International Standard

ISO 24062

First edition
2023-12

Measurement of fluid flow in closed conduits — Clamp-on ultrasonic transit-time meters for liquids and gases

Mesurage du débit des fluides dans les conduites fermées — Débitmètres non intrusifs à ultrasons à temps de transit pour les liquides et les gaz

Reference number
ISO 24062:2023(en)

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Published in Switzerland

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Foreword

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This document was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 5, *Velocity and mass methods*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Non-intrusive (clamp-on) ultrasonic meters (USMs) have become one of the accepted flow measurement technologies for a wide range of applications, including process and control measurements. Non-intrusiveness also brings characteristics relevant for economics, safety, and environment. Ultrasonic technology has inherent features such as no pressure loss and wide rangeability. USMs can deliver diagnostic information through which it may be possible to demonstrate that an ultrasonic flowmeter is performing in accordance with specification.

This document provides a description of the non-intrusive (clamp-on) meter, typical application areas, the measures which should be used in assessing the likely performance in terms of error, repeatability and reproducibility when used under ideal and non-ideal operational conditions.

Measurement of fluid flow in closed conduits — Clamp-on ultrasonic transit-time meters for liquids and gases

1 Scope

This document specifies requirements and recommendations for non-intrusive (clamp-on) ultrasonic flowmeters (USMs), which use the transit time of ultrasonic signals to measure the volumetric flowrate in closed conduits. Transit time flowmeters are predominantly used on single-phase fluids (liquid and gases) but can also be used where small quantities of additional phases are present.

This document specifies performance, calibration, and output characteristics, and deals with installation conditions.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4006, *Measurement of fluid flow in closed conduits — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 4006 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 Quantities

3.1.1
volume flowrate
q_V

$$q_V = \frac{dV}{dt}$$

where

V is volume;

t is time

[SOURCE: ISO 80000-4:2006, 4-31[2]]

3.1.2
mean flow velocity
v_p
volume flowrate (3.1.1) divided by the cross-sectional area of the pipe

3.1.3
path velocity
v_l
average fluid velocity on an ultrasonic path

3.1.4
Reynolds number
Re_D
dimensionless parameter expressing the ratio between the inertia and viscous forces in the fluid

$$Re_D = \frac{\rho v_A D}{\mu} = \frac{v_A D}{v_{kv}}$$

where

ρ	is density;
v_A	is the mean flow velocity;
D	is the pipe internal diameter;
μ	is the dynamic viscosity;
v_{kv}	is the kinematic viscosity

3.2 Meter design

3.2.1
ultrasonic path
path travelled by an ultrasonic signal between a pair of ultrasonic transducers

3.2.2
electronic unit
part of the meter that controls the transducers, processes the signals into a flowrate and provides outputs (see 4.2.3)

3.3 Thermodynamic conditions

3.3.1
metering conditions
conditions, at the point of measurement, of the fluid of which the volume flow is to be measured

Note 1 to entry: Also known as operating conditions or actual conditions.

3.3.2
standard conditions
defined temperature and pressure conditions used in the measurement of fluid quantity so that the standard volume is the volume that would be occupied by a quantity of fluid if it were at standard temperature and pressure

Note 1 to entry: Standard conditions may be defined by regulation or contract.

Note 2 to entry: Not preferred alternatives: reference conditions, base conditions, normal conditions, etc (see ISO 91[3]).

Note 3 to entry: Metering and standard conditions relate only to the volume of the fluid to be measured or indicated and should not be confused with rated operating conditions or reference conditions (see ISO/IEC Guide 99:2007, 4.9 and 4.11[4]), which refer to influence quantities (see ISO/IEC Guide 99:2007, 2.52[4]).

3.4 Statistics

3.4.1
error
measured quantity value minus a reference quantity value

[SOURCE: ISO/IEC Guide 99:2007, 2.16[4]]

3.4.2
repeatability (of results of measurements)
closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement

Note 1 to entry: These conditions are called repeatability conditions.

Note 2 to entry: Repeatability conditions include:

— the same measurement procedure;

— the same observer;

— the same measuring instrument, used under the same conditions;

— the same location;

— repetition over a short period of time.

Note 3 to entry: Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

[SOURCE: ISO/IEC Guide 98-3:2008, B.2.15[5]]

3.4.3
reproducibility (of results of measurements)
closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement

Note 1 to entry: A valid statement of reproducibility requires specification of the conditions changed.

Note 2 to entry: The changed conditions may include:

— principle of measurement;

— method of measurement;

— observer;

— measuring instrument;

— reference standard;

— location;

— conditions of use;

— time.

Note 3 to entry: Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.

Note 4 to entry: Results are here usually understood to be corrected results.

[SOURCE: ISO/IEC Guide 98-3:2008, B.2.16[5]]

3.4.4
resolution
smallest difference between indications of a meter that can be meaningfully distinguished

3.4.5
zero flow
meter reading when the fluid is at rest, i.e. both axial and non-axial velocity components are essentially zero

3.4.6
uncertainty (of measurement)
parameter, associated with the result of measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

Note 1 to entry: The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

Note 2 to entry: Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.

Note 3 to entry: It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

[SOURCE: ISO/IEC Guide 98-3:2008, B.2.18[5]]

3.4.7
standard uncertainty
u
uncertainty of the result of a measurement expressed as a standard deviation

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.1[5]]

3.4.8
expanded uncertainty
U
quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.5[5]]

Note 1 to entry: The large fraction is normally 95 % and is generally associated with a coverage factor $k = 1,96$.

Note 2 to entry: The expanded uncertainty is often referred to as the uncertainty.

3.4.9
coverage factor
numerical factor used as a multiplier of the standard uncertainty in order to obtain an *expanded uncertainty* (3.4.8)

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.6[5]]

3.5 Calibration

3.5.1
flow calibration
calibration of a meter against a reference using fluid flowing through the meter

3.6 Symbols and subscripts

The symbols and subscripts used in this document are given in Table 1 and Table 2.

Table 1 — Symbols

Quantity	Symbol	Dimension[a]	SI unit
Cross-sectional area of pipe	A	L^2	m^2
Speed of sound in fluid	c	LT^{-1}	m/s
Internal pipe diameter	D_i	L	m
External pipe diameter	D_e	L	m
Integers (1.2.3. ,,,)	i,j,n	—	1
Calibration factor	K	—	1
Path-geometry factor	K_g	L^b or LT^{-1} [c]	m^b or m/s [c]
Velocity profile correction factor	K_p	—	1
Minimum distance to a specified upstream flow disturbance	l_{min}	L	m
Path length	l_p	L	m
Absolute pressure	p	$ML^{-1}T^{-2}$	Pa
Volume flowrate	q_V	L^3T^{-1}	m^3/s
Pipe Reynolds number	Re_D	—	1
Transit time	t_{tr}	T	s
Delay time	t_0	T	s
Compressibility	Z	$M^{-1}LT^{-}$	Pa^{-1}
Pipe wall thickness	δ	L	m
Dynamic viscosity	μ	$ML^{-1}T^{-1}$	Pa s
Kinematic viscosity	ν_{kv}	L^2T^{-1}	m^2/s
Density of the fluid	ρ	ML^{-3}	kg/m^3
Angle between ultrasonic path and pipe axis	ϕ	—	rad

[a] M ≡ mass; L ≡length; T ≡ time; Θ ≡ temperature.

[b] Non-refracting configuration.

[c] Refracting configuration.

Table 2 — Subscripts

Subscript	Meaning
cal	under calibration conditions
meas	measured (uncorrected)
op	under operational conditions
true	actual (corrected)

4 Principle of measurement

4.1 General

This subclause is a generic description of USMs for liquids and gases. It recognizes the scope for variation within commercial designs and the potential for new developments. For the purpose of description, USMs are considered to consist of several components, namely:

a) transducers and mounting arrangement

b) electronic data processing and presentation unit.

4.2 Generic description

Ultrasonic transit time clamp-on flowmeters measure non-intrusively. Figure 1 outlines the basic system setup to demonstrate the principle. A pair of transducers is located on the outside of the pipe. The transducers are alternatively working as transmitter and receiver. Ultrasonic pulses are sent through the fluid, in the flow direction, and against it. The transit-time $t_{\mathrm{me\_dn}}$ of the ultrasonic signal propagating in the flow direction (down-stream) is shorter than the transit-time $t_{\mathrm{me\_up}}$ of the signal propagating against the flow direction (up-stream). The average flow velocity v_l on the sound path is directly proportional to the measured difference Δt in transit time[6]:

$$v_l = \frac{c_t}{\cos\phi_t} \frac{\Delta t}{\left(t_{\mathrm{me\_up}} + t_{\mathrm{me\_dn}} - 2t_0\right)} \quad (1)$$

The delay time t_0 is the portion of the transit time outside the flowing fluid. The average of the transit times measured upstream and downstream is the transit time t_{tr} at zero flow:

$$t_{\mathrm{tr}} = \frac{1}{2}\left(t_{\mathrm{me\_up}} + t_{\mathrm{me\_dn}}\right) \quad (2)$$

The angle ϕ_t and the sound speed c_t in the coupling wedge define the propagation angles δ and ϕ in the pipe wall and the fluid according to Snell's law:

$$K_{\mathrm{g}} = \frac{c_t}{\cos\phi_t} = \frac{c_\Delta}{\cos\phi_\delta} = \frac{c}{\cos\phi} \quad (3)$$

K_{g} could be denoted as the path-geometry factor, according to.[6] The ultrasonic signal is shifted in axial direction while propagating through the flowing fluid. K_{g} defines the ratio of the shift to the time difference measured. With Formulae (2) and (3), Formula (1) results in:

$$v_l = K_{\mathrm{g}} \frac{\Delta t}{2(t_{\mathrm{tr}} - t_0)} \quad (4)$$

When multiple paths are installed a weighted sum of the path velocities is calculated.

