ASME MFC-5.3–2013

Measurement of Liquid Flow in Closed Conduits Using Doppler Ultrasonic Flowmeters

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Two Park Avenue • New York, NY • 10016 USA

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FOREWORD

The need for a document describing measurement of liquid flows by means of ultrasonic flowmeters has been recognized for many years. The ASME Committee on Measurement of Fluid Flow in Closed Conduits (MFC) and its Subcommittee 5: Ultrasonic Flowmeters (SC 5) have agreed to publish three standards to assist the users in understanding the three technologies: transit time, cross-correlation, and scattering (Doppler).

Published in June 2011, ASME MFC-5.1, Measurement of Liquid Flow in Closed Conduits Using Transit-Time Ultrasonic Flowmeters, applies to ultrasonic flowmeters that base their operation on the measurement of transit time of acoustic signals. MFC-5.1 concerns the volume flow-rate measurement of a single-phase liquid with steady flow or flow varying only slowly with time in a completely filled closed conduit.

This Standard, Measurement of Liquid Flow in Closed Conduits Using Doppler Ultrasonic Flowmeters, applies to ultrasonic flowmeters that base their operation on the reflection of waves. It concerns the volume flow-rate measurement of a liquid dominant fluid with steady flow or flow varying only slowly with time in a completely filled closed conduit.

Suggestions for improvement of this Standard are welcome. They should be addressed to the Secretary, ASME MFC Standards Committee, Two Park Avenue, New York, NY 10016-5990.

This Standard was approved as an American National Standard on April 12, 2013.

ASME MFC COMMITTEE
Measurement of Fluid Flow in Closed Conduits

(The following is the roster of the Committee at the time of approval of this Standard.)

CORRESPONDENCE WITH THE MFC COMMITTEE

General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, MFC Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
http://go.asme.org/Inquiry

Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard, the paragraph, figure or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

Interpretations. Upon request, the MFC Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the MFC Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The MFC Standards Committee regularly holds meetings that are open to the public. Persons wishing to attend any meeting should contact the Secretary of the MFC Standards Committee.

MEASUREMENT OF LIQUID FLOW IN CLOSED CONDUITS USING DOPPLER ULTRASONIC FLOWMETERS

1 GENERAL

1.1 Scope

This Standard applies only to ultrasonic flowmeters that base their operation on the reflection of acoustic waves, frequently referred to as a Doppler flowmeter. The flow measurement utilizes either frequency or time domain techniques. This Standard concerns the volume flow-rate measurement of a liquid dominant fluid with steady flow or flow varying only slowly with time in a completely filled closed conduit.

1.2 Purpose

This Standard provides a

(a) description of the operating principles employed by the ultrasonic flowmeters covered in this Standard

(b) guideline to expected performance characteristics of ultrasonic flowmeters covered in this Standard

(c) description of calibration and diagnostic procedures

(d) description of potential uncertainty sources and their reduction

(e) common set of terminology, symbols, definitions, and specifications

1.3 Terminology and Symbols

Paragraph 1.3.1 lists definitions from ASME MFC-1M used in this Standard. Paragraph 1.3.2 lists definitions specific to this Standard. Table 1.3-1 lists symbols used in this Standard. Table 1.3-2 lists subscripts used in this Standard.

1.3.1 Definitions From ASME MFC-1M

accuracy: the degree of freedom from error; the degree of conformity of the indicated value to the true value of the measured quantity.

NOTES:
(1) The concept measurement accuracy is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it provides a smaller measurement error.
(2) The term measurement accuracy is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measured. Measurement accuracy should not be mistaken for measurement precision.

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.

calibration: the experimental determination of the relationship between the quantity being measured and the device that measures it, usually by comparison with a traceable reference standard. Also, the act of adjusting the output of a device to bring it to a desired value, within a specified tolerance, for a particular value of the input.

NOTE: This document is written with calibration defined as the determination of difference from a reference and the adjustment to align within a specified tolerance. This is common U.S. usage.
It is understood that in other parts of the world, some countries and groups define calibration as only the determination of difference from a reference. A second term used is calibration adjustment, which is to align within a specified tolerance.

cross-flow velocity: component of liquid flow velocity at a point in the measurement section that is perpendicular to the measurement section's axis.

nonrefractive system: an ultrasonic flowmeter in which the acoustic path crosses the solid/process liquid interfaces at a right angle.

refractive system: an ultrasonic flowmeter in which the acoustic path crosses the solid/process liquid interfaces at other than a right angle.

uncertainty: the range within which the true value of the measured quantity can be expected to lie with a specified probability and confidence level.

velocity profile correction factor, S: dimensionless factor based on measured knowledge of the velocity profile used to adjust the meter output.

1.3.2 Definitions Specific to This Standard

diagnostics: comparison of internal direct and derived measurement values to allow the user to ascertain the condition of the operation of the ultrasonic flowmeter.

measurement section: section of conduit in which the volumetric flow rate is sensed by the acoustic signals. The measurement section is bounded at both ends by planes perpendicular to the axis of the section and located at the extreme upstream and downstream transducer positions. The measurement section is usually circular in cross section; however, it may be square, rectangular, elliptical, or some other shape.

