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Use of clamp-on (externally mounted) ultrasonic flow-metering techniques for fluid applications – Guide

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This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 74, an inside back cover and a back cover.

Foreword

Publishing information

This British Standard is published by BSI and came into effect on 31 December 2010. It was prepared by Subcommittee CPI/30/5, *Velocity based methods*, under the authority of Technical Committee CPI/30, *Measurement of fluid flow in closed conduits*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

This British Standard supersedes BS 8452:2005, which is withdrawn.

Information about this document

This guide now covers gas and liquid applications. It draws on practical user experience and various pieces of research work funded by DTi and other bodies.

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Any user claiming compliance with this British Standard is expected to be able to justify any course of action that deviates from its recommendations.

Presentational conventions

The provisions in this standard are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is "should".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

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Introduction

This British Standard identifies factors likely to affect the performance of clamp-on (externally mounted) ultrasonic flow-meters for closed conduits running full. One of the significant advantages in employing ultrasonic techniques in fluid flow-metering is that not only can the meters be used non-intrusively, i.e. the sensors do not intrude into the flow path, but they can also be used non-invasively, i.e. with the transducers mounted onto the outside of the pipe work. Such methods are commonly referred to as clamp-on ultrasonic techniques because the transducers are clamped or held onto the outside of the pipe work.

These methods enable measurements to be made without breaking into the pipe work; therefore, measurements can be made where, for reasons of safety, hygiene, continuity of supply or cost, it is not possible to break containment.

Non-invasive ultrasonic metering techniques can thus provide a basis for checking existing meters, and be used as a temporary, semi-permanent or permanent method of measurement.

1 Scope

This British Standard identifies factors, including installation effects, pipe work and fluid effects, operational effects and supplier specific effects, which are likely to affect the performance of clamp-on (externally mounted) ultrasonic flow-meters This includes hybrid spool type clamp-on meters where the clamp-on transducers are permanently mounted to a spool piece of precisely known physical dimensions. In doing so it also identifies best operational practice for such meters and provides estimates of the overall uncertainty that can be achieved when employing best practice.

This standard provides a description of the non-invasive 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 flow, pipe, fluid and operational conditions based upon available data.

There are currently three commonly used non-invasive ultrasonic flow measurement technologies. These are the transit time ultrasonic flow-meter (TTUF), Doppler ultrasonic flow-meter (DUF) and the cross-correlation ultrasonic flow-meter (CCUF). However, technological innovation has seen variants of these techniques developed to improve the operation of the meters. The scope of this British Standard is restricted to the use of base technology employed in the meters so as not to preclude further developments. Each technique has its advantages and disadvantages depending upon the application. In order to provide the reader with as much information as possible the different ultrasonic technologies hybrids and their applications are discussed in Annex B to provide a comparative overview of the additional capabilities they offer.

2 Symbols and abbreviations

2.1 Symbols

Symbol	Meaning	Units
C_f	velocity of sound in fluid	m/s
C_p	velocity of sound in pipe wall	m/s
C_w	velocity of sound in transducer wedge	m/s
D	pipe internal diameter	m
E	indicated flow rate error	%
E	average flow rate error for all test runs	%
E_i	flow rate error of the i^{th} test run	%
f_d	Doppler frequency shift	Hz
f_t	transmission frequency	Hz
h	height of wedge	m
K	meter factor	—
k_h	profile correction factor	—
k_r	uniform equivalent roughness	m
n	number of test runs	—
Q_v	volumetric flow rate	m^3/s
R	repeatability	—
Re	Reynolds number	dimensionless
ρ	density of fluid	kg/m^3
μ	viscosity	Poise
ν	velocity	m/s
S	transducer separation	m
S_f	separation through the fluid	m
S_p	separation through the pipe wall	m
S_w	separation through the transducer wedge	m
t	pipe wall thickness	m
t_{12}	transit time for ultrasound to travel from transducer 1 to transducer 2	s
t_{21}	transit time for ultrasound to travel from transducer 2 to transducer 1	s
Δt	time difference $t_{12} - t_{21}$	s
v_{pipe}	mean pipe velocity	m/s
V_{ind}	volume indicated by test meter	m^3
V_{std}	volume indicated by reference meter	m^3
α	angle between the direction of ultrasound in the transducer wedge and the pipe axis	° (degrees)
θ	angle between the direction of ultrasound in the liquid and the pipe axis	° (degrees)
λ	wavelength	m
λl	wavelength of ultrasound in the fluid	m

Symbol	Meaning	Units
v_{path}	averaged axial component of velocity along path between transducers	m/s
v_{s}	velocity of scatterers	m/s
Z	acoustic impedance	MRayls

2.2 Abbreviations

ABS	Acrylonitrile butadiene styrene
CCUF	cross-correlation ultrasonic flow-meter
CPVC	Chlorinated polyvinyl chloride
DUF	Doppler ultrasonic flow-meter
GRP	Glass Reinforced Plastic
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
MDPE	Medium Density Polyethylene
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
PVDF	Polyvinylidene Fluoride
RTV	Room Temperature Vulcanizing (elastomer sealant)
TTUF	transit time ultrasonic flow-meter
UFS	Ultrasonic Flow Meter System
USM	Ultrasonic Meter

3 Clamp-on ultrasonic flow-meters

3.1 General

A typical clamp-on ultrasonic flow-meter comprises three elements:

- The transducers and associated cables.
- The clamping arrangement.
- The signal processing and user interface electronic package.

The transducers are generally piezoelectric devices generating ultrasound that penetrates through the pipe wall and is transmitted through the fluid.

The clamping arrangements enable the transducers to be in good sonic contact with the pipe wall and correctly positioned, given the particular clamp-on technology employed and the specific pipe and fluid application.

3.2 Beam refraction – Snell's law

It is worth reiterating the impact of Snell's law as it applies to all forms of clamp-on ultrasonic meter. This is shown graphically in Figure 1 and in the following analysis.

Refraction of ultrasound is governed by Snell's law, which can be presented as:

$$\frac{\cos\alpha}{c_1} = \frac{\cos\beta}{c_2} = \frac{\cos\theta}{c_f} \qquad (1)$$

where:

c_1 is...velocity of sound of the transduer

c_2 is...velocity of sound in the pipe

c_f is...velcoity of sound in the fluid

If the transducers are configured such that $\alpha_t = \alpha_r = \alpha$ then Equation 1 can be rewritten as:

$$\delta f = 2f_t\left(\frac{v\cos\theta}{c_f}\right) \qquad (2)$$

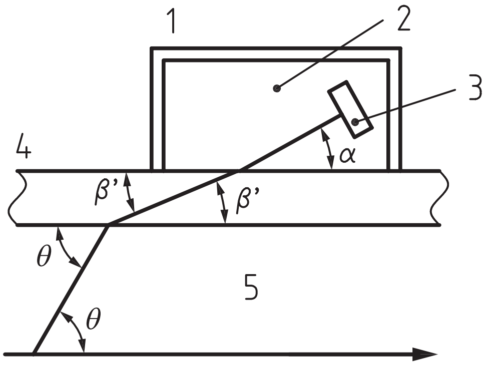
substituting $\frac{\cos\alpha}{c_1}$ for $\frac{\cos\theta}{c_f}$ and rearranging for *v* yields:

$$v = \frac{\delta f c_1}{2f_t\cos\alpha} \qquad (3)$$

i.e. the measured velocity is proportional to δf and independent of the acoustic properties of the fluid and the pipe wall. The angle *a* and velocity of sound c_1 are assumed to have known values.

However, temperature dependence of c_1, the velocity in the transducer "potting" or internal coupling material, can give rise to errors in the measurement of velocity. The USM manufacturer should be consulted regarding the temperature dependence of the particular transducers employed and the likely impact of temperature variation.

Figure 1 **Refraction of ultrasound signals through pipe wall**



Key

1 Housing

2 Internal coupling

3 Transducer

4 Pipe wall

5 Liquid

3.3 Transit time ultrasonic flow meter

Figure 2 shows the principle of operation of the clamp-on TTUF measuring the flow rate of a fluid whose velocity of sound is c_f in a pipe of internal diameter *D*. This technology is applicable to both liquid and gas applications. Figure 3 illustrates a typical TTUF configuration. The signal processing electronics measures the time taken for ultrasonic waveforms to be alternately passed upstream and downstream. Any resulting difference in times (Δt) is directly related to the velocity of the fluid. The velocity is converted to a flow rate, which is typically displayed on a user interface either in numerical or graphical format. An analogue and/or digital output might be provided. A means is also provided for the user to enter application specific data.

Although different manufacturers undertake the measurement in a variety of ways and employ different algorithms to compute the flow rate from the measurements they make, the following gives in generic form the basis of the measurement.

The flow rate is determined using the transit time difference between the time taken for ultrasound to travel upstream from Transducer 1 to Transducer 2 and the time taken to travel downstream from Transducer 2 to Transducer 1. If the ultrasonic beam in the fluid is at an angle θ to the pipe axis and the path orientation is as shown in Figure 2 the individual transit times would be defined as Equation 4 and Equation 5.

$$T_{up} = P / (c - \bar{V}\sin\theta) \tag{4}$$

$$T_{dn} = P / (c + \bar{V}\sin\theta) \tag{5}$$

where:

$\bar{V}$ is the average flow velocity along the acoustic path

c is fluid soundspeed

Combining (1) and (2) gives:

$$\bar{V} = \frac{P}{2\sin\theta} \cdot \frac{\Delta t}{T_{up} \cdot T_{dn}} \tag{6}$$

where:

$$\Delta t = T_{up} - T_{dn}$$

The volumetric flowrate is given by:

$$Q = K \cdot \bar{V} \cdot A \tag{7}$$

where:

K is a meter factor to take profile effects into account

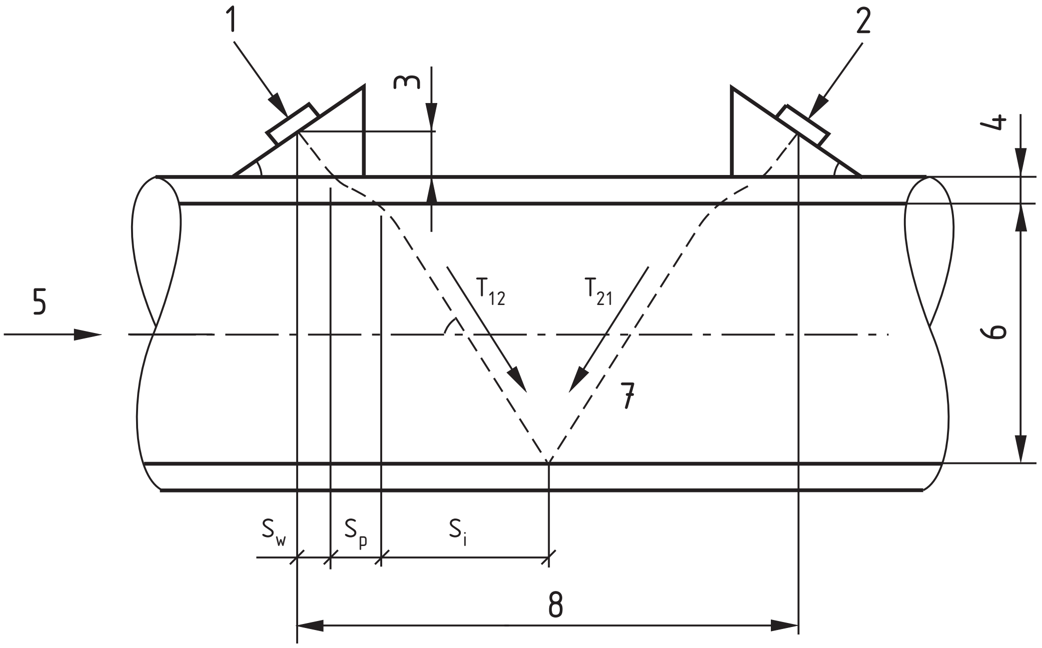
A is the cross-sectional area of the pipe

Also by combining (1) and (2) the velocity of sound can also be calculated directly from the equation:

$$C = \frac{P}{2} \cdot \left(\frac{1}{T_{up}} + \frac{1}{T_{dn}} \right) \tag{8}$$

A detailed account of the flow algorithm is given in Annex C.

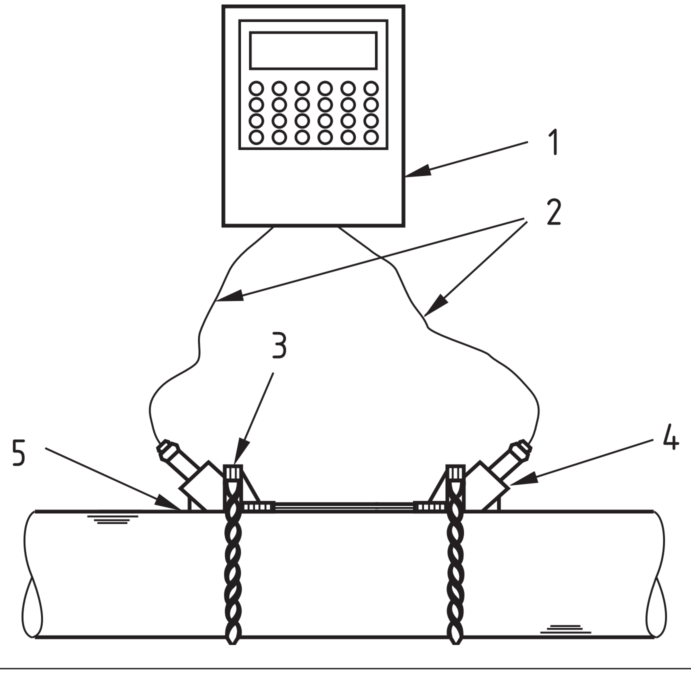
Figure 2 **Schematic of a clamp-on transit time ultrasonic flow-meter**



Key

1	Transducer T2	5	Flow
2	Transducer T1	6	Pipe i.d. *D*
3	Height of wedge *h* Velocity of sound C_w	7	Velocity of sound C_1
4	Pipe wall thickness t Velocity of sound C_p	8	Transducer separation *s*

Figure 3 **A typical clamp-on TTUF**



Key

1 Flow-meter electronics
2 Cables (matched pair)
3 Clamping device
4 Transducers
5 Couplant

3.4 Cross-correlation ultrasonic flow meter

Cross-correlation ultrasonic flow-meters (CCUFs), although not widely used, are commercially available from some manufacturers. Figure 4 shows the basis of operation of a cross correlation ultrasonic flow meter.

Modulation of the ultrasound by particulate matter, gas bubbles or turbulence is detected at two stations axially separated by a distance, L, which is typically between $0.5D$ and D. The flow velocity is estimated by cross-correlation of the noise signals generated by modulation phenomenon. The time delay between the arrival of similarly modulated signals provides a peak in the cross-correlation function of the noise at each receiver and provides an estimate of the time for a particular distribution of scatterers to travel along the pipe from one beam to another.

In two-phase flow, the signal is affected by factors such as the number of scatterers per unit volume, the distribution of scatterer sizes, their spatial arrangement and the velocity profile across the pipe. Consequently, a calibration obtained under a particular set of operating conditions might not apply to another.

Cross-correlation technology is applicable to both liquid and gas applications, but commercially CCUFs are mostly applied to gases. A CCUF requires a 2-channel meter and two pairs of transducers. Approximate purchase price would be 50% more than a TTUF for the equivalent line size. It is therefore advised that the manufacturer be consulted regarding selection of CCUF over TTUF.

3.5 Clamp-on DUFs

As the majority of CUF applications involve liquid as opposed to gas, a potential user of a CUF is most likely to encounter either TTUF or DUF technology. A TTUF operates in the time domain and a DUF in the frequency domain. The areas of application are essentially different, but there is an overlap, and the potential user might be drawn to the lower price of a DUF. It should be understood that DUF performance, e.g. accuracy, will inherently be inferior to that of a TTUF.

Figure 5 shows the basic operation of a DUF, whereby gas bubbles or solid particles are necessary to reflect or scatter the propagated ultrasound. Assuming that all the scatterers are moving with a velocity, v_s, then the Doppler shift, f_d, of the transmitted ultrasound is given by:

$$f_d = 2f_t \frac{v_s}{C_l} \cos\theta$$

where

f_t is the transmission frequency;

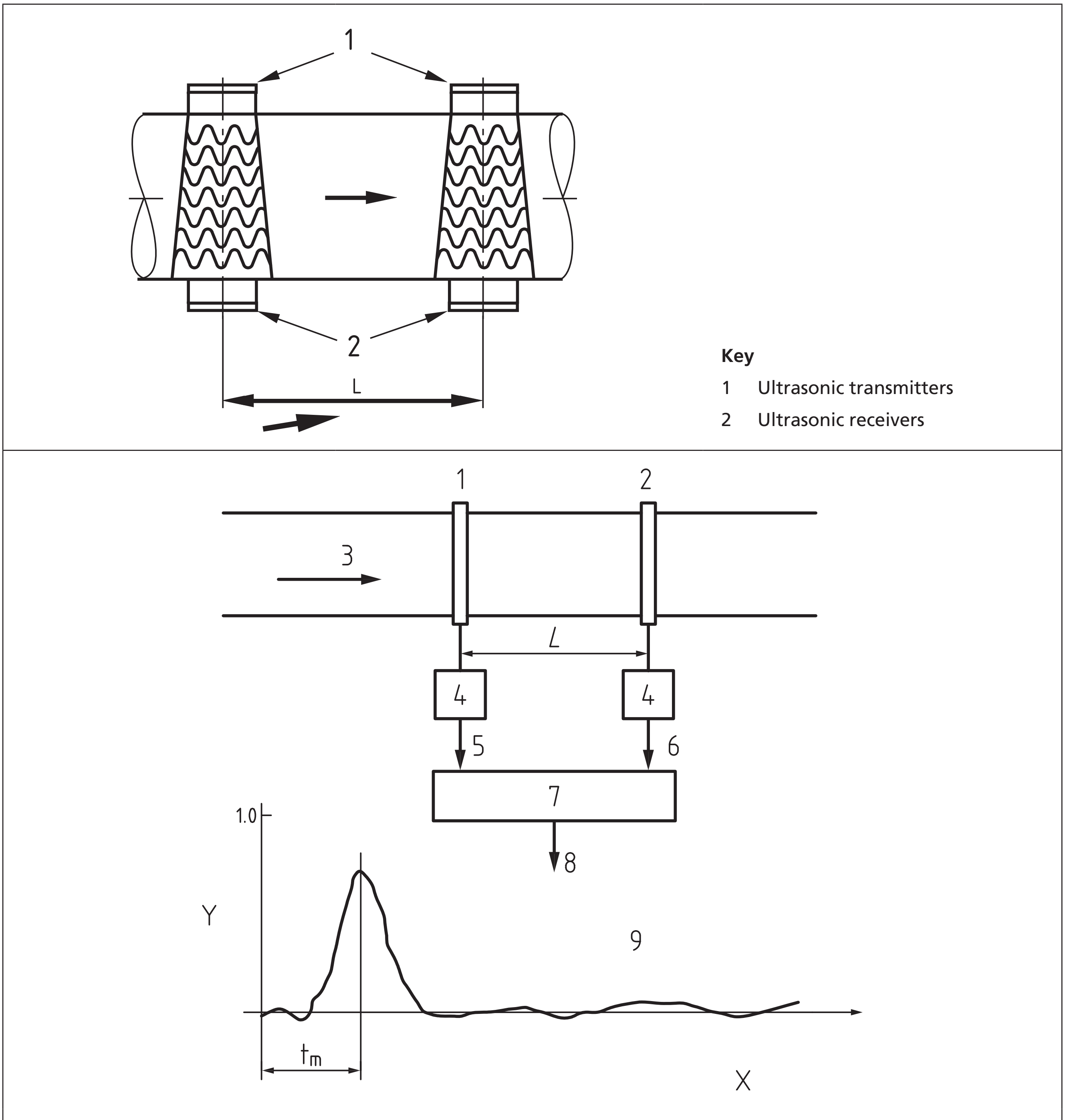
C_l is the velocity of sound in the liquid; and

θ is the angle of the ultrasonic beam with respect to the pipe axis.

The different frequency is known as the Doppler shift and is linearly proportional to the fluid velocity.

In general, the Doppler shift is not a single frequency because broadening of the spectrum occurs as the suspended bubbles or particles, i.e. scatter sources, have a range of velocities and are further affected by turbulence, the ultrasonic beam has a finite width, and the angle of the beam relative to the direction of liquid flow has a range of values. An estimate therefore has to be made of the average Doppler shift from a spectrum, which typically looks like that in Figure 5.

Figure 4 **Cross-correlation ultrasonic flow-meter (CCUF)**



Key

1 Ultrasonic transmitters

2 Ultrasonic receivers

Key

1 Sensor (x)

2 Sensor (y)

3 Flow

4 Signal conditioning

5 x(t)

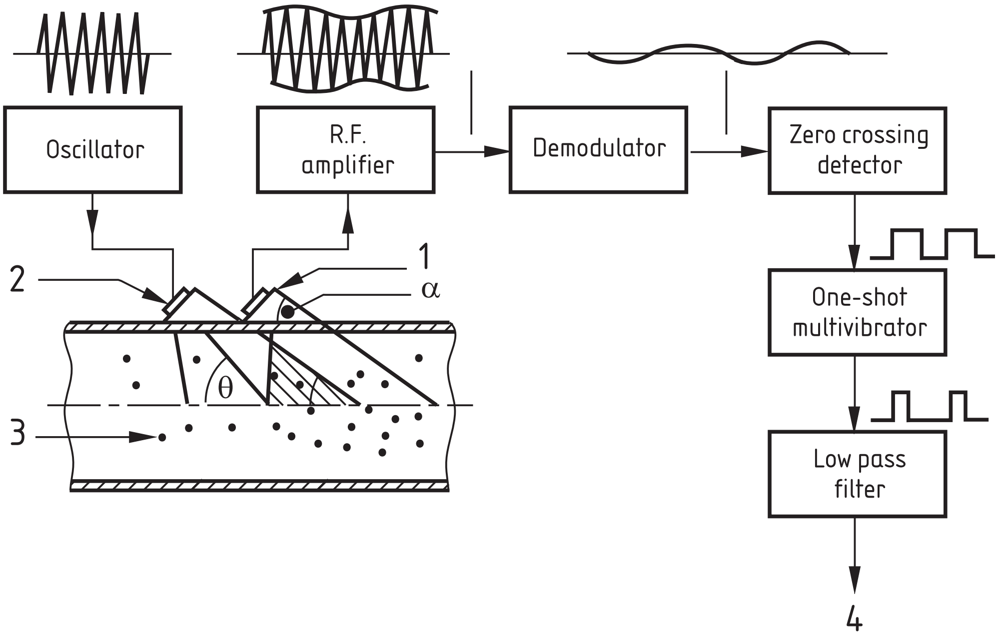
6 y(t)

7 Correlator

8 $R_{xy(\tau)}$

9 Flow velocity $V = L / \tau_m$

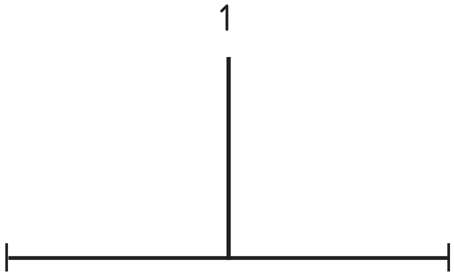
Figure 5 **Basic operation of a DUF**



Key

1	Receiver	3	Scatterers
2	Transmitter	4	Output proportional to flow

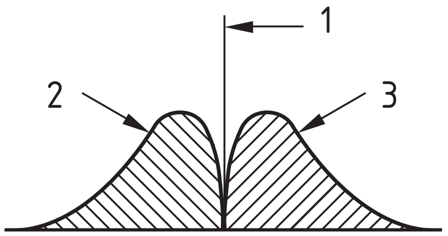
a)



Key

1 Transmitter frequency spectrum

b) Transmitted spectrum



Key

1	Transmitter frequency	3	Reverse flow
2	Forward flow		

c) Received spectrum

The performance of Doppler flow-meters (DUFs) is limited due to the nature, size, spatial distribution of the scatterers which varies the attenuation of the ultrasonic beam. The zone that contributes to the velocity measurement is not well defined. In large pipes it is likely to be close to the wall. The relationship between the sensed velocity and the mean velocity in the pipe is unknown. The velocity being sensed is that of the scatterers and, because of slippage, it might not correspond to the liquid velocity.