The mean velocity is obtained by applying a velocity profile factor, K_{p}, which expresses the relationship between the mean velocity v_A and the measured path velocity v_l:

$$v_A = K_{\mathrm{p}} \cdot v_l \quad (5)$$

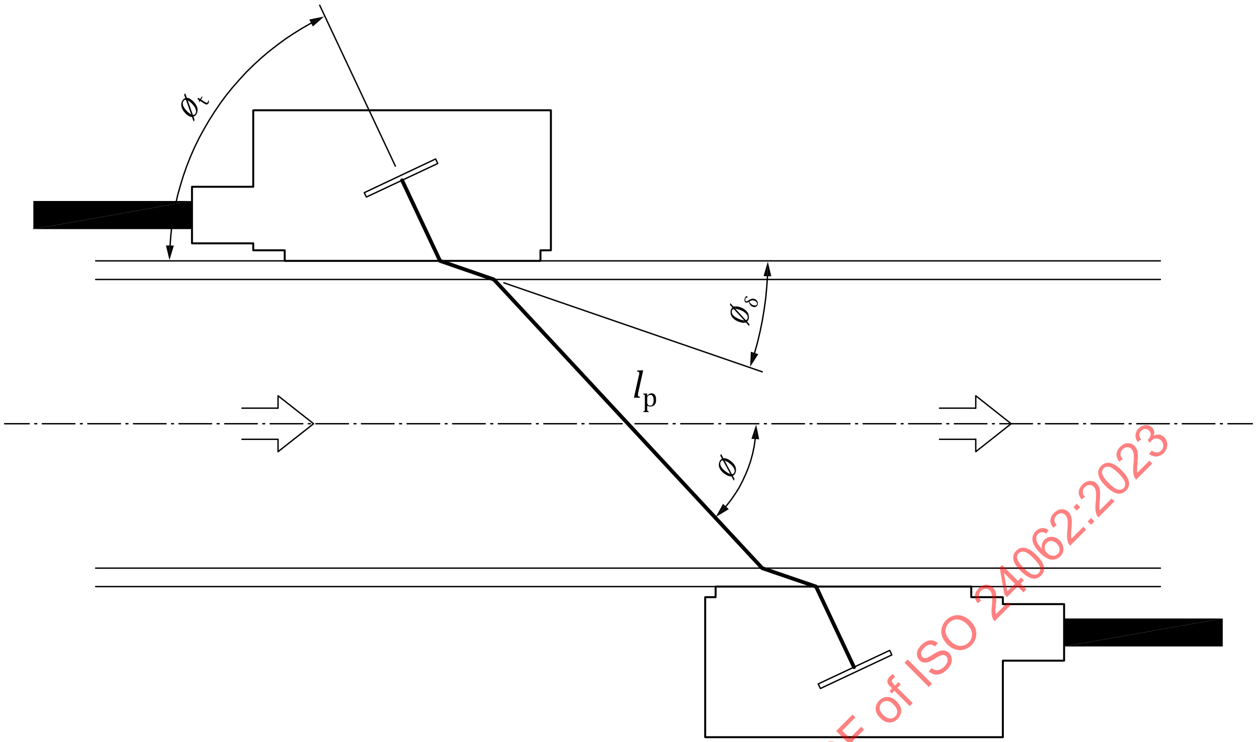
The velocity profile factor K_{p} is calculated by the meter based on an empirical model of the flow profile assuming a fully developed turbulent flow profile. The model is parameterized by the Reynolds number and the roughness of the inner pipe wall. The influence of upstream flow disturbances can be corrected based on experimental or validated computational evaluation.

The volume flowrate is given as the product of the mean velocity and the cross-sectional area A of the pipe:

$$q_V = A \cdot v_A \quad (6)$$

With Formulae (4), (5) and (6) the meter formula for the volume flowrate would be:

$$q_V = A \cdot K_{\mathrm{p}} \cdot K_{\mathrm{g}} \frac{\Delta t}{2(t_{\mathrm{tr}} - t_0)} \quad (7)$$



Key

ϕ_t incident wedge angle

ϕ_δ pipe wall refracted angle

l_p path length

ϕ angle between ultrasonic path and pipe axis

Figure 1 — Basic system setup of clamp-on flowmeter

4.2.1 Transducers

Transducers are the transmitters and receivers of the ultrasonic signal. They can be supplied in various forms. Typically, they comprise a piezoelectric element with electrode connections and a supporting mechanical structure with which the process connection is made.

The Transducers frequency is defined by the materials used and its dimensions, in the case of piezoelectric elements, the lateral dimensions and thickness of this element.

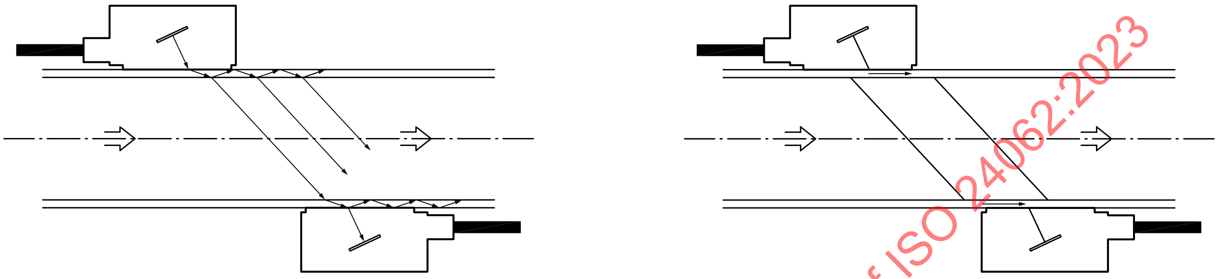
Selection of an appropriate frequency will be dependent on the application. It mainly depends on the pipe diameter. As a rough orientation, the proportion of the ultrasonic wavelength to the pipe diameter should be kept within a certain range. As the wavelength decreases with increasing frequency, lower frequencies are used on bigger pipes and higher frequencies on smaller pipes. In addition, the attenuation increases with the frequency. Therefore, if the fluid has a high ultrasonic attenuation, a lower frequency may be beneficial. Another aspect is the resolution of the time measurement which increases with the frequency. Refer to manufacturer guidance for the best choice for a particular application.

There are two main types of transducers used for clamp-on transit-time flow measurement: shear wave and Lamb wave. It is most common to find shear wave transducers used on liquid applications however both shear and Lamb wave transducers can be used for gas flow measurement.

Typical arrangements are shown in Figure 1 and Figure 2. To measure the axial velocity, the transducer transmits ultrasonic waves at a non-perpendicular angle to the pipe axis in the direction of a second transducer or reflection point on the inner pipe wall.

Shear wave transducers (see Figure 2 a)) operate by the direct transmission of the ultrasound through both pipe and media and are conventionally the standard for ultrasonic liquid meters. They are called shear wave as they are designed to produce a shear wave in steel pipes and pipe materials of similar sound speed. They are, however, suitable for most pipe materials and most liquids and are not constrained by pipe thickness within the capability of the individual instrument and application.

Lamb wave transducers (see Figure 2 b)) involve ultrasonic signals being excited into the pipe at an appropriate frequency for the pipe wall which causes the pipe to become part of both the transmitting and sensing device. The active transmission area of the pipe wall created is several times the length of the actual transducer, resulting in broader signal characteristics which allow measurements over a wider range of operating conditions. Lamb wave transducers are not suitable for the measurement of flow on all pipe materials and will have pipe thickness limitations.



a) Shear wave configuration **b) Lamb wave configuration**

Figure 2 — Shear and lamb wave configurations

Since the transducers are external to the pipe wall boundary, the beam is always refracted. The geometry of a refracted beam is governed by Snell's law as shown in Formula (3). The beam geometry determines the optimal transducer position. If the transducers are not placed at their optimal position, the measurement uncertainty increases.

4.2.2 Ultrasonic path configurations

4.2.2.1 General

Although clamp-on meters can be delivered with the transducers mounted on a spool piece to factory specification, they usually are installed on existing pipe.

Sound paths are either direct paths as shown in Figure 3 a) or reflect paths as shown in Figure 3 b). Two-path configurations are shown in Figure 3 c) and Figure 3 d). Velocity measurements made on multiple paths are typically less susceptible to non-ideal upstream flow conditions than those made on a single path. Reflecting paths and crossed direct paths are much less sensitive to non-axial velocity components than a single direct path (see 6.2.1). The effect of non-symmetrical flow profiles can be reduced by installing in multiple planes as shown in Figure 3.

