

The selection, installation, operation and calibration of diagonal path transit time ultrasonic flowmeters for industrial gas applications

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Contents

	Page
Committees responsible	Inside front cover
Foreword	ii
1 Scope	1
2 Normative references	1
3 Symbols and abbreviations	1
4 Selection	2
5 Installation recommendations	7
6 Operational consideration	11
7 Ultrasonic flowmeter certification	16
Annex A (informative) Uncertainty calculation for ultrasonic flow meters	21
Annex B (informative) Performance specification	29
Annex C (informative) Derivation and correction of flow measurement errors	32
Bibliography	35
Figure 1 — General ray geometry for transit time velocity measurement	2
Figure 2 — Intrusive a) and non-intrusive b) transducer designs	5
Figure 3 — Variations in path configuration	5
Figure 4 — Some typical cross-sectional acoustic path configurations	6
Figure 5 — Performance specification summary	12
Figure B.1 — Performance specification for class 1 meters	30
Figure B.2 — Performance specification for class 2 meters	31
Figure B.3 — Performance specification for class 3 meters	31
Figure B.4 — Performance specification for class 4 meters	32
Figure C.1 — Un-corrected and WME-corrected flow calibration data plot for 200 mm diameter USM	34
Table 1 — USM Classification	6
Table 2 — Installation criteria	7
Table 3 — Internal diameter tolerances	17
Table 4 — Uncertainty tolerances for beam path lengths	17
Table 5 — Nominal test flow rates	20
Table C.1 — Flow calibration data table for 200 mm diameter USM	33
Table C.2 — Flow weighted mean error calculation summary for 200 mm diameter USM	33
Table C.3 — “WME-corrected” flow calibration data summary for a 200 mm diameter USM	34

Foreword

This British Standard has been prepared by Subcommittee CPI/30/5/1. This is a new standard, and no other standard is superseded or withdrawn.

As a guide, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification and particular care should be taken to ensure that claims of compliance are not misleading.

Annexes A, B and C are informative.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 35 and a back cover.

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1 Scope

This British Standard provides guidance on the selection, installation, operation and calibration of diagonal path transit time gas ultrasonic flowmeters (USMs) for industrial gas applications

It is applicable only to those devices in which the entire gas stream flows through the body of the USM and the transducers are in contact with the fluid (wetted or invasive type). This includes both full-bore and insertion type meters employing direct or reflective paths. It is also applicable to “dirty gases” i.e. where the gas is contaminated with solids and/or liquids in small quantities.

It is not applicable to clamp-on/externally mounted meters.

NOTE As an aid to selection, this standard incorporates an uncertainty classification for USMs. This takes into account the components of uncertainty relating to the meter plus those additional uncertainties associated with installation and operation effects. There are four classifications offered. These range from high accuracy “fiscal” applications (class 1) to general-purpose process flow indication and control applications (class 4).

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this British Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the latest edition of the publication referred to applies.

BS 7834, *Specification for turbine meters used for the measurement of gas flow in closed conduits*.

BS EN 50081-1, *Electromagnetic compatibility — Generic emission standard — Part 1: Residential, commercial and light industry*.

BS EN 50082-2, *Electromagnetic compatibility — Generic immunity standard — Part 2: Industrial environment*.

BS EN ISO 5167-1, *Measurement of fluid flow by means of pressure differential devices — Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full*.

BS ISO TR 12765, *Measurement of fluid flow in closed conduits — Methods using transit-time ultrasonic flow-meters*.

ASTM E 1002-93, *The American Society for Testing Materials, Electrical Insulation and Electronics, Volume 10.02*.

3 Symbols and abbreviations

Symbol	Meaning	Units
A	cross-sectional area of meter body	m ²
C_f	velocity of sound in a fluid	m/s
D	diameter of meter spool	m
E_i	indicated flow rate error in percent	(%)
F	single calibration factor	—
f_r	frequency	Hz
f_i	variable weighting factor for i th velocity path	—
k_h	velocity distribution factor	—
k_r	uniform equivalent roughness	m
K	meter factor	—
L	acoustic path length between 2 ultrasonic transducers	m
Mol %	mole percentage	—
mA	current in milli-amps	milli-amps
P	absolute static pressure of gas	Bar
$q_{\max}$	maximum volumetric flow rate of meter	m ³ /s
$q_{\min}$	minimum volumetric flow rate of meter	m ³ /s
q_t	transitional volumetric flow rate of meter where meter performance increases significantly	m ³ /s
q_v	volumetric flow rate	m ³ /s
R_a	roughness profile of meter bore	m
T	temperature of fluid	°C
t_{ab}	transit time for ultrasound to travel from transducer a to transducer b	s
t_{ba}	transit time for ultrasound to travel from transducer b to transducer a	s
Δt	$t_{ba} - t_{ab}$	s