Table 1.3-1 Symbols

Quantity (First Location)	Symbol	Dimensions	SI Units
Cross-sectional area	A	L^2	m^2
Sound propagation speed [eq. (1)]	c	LT^{-1}	m/s
Frequency	f	T^{-1}	Hz
Distance between transmitter/receiver and scatterer	l	L	m
Volume flow rate	Q	L^3T^{-1}	m^3/s
Velocity profile correction factor	S	. . .	. . .
Time	t	T	s
Velocity of wave source (Fig. 2.1-1)	v_{ws}	LT^{-1}	m/s
Flow velocity	v	LT^{-1}	m/s
Average velocity	$\bar{v}_x$	LT^{-1}	m/s
Mean axial velocity	$\bar{v}$	LT^{-1}	m/s
Velocity of a scatterer (Fig. 2.1-2)	v_s	LT^{-1}	m/s
Doppler shifted frequency [eq. (1)]	f'	T^{-1}	Hz
Doppler frequency shift	Δf	T^{-1}	Hz
Source frequency (carrier frequency) [eq. (1)]	f_0	T^{-1}	Hz
Transducer transmit signal [eq. (9)]	$s_t(t)$	. . .	. . .
Transducer receive signal [eq. (9)]	$s_r(t)$	. . .	. . .
Round-trip time [eq. (9)]	t_{rt}	T	s
Delta round-trip time [eq. (13)]	Δt_{rt}	T	s
Time difference between successive transmissions	Δt_p	T	s
Weighting factor for acoustical path	w	. . .	. . .
Angle between the pipe wall and direction of acoustic propagation	φ	. . .	rad

measurement volume: region within the measurement section from which acoustic waves reflected by scatters are received by the receiving transducer.

mode conversion: when an ultrasonic wave passes at an oblique angle between two materials of variant acoustic impedance, mode conversion can occur. As an example, when a wedge-type transducer is coupled to the outside of a pipe, the longitudinal waves generated by the ultrasonic transducer can produce multiple other types of waves (e.g., shear waves) in the pipe wall.

scatterer(s): discontinuity in the acoustic impedance of the liquid. Scatterers are suspended solids or gas bubbles that reflect the sound in the liquid. Meter manufacturers may call them reflectors.

ultrasonic transducer: a device designed to convert electrical signals into directed ultrasonic waves and vice versa, usually by inclusion of materials exhibiting the piezoelectric or piezomagnetic effects. When employed for flow measurement, ultrasonic transducers are commonly referred to as simply as *transducers*.

1.3.3 Symbols Used in This Standard. See Table 1.3-1.

1.3.4 Subscripts Used in This Standard. See Table 1.3-2.

Table 1.3-2 Subscripts

Subscript Symbol	Description
x	Direction corresponding to the pipe axis
y	Direction orthogonal to the pipe axis and in the plane formed by the acoustic beam and pipe axis
s	Scatterer velocity
rt	Round-trip
ws	Wave source

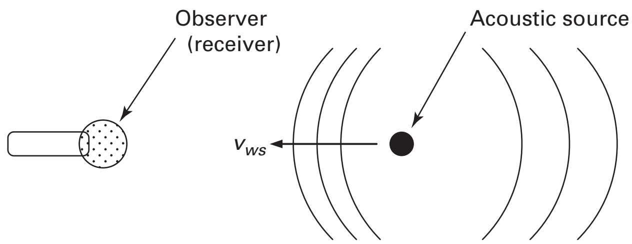
2 PRINCIPLE OF OPERATION

The ultrasonic flowmeter can be thought of as comprising a primary and secondary device. The primary device consists of a measurement section with the installed transducers. The measurement section may be a whole spool piece or an existing section of pipe to which transducers are installed.

The secondary device comprises the electronic equipment required to operate the transducers, make the measurements, process the measured data, and display or record the results. The secondary processing section, in addition to estimating the flow rate from the measurement, should be capable of rejecting invalid measurements, noise, etc. The indicated flow rate may be the result of one or more individual flow velocity determinations.

Most meters have outputs available, either as standard features or as optional equipment. Displays may show flow rate, integrated flow volume, and/or direction and may be analog or digital. Signal outputs usually include one or more of the following: current, voltage, digital,

Fig. 2.1-1 Doppler Phenomena Without a Scatterer



and a pulse rate proportional to flow. These outputs may or may not be electrically isolated. Flowmeters may also include alarms and diagnostic aids.

Doppler ultrasonic flowmeters base their operation on acoustic waves reflected at scatterers. Scatterers are discontinuities in the acoustic impedance of the fluid. It is assumed that the scatterers flow with the same velocity as the fluid. This assumption is required to be correct for the Doppler meter to accurately measure the flow rate of the liquid.

The Doppler effect is usually described as a frequency shift but can also be described as a change in the round-trip time between the transducer and a scatterer. The effect can be observed either as a shift in the frequency of a continuous wave or directly as a shift in the round-trip time of time-limited signals. The frequency domain approach is described in para. 2.1. The time domain approach is described in para. 2.2.

2.1 Frequency or Continuous Wave Domain

The Doppler effect is observed whenever there is a relative motion between the source of waves and an observer. In ultrasonic flow metering, the Doppler shift is caused by reflection of the ultrasonic wave at scatterers in the moving fluid. The Doppler shift is proportional to the velocity of the scatterers.

When an acoustic wave source moves towards a stationary observer, there is an apparent increase in the frequency measured by the observer (see Fig. 2.1-1). When the source moves away from the stationary observer, there is an apparent decrease in the frequency observed.

In either case, the Doppler-shifted frequency, f', is related to the source frequency, f_0, by the following expression, where ν_{ws} is the velocity of the wave source, and c is the sound propagation speed in the surrounding media:

$$f' = f_0 \frac{c}{c + \nu_{ws}} \tag{1}$$

where

c = sound propagation speed
f_0 = source frequency
ν_{ws} = velocity of the wave source

Figure 2.1-2 illustrates a fixed frequency emitting source and a moving scatterer. The source emits ultrasound at a frequency, f_0, but the scatterer observes a frequency lower than this as it is moving away with a velocity, ν_s. The scatterer is also moving away from the receiver, which is also the source, so the observed frequency at the receiver is lower still. Hence, the receive signal has experienced two Doppler frequency shifts. The transducer will emit a frequency spectrum rather than a single frequency with a bandwidth dependent on the properties of the piezoelectric crystal. The transducer must be sufficiently broadband to receive the Doppler-shifted frequency, which is typically within a few percentage points of the source frequency.