Generally, DUFs are application specific and require considerable product and application knowledge if the use of this technology is to be successful. Variants of the technology are used by manufacturers and include pure Doppler, gated Doppler and speckle-tracking methods.

Upstream disturbances, in the form of bends, valves, pipe work and probes causing vortices can all cause the meter to read in error. Errors can also be caused by vibration. In order to obtain an accurate volumetric flow rate measurement, the internal diameter of the pipe work needs to be measured accurately. Typical application areas for DUFs are raw sewage, sludge, slurries and paper pulp.

Some manufacturers of clamp-on TTUFs provide dual modes of operation. In the absence of scatterers, the meters operate as conventional TTUFs. When the scatterers in the form particulate matter or gas bubbles rise above a certain level, the meter changes its mode of operation and it then operates as a DUF.

4 Application areas

4.1 General

4.1.1 Typical applications

Table 1 and Table 2 identify typical applications for the various clamp-on technologies, drawn from manufacturer's application data, identifies typical application areas to which clamp-on meters are being applied.

This is not meant to be an exhaustive list and, for specific areas of application outside those identified in Table 1 and Table 2, potential users should consult meter manufacturers.

The application areas for clamp-on meters, where they show significant advantages over other techniques, are those where:

- the pipe cannot be cut for reasons of safety or hygiene or possible process contamination;
- the cost of breaking into the pipe work and installation are too high;
- for reasons of continuity of supply, maintenance or service, flow measurement must be achieved without a process shut-down;

on larger pipes, the cost–benefit over other in-line meters is greatest.

In Table 1 and Table 2 there is an indication P or T which relates to either permanent or temporary installations. These are categorized in **4.1.2** and **4.1.3**.

Table 1 **Clamp-on meter selection table – liquids**

Technology selection for liquid applications					
Industry	**Application**	**P/T**	**Transit time**	**Doppler**	**Cross-correlation**
Water	Leak detection	P/T	Yes	Yes	
	Network analysis	T	Yes		
Oil and gas	Fire pump test	T	Yes		
	Crude oil	P	Yes		
	Water injection	P	Yes		
	Diesel flow	P	Yes		
	Produced water	P	Yes	Yes	Yes
	Condensate	P	Yes		
Food	Food blending	P	Yes	Yes	
	Food batching	P	Yes	Yes	
Semiconductor	High purity liquid	P	Yes	No	
	Aggressive liquid	P	Yes		
Pharmaceutical	—	P/T	Yes		
Chemical	Check metering	T	Yes	Yes	
Power	Coolant flow	P	Yes		Yes
	Nuclear feed water	P	Yes		Yes
	Hydro electric turbine flows	P	Yes		
	Coal slurry	P		Yes	Yes
Miscellaneous	Cold utility water	P	Yes		
	Hot utility water	P	Yes		
	Heat metering	P	Yes		
	Air conditioning	P	Yes		
	Raw sewage	P	Yes	Yes	

Table 2 **Clamp-on meter selection table – gases**

Technology selection for gas applications					
Industry	**Application**	**P/T**	**Transit time**	**Doppler**	**Cross-correlation**
Oil and gas	Hydrocarbon processing	p	Yes	No	No
	Gas transmission	P	Yes	No	Yes
	Check metering	T	Yes	No	Yes
	Network analysis	T	Yes	No	Yes
Food	Food blending	P	Yes		
	Food batching	P			
Semiconductor	High purity gas	P	Yes	No	Yes
	Aggressive gas	P	Yes	No	Yes
Pharmaceutical	—	P/T	Yes	Yes	
Chemical	Process air	T	Yes	No	Yes
Miscellaneous	Heat metering	P/T	Yes		
	Air conditioning	P/T	Yes	No	Yes

4.1.2 Permanent installation

Applications where hygiene or contamination; operation, e.g. supply interruption; high purity; aggressive substances; maintenance and cost are of major consideration resulting in the provision of a permanently installed meter.

4.1.3 Temporary/Semi-permanent installation

Applications where the requirement for the meter is short term or periodic, e.g. validating other installed meters; leakage determination; pump testing or network analysis.

Gas clamp-on TTUFs are designed to be used with dry gases, although they can operate in the presence of limited amounts of either particulate matter or liquid droplets. (Guidance on operating in the presence of particulate matter or liquid droplets is found in Clause **8**.)

4.2 Specific considerations

4.2.1 TTUF

Liquid clamp-on TTUFs are designed to be used with clean liquids, although they can operate in the presence of limited amounts of either particulate matter or gas bubbles. (Guidance on operating in the presence of particulate matter or gas bubbles is found in Clause **8**.)

4.2.2 Cross-correlation

The application areas to which such flow-meters have been employed are in the measurement of single phase liquids; liquid–solid mixtures; liquid–gas mixtures; liquid–liquid mixtures; low pressure gas and high pressure gas.

4.2.3 Doppler

Applications might be limited by the lack of scatterers requiring each application to be considered on its own merits.

5 Performance measures

5.1 General

Clamp-on meters generally provide outputs indicative of volumetric flow rate or totalized volume flow. In assessing the performance of the meter, three measurements are of interest. These are:

- the percentage error of the indicated volumetric flow rate or totalized volume flow (see **5.2**);
- the repeatability of the measurement (see **5.3**); and
- the reproducibility of the measurement (see **5.4**).

In employing these terms, it is important that they should correspond to standard usage. The following sub clauses define the three terms.

5.2 Percentage error

The percentage error of the volumetric flow rate measurement is given by:

$$E = \left(\frac{V_{\mathrm{ind}} - V_{\mathrm{std}}}{V_{\mathrm{std}}} \right) \times 100\% \tag{9}$$

where:

V_{ind} is the volume of fluid passed as indicated by the meter under test during the duration of the test

V_{std} is the recorded reference volume of fluid passed during the same time.

It is usually expressed as a function of flow velocity through the meter.

5.3 Repeatability

The repeatability of the measurement is a measure of the ability to provide repeatable measurements under the same set of conditions. It is a measure of the random uncertainty in the measurement, R, which is defined as:

$$R = 2.83ms_{\mathrm{E}}$$

and:

$$s_{\mathrm{E}} = \sqrt{\frac{\sum_{i=1}^{n} \left(E_{\mathrm{i}} - \bar{E} \right)^2}{n-1}} \tag{10}$$

Where:

E_{i} is the error of the i^{th} run within the test series

$\bar{E}$ is the average error of all the runs in the test series

n is the number of runs in the test series

m is a scaling factor

The use of the scaling factor enables comparisons of repeatability to be made between test series which are different in length by normalizing all the repeatabilities to a standard length of test run.

$$m = \frac{\sqrt{T_{\mathrm{test\ set}}}}{\sqrt{T_{\mathrm{std}}}} \tag{11}$$

where:

$T_{\mathrm{test\ set}}$ is the average length of the test run in a particular set of runs

T_{std} is the time to which the uncertainty is to be normalized.

5.4 Reproducibility

The reproducibility of the measurement is concerned with the degree to which the measurement can be reproduced if the conditions of measurement are changed. Of particular importance in clamp-on meters is the degree to which the readings of the meter are reproducible under unclamping and re-clamping conditions. The reproducibility (r) of the measurements can then be measured by measuring the difference between the average errors in the two sets of tests, one taken before unclamping and re-clamping and the other after, i.e.

$$r = \bar{E}_1 - \bar{E}_2 \tag{12}$$

where:

$\bar{E}_1$ is the average error of the initial tests

$\bar{E}_2$ is the average error of the test undertaken after unclamping and re-clamping

If more than two sets of tests are available, it might be possible to express the reproducibility as a function of the standard deviation of the errors across the whole range of tests. In this case, reproducibility would then be defined as:

$$r = 2.83 s_{\text{reproducibility}} \text{ where } s_{\text{reproducibility}} = \sqrt{\frac{\sum_{i=1}^{n}\left(\bar{E}_i - \bar{E}_{\text{all}}\right)^2}{n-1}} \tag{13}$$

where:

$\bar{E}_i$ is the average error obtained in the i^{th} reproducibility test series

$\bar{E}_{\text{all}}$ is the error average overall the reproducibility test series

N is the number test series undertaken to assess the reproducibility

Reproducibility is generally expressed as a function of flow velocity.

5.5 Uncertainty under ideal flow, pipe fluid and operational conditions

5.5.1 General

Clamp-on USMs are likely to be used over a very wide range of pipe sizes, materials, wall thicknesses and fluids. Because the overall performance achievable in the field depends on the care with which the operators prepare the pipe work and mount the transducers, coupled with an inability to provide traceable calibrations of clamp-on meters in the field, it is difficult to obtain figures for the uncertainty, repeatability and reproducibility of such flow-meters in the field.

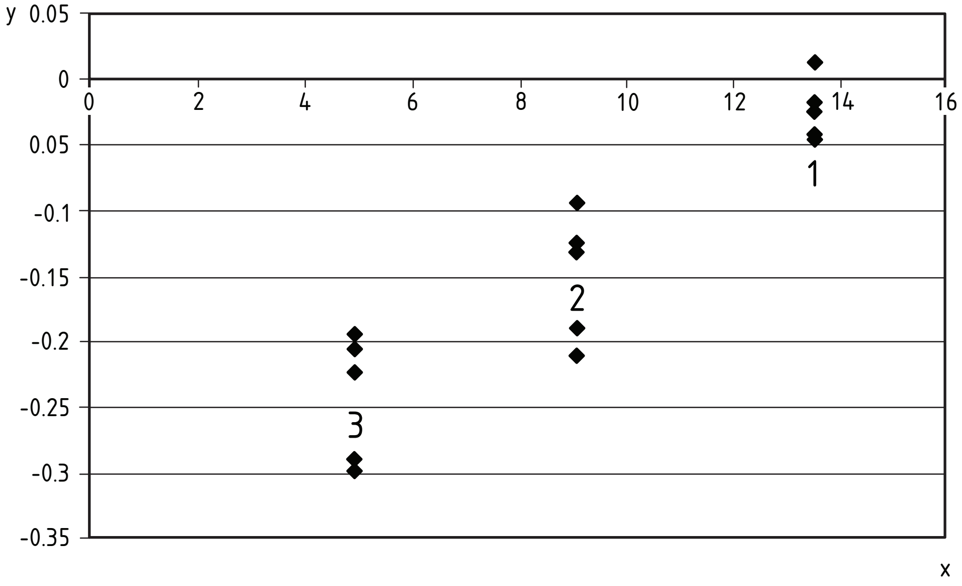
5.5.2 Transit time

The values manufacturers quote for the typical accuracy of clamp-on TTUFs range between ±1% to ±5% of reading with this performance being over a restricted flow range that is generally specified in terms of flow velocity. At the lower flow rates, the performance is generally specified as a fixed uncertainty expressed as a velocity which can range from ±0.01 m/s to ±0.03 m/s, depending on the pipe size and the particular manufacturer. In addition to these accuracy specifications, manufacturers often specify what is termed a calibrated accuracy. This means the accuracy which is achievable in situations where the meter is capable of being calibrated in situ by some other means or where the clamp-on transducers are being used as part of a spool piece.

Typical values for the uncertainty under these conditions range between ±0.5% to ±2% of reading, dependent on manufacturer and pipe size. Repeatabilities quoted by manufacturers typically lie in the range ±0.15% to ±0.5% of reading, depending on application.

A repeatability test was carried out for this to show the results at three flow rates downstream from one elbow; the results are shown in Figure 6.

Figure 6 **Repeatability for installation after a single elbow at 23D**



Key

1 Std. Dev. 0.02%

2 Std. Dev. 0.06%

3 Std. Dev. 0.05%

x Flow velocity (m/s)

y Error

5.5.3 Cross-correlation

The overall accuracy of the technique is estimated to be ±2% to ±5% of reading, although for a particular application where the meter can be calibrated under similar conditions improved accuracy might be expected. Typical repeatability should be 0.5% of reading.

5.5.4 Doppler

The uncertainty with such flow-meters can be high and in some cases likely to be greater than ±10% of reading with a dependency on the size of scatterers in the fluid. However, under closely defined flow conditions, it is possible for the DUF to provide an overall uncertainty of ±2% of reading. Typical manufacturers' specifications indicate that some devices have an expected accuracy of ±2% of full scale, as opposed to % of reading. This must be considered carefully when assessing performance in the lower flow velocity range. Reliable performance further demands minimum scatterer concentrations, often requiring solids or bubbles of minimum size 100 μm, and minimum solids concentration 100 ppm. Typical repeatability expectation is ±0.5% to ±1.0% of reading.

5.6 Factors affecting uncertainty

5.6.1 General

Errors in measurement by clamp-on ultrasonic meters are in the region of 2% to 5% in respect of TTUF and CCUF, and 2% to 10% for DUF, when set up with due care and attention in favourable application conditions. In general the performance of the meters tends to degrade as the fluid velocity decreases and is typically most noticeable below 0.5 m/s.

A USM manufacturer may express performance in terms of device error under reference conditions, as distinct from additional anticipated installation error, the latter being in the form of bias error derived from such sources as incorrect pipe wall thickness, pipe diameter, pipe material, transducer positioning, etc. and as such are beyond the manufacturer's control. For example a 1% error in internal pipe diameter directly creates a 2% error in flow rate as calculated by the USM from flow velocity. This relationship naturally has greater practical implication with smaller pipes than large. For example a pipe with 50 mm diameter needs only a 0.25 mm error in assumed pipe wall thickness to create the aforesaid 1% error in internal diameter and the consequential 2% error in calculated flow rate. Conversely, a 2.5 mm error in wall thickness applies for the same error scenario for a 500 mm diameter pipe.

It is not normal for the effects of flow profile to be accounted for in performance specifications. As is the case with the majority of flow measurement technologies, it is assumed that the meter will be installed in accordance with recommended guidelines e.g. sufficient straight inlet and outlet run, distance from sources of flow disturbance etc. No manufacturer can legislate for the many causes and effects possible in any particular installation.

Even with sound knowledge of the set-up and installation conditions where a clamp-on meter is used, or where there is excessive signal attenuation, it might not be possible in some circumstances to evaluate the uncertainty with acceptable confidence.

There is an assumption that pipes are generally round but on large diameter pipes there is a tendency for them to be slightly oval and if this is not accounted for during set-up and subsequent use of the meter then errors in the measurement will be present.

5.6.2 Comparison of techniques for gas use

Table 3 compares the two methods of transit time and cross-correlation tag meters.

5.6.3 Operational impacts

Irrespective of the meter type (Transit time or Cross-correlation) the fundamental challenge with clamp-on gas measurement is the extremely small amount of ultrasonic energy that can be coupled from transmitter to the pipe and then to the fluid, and back to the receiver, resulting in poor signal-to-noise ratio. A second, but less severe problem is the relatively high acoustic attenuation in the gas compared with most liquids. This is discussed in more detail in **5.6.6**.

Table 3 **Comparison of gas clamp-on flow-metering methods**

Characteristic	Transit time	Cross-correlation TAG
Flow range:		
Low flow limit	Can measure to zero (low flows with reduced accuracy)	Good for Re ≥ 10 000 Possible for Re ≥ 4 000
High flow limit	Typically limited to 10 m/s to 15 m/s, maximum is 30 m/s	Up to 80 m/s or higher
Profile effects	Sensitive to cross-flow. Other profile effects similar to liquid transit time. Reflective mount resists abnormal flow profile conditions such as cross-flow	Relatively insensitive to cross-flow and swirl. Other profile effects similar to transit time meters in theory
Pressure range	Typically > 10 Bar (gage) Possible ≥ 4 Bar (gage) Possible > atmospheric on plastic pipes	Atmospheric pressure and above for most gases including air, irrespective of pipe material
Ease of setup	Spacing coupling etc. generally more critical than liquid apps	Potentially very simple

Table 4 **Acoustic impedances of important materials**

Material	Velocity of sound (c) m/s	Density (ρ) kg/m^3	Z = ρc, MRayls
Air	343	1.3	0.000 4
Water	1 482	1 000	1.5
PVC	2 395	1 400	3.4
Steel	5 890	7 710	45

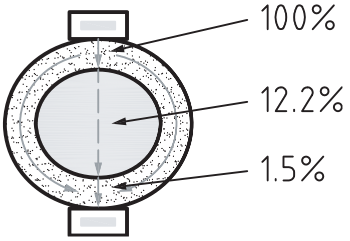
5.6.4 As a result of the very large difference in acoustic impedances between steel and air (and most gases), see Table 4, only a tiny fraction of the transmitted energy travels through the pipe wall and the gas to reach the receiving transducer. Only about 5×10^{-9} of the energy reaches the receiver for gas compared to water in a steel pipe.

5.6.5 A significant amount of the transmitted acoustic energy is coupled into the pipe wall, and travels around the pipe wall as coherent noise or “cross-talk”. This cross-talk for gases at low or moderate pressures overwhelms the gas-borne signal.

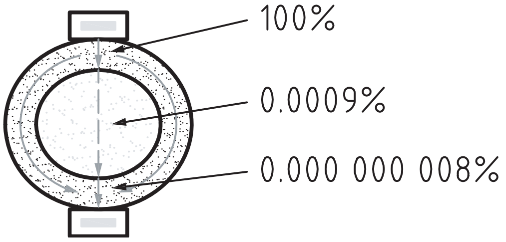
5.6.6 The attenuation of ultrasound in air is also much greater than water at equivalent frequencies. This is also true for most gases versus most liquids. Except for larger pipes, this effect is relatively insignificant compared to the coupling losses described in **5.6.3**. This is demonstrated in Figure 7 and Figure 8.

In spite of these difficulties, clamp-on gas flow-meters using both the transit time methods and the tag cross-correlation method are commercially available, [1]. Methods to mitigate the poor ratio of the gas-borne signal to the pipe-borne short circuit have included damping materials on the outside of the pipe [2], [3], the use of coded signals, quadrature demodulation, and special transducer configurations [4], e.g. those using Lamb or Rayleigh wave propagation. Generally speaking the transit time method has seen greatest success in higher pressure gases and steam, and the tag cross-correlation method has seen success even down to atmospheric pressure, but requires a Reynolds number above about 10000.

Figure 7 **Acoustic energy coupled into pipe and fluid for liquid clamp-on (top) and gas clamp-on (bottom)** [1]

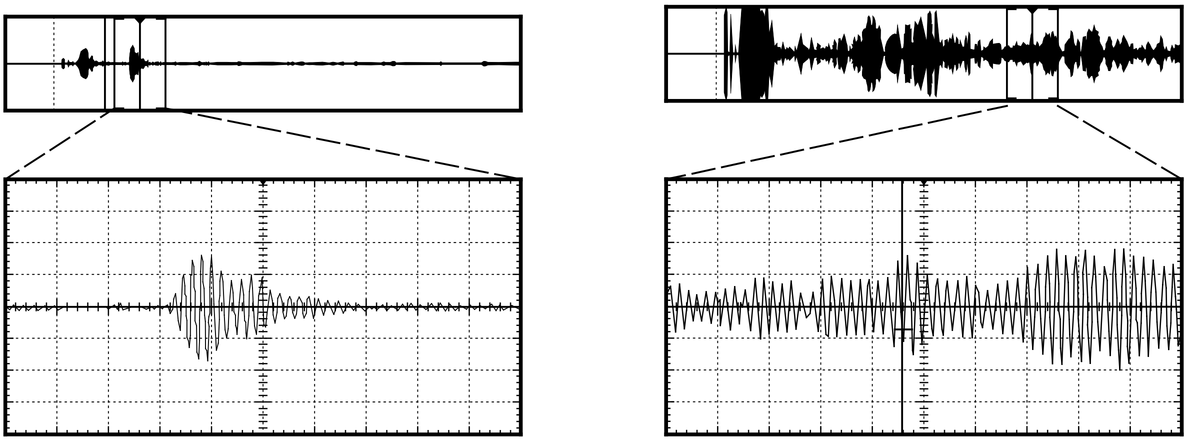


a) Steel pipe with water



b) Steel pipe with air

Figure 8 **Oscillogram of received signal** [1]



a) For liquid clamp-on

b) For gas clamp-on

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[1] © 2008 IEEE, reproduced with permission.

6 Calibration – general

Laboratory calibration is of more limited use for clamp-on ultrasonic meters than it is for many other meter types. This is because when the meter is removed from the laboratory and set up in the field, the conditions (physical attachment to the pipe, the pipe properties, piping configuration, fluid properties and flow profile) will be different. The pipe and transducers together form an integral part of the flow-meter and a result it is currently not possible for a true calibration certificate (e.g. a UKAS certificate) to be issued for an ultrasonic clamp-on meter.

However, a verification utilising the meter's signal diagnostics is very useful for confirming that a given unit and/or sets of transducers are performing to specification. Such an exercise can be readily performed. (Refer also to 10.12 Diagnostics). The results would also help to evaluate more accurately the uncertainty in measurement of the clamp-on meter itself. For TTUFs, it is possible to assess USM flow measurement performance (not withstanding velocity profile effects) by correlating known fluid velocity of sound with the diagnostic value from the USM.

When manufacturing a spool piece for permanent mounting of clamp-on transducers to form a hybrid, and where actual calibration is to be performed, potential problems arising from pipe material variations can be avoided by reserving an off-cut of process pipe for dedicated use during manufacture. The user should be cautioned that clamp-on transducers should of course not be moved once installed on a manufactured spool piece and thereafter calibrated, as any such movement would invalidate the calibration. It is recommended that the manufacturer employs mechanical means to prevent such movement.

Furthermore, the user is advised that if a calibration is performed using water at a given temperature, this will prescribe particular transducer positioning (see **3.2**). If the intended use of the calibrated spool piece hybrid involves a significantly different temperature and/or fluid then USM performance, and even function, may be impaired. A calibration using a fluid with properties that differ significantly from those of the process, or where flow rates differ greatly, should be viewed with caution. Particular attention should be paid to the actual range of Reynolds numbers for the process conditions compared to those of the calibration. The manufacturer should be consulted in this regard. It is unlikely that a DUF would be the subject of such a hybrid given the practical difficulty involved in generating precise volumes of liquid with adequate control of the requisite scatter source.

