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

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This document comprises a front cover, an inside front cover, pages i to ii, pages 1 to 68, an inside back cover and a back cover.

Foreword

Publishing information

This British Standard is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 31 October 2013. 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This British Standard supersedes BS 7965:2009, which is withdrawn.

Information about this document

This is a full revision of the standard, and introduces the following principal changes:

- further division of meter sizes into large, medium and small to incorporate meter sizes with a nominal bore <4 inches;
- meters that are not standard in line meters, such as cartridge type meters;
- where appropriate, the standard is aligned with revisions made to other USM documents such as AGA Report No. 9 [1] and BS ISO 17089-1, taking account of results from research and development projects and end-user experience;
- updated in the light of research and user experience since 2009;
- includes a new section covering condition-based maintenance.

Hazard warnings

CAUTION: High gas velocities can cause flow-induced thermowell vibration, which could result in catastrophic metal fatigue failure of the thermowell.

CAUTION: The use of extractor tools to extract ultrasonic transducers without depressurization should only be undertaken by competent personnel.

Use of this document

As a guide, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice and claims of compliance cannot be made to it.

Presentational conventions

The guidance in this standard is presented in roman (i.e. upright) type. Any 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.

1 Scope

This British Standard gives recommendations and guidance on the selection, installation, operation and calibration of transit time ultrasonic flowmeters (USMs) for industrial gas applications (including flare gas).

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

It is not applicable to clamp-on/externally mounted, domestic or stack/chimney (combustion exhaust) meters.

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 applications (Class 1) to process flow indication and control applications (Class 4).

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

Standards publications

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

BS EN ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

BS ISO 20765-1:2005, *Natural gas – Calculation of thermodynamic properties – Part 1: Gas phase properties for transmission and distribution applications*

BS ISO/TR 12765:1998, *Measurement of fluid flow in closed circuits – Methods using transit-time ultrasonic flowmeters*

Other publications

[N1] AMERICAN SOCIETY FOR TESTING AND MATERIALS. *ASTM E1002-11, Standard practice for leaks using ultrasonics, Book of Standard Volume 03.03*. [1]

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[1] Available from <http://www.astm.org/Standard/index.shtml> [last viewed 14 October 2013].

3 Symbols and abbreviations

For the purposes of this British Standard, the following symbols and abbreviations apply.

Table 1 **Symbols and abbreviations**

Symbol	Meaning	Units
A	cross-sectional area of meter body	m^2
C_f	speed of sound in a fluid	m/s
CI	confidence interval	—
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	theoretical correction factor	—
k_r	uniform equivalent roughness	mm
K	meter factor typically the ratio of reference/meter flows	–
l	acoustic path length between two ultrasonic transducers	M
mA	current in milli-amps	mA
P	absolute static pressure of gas	bar
q_i	flow rate	m^3/s
q_{max}	maximum volumetric flowrate of meter	m^3/s
q_{min}	minimum volumetric flowrate of meter, as specified by the manufacturer, as being the flowrate below which the expanded error limit for the meter class is exceeded.	m^3/s
q_t	transitional volumetric flowrate where the specified performance of the meter changes	m^3/s
q_v	volumetric flow rate	m^3/s
R_a	arithmetic mean deviation of the (roughness) profile	μm
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
USM_{tol}	predetermined tolerance	%
Δt	$t_{ba} - t_{ab}$	s
$\bar{t}$	mean of t_{ab} and t_{ba}	s
τt	average transducer/electronic delay time.	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	V
w_i	constant weighting factor for *i*th velocity path	—
Wf_i	flow rate weighting factor	—
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	°
a.c.	alternating current	A
d.c.	direct current	A

Table 1 **Symbols and abbreviations**

AGC	automatic gain control	—
CBM	Condition-based maintenance	—
CFD	Computational fluid dynamics	—
EU-ETS	European Union Emissions Trading Scheme	—
FWME	flow weighted mean error	—
LDA	Laser–Doppler Anemometry	—
MSOS	measured speed of sound	—
PTZ	pressure, temperature and compressibility	—
SOS	speed of sound	m/s
SNR	signal-to-noise ratio	—
SPU	signal processing unit	—
TSOS	theoretical speed of sound	—
USM	ultrasonic flowmeter	—
USMP	USM package, including meter, meter tubes, flow conditioner and thermowell	—
WME	weighted mean error	—

4 Selection

*COMMENTARY ON CLAUSE **4***

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 Principles of measurement

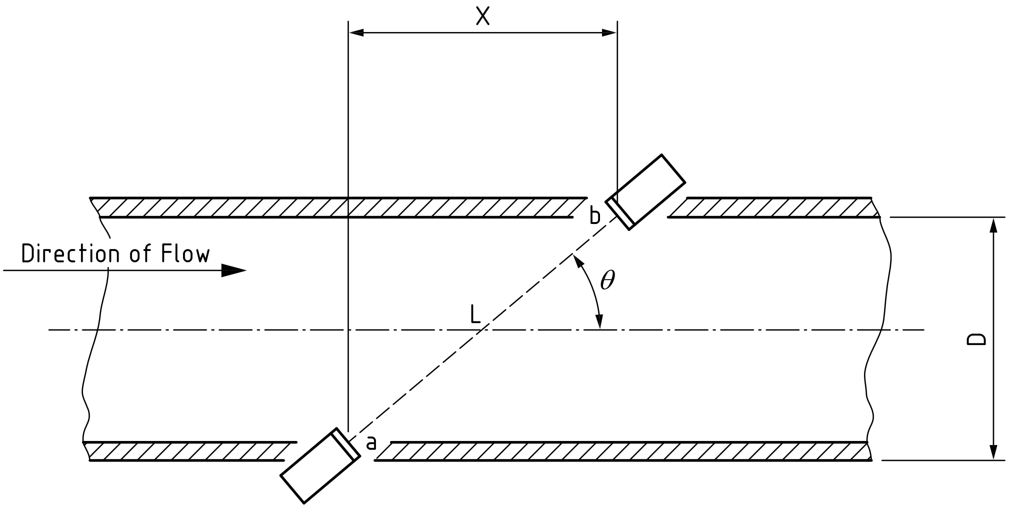
4.1.1 Gas velocity

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 speed 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 speed 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:

$$\mathrm{t}_{ab} = \frac{\mathrm{L}}{\left(\mathrm{C}_f + \mathrm{v}_i \cos\theta\right)} \tag{1}$$

$$\mathrm{t}_{ba} = \frac{\mathrm{L}}{\left(\mathrm{C}_f - \mathrm{v}_i \cos\theta\right)} \tag{2}$$

Figure 1 **General ray geometry for transit time velocity measurement**



Key

X	Distance between transducers in the axial plane	θ	Angle between direction of ultrasound path and axis of pipe
D	Diameter of meter spool	a	Transducer (upstream)
L	Acoustic path length between two ultrasonic transducers	b	Transducer (downstream)

There are four basic methods by which transit time velocity measurement can be performed: direct time differential, phase differential, phase control, and frequency differential as defined in BS ISO/TR 12765:1998, Clause **3** and Clause **5**. 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:

$$\frac{1}{t_{ab}} - \frac{1}{t_{ba}} = \frac{(C_f + v_i\cos\theta) - (C_f - v_i\cos\theta)}{L} \tag{3}$$

$$v_i = \frac{L}{2\cos\theta} \times \left(\frac{1}{t_{ab}} - \frac{1}{t_{ba}}\right) = \frac{L}{2\cos\theta} \times \frac{\Delta t}{t_{ab}t_{ba}} = \frac{L^2}{2X} \times \frac{\Delta t}{t_{ab}t_{ba}} \tag{4}$$

Where:

$$\cos\theta = X/L$$

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:

$$q_v = A\bar{v} \tag{5}$$

Where:

$$\bar{v} = f(v_1, \ldots, v_n) \tag{6}$$

Where:

n is the total number of paths.

Even for a given number of paths, the exact form of

$$\bar{v} = f(v_1, \ldots, v_n)$$

differs due to variations in path configuration and different proprietary approaches to solving Equation 6 (see **4.3**).

4.1.2 Density/molecular weight

The dynamically measured average speed of sound, after correcting for pressure and temperature, or possibly some other disruptive variables, suffices to determine the molecular weight and density of the flowing medium.

An alternative indirect mass method is to enter a fixed static density into an ultrasonic flow meter that assumes a well defined and constant gas composition.

The dynamic function is often employed in flare gas mass flow measurement. The accuracy of density determination is generally stated by manufacturers as better than 2.0%; a value that can be improved upon if the composition of the flare gas is well defined and relatively constant. An example of a disruptive variable for a flare gas measurement is that of nitrogen as a non-hydrocarbon.

The determination of density from speed of sound measurement, in an ultrasonic flow meter, has been demonstrated as capable of matching traditional vibrating tube densitometers when employed on single component, ultra-pure fluids such as Ethylene.

Determination of molecular weight of flare gas may be employed in identifying specific flare gas sources in common flare gas headers such as in an oil refinery or petro-chemical complex. Specific molecular weights or changes from the average molecular weight can signal and help identify leakages into the flare gas stream from passing relief valve systems.

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, as applicable to the class of meter, prior to delivery) include the:

- geometry of the meter body and ultrasonic transducer locations and the uncertainty with which these are known;
- accuracy and quality of the transducers and electronic components used in the transit time measurement circuitry (e.g. the electronic clock stability);
- techniques used 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 applicable to the class of meter (for static calibrations this includes proper compensation for signal delays in electronic components and transducers);
- thermal expansion coefficient of the meter body;
- pressure coefficient of the meter body.

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

- flow velocity profile;
- temperature distribution;
- flow pulsation;
- gas composition;

- noise (acoustic and electromagnetic);
- solid and liquid contamination;
- impurities in the gas.

4.3 Description of generic types

4.3.1 General

This subclause 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 consist of several components, namely:

- transducers, see **4.3.2**;
- meter spool (and acoustic path configuration), see **4.3.3**;
- electronics, data processing and presentation unit(s), see **6.5**.

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 can be welded, flanged or threaded, or can be more mechanically complex, for example, to allow removal of transducers from a pressurized line. When inserted in the line, the active element transmits 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 might be needed to cope with the conditions detailed below. These special transducers 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:

- high gas flow velocities;
- high, low and/or rapid cyclic temperature;
- high, low and/or rapid cyclic pressure;
- corrosion/erosion;
- wet or "dirty" gas;
- close proximity to high ultrasonic noise sources;
- the gas composition.

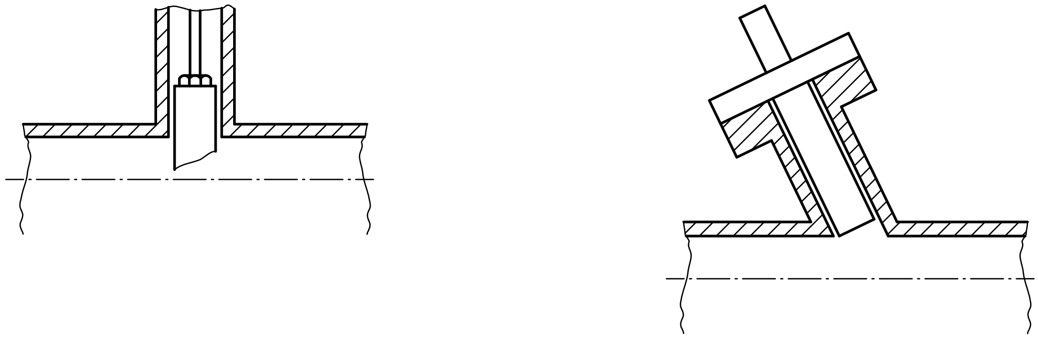
Two general examples of transducer design are depicted in Figure 2.

4.3.3 Meter spool and acoustic path configurations

4.3.3.1 General

The meter spool is a conduit comprising one or more pairs of 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 and/or built in redundancy requirements.

Figure 2 **Transducer designs**



a) Intrusive b) Non-intrusive

As well as variations in the location of the measurement paths in the cross-section, the path configuration can be varied in orientation to the pipe axis. By using 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.

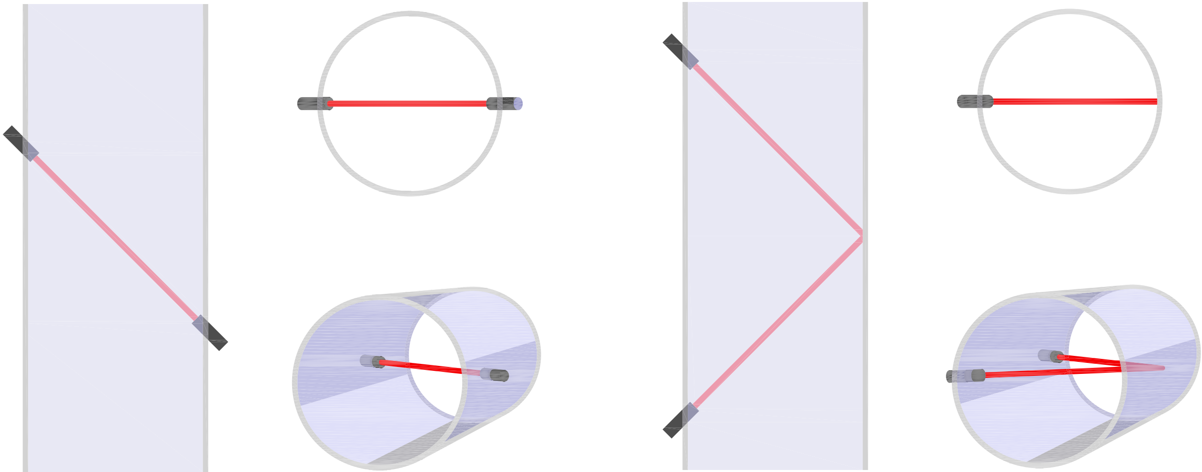
4.3.3.2 Elementary acoustic paths

Elementary acoustic paths are illustrated in Figure 3. The number of traverses and three-dimensional geometry of each traverse describe an arbitrary path.

Certain path configurations might offer reduced susceptibility to disturbed flow profiles. Claims for any such reduced susceptibility will need to have been demonstrated by the manufacturer with appropriate supporting test data.