For a scatterer moving at radial velocity, ν_s, relative to an ultrasonic transducer having a transmit frequency, f_0, the resulting received frequency, f', is calculated by

$$f' = f_0 \frac{c}{c + 2\nu_s} \tag{2}$$

When the Doppler effect is applied to flow measurement, a fixed source emits ultrasound that is reflected by a moving scatterer and then received by a fixed receiver.

This can be rewritten as follows:

$$f' = f_0 \left(1 - \frac{2\nu_s}{c + 2\nu_s}\right) \tag{3}$$

with $c >> \nu_s$, the ν_s term in the denominator can be eliminated.

$$f' = f_0 \left(1 - \frac{2\nu_s}{c}\right) \tag{4}$$

The Doppler frequency shift is then

$$\Delta f = -\frac{2\nu_s}{c} f_0 \tag{5}$$

With the Doppler beam not parallel to the flow direction (see Fig. 2.1-3), the Doppler frequency shift becomes

$$\Delta f = -\frac{2\nu_s}{c} f_0 \sin \varphi \tag{6}$$

Fig. 2.1-2 Doppler Phenomena With a Scatterer

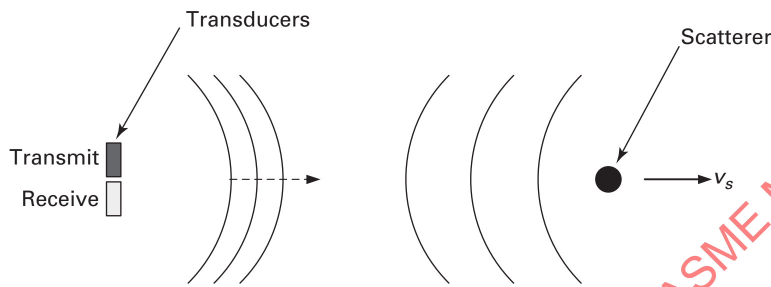


Fig. 2.1-3 Doppler Beam Not Parallel to the Flow Direction

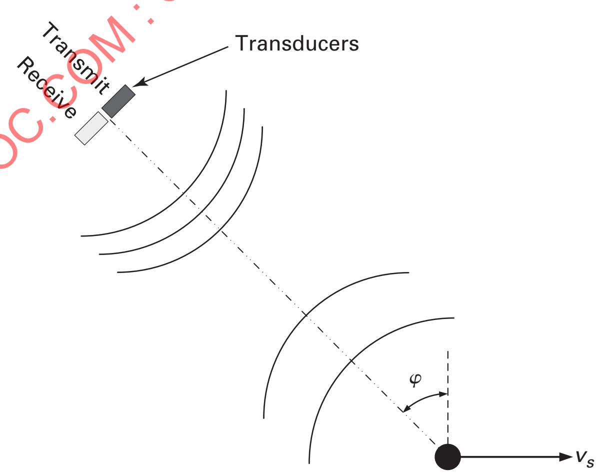
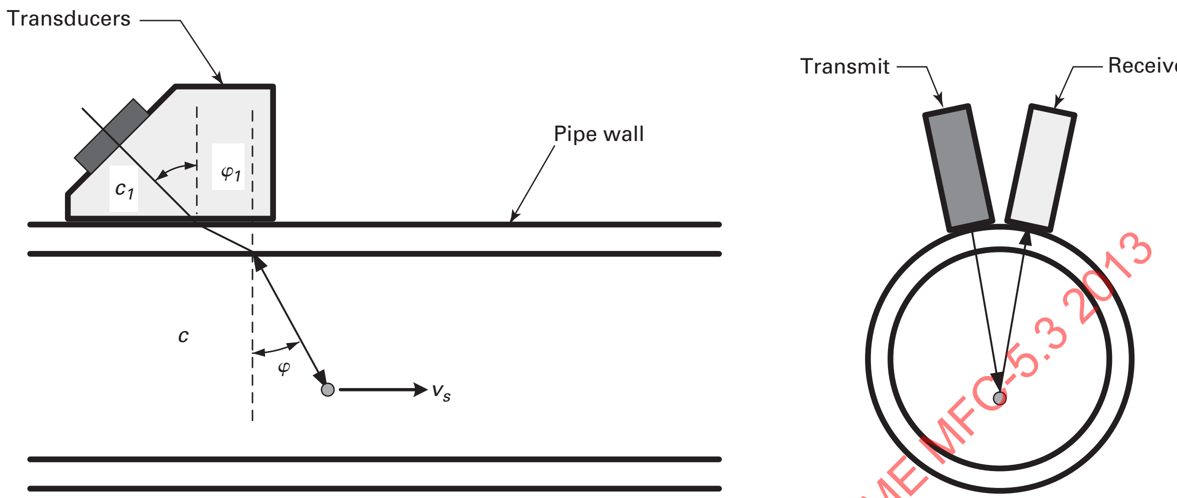


Fig. 2.1-4 Clamp-On Doppler



The scatterer velocity is, therefore

$$\nu_s = -\frac{c}{\sin\varphi}\frac{\Delta f}{2f_0} \tag{7}$$

When using clamp-on transducers, the sound speed and angle in the fluid are substituted, using Snell's law, by the sound speed, c_1, and angle, φ_1, of the coupling wedge as shown in Fig. 2.1-4.

According to Snell's law

$$\frac{c}{\sin\ \varphi} = \frac{c_1}{\sin\ \varphi_1}$$

Therefore

$$\nu_s = \frac{c_1}{\sin\ \varphi_1}\frac{\Delta f}{2f_0} \tag{8}$$

The formula for externally mounted transducers is, therefore, independent of the generally unknown sound speed of the fluid.