Symbol	Meaning	Units
$\bar{t}$	mean of t_{ab} and t_{ba}	s
v_i	averaged axial component of velocity along the path between two transducers	m/s
$\bar{v}$	mean pipe velocity	m/s
V	voltage	volts
w_i	constant weighting factor for i th velocity path	—
x	distance between transducers in the axial plane	m
Z	compressibility of fluid	—
θ	angle between the direction of ultrasound and the axis of the pipe	deg
AC	alternating current	—
ACFH	actual cubic feet per hour	—
DC	direct current	—
ppm	parts per million	—
SNR	signal to noise ratio	—
VOS	velocity of sound	—
SPU	signal processing unit	—
USM	ultrasonic flowmeter	—
WME	weighted mean error	—

4 Selection

There are a number of USMs currently in service and under development. This clause aims to present a generic overview of the meters available and offer guidance as to their selection for specific applications.

4.1 Principle of measurement

USMs are based on the measurement of the propagation time of acoustic waves in a flowing medium. Generally, the assertion that the apparent velocity along a path is given by the velocity of sound in the fluid at rest (C_f) plus the averaged axial component of fluid velocity along the path between the transducers (v_i) is applied. To eliminate the velocity of sound from the subsequent derivation, transit times are determined both in the direction of flow and against it. Considering the general ray geometry shown in Figure 1, the upstream and downstream transit times are given by the following equations:

$$t_{ab} = \frac{L}{(C_f + v_i \cos\theta)} \text{ and } t_{ba} = \frac{L}{(C_f - v_i \cos\theta)} \tag{1}$$

There are four basic methods by which transit time velocity measurement is performed: direct time differential, phase differential, phase control, and frequency differential (see ISO TR 12765). In modern ultrasonic flowmeters the direct time differential method is most common. Short pulses are propagated upstream and downstream and the time interval for each excitation/detection is measured against an accurate high-frequency clock. In this case, the expressions for the upstream and downstream transit times are then solved for v_i as follows:

$$\frac{1}{t_{ab}} - \frac{1}{t_{ba}} = \frac{(C_f + v_i \cos\theta) - (C_f - v_i \cos\theta)}{L} \tag{2}$$

$$v_i = \frac{L}{2\cos\theta} \times \frac{1}{t_{ab}} \times \frac{1}{t_{ba}} = \frac{L}{2\cos\theta} \times \frac{\Delta t}{t_{ab} t_{ba}} = \frac{L^2}{2x} \times \frac{\Delta t}{t_{ab} t_{ba}} \tag{3}$$

where

$$\cos\theta = x/L$$

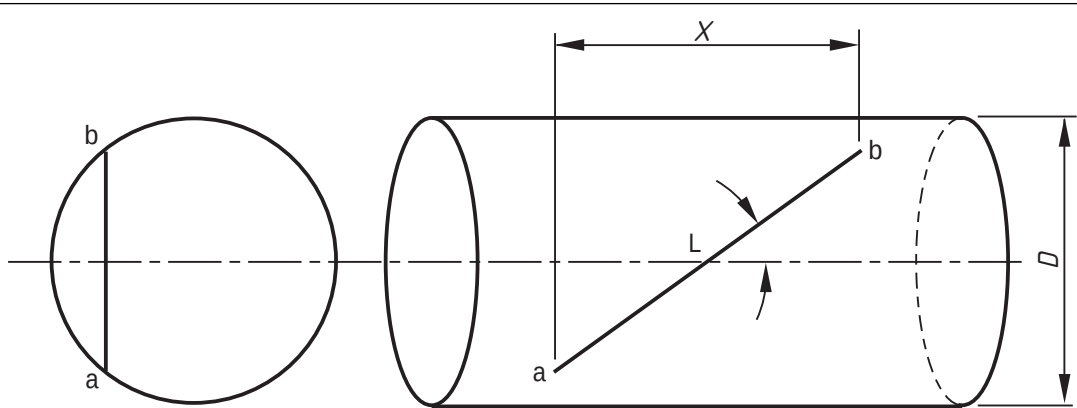


Figure 1 — General ray geometry for transit time velocity measurement

To obtain the volumetric flow rate (q_v), individual velocity measurements are combined by a mathematical function to yield an estimate of the mean pipe velocity and multiplied by the cross-sectional area of the measurement section, A , as follows:

$$q_v = A\bar{v} \quad (4)$$

where

$$\bar{v}_1 = f(v_1, \dots, v_n); \quad (5)$$

n is the total number of paths. Even for a given number of paths, the exact form of $f(v_1, \dots, v_n)$ differs due to variations in path configuration and different proprietary approaches to solving equation 5 (see 4.3).

4.2 Factors affecting performance

The performance of a USM is dependent on a number of intrinsic and extrinsic factors.

Intrinsic factors (i.e. those related to the meter and its calibration prior to delivery) include the following:

- the geometry of the meter body and ultrasonic transducer locations and the uncertainty with which these are known;
- the accuracy and quality of the transducers and electronic components used in the transit time measurement circuitry (e.g. the electronic clock stability);
- the techniques utilized for transit time detection and computation of mean velocity (the latter of which determines the sensitivity of the meter to variations in the flow velocity distribution);
- calibration (including proper compensation for signal delays in electronic components and transducers).

Extrinsic factors (i.e. those related to the flow and environmental conditions of the application) include the following:

- flow velocity profile;
- temperature distribution;
- flow pulsation;
- gas composition;
- impurities in the gas;
- noise (acoustic);
- solid and liquid contamination.

4.3 Description of generic types

4.3.1 General

This sub-clause is a generic description of USMs for gases. It recognizes the scope for variation within commercial designs and the potential for new developments. For the purpose of description, ultrasonic meters are considered to be comprised of several components, namely:

- transducers;
- meter spool (and acoustic path configuration);
- front-end electronics;
- data processing and presentation unit.

4.3.2 Transducers

Transducers can be supplied in various forms. Typically they comprise a piezoelectric element with electrode connections and a supporting mechanical structure with which the process connection is made. The process connection may be welded, flanged, or threaded or may be more mechanically complex, for example, to allow removal of transducers from a pressurised line. When inserted in the line, the active element will transmit ultrasonic waves at an angle to the meter spool axis in the direction of a second transducer or reflection point in the meter spool interior. The active element is usually isolated from the fluid by a mechanical barrier.

For specific applications special transducers can be required. These can differ from the norm in terms of frequency, construction materials and mechanical arrangement. Transducer specification and mounting should be given careful consideration for extreme or difficult application conditions such as the following:

- high temperature;
- high and low pressure;
- rapid or cyclic temperature or pressure changes;
- corrosion/erosion;
- wet or “dirty” gas.

Two general examples of transducer design are depicted in Figure 2.

4.3.3 Meter spool and acoustic path configurations

4.3.3.1 General

The meter spool is a conduit comprising two or more ultrasonic transducers. An acoustic path is the transmission link between two transducers through the flowing fluid. USMs are available in a variety of path configurations. A particular configuration is generally chosen based on a requirement with respect to variations in velocity distribution (see annex C).

As well as variations in the chordal location of the measurement paths in the cross-section, the path configuration can be varied in orientation to the pipe axis. By utilizing reflection of the ultrasonic wave from the interior of the meter spool or from a fabricated reflector, the path can traverse the cross-section several times.

4.3.3.2 Elementary acoustic paths

Elementary acoustic paths are illustrated in Figure 3. The number of traverses and three-dimensional geometry of each traverse describe an arbitrary path. Crossed paths or double traverses in a single plane are essentially insensitive to non-axial velocity components. Other configurations (such as the triple traverse) may be sensitive to non-axial components but can be used in combination to eliminate the effects of swirl and cross-flow under certain conditions.

4.3.3.3 Common cross-sectional configurations

The cross-sectional configuration is important as this dictates what information about the axial velocity distribution is available for computation of the mean axial velocity. A selection of commonly encountered cross-sectional configurations are shown in Figure 4.