In order to increase the transit time in the fluid, the multiple reflection of the signal at the inner pipe wall can be used. Instead of consisting of only two paths a reflecting configuration can consist of 4 or more paths. With a direct path configuration, the number of paths can be 3 or more. This will increase the resolution when measuring on small pipes.

The different path configurations can be described as follows.

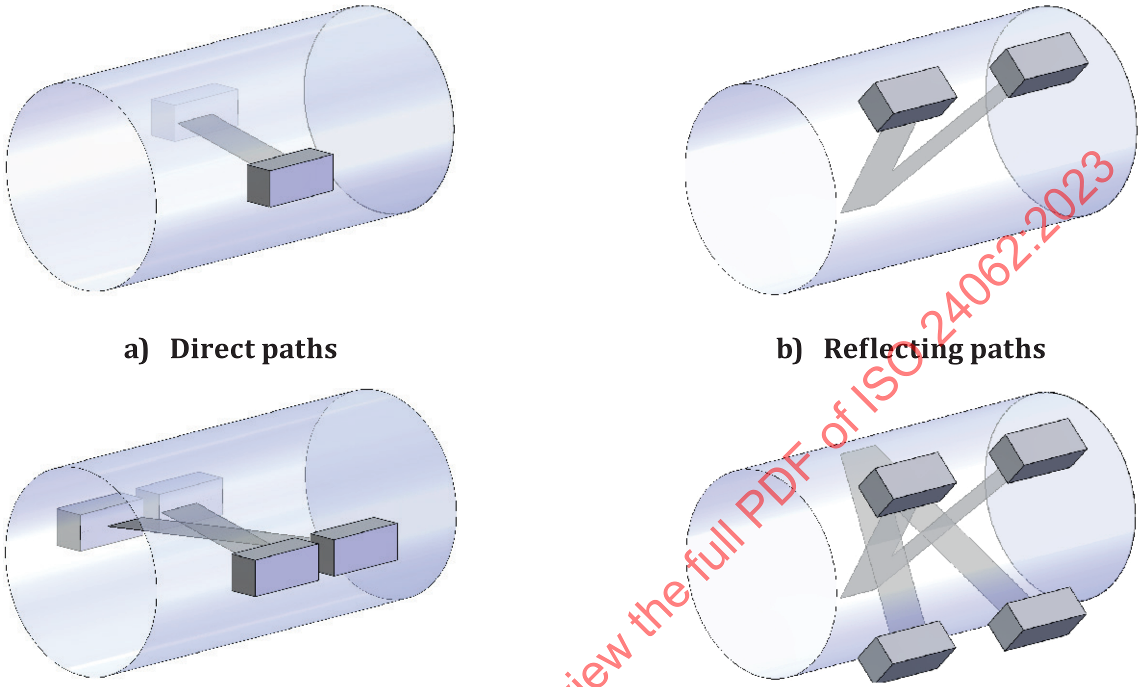
4.2.2.2 Same side

This is referred to in different ways, "Reflection" being one (Figure 3 b)). It can also be defined by the number of reflections of the ultrasonic signal within the pipe: "V" or "Two Paths/Passes" and "W" or "Four Paths/Passes" are common.

4.2.2.3 Opposite side

This is sometimes referred to as, "Diagonal", “Crossed” or "Direct" mode (Figure 3 a)). It is also referred to by the number of "Paths/Passes" such as "1" or "3". A single path/pass may also be named “Z mode”.

This method may be more difficult as the location of the transducers is not easily visible around the circumference of the pipe. It has the advantage of being able to maximise the available received signal by shortening the path length. This is particularly useful on liquids with higher solid or gaseous content.



a) Direct paths

b) Reflecting paths

c) Crossed direct paths

d) Dual reflecting paths

Figure 3 — Ultrasonic path types configurations

A flow profile can be represented by a vector field. The vectors can be expressed as the composition of an axial component and a radial component. With a fully developed flow profile the radial components are zero and the axial components are rotationally symmetric. Any disturbance will cause radial components, also called cross flow or swirl, and asymmetry of the axial components. The sensitivity to such profile distortions depends on the path configuration. Cross flow is strongly compensated by reflecting path configurations as shown in Figure 3. Cross path configurations have the same effect. However, the effect on the axial component is not compensated for. Asymmetries can be reduced by installing multiple planes of measurement as shown in Figure 3 d).

4.2.3 Electronic unit functionality

In addition to the transducers, USMs comprise an electronic unit (sometimes referred to as the Meter Electronics or as a Transmitter) which accomplishes the following functions:

— Generation of a signal to drive the transducers

— Receiving and processing the signal returned from the transducers in order to determine the transit times

— Performing calculations and diagnostic functions to interpret the processed signal

— Providing a user interface

— Displaying the flowrate

The unit may be housed with the transducers or connected to them.

4.3 Special considerations

4.3.1 Gas

The operating principle and meter formula are the same for gases and liquids. So, there is no principal difference between measuring flow of gas and flow of liquids. However, with gas the signal amplitude decreases with decreasing pressure. Therefore, manufacturers specify a lower limit for pressure.

Signal amplitude depends on the loss the ultrasonic signal experiences when propagating from the transmitting transducer to the receiving transducer by crossing the pipe wall boundaries and the fluid.

At each boundary between different materials a part of the signal energy is lost by reflection. This is called insertion loss. The insertion loss depends on the difference in acoustic impedance of the materials on both sides of the boundary. Acoustic impedance is the product of sound speed and density. The density of gas is proportional to pressure. Therefore, the insertion loss increases with decreasing pressure.

While propagating through the fluid the signal amplitude decreases due to absorption. This is called propagation loss. The absorption in gas increases with decreasing pressure.

The difference between clamp-on measurement on gases and liquids is that, depending on gas pressure, the density of gas is much lower than the density of liquids. This can cause a high insertion loss which increases with decreasing pressure. With very low pressure, depending on the type of gas, also the absorption can be high.

4.3.2 Extreme temperatures

The measurement range of the transducer will be defined by the materials used for both the piezo crystal and transducer wedge. Once the temperature exceeds the range of the transducers, they will lose the ability to generate an ultrasonic pulse and cease operation.

It may therefore be necessary for manufacturers to have options for making measurements outside of the normal range both at the upper and lower ends of the scale.

An option is to use a thermal barrier between the surface of the pipe and the measurement surface of the transducer. This generally takes the form of a metallic plate or rod which is coupled to the surface of the pipe allowing propagation of the ultrasonic signal from the transducer, into the pipe. A thermal gradient is created allowing the transducers to remain within their standard operating conditions. However, the impact should be included in the uncertainty estimation.

It is important to consult the manufacturer to determine if the transducers being offered are suitable under the process conditions.

4.4 Additional measurements

4.4.1 Standard volume flow

When the effect of temperature and pressure on the density of the fluid is not negligible the measured volume flow is converted to volume flow at standard temperature and pressure.

Gases are compressible. Their density strongly depends on pressure and temperature. Therefore, with gas measurement applications, standard volume correction usually is required. The correction is calculated using temperature and pressure T and p at operating conditions, standard temperature and standard pressure T_s and p_s and the compressibility factors at operating and standard conditions Z and Z_s:

$$q_s = q_V \frac{p}{p_s} \frac{T_s}{T} \frac{Z_s}{Z} \quad (8)$$

The compressibility factors account for the difference between the real gas and an ideal gas. They depend on the gas composition. The calculation is defined in several International and American standards[7][8].

Liquid flow measurement applications may require standard volume correction. Standard volume correction for liquid flow is calculated by multiplying the measured volume flow with a volume correction factor, V_{CF}:

$$q_s = q_V \cdot V_{CF} \quad (9)$$

Several industry standards define the calculation of the volume correction factor. The correction can be carried out by the flow transmitter, by an external flow computer or by the user in the control system.

4.4.2 Heat flow

Clamp-on ultrasonic flowmeters can be used to measure the heat flow of heating or cooling systems if the volume flow measurement is supplemented with a temperature measurement at the supply and return line. Using clamp-on temperature sensors enables a non-intrusive heat flow measurement. The heat flow is calculated from the volume flow measured in the supply or the return line, the temperature difference between supply and return line and the specific heat capacity of the fluid.

4.4.3 Mass flow

The mass flow can be derived by multiplying the volumetric flow with density if input measurements of pressure and temperature are available. If the fluid composition is constant and known, density can be calculated from the relationship between the fluid density and the pressure and temperature.

If the fluid composition can change, in some applications the density can be calculated with additional consideration of the directly measured sound speed. Examples are hydrocarbons and fluid mixtures consisting of only two components.

5 Test and calibration

5.1 General

The requirements for calibration of clamp-on meters may be substantially different from the requirements for other meters. The calibration requirement depends on the application.

5.2 Individual testing — Flow calibration under flowing conditions

5.2.1 General

A clamp-on USM may be calibrated against a volumetric reference to demonstrate that it meets the manufacturer specification under ideal conditions. Results are based on the measurement setup and conditions during calibration. The specific measurement setups and conditions shall be considered when calibration results will be used in any other application.

