 %

U_i is the expanded uncertainty of individual source, i.

The uncertainty contributions described above and the resulting combined uncertainty in this case are shown in Table D.1 below.

Table D.1: Illustrative Uncertainty for an Ultrasonic Meter with In-Situ Proving

Variable	Uncertainty Component	Component Expanded Uncertainty, U_i (%)	U_i^2
V	Reproducibility	0.08	0.00640
MF	Calibration Reference	0.07	0.00490
MF	Interpolation	0.05	0.00250
MF	Repeatability	0.019	0.00036
K_F	Temperature correction	0.006	0.00004
q_{act}	Combined Uncertainty (%)	0.119	

D.3.2   Ultrasonic meter calibrated in a flow laboratory

In this example it is assumed that the meter has been calibrated in a flow laboratory and then transferred to the field and that there is no further calibration or adjustment performed.

The uncertainty evaluation follows the same process as in the previous section.

D.3.2.1   Calibration Coefficients – Calibration Reference Uncertainty

Here we assume that the meter has been calibrated in a laboratory using a well-maintained ball prover. The facility operates under an ISO/IEC – 17025 [14] accreditation and the volume at line conditions determined using the prover has a documented uncertainty of 0.044 %.

D.3.2.2   Calibration Coefficients – Repeatability

In this example calibration results are accepted when the repeatability meets the acceptance criteria of 0.05 % in 5 runs. The corresponding expanded relative uncertainty in the mean value at each flow rate is 0.027 %. If we consider that the calibration results are used to construct a curve in the meter as a function of Reynolds number or a direct flow profile metric, we can assume that the expanded uncertainty owing to repeatability at a flowrate mid-way between the calibration flowrates is 0.027 % divided by the square root of 2, i.e., 0.019 %.

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D.3.2.3 Calibration Coefficients – Interpolation

In this example we assume that the meter is carrying out the interpolation between results using either an inferred Reynolds number or flow profile metric as the correlating parameter in the meter's electronics. In this case the uncertainty owing to interpolation is considered to be included in the combined uncertainty contribution for linearity and reproducibility of the compound velocity as determined by testing, and therefore a separate allowance for interpolation is not included.

D.3.2.4 Calibration Coefficients – Fluid Dynamic Installation Effects

The meter is installed in the field according to the manufacturer's recommendations. A meter of the same model has been extensively tested with the manufacturer's recommended configuration and a variety of upstream disturbances. The analysis of the test data has resulted in an evaluation of the expanded uncertainty owing to fluid dynamic installation effects of 0.1 %.

D.3.2.5 Calibration Coefficients

Because this meter is being proven in-situ and we have stated our assumption that the fluid properties are the same or very similar to that during proving, it can be assumed that any influence of fluid properties on the application of internal calibration coefficients is reflected in the proving results and therefore this element of uncertainty is already accounted for by the allowance for interpolation and does not need to be included separately.

D.3.2.6 Correction Factor – Temperature

Assuming a value of 11.7×10^{-6} for the fractional change in length per degree C, and a maximum uncertainty in the delta temperature of 0.5 °C, the estimated uncertainty for the temperature correction is 0.0006 %.

D.3.2.7 Area

It is assumed that once the temperature correction above is accounted for, there is no additional uncertainty in the area term, i.e., it is assumed that other than by thermal expansion the area has not changed between calibration in the laboratory and use in the field.

D.3.2.8 Compound Velocity – Linearity and Reproducibility

During laboratory calibration of the meter, two fluids of different viscosity were used to span the full range of Reynolds number and velocity expected for the application. Following entry of the calibration coefficient data into flow meters electronics, an 'as left' calibration was performed. The results of the as left calibration were within +/- 0.08 % over the full range of the calibration. Based on this evaluation of the data and also considering the linearity specification of the meter of +/- 0.1 %, an expanded uncertainty allowance of 0.1 % was made for linearity and reproducibility.

D.3.2.9 Combined Uncertainty

The combination of uncertainties in this simplified example follows the same process as in the previous example, with the same underlying assumptions.

The uncertainty contributions described above and the resulting combined uncertainty in this case are shown in Table D.2 below.

Table D.2: Illustrative Uncertainty for an Ultrasonic Meter with Laboratory Calibration

Variable	Uncertainty Component	Component Expanded Uncertainty, U_i (%)	U_i^2
V	Linearity & Reproducibility	0.1	0.01000
K_C	Calibration Reference	0.044	0.00194
K_C	Fluid Dynamic Effects	0.1	0.01000
K_C	Repeatability	0.019	0.00036
K_F	Temperature correction	0.006	0.00004
q_{act}	Combined Uncertainty (%)	0.149	

D.4   Correlation of Uncertainties

In the two examples in section D.3, the various input uncertainties are considered to be uncorrelated, i.e., they are considered to be independent of each other. Therefore, when combined the overall uncertainty is assessed by taking the square root of the sum of the squared contributions.

In some applications a difference between two meters is computed, for example in leak detection systems. In such cases, it is the uncertainty in the difference that is of interest, and when computing the uncertainty in that difference it can be incorrect to assume that uncertainty contributions are uncorrelated.

