

Use of clamp-on (externally mounted) transit time metering techniques for liquid applications — Guide

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Contents

	Page
Committees responsible	Inside front cover
Foreword	ii
Introduction	1
1 Scope	1
2 Symbols and abbreviations	1
3 Clamp-on transit time ultrasonic flow-meters	2
4 Installation effects	8
5 Pipework effects	10
6 Fluid effects	12
7 Operational effects	13
8 Manufacturer specific	17
Annex A (normative) Reference data	20
Annex B (normative) Clamp-on Doppler ultrasonic flow-meter	31
Annex C (normative) Cross-correlation ultrasonic flow-meters	33
Annex D (informative) Installation effect	35
Bibliography	39
Figure 1 — A typical clamp-on TTUF	3
Figure 2 — Schematic of a clamp-on TTUF	3
Figure 3 — Profile correction factor (k_h) against Reynolds number for fully developed flow in smooth pipes	8
Figure 4 — Two-path measurement	9
Figure 5 — Effect of pipe wall roughness on profile correction factor	11
Figure 6 — Transducer configurations	14
Figure 7 — Leading edge measurement	17
Figure 8 — Phase measurement system	18
Figure B.1 — Basics of Doppler ultrasonic flow-meter	32
Figure C.1 — Cross-correlation ultrasonic flow-meter	34
Figure D.1 — Errors downstream of a conical contraction	35
Figure D.2 — Errors downstream of a conical expansion	35
Figure D.3 — Errors downstream of a single 90° bend	36
Figure D.4 — Errors downstream of two 90° bends in “U” configuration	36
Figure D.5 — Errors from two 90° bend in perpendicular planes	37
Figure D.6 — Errors downstream of a butterfly valve $\frac{2}{3}$ open	37
Figure D.7 — Errors downstream of a globe valve $\frac{2}{3}$ open	38
Figure D.8 — Errors downstream of a gate valve $\frac{2}{3}$ open	38
Table 1 — Application areas of clamp-on TTUFs	5
Table 2 — Installation effect upstream straight length table	9
Table 3 — Ranges of pipe size, material, wall thickness and lining material with which clamp-on TTUFs can be used	10
Table A.1 — Reference clamp-on calibrations	20
Table A.2 — Disturbance calibrations	21
Table A.3 — Solid sound speeds	22
Table A.4 — Fluid sound speeds	23

Foreword

This British Standard has been prepared by Sub-committee CPI/30/5.

This British Standard is based upon the National Measuring System Report 359-99, *Research Into Clamp-on Ultrasonic Meters*, and the work contained therein was funded from the National Measuring System Programme for Flow Measurement.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to ii, pages 1 to 40, an inside back cover and a back cover.

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Introduction

This British Standard identifies factors likely to affect the performance of clamp-on (externally mounted) ultrasonic transit time flow-meters. One of the significant advantages in employing ultrasonic techniques in liquid 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 may also be used non-invasively, i.e. with the transducers mounted onto the outside of the pipework. Such methods are commonly referred to as clamp-on ultrasonic techniques since the transducers are clamped or held onto the outside of the pipework.

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

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

1 Scope

This British Standard identifies factors, including installation effects, pipework, fluid effects, operational effects and supplier specific effects, which are likely to affect the performance of clamp-on (externally mounted) ultrasonic transit time flow-meters (TTUF). This includes hybrid spool type clamp-on meters where the spool piece is specifically machined to suit the clamp-on meter.

This standard examines the likely effect of these factors, 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 TTUF, typical application areas, the performance measures which should be used in assessing the meter performance and the likely performance in terms of error, repeatability and reproducibility when used under ideal flow, pipe, fluid and operational conditions.

It also covers the installation of transit time meters, where the transducers are clamped on to the outside of a proprietary meter spool.