4.3.3.4 Meters with paths of equal radial displacement

Meters with beams of equal radial displacement (e.g. A, B and C in Figure 4) essentially make the same measurement with respect to velocity distribution if the flow is axisymmetric, regardless of the number of paths employed. For this reason, the mean velocity is usually determined by simple average. In fully developed flow a theoretical correction factor, k_h , can be introduced to account for the known variation in velocity profile.

$$\bar{v} = k_h \frac{\sum_{i=1}^n v_i}{n} \quad (6)$$

where

n is the total number of paths.

The k_h factor is a function of Reynolds number, pipe roughness and radial displacement. In practice it can be input as a single constant or may be calculated on the basis of static parameters and/or measured variables.

4.3.3.5 Meters with paths at multiple radial displacements

In the case of these meters (e.g. configurations D and E in Figure 4) the velocity is measured at different radial positions. Several methods can be used when combining the velocities to obtain the mean pipe velocity. These can be classified as follows.

1) Summation with constant weighting:

$$\bar{v} = \sum_{i=1}^n w_i v_i \quad (7)$$

where the radial displacements of the paths and the constants w_i to w_n are determined on the basis of documented numerical integration methods; or

2) Summation with variable weighting:

$$\bar{v} = \sum_{i=1}^n f_i v_i \quad (8)$$

where the radial displacements of the paths are fixed at design and the variables f_i to f_n may be determined from input parameters and/or measured variables (e.g. velocities). To allow analysis of the sensitivity of this meter design to velocity profile, the function used to determine f_i should be documented by the manufacturer.

In any of the given configurations a multiplying or meter factor K (either constant or variable) may be applied after summation to correct for deviations due to manufacturing tolerances and/or incomplete assumptions, i.e.

$$q_v = KA\bar{v} \quad (9)$$

4.4 Criteria for selection

The aim of this sub-clause is to aid the user in making a meter selection based on the overall uncertainty required for the measurement. This process involves dividing the meters available into essentially four classes of performance as outlined in Table 1.