By means of a simple hypothetical example, if two meters had uncertainty of 0.1 % for fluid dynamic installation effects and 0.1 % for reproducibility under changing fluid properties (an no other uncertainties), an assumption that the uncertainties were uncorrelated would result in an expected uncertainty of 0.2 % in the difference between the two meters (the root sum square of 0.1 % and 0.1 % is 0.141 % for each meter, which then combined by root sum square for the two meters gives 0.2 % for the difference). However, it is plausible that the installation and reproducibility effects could both be positive in one case and both negative in the other, and if these errors happed to coincide with the values of the uncertainty at 95 % confidence, then one meter would be reading high by 0.2 % and the other low by 0.2 % and hence the difference would be 0.4 %. In that case it could be thought that the difference is greater than allowable for the uncertainty of the individual meters, where in fact it would be the assumption that there is no correlation that would be incorrect. If the analysis had been performed assuming full correlation of effects, then the individual values of 0.1 % would have been added linearity, resulting in an uncertainty evaluation of 0.4 %.

D.5   Suggested Test Methods for Estimating Uncertainty Components

D.5.1   Uncertainty owing to Linearity and Reproducibility

Uncertainty owing to meter linearity and reproducibility can be evaluated with reference to calibration data. The calibration data can be from a laboratory facility or from proving a meter in the field, so long as the data is representative in terms of meter type and the range of conditions covered. The important factors to consider are:

a) The meter model and size
b) The ranges of temperature, viscosity, flowrate, and Reynolds number

D.5.2   Reproducibility in Velocity Terms

As mentioned in sections D.2.1 and D.2.5, uncertainty in the transit time measurements can lead to a component of uncertainty that increased in relative terms as velocity is reduced. By quantifying this component of uncertainty in units of velocity, it can then be used to quantify the uncertainty in relative terms at any given velocity.

This component of uncertainty can be evaluated by performing a test whereby the flowrate is kept constant, and the sound velocity of the fluid is varied such that the relationship between the arrival time of the signals and any noise in the system is varied systematically through at least two full cycles of the ultrasonic signal waveform. This is usually achieved by varying the temperature of the liquid.

It is recommended that this test be performed at a constant velocity of approximately 1 m/s.

The required total span of sound velocity, $Span\Delta c$, for the test can be calculated using the following approximation:

$$Span\Delta c = \frac{2 \times c^2}{L_{Short} \times f}$$

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where c is the approximate speed of sound in the fluid, L_{Short} is the length of the shortest path in the meter, and f is the transducer frequency.

To ensure a step size of no more than 1/8th of a cycle of the signal the number of test points evenly distributed over $Span\Delta c$ should be equal to

$$Number\ of\ test\ points = \left[\frac{L_{Long}}{L_{Short}} \times 16\right] + 1$$

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where L_{Long} is the length of the longest path in the meter. The result should be rounded to the nearest whole number.

Below is an example of how these equations would be used:

A meter has path lengths of 0.2 m and 0.13 m and the transducer frequency is 1 MHz. It is to be tested using a fluid with a speed of sound of approximately 1370 m/s. Using the equations above, the sound speed should be varied over a span of 29 m/s with 26 test points evenly distributed over that span.

The expanded uncertainty deriving from this test should be expressed in flowrate or velocity terms. It can be calculated by taking the maximum meter factor minus the minimum meter factor, dividing by 2 and multiplying by the average flowrate or velocity at which the test was conducted.

D.5.3 Uncertainty owing to Fluid Dynamic Installation Effects

Tests performed in a flow laboratory can be used to evaluate the uncertainty owing to fluid dynamic effects downstream of disturbance elements such as bends and valves.

This standard does not prescribe a particular set of disturbances to be used. Manufacturers can provide data from type tests prescribed in ISO standards, but these tests are not a mandatory requirement of this chapter. The disturbance elements used in testing should be broadly representative of the conditions in which the meter is to be installed.

Care should be taken that test data used to evaluate uncertainty owing to installation effects encompasses the following:

a) The correct meter model
b) A representative range of Reynolds numbers
c) Realistic variations in upstream geometry
d) Placement of the meter at different distances and/or orientations relative to the disturbance

For more information, refer to ISO 12242 [13] and/or ASME MFC-10M-2000 [11].

Bibliography

[1] API *Manual of Petroleum Measurement (MPMS)* Chapter 4.5, *Master Meter Provers*

[2] API *MPMS* Chapter 4.8, *Operation of Proving Meters*

[3] API *MPMS* Chapter 5.3, *Measurement of Liquid Hydrocarbons Turbine Meters*

[4] API *MPMS* Chapter 5.5, *Fidelity and Security of Flow Measurement Pulsed-Data Transmission Systems*

[5] API *MPMS* Chapter 6 (all sections), *Metering Assemblies*

[6] API *MPMS* Chapter 6.3A, *Pipeline and Marine Loading/Unloading Measurement Systems*

[7] API *MPMS* Chapter 8.2, *Automatic Sampling of Petroleum and Petroleum Products (ASTM D4177)*

[8] API *MPMS* Chapter 13.2, *Statistical Methods of Evaluating Meter Proving Data*

[9] API *MPMS* Chapter 13.3, *Measurement Uncertainty*

[10] API *MPMS* Chapter 21.2, *Electronic Liquid Volume Measurement Using Positive Displacement and Turbine Meters*

[11] ASME MFC-10M-2000, *Method for Establishing Installation Effects on Flow Meters*

[12] ISO 9001, *Quality management systems – Requirements*

[13] ISO 12242, *Measurement of fluid flow in closed conduits – Ultrasonic transit-time meters for liquid*

[14] ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*