One of the main advantages of clamp-on USMs is that they can be retrofitted to existing pipework to measure the flow. If required, a clamp-on flowmeter can be calibrated as a package when the device is attached to a pipe spool. This pipe should be preferably supplied by the end user. However, if the device is dissembled from the pipe the calibration of the “package" is no longer valid and this should be stated on the calibration certificate.

A flow calibration in a laboratory working to ISO/IEC 17025[9] can be used to assess the influencing factors due to operating conditions in the piping system. The flow calibration delivers a set of systematic errors, as a function of the Reynolds number, actual flowrate or velocity. These values can be used to correct the meter output via a calibration curve. This is valid only for the calibration of those specific conditions.

Calibration results are dependent on measurement configuration and calibration conditions. Specific measurement configurations and conditions shall be taken into consideration when using calibration results in any other application.

A flow calibration performed on a pipe in the lab is not fully transferable to a different pipe in the field. This does not preclude the issuing of a test certificate which would include details of the test and the pipe showing the device performed to specification.

5.2.2 Laboratory flow calibration

5.2.2.1 General

In summary, in order to minimize the uncertainty of the calibration, the calibration shall be conducted:

a) under good inlet flow conditions;

b) under steady flow conditions;

c) over a statistically significant duration of time;

d) over the appropriate range of Reynolds numbers to describe the in-service response of the meter. A sufficient number of points to characterize the meter response should be taken;

e) where possible, at a similar viscosity to meter operating conditions. This ensures that not only Reynolds number but also flowrate is matched. If a wide range of viscosity is encountered in the field, then calibration at more than one viscosity may be required, so that the whole Reynolds number range is covered;

f) where possible, at a similar temperature and pressure to meter operating conditions;

g) where the geometry and characteristics (material, internal diameter, wall thickness and surface roughness) of the pipe are known.

5.2.2.2 Duration of the calibration

The duration of a measurement, at one single flowrate, shall be long enough to minimise the effects of random variations within the meter processes due to turbulence in the flow. It shall also be long enough to allow inaccuracy due to response times of the meter processes, introduced by changes in flowrate and conditions prior to and after the test, to be insignificant. As with any meter calibration, the duration shall be long enough to reduce the uncertainty introduced by the meter output resolution to insignificant levels.

5.2.2.3 Uncertainty of the calibration facility

The reference measurement system shall have an uncertainty smaller by a factor of at least three than the system under test, whenever possible.

5.2.2.4 Flow conditions

The conditions at the test facility shall be such that a fully developed flow profile (or as close as possible) is generated at the upstream of the tested flowmeter (or set of flowmeters) to avoid any additional errors arising from flow profiles different from those encountered in actual conditions.

When calibrating a meter to compensate for operating conditions the pipework configuration should replicate as closely as possible the final installation conditions of the meter or use the actual installation pipework.

5.2.2.5 Report

The calibration facility shall provide a report of the meter calibration results. The calibration certificate should state that the results are based on the measurement setup and conditions during calibration. The specific measurement setups and conditions shall be considered when calibration results will be used in any other application.

The certificate shall include the conditions listed in 5.2.2.1. along with the reference method used for the calibration and its associated measurement uncertainty.

6 Installation

6.1 General

The purpose of this subclause is to provide guidance to the user for a robust installation with minimized uncertainty.

Installation of a clamp-on meter shall be carried out by a competent operator to minimise uncertainty.

6.2 Installation location

6.2.1 Upstream and downstream straight pipe length requirements and path configuration

Upstream profile disturbances like fittings, valves and bends can produce velocity profile distortions at the meter location that may result in flowrate measurement errors. The magnitude of the meter error depends on the type and severity of the flow distortion and on the sensitivity of the path configuration to this distortion. This error may be reduced by increasing the length of upstream straight pipes. Alternatively, carrying out flow calibrations *in situ* or under conditions similar to metering conditions allows to correct this error. Extensive research work on installation effects has been completed for single-path devices[10][11][12][13][14][15][16][17][18][19][20].

Table 3 provides some guidance for any fluid on the required straight lengths between fittings and a single path clamp-on USM[21]. Table 3 should be considered as general guidance only and may not hold true for every installation and meter. It is further assumed that ideal flow profile exists preceding the last disturbance before the selected meter run. Additional straight pipe length might be required if this is not the case. An indication of the magnitude of any specific effect can be obtained through testing in a laboratory under similar hydraulic conditions.

Table 3 — Guidance for straight lengths between fittings and single-path USM

Disturbance	Straight lengths required to reduce installation effect to less than	
	±2 % error	±5 % error
Conical contraction	$5D_i$	0
Conical expansion	$20D_i$	$5D_i$
Single 90° bend	$20D_i$	$15D_i$
“U” bend (Two close coupled 90° bends)	$25D_i$	$10D_i$
Two close coupled 90° bends in perpendicular planes	$50D_i$	$20D_i$
Butterfly valve ⅔ open	$20D_i$	$10D_i$
Globe valve ⅔ open	$15D_i$	$5D_i$
Gate valve ⅔ open	$20D_i$	$5D_i$

If the USM provides a disturbance correction these distances could potentially be reduced with due consideration to the user specific upstream pipework and the additional residual uncertainty associated with this disturbance correction function as advised by the meter manufacturer. The impact of a non-ideal velocity profile can be mitigated by using multi-path configurations as described in 4.2.2. Sources of hydraulic disturbances downstream of the meter are considered to have less effect on the measurement. Guidance from manufacturer is typically 2-5D_i straight lengths downstream[14].

6.3 Transmitter programming

When a clamp-on USM is installed, the user will be required to input site specific parameters. These parameters are likely to include but are not limited to:

— pipe outside diameter and pipe wall thickness and lining or pipe inside diameter

— pipe material

— pipe lining material (if applicable)

— pipe roughness

— fluid type and fluid temperature

— transducer type and arrangement (if required)

Pipe outside diameter and wall thickness should be measured on site as they are used by the USM to calculate the cross-sectional area of the pipe and thus have a significant effect on volumetric flow measurement. External diameters may be confirmed using callipers on smaller pipes, or by measuring the circumference with a measuring tape. Wall thickness can be confirmed with an ultrasonic thickness gauge, which may also provide a speed of sound reading that can be used to confirm the pipe material. 8.3.1.1 and 8.3.1.3 provide further guidance on how to perform these measurements in order to minimise measurement uncertainty. Using data from pipe specifications will result in increased measurement uncertainty arising from production tolerances in pipe geometry.

Depending on the manufacturer, the user may be prompted to select the pipe material and fluid type from a list that references parameters stored in the transmitter.

From the choice of pipe material, the speed of sound in the pipe wall is used to calculate the path angle Formula (5) and the delay in the pipe wall Formula (A.8).

From the fluid type and temperature, the sound velocity of the fluid is determined and used to calculate the path angle Formula (5) in the fluid to determine transducer position and an estimate of the expected signal arrival time Formula (A.13). The viscosity of the fluid is used to calculate the Reynolds number for the profile correction Formula (5). In addition, the roughness of the pipe wall can be used as a parameter for the profile correction.

The effect of these parameters on meter performance is described in Clause 8.

Depending on the manufacturer, the user may perform additional measurements such as standard volume flow, heat flow or mass flow. 4.4 provides further guidance on how to perform these measurements.

6.4 Pressure and temperature inputs

If standard volume flow is required, pressure, p and temperature, T inputs to the meters will enable the correction of actual volumetric flowrate to standard volume flowrate as defined in 4.4. The measurements of p and T should be taken from instruments located as close as possible downstream of the flow measurement point so that the pressure and temperature are representative of those at the flowing conditions. In practical terms using a clamp-on temperature sensor will allow live temperature measurement however live pressure measurement requires a pressure sensor tap in the pipe. It is recommended to insulate the area of the pipe where the clamp-on temperature sensor is installed to minimize environmental impact. If no pressure and temperature measurement are available, then fixed values may be used but would have a potential impact on overall uncertainty for standard volume flowrate.

Inputs can also be used to adjust application parameters during measurement or determine power or energy transfer.

6.5 Transducer installation

6.5.1 Transducer type

See 4.2.1 and refer to manufacturer guidance.

6.5.2 Transducer orientation

When installing the transducers, the user has two choices; to mount the transducers on the same side of the pipe, or on opposite sides of the pipe. Each method has both advantages and disadvantages (see 4.2.2). It would be recommended to avoid placing transducers on either the top or bottom on a horizontal pipe unless unavoidable. This is to avoid potential air pocket and debris affecting the ultrasonic signal.

6.5.3 Coupling

6.5.3.1 General

Good sound propagation between the transducer face and the pipe requires that there is no air between the transducer face and the pipe surface. This is achieved by using a coupling means which fills any gaps between transducer face and pipe surface. Well maintained pipe surfaces usually fulfil this condition without further treatment. This means that paint doesn't need to be removed if it is not loose.