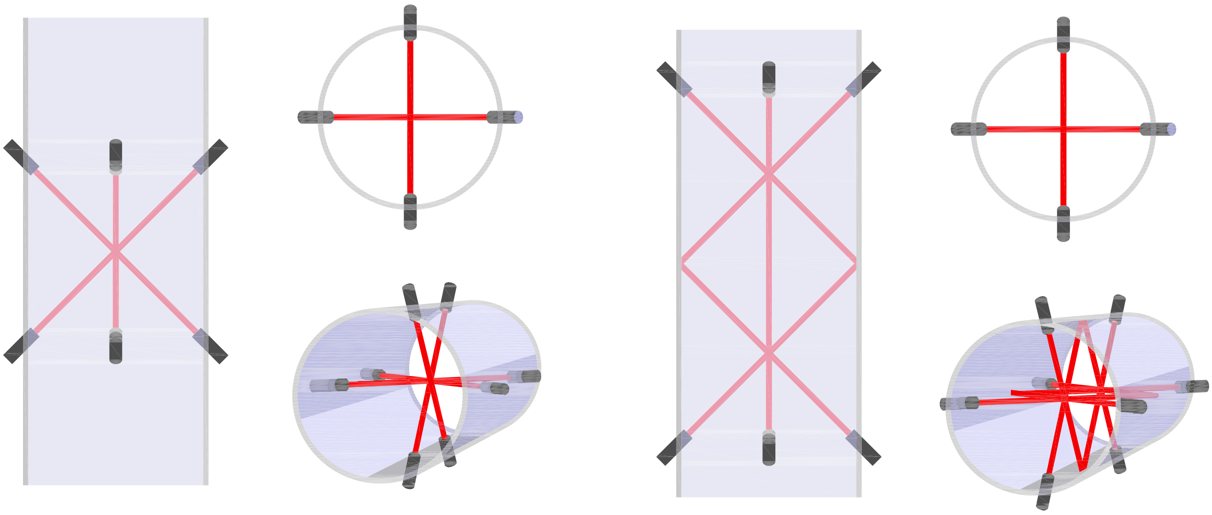
In some specific applications the path length may be reduced, e.g. flare gas meters.

Figure 3 **Variations in path configuration**



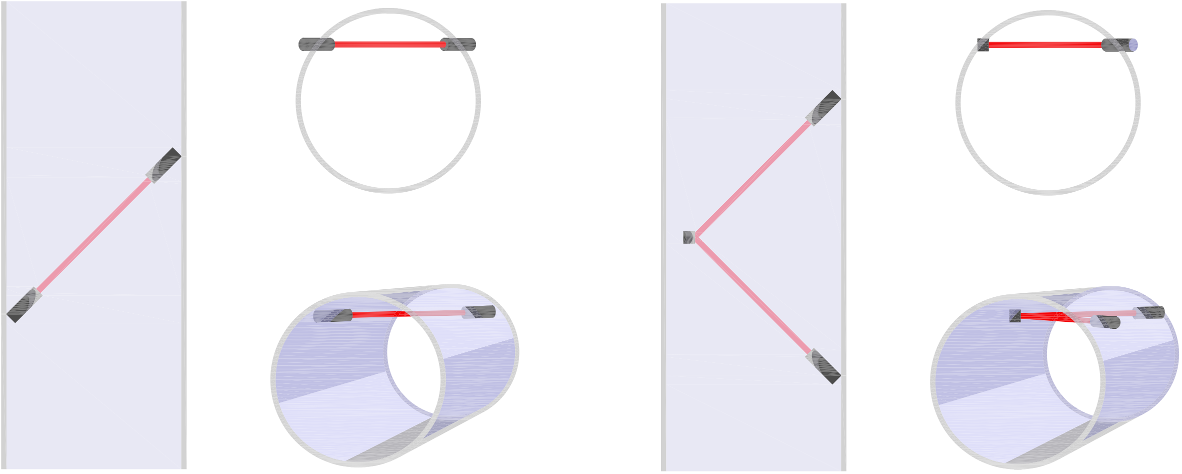
a) Diametric single path

b) Diametric single path reflective



c) Diametric multi-path

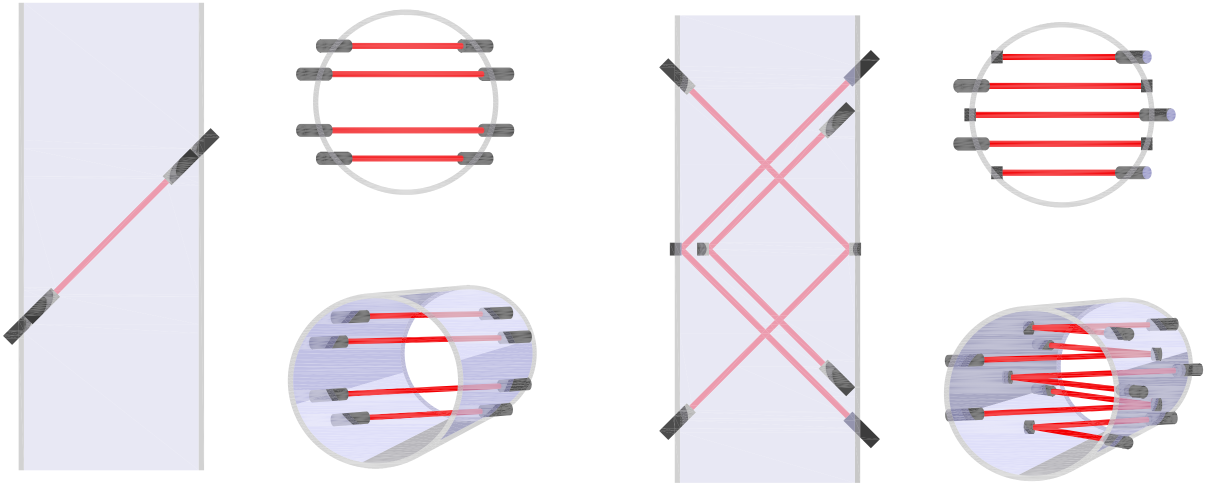
d) Diametric multi-path reflective



e) Single path chordal

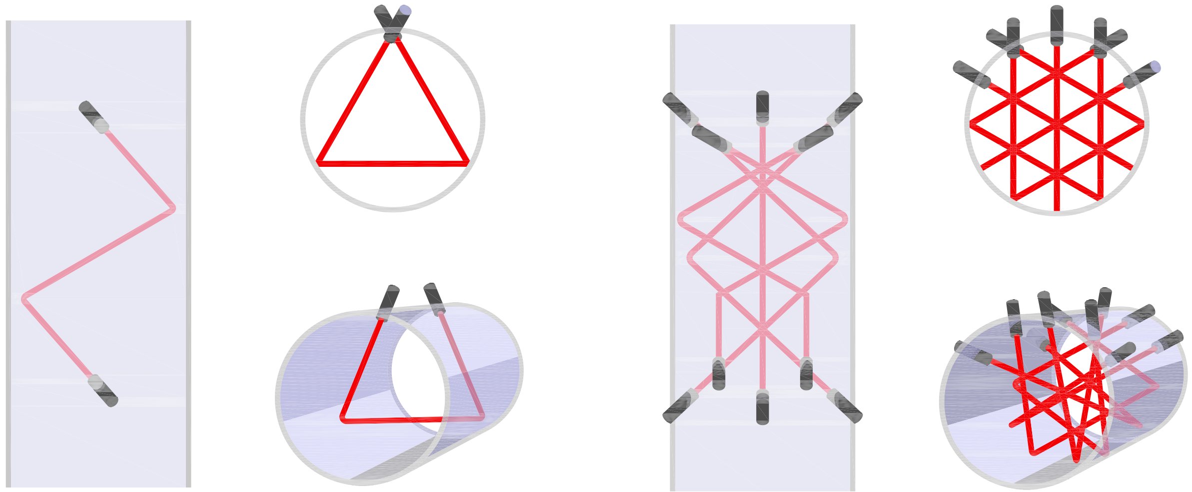
f) Single path reflective chordal

Figure 3 **Variations in path configuration**



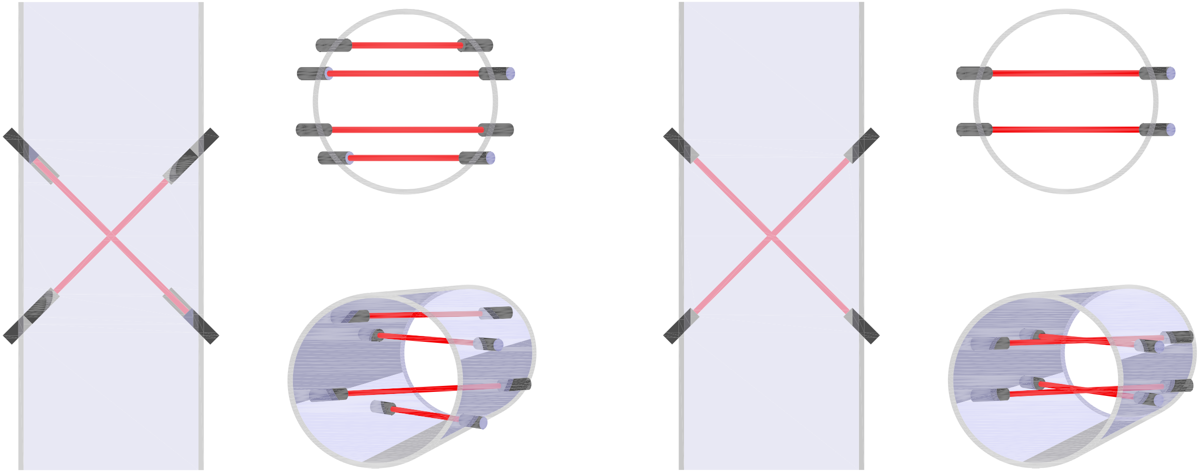
g) Multi-path parallel chord

h) Multi-path parallel chord reflective



i) Single path mid-radius reflective

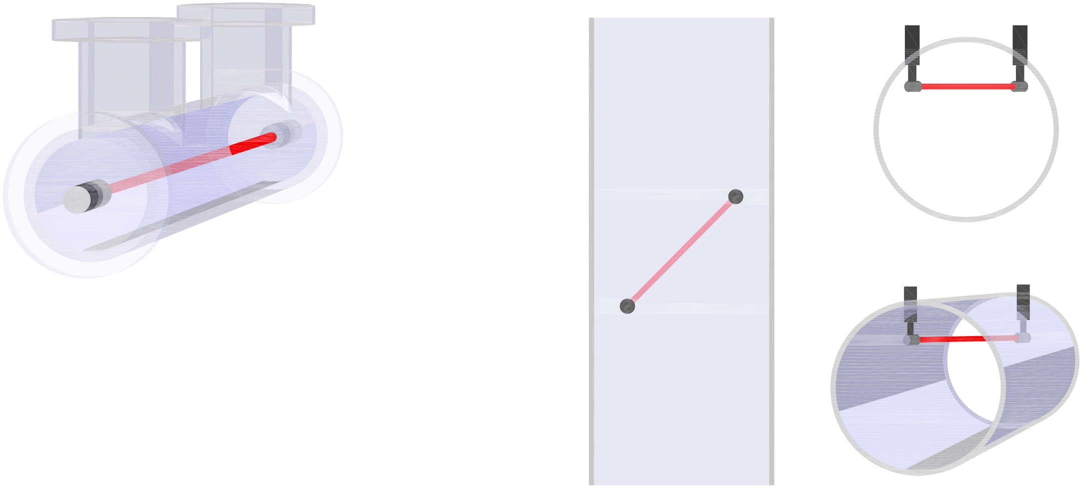
j) Multi-path mid-radius and diametric



k) Multi-path parallel crossed chord

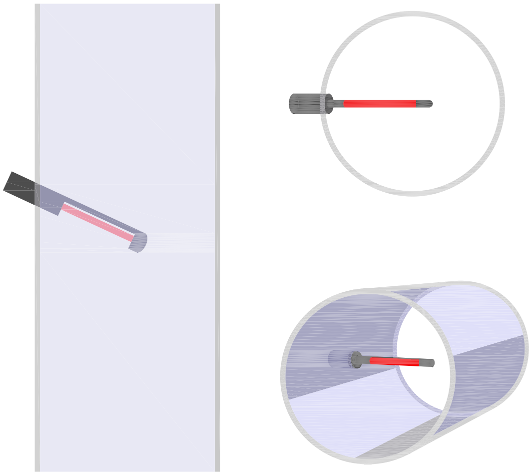
l) Multi-path in-plane crossed chord

Figure 3 **Variations in path configuration**



m) Single path offset axial

n) Single path partial chord



o) Single path one port partial chord

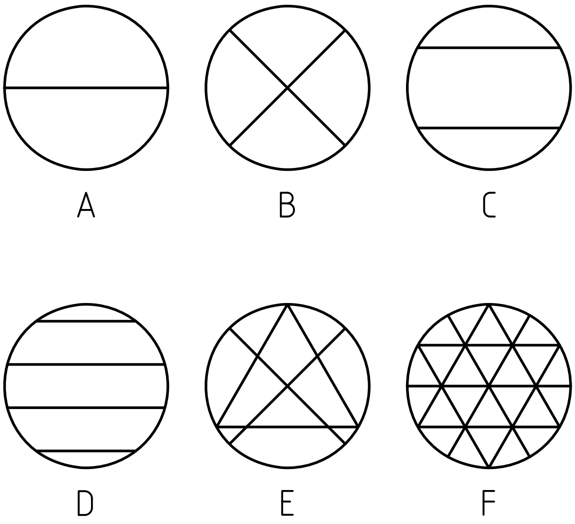
4.3.3.3 Common cross-sectional path configurations

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 is shown in Figure 4. The actual configuration selected by the manufacturer for a specific meter type can incorporate paths of equal radial displacement, paths at multiple radial displacements or a combination of both.

4.3.3.4 Meters with paths of equal radial displacement

Meters with paths of equal radial displacement (e.g. configurations A, B, 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.

Figure 4 **Some typical cross-sectional acoustic path configurations**



NOTE 1 For A, B, C, refer to ***4.3.3.4****.*

NOTE 2 For D, E, F, refer to ***4.3.3.5****.*

$$\bar{v} = k_h \frac{\sum_1^n v_i}{n} \qquad (7)$$

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 can 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, E and F 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.

- Summation with constant weighting:

$$\bar{v} = \sum_1^n w_i v_i \qquad (8)$$

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.

- Summation with variable weighting:

$$\bar{v} = \sum_{1}^{n} f_\mathrm{i} v_\mathrm{i} \tag{9}$$

where the radial displacements of the paths are fixed at design and the variables f_i to f_n can 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 obtained from the manufacturer.

In any of the given configurations, a multiplying or meter factor, *K*, (either constant or variable) can be applied after summation to correct for deviations due to manufacturing tolerances and/or incomplete assumptions (see Equation 10).

$$q_\mathrm{v} = KA\bar{v} \tag{10}$$

4.4 Criteria for selection

The aim of this subclause is to look at the selection of a meter based on the overall uncertainty required for the measurement. This divides the meters available into (essentially) four classes of performance as outlined in Table 2.