2.2 Time Domain

For explaining the operating principle, assume a single small scatterer moving perpendicular to a small transducer as shown in Fig. 2.2-1. If the transducer transmits the signal, $s_t(t)$, it will receive a similar signal, $s_r(t)$, that is delayed by the round-trip time and, due to various damping effects, changed in amplitude by a factor of a.

$$s_r(t) = a \times s_t[t - t_{rt}\ (t)] \tag{9}$$

Since the scatterer is moving, the round-trip time is not constant. Assuming the scatterer at location, l_0, at time, $t = 0$, the round-trip time, t_{rt}, is

$$t_{rt}(t) = 2 \times \frac{l}{c} = 2 \times \frac{l_0 + \nu_s t}{c} \tag{10}$$

where

c = the sound speed of the fluid

ν_s = the velocity of the moving scatterer

Time domain techniques use a succession of time-limited signals. In the simplest case, it is a pair of two identical transmission pulses, transmitted at a time, Δt_p, apart. The received signals, s_{r1} and s_{r2}, differ in the round-trip time, t_{rt}, as follows:

$$s_{r1} = a \times s_1\ [t - t_{rt}\ (t)] \tag{11}$$

$$s_{r2} = a \times s_t\ [t - t_{rt}\ (t + \Delta t_p)] \tag{12}$$

The difference in round-trip time is

$$\Delta t_{rt} = t_{rt}(t + \Delta t_p) - t_{rt}(t) \tag{13}$$

Using eq. (10), the relationship between the difference, Δt_{rt}, in the round-trip time and the time difference, Δt_p, between the successive transmissions, can be expressed as

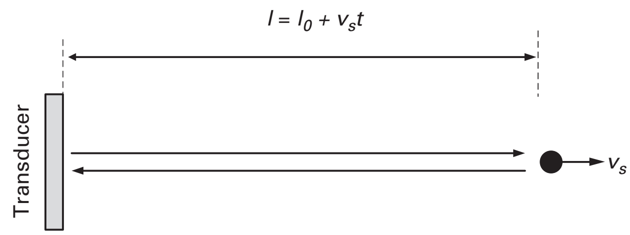
$$\Delta t_{rt} = \frac{2\nu_s}{c}\Delta t_p \tag{14}$$

The difference, Δt_{rt}, in round-trip time can be evaluated by calculating the cross-correlation of s_{r1} and s_{r2}. The maximum of the cross-correlation is located at Δt_{rt}.

When using the Doppler effect in flow measurement, the transducer typically looks at the scatterer under an angle, φ, as shown in Fig. 2.1-3. Equation (10) then becomes

$$t_{rt}(t) = 2 \times \frac{(l_0 + \nu_s \sin\ \varphi)}{c} \tag{15}$$

Fig. 2.2-1 Scatterer Moving Perpendicular to a Transducer



Thus, the change in round-trip time according to eq. (14) becomes

$$\Delta t_{rt} = \frac{2 v_s \Delta t_p}{c} \sin \varphi \tag{16}$$

The velocity of the moving scatterer is

$$v_s = \frac{c}{\sin \varphi} \frac{\Delta t_{rt}}{2\Delta t_p} \tag{17}$$

As with the frequency domain case, for clamp-on transducers, the sound speed and angle in the fluid can be substituted, using Snell's law, by the sound speed, c_1, and angle, φ_1, of the coupling wedge, making this configuration independent of the fluid sound speed.

$$v_s = \frac{c_1}{\sin \varphi_1} \frac{\Delta t_{rt}}{2\Delta t_p} \tag{18}$$

2.3 Estimating Volumetric Flow

The formulas derived so far are valid for a single scatterer and assume the use of a single transducer for both transmission and reception of acoustic waves or where the transmitting and receiving transducers are very close to each other. The signals a Doppler flowmeter actually receives are the sum of the signals caused by multiple scatterers from different locations within the measurement volume. Their velocity differs depending on their location within the flow profile. The contribution of each individual scatterer to the amplitude of the receive signal depends on the attenuation characteristic of the liquid and the scatterers, as well as the directivity characteristic of the transducers.

If the measurement volume is small enough such that all scatterers within it can be assumed to move at the same velocity, then the formulas derived for a single scatterer are valid for the signals created by all scatterers within the measurement volume. Equations (8) and (18) provide an estimate for the average velocity, $\bar{v}_x$, within the measurement volume.

$$\bar{v} = v_s$$

The average velocity, $\bar{v}_x$, is multiplied with the profile correction factor, S, to obtain the mean axial velocity, $\bar{v}$.

$$\bar{v} = S \times \bar{v}_x$$

The volumetric flow rate Q is the product of the mean axial velocity and the cross-sectional area, A, of the measurement section.

$$Q = A \times \bar{v} \tag{19}$$

The time domain and frequency domain technique limit the measurement volume (due to the use of continuous wave transmitters) to a defined region in different ways. The frequency domain Doppler flowmeter works with individual transducers for transmission and reception, where the measurement volume is defined by the interaction of the two transducer beams as shown in Fig. 2.3-1, illustration (a). Because of the time-limited transmit signal, a time domain Doppler flowmeter can operate with a single transducer acting as transmitter and receiver as shown in Fig. 2.3-1, illustration (b). The measurement volume is then defined by the beam geometry, and a time window is applied to the received signals. As the time window can be shifted to measure different volumes in the fluid, the time domain Doppler flowmeter offers the additional possibility to scan the flow profile for improved accuracy.