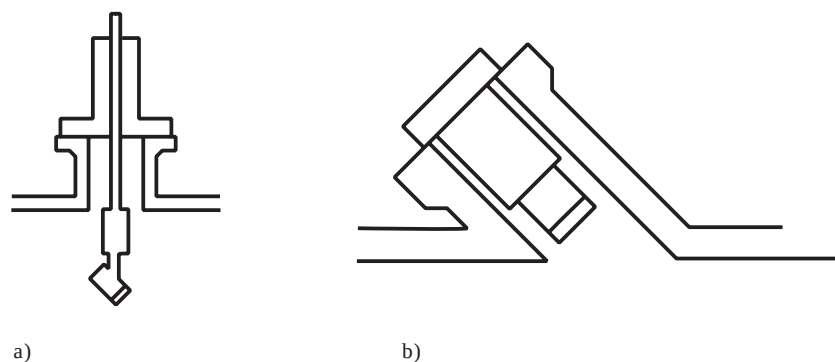


Figure 2 — Intrusive a) and non-intrusive b) transducer designs

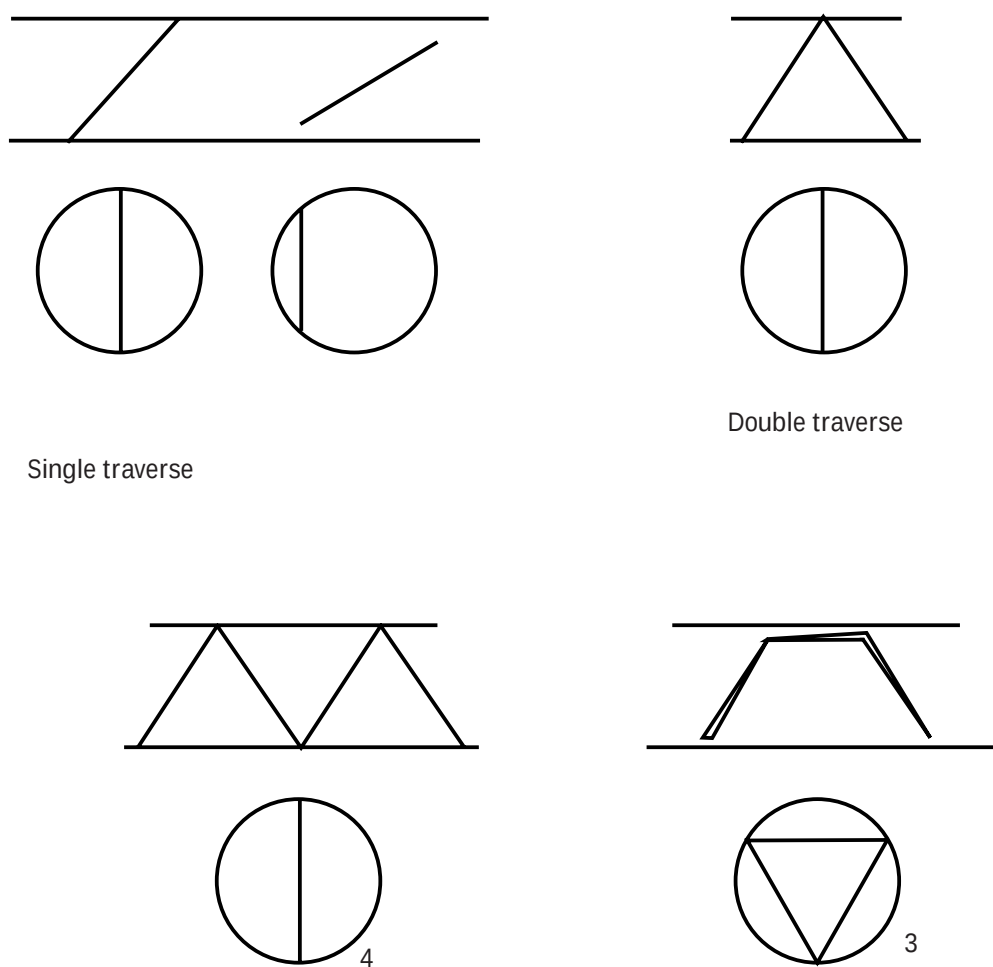


Figure 3 — Variations in path configuration

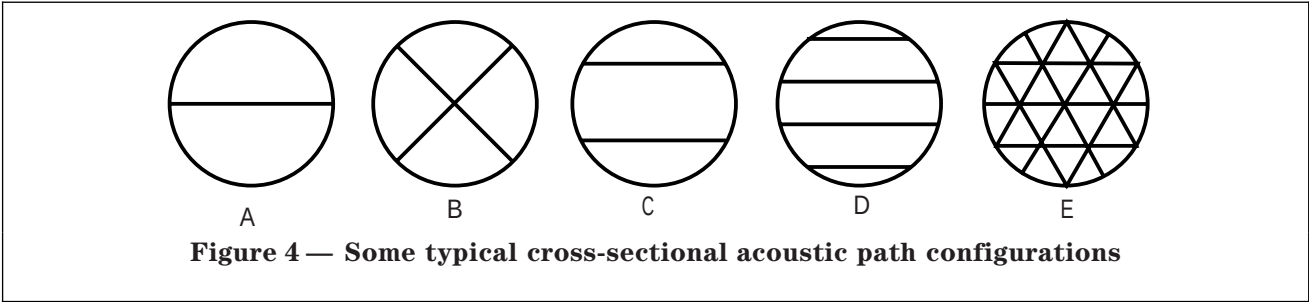


Figure 4 — Some typical cross-sectional acoustic path configurations

Table 1 — USM Classification

Class	Applications	System uncertainty (mass flow)	Total USM uncertainty (actual volume flow) ^a	Repeatability	Resolution	Maximum peak to peak error
1	Custody transfer/ fiscal measurement	< ±1.0 %	< ±0.7 %	< 0.20 %	< 1 mm/s	0.7 %
2	Allocation	< ±2.0 %	< ±1.5 %	< 0.25 %	< 2 mm/s	1.0 %
3	Utilities/fuel gas	< ±4.0 %	< ±3.0 %	< 0.35 %	< 4 mm/s	1.5 %
4	Process/flare gas	< ±10.0 %	< ±7.5 %	< 0.50 %	< 10 mm/s	3.0 %

^a The total uncertainty for the USM is the summation in quadrature of all intrinsic and extrinsic factors. The factors are defined in 4.2.