There are three recognised methods of achieving good coupling:

6.5.3.2 Gel

In simple terms any viscous liquid could act as an acoustic couplant for the flow transducers but conditions such as humidity, temperature and location need to be considered. If the installation is a temporary one then a water-based substance may be used for simplicity, though in humid conditions a fat or oil-based substance may be more suitable.

For permanent installation a gel can still be used but the long-term environmental conditions need to be considered in order to ensure continued reliable measurement. The gel may need to be replaced or replenished periodically. Each manufacturer would be able to make a recommendation as to their preferred substance and quantity to use.

6.5.3.3 Solid coupling pad

An alternative to a gel-based coupling is a solid pad or foil. This is not essential but does have the advantage of providing greater protection against climatic events. The manufacturer should be consulted on the best material to use should a solid coupling be deemed to be the most suitable method.

6.5.3.4 High temperature couplant

For higher temperatures thin strips of appropriate material can be used to provide an acoustic coupling between the transducer assembly and the pipe.

6.5.4 Transducer mounting

In order to achieve and maintain a good acoustic contact between the transducers and the pipe it is essential that they remain securely in place for the duration of the measurement. This dictates a mounting method that can be resistant to vibration or atmospheric/ambient conditions. The mounting system used varies across manufacturers and depends on whether the device is for temporary or permanent use.

For temporary installation, metallic chains, fabric straps, or magnetic rails may be used successfully according to the conditions. For permanent installation steel rails are a popular choice as is stainless steel banding.

Examples of some of the available mounting systems are shown below.

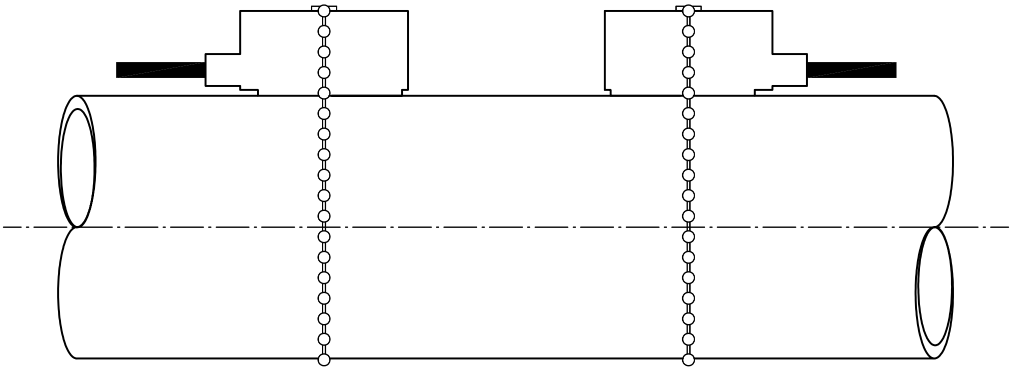


Figure 4 — Metallic chain mounts

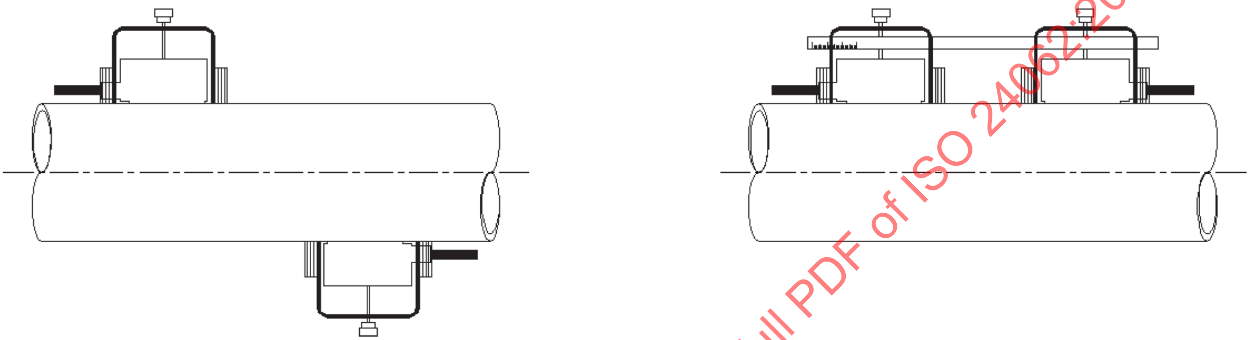


Figure 5 — Magnetic rail mounts

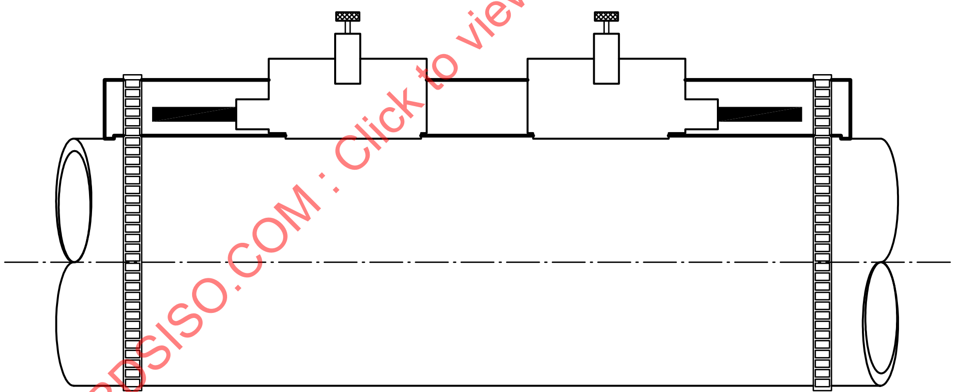


Figure 6 — Mount rails

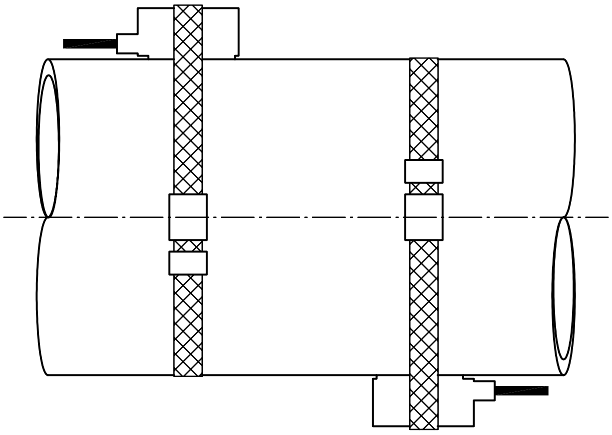


Figure 7 — Fabric straps

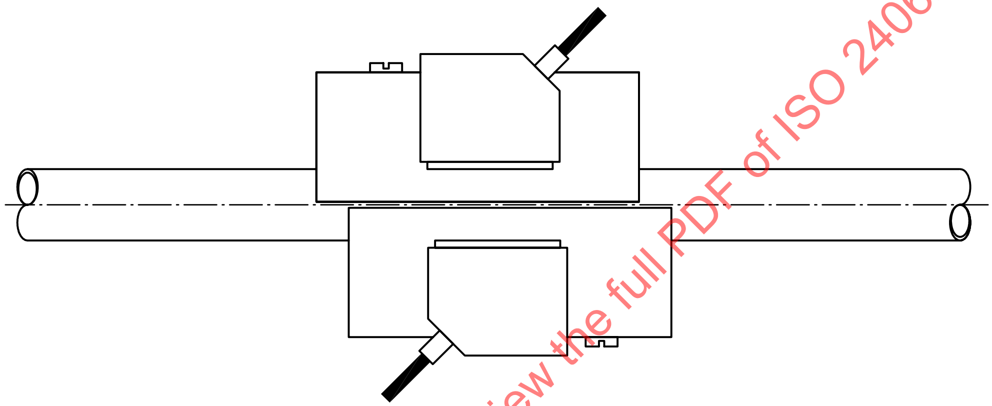


Figure 8 — Small diameter pipe mounting

It is important that the horizontal, vertical and lateral alignment of the transducers is maintained at all times. Attention should be paid to the potential for temperature changes within the process or exposure to the ambient conditions. Thermal expansion or contraction of the pipe can cause the transducer mounting to tighten and break, or loosen, either way causing loss of measurement.

6.6 Gas considerations

When measuring gas flow typically a noise dampening material is necessary in order to reduce the so-called pipe signals (see 4.3). Manufacturers should provide noise dampening material and instructions of how to apply it. The need for applying noise dampening increases with decreasing pressure. Meter diagnostics can indicate if the dampening of pipe signals is sufficient.

Control valves produce acoustic noise that can affect the signal quality. Valve noise can be reduced by avoiding locations close to valves and by avoiding straight pipe between the valve and the location of the meter. The meter may indicate the noise level as low signal to noise ratio (SNR).

6.7 Cable

If the USM is sensitive to the characteristics of the individual transducer cable, then the cable should be treated as an integral part of the meter and should be marked with a warning indicating which characteristic is not to be changed, e.g. length. The use of the manufacturer supplied cable is recommended.

6.8 Additional installation effects

6.8.1 Non-steady flow

Pulsations and non-steady flow beyond the manufacturer's specifications shall be avoided.