There are currently two other commonly used non-invasive ultrasonic flow measurement technologies. These are the Doppler ultrasonic flow-meter (DUF) and the cross-correlation ultrasonic flow-meter (CCUF). The scope of this British Standard is restricted to the use of transit time meters since such flow-meters are likely to give rise to a metering technique with the widest range of application and the highest accuracies and lowest uncertainties. Because of the need to distinguish between the different ultrasonic technologies and their applications, Annex B and Annex C provide a comparative overview of Doppler ultrasonic flow-meters and cross-correlation ultrasonic flow-meters.

2 Symbols and abbreviations

Symbol	Meaning	Units
C_l	velocity of sound in liquid	m/s
C_p	velocity of sound in pipewall	m/s
C_w	velocity of sound in transducer wedge	m/s
CCUF	Cross-correlation ultrasonic flow-meter	
D	pipe internal diameter	m
DUF	Doppler ultrasonic flow-meter	
E	indicated flowrate error	%
$\bar{E}$	average flowrate error for all test runs	%
E_i	flowrate 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 flowrate	m ³ /s
R	repeatability	
Re	Reynolds Number	dimensionless
		ρ
		μ
		ν
S	transducer separation	m
S_l	separation through the liquid	m
S_p	separation through the pipewall	m
S_w	separation through the transducer wedge	m
TTUF	Transit time ultrasonic flow-meter	
t	pipewall 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
$\bar{v}_{\text{pipe}}$	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	°
θ	angle between the direction of ultrasound in the liquid and the pipe axis	°
λ	wavelength	m
λ_l	wavelength of ultrasound in the liquid	m
$\bar{v}_{\text{path}}$	averaged axial component of velocity along path between transducers	m/s
v_s	velocity of scatterers	m/s

3 Clamp-on transit time ultrasonic flow-meters

3.1 General

Figure 1 shows the elements of a typical clamp-on TTUF. The meter consists of three elements:

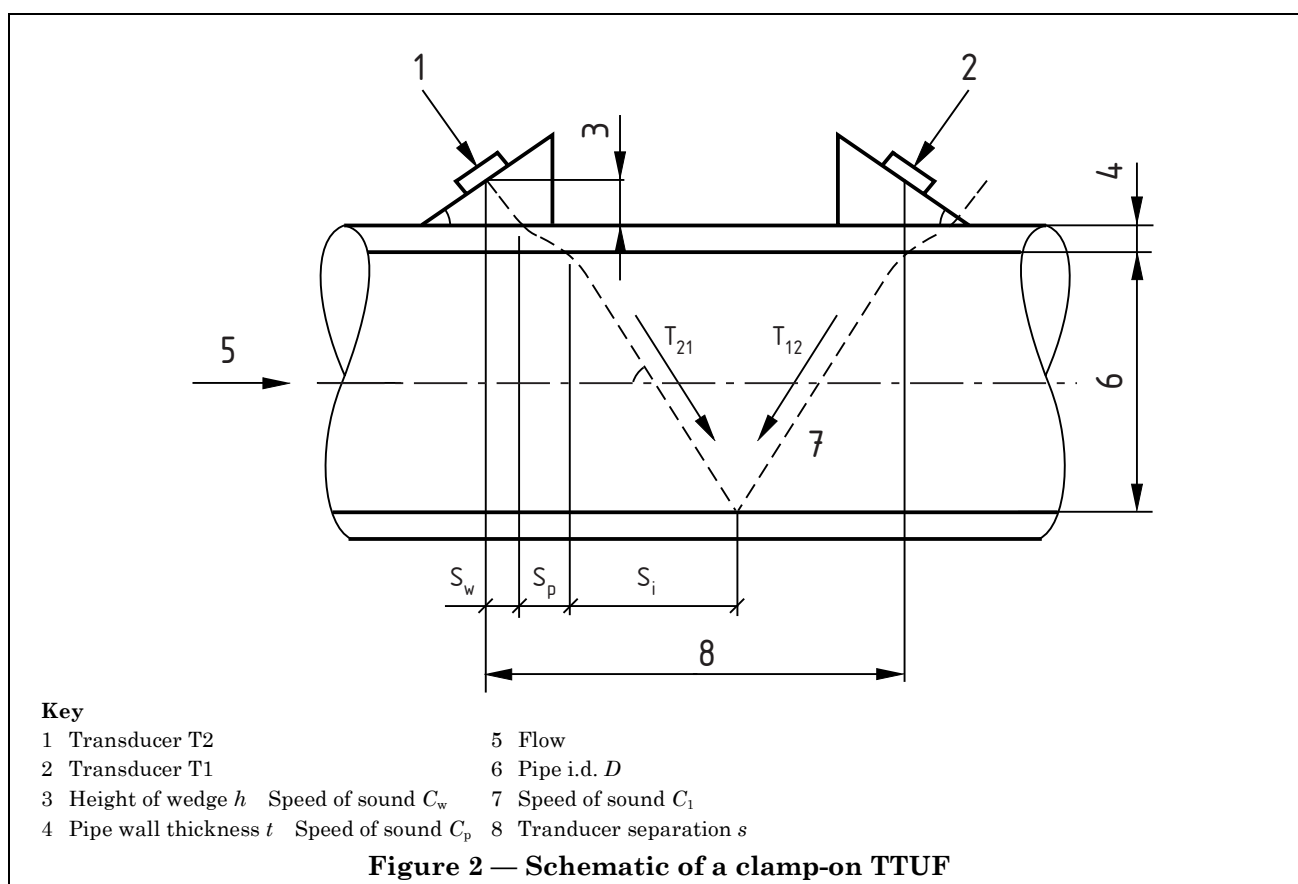
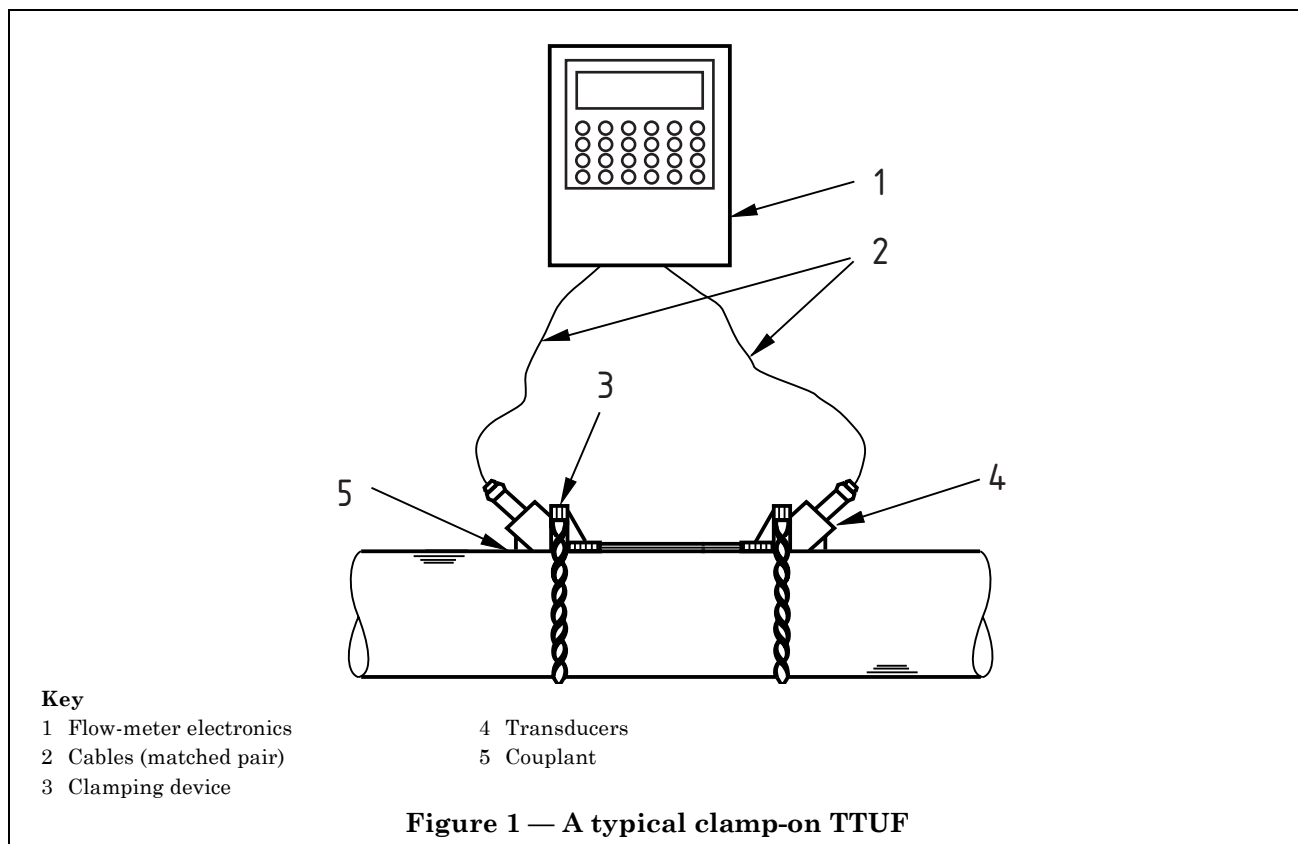
- the transducers;
- the clamping arrangement; and
- the signal processing and user interface electronic package.