This standard suggests that calibrations which have been undertaken under laboratory conditions for transit time ultrasonic flow-meters should not be taken as the basis for a judgement as to the likely performance that could be achieved in the field under actual operating conditions. Performance obtainable in the field is unlikely to be better than that achieved under reference conditions in a calibration laboratory. Additional uncertainty is likely to result when the USM is installed in the field, due to variation in pipe dimensions and material, transducer location and mounting. Whether the transducers are normally field installed, or form part of a hybrid solution described earlier, the actual flow profile of the process fluid may not be fully developed at the installation point.

In some applications, such as nuclear power station performance evaluation using the secondary cooling circuit, significantly better performance has been achieved by providing a full scale model of the pipe work and using this to calibrate the clamp-on TTUF on a test stand. This approach can be employed where the economic cost is justified and where the pipe work material, dimension and conditions are accurately known. Under these conditions and where the in situ calibration is undertaken with the greatest of care, the claimed accuracies of the order of ±1% of reading are probably justifiable.

7 Installation effects

7.1 Equipment

As clamp-on USMs are typically installed as retrofit devices on existing process pipes, both in permanent and more significantly portable/temporary situations, errors in measurement can result if the USM is not correctly installed. It is of great importance that the manufacturer’s instructions are followed when installing the USM thereby minimising the risk of errors in measurement.

Substitution or modification of the cables used by USMs should not be attempted without consultation with the USM manufacturer. Manufacturers typically specify matched pairs of specific type cables, upon which the USM performance can depend. This is most important for TTUFs where the need to establish a zero reading during installation can be eliminated through the use of a single transmit-receive circuit, which is time-shared between upstream and downstream transmission. In such an arrangement, any source of time measurement offset must be avoided, and cable length similarity must fall within specified limits. The importance of this aspect should be taken up with the manufacturer.

It is rarely the case that an operational system or process can be shut down to provide an opportunity for a zero flow check, and even when shut down for this purpose, reliable zero flow conditions may take time to establish, or may even be impossible due to passing valves etc. In the case of liquids, there is a tendency for bi-directional movement or sloshing around to persist within the system for some time after isolation valves have been closed. In gas applications, there can be serious sensitivity to flows created by thermal effects on the pipe work, as well as reflected pressure waves within the gas which can take some time to settle. The USM manufacturer should be consulted regarding the ability of the USM to be installed without zero flow conditions. Many USMs feature a “zero cut-off” feature which allows selection of a low flow value below which flow readings are forced to zero.

7.2 Velocity profile

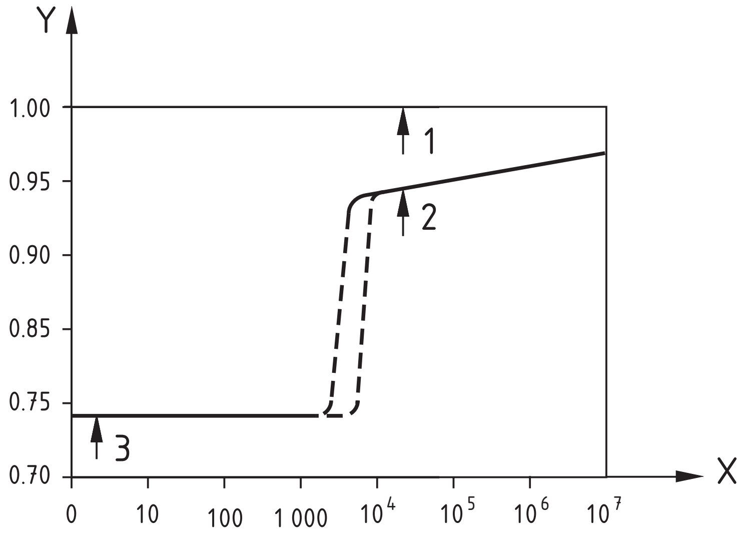
TTUFs

Clamp-on TTUFs are sensitive to velocity profile effects in both fully developed and disturbed flow conditions because, as Equation (1) shows, the device estimates the average velocity across the whole of the pipe cross-section by measuring the average velocity along the path. Even in fully developed flow, the value of the profile correction factor (k_h) is not unity and depends on the Reynolds number and pipe wall roughness.

Figure 8 shows how k_h varies with Reynolds number for smooth pipes. A correction based on Reynolds number might or might not be incorporated by the manufacturer. Where used, effective correction will normally depend upon the input during commissioning of relevant viscosity data for the process fluid, from which Reynolds number may be calculated, and a correction factor established an applied. Figure 9 shows that the corrections required are greatest in the laminar regime. In the transition regime, however, the correction factor might not be well determined and this uncertainty on the correction factor for the meter can add significantly to the overall meter uncertainty. Research has shown that the where the Reynolds number is known to be less than 10 000 and certainly less than 6 000, the aforesaid uncertainty is at its greatest. The degree to which a USM may be affected can depend upon the type of USM involved e.g. TTUF. The manufacturer should be able to give clear advice.

In the case of disturbed profiles, the profile correction factor for fully developed flow is no longer applicable. The flow profile can be disturbed by upstream pipe work configurations such as bends, expansions and contractions and the presence of valves and pumps. Manufacturers often specify a requirement to have 10*D* of straight pipe work upstream of the meter and 5*D* downstream of the meter. Although the downstream conditions are probably satisfactory, the upstream requirement is probably over-optimistic.

Figure 9 **Profile correction factor (k_h) against Reynolds number for fully developed flow in smooth pipes**



Key

X Re

Y k_h

1 k_h = 1 asymptote for flat profile

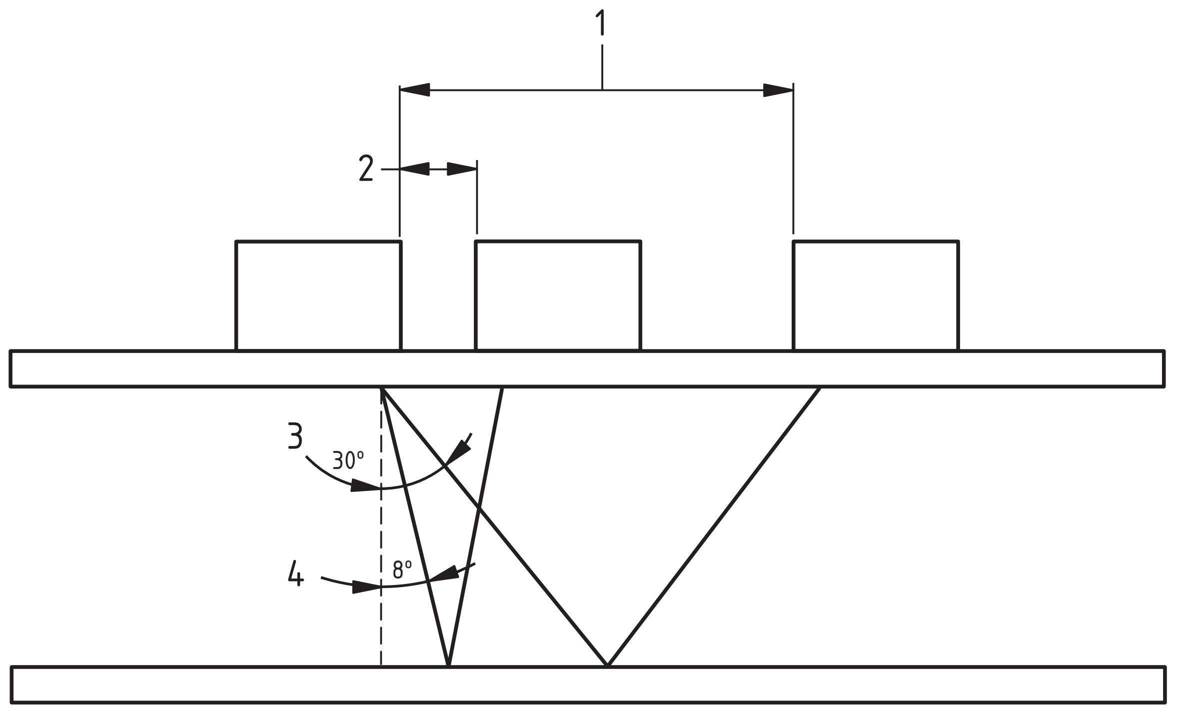
2 k_h = 1/(1.119 – 0.011 log Re) for turbulent flow

3 k_h = 0.75 for laminar flow

7.3 Path angles

Gases support a much lower velocity of sound than liquids, and in accordance with Snell's Law (see also **3.2**), this results in a smaller refraction angle as depicted in Figure 10. Gas compressibility from process pressure adds another dimension to the relationship between velocity of sound, temperature and fluid composition. Given the aforementioned reduction in received signal amplitude in gases, correct transducer position is of greater importance, and all the process parameters that determine refraction angle, and thence transducer position, must be taken into the calculations as normally performed by the USM. The reduced refraction angle for gases, in turn results in a shorter axial component of the acoustic path in the fluid. This will consequently give an increased susceptibility to non-axial flow in clamp-on gas USMs, requiring greater consideration of necessary inlet runs where an upstream flow disturbance source is present.

Figure 10 **Refraction angles**[2)]



Key

1	Liquid spacing	3	Liquid
2	Gas spacing	4	Gas

7.4 Preferred installation conditions

Table 5 provides estimates of straight lengths required downstream of various disturbances in order that the effect of that disturbance on the clamp-on measurement is reduced to ±2% or ±5%. It assumes that the flow directly upstream of the disturbance is fully developed.

[2)] Based on Siemens Controlotron

The data that has been used to provide these distances is based largely on the performance of wetted sensor single beam TTUFs because it is believed that this data is more comprehensive and reliable. The reference list is in the Bibliography (see [5] and [6]). They are generally consistent with the limited data that has been obtained from clamp-on TTUFs but manufacturers' literature about other meter types generally specifies similar straight length requirements. It should be noted that a single path direct configuration would be much more susceptible to cross-flow disturbances than reflective paths; the former therefore requiring a longer straight pipe length.

Installation effect data in graphical form is provided in Annex D for information.

Table 5 should be considered as general guidance only, and may not hold true for every pipe size, fluid type and viscosity. 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. Flow Measurement Guidance Note No.48 [7] has a similar table showing the relationship presented in a different manner. For gaseous applications, there is limited independent test data available, but it is highly probable that the upstream and downstream straight run requirements will be greater in reality than those required for liquids, as a disturbance in a low pressure gas is likely to prevail for longer than in a high pressure gas or liquid.

The most recent work done on installation effects (NMSD Project FEUS05) generally confirms the guidance in Table 5 (see also GN48 from FEUS05), but it offers further guidance regarding the hitherto un-researched effects of downstream disturbances. It can now be assumed that for liquid applications at least, only 3D of outlet run is required, regardless of disturbance type. This advice naturally assists with allowance for the more important upstream inlet run under restricted circumstances. There is also now a better understanding of the reasons for the levels of uncertainty caused by the different sources of disturbance. Of particular importance to single path clamp-on USMs, is the apparent sensitivity of the path orientation to swirl, regardless of meter type. For example, multi-path arrangements, where two paths are installed on the pipe at 90° to each other, and the individual path flows averaged by the USM, tend to reduce the sensitivity of the USM to swirl.

Table 5 **Required straight lengths between fittings and USM**

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

7.5 Flow profile distortion

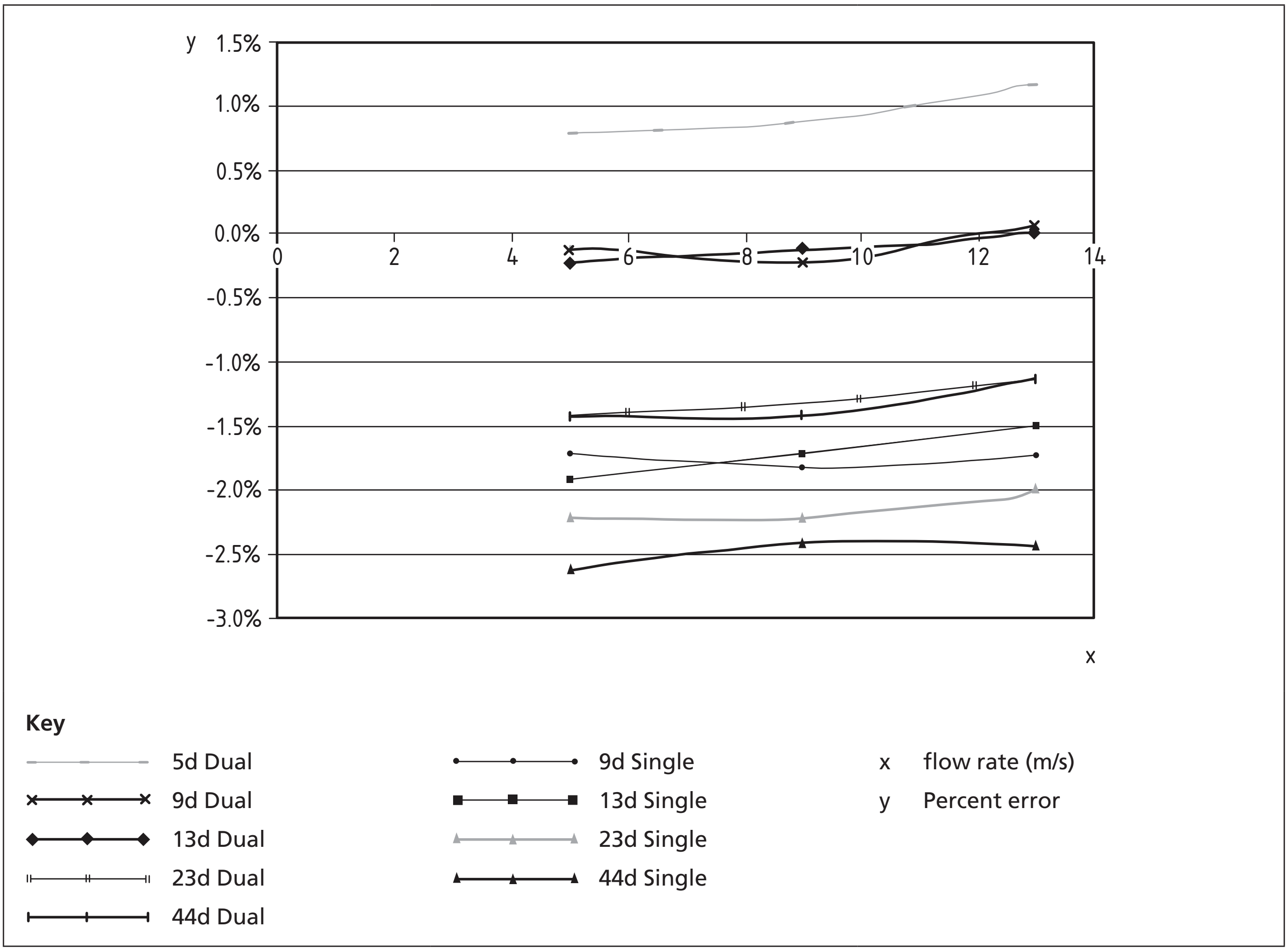
The data illustrated by Figure 10 summarises work carried out by one USM manufacturer[3)] on flow profile distortion for single and double elbows involving a gas TTUF installed in two path configuration.

Some work has been carried out on flow profile distortion for single and double elbows for a two traverse gas meter as follows.

- Dual beam – 10 o'clock and 2 o'clock mounting.
- Mounted on a facility supplied spool of 8" carbon steel schedule 40 stock pipe.
- Transducers remained mounted during entire test.
- No initial adjustments to the meter's parameters prior to the test.

The results for various tests incorporating single and double elbows can be seen in Figure 11 and illustrate the effects on flow profile distortion and should not be taken as definitive meter responses.

Figure 11 **Effects of flow distortion**



FEUS05 [8] and subsequent work show similar sensitivity of single–path meters to swirl effects and the fact that the error is also a function of the installed angle, relative to the 12 o'clock position, and the swirl angle.

[3)] By kind permission of Siemens Controlotron

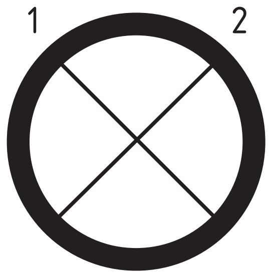
In the light of the limited graphical data shown in Annex D, and the data generated by FEUS05 (8), where the majority of errors from disturbances are negative, it is suggested that the maximum reading obtained during steady flow at several radial positions in the same axial location, be taken as the best estimate of the flow rate.

An alternative method that is often suggested for improving the measurement under disturbed flow conditions is to undertake two measurements in perpendicular planes as shown in Figure 12 and take the average of the two measurements.

Some manufacturers enable this to be undertaken with simultaneous measurements from the two paths being provided using two sets of transducers and one set of processing electronics. If only one set of electronics is available, it is necessary to provide an independent measure of the mean flow rate to account for any changes that can occur in the mean flow-rate between the two measurements. Most manufacturers recommend that the average of the two measurements should be used as the estimate of the flow rate.

An alternative is to employ multiple traverse modes in TTUFs. Each application should be assessed to determine whether multiple traverse modes, e.g. two or four traverse with the ultrasound reflected off the inside of the pipe wall, can be employed to improve the meter's performance. These techniques can minimize the effect of fluid cross flows on the overall measurement but do depend on pipe outside diameter; process conditions, e.g. viscosity in liquids and pressure / density in gases, path length too great, might prevent the implementation of multiple traverses.

Figure 12 **Two-path measurement**



Key

1 Path 1

2 Path 2

7.5.1 Extra information regarding gas TTUFs

Some important points need to be made regarding gas installations.

The current lower pressure limit for most general metal pipe applications is about 2 barg.

Poor pipe outside diameter to wall thickness ratios of less than 15-to-1 and/or pipes with a wall thickness greater than 25 mm might result in lower performance due to pipe noise issues.

Some metal alloys, like aluminium, can provide measurements at lower pressures down to 1 barg.

There is no lower pressure limit when working with plastic pipes, which can be used at atmospheric pressures.

However, as the technology improves then these limitations might change and the user should consult with the manufacturer regarding specific applications.

As for the different modes of operation regarding the input of pressure, temperature and gas composition, the information in Table 6 is offered as guidance.

In the standardized volume and mass cases in Table 6 it is suggested a flow computer and chromatograph should be used where high accuracy, i.e. low uncertainty, is required.

Table 6 **Additional requirements for reporting flow in standard volume and mass terms**

	Condition	**Requirement**
Actual flow	No additional inputs required	—
Standardized flow	Constant gas composition	Pressure and temperature with fixed entry for fixed gas compressibility or internal AGA8 [9], SGERG or NX19 [10] look up table
—	Varying gas composition	Pressure and temperature and external AGA8 [9], SGERG or NX19 [10] compensating flow computer
Mass flow	Low pressure applications with large variation in gas composition	Sonic velocity, temperature input, specific heat ratio input
—	Any pressure but stable composition	AGA8 [9], SGERG or NX19 [10] table, temperature and pressure inputs

8 Pipe work effects

8.1 General

Clamp-on meters are required to operate over a range of pipe sizes, materials, wall thickness and lining materials. Accurate knowledge of the pipe material, its acoustic properties and dimensions are critical to the accuracy of the metered flow rate. Not all manufacturers are able to provide a metering system which operates over the complete range of pipe sizes, materials, wall thicknesses and lining materials shown in Table 7.

Sub clauses **8.2** to **8.7** contain details relating the effects of pipe work on the various technologies.

8.2 Pipe material

As with many pipe parameters it is useful to separate effects that cause malfunction or failure-to-read from those that cause an increase in measurement uncertainty.

As regards failure-to-read issues, the claim made by manufacturers is that the pipe has to be sonically conducting, although the experience of users indicates that whilst some manufacturers might be able to work with particular pipes, others cannot. The following commentary should be taken as indicative and not necessarily as definitive. It identifies pipe materials where the problems most frequently occur. It is based upon user experience and the wide range of tests on TTUFs but can, due to lack of equivalent information, be assumed applicable to CCUF and DUFs because it relates to the basic ability of the ultrasound to propagate through the pipe wall into the fluid.

- Occlusions or pores in cast iron can attenuate the ultrasound.
- Concrete and cement pipes can cause problems but often, if the pipe is fully soaked, the meters can work better.
- With thin wall stainless steel, and certain thick wall plastic or composite materials such as GRP, some manufacturers experience difficulty in achieving adequate signal transmission. This can be a function of the transducer operating frequency, and the manufacturer should be consulted when such materials are involved.

Measurement uncertainty in TTUF is increased if the properties of the pipe wall are unknown because this adds to the uncertainty of the detected transit times. The sensitivity of the USM to the use of incorrect material properties , or incorrect choice of material, may vary between manufacturers, but can be a significant source of flow measurement error in small diameter pipe.

8.3 Pipe thickness

Although manufacturers do not in general specify the range of pipe wall thicknesses with which their flow-meters operate, at least one manufacturer identifies a maximum pipe wall thickness.

Again, the following guidance is based on experience with TTUF but can be expected to be equally applicable to Doppler or cross-correlation meters because it deals with factors that affect the pipe bore or the acoustic propagation through the pipe wall.

Several problem areas have been identified with coatings and pipe linings. Clamp-on meters of any type only work where the coating/lining material is bonded to the pipe material in such a way that there are no air gaps between the two materials, because air gaps prevent successful transmission of the ultrasound.

If the meter is to be clamped on to the coating material, the thickness of the coating should be accurately known in order that the pipe o.d. can be accurately determined. If the pipe is lined, the thickness of the lining is required to be known accurately. The correct sound speeds for the wave which is being transmitted through coating/lining materials are required. Methods for undertaking these measurements are provided in **10.9**.

If a pipe lining material and/or coating is present, account of these is required to ensure that the correct separation of transducers is achieved. Some manufacturers do not enable data from lining materials to be input separately into the flow-meter. In such cases, a thickness corresponding to the sum of the wall and lining thickness has to be entered, together with a velocity of sound which represents a weighted average of the velocity of sound in the two materials, based on their relative thickness. For manufacturers who take into account lining materials and coatings, some allow the user to input more than one lining material or coating.

Table 7 **Ranges of pipe size, material, wall thickness and lining material with which clamp-on TTUFs can be used**

Pipe sizes over which operation of clamp-on flow-meters has been claimed by manufacturers	8 mm i.d. to 6000 mm i.d.
Pipe materials for which manufacturers have used clamp-on TTUFs	Ductile iron, cast iron, carbon steel, stainless steel, copper, aluminium, Hastelloy, asbestos, concrete, glass, LDPE, HDPE, PP, PVC, PTFE, PVDF, ABS, GRP, acrylic
Maximum pipewall thickness for the operation of clamp-on TTUFs	Most manufacturers do not claim an upper limit, although one manufacturer sets this at 25 mm
Maximum pipewall thickness for the operation of clamp-on TTUFs	Tar, epoxy, mortar, rubber

8.4 Pipe bore

It is important to realize that the pipe bore dimension has two distinctly different, but equally important, affects on the metered flow rate.

a) The pipe bore affects the acoustic path length and therefore directly affects the averaged flow velocity measured in TTUF and DUF.

b) Regardless of the clamp-on meter type, the pipe bore affects the pipe flow area and consequently any error in pipe area creates a flow error when multiplied by the average flow velocity across a given path.