Table 2 **Class performance criteria – Meter requirements**

Class	**Total USM uncertainty (actual volume flow)**	**Repeatability**	**Reproducibility**	**Resolution**	**Error limit (plus or minus) (q_t to q_{max})**		
					Large meters	**Medium meters**	**Small meters**
	%	%	%	**mm/s**	%	%	%
1	<±0.7	<±0.20	<±0.30	<1	0.7	1.0	2.0
2	<±1.5	<±0.25	<±0.60	<2	1.0	1.5	3.0
3	<±3.0	<±0.35	<±0.90	<4	1.5	2.0	4.5
					Error limit (plus or minus) (q_{min} to q_{max})		
4	<±7.5	<±1.0	<±1.20	<10	5.0	5.0	7.0

NOTE 1 Large meters are defined as meters with nominal bores equal to or greater than 300 mm (12 inches). Medium meters are defined as meters with a nominal bore below 300 mm (12 inches) but greater than 100 mm (4 inches). Small meters are defined to have a nominal bore equal to or less than 100 mm (4 inches).

NOTE 2 Repeatability is defined as the closeness of agreement between successive flow rate measurements with the same flow meter when obtained under the same conditions (same fluid, same flow meter, same operator, same test facility and a short interval of time) and without disconnecting or dismounting the flow meter.

NOTE 3 Reproducibility is defined as the closeness of agreement between successive flow rate measurements with the same flow meter when obtained under any differing conditions (different fluid, different operator, different test facility) or disconnecting or dismounting and subsequent reinstalling of the flow meter.

Actual meter performance, inclusive of total meter uncertainty, repeatability, resolution and maximum peak-to-peak error, depends upon a number of factors which include:

- pipe internal diameter;
- acoustic path length;
- number of acoustic paths;
- gas composition/speed of sound;

- meter timing repeatability (itself a function of transducer frequency); and
- actual flow velocity.

*NOTE 1 See also **4.2** and **4.3.2**.*

Class 3 and Class 4 meters are often retro-fitted to existing process plant where flow rates are uncertain and sometimes unknown, where piping geometry does not support a fully developed velocity profile, where meter spools are not third-party calibrated or indeed the transducer ports are welded to the parent-pipe section on site and the transducers inserted through hot-tap methods. The user should provide the manufacturer with comprehensive process data and consult with them to assess actual meter performance versus required meter uncertainty for a given application (see Table 3).

Table 3 **System uncertainties and applications – System requirements**

Class	**Typical system uncertainty** %	**Maximum installation effect** %	**Typical applications**
1	<±1.0	0.3	Custody transfer
2	<±2.0	0.5	Allocation
3	<±4.0	1.0	Utilities/fuel gas
4	<±10	5.0	Process/flare gas

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 is different, as outlined within Table 3. To aid meter selection, an approximate uncertainty budget for the meter is suggested in order to meet the system uncertainty budget. Typical uncertainty values from recognized gas flow calibration establishments are in the order of ±0.3%. For Class 1 and 2 meters, this is a significant part of the total value for the USM uncertainty.

NOTE 2 These applications are for guidance only, with each application to be considered on its own merits. Attention is drawn to the European Union Emissions Trading Scheme (EU-ETS).

NOTE 3 See Annex A for the application of flow calibration results and Annex B for methods of correcting flow measurement error.

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 might 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, BS EN ISO 12213-1 and BS EN ISO 12213-2 should be consulted for guidance on the derivation of density and uncertainty.

When identifying a meter for a particular purpose, it is important to have access to the information in Table 2 and Table 3. In respect of Table 2, this information should be obtained from the meter manufacturer and it is recommended that the actual test data regarding the meter performance is reviewed when purchasing for the first time or from a new supplier or manufacturer.

Other criteria for selection can be determined by regulatory or statutory bodies, such as the Department of Energy and Climate Change (DECC) Energy Group: Energy Development Unit, and also by agreements between companies for custody transfer/allocation metering. The accuracy of measurement in the event of a path 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 path failure with USMs, it is possible for some meters to substitute values in place of the failed path 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 path failure under stable flowing conditions is expected to be less than 0.1%.

5 Installation recommendations

5.1 General

The guidance in this clause has 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 might be sensitive to differences between ambient and line temperature and adequate insulation, heating and/or cooling should be installed in order to minimize the effects of extreme differences between ambient and line temperature.

The meter should be able to operate within specification within an ambient air temperature range of −25 °C to 55 °C. This temperature range applies to the meter body with and without gas flow, field mounted electronics, ultrasonic transducers, cabling, etc. The manufacturer should be asked for ambient temperature specifications for the USMs if different from −25 °C to 55 °C.

For Class 1 and Class 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 compressor start-up 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

The manufacturer should be consulted regarding the performance of the meter in a vibrating environment as there is a potential for measurement error. It is recommended that measures are taken to isolate sensitive equipment from the vibration source, such as the provision of anti-vibration mountings.

5.2.3 Electrical noise

Good wiring practice should be implemented to minimize the effect of electrical noise.

NOTE Attention is drawn to EMC-RF obligations for equipment used within the EU, some of which might be met by conformity to BS EN 61000-6-3 and BS EN 61000-6-4.

The meter and associated electrical conduits, cables and circuits should be designed and installed in accordance with applicable electrical codes and particular care should be taken with the type of screening and routing of interconnecting cable installed between the transducers and the control unit.

5.2.4 Mechanical noise

COMMENTARY ON ***5.2.4***

Additional information on gas control valve interference with gas USMs is available in TUV NEL Guidance Note *[2].*

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. The ultrasonic noise from these control valves can interfere with the operation of a nearby ultrasonic flowmeter even when the valve is located downstream of the USM. 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, a means should be provided to monitor its impact on the meter using the signal-to-noise ratio (SNR); an alarm facility might 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. 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.

USM manufacturers recognize the potential for operating problems, and most USMs have diagnostic capabilities that indicate whether acoustic noise impairs meter performance while operating. Strategies have also been devised by users and manufacturers to estimate and/or limit a USM's susceptibility to noise interference, such as:

- evaluation of the USM's response to acoustic noise prior to station installation;
- enhanced signal processing to improve ultrasonic pulse recognition and detection;
- signal filtering to narrow the bandwidth surveyed for better/faster pulse recognition;
- installation of fittings, such as blind tees or filters, to isolate the noise source from the USM;
- development of specialized silencers that are installed in the piping between the USM and the noise source to isolate the meter from the noise.

In general, noise sources upstream of USMs have a more adverse impact on meter performance than those installed downstream, although downstream installation of pressure reduction or other noise generating equipment does not guarantee interference will not occur. Also, greater separation between a noise source and the USM and the consequent increased number of fittings provides more attenuation than would be the case if the meter and source were installed in close proximity to each other.

When considering installation of a USM, particularly in the vicinity of pressure or flow regulation (the most common noise generators), the factors that should be taken into account during the USM station design phase are:

- the installed position of valves (as potential noise sources) relative to the meter (upstream, downstream, distance between meter and source, number and type of fittings between meter and source);
- the operating frequency of the meter and the range of frequencies generated by the noise source (noise reduction trim valves are of particular concern since the design generates noise exceeding audible frequencies which is often in the ultrasonic range);
- whether additional attenuation between noise source and USM is required, which could include blind tees or other fittings or acoustic filters;
- whether enhanced filtering of digital signal processing has to be applied and, if so, whether it slows signal processing time beyond acceptable limits (limits are given for a linear measuring device in the *API Manual of Petroleum Measurement Standards* (MPMS), Chapter 21.1 [3]);
- the cost/benefit of pursuing one or more strategies to limit USM exposure to offending acoustic noise.

When installation of a USM near a potential noise source is anticipated, the manufacturer should be contacted for recommendations specific to their products and the proposed installation prior to finalizing USM station design. Cooperation between specifiers/users and manufacturers during the design of the facilities can avoid the need for potentially expensive remedial actions at a completed meter installation.

Further guidance can be found in ISO 17089-2:2012, Annex A.

5.2.5 Gas composition restrictions

The presence of certain gases might 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 their acoustic absorption properties). Meter manufacturers should be supplied with the expected constituents of the gases to be measured and the associated pressure and temperature range.

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 the markings attached to the meter spool should clearly indicate the primary flow direction.

NOTE For example, plates might be affixed to the meter as a means of marking.

5.3.2 Upstream and downstream fittings

*COMMENTARY ON **5.3.2***

Various combinations of upstream fittings (valves, bends, expanders, tees, reducers, etc.) might produce velocity profile distortions and swirl at the inlet to the USM that could result in measurement errors. 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 could 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, and where a Class 1 or Class 2 meter is involved, it might be necessary to use a flow-conditioner and calibrate the USM and flow conditioner together (see **5.3.3**). Alternatively, it might be necessary to model the system by 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. For Class 1 applications, the meters should only be installed where the impact of fittings and pipework configurations does not have a detectable 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 installed uncertainty of the meter reading are not produced, i.e. that these effects are within the manufacturer’s stated limits for the meter; this might be verifiable at site by on-board diagnostics in certain multi-path USMs.

The user can either verify the USM in-situ or remove the meter to a flow calibration facility in which the test piping configuration is representative of the planned installation. Alternatively, for Class 1 and Class 2 USMs, the manufacturer should be requested to do one of the following as desired by the user.

a) 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 ±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.

b) 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 avoids creating an additional flow rate measurement error of more than ±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.

NOTE Asymmetric velocity profiles can persist for 50 pipe diameters or more downstream from the point of initiation. Swirling velocity profiles can persist for 200 pipe diameters or more. A flow conditioner properly installed upstream of a USM can help shorten the length of straight pipe required to eliminate the effects of an upstream flow disturbance. Some types of USM can compensate for some levels of flow profile disturbance.

USMs are sensitive to flow profile disturbances, for example those created by out-of-plane bends (often causing swirl) and those created by in-plane bends (often causing asymmetry). It is recommended that the upstream straight lengths be as long as possible; multi-path USMs are less sensitive to upstream flow disturbances than those with fewer diagonal path. Also, the use of a flow conditioner, if calibrated with the USM, allows a reduction in the required upstream straight length (see **5.3.3**).

5.3.3 Flow conditioners

One of the major benefits of USMs is the lack of pressure drop due to the unrestricted pipe area available with many USM designs and the ability to reduce the system uncertainty by reproducing calibration conditions.

Flow conditioners might or might not be necessary depending on the manufacturer's meter design and the severity of any upstream flow profile disturbance. The manufacturer should be consulted with to determine the selection and location of flow conditioners with attention being given to the upstream piping configuration.

Where flow conditioners are recommended by the manufacturer, conditioners should be selected that do not generate ultrasonic noise, which can be the case with some perforated plate devices. For Class 1 and Class 2 meters, the installation of flow conditioners should be in the same location and orientation as when the USM package (USMP)/USM flow conditioner combination was calibrated; this needs dowels or other means of mechanical location to ensure the conditioner is correctly installed. The formation of hydrates should also be prevented.

NOTE This might be prevented by good process control and/or the use of a hydrate inhibitor.

Provision for inspection of the flow conditioner, for a build-up of debris and/or particulate contamination, should be ensured; this can be in the form of an inspection port. Where only one inspection port is provided, this should be on the upstream side of the flow conditioner.

The inspection port should be sized and positioned to enable a boroscope to be inserted into the line and the whole of the flow conditioner viewed.

5.3.4 Meter orientation

The manufacturer should be asked whether there is a preferred meter orientation for the given upstream piping configurations and operation conditions which are known to produce flow profile distortions. Consultation should also include the preferred orientation to avoid liquid accumulation if this is a potential hazard. For Class 1 and Class 2 meters and any meters requiring flow calibration, the orientation of the meter during calibration should be the same as during site installation.

5.4 USM spool and meter tube assembly

5.4.1 Protrusions and circularity

Changes in the internal diameters and protrusions at the inlet to the USM spool should be avoided as local disturbances to the velocity profile might be created. For Class 1 and Class 2 meters, mechanical means of alignment should be used, especially on smaller meters (<254 mm).

For Class 1 or Class 2 meters, the USM bore, flanges and adjacent upstream pipe section should all have the same internal bore to within 1.0% of the mean over the minimum recommended upstream section of the meter tube assembly.

For meters that are not of an in-line design, and where the step change limit of 1.0% is exceeded, the manufacturer should be asked to demonstrate that the meter meets its required uncertainty criteria.

The internal mean bore, D, should be the arithmetic mean of at least twelve measured diameters, namely four diameters positioned at approximately equal angles to each other, distributed in each of at least three cross-sections evenly distributed over a length corresponding to the measured bore of the USM. This should also be the case for the upstream pipe section to a minimum of $20D$. Where flow conditioners are installed, this should apply to the length downstream of the conditioner and, in addition, a length upstream of the conditioner in accordance with the manufacturer's recommendation. In the event of not using flow conditioners, if the upstream length is less than $20D$, an analysis of the impact of fluid hydraulics should be undertaken.

The USM and meter tube piping should ideally be installed in a region of zero stress in the pipeline, so as to minimize strain on the meter. For meters having a bore diameter different from the meter tube, a maximum transition taper should be 8° outside of the measurement section. The upstream pipework should be carefully aligned to minimize flow disturbances, especially at the upstream flange of the meter. For optimum accuracy the actual step caused by misalignment and/or change in diameter should not exceed 1.0% at any point in the internal circumference of the pipe. Therefore, mating flanges need the bores to be matched and the flanges aligned on installation. All internal welds should be checked to see that they have been machined flush and no part of the upstream flange or gasket protrudes.

If liquids are to be encountered, then the USM should be sloped in the direction of flow to allow draining of the meter. It is also recommended that care should be taken that the meter is not placed in such a position that the transducer ports collect liquid. If the design of the USM is such that the transducer ports could potentially collect liquid, the design of the transducers should be such that any accumulated liquid does not impact upon or adversely affect the USM performance. If possible, areas of the pipework used for ultrasonic path reflection should be kept free of liquid accumulation. There should not be steps at the flange connections that allow liquids to collect.

In respect of the downstream section, the step in adjacent pipe sections up to 3*D* from the meter should be limited to 1.0% (visual inspection is normally sufficient to determine the circularity of the downstream cross-section). The upstream and downstream flange internal weld bead should be ground smooth to ensure that the diameter is within the piping tolerance.

Experience with Class 1 meters has shown that diameter steps between the upstream pipe and the meter cause metering errors of the order of 0.05% systematic error per 1% diameter step; an error that can be reduced by chamfering as long as the angle of inclination is less than 7°.

Thermowells, located as described in **5.4.5**, are excluded from the above protrusion limits.

If gaskets or sealing rings are used, they should be fabricated and installed in such a way that they do not protrude at any point inside the meter tube assembly by more than 1.0% of the mean bore, i.e. over the minimum recommended upstream straight pipe section (20*D*) of the meter tube assembly and at the downstream meter flanges.

NOTE During the installation of bolted flanges, three or more insulating flange bolt sleeves can be used at the 4, 8 and 12 o'clock positions to keep the gasket centred while tightening the nuts.

5.4.2 Internal surface

The interior of the meter and meter tube assembly should be clean at all times, as even a thin coating of contaminant can be sufficient to alter the surface roughness without significantly altering the internal cross-sectional area of the meter; however, changes in pipe surface roughness, in turn, can cause changes in the velocity profile.