The transducers are piezoelectric devices generating ultrasound that penetrates through the pipe wall and is transmitted along the paths shown within the fluid.

The clamping arrangements enable the transducers to be in good sonic contact with the pipe wall and at the correct distance for the particular pipe and liquid application. The signal processing electronics measures the difference in time between ultrasonic pulses passed upstream and downstream as a consequence of the flow of the liquid. This is converted to a flowrate which is typically displayed on a user interface either in numerical or graphical format, with an analogue and/or digital output. A means is also provided for the user to enter application specific data.

3.2 The principle of operation

Figure 2 shows the principle of operation of the clamp-on TTUF measuring the flowrate of a liquid whose speed of sound is C_l in a pipe of internal diameter D .



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 per Figure 2 (i.e. dual traverse) then the volumetric flow rate Q_v is related to the time difference $\Delta t = t_{12} - t_{21}$ by:

$$Q_v = \frac{k_h \pi D C_1^2 \Delta t}{16 \cot \theta} \quad (1)$$

where

- C_1 is the speed of sound in the liquid;
- D is the internal diameter of the pipe; and
- k_h is the profile correction factor, given by:

$$k_h = \frac{\bar{v}_{\text{pipe}}}{\bar{v}_{\text{path}}} \quad (2)$$

where

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

$\bar{v}_{\text{path}}$ 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 speed of sound is C_w and having an angle α to the pipe axis, then equation (1) can be re-written as:

$$Q_v = \frac{k_h \pi C_1 C_w D \sqrt{1 - \left(\frac{C_1 \cos \alpha}{C_w} \right)^2} \Delta t}{16 \cos \alpha} \quad (3)$$

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 speed of sound of the liquid, input by the user (or measured on line) and internally held variables such as the k factor, the wedge angle and the speed of sound in the wedge it is possible to provide a measurement of the volumetric flow rate of the liquid.

In order to obtain an accurate measurement, it is necessary to obtain an accurate measurement of the required separation of the transducer T1 and T2. From simple geometric considerations this separation, S , in the case of a single path meter to be:

$$S = 2S_w + 2S_p + 2S_1 \quad (4)$$

where

- S_w is the separation through the wedge;
- S_p is the separation through the pipe; and
- S_1 is the separation through the liquid

This can be shown to be given by:

$$S = 2 \frac{h}{\tan \alpha} + 2t \frac{\frac{C_p \cos \alpha}{C_w}}{\sqrt{1 - \left(\frac{C_p \cos \alpha}{C_w} \right)^2}} + 2D \frac{\frac{C_1 \cos \alpha}{C_w}}{\sqrt{1 - \left(\frac{C_1 \cos \alpha}{C_w} \right)^2}} \quad (5)$$

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 speed of sound in the pipe wall, C_p , material and the speed of sound in the liquid, C_1 . This can be used with internally stored values to indicate to the user the required separation.