Often, the pipe bore is inferred from a measurement of external diameter, coating or liner thickness and the pipe wall thickness. Uncertainty in any of these carries through to an uncertainty in the pipe bore. This is particularly critical in small bore pipe.

8.5 Effects of pipe wall roughness on measurement performance

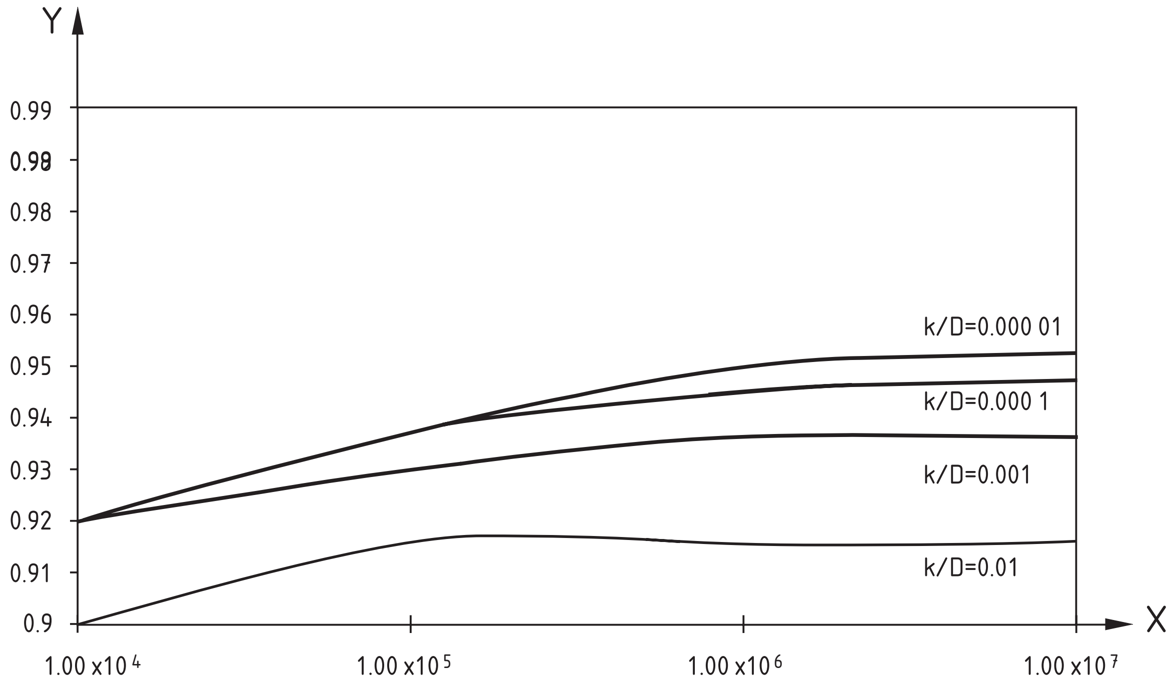
The roughness of the internal wall of the pipe is likely to cause two sets of problems. The fully developed profile in a pipe depends on the pipe wall roughness. Because the velocity profile is affected, so the profile correction factor (k_h) required to correct the measured velocity along the path to the average velocity across the pipe cross-section is affected. Figure 13 shows the correction factor required for fully developed flow for a series of pipe relative roughness, k/D (roughness to diameter ratio) and shows that pipe wall roughness can cause an error of up to 4% in very rough pipes.

In addition to affecting the profile, the pipe internal roughness can also cause significant scattering of the ultrasonic signals from TTUFs: this does not as such cause a measurement error but might cause the meter to fail to read. The degree of scattering is related to the absolute level of roughness compared to the wavelength of the ultrasound being employed. Thus it is related to the ratio of λ/k where λ is the wavelength of ultrasound in pipe wall material and k is the roughness.

Because λ is inversely proportional to the frequency of excitation of the flow-meter, a typical wavelength in a metal pipe at 1 MHz is 6 mm whereas at 500 kHz the wavelength is 12 mm. Therefore, as a general guideline, the rougher the inner surface of the pipe work is, the lower the frequency of operation of the flow-meter should be.

Rougher pipe work also, due to the reduction in signal strength, limits the number of wall reflections (see **6.2**) which can be used. Pipe wall roughness can also affect the estimation the pipe internal diameter from the pipe outside diameter and pipe wall thickness measurements (see **6.10**).

Figure 13 **Effect of pipe wall roughness on profile correction factor**



Key

X Pipe Reynolds number

Y Meter correction factor

8.6 Ultrasonic properties of pipe work

In order to obtain the correct separation of the transducers, both the thickness of the pipe wall and the velocity of sound in the material need to be known. Manufacturers have available tables of speeds of sound in different material. The nature of the ultrasonic wave transmitted through the pipe can either be a longitudinal wave, a shear wave or a Lamb wave. It is therefore particularly important to input the correct velocity of sound in the wall material during the set up phase of the meter. Annex A includes a table of the velocity of sound in commonly used wall materials. In the case of materials where the velocity of sound is uncertain, an ultrasonic thickness gauge applied to a sample of the material of known thickness can be used to provide a measurement of the velocity of sound.

8.7 Reynolds number correction

Any clamp-on metering technology that measures an average velocity across a path or that correlates information from two acoustic paths can be expected to be equally sensitive to the Reynolds number of the flow. This is because the flow velocity profile is a function of Reynolds number and hence influences the flow profile correction factor used to translate a path velocity average into an average flow across the pipe.

As has been shown in Clause **4**, clamp-on TTUFs are sensitive to the Reynolds number. Manufacturers might or might not compensate for this. For those manufacturers who do compensate, the compensation is generally based on knowledge of the particular fluid being monitored. For products whose temperature is changing significantly during the measurement, then compensation for Reynolds number on-line is required. Enquiries should be made to manufacturers as to whether or not they provide on-line correction.

9 Fluid effects

9.1 General

It is extremely important that the properties of a process fluid be defined prior to a clamp-on flow measurement being attempted. The properties of a fluid affect the efficiency with which ultrasound passes from pipe to fluid, the way in which ultrasound travels through the fluid, the correct programming and installation of the meter, and the correction needed during operation in respect of velocity profile.

9.2 Velocity of sound

9.2.1 Transit time

9.2.1.1 General

Clamp-on TTUFs require the user to input the fluid velocity of sound into the meter at the initialization stage, as part of the procedure to set the correct distance between the two transducers. This is often achieved simply by selection of a pre-programmed fluid from menu during set up. Alternatively tables are available to provide this information, often found in the operating manual of the flow-meter, or reference can be made to Table A.4. The reader is advised to refer also to **9.3** regarding the effects of temperature in respect of velocity of sound.

Additionally during initialization, the velocity of sound of the pipe material and, if present, the liner material are selected. As with fluids, a clamp-on TTUF normally has a menu of common materials. Where a material is not found in the meter's menu, reference can be made to Table A.1.

With knowledge of fluid and pipe materials, or more specifically the velocities of sound, and pipe outer diameter and wall thickness (and liner thickness where present), the TTUF can employ Snell's law to determine refraction angles for the ultrasonic path at each material interface, and the distances travelled by the ultrasound along each component path. It can then calculate transducer separation distance and calculate non-fluid transit time components, allowing these to be later subtracted from total measured transit time, thereby assisting the accurate calculation of fluid velocity of sound.

Depending upon the design of the flow-meter, this velocity of sound can then be used in the defining equation of the flow-meter, though this is unlikely given that transit times are rapidly and alternately measured in both upstream and downstream directions, and thus fluid velocity of sound plays no effective role in the resulting calculation of flow velocity and flow rate. A new velocity of sound is estimated from the transit time measurements during each update of the TTUF. After initialization, the calculated value can be compared to the programmed value and where different than by perhaps 3%, the calculated value can itself be programmed into the TTUF and transducer separation adjusted where a new value results. This procedure allows an optimized installation where the velocity of sound of the process fluid was estimated. The correct separation of the transducers and the correct velocity of sound are important to the correct operation of the flow-meter.

9.2.1.2 Liquid applications

In the case of water or water based solutions, velocity of sound increases as temperature increases to 74 °C whereupon the effect inverts. This is unique, but as it is unlikely that a water application involves operation over a temperature range that is distributed about this value, the problem of a single velocity of sound value being seen for the same pipe at two different temperatures is remote. In hydrocarbon liquids, increasing temperature causes a decreasing velocity of sound. When the user is attempting to use tables to determine a value for liquid velocity of sound attention should be paid to the correct polarity of any published value of "Δv/°C" and the temperature for which the nominal value of velocity of sound is referenced, e.g. AA gravity fuel oil 1 485 m/s (referenced to 25 °C) has a "Δv/°C" value of –3.7 m/s/°C and so when operated at 50°C the correct value to use would be 1 485 – (3.7 x 25) m/s = 1 392.5 m/s. By contrast water at 25 °C has a velocity of sound of 1 496 m/s but at 50 °C the value rises to 1 543 m/s.

9.2.1.3 Gas applications

Increasing temperature always results in an increasing velocity of sound and vice verse. In the case of pure gases, data can be obtained from industry sources but where mixtures are present the use of a proprietary software package to calculate the velocity of sound by entering the gas composition and key information relating to the gas, e.g. velocity of sound, viscosity and compressibility at specified pressure and temperature; see BS ISO 20765-1or AGA10 [11].

9.2.2 Cross-correlation

A clamp-on CCUF requires the user to input the fluid velocity of sound into the meter at the initialization stage, as part of the procedure to set the correct distance between each pair of the transducers employed. Additionally during initialization, the velocity of sound of the pipe material is selected. A clamp-on CCUF normally has a menu of common pipe materials. Where a material is not found in the meter's menu, reference can be made to Table A.1.

With knowledge of fluid and pipe materials, or more specifically the velocities of sound, and pipe outer diameter and wall thickness, the CCUF can employ Snell's law to determine refraction angles for the ultrasonic path at each material interface, and the distances travelled by the ultrasound along each component path. It can then calculate separation for each transducer pair.

As CCUFs are most commonly employed on low pressure gases, it might be adequate to select a pre-programmed fluid and hence velocity of sound from menu during set up. The reader is advised to refer also to **9.3** regarding the effects of temperature in respect of velocity of sound. Increasing temperature always results in an increasing velocity of sound and vice verse. In the case of pure gases data can be obtained from industry sources or possibly found in the operating manual of the flow-meter, but where mixtures are present the use of a proprietary software package to calculate the velocity of sound by entering the gas composition and key information relating to the gas, e.g. velocity of sound, viscosity and compressibility at specified pressure and temperature; see BS ISO 20765-1 AGA10 [11].

Whilst velocity of sound has no direct relationship to functionality or performance of a CCUF, it can still serve to help confirm correct set up in respect of each transducer pair.

9.2.3 Doppler

If a DUF employs fluid velocity of sound as a means of determining the position of scatterer/reflector source relative to the pipe diameter for the purposes of flow profile error correction, then this parameter should be determined

9.3 Temperature

9.3.1 General

It is assumed that a clamp-on ultrasonic meter is only applied to pipes whose surface temperature does not exceed the specified maximum (or minimum) for the transducers being used. The user should be cautioned that exposure to over-temperature conditions might destroy the transducers. The user should also be aware of the effects that changing temperature can have on meter installation and operation.

9.3.2 Transit time

9.3.2.1 General

In a TTUF, as explained in **9.2.1**, the lengths and angles of the acoustic path between transducers, and hence the transducer separation, is determined significantly by velocity of sound in the pipe materials and fluid. For fluids for which the temperature is significantly changing, enquiries should be made to the manufacturer as to the likely extent of additional error, and what means of temperature compensation might be considered.

9.3.2.2 Liquids

The likely impact of uncorrected errors would be <0.5% of reading / 10 °C change, and by selecting a temperature for TTUF programming that is in the centre of the expected temperature band, the impact is minimized. Caution should be exercised on large pipes where even a small change in the angle of refraction of the acoustic path can translate to a significant change in transducer separation. In this situation, the user is advised to consult the manufacturer as to possibility of degraded signals when at the extreme of expected temperatures. A compromise can normally be found to maintain reliable operation.

9.3.2.3 Gases

An approximation of error resulting from changing fluid temperature without any form of correction is not available. The manufacturer should be consulted regarding the expected process temperature variation and the optimum transducer location to minimize such error.

Temperature also influences fluid viscosity. Viscosity effects are discussed in **9.4**. The user should remember that viscosity in liquids decreases as a function of increasing temperature (inverse relationship) but in gases there is a direct increase in viscosity as a function of increasing temperature. However, it is in liquids where the impact of viscosity is greatest, where the value drives a change in Reynolds number which in turn determines the appropriate flow profile correction factor k_h.

9.3.3 Cross-correlation

In a CCUF, as explained in **9.2.2**, the lengths and angles of the acoustic path between transducers, and hence the transducer separation for each pair, is determined significantly by velocity of sound in the pipe materials and fluid. An approximation of error resulting from changing fluid temperature without any form of correction is not available. The manufacturer should be consulted regarding the expected process temperature variation and the optimum transducer location to minimize such error.

In respect of the impact of temperature on viscosity, it is perceived that CCUF flow-meters are less susceptible to flow profile influence than a TTUF, but at this time there is an absence of data to support this view.

9.3.4 Doppler

A correction for velocity profile might be made by a DUF, and therefore changing temperature indirectly influences the validity of such a correction as viscosity is caused to change. The manufacturer should advise the user on which form the correction takes, the dependency on assumed constant viscosity and the resulting error from the temperature variation.

Any significant increase in fluid temperature which causes reduction of viscosity could assist suspended gas bubbles to return to solution and thus diminish the gas bubble content and consequently the reliability of signal-dependent scatter sources.

9.4 Pressure

9.4.1 General

The pressure of a fluid impacts its molecular density, and hence the efficiency of ultrasonic transmission through the fluid. The pressure of a liquid, however, unless significantly compressible, has negligible impact on the performance of a clamp-on TTUF, whereas in a gas the impact of pressure becomes significant.

9.4.2 Transit time

9.4.2.1 Liquids

Lowering pressure can assist with gas bubble formation where dissolved gases might otherwise remain in solution. The effect of gas bubbles is discussed in **9.6.1**. Conversely, increasing pressure can cause suspended gas bubbles to go back in solution thus improving chances of successful meter performance.

9.4.2.2 Gases

At lower pressures, it might prove difficult or even impossible to successfully transmit ultrasonic pulses through a gas in a metal pipe. The manufacturer or the flow-meter data sheet should be consulted regarding minimum operating pressure when selecting a clamp-on TTUF. This minimum operating pressure might vary from manufacturer to manufacturer, but depends upon such factors as transducer frequency, pipe diameter, pipe material and gas composition. The user should also be aware that changing pressure impacts the compressibility factor for the gas in question. Gas pressure is a significant component in the calculation of corrected/standard volume. Given the accuracy expectation for a clamp-on gas meter (i.e. meter class) the impact of pressure related pipe expansion on factors such as diameter/internal cross-sectional area or acoustic path length can be neglected.

9.4.3 Cross-correlation

Comments are confined to gaseous applications in this revision of the standard as CCUF technology appears to be commercially confined to gases.

The successful transmission of a carrier signal between transducer pairs in a CCUF might be impaired by reduced molecular density, which results as a function of lowering pressure. However, this technology does function at low or even atmospheric pressure in metal pipes or plastic/composite pipes. It is also possible that the flow signature, in the form of minute, localized density variations, which might be required to modulate the carrier signal in a CCUF, are reduced in intensity as gas pressure increases, thus potentially adding to any operational difficulty.

9.4.4 Doppler

The most likely impact on this technology might be the reduction or variability of suspended gas bubble content where this, as opposed to suspended solids, is relied upon for the source of reflection of the ultrasonic pulses. Therefore pressure variation in a liquid where gas bubble content is unreliable could prove to be problematic.

9.5 Viscosity

9.5.1 General

All types of ultrasonic flow-meter can be adversely affected if applied to highly viscous liquids. The effect varies according to the type of ultrasonic flow-meter (i.e. TTUF, DUF), the transducer operating frequency, pipe diameter, etc. Highly viscous liquids generally have associated with them high levels of attenuation of ultrasound. So, for example, water having a kinematic viscosity of 1.003×10^{-6} $m^2 \cdot s^{-1}$ at 20 °C has an attenuation at 1 MHz of a pressure wave of 0.22 dB/m, whereas a product such as castor oil, having a kinematic viscosity of 1.1×10^{-2} $m^2 \cdot s^{-1}$ has an attenuation of 95 dB/m at 1 MHz.

Thus it is possible that the attenuation in a high viscosity fluid can be so high as to prevent operation of the flow-meter. Because viscous attenuation is generally a function of frequency; lowering the frequency of operation of the flow-meter might enable measurements to be made.

Clamp-on meters by default employ one or more acoustic paths through the fluid along a diameter. Such an acoustic path is subject to maximum influence from the fluid velocity in the central region of the pipe or conduit, where it is always at its highest, and not representative of the bulk average velocity. It is normal that the transmitter section of a clamp-on meter applies in software a correction factor (defined herein as k_h) for velocity profile. In fully developed flow, the k correction factor k_h for the meter depends on the Reynolds number, Re, given by:

$$\mathrm{Re} = \frac{v_{\mathrm{pipe}} d\rho}{\mu} \tag{14}$$

Thus operating a clamp-on meter requires knowledge of the density ρ and the viscosity μ or alternatively the kinematic viscosity ν which is given by μ/ρ. It is particularly important to know the viscosity of high viscosity products for which measurement are being undertaken in small pipes because these flows might be in the laminar flow regime.

Table A.4 provides a table of fluid sound speeds wherein available kinematic viscosities can be found for a range of liquids.

The algorithm employed by an individual clamp-on meter in respect of velocity profile correction is manufacturer dependent, though likely to be based upon proven fluid dynamics research e.g. Nikuradse, requiring knowledge of pipe internal diameter, kinematic viscosity and raw (uncorrected) flow velocity. In the absence of a live input of measured fluid viscosity, it is normal that a single fixed value for kinematic viscosity is applied. As this parameter varies as a function of temperature, then assuming fluid composition remains unchanged, a mean value for kinematic viscosity might often be used for the range of temperatures expected for the application. The potential for additional error exists, but in practice large changes in kinematic viscosity might translate to small errors as a result of incorrect $k_{h.}$ Alternatively, an input of measured liquid temperature could be used by the clamp-on meter to access a look-up table of empirically established k_h values.

The significance of viscosity effects for clamp-on ultrasonic meters in gases is less pronounced than in liquids, and given the expected uncertainty of a clamp-on meter, viscosity effect might be considered negligible. The meter manufacturer should be consulted in this regard, as little data is available at this time.

9.5.2 Transit time

The range of kinematic viscosity should always be established for a liquid TTUF and the resulting ranges for Reynolds number and corresponding applied correction factors (k_h) should be considered to establish expected additional error resulting from the use of a single fixed value for kinematic viscosity. Selecting a value mid-range can of course minimize the impact. It might be possible to iteratively calculate k_h values within the TTUF transmitter electronics using a live process temperature input, where viscosity change is resulting only from this parameter. If liquid composition is changing, then unless a live viscometer input is possible, then such correction cannot be performed. There is no data available at this time concerning such a solution.

A secondary concern with highly viscous liquids is their tendency to retain gas bubbles in suspension, which can prove to be problematic for a TTUF. The manufacturer should always be consulted regarding entrained air/gas bubbles.

9.5.3 Cross-correlation

As a CCUF is unlikely to be used on liquid applications, the effects of viscosity are limited to resulting velocity profile change where there is no compensation for deviation from the programmed constant value.

9.5.4 Doppler

As with a TTUF, a DUF could experience difficulty in ultrasound propagation in highly viscous fluids. Whilst not transmitting completely across the pipe or conduit, the distance travelled can amount to the same when the active reflection source is near the flowing centre. There might also be some additional uncertainty resulting from incorrect flow profile correction where actual viscosity deviates from a programmed constant value.

There is also the risk that reduction in liquid viscosity due to, for example, an increase in temperature might give rise to a reduction in gas bubble formation, and hence a weakening of the signal.

9.6 Density

9.6.1 General

There is an indirect relationship between density and flow profile correction but where a value of kinematic viscosity is employed in any applied flow profile correction algorithm, as opposed to absolute viscosity, then density ceases to be a factor. There also exists an indirect relationship between fluid density and velocity of sound, but density also ceases to be a factor, and rather it is temperature which drives the greatest impact, and this is discussed in **9.2**.

9.6.2 Transit time

No significant impact as discussed **9.6.1**.

9.6.3 Cross-correlation

An increase in bulk gas density eventually diminishes the effects of the small localized density variations which a CCUF can rely upon for carrier wave modulation.

9.6.4 Doppler

No information available at time of issue of this British Standard.

9.7 Entrained gas bubbles/liquid droplets

9.7.1 General

It should be remembered that neither form of clamp-on meter is intended for two-phase or multi-phase applications. It is obvious that gas bubbles relate to liquid systems and liquid droplets to gas systems but the impact of each is similar.

Where there is a second phase and gas clamp-on flow-meters are present, similar rules seem to apply. The meters can handle low percentages of moisture and solids as long as these are held in suspension. Although the selection of a 9 o’clock to 3 o’clock acoustic path avoids solid sediment collection in the bottom section of horizontal pipes, there can be difficulties with acoustic transmission from pipe to gas when process conditions allow condensate formation to form as droplets over the complete inside pipe surface; such liquid droplets cause scattering of ultrasound. Also, where condensate might be lying and running in the bottom of a pipe, the gas might remain free of suspended droplets during lower flow rates. However, as flow increases the liquid surface may form wave crests from which droplets can start to break loose and become suspended in the flowing gas above. Under such circumstances, problems can occur which are flow velocity related. Typical applications are air compressor packages where readings have been obtained on the pre-dryer sections of line and on gas storage facilities where sand particles are carried in the gas stream when gas is drawn from storage wells.

The user should not lose sight of the fact that with a 5% gas void fraction in a liquid, or say a 5% liquid fraction in gas, there can be no hope of maintaining an expected 2% of reading flow measurement uncertainty.

9.7.2 Transit time

TTUFs are designed for operation with liquids that have a low content of 2nd phase components. The effect of gas bubbles is to scatter the ultrasound but also reduce the velocity of sound in the liquid by increasing the compressibility of the fluid. Bubbles attenuate the signal and degrade the signal to noise ratio of the flow-meter.

The degree of scattering and attenuation is dependent on the size, number and distribution of the gas bubbles. Factors such as flow velocity, system pressure and fluid viscosity affect the size, number and distribution of gas bubbles. Manufacturers provide typical levels of entrained gas with which their meter continues to operate, typically less than 5% by volume. It is possible for larger gas fractions to be tolerated, but there is no practical way for a process operator to know the size of the gas bubbles in a liquid, and without that knowledge it is not possible to start to predict how the operating frequency of the transducers might tolerate them. Small bubbles with a low operating frequency might have a larger tolerance for gas fraction than larger bubbles at high frequency.

The smaller wavelength in gas might make clamp-on gas meters more susceptible to droplets, as compared to the equivalent bubbles in liquid.

9.7.3 Cross-correlation

Similar to CTUF.