The four classes represent different measurement specifications commonly applied in UK industry. Depending on the importance of measurement with respect to regulatory or fiscal demands, the total uncertainty budget for the system will be different. To aid the user in meter selection, an approximate uncertainty budget for the meter is suggested in order to meet the system uncertainty budget. A significant part of the total value for the USM uncertainty comes from the uncertainty of the calibration facility where the meter was flow calibrated. Typical uncertainty values from recognized gas flow calibration establishments are in the order of ±0.3 %.

NOTE It should be noted that these applications are for guidance only — each application should be considered on its own merits.

The difference between the uncertainty figures of the meter and the system indicates the uncertainty budget permitted in determining additional uncertainties associated with the metering process e.g. secondary instrumentation, derivation of density and flow computers. For example the composition, pressure and temperature of a gas may result in an uncertainty value for the derivation of density that causes the budget available for the system to be exceeded. For these reasons it is important that this aspect is not neglected. For natural gas, A. G. A. Report No. 8 gives guidance on the derivation of density and uncertainty. One method of calculating and presenting a system uncertainty budget is presented in annex A.

Table 2 gives example installation criteria that a user should take into account. These examples are not exhaustive and should be applied in conjunction with the rest of this British Standard.

Table 2 — Installation criteria

Number of velocity measuring paths	Minimum upstream straight pipe requirements	Downstream straight pipe requirements
≥ 4	$\geq 10 D$	$\geq 3 D$
≥ 2	$\geq 20 D$ or $\geq 10 D$ with flow conditioner	$\geq 5 D$
≥ 1	$\geq 20 D$ or $\geq 10 D$ with flow conditioner	$\geq 5 D$

When identifying a meter for a particular purpose, it is important for the user to have access to the information outlined in Tables 1 and 2. The information should be available from the meter manufacturer and it is recommended that the user reviews actual test data regarding the meter performance when purchasing for the first time or from a new supplier or manufacturer.

Other criteria for selection may be determined by the regulatory or statutory bodies, such as the DTI Oil and Gas Office, and also agreements between companies for custody transfer/allocation metering. USMs have a large potential advantage over other forms of flowmeter owing to the availability of diagnostic software. This means that not only is a measurement made, but also information is gathered regarding the measurement process and the fluid itself. This can in turn allow for further criteria for selection. For example the accuracy of measurement in the event of a chord failure is important in many custody transfer applications. For most other forms of flowmeter a major failure in the measurement process would lead to a complete shutdown while the meter is replaced. In the event of a chord failure with USMs it is possible for some meters to substitute values in place of the failed chord measurements from knowledge of the velocity profile present in the meter prior to the failure. For class 1 meters, the additional error owing to a chord failure should be less than 0.1 % assuming no significant change to the process conditions.

An alternative approach to the derivation of a performance specification for USMs is presented, for information purposes, in annex B.

5 Installation recommendations

5.1 General

The statements contained in this sub-clause have been derived from comparable meter standards, good engineering practice and experience gained to date in the testing of these meters.

Installation criteria should be considered in conjunction with specific recommendations from outside agencies such as the meter manufacturers, the statutory authorities and other interested parties.

5.2 Environmental considerations

5.2.1 Temperature

Some USMs may be sensitive to differences between ambient and line temperature and adequate insulation, heating and/or cooling should be provided in order to minimize the effects of extremes in ambient temperature.

The ambient air temperature range should, as a minimum, be -25°C to 65°C . This temperature range applies to the meter body with and without gas flow, field mounted electronics, ultrasonic transducers, cabling, etc. The manufacturers should provide ambient temperature specifications for the USMs if different from the above.

For class 1 and 2 applications, where optimum accuracy is required or the gas temperature varies from the ambient temperature, the meter spool and the meter tube assembly including the upstream and downstream pipework should be fully insulated. This insulation should extend up to and include the thermowell housing of the temperature element and also any intermediate flanges and fittings.

Sudden large changes in temperature caused for example by compressors “kicking-in” or close proximity to a flare stack should be avoided. It is also important to insulate the meter spool when there is a deep cavity between the inner pipewall and the transducer fronts.

5.2.2 Vibration

USMs should not be installed where vibration levels can interfere with the operation of the meter. The manufacturer should be consulted regarding the performance of the meter in a vibrating environment.

5.2.3 Electrical noise

Good wiring practice should be implemented to minimize the effect of electrical noise. Any equipment operated in the EU has to meet EMC-RF requirements including those contained within EN 50081-1 and EN 50082-2.