3.3 Application areas

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 6.3.) Table 1, drawn from manufacturers application data, identifies typical application areas to which clamp-on TTUFs are being applied.

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

The application areas for clamp-on TTUFs, 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 pipework are too high;
- for reasons of continuity of supply, installation, maintenance or service, measurement needs to be carried out without a shut-down in the process;
- on larger pipes, the cost-benefit over other in-line meters is greatest.

Table 1 — Application areas of clamp-on TTUFs

Sector	Application
Water industry	Temporary/Semi-permanent installation Checking of installed meters; leakage determination; network analysis. Permanent installation Applications where hygiene, operation (e.g. supply interruption), maintenance and cost are of major consideration.
Oil industry	Permanent installations Used for measurement of crude oil after first stage separator; offloading of crude oil; water injection; refined oil.
Food industry	Permanent installations Blending and batching of food and drink where issues of hygiene and contamination are of major concern.
Semiconductor industry	Permanent installations Process applications of high purity and aggressive liquids where measurements can be made with a meter that can be serviced without having to shut down the process.
Chemical industry	Temporary installations Employed as a tool for checking, servicing and maintaining existing flow-meters. Permanent installations Process monitoring and control of liquids where application and maintenance can be achieved without breaking into the pipework and where meter process compatibility can be achieved by using the existing pipework; pump protection.
Miscellaneous applications	Temporary/semi permanent/permanent systems Measurement of cold and hot water flows in large building complexes such as hospitals, schools, factories and offices to monitor and control usage. Heat metering and air conditioning applications in “dirty liquids”, e.g. raw sewage.

3.4 Performance measures

TTUFs 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;
- the repeatability of the measurement; and
- the reproducibility of the measurement.

In employing these terms, it is important that they should correspond to standard usage. The following provides standard definitions of the three terms.

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

$$E = \left(\frac{V_{\text{ind}} - V_{\text{std}}}{V_{\text{std}}} \right) \times 100 \% \quad (6)$$

where

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

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

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

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-

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

and

$$s_{\text{E}} = \sqrt{\frac{\sum_{i=1}^n (E_i - \bar{E})^2}{n-1}} \quad (7)$$

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; and

n is the number of runs in the test series.

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

$$m = \frac{\sqrt{T_{\text{test set}}}}{\sqrt{T_{\text{std}}}} \quad (8)$$

where

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

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

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 TTUFs 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.

$$r = \bar{E}_1 - \bar{E}_2 \quad (9)$$

where

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

$\bar{E}_2$ 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:

$$r = 2.83s_{\text{reproducibility}}$$

where

$$s_{\text{reproducibility}} = \sqrt{\frac{\sum_{i=1}^n (\bar{E}_i - \bar{E}_{\text{all}})^2}{n-1}} \quad (10)$$

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; and

n is the number test series undertaken to assess the reproducibility. Reproducibility is generally expressed as a function of flow velocity.

3.5 Uncertainty, repeatability and reproducibility under ideal flow, pipe fluid and operational conditions

TTUFs are likely to be used over a very wide range of pipe sizes and liquids. Because the overall performance achievable in the field depends on the care with which the operators prepare the pipework 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.

The values manufacturers quote for the typical accuracy of clamp-on TTUFs range between $\pm 1\%$ to $\pm 5\%$ 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 $\pm 0.5\%$ to $\pm 2\%$ of reading, dependent on manufacturer and pipe size. Repeatabilities quoted by manufacturers typically lie in the range $\pm 0.15\%$ to $\pm 0.5\%$ of reading, depending on application.

The evidence of users on performances achieved in the field indicate that over a range of pipe and fluid conditions, the specifications provided by manufacturers might not always be achievable, although there is little hard evidence on which to base such judgements.