9.7.4 Doppler

Gas bubbles are an essential ingredient for the successful operation of a DUF. Typical gases or air have a velocity of sound that is three to five times lower than that of the probable carrier liquid, and the very significant difference in sonic impedance makes gas bubbles a perfect scatter source and the desired reflection of ultrasound is at its most efficient, certainly more efficient than when the scatter source is solid material.

Problems can arise when the size, distribution and presence of the bubbles are unreliable or highly variable due to process dynamics.

9.8 Suspended solids

9.8.1 General

It should be remembered that neither form of clamp-on meter is intended for two-phase or multi-phase applications. A liquid containing 5% volume of suspended solids cannot yield a volume flow accuracy of 2% of reading.

9.8.2 Transit time

As with suspended gas bubbles in a liquid, it is difficult to give guidance on the likely limit for the concentration of solids. This depends upon the size, distribution and density of the solids and the frequency of the transducers employed. A rough general guide to a limit, expressed in percent by volume terms might be 5%–10%. The effect of solid material is to scatter the ultrasound. Low densities of solids which have particle diameters of less than $\lambda_l/8$, where λ_l is the wavelength of ultrasound in the liquid, are unlikely to cause a significant effect on the meter performance. It has been found in waste water applications that using transducers with a lower operating frequency can improve measurement reliability. This serves to confirm the earlier premise that when the size of individual solid material particles is significantly smaller that one wavelength of the ultrasonic signal, the particle becomes invisible to the ultrasound. Conversely, significantly large solids can equate to a 10% fraction but cause relatively little problem for a TTUF as almost all of the rapidly transmitted pulses remain unaffected by the suspended solids as only small numbers might be scattered or blocked at any instant.

9.8.3 Cross-correlation

Based upon the assumption that commercially available CCUF flow-meters are confined to gases, suspended solids are most likely to take the form of suspended dust in dirty air applications. There is an absence of data in this regard, but it might be reasonable to assume that >10% volume would start to create carrier wave transmission issues and the effect of the moving particles on the carrier wave would overwhelm the desired flow signature detection.

9.8.4 Doppler

Generally, for solid material suspended in a flowing liquid to be an effective scatter source to cause the desired Doppler reflection, the difference in the velocity of sound of the solid material should be >10% more than that of the carrier liquid. There should be particles capable of longitudinal reflection, effectively meaning > 35 μm in size. The suspended material causing the reflection should be travelling at the same velocity in the liquid as the carrier liquid itself if additional measurement uncertainty is to be avoided.

9.9 Fluid composition

The effects of fluid composition are more prevalent to gas meter operation but can be found in liquids. The presence of certain gases can impact on the performance of a meter (for example, high levels of carbon dioxide and hydrogen in a gas mixture can influence and even inhibit the operation of a USM owing to its acoustic absorption properties). Users and specifiers should supply meter manufacturers with the expected constituents of the gases to be measured and the associated pressure and temperature range.

10 Operational effects

10.1 User training

The simple appearance of the meter and the simplified principle often presented belies the fact that it is a very sophisticated flow-meter and there are many complex interrelated phenomena involved in producing a measurement. Users who undertake the measurement should be aware of these factors and take them into account when undertaking the measurement. It should be stressed that clamp-on meters should be installed by trained personnel. A minimum of a few hours of training is strongly recommended for all operators – even if the intended operator has a good theoretical understanding.

The following points are particularly recommended:

- Try the clamping arrangement and check how easy it is to mount, remove and re-mount the clamp and transducers in exactly the same position.
- Determine from the manufacturer what level of onboard diagnostics is available and consider how easy to understand and informative these might be for the intended user.
- Agree with the manufacturer during training/product selection, the critical indicator(s) which should be monitored during operation and ensure that the engineers using the device are aware of these.
- Flow profile (Reynolds number) correction is an important feature with these devices. Ask the manufacturer if there is such on-board correction and, if so, how it works when faced with changing fluid properties such as temperature.

10.2 Transducer configuration

10.2.1 General

Transducers should not be specific to the transmitter unit, and it should be possible for other transducers supplied by the manufacturer to be used. However, it should be stressed that where one transducer has been matched to the other by the manufacturer, care should be taken to avoid mismatching transducer pairs.

10.2.2 Transducer configurations for TTUFs

The three most commonly used configurations to mount the transducers are shown in Figures 14a), Figure 14b) and Figure 14c).

- Single traverse, Figure 14a), is used for large pipe sizes as the path length is shorter than the other configurations and thus less signal loss occurs. Correct installation is more difficult to achieve than two or four traverse. Transducer alignment and axial spacing are prone to error unless transducer location is accurately determined.
- Two traverse, Figure 14b), is the recommended installation method. The path length is longer giving better time resolution. The set up and alignment of the transducers are much easier as they are on the same side of the pipe. The location of the transducers and their separation are easier and potentially more accurate.
- Four traverse, Figure 14c), might be used on small pipes to increase the transit time difference by increasing the ultrasound path between the transducers.

Other combinations can also be used depending on the particular application; however, odd number traverses are difficult to set up.

In confined spaces, two or more traverses might be difficult or precluded due to limited axial length. Furthermore, it should be noted that other mounting configurations are possible in special situations, i.e. any number of odd transverses (transducers are mounted on opposite sides of the pipe), or any even number of transverses (transducers are mounted on the same side of the pipe).

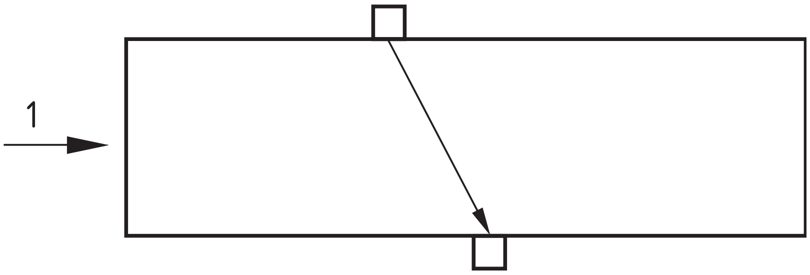
For gas applications it is recommended that meters, which operate with Raleigh-wave transducers, also known as Lamb-wave, be mounted in multiple traverse mode first, starting at either two or four traverse for ease of installation. This is most important as getting these multiple traverses removes almost all of the cross flow effects caused by the very low viscosity of gas. Clamp-on gas meters utilizing shear-wave transducers mostly use a single traverse due to the high signal attenuation effects of the gas.

10.2.3 Transducer configurations for CCUFs

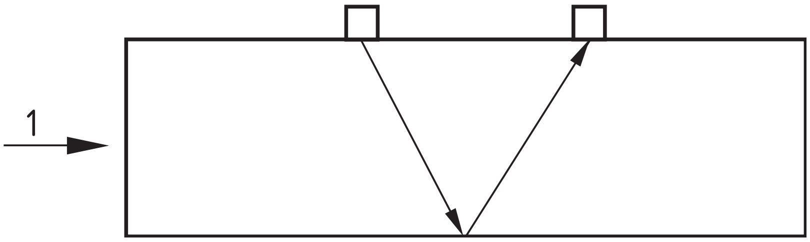
Generally, the CCUF is dependent on two sets of transducers mounted perpendicular to the pipe wall. They are separated by a prescribed distance that is dependent on pipe diameter. No alternate configurations are used.

In the case of hybrids or enhanced meters then additional vortex devices might be incorporated to improve meter performance but these require access to the internal space of the pipe that is not available unless the application has CCUFs selected as the meter of choice prior to construction.

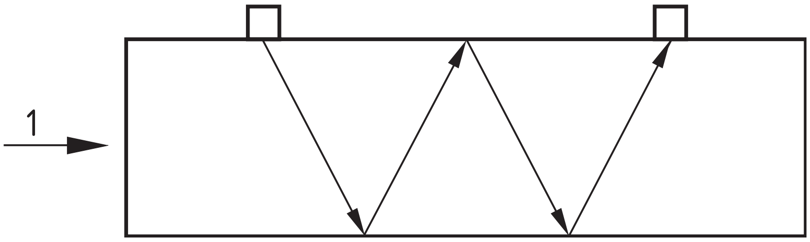
Figure 14 **TTUF transducer configurations**



a) Single traverse



b) Two traverse



c) Four traverse

Key

1 Flow

10.2.4 Transducer configurations for DUFs

Positioning of the transducers in a DUF is also critical for the correct measurement of flow velocity. These are generally the same as for transit time meters.

As with TTUFs the transducers should be mounted away from any flow disturbances and also any device that causes and increase in flow velocity or cause flow cavitations.

10.3 Location of the transducers with respect to the pipe

10.3.1 TTUF

For horizontal pipe runs, it is recommended that the transducers for TTUF are not mounted at or near the top (12 o’clock position) nor the bottom (6 o’clock position). By avoiding these positions, it is less likely that the meter might encounter gas bubbles, which have a tendency to float to the top, or particles, which tend to settle at the bottom of the pipe.

If there is gas at the top and sediments on the bottom for liquids meters or liquid at the bottom for gas meters, the effective flow area is different from the pipe area and hence the volume flow will be in error.

The location of transducers with respect to welds should be considered in all applications. For gas applications butt welds between pipe sections should be avoided as they create a reflector that can cause a short circuit signal within the pipe wall.

Choose a site that is at least 20*D* downstream of any disturbances, i.e. avoiding measurement locations which are downstream of swirl-inducing fittings, e.g. double bends. If this is impractical, position the transducers as far downstream as possible and then consider the following:

- when under conditions of steady flow, it is good practice to try the transducers in several different locations. The highest flow indication is likely to be the best representation of the true flow, as upstream disturbances trend to cause TTUFs to under-read, or
- make allowances based on the performance under test conditions, see Annex D.

Where there is a choice between positioning the transducers just upstream (<10*D*) or up to 10D downstream of a disturbance, current evidence suggests that, the instrument is likely to be less affected if mounted just upstream of the disturbance.

10.3.2 CCUF

The transducers for cross-correlation meters are generally installed in a similar manner to CCUFs ensuring there is alignment between the transducer pairs.

10.3.3 DUF

On horizontal pipes the positioning of the transducers is dependent on the concentration of the scatterers. In liquid applications the 12 o’clock position should be used for low concentrations of gas or solids and the 3 o’clock position for high concentrations of gas or solids.

In vertical pipes the flow is generally considered to be evenly distributed.

10.4 Positioning of the transducers

10.4.1 General

The method of positioning depends on the transducer design and the method of transmission. Transducers are usually clamped in position by a clamping mechanism incorporating a strap or chain, and then located by a distance measurement of the prescribed spacing. Most suppliers also offer a calibrated track, i.e. a track with graduations engraved on it, to help with the measurement and location. Some suppliers provide locating spigots on the clamping mechanisms. These spigots are located into appropriate holes in a spacer to give the correct transducer spacing.

Ultrasonic meters should be stable in the long term provided three conditions are met:

- The condition of the transducers and their coupling to the pipe is not significantly altered;
- The condition of the pipe is not significantly altered;
- The fluid and flow behaviour do not change significantly.

10.4.2 TTUF

It is difficult to achieve precise transducer location in the single traverse configuration. There are several methods described by manufacturers but all rely on creating a datum around the pipe circumference from which to measure the transducer separation and a lateral line to ensure the transducers lie on the centreline of the pipe. The key to the measurements is applying consistency to the reference points used; it is often easier to measure from the heel of the transducer than the centre point as recommended in some cases. One method that might be used in some applications or can be adapted is as follows: a sheet of paper is wrapped around the pipe to mark the position of the circumference. If the paper is square cut it also provides a reference for the lateral position. The sheet is then removed and the final locations calculated and the position of the transducers marked on it. The sheet is replaced on the pipe and the transducers located in position against the template. It is suggested that the template marks are transferred to the pipe if possible to aid tuning of the meter. In a confined space, this can be very difficult.

Velocity profile and swirl have a large influence on the measurement. The recommendations of Clause **4** with regard to mounting downstream and upstream of disturbances should be adhered to. However, the following steps can be used to ensure the best results.

- By moving the transducers around the pipe circumference and checking the velocity, it is possible to determine whether there is a large asymmetry of profile. All the published experimental evidence suggests that, because the meter reads low under asymmetric conditions, the highest reading found is likely to be the closest to the actual mean velocity.
- It is possible to get an indication of swirl by comparing the measured flow velocity from the dual traverse and the single traverse modes. If they are very different, severe cross-flow is present. The measurement should be treated with caution.

It has been shown that unclamping and re-clamping of transducers can result in a difference in indicated flow rate of the order of one or two percent. Therefore, in situations where repeated verifications are carried out on the same pipe, it is advisable to use welded yokes to hold the transducers and, if possible, to use a dedicated pair of transducers with solid couplant so that they can be left in-situ undisturbed. As an alternative for periodic process health-check applications where this is not possible and the transducers are removed and replaced frequently, ensure that the exact mounting position is clearly marked on the pipe.

10.4.3 Cross-correlation

Generally the same guidance as for TTUFs applies to CCUFs.

10.4.4 Doppler

Positioning of the transducer(s) in a DUF is also critical for the correct measurement of flow velocity. The transducer(s) should be mounted accurately, parallel to the pipe axis and transducer to pipe contact should be along the centre line of the transducer head.

As with TTUFs the transducers should be mounted away from any flow disturbances and also any device that causes and increase in flow velocity or cause flow cavitation. They should also be mounted on a diametric line.

10.5 Method of clamping

There are a variety of methods used for holding the transducers in position.

- The simplest method is to use straps, usually nylon with quick release and grip buckles. These are easy to locate and tension. They do, however, stretch with time and should not be used for long term measurement.
- Chains are often used. These are particularly effective for temporary and permanent installation.
- Steel ropes, with quick release and grip mechanisms are used but tend to be cumbersome.
- Jubilee clips can be used for smaller pipes and are very effective for permanent installation.
- With iron-based pipes, magnetic clamps can be used. These are very easy to position, but care should be taken not to adjust the clamping mechanism too tightly, as the magnets tend to loosen. Magnetic clamps should not be used when the temperature exceeds 50 °C.

10.6 Couplant and pipe preparation

The purpose of the couplant is to provide a reliable transmission of ultrasound between the transducer and pipe wall. Different couplants are used for long and short-term use.

The long-term types of couplant are silicon rubber pads, urethane resins and epoxy resins without fillers that diffuse the sound. For permanent installations, periodic checking of flow-meter diagnostics is required. The frequency of checking depends on supplier and couplant type.

Short-term types are silicon grease, axle grease, etc. With a short term couplant, it is important to ensure that it does not dry out. Flow-meter diagnostics can be used to indicate when couplant is due for replacement.

It is suggested that a thin bead of couplant is run along the centreline of the transducer and then compressed on to the pipe. The size of this bead is dependent on the pipe and transducer sizes and manufacturers instructions should be followed but as a rule it is highly recommended that the smaller the pipe gets the less couplant is used. The reason for this is that too much couplant encourages the sound waves to go around the pipe and on smaller pipes this means that the arrival time of the signal through the pipe coincides with the noise around the wall.

The following precautions should be taken with couplants:

- Always clean and degrease the transducer pipe area.
- If there is a coating on the outside of the pipe, it might be necessary to remove it, particularly a coating containing fibres or metal strengthener.
- Care should be taken to ensure that spreading or mixing does not introduce air.
- Excessive amounts of couplants should not be used. For smaller pipes, the transducers could become acoustically connected via the couplant.
- If there is pitting in the pipe walls, enough couplant should be used to cover the pits and make a full acoustic path.
- With plastic pipes, it might be necessary to roughen the surface slightly to ensure adhesion of epoxy resin.
- Care should be taken in dusty/flaky environments. Mixing with the couplant can reduce the effectiveness of the couplant. It can also make the couplants dry out.
- It is essential that users are made aware of the COSHH regulations, as some couplants are irritants.
- The temperature compatibility of the couplant and the process needs to be checked before use.

It is essential that pipe surface preparation is done carefully to preserve the original curvature of the pipe. It is important that the transducer faces and the pipe axis are parallel as one degree error could lead to approximately one percent change in path length.

Good ultrasonic coupling to the outside of the pipe and precise transducer positioning are a pre-requisite for good measurement.

10.7 Damping material installation and impact for gas installations required

In some gas applications the use of damping material is required to improve the performance of the TTUF, particularly on metal pipes and is dependent upon, amongst other factors, gas density, pipe and process conditions and number of traverses; the aim is achieving an acceptable signal-to-noise ratio. It acts to reduce surface wave propagation not noise within the pipe wall or short circuit signal within the wall as is commonly misunderstood. It is a misconception that it is a necessary requirement. Using increased numbers of traverses or odd or even numbers of traverses is the best cure for short circuit signals. Some transducers are optimized with launch angles suited to single or dual traverse.

Should damping material be required then the thickness and number of layers of the damping material required is dependant on the velocity of sound in the damping material and the frequency at which the transducer operates.

10.8 Process temperature

Process temperature has several interacting effects. It affects the velocity of sound, fluid density, viscosity and hence the Reynolds number and the velocity profile. These effects have been covered in Clause **9**. Changes in the velocity of sound in the fluid have the effect of changing the angle of the beam in the fluid and hence the sensitivity of the flow-meter as shown in equation (1). For processes where the process fluid temperature is likely to change it is important that a flow-meter with velocity of sound compensation is employed.

Process temperature also has an impact on the selection of transducers and the couplant. Special transducers are required for low and high temperatures. The transducers often use a potting compound to protect the piezoelectric crystals. Temperature can increase the attenuation of some potting materials. The piezoelectric crystals are bonded to a matching layer / backing material; this bonding agent might also be a limiting factor of the overall temperature capability of the transducer. Temperature can cause expansion of the materials at different rates causing them to separate or delaminate and either destroy them, or form air bubbles. In other cases the mounting block can be partially melted and deformed thereby affecting the coupling capability and the path length.

If the temperature is too high, the efficiency of the piezoelectric crystals is reduced and might eventually stop working. A typical temperature range for a standard transducer is –40 °C to +100 °C, although transducers are available for temperatures in the range –190 °C to +500 °C for high and low temperature systems.

For low temperature applications, the transducer can be coupled using a metal couplant and buffered from the process by being mounted on the ends of long buffer rods. It is important to clean the pipe and ensure it is moisture free. Mount the transducers with a suitable low temperature couplant and then seal this in with a suitable setting compound, probably a silicon based RTV. This effectively seals out the moisture which would form ice and push the transducer away from the pipe. The biggest problem is mounting the transducers as this also gets pushed away from the pipe with the ice build-up.

At extremes of temperature the flow-meter manufacturer should be consulted regarding the choice of couplant.

a) At high temperatures, water-based couplants can evaporate. At low temperatures, water-based couplants can freeze and change characteristics.

b) At high temperatures, some oil-based couplants can flow. At low temperatures, some oil-based couplants change their transmission characteristics.

As an alternative, a solid type couplant can be used which offers a more permanent solution and might be in the form of an acoustically matched neoprene style patch or a 2-part epoxy resin. Assuming it is suitable for the application, it might eliminate some of the issues noted in a) and b).

10.9 Pipe size and transducer frequency

All suppliers support a large range of pipe sizes. Different transducers are often used to cover the range.

- 1 MHz transducers appear to be the standard. These cover approximately the pipe size range of 50 mm to 2 000 mm.
- 2 MHz transducers are used for smaller pipe sizes, below 100 mm diameter and down to 10 mm.

- 0.5 MHz transducers are used for large pipe diameters, approximately 500 mm to 5 000 mm diameter.
- Transducers operating at 4 MHz are offered in very small sizes.

In general, where there are bubbles or particles in the fluid flow, a lower frequency is recommended.

Clamp-on gas transducers operate in the frequency range of 200 kHz to 500 kHz depending on the pipe outside diameter, wall thickness, wall material, the gas to be measured and the operating pressure. Shear-wave and Lamb-wave transducers are used for gas flow measurement applications. The manufacturer should be consulted for the best choice of transducer for a particular application.

Any problems with signal attenuation can be alleviated to a degree by using lower frequency transducers. It should, however, be noted that higher frequencies are to be preferred as they can be timed more accurately.

Some manufacturers change the transducer driving frequency in order to find the resonant frequency of the transducer/pipe system to establish the best acoustic match in terms of receive-amplitude. This is done to match the harmonic frequency of the pipe wall to get the best transmission of sound through the wall to the other side.

The way in which the best harmonic is chosen is by creating a received signal power curve where the peak of the power curve is the best fit frequency.

10.10 Pipe diameter and wall thickness measurement

The internal pipe area is required to calculate the volumetric flow rate from the measured velocity. As the internal pipe diameter cannot be measured directly, it is often inferred from the outside diameter and the wall thickness. The uncertainty of internal diameter measurement is a major contributor to the flow uncertainty. Errors in wall thickness determination can become very significant in area terms and hence volumetric flow terms when using small bore pipes.

Pipe wall thickness is also required, in combination with the material, to work out the transducer positions. Thus, wall thickness also affect the velocity measurement.

The recommended procedure for pipe internal diameter measurement is as follows.

a) Measure the circumference of the pipe using a traceable and accurate tape, or pipe tape.

b) Check the ovality using callipers.

c) Determine the pipe outside diameter.

d) Measure the wall thickness.

e) Subtract twice the wall thickness from the pipe outside diameter.

The wall thickness can be obtained by a number of methods:

1) from a set of drawings or pipe specification;

2) by using an ultrasonic wall thickness gauge. However, it is not possible to tell whether the pipe is lined, or measure the thickness of the liner if present, using simple gauges of this type. There are more sophisticated gauges that can show the different reflections, which could be of some assistance to the skilled user.

If there is build-up on the inside of the pipe, it might not give the correct reading;

3) using a tapping to insert a thickness gauge or direct diameter measuring device. At the same time, the pipe walls can be checked for deposits or erosion;
4) obtaining a section of pipe used in the fabrication of the meter spool for reference purposes.

10.11 Configuration of transmitter/computer

Just as important as the location and positioning of the transducers is the configuration of the instrument. This is particularly true for TTUFs; tests have indicated that they are highly dependent on the accuracy of the user-entered process/installation data. In some cases this might require the operator to find an alternative source for some parameters as they might not be provided either in the meter or the associated documentation.

Ensure that all variables used by the instrument are correctly programmed and that no previous, inappropriate data remains.

Clearly identify the fluid and its associated properties (especially the viscosity and the temperature) and programme in the correct values. It is also useful to establish independent sound-speed data for the fluid which you can then check (where the facility is available) against the instrument’s pre-programmed or calculated value.

Clearly identify the pipe material and grade in use before programming the meter. Errors in excess of 10% are possible if the wrong material is selected in small bore applications. Identify whether there are any lining materials and the thickness as these are not easy to measure.

10.12 Diagnostics

Nearly all manufacturers provide the user with an indication of the signal strength being received by the transducers and incorporate some means of automatic gain control to compensate for attenuation of the ultrasound in the pipe wall and in the fluid.

Because most of the measurement systems are microprocessor based they include a range of diagnostic tools. These enable the hardware and the software of the system to be checked and error codes flagged which allow the specific error to be identified. These diagnostic functions vary from manufacturer to manufacturer and enquiries should be made to potential suppliers as to the range of diagnostic functions they provide.

Additional diagnostics during the measurement phase can be employed. These diagnostics measure the modulation of the received signal (indicating the presence of a second phase such as air bubbles or solids and the need to switch operation from TTUF mode to DUF mode) or the signal to noise ratio of the received signal that provides an indication of the likely quality of the measurement.