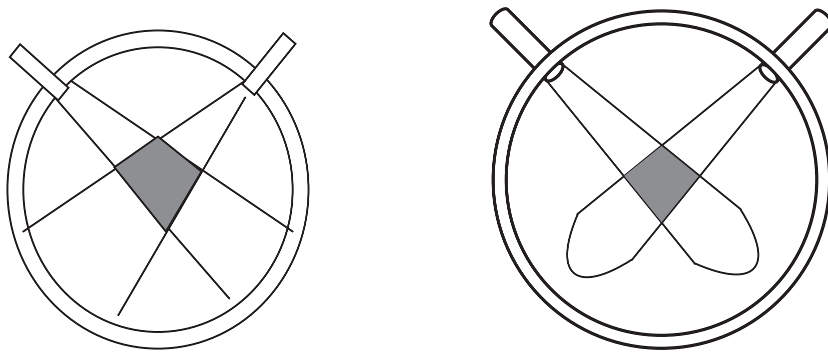
In practical applications, the assumption of the measurement volume being small compared with the pipe size is valid only to a certain degree. Therefore, the reading of the Doppler flowmeter is dependent on the distribution of scatterers within the measurement volume and attenuation of the fluid.

3 UNCERTAINTY SOURCES AND UNCERTAINTY REDUCTION

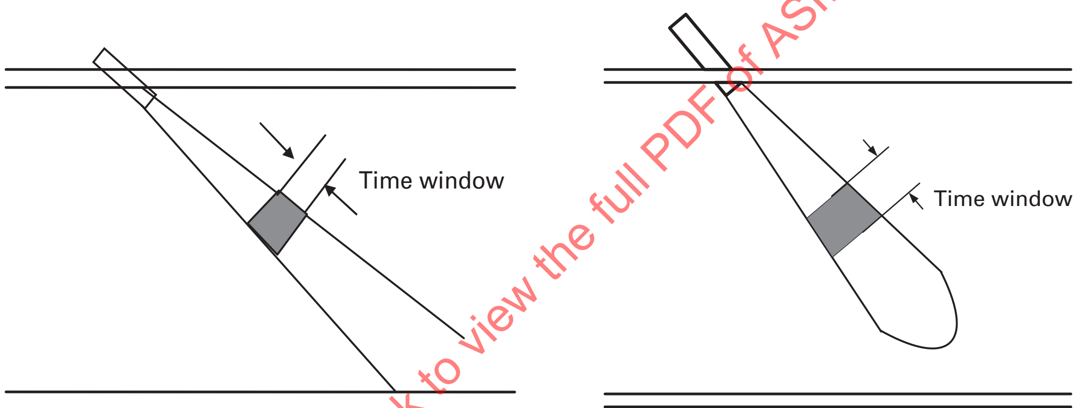
The purpose of this section is to describe some of the possible uncertainty sources for Doppler ultrasonic flowmeters. These components should be addressed in detail when doing an uncertainty analysis for a particular installation.

According to eq. (19), the volume flow is calculated as a product of three factors: the velocity, v_x, the flow profile correction factor: S, and the cross section, A, of the measurement section. This means that many sources of the uncertainty can be grouped into three classes: flow velocity uncertainty, flow profile related uncertainty, and uncertainty due to the pipe geometry.

Fig. 2.3-1 Doppler Measurement Systems



(a) Measurement Volume of an Arrangement With Two Transducers



(b) Measurement Volume of a Time or Pulse Doppler Flowmeter

In-situ flowmeter calibration can reduce measurement uncertainty from flow profile effects, installation effects, and other sources (see para. 5).

3.1 Uncertainty in the Flow Velocity Measurement

3.1.1 Acoustic Beam Angle. With nonrefractive systems, the determination of scatterer velocity from the Doppler frequency shift, or round-trip time difference for the time domain method, is based on the liquid sound speed, c, and acoustic beam angle (φ) [see eqs. (7) and (17)]. The uncertainty in $\overline{v}_x$ is in direct proportion to the uncertainty in the acoustic beam angle. Uncertainty in the acoustic beam angle for nonrefractive systems can be reduced by accurate geometric measurements.

With refractive systems, the flow velocity is calculated by eq. (8) or (18) from the Doppler frequency shift or round-trip time difference, the sound speed in the wedge, c_1, and the sine of the wedge angle, φ_1. In reality, the received signal is comprised of many different beam angles resulting from reflections off scatterers having varying size, shape, and distribution within the flow stream. A clamp-on transducer is able to receive a wider range of scattering angles due to the extended propagation of ultrasound along the pipe wall. This effect will result in a broadening of the Doppler frequency spectrum giving somewhat greater uncertainty in the Doppler frequency and therefore flow velocity.

3.1.2 Sound Speed Dependency. In refractive Doppler systems, the change in liquid sound speed causes a compensating change in the acoustic beam angle; therefore, accurate knowledge of liquid sound speed is not required for this type of system.

Nonrefractive (insert-type) systems, however, do require accurate knowledge of liquid sound speed. For example, in a water application, a change in process temperature from 10°C to 16°C (50°F to 61°F) may result in an additional flow indication error of approximately −1.4%, if not compensated.

3.1.3 Doppler Shift (Frequency Domain Systems). The uncertainty in $\overline{v}_x$ is proportional to the uncertainty in the Doppler shift frequency measurement. Manufacturers may use different approaches to measure the Doppler shift frequency, but they all require accurate knowledge of the transmit signal, since this serves as the reference frequency in eq. (8).

A demodulator technique is commonly used for continuous wave (CW) Doppler flowmeters where the demodulator output represents Doppler shift frequency. The Doppler shift frequency can then be digitally sampled and analyzed using a digital processing technique, such as fast Fourier transforms (FFT).

Uncertainties associated with the transmit frequency and digital sampling of the demodulator output can be reduced by the use of a stable high frequency oscillator.