This standard suggests that the calibrations which have been undertaken under laboratory conditions should be taken as the basis for a judgement as to the likely performance that could be achieved in the field under operating conditions. The results obtainable in the field are unlikely to be better than the performances achieved in the laboratory under fully developed flow conditions and with extreme care being taken in the mounting and positioning of the transducers. The results obtainable under non-ideal flow conditions and poor mounting of the transducers and incorrect spacing are likely to increase the error of the measurement.

The calibrations on which estimates provided have been based are identified in Annex A of this standard. These calibrations have been undertaken over a range of pipe materials and sizes, although the majority of publicly available calibrations have been undertaken on pipe sizes greater than 50 mm. These results indicate overall that an uncertainty within $\pm 5\%$ of reading can be obtained for velocities greater than 1 m/s

for a range of pipe sizes and materials. A typical repeatability is $\pm 1\%$ of reading and reproducibility under unclamping and re-clamping conditions of $\pm 2\%$ of reading.

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 pipework 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 pipework 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 better than $\pm 1\%$ of reading are probably justifiable.

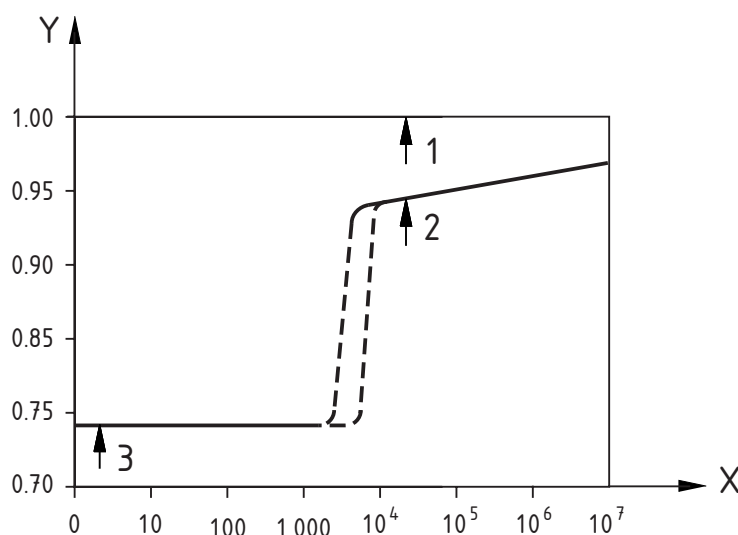
4 Installation effects

4.1 General

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 3 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. Figure 5 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.

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 pipework configurations such as bends, expansions and contractions and the presence of valves and pumps. Manufacturers often specify a requirement to have $10D$ of straight pipework upstream of the meter and $5D$ downstream of the meter. Although the downstream conditions are probably satisfactory, the upstream requirement is probably over-optimistic.



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

Figure 3 — Profile correction factor (k_h) against Reynolds number for fully developed flow in smooth pipes

4.2 Preferred installation conditions

Table 2 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 $\pm 2\%$ or $\pm 5\%$. It assumes that the flow directly upstream of the disturbance is fully developed.

The data that has been used to provide these distances is based largely on the performance of wetted sensor single beam TTUFs since it is believed that this data is more comprehensive and reliable. The reference list is in the Bibliography. They are generally consistent with the limited data that has been obtained from clamp-on TTUFs.