The meter and associated electrical conduits, cables and circuits should be designed and installed in accordance with applicable electrical codes. Particular care needs to be taken for the type of screening and routing of interconnecting cable installed between the transducers and the control unit. Again reference should be made to the manufacturer's recommendations.

5.2.4 Mechanical noise

Some installations, including for example pressure reducing control valves, which are specifically designed to reduce audible noise, can produce very high levels of ultrasonic noise under certain flow conditions (even when the valve is located downstream of the USM). The ultrasonic noise from these “quiet” control valves can interfere with the operation of a nearby ultrasonic flowmeter. The manufacturer should be consulted when planning to install a USM in the vicinity of a pressure-reducing component including control valves, reducers, etc.

If acoustic noise is considered to be a potential problem for the USM in service then a means should be provided to monitor its impact on the meter using the signal to noise ratio (SNR). An alarm facility can be needed to advise the operator when the ratio exceeds an acceptable level.

In general it is good practice to locate control valves, compressors, etc. downstream of the USM. If this is not possible then the maximum distance between the control valve and the USM should be targeted. The use of blind tees, baffles and other such fittings, which provide high attenuation, should be fitted between any source of noise and the USM. This precaution should be taken for both downstream and upstream sources of noise. These devices should be fitted at the maximum distance from the USM that the pipework allows given that some of them can and will produce distorted velocity profiles.

5.2.5 Gas composition restrictions

The presence of some components in the gas can impact on the performance of a meter. In particular, high levels of CO₂ in a gas mixture can influence and even inhibit the operation of a USM owing to its acoustic absorption properties.

Manufacturers should be consulted for details of the maximum Mol % of any component in the gas that can influence the performance of the meter and if any of the following are expected:

- carbon dioxide levels above 10 %;
- operation near the critical density of the natural gas mixture; or
- total sulfur mass fraction exceeds 3.2×10^{-4} including mercaptans, H₂S and elemental sulfur compounds.

5.3 Installation conditions

5.3.1 Flow direction

Where the flow is in one direction only this should be clearly marked on the body of the meter. For bi-directional applications, both ends of the USM should be considered upstream and a plate attached to the meter spool clearly indicating the normal or forward flow direction.

5.3.2 Upstream and downstream fittings

Various combinations of upstream fittings (valves, bends, expanders, tees, reducers, etc.) can produce velocity profile distortions and swirl at the inlet to the USM that can result in measurement error. The magnitude of error is dependent on the type and severity of the flow distortion and the ability of the USM to compensate for this distortion. To a much lesser extent, downstream fittings can also affect the accuracy of the meter.

The manufacturer should be consulted to evaluate how upstream and/or downstream fittings and piping configurations can affect the performance of the USM. In the absence of performance data for a specific installation a flow-conditioning device should be considered (see 5.5.1). In this case it can be necessary to model the system by mathematical or experimental means in order to determine its impact on the USM.

The general configuration of the pipework upstream of the meter tube assembly and the self-compensating features associated with the USM should be taken into account when assessing the potential impact of pipe geometry on the velocity profile of the gas. In any event, for class 1 applications the meters should only be installed where the impact of fittings and pipe-work configurations does not have a measurable effect on the performance of the meter. In all circumstances the pipework should be designed so that swirl or poor velocity profiles that affect the uncertainty of the meter reading are not produced i.e. that these effects are within the manufacturer's stated limits for the meter. This is often verifiable at site by USM on-board diagnostics.

To ensure that the USM, when installed in the user's piping system, will perform within the specified flow rate measurement accuracy limits, good metering practice should be followed. The manufacturer should do one of the following as desired by the user.

- 1) Recommend at least one upstream and downstream piping configuration, without a flow conditioner and one configuration with a flow conditioner that will not create an additional flow rate measurement error of more than $\pm 0.3\%$ due to the installation configuration. This error limit should apply for any gas flow rate between $q_{\min}$ and $q_{\max}$. This recommendation should be supported by test data.
- 2) Specify the maximum allowable flow disturbance (e.g. the limits on swirl angle, velocity profile asymmetry, turbulence intensity) at the meter's upstream flange, or at some specified axial distance upstream of the meter, that will not create an additional flow rate measurement error of more than $\pm 0.3\%$ due to the installation configuration. This error limit should apply for any gas flow rate between $q_{\min}$ and $q_{\max}$. This recommendation should be supported by test data.