Manufacturers should be able to provide users with guidelines on acceptable ranges for each of the diagnostic parameters.

In the event of a poor diagnostic indication check the mounting arrangement is correctly aligned with the pipe and that an appropriate amount of couplant has been used.

If the signal strength is low or a critical indicator shows a problem and the location has not previously delivered good data, try repositioning the transducers to achieve acceptable indications.

Annex A (normative) Reference data

Table A.1 gives a list of reference calibrations carried out by a number of test organizations.

Table A.2 provides a list of calibrations with various disturbance fittings by a number of test organizations.

Table A.3 a list of sound speeds for some common solids that may be found in the construction of pipes.

Table A.4 a list if sound speeds for liquids.

Table A.1 **Reference clamp-on calibrations**

Calibration ID	Pipe material	Pipe schedule	Internal diameter mm	Wall thickness mm	Lining/thickness mm	Flow velocities	Testing organization	Reference ID
1	Copper	DN 25				0.394–9.86	University of Tampere	1
2	Stainless steel	DN 25				0.394–9.86	University of Tampere	1
3	Iron	DN 25				0.394–9.86	University of Tampere	31
4	HDPE	DN 25				0.394–9.86	University of Tampere	31
5	Stainless steel	DN 50				0.04–2.4	University of Tampere	31
6	Mild steel	50 mm	53.4	3.5		0–5.0	Cranfield University	19
7	Mild steel	100 mm	100.6	6.5		0–5.0	Cranfield University	19
8	Mild steel	300 mm	310	14.0		0 –1.5	Cranfield University	19
9	PVC	100 mm	104.5	4.9		0–4.75	Cranfield University	19
10	ABS	100 mm	100.9	6.7		0–5.0	Cranfield University	19
11	Ductile iron	100 mm	104.3	6.6		0–4.75	Cranfield University	19
12	Ductile iron	100 mm	104.3	6.6	Bitumen lined/coated	0–4.75	Cranfield University	19
13	Ductile iron	100 mm	93.3	6.6	Mortar lining 6.5 mm thick	0–4.75	Cranfield University	19
14	70/30 Cupro/Nickel	25 mm	21.03	2.015		0–1.0	Cranfield University	19
15	70/30 Cupro/Nickel	16 mm	13.95	1.04		0–3.5	Cranfield University	19
16	Stainless steel	100 mm	99.3	20.9		0–5.0	Cranfield University	19
17	Stainless steel	100 mm	108.2	3.05		0 –5.0	NEL	27
18	Stainless steel	200 mm	202.7	8.2		0–5.0	NEL	27
19	Carbon steel	200 mm	206.4	6.35		0–5.0	NEL	27
20	Carbon steel	600 mm	598.2	5.2		0–5.0	NEL	27
21	MDPE	200 mm	199.4	12.8		0–5.0	NEL	27
22	Ductile iron	200 mm	195	6.4	Cement lining 5 mm thick	0–5.0	NEL	27

Table A.2 **Disturbance calibrations**

Calibration ID	Pipework	Disturbance	Distances in *D*s	Velocities	Ref ID
1	Stainless steel 200 mm	Contraction	0, 10, 20	0–5.0	27
2	Stainless steel 200 mm	Expansion	0, 10, 20	0–5.0	27
3	Stainless steel 200 mm	Single bend	0, 10, 20	0–5.0	27
4	Stainless steel 200 mm	Double bend	0, 10, 20	0–5.0	27
5	ABS 100 mm	Single bend	5, 10, 15	0–10	4
6	ABS 100 mm	Double bend	5, 10, 15	0–10	4
7	ABS 100 mm	Gate valve	5, 10		
8	ABS 100 mm	Gate valve	5, 10, 15	0–10	4
9	Stainless steel 50 mm	Single bend	5, 20	0.04–2.4	31
10	*Material unknown* 150 mm	Double bend	2.1, 6.2, 10.4, 20.8, 38.8, 80.8	0.8–1.0, 3.2–4.0	5
11	*Material unknown* 150 mm	Hairpin bend	2.1, 6.2,10.4, 20.8, 38.8, 80.8	0.8–1.0, 3.2–4.0	5
12	*Material unknown* 150 mm	Expansion	2.1, 6.2, 10.4, 20.8, 38.8, 80.8	0.8–1.0, 3.2–4.0	5
13	*Material unknown* 150 mm	Contraction	2.1, 6.2, 10.4, 20.8, 38.8, 80.8	0.8–1.0, 3.2–4.0	5
14	*Material unknown* 150 mm	Globe valve	2.1, 6.2, 10.4, 20.8, 38.8, 80.8	0.8–1.0, 1.6–2.0	5
15	*Material unknown* 150 mm	Gate valve	2.1, 6.2, 10.4, 20.8, 38.8, 80.8	0.8–1.0, 1.6–2.0	5
16	*Material unknown* 150 mm	Butterfly valve	2.1, 6.2, 10.4, 20.8, 38.8, 80.8	0.8–1.0, 1.6–2.0	5
17	*Material unknown* 150 mm	Pump	2.1, 6.2, 10.4, 20.8, 38.8, 80.8	0.8–1.0	5

Table A.3 **Solid sound speeds**

Material	**Sound speed* shear wave (25°C)**		**Sound Speed* long (Lamb) wave (25°C)**	
	m/s	**ft/s**	**mm/µs**	**in./µs**
Steel, 1% carbon, hardened	3150	10335	5.88	0.2315
Carbon steel	3230	10598	5.89	0.2319
Mild steel	3235	10614	5.89	0.2319
Steel, 1% carbon	3220	10565		
302 stainless steel	3120	10236	5.690	0.224
303 stainless steel	3120	10236	5.640	0.222
304 stainless steel	3141	10306	5.920	0.233
304L stainless steel	3070	10073	5.790	0.228
316 stainless steel	3272	10735	5.720	0.225
347 stainless steel	3095	10512	5.720	0.225
duplex stainless steel	2791	9479		
Aluminum	3100	10171	6.32	0.2488
Aluminum (rolled)	3040	9974		
Copper	2260	7415	4.66	0.1835
Copper (annealed)	2325	7628		
Copper (rolled)	2270	7448		
CuNi (70%Cu 30%Ni)	2540	8334	5.03	0.1980
Brass (Naval)	2120	6923	4.43	0.1744
Gold (hard-drawn)	1200	3937	3.24	0.1276
Inconel	3020	9909	5.82	0.2291
Iron (electrolytic)	3240	10630	5.90	0.232 3
Iron (Armco)	3240	10630	5.90	0.232 3
Ductile iron	3000	9843		
Cast iron	2500	8203	4.55	0.179 1
Monel	2720	8924	5.35	0.210 6
Nickel	2960	9721	5.63	0.221 7
Tin, rolled	1670	5479	3.32	0.130 7
Titanium	3125	10253	6.10	0.240 2
Tungsten, annealed	2890	9482	5.18	0.203 9
Tungsten, drawn	2640	8661		
Tungsten, carbide	3980	13058		
Zinc, rolled	2440	8005	4.17	0.164 2
Glass, Pyrex	3280	10761	5.61	0.220 9
Glass, heavy	2380	7808		
Silicate flint				
Glass, light	2840	9318	5.26	0.207 1
Borate crown				
Nylon	1150	3772	2.40	0.094 5
Nylon-6,6	1070	3510		
HDPE			2.31	0.090 9

Table A.3 **Solid sound speeds** *(continued)*

Material	**Sound speed* shear wave (25°C)**		**Sound Speed* long (Lamb) wave (25°C)**	
	m/s	**ft/s**	**mm/μs**	**in./μs**
LDPE	540	1 772	1.94	0.076 4
PVC, CPVC	1 060	3 477	2.40	0.094 5
Acrylic	1 430	4 690	2.73	0.107 5
Asbestos cement			2.20	0.086 6
Tar epoxy			2.00	0.078 7
Mortar			2.50	0.098 4
Rubber			1.90	0.074 8

NOTE These values should be considered as nominal. Solids might be inhomogenous and anisotropic. Actual value depends on exact composition, temperature and to a lesser extent, on pressure or stress.

Further information for gas can be found at:
http://webbook.nist.gov/chemistry/fluid/

NOTE This is the NIST website location for "Vapor and Liquid Phase Data".

The following is a combination of empirical and reference data supplied by GE Panametrics.

Table A.4 **Fluid sound speeds**

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δv/°C** –ms^{-1}/ °C	**Kinematic viscosity** m^3/s × 10^{-4}
Acetic anhydride	$(CH_3CO)_2O$	1.082 (20 °C)	1 180	2.5	0.769
Acetic acid, anhydride	$(CH_3CO)_2O$	1.082 (20 °C)	1 180	2.5	0.769
Acetic acid, nitrile	C_2H_3N	0.783	1 290	4.1	0.441
Acetic acid, ethyl ester	$C_4H_8O_2$	0.901	1 085	4.4	0.467
Acetic acid, methyl ester	$C_3H_6O_2$	0.934	1 211		0.407
Acetone	C_3H_6O	0.791	1 174	4.5	0.399
Acetonitrile	C_2H_3N	0.783	1 290	4.1	0.441
Acetonylacetone	$C_6H_{10}O_2$	0.729	1 399	3.6	
Acetylene dichloride	$C_2H_2Cl_2$	1.26	1 015	3.8	0.40
Acetylene tetrabromide	$C_2H_2Br_4$	2.966	1 027		
Acetylene tetrachloride	$C_2H_2Cl_4$	1.595	1 147		1.156 (15 °C)
Alcohol	C_2H_6O	0.789	1 207	4.0	1.396
Alkazene-13	$C_{15}H_{24}$	0.86	1 317	3.9	
Alkazene-25	$C_{10}H_{12}Cl_2$	1.20	1 307	3.4	
2-Amino-ethanol	C_2H_7NO	1.018	1 724	3.4	
2-Aminotolidine	C_7H_9N	0.999 (20 °C)	1 618		4.394 (20 °C)
4-Aminotolidine	C_7H_9N	0.966 (45 °C)	1 480		1.863 (50 °C)
Ammonia	NH_3	0.771	1 729 (–33 °C)	6.68	0.292 (–33 °C)
Amorphous polyolefin		0.98	962.8 (190 °C)		26 600
t-Amyl alcohol	$C_5H_{12}O$	0.81	1 204		4.374
Aminobenzene	$C_6H_6NO_2$	1.022	1 639	4	3.63

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δv/°C** –ms^{-1}/ °C	**Kinematic viscosity** m^3/s × 10^{-4}
Aniline	$C_6H_5NO_2$	1.022	1 639	4	3.63
Argon	Ar	1.400 (–188 °C)	853 (–188 °C)		
Azine	C_8H_5N	0.982	1 415	4.1	0.992 (20 °C)
Benzene	C_6H_6	0.879	1 306	4.65	0.711
Benzol	C_6H_6	0.879	1 306	4.65	0.711
Bromine	Br_2	2.928	889	3.00	0.323
Bromobenzene	C_6H_5Br	1.522	1 170 (20 °C)		0.693
1-Bromobutane	C_4H_9Br	1.276 (20 °C)	1 019 (20 °C)		0.49 (15 °C)
Bromoethane	C_2H_5Br	1.46 (20 °C)	900 (20 °C)		0.275
Bromoform	$CHBr_3$	2.89 (20 °C)	918	3.1	0.654
n-Butane	C_4H_{10}	0.601	1 085 (–5 °C)	5.8	
2-Butanol	$C_4H_{10}O$	0.81	1 240	3.3	3.239
sec-Butylalcohol	$C_4H_{10}O$	0.81	1 240	3.3	3.239
n-Butylbromide	C_4H_9Br	1.276 (20 °C)	1 019 (20 °C)		0.49 (15 °C)
n-Butylchloride	C_4H_9Cl	0.887	1 140	4.57	0.529 (15 °C)
t-Butylchloride	C_4H_9Cl	0.84	984	4.2	0.646
Butyl oleate	$C_{22}H_{42}O_2$		1 404	3.0	
2,3-Butylene glycol	$C_4H_{10}O_2$	1.019	1 484	1.51	
Cadmium	Cd		2 237.7 (400 °C)		1.355cp (440 °C)
Carbinol	CH_4O	0.791 (20 °C)	1076	2.92	0.695
Carbitol	$C_6H_{14}O_3$	0.988	1458		
Carbon dioxide	CO_2	1.101(–37 °C)	839 (–37 °C)	7.71	0.137 (–37 °C)
Carbon disulphide	CS_2	1.261 (22 °C)	1 149		0.278
Carbon tetrachloride	CCl_4	1.595 (20 °C)	926	2.48	0.607
Carbon tetrafluoride (Freon 14)	CF_4	1.75 (–150 °C)	875.2 (–150 °C)	6.61	
Cetane	$C_{16}H_{34}$	0.773 (20 °C)	1 338	3.71	4.32
Chloro-benezene	C_6H_5Cl	1.106	1 273	3.6	0.722
1-Chloro-butane	C_4H_9Cl	0.887	1 140	4.57	0.529 (15 °C)
	$CHClF_2$	1.491 (–69 °C)	893.9 (–50 °C)	4.79	
Chloroform	$CHCl_3$	1.489	979	3.40	0.55
1-Chloropropane	C_3H_7Cl	0.892	1 058		0.378
Chlorotrifluoromethane	$CClF_3$		724 (–82 °C)	5.26	
Cinnamaldehyde	C_9H_8O	1.112	1 554	3.2	
Cinnamic aldehyde	C_9H_8O	1.112	1 554	3.2	
Colamine	C_2H_7NO	1.018	1 724	3.4	
o-Cresol	C_7H_8O	1.047 (20 °C)	1 541 (20 °C)		4.29 (40 °C)
m-Cresol	C_7H_8O	1.034 (20 °C)	1 500 (20 °C)		5.979 (40 °C)
Cyanomethane	C_2H_3N	0.783	1 290	4.1	0.441
Cyclohexane	C_6H_{12}	0.779 (20 °C)	1 248	5.41	1.31 (17 °C)

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δv/°C** $-ms^{-1}$/ °C	**Kinematic viscosity** $m^3/s \times 10^{-4}$
Cyclohexanol	$C_6H_{12}O$	0.962	1 454	3.6	0.071
Cyclohexanone	$C_6H_{10}O$	0.948	1 423	4.00	
Decane	$C_{10}H_{22}$	0.73	1 262		1.26 (20 °C)
1-Decane	$C_{10}H_{20}$	0.746	1 235	4.0	
n-Decylene	$C_{10}H_{20}$	0.746	1 235	4.0	
Diacetyl	$C_4H_6O_2$	0.99	1 236	4.6	
Diamylamine	$C_{10}H_{23}N$		1 256	3.9	
1,2-Dibromo-ethane	$C_2H_4Br_2$	2.18	995		0.79 (20 °C)
trans-1,2-dibromoethene	$C_2H_2Br_2$	2.231	935		
Dibutyl phthalate	$C_8H_{22}O_4$		1 408		
Dichloro-*t*-butyl alcohol	$C_4H_8Cl_2O$		1 304	3.8	
2,3 dichlorodioxane	$C_2H_6Cl_2O_2$		1 391	3.7	
Dichlorodifluoromethane (Freon 12)	CCl_2F_2	1.516 (–40 °C)	774.1	4.24	
1,2-dichloroethane	$C_2H_4Cl_2$	1.253	1 193		0.61
Cis-1,2-dichloroethene	$C_2H_2Cl_2$	1.284	1 061		
Dichloro-fluoromethane (Freon 21)	$CHCl_2F$	1.426 (20 °C)	891 (0 °C)	3.97	
1-2-Dichlorohexafluoro-cyclobutane	$C_4Cl_2F_6$	1.654	669		
1-3-Dichloro-*iso*-butane	$C_4H_8Cl_2$	1.14	1220	3.4	
Dichloromethane	CH_2Cl_2	1.327	1070	3.94	3.1
1,1-Dichloro-1,2,2,2-tetra fluoroethane	$CClF_2\text{-}CClF_2$	1.456	665.3 (–10 °C)	3.73	
Diethyl ether	$C_4H_{10}O$	0.713	985	4.87	0.311
Diethylene glycol	$C_4H_{10}O_3$	1.116	1 586	2.4	
Diethylene glycol, monoethyl ether	$C_6H_{14}O_3$	0.988	1 458		
Diethylenimide oxide	C_4H_9NO	1.00	1 442	3.80	
1,2-bis-(difluoramino) butane	$C_4H_8(NF_2)_2$	1.216	1 000		
1,2-bis-(difluoramino)-2-methylpropane	$C_4H_9(NF_2)_2$	1.213	900		
1,2-bis-(difluoramino) propane	$C_3H_6(NF_2)_2$	1.265	960		
2,2-bis-(difluoramino) propane	$C_3H_6(NF_2)_2$	1.254	890		
2,2-Dihydroxydiethyl ether	$C_4H_{10}O_3$	1.116	1 586	2.4	
Dihydroxyethane	$C_2H_6O_2$	1.113	1 658	2.1	
1,3-Dimethylbenzene	C_8H_{10}	0.868 (15 °C)	1343 (20 °C)		0.749 (15 °C)
1,2-Dimethylbenzene	C_8H_{10}	0.897 (20 °C)	1 331.5	4.1	0.903 (20 °C)
1,4-Dimethylbenzene	C_8H_{10}		1 334 (20 °C)		0.662

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δv/°C** $-ms^{-1}$/ °C	**Kinematic viscosity** $m^3/s \times 10^{-4}$
2,2-Dimethylbutane	C_6H_{14}	0.649 (20 °C)	1 079		
Dimethylketone	C_3H_6O	0.791	1 174	4.5	0.399
Dimethylpentane	C_7H_{18}	0.674	1 063		
Dimethylphthalate	$C_8H_{10}O_4$	1.2	1 463		
Diiodomethane	CH_2I_2	3.235	980		
Dioxane	$C_4H_8O_2$	1.033	1 376		
Dodecane	$C_{12}H_{26}$	0.749	1 279	3.85	1.80
1,2-Ethanediol	$C_2H_6O_2$	1.113	1 658	21	
Ethanenitrile	C_2H_3N	0.783	1 290		0.441
Ethanoic anhydride	$(CH_3CO)_2O$	1.082	1 180		0.769
Ethanol	C_2H_6O	0.789	1 207	4.0	1.39
Ethanol amide	C_2H_7NO	1.018	1 724	3.4	
Ethoxyethane	$C_4H_{10}O$	0.713	985	4.87	0.311
Ethyl acetate	$C_4H_8O_2$	0.901	1 085	4.4	0.489
Ethyl alcohol	C_2H_6O	0.789	1 207	4	1.396
Ethyl benzene	C_8H_{10}	0.867 (20 °C)	1 338 (20 °C)		0.797 (17 °C)
Ethyl bromide	C_2H_5Br	1.461 (20 °C)	900 (20 °C)		0.275 (20 °C)
Ethyl iodide	C_2H_5I	1.950 (20 °C)	876 (20 °C)		0.29
Ether	$C_4H_{10}O$	0.713	985	4.87	0.311
Ethyl ether	$C_4H_{10}O$	0.713	985	4.87	0.311
Ethylene bromide	$C_2H_4Br_2$	2.18	995		0.79
Ethylene chloride	$C_2H_4Cl_2$	1.253	1 193		0.61
Ethylene glycol	$C_2H_6O_2$	1.113	1 658	2.1	17.206 8(20 °C)
50% glycol/50% H_2O			1 578	3.2	
d-Fenochone	$C_{10}H_{16}O$	0.947	1 320		0.22
d-2-Fenechanone	$C_{10}H_{16}O$	0.947	1 320		0.22
Fluorine	F	0.545 (–143 °C)	403 (–143 °C)	11.31	
Fluoro-benzene	C_6H_5F	1.024 (20 °C)	1 189		0.584 (20 °C)
Formaldehyde, methyl ester	$C_2H_4O_2$	0.974	1 127	4.02	
Formamide	CH_3NO	1.134 (20 °C)	1 622	2.2	2.91
Formic acid, amide	CH_3NO	1.134	1 622		2.91
Freon R12			774.2		
Furfural	$C_5H_4O_2$	1.157	1 444	3.7	
Furfuryl alcohol	$C_5H_6O_2$	1.135	1 450	3.4	
Fural	$C_5H_4O_2$	1.157	1 444	3.7	
2-Furaldehyde	$C_5H_4O_2$	1.157	1 444	3.7	
2-Furancarboxaldehyde	$C_5H_4O_2$	1.157	1 444	3.7	
2-Furylmethanol	$C_5H_6O_2$	1.135	1 450	0.75	

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δ*v*/°C** –ms^{-1}/ °C	**Kinematic viscosity** m^3/s × 10^{-4}
Gallium	Ga	6.095	2870 (30 °C)		
Glycerin	$C_3H_8O_3$	1.26	1904	2.2	757.1
Glycerol	$C_3H_8O_3$	1.26	1904	2.20	757.1
Glycol	$C_2H_6O_2$	1.113	1658	2.1	
Helium	He	0.125 (–268.8 °C)	183 (–268.8 °C)		0.025
Heptane	C_7H_{16}	0.684 (20 °C)	1131	4.25	0.598 (20 °C)
n-Heptane	C_7H_{16}	0.684	1180	4.0	
Hexachlorocyclopentadiene	C_5Cl_8	1.718	1150		
Hexadecane	$C_{16}H_{34}$	0.773	1338	3.71	4.32 (20 °C)
Hexalin	$C_6H_{12}O$	0.962	1454	3.6	70.69 (17 °C)
Hexane	C_6H_{14}	0.659	1112	2.71	0.448
n-Hexane	C_6H_{14}	0.649	1079	4.53	
2,5-Hexanedione	$C_6H_{10}O_2$	0.729	1399	3.6	
n-Hexanol	$C_6H_{14}O$	0.819	1300	3.8	
Hexahydrobenzene	C_8H_{12}	0.779	1248	5.41	1.31 (17 °C)
Hexahydrophenol	$C_6H_{12}O$	0.962	1454	3.6	
Hexamethylene	C_8H_{12}	0.779	1248	5.41	1.31 (17 °C)
Hydrogen	H_2	0.071 (–256 °C)	1187 (–256 °C)		0.003 (–256 °C)
2-Hydroxy-toluene	C_7H_8O	1.047 (20 °C)	1541 (20 °C)		4.29 (40 °C)
3-Hydroxy-tolune	C_7H_8O	1.034 (20 °C)	1500 (20 °C)		5.979 (40 °C)
iodo-benzend	C_6H_5I	1.823	1114 (20 °C)		0.954
Iodoethane	C_2H_5I	2	876 (20 °C)		0.29
Iodomethane	CH_3I	2.28	978		0.211
Isobutyl acetate	$C_6H_{12}O$		1180 (20 °C)	4.85	
Isobutanol	$C_4H_{10}O$	0.81 (20 °C)	1212		
Iso-Butane			1219.8		
Isopentane	C_5H_{12}	0.62	980	4.8	0.34
Isopropanol	C_3H_8O	0.785	1170 (20 °C)		2.718
Isopropyl alcohol	C_3H_8O	0.785	1170 (20 °C)		2.718
Kerosene		0.81	1324	3.6	
Ketohexamethylene	$C_6H_{10}O$	0.948	1423	4.0	
Lithium fluoride	LiF		2485 (900 °C)	1.29	
Mercury	Hg	13.594	1449 (23.8 °C)		0.114
Mesityloxide	$C_6H_{16}O$	0.85	1310		