To maintain accuracy, the meter bore should have a surface roughness, R_a, such that:

$$k_r/D \leq 10^{-4} \tag{11}$$

where:

k_r (the pipe wall uniform equivalent roughness) is approximately equal to $R_a \times \pi$, examples of which can be found in BS EN ISO 5167-1:2003, Annex B.

The manufacturer should be able to demonstrate that the flow meter meets this roughness criterion. This can be demonstrated by measurement or by other means, e.g. reference to industry standard pipe quality data such as that given in BS EN ISO 5167-1:2003, Annex B.

Any change in velocity profile should be treated as a component of the installation effects given in **5.3.2**.

The USM's operation depends on a known cross-sectional area to convert mean gas velocity to a flow rate. If there is a change in the cross-sectional area of the meter due to deposits or erosion then a mis-measurement will occur.

5.4.3 Flanges

When the meter is supplied with flanged joints or hub connectors for upstream and downstream connections, the respective bores of the mating flanges within the meter tube assembly should conform to the step criteria detailed in **5.4.1**.

The exception to this is the recess or groove between adjacent flange bores; it should be assumed that these bores are in direct metal to metal contact for the purpose of step determination.

5.4.4 Straightness

The straight lengths comprising the upstream and downstream meter tube pipe sections should be considered straight when they appear so by visual inspection.

5.4.5 Thermowells

CAUTION: High gas velocities can cause flow-induced thermowell vibration, which could result in catastrophic metal fatigue failure of the thermowell.

For uni-directional flow, the thermowell should be installed downstream of the USM and the distance from the downstream flange face to the thermowell should be a minimum of $2D$ and a maximum of $5D$.

If the meter has a feature to have inbuilt thermowell(s) these may also be used.

For bi-directional flow installations, requiring optimum accuracy, the thermowell should be located either:

- at least $10D$ from either USM flange face; or
- between $5D$ and $10D$ from either USM flange face, in which case, the meter should be flow-calibrated in both directions with the thermowells installed and two correction factors derived.

The recommended insertion depth for the thermowell and the pockets is between $D/10$ and $D/6.67$. Where the insertion depth $>D/3.33$ then the meter run might not need to be insulated. Where insertion depth $<D/3.33$ (or where surface mount technology is used) then the meter run should be insulated from the meter inlet until at least $1D$ downstream of the temperature measurement point.

If flow conditioning devices are installed in bi-directional flow installations, there is then generally a need for a number of uninterrupted straight diameters between the flow conditioner and the USM. The ideal solution would employ two USMs with the thermowell located in the centre section (see Annex C); where this is not appropriate and only one USM is employed, the thermowell should be located $3D$ to $5D$ downstream of the USM when the flow is in the primary (forward) direction (see Annex C). In order to minimize the impact of potential profile distortion caused by the thermowell when flow is in the secondary direction (reverse), the meter should be calibrated in both directions with the thermowell installed.

The thermowell orientation, with respect to acoustic paths, should be as recommended by the manufacturer.

5.4.6 Pressure tappings

The pressure measurement should be made at the point at which the flow velocity is determined.

The breakthrough should be between 3 mm and 13 mm; taking into account the need to prevent blockage and to provide satisfactory dynamic performance. In addition a tapping should be cylindrical over a length of at least 2.5 times the diameter of the tapping, measured from the inner wall of the meter spool. For a USM with a wall thickness less than 8 mm, the hole should nominally be 3 mm in diameter.

The tapping hole edges at the internal wall of the meter spool should be free of burrs or wire edges with minimum rounding.

A pressure tapping may be located at the top, left side, and/or right side of the meter spool. Additional tappings can provide added flexibility for maintenance access and proper drainage of impulse line liquids back into the meter spool.

NOTE For low pressure applications, for example flare measurements, absolute pressure measurement transmitters should be used.

5.4.7 Ultrasonic transducer ports

CAUTION: The use of extractor tools to extract ultrasonic transducers without depressurization should only be undertaken by competent personnel.

Since gas might contain some impurities, e.g. light oils or condensates, the transducer ports should be designed in such a way as to reduce the possibility of liquids or solids accumulation. If the design of the USM is such that the transducer ports could potentially collect liquid, the design of the transducers should be checked to ensure that any accumulated liquid does not impact upon or adversely affect the USM performance (see **5.4.1**).

If specified by the user and available from the manufacturer, the USM can be equipped with double block and bleed valves, extractor tools, or alternative proven design, in order to make it possible to replace the ultrasonic transducers without depressurizing the meter run. In this case, a bleed valve might be required in addition to the isolation valve, to ensure that no pressure exists behind a transducer before releasing the extraction mechanism.

5.4.8 Transducer specifications

The general specifications of ultrasonic transducers, such as critical dimensions, maximum allowable operating pressure, operating pressure range, operating temperature range and gas composition limitations should be stated by manufacturers.

For the particular application, the manufacturer should specify the minimum operating pressure based on the ultrasonic transducer model, USM size and expected operating conditions. This minimum pressure should have been marked or tagged on the USM to alert the users that the meter might not register flow at reduced pipeline pressures.

5.5 Ancillary fittings

In order not to affect the flow profile, stream isolation valves located upstream of the meter tube assembly should be of the full bore type or of such a construction as to present minimal restriction to fluid flow when fully open.

For Class 1 and Class 2 meters, where high accuracy pressure and temperature devices are used, the signals should be fed to the interface unit or computer for the application of meter body expansion routines and pressure, temperature and compressibility (also known as PTZ density) determination, as appropriate.

Filtration might be necessary to avoid the accumulation of dirt, mill scale, liquids and/or lubricating oils.

Meters should be selected that have been designed in such a way that the body does not roll when resting on a smooth surface with a slope of up to 10%: this is to prevent damage to the protruding transducers and signal processing unit (SPU) when the USM is temporarily set on the ground during installation or maintenance work.

Meters should also be selected that have been designed in such a way that permits easy and safe handling of the meter during transportation and installation; provisions should have been made for hoisting eyes, or clearance for lifting straps should be provided.

6 Operational considerations

6.1 Performance recommendations

6.1.1 General

The flow measurement performance recommendations described in this subclause apply to both flow-calibrated and static-calibrated meters. For each meter design and size, the manufacturer should have specified flow rate limits for q_{max}, q_t, and q_{min}, as detailed in Figure 5 to Figure 8 for Class 1, Class 2, Class 3 and Class 4 applications where q_t is given as $\leq q_{max}$. Each USM, whether flow calibrated or not, should perform within the more accurate measurement range detailed in Figure 5 to Figure 8 for gas flow rates from q_t to q_{max}, and within the less accurate range again detailed in Figure 5 to Figure 8 for flow rates less than q_t but greater than or equal to q_{min}.

For the avoidance of doubt, such performance criteria should include non-linearity and hysteresis. The manufacturer should be asked to provide objective evidence or test data confirming that the USM (either flow calibrated or static calibrated) meets the recommendations of this subclause.

The user may specify that a meter be flow calibrated prior to installation as a means of eliminating or minimizing systematic, intrinsic errors (Type B uncertainties, see **B.1**) that might exist as a result of these performance recommendations with the static-calibrated meter. See Clause **7** for recommendations on flow-calibration tests. users should also carefully follow the installation recommendations of Clause **5**, as any installation effects add to the overall measurement uncertainty.

The transitional volumetric flowrate, where the specified performance of the meter changes, q_t, as presented within Figure 5 to Figure 8, is for general representation (the meter itself does not have a step change in performance).

6.1.2 Pressure, temperature and gas composition influences

The USM should meet the appropriate flow measurement accuracy recommendations given in Figure 5 to Figure 8 over the full operating pressure, temperature and gas composition ranges without the need for manual adjustment, unless otherwise stated by the manufacturer. If the USM requires a manual input to characterize the flowing gas condition, e.g. gas density and viscosity, the manufacturer should be asked to state the sensitivity of these parameters so that the user can determine the need to change them as operating conditions dictate.