6.8.2 Contamination by secondary phase

Like other measurement techniques, successful, accurate measurement of flow using ultrasonic clamp-on techniques in fluids with a second phase such as solids, multi liquid or gas can be more problematic. Refer to manufacturer guidance on performance when a secondary phase is present.

This is due to signal attenuation as a result of reflection or refraction. Since transit time measurement is a velocity measurement, accuracy is likely to be impacted because the measured velocity will be for the main phase and may not take into account the velocity of the second phase. Corrections for this for ultrasonic techniques are not easily derived from physical models and may require testing to determine the limits for each application.

Individual manufacturers can advise on the best way to handle such circumstances and how the meter systems can be configured to function most accurately under such circumstances.

Fluids such as drilling mud, paper pulp etc. where the solids content is high can cause high signal attenuation.

Measurement of flow in liquids where there is gas present is highly dependent on the gas content and its distribution within the liquid. High concentrations of gas will restrict the passing of ultrasound and could make the measurement unreliable.

Produced water from offshore and onshore oil installations is a measurement that requires care because of potential second phase as a result of gassing off in addition to a mix of water with variable salinity and a small hydrocarbon content. Research has been performed to identify the points in a production train where measurement was possible or not recommended. It was observed that where the line pressure is close to the vapour pressure then successful measurement was less likely[22].

An application that is well understood is wet gas. Per definition the LVF (Liquid Volume Fraction) of wet gas is below 5 % and the XLM (Lockhart Martinelli Number) is below 0,3. Laboratory testing has demonstrated that ultrasonic transit time meters may be applicable under these conditions. The over reading the liquid phase causes can be partly-corrected if the relevant process parameters are known[23].

6.8.3 Vibration

USMs should not be exposed to vibration levels or vibration frequencies that might excite the natural frequencies of electronic system boards, components or ultrasonic transducers. Vibration levels should not exceed those specified by the manufacturer.

6.8.4 Thermal insulation

In some circumstances, insulating the meter and pipework may be necessary to avoid incurring additional uncertainty.

In low Reynolds number applications, where the flow may be in laminar or transitional regimes, insulation may be effective in preventing the formation of thermal gradients, which can result in additional uncertainty in the path geometry factor (see 8.3.3). In order for insulation to be effective in laminar and transitional flows, insulation should be applied from a point upstream, where the flow is well mixed, up to and including the meter itself and the straight pipe immediately downstream of the meter.

6.8.5 Stratification

Stratification can occur especially when measuring gas flow under the following conditions:

a) where the velocity of the fluid is low and the pipe on which the transducers are located is in the horizontal plane; or

b) where two gases come together with the same composition but with differing temperatures.

Lighter gases such as hydrogen will rise to the top of the pipe and the heavier gases will drop to the lower section of the pipe. This results in a velocity profile that is not characterised by the normal formulae and as a result, the measured path velocity may not be representative of the bulk velocity in the line. It also means that the measured speed of sound for the chosen path could be different from the speed of sound for the gas being measured when it is homogeneously mixed. Stratification is less likely to result in the loss of signal but would most likely result in a loss of accuracy at lower velocities. Particular attention should therefore be given in this situation to meter location and to the selection of the number and position of paths in order to obtain the best possible measurement accuracy.

6.8.6 Wall roughness signal considerations

In addition to affecting the profile (see 4.1), the internal roughness of the section of pipework where the transducers are installed can also cause significant scattering of the ultrasonic signal. In many cases, it does not cause a measurement error, but can cause the meter to fail to read. Rougher pipework, owing to the reduction in signal strength, also limits number of reflections with reflecting path configurations. Pipe wall roughness can also affect the estimation of the pipe internal diameter from pipe outside diameter and wall thickness measurements.

6.8.7 Non-Newtonian fluids

Care shall be taken with the use of clamp-on USMs with non-Newtonian fluids. The effect on the velocity profile will cause a change to the profile factor and therefore there is likely to be an increase in measurement uncertainty.

Measurement of raw velocity may be possible, but the corrected velocity and volumetric flowrate calculated may not be representative of the flowrate in the line.

6.9 Operational diagnostics

The diagnostic values produced by the meter provide data for verification of the installation. Refer to manufacturer guidance on their use. Most manufacturers provide gain, signal to noise ratio and measured speed of sound but the diagnostics provided can vary by manufacturer.

6.9.1 Fluid speed of sound

Fluid sound speed can be used to verify the geometry of installation, or assumptions on the fluid. If the speed of sound of the fluid is known, it can be compared to the speed of sound measured by the meter. This is the case with many pure liquids like water or for example with natural gas when the gas composition is known. Fluid sound speed depends on temperature and in case of gases also on pressure. So, in order to use sound speed for meter verification these parameters shall be known.

The measurement of speed of sound is based on the geometry of the measurement section and the transit time measurement. Therefore, a difference between the expected and measured speed of sound is caused either by the time measurement uncertainty or an error in the geometry of the meter or both. These are either an error in measured inner pipe diameter, wall thickness or transducer spacing.

Pipe linings can be particularly problematic. The presence of a liner may not always be known. If it is known, then the liner material and thickness may not be known. The presence or absence of a liner can often be deduced from the diagnostic facilities on the meter, for example poor signal strength readings or inconsistencies in the calculated sound speed.

6.9.2 Gain

Gain can be used for predictive maintenance. The gain is the value by which the amplifier increases the ultrasonic signal in order to enable the electronics to measure the transit time. The gain therefore indicates the signal amplitude. Transmitters incorporate automatic gain control to compensate for changing attenuation of the ultrasound in the pipe wall and in the fluid.

A change of gain over time, therefore, indicates a change of attenuation. If the fluid has not changed, this potentially indicates build up on the inner pipe wall, degradation of transducer coupling or even a degradation of the transducers.

6.9.3 Signal to noise ratio

Signal to noise ratio (SNR) can be used to verify the electrical installation. Signal to noise ratio depends on both, signal amplitude and noise. A certain noise level is unavoidable and signal amplitude can vary widely between different types of application. A low SNR therefore does not necessarily indicate bad measurement condition. Manufacturer may provide guidance on the minimum SNR required and on the value of SNR expected with a certain signal amplitude.

An SNR below the expected value can indicate wrong or insufficient installation of electric shielding on the transducer cabling or the presence of strong electromagnetic disturbances. Another potential source of noise are control valves which are used in gas facilities.

7 Maintenance

Maintenance of a clamp-on ultrasonic meter is generally limited to the need to confirm the operational diagnostics (see 6.9) are within the expected limits and to inspect the mounting of the transducers periodically to ensure that the coupling to the pipe remains reliable and that alignment remains correct. The following should be considered:

— Where coupling gel is used, the gel can dry out leading to poor coupling and should be replaced;

— Coupling pads should be checked to ensure that they remain in good condition and provide suitable coupling;

— Vibration, being knocked and environmental factors can cause the transducers to become displaced and require reinstallation or realignment;

— Attachment straps can become stretched, thus loosening the attachment of the transducers, and require retightening;

— Deterioration of the pipe surface due to, for example, corrosion can degrade the coupling or cause transducer movement.

Changes in the internal condition of the pipe due to fouling, tuberculation and corrosion will cause errors in measurement as the internal dimensions change. Changes in the thickness of the pipe wall material may be detected by carrying out checks using, for example, an ultrasonic thickness gauge. The meter can then be reprogrammed with the new dimensions and the transducers reinstalled, if necessary. It should be noted that such checks are unlikely to detect changes in dimensions due to internal fouling.

8 Uncertainty in measurement

8.1 General

All calculations here are based on the methods presented in ISO/IEC Guide 98-3:2008[5]. The uncertainty calculation is based on the mathematical model of the measurement. This allows the user to quantify the sensitivity of the measurand to each input uncertainty caused by the flowmeter and the application. The input uncertainties caused by the flowmeter are determined by the manufacturer in the factory and/or by calibration in a laboratory. All input uncertainties estimation should be performed using calibrated instruments, and if not possible, estimated by validated methods. In order to allow the user to perform the calculation, the manufacturer shall provide these input uncertainties. Uncertainties caused by the application conditions are determined during installation, usually based on guidance given by the manufacturer.

The standard uncertainty of each input quantity is evaluated, and the combined uncertainty is derived by propagation of uncertainty. A coverage factor can be applied to report an expanded uncertainty with a higher level of confidence; usually the coverage factor is k = 2, resulting in a level of confidence of approximately 95 %

8.2 Mathematical model

With Formula (10) given in 4.2, the volume flow measurand on one acoustic path is:

$$q_V = A \cdot K_\mathrm{p} \cdot K_\mathrm{g} \frac{\Delta t}{2(t_\mathrm{tr} - t_0)} \quad (10)$$

The relative standard uncertainty of volume flow is calculated by propagation of uncertainty:

$$u_\mathrm{r}^2(q_V) = u_\mathrm{r}^2(A) + u_\mathrm{r}^2(K_\mathrm{p}) + u_\mathrm{r}^2(K_\mathrm{g}) + u_\mathrm{r}^2(t_\mathrm{tr}) + \left(\frac{t_0}{t_\mathrm{tr} - t_0}\right)^2 u_\mathrm{r}^2(t_0) + u_\mathrm{r}^2(\Delta t) \quad (11)$$

The details of derivation of Formula (11) are shown in A.1.5. A few conclusions can be drawn directly from this Formula (11) without doing numerical calculations.