3.1.4 Round-Trip Time Difference (Time Domain Systems). Uncertainty in the round-trip time difference measurement will result in a corresponding uncertainty in $\overline{v}_x$. This timing uncertainty can be associated with limitations in the electronic timing circuitry, such as from clock jitter or drift. Timing errors can also result from excessive flow velocity, especially for the time domain or pulse Doppler methods, where a large change in the scatterer position (between successive transmits) can produce unreliable signal correlation.

Uncertainty in the measurement of time may be reduced by the use of stable and accurate high frequency oscillators, averaging of many individual round-trip time measurements and by selectively rejecting receive signals that are considered unacceptable for reliable time measurement.

3.1.5 Noise. Noise sources may be either electrical or acoustic and either asynchronous (random) or synchronous with respect to the received signal. The effect of random noise is generally an increased standard deviation of the measurement result. The degree of influence is dependent on the signal-to-noise ratio (SNR) and spectral content of the noise. Random noise contribution to uncertainty in the long-term average of the measurement result should be negligible, as long as the noise level is not so high that the scattered signal cannot be reliably detected and processed by the flowmeter.

As all electronic components produce noise, a certain level of electrical noise is unavoidable. External sources of electrical noise are, for instance, DC/DC converters and variable frequency drives (VFDs) driving electrical machines. Possible sources of external acoustic noise are pumps and flow-restricting plumbing components, such as regulator valves.

External noise that includes frequency components that are similar to the source or carrier frequency will have the greatest influence on the flow measurement accuracy, since this noise cannot be removed by filtering.

External electrical noise can be attenuated by appropriate shielding and grounding according to the manufacturer's recommendations. Receive signal level can be increased by increasing the transmitted signal level.

Synchronous noise is inherently present in most Doppler systems, especially when just one transducer is used as both transmitter and receiver. This type of noise represents the carrier signal in a continuous wave Doppler system and therefore does not impact the uncertainty of the flow measurement; however, excessive synchronous noise may limit the sensitivity of the device to reduced levels of scatterers in the liquid.

3.2 Flow Profile Related Uncertainties

The ultrasonic flowmeter calculates the mean velocity based on a fully developed, symmetrical velocity profile and a well-defined geometry of the measurement volume. When these assumptions are valid, the Reynolds number and pipe roughness, which determine the friction factor, are sufficient to determine the velocity profile correction factor, S.

Disruption of the flow profile can be caused by upstream and downstream pipe disturbances, such as pumps, elbows, tees, reducers, and valves, or by pipe intrusions, such as thermo wells or sampling probes. Velocity profile variations can also be caused by changes in flow rates (including transients), wall roughness, temperature, viscosity, transducer projections, and transducer cavities.

Disturbances upstream of the flowmeter installation location usually have a greater influence on the flow profile than those that are located downstream.

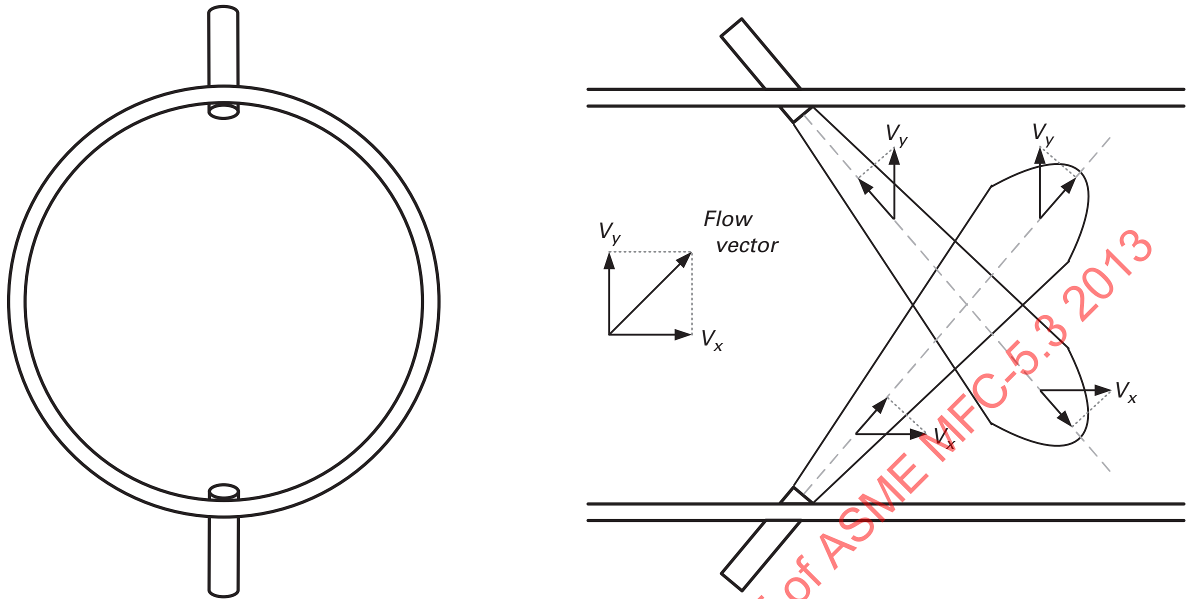
The flow profile related uncertainty can be reduced by increasing the upstream straight pipe length, increasing the number of transducers by choosing an appropriate transducer location, and by the use of flow conditioners. However, be aware that the flow conditioner can become fouled and may adversely influence the velocity profile that it was meant to correct (see ASME MFC-3Ma–2007, Nonmandatory Appendix 1c).

High acoustic attenuation of the fluid can affect the penetration depth of the ultrasonic signals, thus causing a change of the shape and location of the measurement volume. When the measurement volume is shifted toward the pipe wall, a corresponding shift in the profile correction factor, S, is generally required.