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

Table 2 — Installation effect upstream straight length table

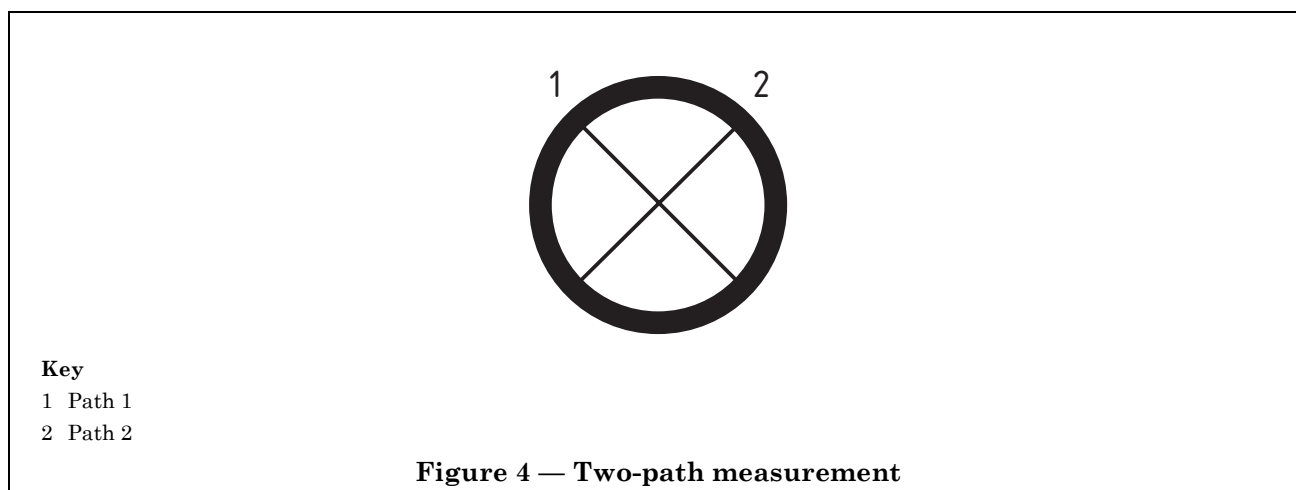
Disturbance	Straight lengths required to reduce installation effect to less than:	
	$\pm 2\%$	$\pm 5\%$
Conical contraction	$5D$	0
Conical expansion	$20D$	$5D$
Single 90° bend	$30D$	$15D$
“U” bend (Two close-coupled 90° bends)	$25D$	$10D$
Two close-coupled 90° bends in perpendicular planes	$50D$	$20D$
Butterfly valve $\frac{2}{3}$ open	$20D$	$10D$
Globe valve $\frac{2}{3}$ open	$15D$	$5D$
Gate valve $\frac{2}{3}$ open	$20D$	$5D$

4.3 Reducing the effects of disturbed flows

One 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 4 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. In the light of the limited graphical data shown in Annex D, where the majority of errors from disturbances are negative, it is suggested that the maximum reading be taken as the best estimate of the flow rate.

It should also be noted that ideally clamp-on meters should be operated in two traverse or four traverse mode i.e. with both transducers on the same side of the pipe and the ultrasound reflected off the inside of the pipe wall. These techniques minimize the effect of fluid cross flows on the overall measurement.



5 Pipework effects

5.1 Typical ranges of pipe size, pipe material, lining material and wall thickness to which the technology can be applied

Clamp-on TTUFs are required to operate over a range of pipe sizes, materials, wall thicknesses and lining materials. Particular manufacturers will claim to be able to work with particular pipe sizes, pipe materials, wall thicknesses and lining materials and not all manufacturers will be able to provide a metering system which will operate over the complete range of pipe sizes, materials, wall thicknesses and lining materials shown in Table 3.

The claim made by manufacturers is that the pipe has to be sonically conducting, although the experience of users indicate that whilst some manufacturers may 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.

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. There is evidence that, with stainless steel and GRP, some manufacturers experience difficulty in achieving adequate signal transmission. For some manufacturers, the pipe size and/or material may limit the particular mode in which the flow-meter can be operated.

Although manufacturers do not in general specify the range of pipe wall thicknesses with which their flow-meters will operate, at least one manufacturer identifies a maximum pipe wall thickness and there is evidence in small diameter pipe having thick walls that there can be significant errors. See Table 3.

Table 3 — 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 6 000 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
Lining materials and external coatings with which manufacturers claim to be able to use clamp-on TTUFs	Tar, epoxy, mortar, rubber

Several problem areas have been identified with coatings and pipe linings. Clamp-on TTUFs will only successfully 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, since air gaps will prevent successful transmission of the ultrasound.

If the meter is to be clamped on to the coating material, the thickness of the coating must 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 7.10.

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 this case, a thickness corresponding to the sum of the wall and lining thickness has to be entered, together with a speed of sound which represents a weighted average of the speed 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.