Figure 5 **Performance specification summary for Class 1 meters**

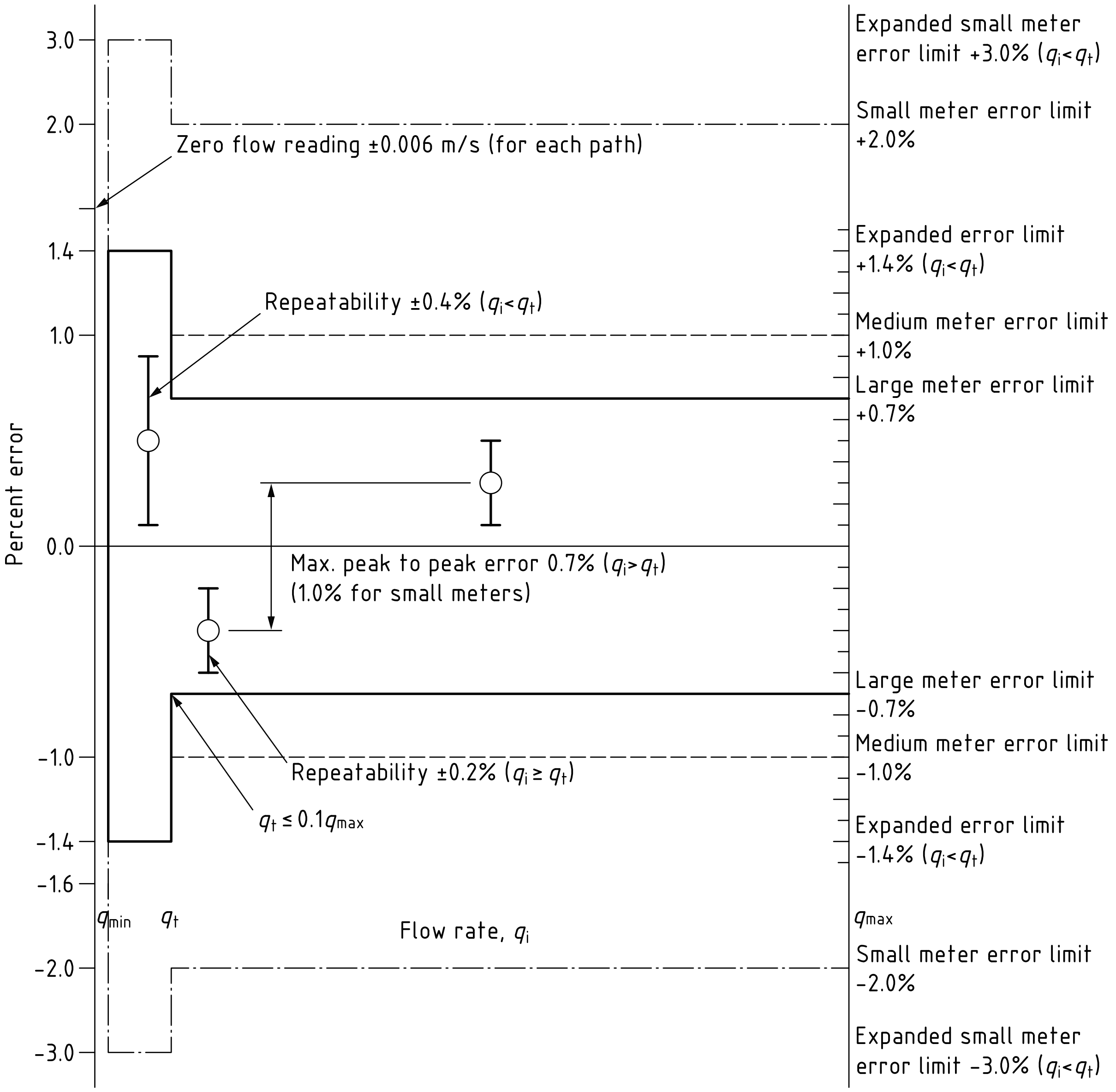


Figure 6 **Performance specification summary for Class 2 meters**

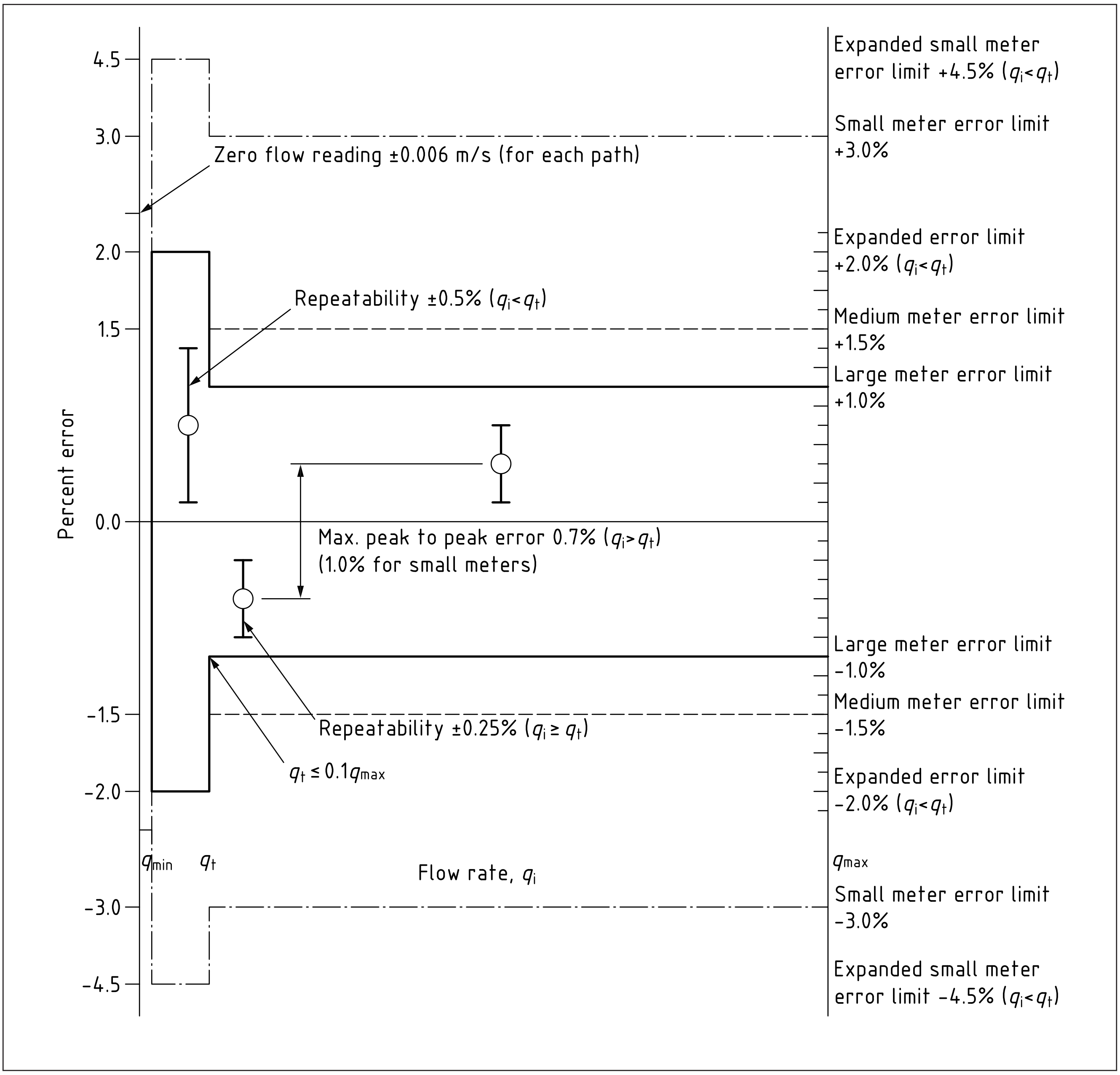


Figure 7 **Performance specification summary for Class 3 meters**

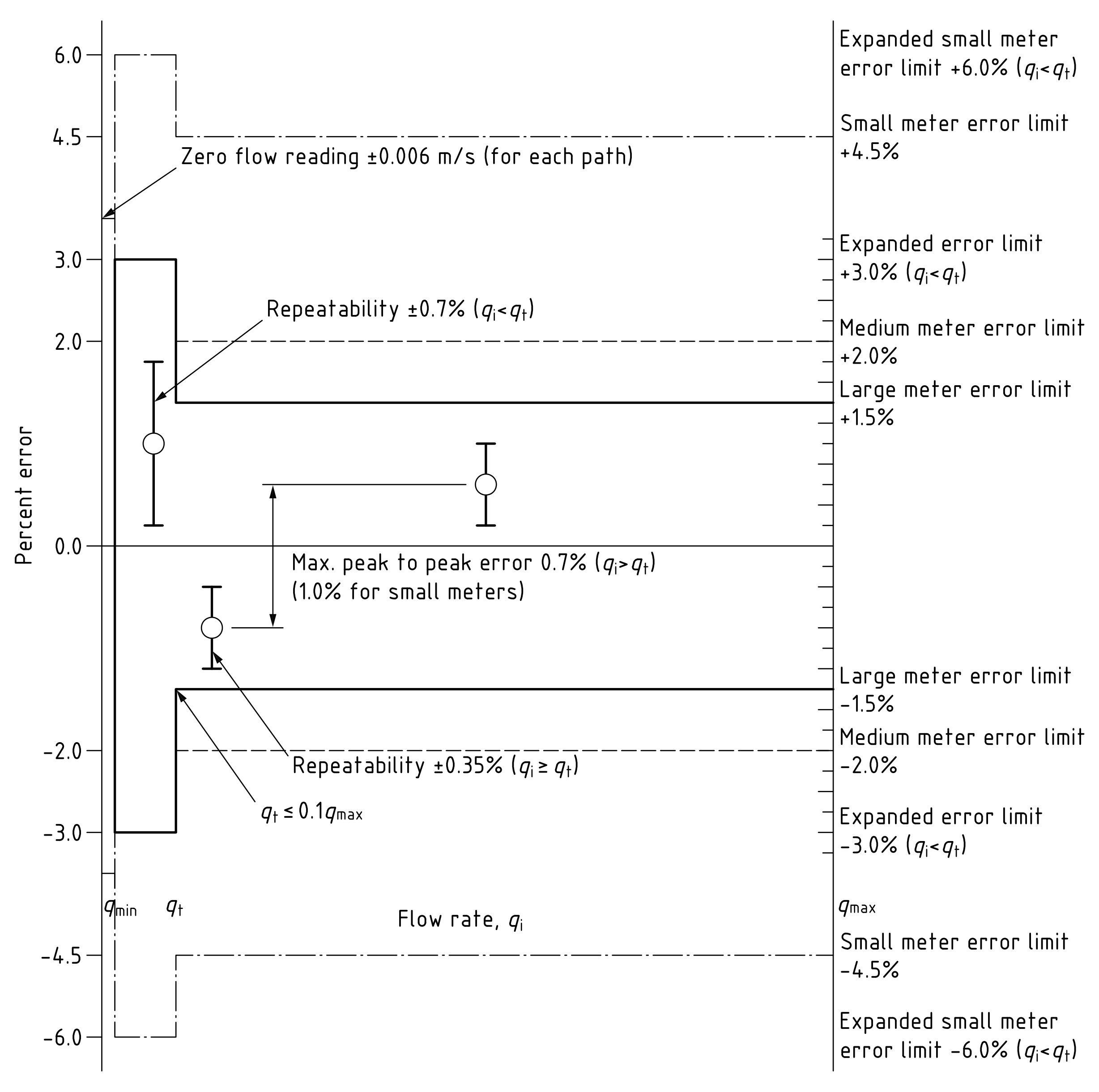
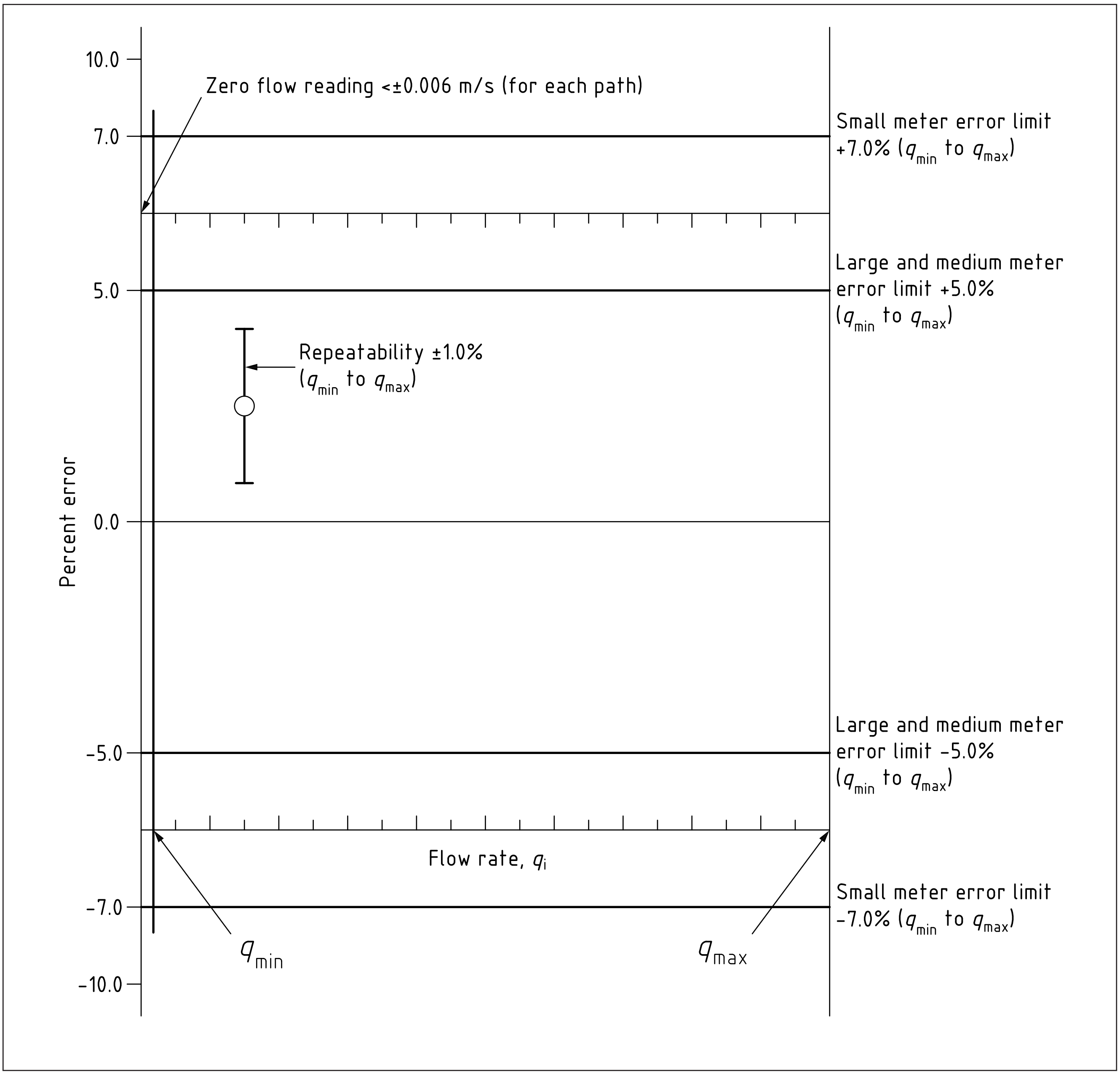


Figure 8 **Performance specification summary for Class 4 meters**



6.1.3 Pressure and temperature correction for meter body geometry effects

Flow meters are often calibrated at temperature and pressure conditions that are different from the conditions that the meter will see in service. These temperature and pressure differences change the diameter and length of the meter and this can, depending on the magnitude and direction of the temperature or pressure difference, introduce a significant systematic error in meter accuracy.

The flow error effect $\Delta Q/Q$ due to a body temperature change, ΔT, is given by:

$$\left(\frac{\Delta Q}{Q}\right)_{bodytemperature} = 3\alpha\Delta T \qquad (12)$$

Table 4 gives typical values of α for common materials. If ΔT is negative, the error will be negative.

Table 4 **Common thermal expansion coefficients in the 0 to 100 °C range**

Material	Value m/m °C
Carbon steel	12×10^{-6}
Stainless steel (austenitic)	10×10^{-6}
Stainless steel (ferritic)	13×10^{-6}

NOTE Source: Kaye and Laby Tables (see <http://www.kayelaby.npl.co.uk> [last viewed 14 October 2013]).

An estimate of the maximum expected flow error due to a body pressure change, ΔP, is given by:

$$\left(\frac{\Delta Q}{Q}\right)_{body pressure, maximum} = 4\left(\frac{\Delta R}{R}\right) = 4\left(\frac{a^2+R^2}{a^2-R^2}+\sigma\right)\left(\frac{\Delta P}{E}\right) \qquad (13)$$

Where:

σ is Poisson’s ratio (0.3 for steel);

a is the outside radius;

R is the internal radius;

E is Young’s modulus of body (bar).

Equation 13 is for a cylindrical body subject to uniform radial internal pressure with no end loads and for ends free to move axially; this condition is a worst case for the amount of radial expansion on the body and consequently is taken as a worst case for any type of meter body.

Assuming each of the $\Delta Q/Q$ values is small, the combined initial estimate of flow error is given by:

$$\left(\frac{\Delta Q}{Q}\right)_{combined, estimate} = \left(\frac{\Delta Q}{Q}\right)_{body pressure, maximum} + \left(\frac{\Delta Q}{Q}\right)_{body temperature} \qquad (14)$$

This initial estimate indicates the potential severity of the expected flow error and is used solely as an aid to decide whether a detailed calculation of flow error is required.

If this flow error exceeds 0.1% then a detailed calculation needs to be performed to obtain a flow correction factor – see Paper 6.2 from the 2008 North Sea Flow Measurement Workshop [4].

6.2 Operating conditions

6.2.1 Pressure and density

Ultrasonic transducers used in USMs require a minimum gas pressure (density) to form acoustic coupling of the sound pulses to and from the gas. Therefore, users should state the expected minimum operating pressure as well as the maximum operating pressure. If, during operation, the density of the gas falls below the lower limit, the accuracy of the meter will deteriorate as individual signals are lost.

6.2.2 Operating temperatures

The USM should operate over a flowing gas temperature range of –25 °C to +55 °C. The user should state the expected operating gas temperature range. The manufacturer should be asked to provide gas flow temperature specifications for the USM, if different from this.

In situations where the meter might be installed in pipelines that are subject to steam, high temperature or chemical cleaning procedures, care should be taken to ensure that the cleaning process will not damage the meter.

It has been found that temperature gradients across the transducers can lead to measurement error; for Class 1 and Class 2 meters, where optimum accuracy is required, insulation should be in place to keep the temperature gradients across the transducers and within the cavity of the transducer ports to a minimum.

The upstream pipe, the meter body, the transducer nozzles, the transducer assemblies and downstream pipe to 1*D* beyond the thermowell should be insulated using fixed and removable insulation.

6.2.3 Gas flow considerations

The actual velocity of the flowing gas determines the flow rate limits that can be measured by a USM. The specifier should determine the expected gas flow rates and verify that these values are within the $q_{\min}$, q_t and $q_{\max}$ specified by the manufacturer. The user should be aware that low flow velocities increase the measurement uncertainty and should carefully consider the maximum velocity with respect to noise and safety concerns (such as erosion, thermowell vibrations, etc.).

USMs have the inherent capability of measuring flow in either direction with equal accuracy, i.e. they are bi-directional. Specifiers should state whether bi-directional measurement is required so that the manufacturer can properly configure the signal processing unit (SPU) parameters.

6.3 Piping configuration – internal surface

The internal surface of the USM should be kept clean of any deposits, for example liquids or particulates, which can affect the meter's cross-section area; surface deposits might also influence the meter accuracy without significantly changing the cross-sectional area; contamination of transducers can alter the acoustics, and surface roughness changes might alter the profile.

Notwithstanding the above, field experience with some USMs suggests that surface aging can occur and that this impacts on the meter performance; under such circumstances for Class 1 and Class 2 meters subject to periodic recalibration, it is recommended that the internal surface of the USMs be left uncleaned until after the next "as found" calibration; after which an "as left" recalibration should be carried out.

NOTE "As found" means the results/indications from a piece of equipment before any adjustments are made. "As left" means the results/indications from a piece of equipment after any adjustments are made.

6.4 Transducers

6.4.1 Rate of pressure change

Rapid pressurization or depressurization of the meter should be avoided to prevent possible damage to the transducers. If necessary, clear instructions should be requested from the manufacturer for depressurization and pressurization of the meters and transducers during installation, start-up, maintenance and operation. Special care should be taken when removing transducers under pressure using full bore valves. The user should ensure that a full procedure for such an activity is agreed with the USM manufacturer before transducer removal. In the absence of alternative information from the manufacturer, 5 bar per minute is considered to be a reasonable rate for a controlled depressurization.

6.4.2 Transducer exchange

Where in-field removal of transducers is possible by virtue of the meter design, replacing or relocating transducers, cables or parts of the SPU might result in a change in meter performance. For Class 1 and Class 2 meters, the effect on the performance should either be demonstrated by the manufacturer or should be quantified at similar conditions during the meter's initial flow calibration.

This means that after an exchange of transducers and a possible change of SPU software constants, as directed by the manufacturer, the resulting metering error should not be more than the allowable reproducibility of the meter. The manufacturer should state that this is the case and specify procedures to be used when transducers have to be exchanged, including possible mechanical, electrical, or other measurements and adjustments. For Class 1 meters, where even small deviations are not tolerable, either spare transducers should be calibrated with the meter or after a transducer exchange, the meter should be re-calibrated at a calibration facility.