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δv/°C** $-ms^{-1}$/ °C	**Kinematic viscosity** $m^3/s \times 10^{-4}$
Methane	CH_4	0.162 (–69.15 °C)	405 (–89.15 °C)	17.50	
Methanol	CH_4O	0.791 (20 °C)	1 076	2.92	0.695
Methyl acetate	$C_3H_6O_2$	0.934	1 211		0.407
o-Methylaniline	C_7H_9N	0.999 (20 °C)	1 618		4.394
4-Methylaniline	C_7H_9N	0.966 (45 °C)	1 480		1.863 (50 °C)
Methyl alcohol	CH_4O	0.791 (20 °C)	1 076	2.92	0.695
Methyl benzene	C_7H_8	0.867	1 328 (20 °C)	4.27	0.644
2-Methyl-butane	C_5H_{12}	0.62 (20 °C)	980		0.34
Methyl carbinol	C_2H_6O	0.789	1 207	4	1.396
Methyl-chloroform	$C_2H_3Cl_3$	1.33	985		0.902 (20 °C)
Methyl-cyanide	C_2H_3N	0.783	1 290		0.441
3-Methyl cyclohexanol	$C_7H_{14}O$	0.92	1 400		
Methylene chloride	CH_2Cl_2	1.327	1 070	3.94	0.31
Methylene iodide	CH_2I_2	3.235	980		
Methyl formate	$C_2H_4O_2$	0.974 (20 °C)	1 127	4.02	
Methyl iodide	CH_3I	2.28 (20 °C)	978		0.211
1-methylnaphthalene naphthalene	$C_{11}H_{10}$	1.09	1 510	3.7	
2-Methylphenol	C_7H_8O	1.047 (20 °C)	1 541 (20 °C)		4.29 (40 °C)
3-Methylphenol	C_7H_8O	1.034 (20 °C)	1 500 (20 °C)		5.979 (40 °C)
Milk, homogenized			1 548		
Morpholine	C_4H_9NO	1	1 442	3.8	
Naphtha		0.76	1 225		
Natural gas		0.316 (–103 °C)	753 (–103 °C)		
Neon	Ne	1.207 (–246 °C)	595 (–246 °C)		
Nitrobenzene	$C_6H_5NO_2$	1.204 (20 °C)	1 415 (20 °C)	4.00	1.514
Nitrogen	N_2	0.808 (–199 °C)	962 (–199 °C)		0.217
Nitromethane	CH_3NO_2	1.135	1 300	4.00	0.549
Nonane	C_9H_2O	0.718 (20 °C)	1 207	4.04	0.99 (20 °C)
1-Nonene	C_9H_{18}	0.736	1207	4.00	
Octane	C_8H_{18}	0.703	1 172	4.14	0.73
n-octane	C_8H_{18}	0.704 (20 °C)	1 212.5	3.5	0.737
1-octane	C_8H_{18}	0.723	1 175.5	4.10	
Oil of camphor sassafrassy			1 390	3.8	
Oil, car (SAE 20a,30)		1.74	870		190
Oil, castor	$C_{11}H_{10}O_{10}$	0.969	1 477	3.6	0.67
Oil , diesel		0.8	1 250		
Oil, fuel AA gravity		0.99	1 485	3.7	

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δ*v*/°C** –ms^{-1}/ °C	**Kinematic viscosity** m^3/s × 10^{-4}
Oil (lubricating X200)			1 530		
Oil (olive)		0.912	1 431	2.75	100
Oil (peanut)		0.936	1 458		
Oil (sperm)		0.88	1 440		
Oil, 6			1 509 (22 °C)		
2,2-Oxydiethanol	$C_4H_{10}O_3$	1.116	1 586	2.40	
Oxygen	O_2	1.155 (–186 °C)	952 (–186 °C)		0.173
Pentachloroethane	C_2HCl_5	1.687	1 082		
Pentalin	C_2HCl_5	1.687	1 082		
Pentane	C_5H_{12}	0.626 (20 °C)	1 020		0.363
n-Pentane	C_5H_{12}	0.557	1 006		0.41
Perchlorocyclopentadiene	C_5H_6	1.718	1 150		
Perchloro-ethylene	C_2Cl_4	1.632	1 036		
Perfluoro-1-Heptene	C_7F_{14}	1.67	583		
Perfluoro-n-Hexane	C_6F_{14}	1.672	508		
Phene	C_6H_6	0.879	1 306	4.65	0.711
Phenylamine	$C_6H_5NO_2$	1.022	1 639	4.0	3.63
Phenyl bromide	C_6H_5Br	1.522	1 170 (20 °C)		0.693
Phenyl chloride	C_6H_5Cl	1.106	1 273	3.6	0.722
Phenyl iodide	C_6H_5I	1.823	1 114 (20 °C)		0.954 (20 °C)
Phenyl methane	C_7H_8	0.867 (20 °C)	1 328 (20 °C)	4.27	0.644
3-Phenyl propenal	C_9H_8O	1.112	1 554	3.2	
Phthalardione	$C_8H_4O_3$		1 125 (152 °C)		
Phthalic acid, anhydride	$C_8H_4O_3$		1 125 (152 °C)		
Phthalic anhydride	$C_8H_4O_3$		1 125 (152 °C)		
Pimelic ketone	$C_8H_{10}O$	0.948	1 423	4.00	
Plexiglas, lucite, acrylic			2 651		
Polyterpene resin		0.77	1 099.8 (190 °C)		39,000
Potassium bromide	KBr		1 169 (900 °C)	0.71	.715cp (900 °C)
Potassium floride	KF		1 792	1.03	
Potassium iodide	KI		985 (900 °C)	0.64	
Potassium nitrate	KNO_3	1.859 (352 °C)	1 740.1 (352 °C)	1.10	1.19 (327 °C)
Propane (–45 to –130 ^{O}C)	C3H8	0.585 (–45 °C)	1 003 (–45 °C)	5.7	
1,2,3-Propanetriol	$C_3H_8O_3$	1.26	1 904	2.2	.757x10^{-3}
1-Propanol	C_3H_8O	0.78 (20 °C)	1 222 (20 °C)		
2-Propanol	C_3H_8O	0.785 (20 °C)	1 170 (20 °C)		2.718
2-Propanone	C_3H_6O	0.791	1 174	4.5	0.399
Propane	C_3H_6	0.563 (–13 °C)	963 (–13 °C)	6.32	
n-Propyl acetate	$C_5H_{10}O_2$		1 280 (2 °C)	4.63	

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δv/°C** $-ms^{-1}$/ °C	**Kinematic viscosity** $m^3/s \times 10^{-4}$
n-Propyl-alcohol	C_3H_8O	0.78 (20 °C)	1 222 (20 °C)		2.549
Propylchloride	C_3H_7Cl	0.892	1 058		0.378
Propylene	C_3H_6	0.583 (–13 °C)	963 (–13 °C)	6.32	
Pyridine	C_6H_5N	0.982	1 415	4.1	0.992 (20 °C)
Refrigerant 11	CCl_3F	1.49	828.3 (0 °C)	3.56	
Refrigerant 12	CCl_2F_2	1.516 (–40 °C)	774.1 (–40 °C)	4.24	
Refrigerant 14	CF_4	1.75 (–150 °C)	875.24 (–150 °C)	6.61	
Refrigerant 21	$CHCl_2F$	1.426 (0 °C)	891 (0 °C)	3.97	
Refrigerant 22	$CHClF_2$	1.491 (–69 °C)	893.9 (50 °C)	4.79	
Refrigerant 113	$CCl_2F\text{-}CClF_2$	1.563	783.7 (0 °C)	3.44	
Refrigerant 114	$CClF_2\text{-}CClF_2$	1.455	665.3 (–10 °C)	3.73	
Refrigerant 115	C_2ClF_5		656.4 (–50 °C)	4.42	
Refrigerant C318	C_4F_8	1.62 (–20 °C)	574 (–10 °C)	3.88	
Selenium	Se		1 072 (250 °C)	0.68	
Silicone (30cp)		0.993	990		30
Sodium fluoride	NaF	0.877	2 082 (1 000 °C)	1.32	
Sodium nitrate	$NaNO_3$	1.884 (336 °C)	1 763.3 (336 °C)	0.74	1.37 (336 °C)
Sodium nitrite	$NaNO_2$	1.805 (292 °C)	1 876.8 (292 °C)		
Solvasso #3		0.877	1 370	3.7	
Spirit of wine	C_2H_8O	0.789	1 207	4.0	1.396
Sulphur	S		1 177 (250 °C)	–1.13	
Sulphuric acid	H_2SO_4	1.841	1 257.6	1.43	11.16
Tellurium	Te		991 (450 °C)	0.73	
1,1,2,2-Tetrabromoethane	$C_2H_2Br_4$	2.966	1 027		
1,1,2,2-Tetrachloroethane	$C_2H_2Cl_4$	1.595	1 147		1.156 (15 °C)
Tetrachloroethane	$C_2H_2Cl_4$	1.553 (20 °C)	1 170 (20 °C)		1.19
Tetrachloroethene	C_2Cl_4	1.632	1 036		
Tetrachloromethane	CCl_4	1.595 (20 °C)	926		0.607
Tetradecane	$C_{14}H_3O$	0.763 (20 °C)	1 331 (20 °C)		2.86 (20 °C)
Tetraethylene glycol	$C_8H_{18}O_5$	1.123	1 586	3	
Tetrafluoro-methane (Freon 14)	CF_4	1.75 (–150 °C)	875.24 (–150 °C)	6.61	
Tetrahydro-1,4-isoxazine	C_4H_9NO	1	1 442	3.8	
Toluene	C_7H_8	0.857 (20 °C)	1 328 (20 °C)	4.27	0.644
o-Toluidine	C_7H_9N	0.999(20 °C)	1 618		4.394 (20 °C)
p-Toluidine	C_7H_9N	0.966 (20 °C)	1 480		1.863 (50 °C)
Toluol	C_7H_8	0.866	1 308	4.2	0.58
Tribromo-methane	$CHBr_3$	2.89 (20 °C)	918		0.654

Table A.4 **Fluid sound speeds** *(continued)*

Substance	**Form index**	**Specific gravity**	**Sound speed** m/s	**Δv/°C** $-ms^{-1}$/ °C	**Kinematic viscosity** $m^3/s \times 10^{-4}$
1,1,1-Trichloro-ethane	$C_2H_3Cl_3$	1.33	985		0.902 (20 °C)
Trichloro-ethene	C_2HCl_3	1.464	1 028		
Trichloro-fluoromethane (Freon 11)	CCl_3F	1.49	828.3 (0 °C)	3.56	
Trichloro-methane	$CHCl_3$	1.489	979	3.4	0.55
1,1,2-Trichloro-1,2,2 trifluoroethane	$CCl_2F\text{-}CClF_2$	1.563	783.7 (0 °C)		
Triethylamine	$C_6H_{15}N$	0.726	1 123	4.47	
Triethylene glycol	$C_6H_{14}O_4$	1.123	1 608	3.80	
1,1,1-Trifluoro-2-chloro-2-Bromoethane	$C_2HClBrF_3$	1.869	693		
1,2,2-Trifluorotrichloro-ethane (Freon 113)	$C_7H_5(NO_2)_3$	1.583	783.7 (0 °C)		
d-1,3,3-Trimethylnorcamphor	$C_{10}H_{18}O$	0.947	1 320		0.22
Trinitrotoluene	$C_7H_5(NO_2)_3$	1.64	1 610 (81 °C)		
Turpentine		0.88	1 255		1.4
Unisis 800		0.87	1 346		
Water, distilled (49,50)	H_2O	0.996	1 498	-2.4	1.00
Water, heavy	D_2O		1 400		
Water, sea		1.025	1 531	-2.4	1.00
Wood alcohol (40, 41)	CH_4O	0.791 (20 °C)	1 076	2.92	0.695
Xenon (45)	Xe		693 (–109 °C)		
m-Xylene (46)	C_8H_{10}	0.868 (15 °C)	1 343 (20 °C)		0.749 (15 °C)
o-Xylene (29,46)	C_8H_{10}	0.897 (20 °C)	1 331.5	4.1	0.903 (20 °C)
p-Xylene (46)	C_8H_{10}		1 334 (20 °C)		0.662
Xylene hexafluoride	$C_8H_4F_8$	1.37	879		0.613
Zinc (7)	Zn		3 298 (450 °C)		

NOTE All figures are given at 25 °C unless specified otherwise.

Annex B (normative) Variants to base technologies

B.1 Measurement of time difference – TTUF

Most manufacturers use a variant of the leading edge measurement technique shown in Figure B.1. In this configuration, the transducers are pulsed and the time is measured from the arrival of the receive pulse. In some designs, a phase measurement system, see Figure B.2, is employed in which a sinusoidal burst is sent out from both transducers and the phase of the received signals compared. Such a technique enables multiple measurement of the phase over several cycles within the receive burst, with gas metering applications, exhibiting much higher velocities than liquids, working at many cycles out of phase, sometimes as high as 10 to 15 times or 5 400° out of phase.

This has had the benefit of moving back into liquid applications where problems had originally been experienced. Therefore some of the newer systems on the market can operate at many cycles out of phase for liquids and it is recommended that a user consults their meter manufacturer for further information in this regard.

Some manufacturers employ a digital signal cross-correlation technique to determine the signal arrival time at the receiving transducer. It is claimed that this technique significantly improves the accuracy of the transit time measurement.

Figure B.1 **Leading edge measurement**

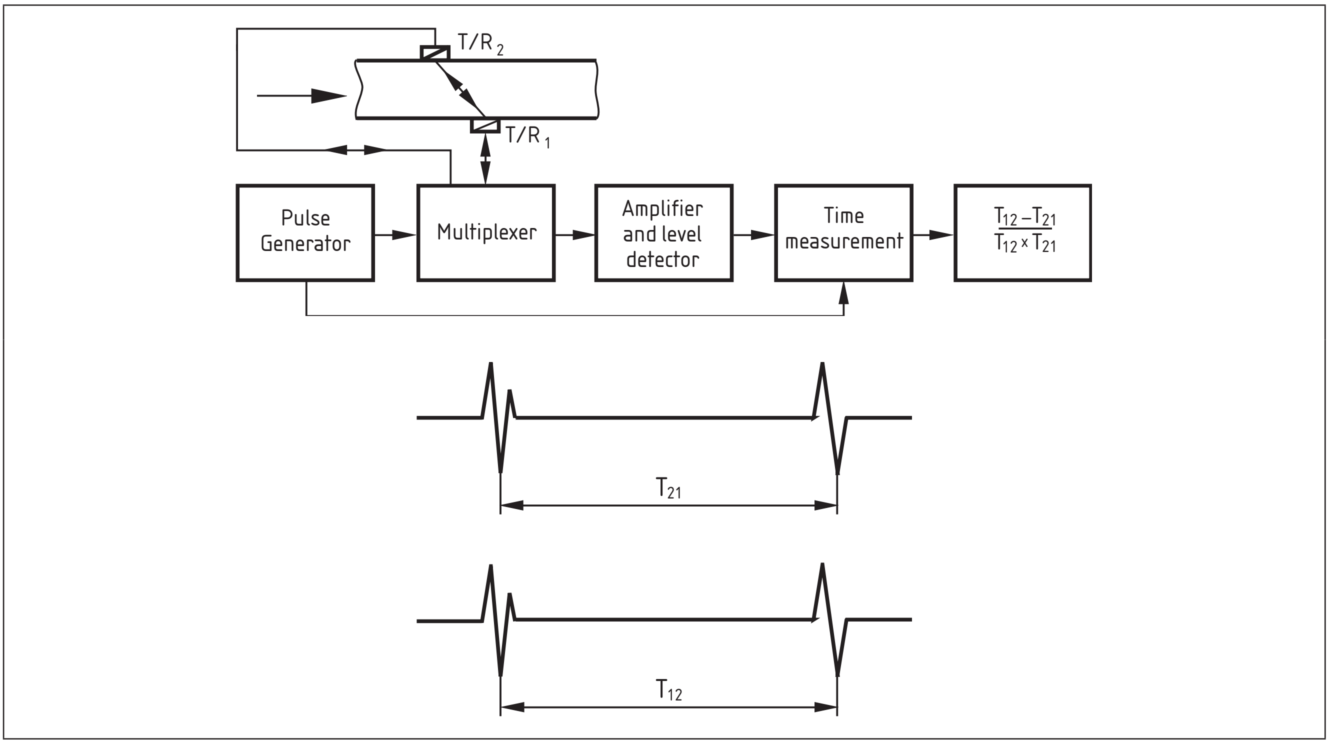
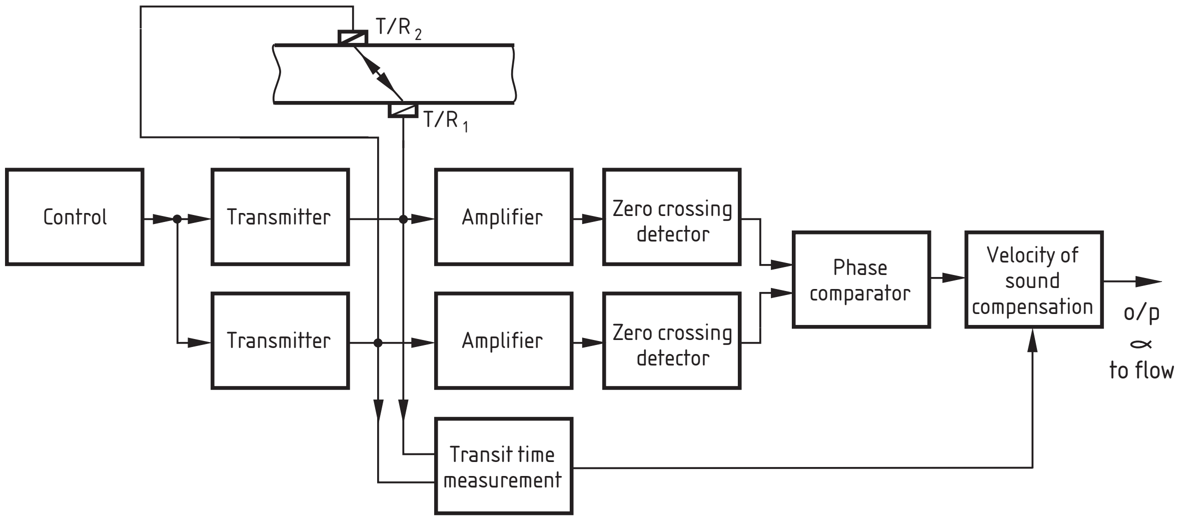
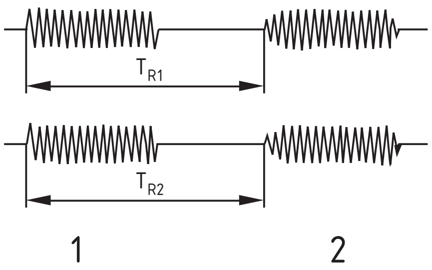


Figure B.2 **Phase measurement system**



a) Electronics of systems

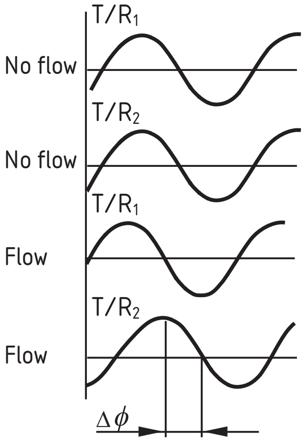


Key

1 Transmit burst

2 Receive burst

b) Transmit and receive burst relationships



c) Phase relationship of individual cycles within the receive burst

B.2 Cross-correlation tag ultrasonic flow-meter

B.2.1 General

In addition to traditional transit time, cross-correlation transit time and Doppler there is also the TAG cross-correlation technique. The theoretical principle of TAG is well established and documented, and is by no means limited to ultrasound. Other techniques that employ the TAG principle are optical, radiation, capacitance and conductance. However, for the purposes of this document the focus relates to acoustics.

B.2.2 Method of operation

Generally, a minimum of four transducers are required, two of which are transmitters and two of which are receivers. It takes one transmitter and one receiver to make a transducer pair, or station as they are sometimes referred to, as indicated on Figure B.3. However, whereas in traditional transit time applications the transmitting and receiving of signals often alternates between the upstream and downstream transducers, this is not the case with the tag principle. The receiving transducers are always receiving and the transmitting transducers are always transmitting, they do not alternate. The TAG technique also employs a mode of continuous wave transmission which means that the transmitting transducer continually transmits, unlike traditional transit time where the signal is often coded and transmitted in bursts.

The two pairs of transducers or stations are axially separated by a distance which is typically between 0.5*D* and 1*D*. and positioned to transmit diametrically across the pipe as shown in Figure B.3. Although Figure B.3 illustrates a clamp-on configuration, this technique can be applied to wetted and clamp-on applications alike (see [12], [13]).

In order to help eliminate cross talk between the two stations, each station can be operated at a slightly different frequency although this is not always the case.

Station 1 transmitter beams a constant ultrasonic signal through the flow to Receiver 1. Assuming the fluid is turbulent, the signal is modulated by local density variation in the fluid flow

Likewise, Station 2 transmitter beams a constant ultrasonic signal through the flow to Receiver 2. Assuming the fluid is turbulent, the signal is modulated by local density variation in the fluid flow

In order for the tag principle to operate, there are two fundamental requirements. Firstly, the fluid should be turbulent (or alternatively include a second phase) so that modulation can occur. Secondly, the fluid should be flowing in order to transport the density variations that modulate the signals between the two stations.

Turbulent flow has a pattern of eddies, and these eddies modulate the ultrasonic beam as they pass between the transducer pairs.

Both signals are demodulated to eliminate the carrier signal; see Figure B.4.

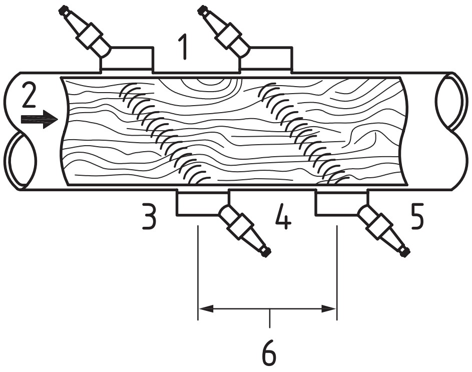
The two signals are then cross-correlated to see if there is a discernable pattern.

The eddies have a finite lifetime, and provided that the transducer pairs are placed sufficiently close together, the pattern of turbulence and resulting modulation is similar for the downstream pair of transducers as for the upstream pair, but delayed by time, τ_0, where:

$$\tau_0 = \frac{s}{\overline{V}}$$

A distinct peak occurs if the turbulence signature is recognized at both Station 1 and Station 2. The peak is the τ (tau) value and indicates the time it took the turbulence pattern to travel the distance from Station 1 to Station 2. See Figure B.6.