— Contributions from the installation are separated from contributions from the flowmeter except for the delay time.

  — Contributions from the installation are the uncertainty in cross sectional area of the pipe and of the profile factor.

  — Contributions from the flowmeter are the uncertainty of the path-geometry factor and time measurement.

  — The delay time consists of the time in the transducer determined in the factory and the time in the pipe wall calculated by the flowmeter based on the wall thickness and sound speed of the wall material. The sensitivity for delay time is the ratio of delay time to the time in the fluid, hence the contribution of the delay time uncertainty will be small when the time outside the fluid is much smaller than the time in the fluid which usually is the case.

— Only the transit time difference causes an uncertainty contribution depending on flow velocities. All other contributions are constant for a given installation. The uncertainty contribution of the profile factor may show a dependence on Reynolds number.

  — Because the transit time difference increases with the flow velocity, its relative uncertainty contribution decreases with flow velocity. The transit time difference also increases with the time the signal propagates through the fluid, and so increases with the pipe diameter. Increasing the path length by using reflect mode installation or multiple reflections will have the same effect.

  — The uncertainty of time measurement is related to signal frequency which is given by the transducer frequency. A transducer of a given frequency will enable lower uncertainty in time measurement when it is used on the upper end of its specified range of pipe diameters.

In the following, the individual uncertainty contributions in Formula (11) are evaluated. Numerical examples for the combined standard uncertainty are given in A.1.4.

8.3 Evaluation of the contributory variances

8.3.1 Uncertainty of the cross-sectional area, $u(A)$

The cross-sectional area (Figure 1) is calculated from the internal pipe diameter by Formula (12):

$$A = \frac{\pi}{4} D_i^2 \quad (12)$$

Propagation of uncertainty from this formula yields following relative uncertainty of cross-sectional area to Formula (13):

$$u_r(A) = 2u_r(D_i) \quad (13)$$

Because Formula (12) contains the squared internal diameter the relative uncertainty of the cross-sectional area is double the relative uncertainty of the internal pipe diameter. This underlines the need to measure the internal diameter accurately.

Clamp-on ultrasonic meters usually are installed without interrupting the pipeline. Therefore, the internal diameter is usually calculated from the external diameter D_e and wall thickness δ as given in Formula (14):

$$D_i = D_e - 2\delta \quad (14)$$

The relative uncertainty of the measurement of internal pipe diameter, $u_r(D_i)$, is given by Formula (15):

$$u_r(D_i) = \frac{\sqrt{u(D_e)^2 + [2u(\delta)]^2}}{D_i} \quad (15)$$

Thus, the uncertainty of the cross-sectional area, $u(A)$, is determined by the uncertainty of the measurement of the external diameter, $u(D_e)$, and the uncertainty of the measurement of the wall thickness, $u(\delta)$.

8.3.1.1 Uncertainty of measurement of wall thickness

The wall thickness at the transducer location can be measured non-intrusively by an ultrasonic wall thickness gauge, which measures the transit time of an ultrasonic signal through the pipe wall. This requires knowledge of the wall material. Ultrasonic thickness gauges usually provide a choice of materials with their sound speeds pre-programmed, though some also allow direct input of the material sound speed if known. Thus, the uncertainty of wall thickness measurement is determined by the uncertainty of the sound speed in the wall and by the uncertainty of time measurement specified for the thickness gauge.

In operational situations, uncertainty in the speed of sound in the wall arises from:

— Small variations in the speed of sound due to the precise composition of the material;

— The material selection on the thickness gauge not having the correct grade of the material.

These uncertainties may be minimised if coupons taken from the pipe or offcuts are available and may be measured and used to calibrate the thickness gauge.

Generally, the wall thickness varies around the circumference of the pipe and also along the pipe axis, due to factors such as:

— Natural variations during the manufacturing process;

— Tuberculation and internal corrosion in older pipes, (note that this may not always be determined reliably by a thickness gauge);

— Variations in lining thickness;

— The distribution of the reinforcing material(s) in the binder (matrix) in composite materials (e.g. concrete, GRP, cement linings).

In order to measure the average wall thickness, it is recommended to take eight points around the pipe circumference and take these measurements at three different axial positions at the transducer location. The uncertainty of the average acquired by this method depends on the character of the variations of the wall thickness. Variations caused by manufacturing tolerances usually are averaged very accurately by taking eight circumferential points. The uncertainty depending on the number of thickness measurement points can be estimated by taking a second measurement at another eight positionings in between the previous measurement points. The difference between the two measurements can be used as an estimate for the uncertainty of the mean.

Some uncertainties can remain which should be considered on a site-by-site basis. This will include difficulty in detecting lining materials, particularly if they are poorly adhered to the internal pipe wall. However, when the sound speed of the fluid is known, in certain cases it can be possible to deduce the thickness of the liner from the transit time through the measurement setup.

8.3.1.2 Direct measurement of internal diameter

On some sites, a tapping may be available to permit an internal gauging rod to be inserted. The uncertainty of the gauge shall be considered when evaluating the uncertainty in the cross-sectional area.

Additional errors may be incurred due to, for example:

— Axial misalignment of the probe which will induce a positive error;

— Measurement across a chord, i.e. where the gauging rod does not pass through the geometric centre of the pipe, leading to a negative error;

The user may add an additional component of uncertainty to account for such errors.

As tappings are often only available on one, or at most two diameters, pipe ovality and irregularities in the pipe wall, e.g. due to uneven linings, corrosion or tuberculation, can be difficult to identify and will further increase uncertainty. This method is of benefit on pipes were ultrasonic wall thickness gauges cannot be used.

8.3.1.3 Uncertainty of measurement of external diameter

The external pipe circumference at the transducer location can be measured with a measuring tape, thus allowing the external diameter to be calculated. The uncertainty of the tape determines the uncertainty of the external diameter. With small pipes, direct measurement of the diameter using a calliper will often be more practical.

Pipes are not perfectly round; a degree of ovality is often present and therefore the diameter varies around the circumference. Provided that the degree of ovality is small, a measuring tape used to measure the circumference allows a good average of the diameter to be calculated. This will represent the equivalent diameter of an ideally round pipe of the same cross-sectional area as the real pipe. When using a calliper, the average diameter should be calculated from multiple measurements taken around the pipe circumference.

When measuring the external diameter or circumference of a pipe, care shall be taken to ensure that the measurement is conducted perpendicular to the pipe axis. If the calliper or tape is slightly skewed, then the measurement will have a positive error which is a function of the angle of skew. The measured diameter or circumference will be a factor of $(1/\cos\theta)$ larger than the true value, where θ is the angle of skew. In order to minimise such errors, a number of measurements should be taken and the lowest used.

8.3.2 Uncertainty in the velocity profile, $u(K_p)$

The uncertainty caused by the flow profile depends on the upstream conditions, upstream pipe length, Reynolds number, pipe roughness, and path configuration as described in 4.2.2. Manufacturers usually specify the uncertainty for fully developed turbulent flow because this is the condition for which the models for flow profiles provided by fluid dynamics are applicable. Fully developed turbulent flow requires ideal upstream conditions and a Reynolds number greater than 10 000.

Many devices include Reynolds number correction which allows for the change in velocity profile in the laminar flow region. However, there is likely to be an increase in uncertainty in the transition region between laminar and turbulent flows, which will typically occur between Reynolds numbers of 5 000 and 10 000. However, the extent of this effect will vary from meter to meter and manufacturer's guidance should be sought if the meter is to be used at Reynolds numbers below 10 000.

The uncertainty under non-ideal conditions can be determined by testing in a flow lab or by CFD calculation. The influence of upstream flow conditions on the uncertainty of the profile factor is nearly identical with all types of clamp-on meters since all meters described in this standard use diametric paths. However, different path configurations can be used. This regards the number of paths and whether they are installed in reflect mode or in direct mode (see 4.2.2). In particular, cross flow compensating configurations like reflecting paths are much less sensitive to upstream flow conditions than single direct paths (see 4.2.2). Therefore, when using test results, the path configuration used at a specific test needs to be considered.

Some manufacturers incorporate settings within their devices that allow the user to specify the upstream pipe configuration and hence allow for profile distortion in the measurement. Manufacturers shall provide the remaining uncertainty when using these settings.

8.3.3 Uncertainty of the path-geometry factor, $u(K_g)$ and time measurement

These uncertainties depend on the transducers and the measurement transmitter. A manufacturer may also quantify an uncertainty for the measurement system consisting of transducers and transmitter (including clock resolution) or quantify both contributions separately.

The uncertainty in the path geometry factor, $u(K_g)$ is dependent on the transducer geometry and the uncertainty in time measurement is dependent on both the transducer frequency and processing factors within the transmitter such as the clock frequency. Manufacturers shall provide these uncertainty factors.