6.4.3 Transducer tests

As part of a USM's quality assurance program, the manufacturer should be asked to test each transducer or pair of transducers and the results documented. Each transducer should be marked or tagged with a permanent serial number and be provided with the general transducer data listed in **5.4.8**. If the signal processing unit (SPU) (see **6.5.1**) requires specific transducer characterization parameters, each transducer or transducer pair should also be provided with test documentation that contains the specific calibration test data, calibration method used and characterization parameter(s).

6.4.4 Transducer failure

The performance of a USM following a transducer failure is dependent upon the type of meter and the number of paths in service. A failure of a transducer from a single path meter would render the USM unserviceable until the defect has been corrected, whilst the failure of a transducer within a multi-path meter will not inhibit its operation, but might impact on USM performance.

The manufacturer should be consulted concerning the impact of transducer failures on the performance and accuracy of a USM. In some cases, if a path fails, it might be necessary for the meter to disable an associated path for best results.

If it is expected that the USM is to remain in service in the event of a path failure, the manufacturer should be asked to state the effect such a failure would have on the USM performance.

For Class 1 and Class 2 applications, a meter experiencing failed transducers should be removed from service and re-calibrated with replacement transducers at the earliest practical opportunity. Alternatively, the significance on the performance of path failures should be quantified with supporting evidence by the manufacturer.

6.5 USM electronics

6.5.1 General recommendations

The USM's electronics system, including power supplies, microcomputer, signal processing components and ultrasonic transducer excitation circuits, can be housed in one or two enclosures mounted on or next to the meter. This is referred to as a signal processing unit (SPU).

Optionally, a remote unit containing the power supplies and operator interface could be installed in a non-hazardous area and connected to the SPU by multi-conductor cable.

The SPU should operate over the entire specified environmental conditions without a significant change in meter performance. It should also be possible to replace the entire SPU, or change any field replacement module, without a significant change in meter performance. For Class 1 and Class 2 meters, the USM should be re-calibrated unless the effect on its performance has been demonstrated by the manufacturer or quantified at similar conditions during the meter's initial flow calibration.

The system should be specified to contain a "watchdog-timer" function to ensure automatic restart of the SPU in the event of a program fault or lock-up. The meter should operate at a mains power supply of nominally 110 V a.c. to 120 V a.c. or 220 V a.c. to 240 V a.c. at 50 Hz or 60 Hz, or from nominal 12 V d.c. or 24 V d.c. power supply/battery systems, as requested by the specifier.

6.5.2 Output signal specifications

The SPU should be specified to be equipped with at least one of the following outputs:

- serial data interface, e.g. RS-232, RS-485, field-bus or equivalent;
- frequency or pulse stream output with each pulse representing a specific volume at line conditions and that are accumulated by a flow computer.

The meter can also be equipped with an analogue (4 mA d.c. to 20 mA d.c.) output for flow rate at line conditions.

The flow rate signal should be specified as scaleable up to 110% of the meter's maximum flow rate, q_{max}.

A low-flow cut-off function should be requested that sets the flow rate output to zero when the indicated flow rate is below a minimum value. Setting the output to zero at low flow can cause problems if the USM output is used to control valve settings. In a noisy environment appropriate shielding should be installed if possible.

Two separate flow rate outputs or serial data values should be requested for bi-directional applications, to facilitate the separate accumulation of volumes by the associated flow computer(s) and the directional state output signal. Alternatively, a single flow computer that accumulates the two flows in separate registers can be considered, provided the USM generates a signal confirming the direction of flow.

All outputs should be isolated from ground and have the necessary voltage protection to meet the designated electrical testing requirements.

6.5.3 Cable jackets and insulation

Cable jackets, rubber, plastic and other exposed parts should be specified as resistant to ultraviolet light, flames, oil and grease and suitable for the operating environment.

6.6 Computer programs

6.6.1 Firmware-resident programs and code

Computer codes responsible for the control and operation of the meter should be stored in a non-volatile memory. All flow calculation constants and user-entered parameters should also be stored in non-volatile memory.

For auditing purposes, it should be possible to verify all flow calculation constants and parameters whilst the USM is in operation. All changes to USM operating parameters and calculation constants, including manual data entries, should be logged. For Class 1 and Class 2 USMs, this should include some electronic format.

A record should be kept of all firmware revisions including revision serial number, date of revision, applicable meter models and circuit board revisions, and description of changes to firmware. If necessary, the user should check their records against the manufacturer's records.

The firmware revision number, revision date, serial number and/or checksum should be available (for any auditing purposes) for visual inspection of the firmware chip, display or digital communications port.

The manufacturer might offer firmware upgrades from time to time to improve the performance of the meter and/or add additional features. The user should ask the manufacturer to notify the user if the firmware revision can affect the accuracy of a flow-calibrated meter.

For Class 1 and Class 2 meters, the USM should be re-calibrated after firmware exchanges unless the significance on its performance is demonstrated by the manufacturer or quantified at similar conditions during the meter's initial flow calibration.

6.6.2 Configuration and maintenance software

Class 1 and Class 2 meters should be specified to have a capability for local or remote configuration of the SPU and for monitoring the operation of the meter. As a minimum, the software should be able to display and record the following measurements: flow rate (at flowing conditions), mean velocity, average speed of sound, individual path speed of sound, individual path velocities and ultrasonic acoustic signal quality received by each transducer.

6.6.3 Alarms

The USM should be specified to give an "output invalid" alarm status when the indicated flow rate (or volume) at line conditions is invalid. The alarm output should be generated by fail-safe, dry, relay contacts or voltage-free solid-state switches isolated from ground. The following may also be requested:

- a partial failure alarm, when one or more of the multiple ultrasonic path results is not usable;
- a general alarm, when any of several monitored parameters fall outside of normal operation for a significant period of time.

6.6.4 Diagnostic measurements

The manufacturer should be consulted to ensure that the USM provides the user with easy access to those operational diagnostics which are essential for confirmation of correct USM function and which confirm USM performance. These diagnostics should be available via USM display and/or the USM output or communications protocols. For specific applications, where for example secondary parameters are derived from the USM, it might require additional diagnostics.

For Class 1 and Class 2 meters these diagnostics should include:

- average axial flow velocity through the meter;
- flow velocity for each acoustic path (or equivalent for evaluation of the flowing velocity profile);
- speed of sound along each acoustic path;

- angle of swirl of flow profile;
- average speed of sound;
- velocity sampling interval;
- averaging time interval;
- percentage of accepted pulses for each acoustic path;
- status and measurement quality indicators;
- alarm and failure indicators;
- automatic gain control (AGC) levels on individual paths and number of samples used for calculation.

For Class 3 and Class 4 meters, these diagnostics should include the following for each acoustic path, with, additionally, an average where multiple paths are employed:

- axial velocity through the meter;
- speed of sound;
- signal strength/quality indicators;
- averaging time interval;
- data acceptance/rejection level;
- fault conditions;
- alarm conditions;
- AGC level.

6.6.5 Associated flow computer

The USM's output is typically an uncorrected volume, either per unit of time or accumulated. Therefore, an associated flow computer or corrector needs to be installed to correct for pressure, temperature, compressibility factor, accumulate volumes and curve fit correction. This will provide an integrated package to facilitate data retention and audit trails. Optionally, the manufacturer could be requested to integrate the flow computer functions into the USM's electronics unit.

For bi-directional applications, the USM should be treated as two separate meters, associated with two "meter runs" in a single flow computer or with two separate flow computers.

6.6.6 Flow computer calculations

Where the output of the USM is a frequency indicating volume flow rate, the equations used in the flow computer should be equivalent to those in BS 7834. These equations are corrected for pressure, temperature and compressibility of the gas.

Where the output of the USM is based on a digital link to the flow computer, then the algorithms to be used by the computer depend on the information supplied by the USM and the equations that should be used need to be as stated by the manufacturer of the USM.

6.7 Start-up recommendation

6.7.1 Field verification tests

The specifier/user should request a written field verification test procedure that allows the USM to be functionally tested to ensure that the meter is operating properly. These procedures can include a combination of a zero flow verification test, a speed of sound measurement analysis, individual path measurement analysis, internal inspection, dimensional verification and other mechanical or electrical tests.

The specifier/user should also request an uncertainty analysis from the manufacturer demonstrating that these field performance verification tests are sufficient to validate the meter's specified physical and electrical performance characteristics.

For Class 1 and Class 2 applications, some performance aspects of the USM's condition should be evaluated by comparing the speed of sound (SOS) reported from the meter against a SOS value calculated from BS ISO 20765-1. A chromatographic analysis from a sample of gas taken at the time of the SOS measurement is required for valid comparison.

The decision as to whether or not to perform periodic transfer proving or flow calibration should be left to the parties using the meter and any regulatory requirements.

6.7.2 Pre-flow checks

6.7.2.1 General

Prior to the flow of gas through a meter installation, particularly on new lines or lines that have been repaired, the line should first be cleaned to remove any rust accumulation or collection of pipeline debris. The meter should be removed during all hydrostatic testing and line cleaning operations to prevent damage to the transducers and to prevent altering the meter's physical dimensions, surface roughness or surface finish.

6.7.2.2 Over-range protection

Generally, USMs are able to withstand quite high over-ranging without suffering any internal damage but any manufacturers' recommendations should be followed.

6.7.2.3 Pressurization

As with all meters, USMs should be pressurized and depressurized slowly (shock loading by opening valves quickly can result in transducer damage). The installation of a small bypass round the upstream metering isolation valve can be used to safely pressurize the system to obtain operating pressure.

Every USM, complete with transducers and transducer isolation valves (if used), should have been leak tested by the manufacturer after final assembly and prior to shipment to the user or flow calibration facility. The test medium should be an inert gas, such as nitrogen. The leak test should be conducted at 1.5 times the design pressure or at a minimum of 13.8 bar, whichever is the greater, maintained for a minimum of 15 min, with no leaks detectable with a non-corrosive liquid solution or an ultrasonic leak detector in accordance with ASTM E1002-11 [N1].

NOTE This leak test does not preclude any requirements to perform a hydrostatic qualification test as detailed in pressure regulations, e.g. pressure testing to 1.5 times design pressure, welding certification, x-rays, etc.

Where the operator has to follow their company's own compliance procedure, this procedure should be supplied to the USM manufacturer.

6.7.2.4 USM bypass

If an interruption of gas supply cannot be tolerated, a bypass should be installed. If the gas needs to be continually metered (i.e. for custody transfer) then a stand-by meter should be installed so that the measurement can be maintained. With the introduction of multi-path USMs, some redundancy can be provided by the meter.

Where the installation of a bypass is permitted the bypass should be fitted with double block and bleed valves to confirm the integrity of the isolation.

6.7.2.5 Flow direction

The majority of USMs can flow in both directions. However, most USMs are calibrated in one direction only and therefore should be installed as a device that is sensitive to flow direction. For bi-directional applications, both ends of the meter should be considered upstream and particular attention should be paid to the thermowell fitting (see **5.4.5**).

6.8 Maintenance and inspection functions

6.8.1 Frequency of maintenance and inspection functions

*COMMENTARY ON **6.8.1***

The flow measurement uncertainty attributed to the USM is dependent on good system design and installation, and on good maintenance practice and adequate frequency of inspection. The time between meter inspections is dependent upon the level of confidence required, the gas conditions and any regulatory requirements. The need for higher levels of confidence and the use of meters in dirty gas conditions necessitate more frequent attention than when meters are used in clean gas or lower system integrity is required.

The design of the USM should be such that the flow measurement configuration parameters used by the SPU are made available for inspection.

Provisions should be specified to prevent an accidental or undetectable alteration of those parameters that affect the performance of the meter. Any changes made to the settings on the SPU printed circuit boards should be easily viewable; suitable provisions include a selectable switch or jumper, a permanent programmable read-only memory chip or a password in the SPU.

It should be possible to verify that all algorithms, constants, and configuration parameters being used in any specific meter are producing the same or better performance when compared with the specific meter's last flow calibration where some of the calibration factors can have changed.

NOTE The manufacturer might have to be relied upon for portions of this verification because of the proprietary nature of some USM algorithms.

6.8.2 Maintenance

The user should follow the manufacturer's recommendations for maintenance. Periodic maintenance can be as simple as monitoring several SPU diagnostic measurements, such as signal quality and speed of sound for each acoustic path. For example, it can be possible to detect an accumulation of deposits on the transducer faces by measuring a reduction in the received ultrasonic pulse strength.

When possible, the user should verify that the USM measures near zero when no gas is flowing through the meter. When performing this test, the user should bypass any low flow cut-off function, and be aware that any meter run temperature differences would cause thermal convection currents in the gas to circulate inside the meter which the USM might measure as a flow rate. As a precaution, bypassing the low flow cut-off function should only be done while the flow computers are in maintenance mode in order to inhibit the flow totalizers.

The manufacturer should provide values for acceptable path velocities for the meter under no flow, i.e. zero flow conditions; typically a few mm/s.

7 Ultrasonic flowmeter verification and calibration

7.1 General

COMMENTARY ON ***7.1***

There are two methods of testing:

- *static (dry) verification based on metrology of time and length;*
- *dynamic (flow/wet) calibration against an approved reference.*

One of the major advantages of USMs is that static verification depends only on the fundamental measurements of time and length. This can, in theory, offer the ability to verify purely from the meter dimensions and meter zero parameters (to establish accurate transit time measurements).

Like all flowmeters, USMs display a calibration offset within the bounds of combined static meter calibration and reference meter uncertainty limits when individually tested against a certified reference metering system. The dynamic calibration method allows correction factors to be applied to individual meters to improve measurement uncertainty to that approaching the reference metering system uncertainty.

Dynamic calibration has a significant cost impact at both the installation and operational stages as this requires shipping the meter to an approved test facility prior to installation and subsequently at defined regular intervals throughout the operational life of the meter.

There are two alternatives to reduce the need for discrete flow calibrations:

- *a master meter can be incorporated into the metering system, but the resultant uncertainty will be greater than for a primary calibration;*
- *a condition-based maintenance (CBM) system can be incorporated in the system design and use continuous operational data together with flow calibrations in early operational life to justify reducing the need for flow calibrations at a test facility – see Clause* ***8****.*

USM technology is developing and manufacturers are producing smaller bore meters and this imposes challenges for the verification of meters. For Class 1 and Class 2 applications, where optimum accuracy is required, dynamic calibration in association with CBM might be used.

All classes of meter should undergo a static verification to confirm the critical dimensions of the meter and position of the associated transducers.

For Class 1 and Class 2 applications, meters should be dynamically calibrated prior to installation and should be re-calibrated at regular intervals to ensure compliance. The period between calibrations is dependent on the service, financial risk and whether or not CBM has been implemented.

The degree to which calibration procedures are applied should be as shown in Table 5, and the associated required tolerances should be influenced by the class of meter being considered. The classes range from Class 1 (±0.7%), normally expected of fiscal type applications, through to Class 4 (±7.5%), typically required of flare gas, vent gas or some non-critical process metering applications.