3.2.1 Multiple Acoustic Paths. The use of multiple Doppler measurements on the same pipe section may be used to reduce the uncertainty from a flow profile disturbance, e.g., installing a second measurement path on the opposite side of the pipe may be justified in cases where the beam penetration into the liquid is limited by high concentrations of scatterers.

3.2.2 Nonaxial Flow. Velocities that are normal or not axial do not contribute to the flow rate, but they can cause uncertainty in the ultrasonic flowmeter response

Fig. 3.2.2-1 A Typical Cross-Path Ultrasonic Flowmeter Configuration



due to the location and orientation of the paths. However, nonaxial flow uncertainty can be reduced by the use of an appropriate acoustic path orientation or by computing velocities on appropriate multiple acoustic paths, e.g., by crossed paths as illustrated in Fig. 3.2.2-1.

ν_x = axial velocity
ν_y = nonaxial velocity

The ν_y component along one path is in the same direction as the ν_x component but in the opposite direction on the crossed path, thus cancelling the nonaxial flow component.

3.2.3 Scanning of the Flow Profile. The time domain technique of Doppler flow measurement has the potential to scan the flow profile. This requires that the measurement volume is small compared with the dimensions of the pipe. It also requires that the penetration depth of the signals is not affected by the attenuation of the fluid. Based on the measured flow profile, it is possible to reduce the uncertainty caused by profile distortions.

Knowledge of the liquid sound speed is required to accurately infer the location of the measurement volume within the pipe cross section. Any error in the measurement volume location will result in the incorrect weighting factor being applied to the associated velocity measurement. Fig. 3.2.3-1 illustrates how the measurement volume location can affect the contribution to the average flow velocity, where velocities measured near the center of the pipe contribute less to the overall flow measurement.

Additional flow profile-related uncertainties can occur from pipe wall propagation delays for clamp-on systems installed on metal pipes, where identical round-trip arrival times can be associated with multiple depths into the liquid (see Fig. 3.2.3-2).

3.3 Cross-Section Dimensional Uncertainty

Uncertainty in the assumed cross-sectional area of the measurement section causes an uncertainty in the volume flow rate estimate. This uncertainty may be due to initial measurement section shape irregularities, such as out-of-roundness or manufacturing tolerances, or it may be due to changes in the initial shape caused by temperature, pressure, or structural loading.

In case of field-mounted transducers, the pipe inside diameter should be calculated from circumference and wall thickness measurements. The flowmeter utilizes pipe dimensions to calculate the cross-sectional area of the pipe. Nominal values taken from pipe tables will match the actual pipe dimensions to within a certain tolerance; however, the best performance is achieved when actual pipe measurement information is entered into the flowmeter.

The pipe outside diameter can be calculated from a circumference measurement. An ultrasonic wall thickness gage can be used to reduce the uncertainty associated with the pipe inside diameter; however, these devices typically will not detect or measure a pipe lining or material buildup if present.

The cross-sectional area may change because of the formation of deposits or growths, such as erosion, corrosion, scale, wax, hydrates, and algae in the measurement section. Periodic inspection can determine dimensional change due to deposits or growths, but the frequency of the inspection is beyond the scope of this Standard.

Fig. 3.2.3-1 Measurement Volume Location and Flow Profile Averaging

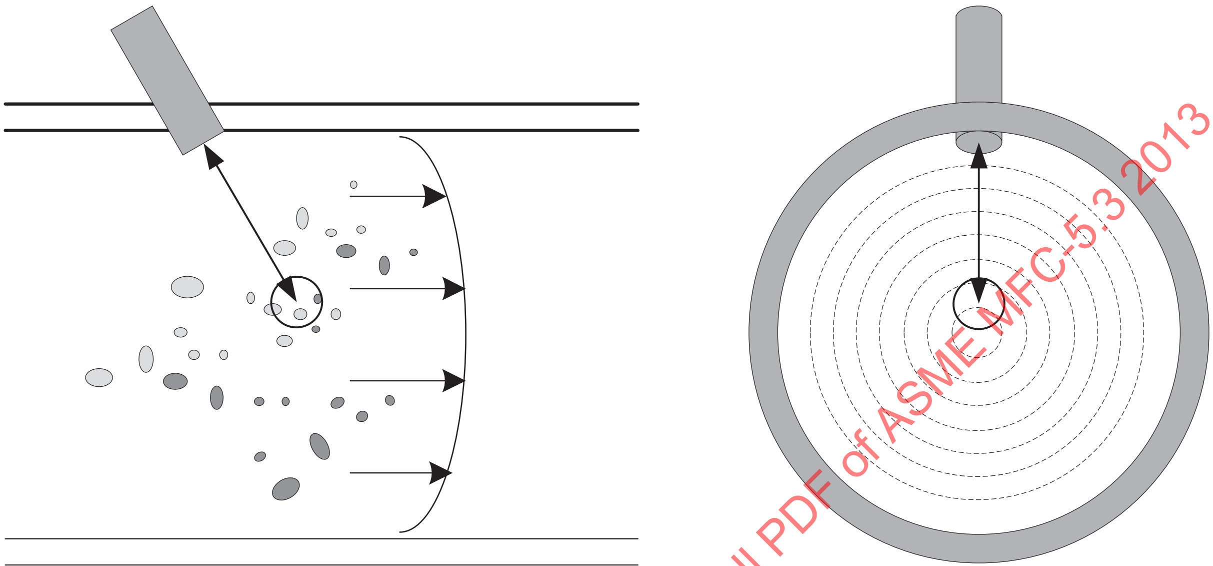
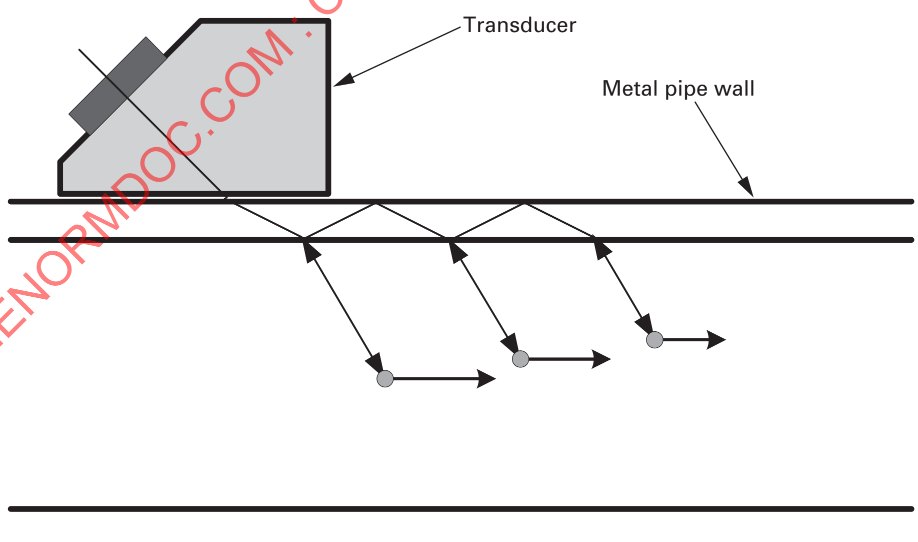