8.3.4 Uncertainty of time measurement

The uncertainty $u(t_{tr})$ and $u(\Delta t)$ of transit time measurement and time difference measurement depend on the time measurement capability of the flowmeter. These values are determined by the manufacturer in the factory and shall be provided to the user.

8.3.5 Uncertainty of the delay time, $u(t_0)$

The delay time is the sum of twice the transit time in the transducer's coupling wedge, t_t, and twice the transit time in the pipe wall, t_w, as given in Formula (16):

$$t_0 = 2t_t + 2t_w \tag{16}$$

The uncertainty of the delay in the coupling wedge is determined in the factory.

The transit time in the pipe wall is calculated by the meter from the path length and the sound speed in the pipe wall. Therefore, the relative uncertainty of the transit time in the wall is determined by the uncertainty of time measurement of the meter and the uncertainty of the sound speed in the wall.

The total uncertainty contribution of delay time includes the sensitivity $c_{r,t_0} = t_0 / (t_{tr} - t_0)$. Usually, the delay time is less than 1/10 of the transit time. Therefore, the contribution of the uncertainty of delay time, usually, is small.

8.3.6 Effect of multiple paths

Using multiple paths by installing multiple pairs of transducers will reduce the uncertainty of all contributions that are not correlated between the paths. The uncertainty of the cross-sectional area of the pipe is not reduced.

Non-correlated contributions are those that vary randomly between the paths, like the uncertainty of the time measurement and the uncertainty of the path-geometry factor. The reduction for these random effects equals the square root of the number of paths assuming a Gaussian probability distribution for these effects.

Multiple paths will reduce the uncertainty in profile as discussed in 8.3.2.

8.4 Additional effects on measurement uncertainty

While 8.2 and 8.3 explain how the total uncertainty can be calculated based on the meter formula and the contributing uncertainties this clause provides guidance on assessing the total uncertainty experimentally. This is useful for effects that are not fully covered by the meter formula.

The total uncertainty associated with the measurement system can be obtained from repeated tests on a flow calibration rig. This should be carried out on a length of pipe for which the geometry and properties are known with a low uncertainty.

8.4.1 Effect of pipe material on sound speed

Most instruments will offer the user a choice of materials, but the range of materials offered varies from meter to meter. It is also unlikely to include all variants of a specific material, for example the various grades of stainless steel. Taking stainless steel as an example, these have different sound speeds through them, and hence the refraction angles as the signal passes into or out of them are different. This alters the calculated path length, and hence the measured velocity. Errors have been observed when an instrument was programmed with an incorrect pipe material[14]. This effect can be assessed in the laboratory or in the field by observing the change in meter reading caused by a change in the pipe material setting under the condition of constant flow.

Published tables of sound speeds in different materials allow the user to estimate the likely contribution to uncertainty by examining the variability of sound speeds for similar materials where the material is not known precisely.

8.4.2 Effect of fluid sound speed

Incorrect assumptions in the characteristics of a fluid can lead to an increase in uncertainty if not corrected prior to operation. Consult manufacturer guidelines on the best way for this to be achieved. The main characteristic is the sound speed of the ultrasonic signal through the fluid which will affect the calculation of the refraction angles passing from the wall into the fluid and the path length.

Manufacturers will typically provide a range of pre-programmed fluids with their corresponding sound speeds covering common applications. However, sound speeds may change if the fluid is a different concentration, for example.

The presence of contaminants, including dissolved material, within a fluid are likely to alter the speed of sound in the fluid which can be difficult to quantify. This should be assessed on a site-by-site basis.

8.4.3 Reproducibility of transmitter mounting

Removal and reattachment of ultrasonic transducers in the same location can give rise to a change in the measurement[13]. The user can carry out such an assessment on each individual installation under the condition of a constant flow by repeating the installation. The results should be included within the uncertainty budget.

8.4.4 External influences

The impact of influence conditions such as ambient temperature and variations in power supply are generally negligible. However, this should be evaluated for specific instruments by laboratory tests.

Annex A
(informative)

Example of uncertainty calculation

A.1 General

The purpose of this annex is to demonstrate how the general procedure described in Clause 8 can be applied to concrete examples. All calculations here are based on the methods presented in ISO/IEC Guide 98-3[5]. All numbers used for the uncertainty contributions in this clause are chosen in order to provide examples. They should be adapted for particular applications and devices and are not universal for all applications.

The uncertainty calculation is based on the mathematical model of the measurement. This allows the user to quantify the sensitivity of the measurand to each input uncertainty caused by the flowmeter and the application. The input uncertainties caused by the flowmeter are determined by the manufacturer in the factory and provided to the user. The input uncertainties caused by the application conditions are determined during installation, usually based on guidance given by the manufacturer and using calibrated instruments, and if not possible, estimated by validated methods.

A.1.1 Mathematical model

With Formula (10) given in 8.2, the relative standard uncertainty of volume flow is given as:

$$u_r^2(q_V) = u_r^2(A) + u_r^2(K_p) + u_r^2(K_g) + u_r^2(t_{tr}) + \left(\frac{t_0}{t_{tr} - t_0}\right)^2 u_r^2(t_0) + u_r^2(\Delta t) \qquad (A.1)$$

The details of derivation of Formula (A.1) are shown in A.1.5. The calculation of the total uncertainty requires evaluation of the contributary variances as shown in the following subclauses.

A.1.2 Installation conditions

The following values for the installation conditions are used in these examples:

- pipe external diameter: 219,1 mm;
- pipe wall thickness: 5,0 mm;
- fluid: water;
- range of path velocity: 0,3 to 5 m/s;
- fluid temperature: 20 °C;
- upstream flow conditions: 30*D* after a single 90° bend.

A.1.3 Evaluation of the contributory variances

A.1.3.1 Uncertainty of the cross-sectional area, $u(A)$

The uncertainty of cross-sectional area is given with Formula (12) in 8.3.1 as Formula (A.2):

$$u_{\mathrm{r}}(A) = 2u_{\mathrm{r}}(D_{\mathrm{i}}) \tag{A.2}$$

The internal diameter is determined by measuring the external diameter and the wall thickness. The relative uncertainty of the measurement of internal pipe diameter is given with Formula (14) in 8.3.1 as Formula (A.3):

$$u_{\mathrm{r}}(D_{\mathrm{i}}) = \frac{\sqrt{u(D_{\mathrm{e}})^2 + [2u(\delta)]^2}}{D_{\mathrm{i}}} \tag{A.3}$$

The wall thickness is measured by an ultrasonic wall thickness gauge. The uncertainty of this measurement depends on the uncertainty of time measurement and the uncertainty of sound speed in the wall. Assuming the longitudinal sound speed of carbon steel is $c_{\mathrm{L}} = 5\,920\ \mathrm{m/s}$, and its uncertainty is $u(c_{\mathrm{L}}) = 40\ \mathrm{m/s}$, this results in a relative uncertainty of $u_r(c_{\mathrm{L}}) = 0{,}68\,\%$. Assuming that the time measurement uncertainty is neglectable compared to the uncertainty of sound speed, this results in an uncertainty of wall thickness of $u(\delta) = 5\,\mathrm{mm} \cdot 0{,}68\,\% = 0{,}04\,\mathrm{mm}$.

The standard uncertainty of the measurement of external diameter made with a circumferential tape measure is assumed to be $u(D_{\mathrm{e}})$ = 0,2 mm.

With Formulae (A.2) and (A.3) this results in a relative uncertainty of cross-sectional area of:

$$u_{\mathrm{r}}(A) = 2u_{\mathrm{r}}(D_{\mathrm{i}}) = 2\frac{\sqrt{u(D_{\mathrm{e}})^2 + [2u(\delta)]^2}}{D_{\mathrm{i}}} = 2\frac{\sqrt{0{,}2^2 + (2 \cdot 0{,}04)^2}}{219{,}1 - 2 \cdot 5} = 0{,}2\,\% \tag{A.4}$$

A.1.3.2 Uncertainty in the velocity profile, $u(K_{\mathrm{p}})$

The uncertainty caused by the flow profile depends on the upstream flow conditions. In this example the meter is installed at 30*D* after a 90° bend. It is assumed that the standard uncertainty caused by the flow profile under these conditions is determined by testing to be as in Formula (A.5):

$$\frac{u(K_{\mathrm{p}})}{K_{\mathrm{p}}} \approx 0{,}3\,\% \tag{A.5}$$

A.1.3.3 Uncertainty of the path-geometry factor, $u(K_{\mathrm{g}})$

The standard uncertainty of the path-geometry factor is determined in the factory. In this example it is assumed to be $u(K_{\mathrm{g}})$ = 0,3 %. The temperature dependency of K_{g} is assumed to be largely compensated for by the meter. The remaining uncertainty due to temperature is negligible in this example because the installation is near reference temperature.

A.1.3.4 Uncertainty of the time measurement

The uncertainty of time measurement is related to signal frequency which is given by the transducer frequency. In these examples it is assumed that the ratio of standard uncertainty of time measurement to signal period T_0 is a constant:

$$\frac{u(t_{\mathrm{tr}})}{T_0} = 0{,}1;\ \frac{u(\Delta t)}{T_0} = 3E - 4 \tag{A.6}$$