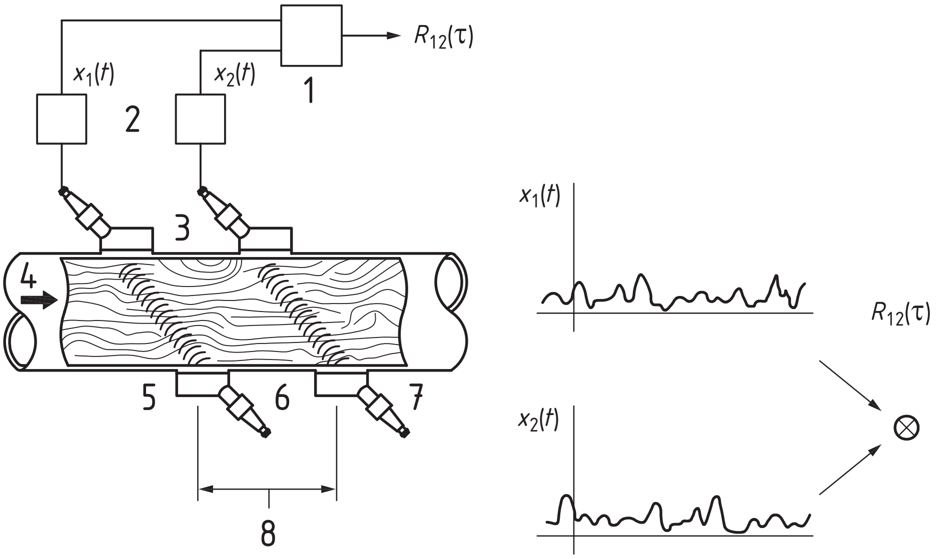
Figure B.3 **Cross-correlation tag time meter**



Key

1	Receivers	4	Transmitters
2	Flow	5	Station 2
3	Station 1	6	Tag path

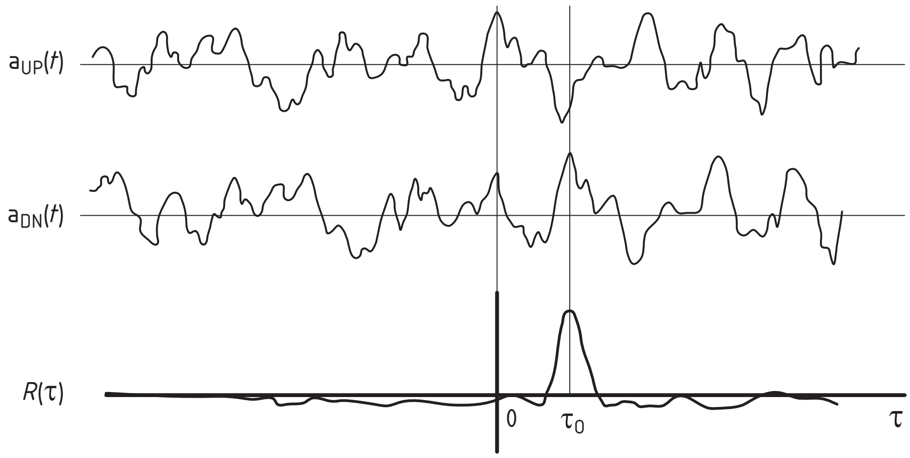
Figure B.4 **Signal set demodulated**



Key

1	Correlation	5	Station 1
2	Demodulation	6	Transmitters
3	Receivers	7	Station 2
4	Flow	8	Tag path

Figure B.5 **Demodulated signals and cross-correlation function**



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The delay time, τ_0, is normally determined from the peak of the cross-correlation function.

$$R(\tau) = \frac{1}{2T}\int_{-T}^{+T} a_{up}(t)a_{dn}(t+\tau)dt$$

The τ (tau) value directly proportional to velocity.

Annex C (normative)

Detailed equations

The calculation of flow for a TTUF is described in detail below. For ease of reading Figure 3 is repeated.

$$Q_v = \frac{k_h \pi D C_l^2 \Delta t}{16\cot\theta} C_f \tag{C.1}$$

where

C_f is the velocity of sound in the fluid;

D is the internal diameter of the pipe; and

k_h, is the profile correction factor, given by:

$$k_h = \frac{\bar{v}_{pipe}}{\bar{v}_{path}} \tag{C.2}$$

where

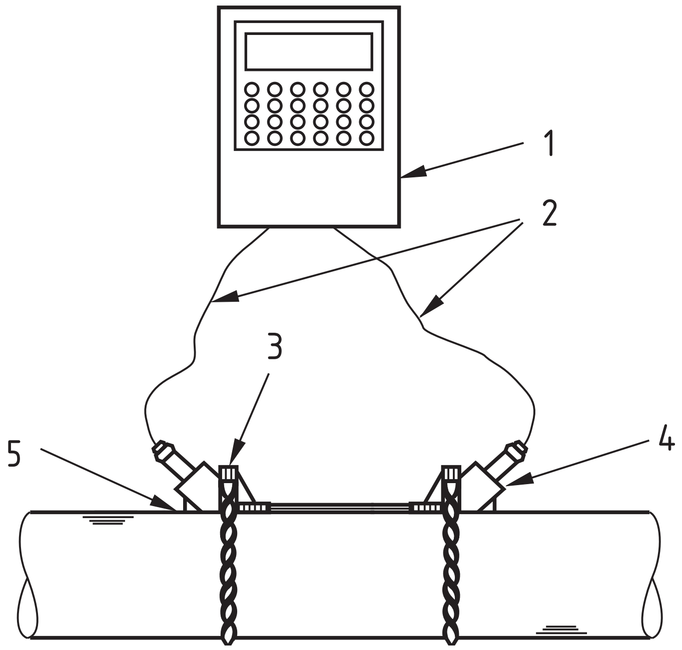
$\bar{v}_{pipe}$ is the actual average velocity in the pipe; and

$\bar{v}_{path}$ is the average velocity measured along the path.

If the wedge on which the transducers are mounted is made of a material for which the velocity of sound is C_w and having an angle α to the pipe axis, then equation (1) can be re-written as:

$$Q_v = \frac{k_h \pi C_l C_w D \sqrt{1 - \left(\frac{C_l \cos\alpha}{C_w}\right)^2}\,\Delta t}{16\cos\alpha} \tag{C.3}$$

Figure 3 **A typical clamp-on TTUF** *(repeated)*



Key

1	Flow-meter electronics
2	Cables (matched pair)
3	Clamping device
4	Transducers
5	Couplant

By measurement of the transit time difference, Δt, together with knowledge of factors specific to the measurement, namely the internal diameter of the pipe and the velocity of sound of the fluid, input by the user (or measured on line) and internally held variables such as the *k* factor, the wedge angle and the velocity of sound in the wedge it is possible to provide a measurement of the volumetric flow rate of the fluid.

In order to obtain an accurate measurement, it is necessary to obtain an accurate measurement of the required separation of the transducer *T*1 and *T*2. From simple geometric considerations this separation, *S*, in the case of a single path meter to be:

$$S = 2S_\mathrm{w} + 2S_\mathrm{p} + 2S_\mathrm{l} \tag{C.4}$$

where

S_w is the separation through the wedge;

S_p is the separation through the pipe; and

S_l is the separation through the fluid.

This can be shown to be given by:

$$S = 2\frac{h}{\tan\alpha} + 2t\frac{\dfrac{C_\mathrm{p}\cos\alpha}{C_\mathrm{w}}}{\sqrt{1-\left(\dfrac{C_\mathrm{p}\cos\alpha}{C_\mathrm{w}}\right)^2}} + 2D\frac{\dfrac{C_\mathrm{l}\cos\alpha}{C_\mathrm{w}}}{\sqrt{1-\left(\dfrac{C_\mathrm{l}\cos\alpha}{C_\mathrm{w}}\right)^2}} \tag{C.5}$$

The correct separation of the transducers can be obtained by providing the flow-meter with the pipe wall thickness, *t*, and internal diameter, *D*, and the velocity of sound in the pipe wall, C_p, material and the velocity of sound in the fluid, C_l. This can be used with internally stored values to indicate to the user the required separation.

Annex D (informative) Installation effects

The graphs in Figures D.1 to D.8 are supplied for information only. They can be used to provide an estimate of the additional uncertainty generated by each flow disturbance.

Figure D.1 **Errors downstream of a conical contraction**

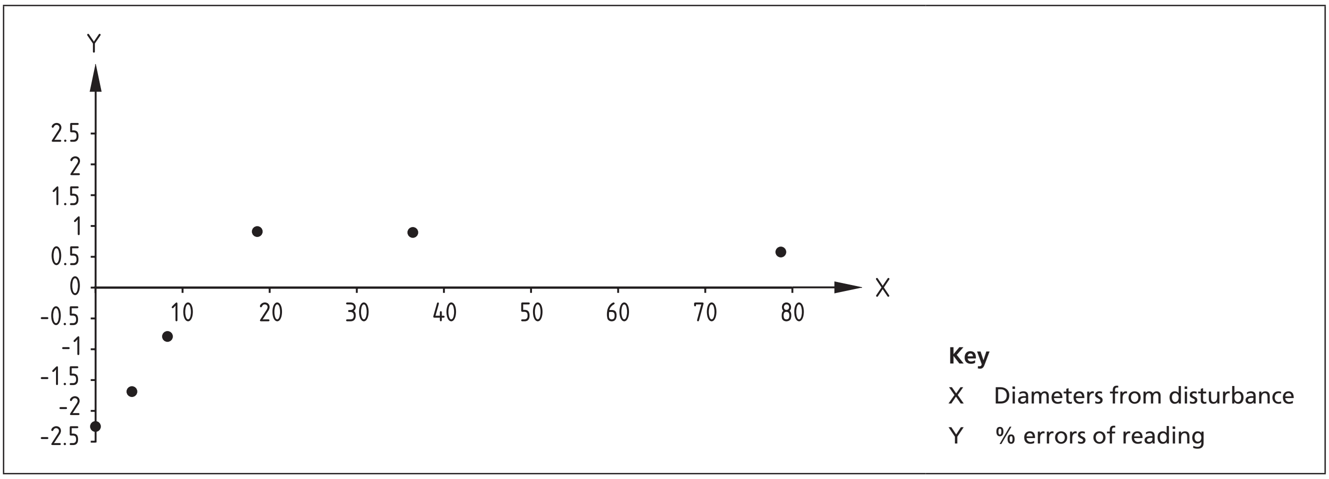


Figure D.2 **Errors downstream of a conical expansion**

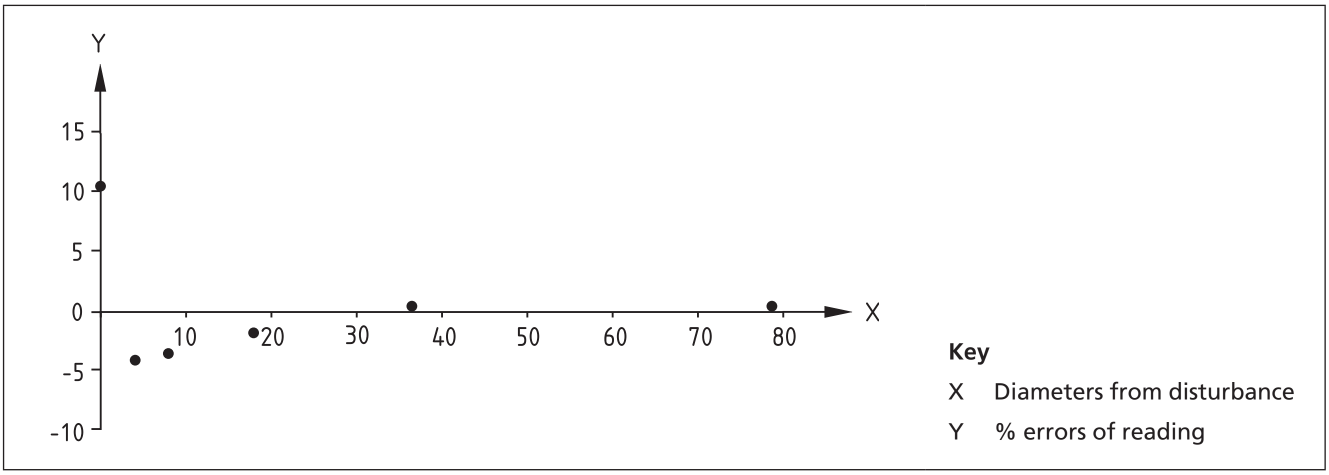


Figure D.3 **Errors downstream of a single 90° bend**

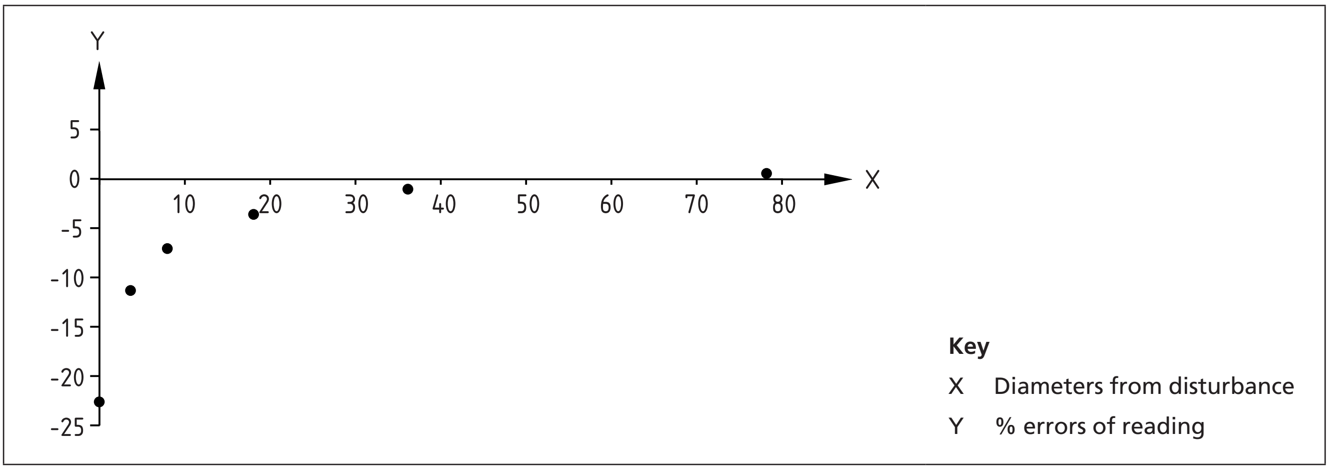


Figure D.4 **Errors downstream of two 90° bends in "U" configuration**

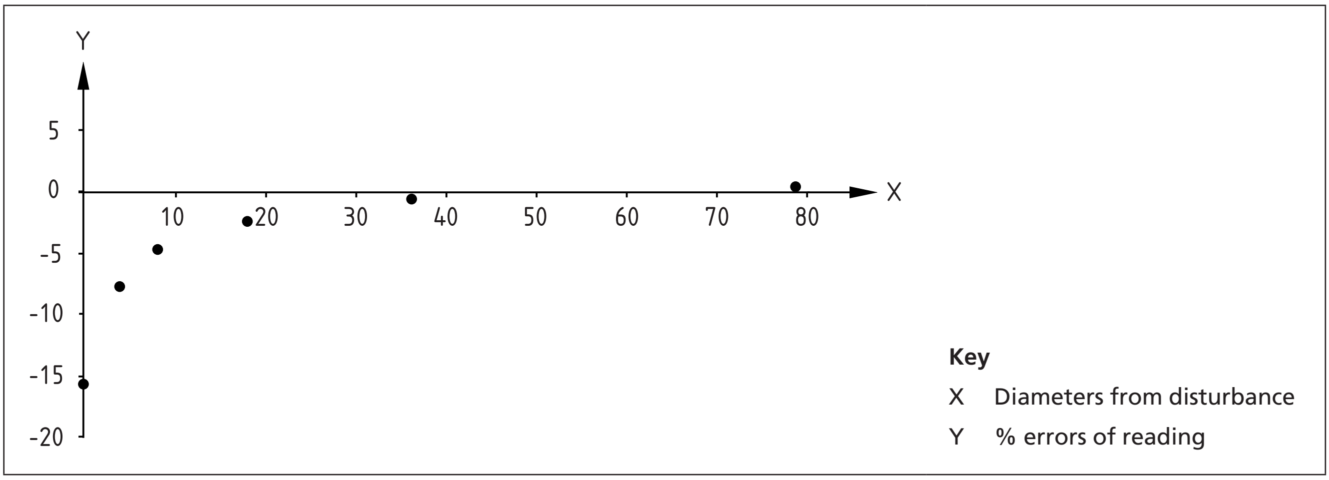


Figure D.5 **Errors from two 90° bends in perpendicular planes**

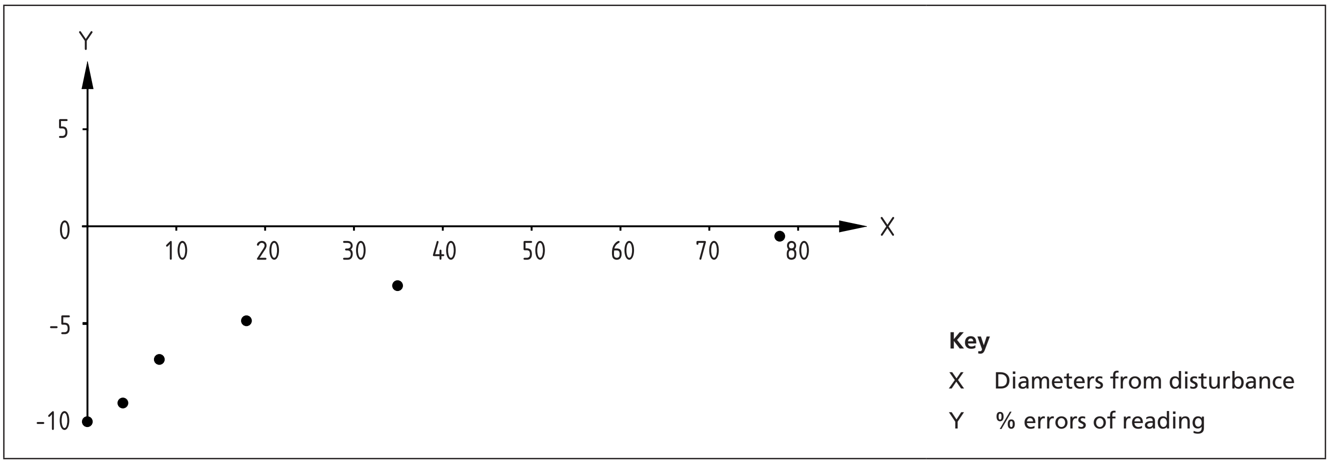


Figure D.6 **Errors downstream of a butterfly valve ⅔ open**

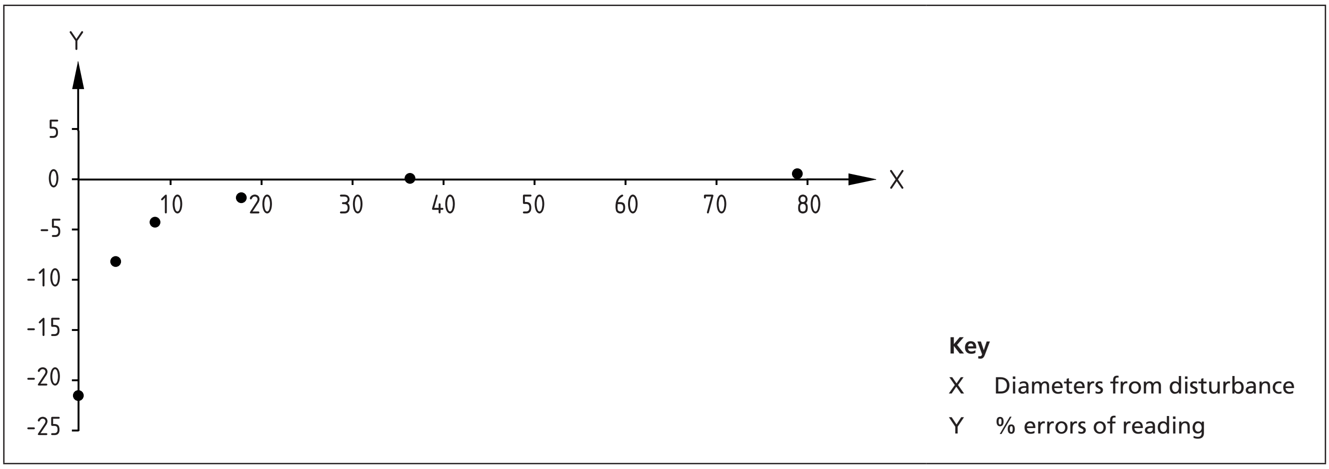
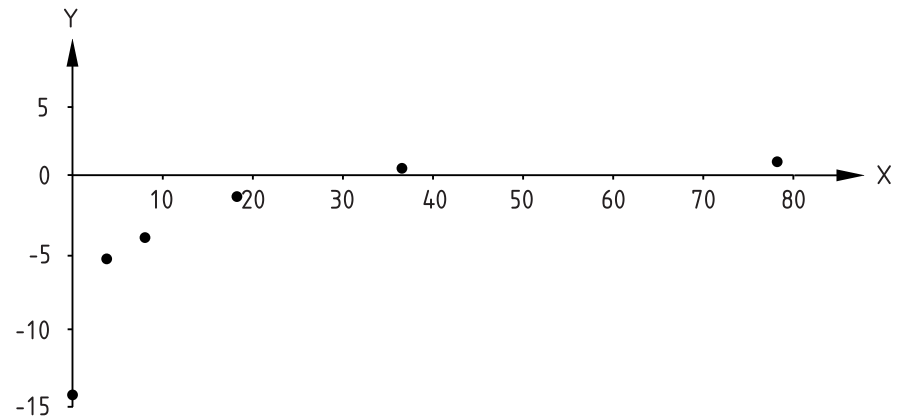


Figure D.7 **Errors downstream of a globe valve ⅔ open**

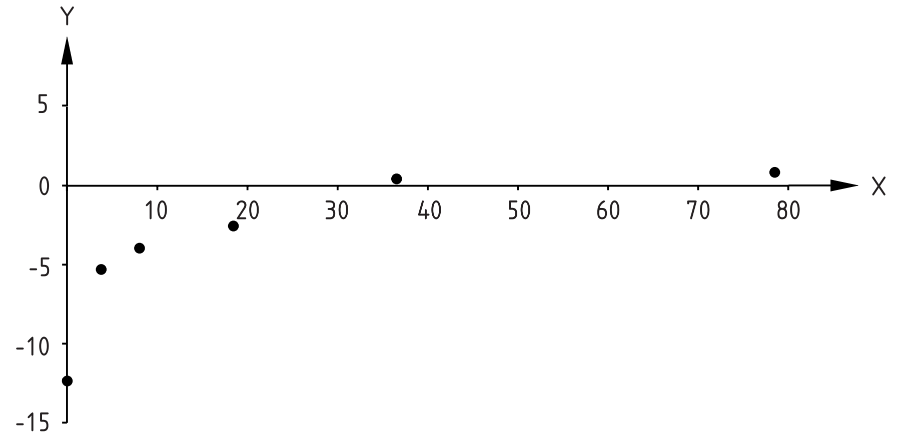


Key

X Diameters from disturbance

Y % errors of reading

Figure D.8 **Errors downstream of a gate valve ⅔ open**



Key

X Diameters from disturbance

Y % errors of reading

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