Table 5 **Calibration options and applications**

Meter class	Metrology	Static verification	Zero flow verification	Dynamic calibration
1	✓	✓	✓	✓
2	✓	✓	✓	✓
3	✓	✓	✓	optional
4	✓	✓	✓	optional

7.2 Dimensional measurements

7.2.1 General

The recommendations within this subclause apply to both static verification and the flow methods of calibration. The user should ensure that the USM has the dimensions, properties and tolerances described in this subclause (this can be achieved by checking with the manufacturer).

7.2.2 Full and reduced bore meters

*COMMENTARY ON **7.2.2***

Class 1 and Class 2 applications need closely-controlled meter spool dimensions, normally implying the use of a spool piece construction with machined internal surfaces. Class 3 meters might require machined spools unless the requirement for not machining can be proved. Class 4 is a much more relaxed requirement and can be achievable employing non-machined commercially available pipe.

The average internal diameter of the meter spool within the measurement paths should be calculated from the arithmetic mean of a total of twelve inside-diameter measurements, or the equivalent determined by a coordinate measuring machine. Four internal-diameter measurements (one in the vertical plane, another in the horizontal plane and two in planes approximately 45° from the vertical plane) should be made at the following three meter cross-sections:

- near the set of upstream ultrasonic transducers;
- near the set of downstream transducers; and
- half way between the two transducer sets.

The meter spool internal diameter outside the measurement paths should be measured over at least two diameters (one upstream and one downstream) distributed in each of at least three cross-sections. No diameter in any plane should differ from the mean bore *D* by more than the amounts given in Table 6.

Table 6 **Internal diameter tolerance**

Class 1	Class 2	Class 3	Class 4
0.25%	0.3%	0.4%	1.2%

The parallelism of the meter bore and, where appropriate, the beam path ports, as well as the beam path lengths and the path angles (transducer inclination) should be determined by metrology.

If the acoustic path lengths or the axial distances between ultrasonic transducer pairs cannot be directly measured, then these distances should be calculated using trigonometry and the distances that can be measured directly.

Beam path lengths should have an uncertainty of no more than the values detailed in Table 7.

Table 7 **Tolerance for beam path length**

Class 1	Class 2	Class 3	Class 4
0.1%	0.15%	0.25%	1.0%

For Class 1 and Class 2 meters, the temperature at which the meter is measured should be recorded. This temperature can be used to calculate the correct diameter at the operating temperature. This correction should take account of the coefficient of thermal expansion for the meter spool material. The individual corrected lengths should be reported to the nearest 0.01 mm.

All instruments used to perform these measurements should have valid calibration certificates traceable to national standards.

These measurements and calculations should, for all classes of meter, be documented on a certificate, along with:

- the name of the USM manufacturer;
- the USM model number;
- the USM serial number;
- the ultrasonic transducer serial numbers and their relative locations in the meter body, if required by the meter design or manufacturer;
- the confirmation that the transducer ports, cables or electronic port/connectors are uniquely identified such that the path configuration data entered into the SPU can be validated;
- the meter body temperatures at the time the dimensional measurements were made;
- the date of calibration and the date the certificate was issued;
- the name of the individual who made the measurements and the name of the inspector, if present.

7.2.3 Insertion meters

*COMMENTARY ON **7.2.3***

For meters where transducer tappings are to be attached to existing pipework, internal diameter and concentricity can be determined from standard pipe tables appropriate to the pressure rating and corrosion allowances for the application. This is adequate for relatively new and/or clean service conditions, but for older pipe or pipe that has been fabricated and might not conform to standard pipe tables, it can be necessary to determine the mean internal diameter from circumferential measurements, and ultrasonic measurements of pipe wall thickness.

The mean pipe external circumference should be measured at three locations which at least encompass the cross-sections where the pipe wall thickness measurements are taken. The calculated external diameters should differ by no more than 0.4% from the mean. For large diameter horizontal pipes, such as can be found on refinery main flares, there is the possibility of ovality, and circumferential measurements might not be adequate to establish the effective internal diameter in respect of the transducer insertion depth at each tapping point. The use of large callipers or a dimensional survey using more sophisticated methods should therefore be considered.

The pipe wall thickness should be measured at least at two cross-sections (one at the upstream transducer tapping location and one at the downstream transducer tapping location) with at least three points distributed equally round the circumference to confirm the assumed pipe schedule. A closer grouping of four wall thickness measurements should be taken at each of the intended transducer tapping locations, to assist with precise calculation of final installed transducer depth. There should not be a difference greater than 1.5 mm/ 0.06 inch between the mean of the measured pipe wall thicknesses taken from each of the two intended transducer tapping locations. However, the flow meter manufacturer's own tolerance should take precedence, as wall thickness differences can ultimately determine transducer insertion depth and hence flow meter performance.

Correct transducer alignment is also critical to flow meter performance. Dimensional and angular positioning should be carefully controlled during the attachment of the transducer mounting hardware to the parent pipe, especially where such mounting hardware is welded directly to the parent pipe, as there is the possibility for significant movement and misalignment to occur at each stage of the welding process. Mechanical aids for attachment of mounting hardware as supplied by the flow meter manufacturer should always be used in strict accordance with their installation instructions. It is not only necessary to establish the final or "as built" separation between the transmitting faces of each transducer pair (acoustic path length), but also the axial separation of the effective acoustic path internal to the pipe. Angular tolerance of the defined angle should also be observed, in order that dimensional references made to the installed transducers after installation is complete are not undermined.

Flow meter precision is a function of dimensional and angular precision in respect of insertion transducers. The flow meter manufacturer should be asked to prescribe their "as built" tolerances required to uphold specified performance, but meeting those tolerances might require dimensional survey methodology (indeed, such methodology can be employed to "rescue" a poor installation by establishing the "as built" metrology after the fact).

7.2.4 Cartridge type meters

*COMMENTARY ON **7.2.4***

Cartridge meters consist of two sections, a meter body which will reside in the metering line and a measurement cartridge that can be removed. It is possible to exchange only the measurement cartridge rather than replacing the complete meter.

Prior to a cartridge being removed from the body, a meter logfile should be taken including set up parameters and current readings. The calibrated range of the new cartridge should match the current calibration range of the old cartridge unless a change in process conditions necessitates a change in range.

An exchange report should be compiled containing:

- date and time of exchange;
- meter serial numbers;
- confirmation that metrological seals are intact on the meter being replaced;
- confirmation that the metrological seals are intact on the new meter;
- meter readings on old meter at time of removal and new meter once installed.

7.3 Static verification

*COMMENTARY ON **7.3***

Static verification requires accurate determination of the meter body diameter, the acoustic path lengths and acoustic path geometry along with an accurate zero flow verification test to account for electronic and transducer time delays in the transit time measurement. Calibration also relies on the accurate and reliable measurement of the transit time for the ultrasonic signals. Pressure and temperature dependence of zero flow calibration can also be determined during static verification in addition to the zero flow verification.

7.3.1 General

Static verifications should be performed prior to the delivery and/or commissioning of a meter and should be periodically verified during the working life of the meter. Specifying close-coupled full-bore isolation valves should be considered to allow in-situ testing in the metering facility.

The static verification should be performed in a temperature stabilized environment and should include the measurement of the meter body dimensions and the time delays of electronics and transducers as well as a zero flow verification test. For Class 4 meters these tests can be conducted in the field where the meter is permanently installed.

In all cases, the certificate should document the following:

- the average internal diameter of the meter (see **7.2.2**);
- the length of each acoustic path between transducer faces;
- the inclination angle of each acoustic path or the axial (meter body axis) distance between transducers;
- the pipe wall thickness;
- the temperature at which the above measurements were made.

In-field checking of key dimensions such as surface roughness or cleanliness can be accomplished by inspection via the transducer ports. This need not be as comprehensive a check as is needed prior to meter delivery.

7.3.2 Static verification report

A report should be generated following completion of the static verification. This report should contain:

a) the date(s) of the test;

b) data of the manufacturer such as meter size and meter serial number, for the meter being tested;

c) a written description of the test procedure;

d) the nature (e.g. gas composition, humidity) and conditions (pressure and temperature) of the test gas;

e) measured speed of sound (MSOS) from the meter being tested and the theoretical speed of sound (TSOS) derived from gas composition, pressure and temperature of the test gas;

f) source reference for TSOS;

g) the log file containing all data taken during testing and/or calibration;

h) a record and parameter setting report;

i) a description of any variations or deviations from the required test conditions.

7.4 Zero flow verification test: controlled conditions

7.4.1 General

This subclause deals with the zero flow test carried out under controlled conditions, typically as part of the meter manufacture, in order to determine the transducer response and final electronic configuration of the meter. The specifier should check with the manufacturer that the procedures have been performed.

7.4.2 Test conditions

The following procedures should be carried out, according to the recommendations of Table 5 and **7.1**.

Zero flow verification tests should be determined at thermal equilibrium. This should be carried out with either:

a) the transducers mounted in the meter where blind flanges or close coupled isolation valves are to be employed in order to limit the secondary effects of convection on the meter output; or

b) alternative method of mounting the transducer pair in a calibration chamber can also be employed.

An important component of the absolute transit time is the average delay time, which is a composite function of a number of factors including cable type, electronics, transducers and waveform detection/processing. The average delay time should be determined for each transducer or transducer pair. Despite the efforts to determine the delta delay time as accurately as possible, a zero error might still be present in the USM (this applies whether the transducers are mounted in the meter or in a calibration chamber).

NOTE 1 In addition to the average delay time, the zero flow tests can also be used to establish any biases in the delta time computed under zero flow conditions. These delta time-zero biases can exist as a result of noise and/or non-reciprocal behaviour of the electronics, cables and transducers.

Delta times should be measured for each path in units of time under zero flow conditions, and can have positive or negative values. Normally, the electronics have the ability to store these values and subsequently subtract the bias from the measured delta time under flowing conditions. This can improve the accuracy of the flow measurements, especially at low velocities where the delta times are smaller and the zero bias would have greater effect. Any delta time corrections applied in the meter should be documented.

NOTE 2 In some instruments, switched mode electronics are used, such that a single, shared transmit and receive arrangement is used for both the upstream and downstream pulse transit time measurement alternately. Non-reciprocity of the electronics caused by any gradual change or ageing of electrical property within electronic components is effectively eliminated.

The user should periodically establish correct reciprocity in respect of transducers, cable and any associated devices, e.g. pre-amplifiers, using test cells and any other verification tools that the manufacturer might supply or recommend, whereby the effects of the process are eliminated and pure timing precision both upstream and downstream can be established.

7.4.3 Test with transducers mounted in meter

After blind flanges are attached to the ends of the meter body, the meter should be purged and pressurized with a test gas of known composition. The acoustic properties of the test gas should be well known and documented.

The gas pressure and temperature should be allowed to stabilize at the outset of the test. The gas velocities for each acoustic path should be recorded for at least 30 s, or a time equivalent to a minimum of 50 transit times measured upstream and downstream, whichever is the greater. The mean gas velocity and standard deviation for each acoustic path should then be calculated. Zero flow is defined when the standard deviation of the measured velocities at each acoustic path is of the same order as the meter-specified resolution.

Adjustments to the meter should be made as necessary to bring the meter performance into conformity with the manufacturer's specification.

NOTE It is difficult to perform a delta delay time calibration in-situ owing to the possibility of thermal currents causing "pseudo-flow" in zero flow conditions. Great care needs to be taken to ensure that a zero flow error is not incorporated into the measurement process.

7.4.4 Test with transducers mounted in a calibration chamber

*COMMENTARY ON **7.4.4***

Each pair of transducers can be tested in a small chamber of known dimensions. In such a chamber it is simpler to control zero flow conditions and this method has the advantage of lower usage of test gas. It offers the possibility of verification without taking the meter off line, assuming transducer extraction facilities are available with approved transducer port isolation and individual ultrasonic path redundancy capability within the meter.

An advantage of this type of method is that a calibration chamber can be constructed which can have one adjustable transducer, so that two known different path lengths can be used. This two-path length method eliminates the need to know the speed of sound (SOS):

$$VOS = \frac{L_1}{t_1 - \tau t} = \frac{L_2}{t_2 - \tau t} \tag{15}$$

$$\therefore \tau t = \frac{L_1 t_2 - L_2 t_1}{L_1 - L_2} \tag{16}$$

Where:

L_1 and L_2 are the test path lengths;

t_1 and t_2 are the measured times including delay times;

τt is the average transducer/electronic delay time.

For each test length, the pressure and temperature should be kept constant.

If the interface equipment (computer) provided with the meter has a facility for offsetting the impact of the systematic uncertainty introduced by the average delay times, then this should be applied. The SOS can then be checked across all chords for comparability with each other and the ascribed value for the test gas to within 0.1%.

If the measured SOS values are compared with theoretical values, the theoretically determined value should be computed using a complete analysis of the test gas comprising composition, precise measurements of pressure and temperature, and the application of the equation of state used in BS ISO 20765-1 in the case of Class 1 and Class 2 USMs. For Class 3 and Class 4 applications, confirmation of measured SOS values can be achieved using other recognized and proprietary software.

As part of the test procedure, the ultrasonic transducer serial numbers and their relative locations in the meter body should be documented. Also, the constants used by the meter (e.g. transducer/electronic transit time delays, τt timing corrections, acoustic path lengths, angles, diameters and other constants used in the calculation of the gas velocity for each acoustic path) should be documented.

If transducer constants vary for each pair of transducers, the constants associated with spare transducer pairs should also be determined.

To test for pressure and temperature dependence of the zero calibration, the chamber should be pressurized with nitrogen (N_2). The meter should be properly zero calibrated for the pressure and temperature range used during the test.

Either pressure or temperature can be kept constant and the remaining parameter varied within a pre-defined interval. There should be no manual adjustment of the meter during this test. The zero flow reading at each acoustic path should be within the specified zero flow reading over the entire temperature or pressure range used during the test.

All information for zero verification should be traceable.

NOTE For Class 4 meters, the relaxed uncertainty requirement can allow the zero adjustment to be carried out on the electronics and cables only providing that the transducers themselves are manufactured to high standards in a repeatable and predictable way such that the individual transducer delay times can be predicted. This method uses a test chamber with substitute transducers eliminating the need to withdraw transducers from the line.

7.5 Zero flow verification test: field conditions

*COMMENTARY ON **7.5***

This subclause describes the zero flow test that can be carried out as part of the field verification of the meter performance. The system would have to be taken off line for about 30 min but this could prove to be beneficial, particularly for Class 1 and Class 2 meters.

The zero flow test is carried out on a product, at operating pressure and zero flow conditions and isolated at the closest valves to the meter; once flow is confirmed to be zero the individual path velocities are measured. During the Factory Acceptance Test under controlled conditions, a limit of <±0.006 m/s for each acoustic path should be achievable when averaged over a period of not less than 100 s.