Fig. 3.2.3-2 Uncertainty in Penetration Depth Due to Pipe Wall Reflections



Cross-section dimensional uncertainty can be reduced by manufacturing or choosing a measurement section that has constant dimensions along its length, can be accurately measured, and has a stable surface, so that cross-section changes with time, due to corrosion, material buildup, or loss of protective coatings, will be small. Calculating the diameter from the circumference minimizes the effects of out-of-roundness on cross-section dimensional uncertainty. The effect of a diameter variation in axial direction can be reduced through averaging of diameter measurements made at the upstream, middle, and downstream ends of the measurement section.

The measurement section should be inspected or measured with instrumentation periodically to determine if the dimensional factor should be adjusted to compensate for observed changes.

3.4 Installation Effects

3.4.1 Temperature. Temperature can affect the flow measurement accuracy by its influence on either the liquid sound speed or the transducer wedge sound speed.

For nonrefractive insertion type Doppler flowmeters, the error in flow velocity is directly proportional to the error in the liquid sound speed [see eqs. (7) and (17)]. This type of temperature-dependent flow error may be automatically compensated in cases where the sound speed of the liquid is well defined over the operating temperature range, such as for water.

Clamp-on-type Doppler flowmeters do not rely on precise knowledge of the liquid sound speed; however, the sound speed of the transducer wedge [c_1 in eqs. (8) and (18)] will also vary with temperature and must therefore be taken into account for improved flow accuracy.

3.4.2 Vibration. With clamp-on transducers, vibration can interrupt the mechanical coupling to the pipe. The use of secure transducer-mounting assemblies and dry coupling materials can minimize the impact of vibration on clamp-on meter operation.

Pipe vibrations may also influence the short-term position of the scatterers relative to the transducers on the pipe wall. If these vibrations are of high enough frequency, flow sample aliasing may result in measurement errors.

3.4.3 Pulsating Flow. Uncertainty can occur if the sampling rate of the flowmeter is not at least two times faster than fluid pulsation frequency.

3.4.4 Two or More Phase Flow. A Doppler system requires a liquid with small to moderate levels of scatterers in the liquid. However, if the volume fraction of gas or solids becomes too great, the scatterers are no longer neutrally suspended and, therefore, less likely to be moving at the same velocity as the liquid itself. This situation will lead to large measurement errors, since the Doppler system responds only to the movement of scatterers within the liquid.

3.4.5 Equipment Degradation. Fouling or physical degradation of the equipment can increase the measurement uncertainty. Equipment design should include reasonable tolerance to changes in component values and process conditions. The equipment should also indicate when degradation of flowmeter performance occurs. The probability of uncertainty can be reduced considerably by including suitable self-test or diagnostic circuits in the equipment.

3.4.6 Computation. There is a degree of uncertainty associated with the computations made by the electronic circuits because of the finite limits in processing accuracies. However, this uncertainty will normally be negligible.

4 APPLICATION AND SELECTION

4.1 Installation Considerations

Some of the uncertainty sources listed in section 3 can be reduced or eliminated by proper installation. Uncertainties the user should address during the design phase of a project are listed below.

4.1.1 Partially Filled Pipe. The ultrasonic meters referenced in this Standard do not incorporate a means to compensate for portions of a fluid conduit that may not be entirely filled with liquid.

A primary consideration of the installation of any ultrasonic flowmeter should include mounting of the transducer in a section of the piping system where the liquid will completely fill the conduit when measurements are to be made. Installation locations where the conduit potentially is not completely filled with liquid, such as spilling into an open container or at the uppermost point in a piping system, should be avoided. Manufacturers will typically recommend that installation of transducers on horizontal pipes be limited to the sides, avoiding the top of the pipe, as gas may accumulate and cause the flowmeter to lose signal.

Installations on vertical pipes should be limited to sections where flow is traveling in the upward direction unless sufficient backpressure is present that ensures a completely filled pipe at all times.

4.1.2 Entrained Gas. Velocity/area flowmeters, such as ultrasonic flowmeters, do not have an absolute means to compensate for the volume of gases that may be suspended within the carrier liquid. As an example, if entrained gases make up 2% of the volume of the liquid/gas composition passing through the flowmeter-measuring region, a 2% volumetric liquid measurement uncertainty will result, assuming that the bubbles are dispersed and moving with the same velocity as the liquid.