In the field under true, verified zero flow conditions, a limit of <±0.012 m/s for each acoustic path should be achievable when averaged over a period of not less than 100 s. If in any doubt, the manufacturer should be consulted.

NOTE The results of this test can give a quick indication of the condition of the individual pairs of transducers. Minor errors in path velocities have a small impact at high flow rates, i.e. high flow velocity, but at low flow rates the impact might be considerable and lead to mismeasurements.

If this test has been completed by the manufacturer or at a dynamic calibration, then a comparison should be made between the values obtained at a similar test undertaken when the meter was initially installed for service. This confirms that no faults or damage has occurred during transit.

This test should be performed prior to circulating currents developing within the meter as these affect the individual path readings.

Advice on the interpretation of results from this test should be sought from the manufacturer.

7.6 Dynamic calibration test

7.6.1 Nominal test flow rates

Two principal methods of calibration under flowing conditions are used:

a) laboratory flow calibration;

b) field flow calibration (not recommended for Class 1 or Class 2 meters).

The flow calibration delivers a set of systematic errors, as a function of flow rate (or Reynolds number), which can be used to correct the meter output. This set is usually presented as a “calibration curve”.

Where possible, the USM should be calibrated at a similar pressure and temperature to meter operating conditions. The difference in dimensions due to pressure and temperature deviations between calibration and operation can be corrected as described in **6.1.3**.

If a dynamic calibration is performed, the nominal test flow rates in Table 8 are recommended as a minimum.

Table 8 **Minimum nominal test flow rates**

Test point	Flow rate
1	q_{min}
2	10% of q_{max}
3	25% of q_{max}
4	50% of q_{max}
5	75% of q_{max}
6	100% of q_{max}

Other test point scenarios should be considered depending on:

- the operating range of the meter, which could be a limited sub-range of the meter, e.g. for a constant flow rate system; in this case the calibration will be between boundary rates that encompass the normally expected operating flow rate;
- the design turndown of the system.

7.6.2 Number of calibration data readings

For flow calibrations, a high level of confidence in the derived average run values at each test point is required. Statistically, the more readings taken, the greater the confidence in the average recorded flow rate value. For the greatest confidence in the average value at each test point, a large number of test run readings should be recorded, especially if there is scatter in the errors recorded for the test points. Observations show that the greatest scatter is most likely to occur at the lower flowrates.

When considering averaging calibration readings, a check should be made to see if the test facility is also averaging the flow rate readings over a time period to produce a single reading.

When a small number of readings are taken of the calibration error at each test point, the distribution of these errors could be very wide, giving poor confidence in the resulting average.

Experience has shown that:

a) with good calibration conditions with very low scatter, as a minimum, five test run readings of typically 65 to 100 s should be recorded for each test point; where extended test periods are utilized (typically 300 s) the number of test runs may be reduced;

b) for the lower flow rates, e.g. q_{min} to q_{t} (higher scatter and poor repeatability), consideration should be given to increasing the amount of test run readings.

A practical approach should be taken to consider the effect of taking additional readings on the average of the flow rate error. If the results have low scatter, then one more reading has very little effect on the average. However, if there is wide scatter, another reading will have a significant effect on the average value of the error, resulting in a requirement to take more readings to reduce the average value of the error.

An improvement cannot be guaranteed by taking more readings, especially if the scatter is very high, in which case both the USM and the test facility should be scrutinized to ensure that both are without any faults.

When a single resulting flow error is very far out of the range of the other test points, the Grubbs test [5] (also known as the maximum normalized residual test), for example, can be used to establish if a single test point is an outlier.

Table 9 shows a method for determining the required number of points similar to the proving methods set out in the API Manual of Petroleum Measurement Standards [6] (see, for example, Chapter **5.8** of this). Table 9 provides explicit targets for the uncertainty of the mean, consistent with the overall accuracy requirements laid out for each class of meter in Clause **4** and Clause **6** of this standard. With the target uncertainty values that have been used to create Table 9, up to nine test runs can be used before the spread will be outside of the repeatability requirement stated in Table 2. For low flows where the repeatability figure is doubled (see Figure 5 to Figure 8), Table 9 allows up to 20 points to be taken before the spread will be outside of the repeatability required of the meter.

An example of the use of this method for a Class 1 meter is shown in Table 10. The table shows the error values and the spread (max. to min.) calculated after three points and more.

From the table, after three test points the spread is 0.12%, which is greater than the value of 0.07% given in Table 9 for Class 1 meters, so more test points are required. The fourth test point gives a low error value and the spread increases to 0.15%. This is still greater than the 0.13% given for four test points in the table above, so still more points are required. The error from the fifth test point lies within the range of the previous four test points, so the spread has remained at 0.15%, which is now less than the corresponding value of 0.19% for five test points given in Table 9. At this point the uncertainty in the mean value is less than ±0.1% and the calibration can proceed to the next flowrate.

The spread to uncertainty conversion factor in Table 9 can also be used to estimate the uncertainty in the mean directly, simply by multiplying the spread by the conversion factor, as shown in the two right-hand columns of Table 10. Table 10 also clearly illustrates the diminishing effect of adding another test point as the number of points increases.

Simple statistical checks should be carried out on both the USM and reference meter flow rates to identify performance issues with the USM and/or test facility. For example, a large standard deviation in the reference meter readings indicates that the flow rate is not steady. This in itself might not be an issue but it would be preferable to have a stable flow rate. Likewise, erratic flowrate readings from the USM when the reference flow is steady could indicate a problem with the USM.

Table 9 **Spread or repeatability (max. error minus min. error) versus number of test points for a specified uncertainty in the mean**

Number of test points	Target uncertainty in the mean value (±%)				Spread to uncertainty conversion factor
	Class 1	Class 2	Class 3	Class 4	
	0.10	**0.125**	**0.175**	**0.25**	
	Maximum allowable spread (max. error to min. error) for given uncertainty in the mean value, %				
	Class 1	Class 2	Class 3	Class 4	
3	0.07	0.08	0.12	0.17	1.477
4	0.13	0.16	0.23	0.32	0.776
5	0.19	0.23	0.33	0.47	0.537
6	0.24	0.30	0.42	0.60	0.417
7	0.29	0.36	0.51	0.73	0.344
8	0.34	0.42	0.59	0.85	0.296
9	0.38	0.48	0.67	0.96	0.261
10	0.43	0.53	0.75	1.07	0.234
11	0.47	0.59	0.82	1.17	0.213
12	0.51	0.64	0.89	1.27	0.196
13	0.55	0.69	0.96	1.37	0.182
14	0.59	0.73	1.03	1.47	0.171
15	0.62	0.78	1.09	1.56	0.160
16	0.66	0.82	1.15	1.65	0.152
17	0.69	0.87	1.22	1.74	0.144
18	0.73	0.91	1.27	1.82	0.137
19	0.76	0.95	1.33	1.90	0.131
20	0.79	0.99	1.39	1.99	0.126

Table 10 **Effects of number of readings**

Test point	Error %	Running average	Spread %	Conversion factor	Uncertainty ± %
1	0.547 5	0.547 5	—	—	—
2	0.546 7	0.547 1	—	—	—
3	0.427 6	0.507 3	0.118 8	1.477	0.177
4	0.402 4	0.481 1	0.145 1	0.776	0.113
5	0.491 5	0.483 1	0.145 1	0.537	0.078
6	0.493 7	0.484 9	0.145 1	0.417	0.060
7	0.421 2	0.475 8	0.145 1	0.344	0.050
8	0.529 5	0.482 5	0.145 1	0.296	0.043
9	0.419 3	0.475 5	0.145 1	0.261	0.038
10	0.487 6	0.476 7	0.145 1	0.234	0.034

The only criterion applicable is that the flow rates should lie within a band of the expected flow rate for that test point. The test facility standard deviation for the flow rates at a single calibration point should be better than 0.25% (typical values are between 0.1% to 0.25%). Any values greater than 0.5% for the standard deviation for the test facility flow rate at any single calibration point implies that the flow rate is not stable and is either climbing or falling during that test.

In addition to the meter performance under flowing conditions, the meter response under no flow conditions should also be recorded, i.e. a zero flow check as described in **7.5**. The additional data set will prove useful during field verification testing in identifying possible faults on individual path transducers during meter service.

NOTE 1 These data may form part of the certification.

It is recognized that it might not be possible to test large USMs up to their maximum capacity because of the limitations of currently available test facilities. In such cases a lower flow rate instead of q_{max} should be specified. It should be stated on all applicable documents if a reduced q_{max} was used during flow calibration tests. For Class 1 and Class 2 applications, meters should not be operated above the maximum calibrated flowrate, i.e. no extrapolation above the maximum calibrated flowrate.

NOTE 2 However, if all parties agree, extrapolation may be considered if the amount of additional uncertainty associated with the extrapolation is acknowledged and acceptable.

Flow calibration tests should be performed at a gas density near the expected operating condition. Flow calibration at other test flow rates and/or a specific test pressure, temperature or gas density range may be specified. If it is considered that the upstream piping configuration will influence the meter performance, then specific piping configurations and/or flow conditioners should be specified and used during the flow calibration tests.

7.6.3 Preparation for meter dynamic calibration

The meter should have been inspected at the calibration facility for any obvious physical damage that might have occurred during removal and transportation. It should also be confirmed that the physical meter configuration matches the declared configuration for the meter. The functionality of the SPU should also be verified prior to a zero flow check.

For Class 1 and Class 2 meters, which are subjected to dynamic calibration, the internal bore of the meter and transducers should not be cleaned prior to the calibration. Providing the degree of contamination does not impact the operation of the meter and is not likely to contaminate the test facility, it should be left in place.

NOTE 1 It has been found that USMs generally build up a thin coating of contaminants, e.g. dust or oil, and the thickness of this layer becomes self maintaining.

Following calibration, the meter should be returned to service and a history of calibration responses built over time without any cleaning of the meter.

NOTE 2 Trend analysis of the meter's calibration responses over time usually indicates that the response fluctuates about a set response level.

In cases where the degree of contamination is deemed to be excessive, then an "As Found" calibration should be performed, if possible, prior to any cleaning in order to provide data for a potential retrospective mismeasurement calculation (see Annex A). Once complete, the meter should then be thoroughly cleaned and the calibration repeated to produce an "As Left" certificate for future service.

If the degree of contamination remains high over time, then investigations should be made to identify the source and implement remedial actions to reduce the problem.

For Class 1 and 2 applications (and wherever practicable for other classes), the meter's upstream and downstream meter spools or dedicated calibration spools and/or flow conditioners (when applicable) should be used during the flow calibration. The upstream flange and piping internal diameters should match and be aligned with the meter being flow tested in accordance with **5.4**.

For meters >4 in, a typical tolerance of ±0.3% of FWME (flow weighted mean error) should be allowed between subsequent calibrations. For meters ≤4 inches, the allowable shift is 0.5% of FWME.

7.6.4 Meter flow verification criteria

All test measurements performed by a flow calibration facility should be traceable (with current calibration certificates) in accordance with BS EN ISO/IEC 17025. Any thermophysical values (e.g. density, compressibility, speed of sound, critical flow factor) used during flow calibration should be computed using appropriate gas property routines such as those in BS EN ISO 12213-1, BS EN ISO 12213-2 and BS ISO 20765-1.

NOTE As a guide to levels of gas flow metering reference uncertainty, laboratory intercomparisons by Tedeschi et al GERG [7] show that for high pressure gas test facilities the reference uncertainties at 95% confidence limits agree within ±0.25% of each other. During testing, short term repeatability is of the order of 0.1% with long term reproducibility in the order of 0.15%.

It is recommended that (unless in-situ gas provers are available) dynamic calibrations for Class 1, Class 2 and Class 3 meters are performed by transfer of the meter to an approved calibration facility. However, for Class 4 meters, it is acceptable to confirm meter calibration against other reference metering techniques and indeed it might be the only possible route to take (e.g. flare or vent gas meter with tapped transducers into existing pipework). Typical reference metering methods used are: known gas injection (e.g. by calibrated meters such as orifice plates) and flow tracer techniques (e.g. nucleonic tracers, dilution tracers).

Using in-situ flow testing introduces difficulties in obtaining and/or controlling flow rates and conditions at the meter under test and it is not usually practical to test at anything more than one or two flow rates at the most. Known gas injection uncertainty of reference should be of the order of 2% and flow tracer uncertainty can be as high as 5%.

7.6.5 Path failure simulation and exchange of components

Where a Class 1 or Class 2 meter remains in service in the event of path failure, the effect of the failure should be determined during meter calibration by simulating the failure of one or more paths. The test should be carried out at or around the mid-point of the expected operating range of the meter. During the test, the flow rate should be varied by 20% of the flow rate to ensure that the meter responds appropriately.

The manufacturer should demonstrate the capability of the meter to replace or relocate transducers, electronic parts and software without a significant change in meter performance. This should be demonstrated for:

a) the electronics;

b) transducers of different path types.

When components are exchanged, the resulting shift in the FWME of the meter should not be more than 0.2%.

7.6.6 Calibration data dossier

It is important that any meter flow re-calibrations, i.e. calibrations after the pre-service calibration, replicate the original calibration. Information required to ensure that successive calibrations are comparable should be contained in a calibration dossier or "data pack".

The dossier/data pack should contain the following:

a) details of the meter, e.g. size, class, manufacturer, serial number(s) and max. range;

b) calibration flow rates and number of runs per point;

c) reference meters used and position if not in a standard position;

d) any calibration spools used with the meter and their identification numbers;

NOTE 1 The majority of users are likely to have spool sets dedicated to a particular size and rating of meter but in the future it is possible that test facilities might have their own or that there might be an agreement between users to "share" meter spools sets.

e) the layout of the test rig detailing the spools used and the position of any reducers;

f) whether a flow conditioner is used, the type and the position in which it is installed;

g) meter alignment details, in accordance with **5.4**;

h) specific user requirements;

i) a written description of the test procedure;

j) the USM configuration and a log of its performance during calibration, to be compared for when it is in service.

NOTE 2 It might be necessary in some cases where corrections are applied at the meter head, to remove the correction in order to re-calibrate the meter.

The provision of the dossier/data pack provides an auditable trail for recalibrations and should be kept with the meter records.

7.6.7 Calibration certificate

An individual calibration of each meter can be made, depending on class requirements. The results of this calibration should be available on request, together with a statement of conditions under which the calibration took place.

The calibration data provided should include:

a) the errors at the specified test flowrates and where applicable the associated meter K-factors at those flowrates;

b) in the case of bidirectional meter applications: "forward flow" or "reverse flow";

c) in the case that the error for $q_{\max}$ has not been determined by flow testing, then "limited calibration" should be annotated on the certificate;

d) the value of the meter factor before adjustment and the value after adjustment;

e) the value of the meter factor matching the calibration results or a statement making clear which of the meter factor values matches the calibration results;

f) data of manufacturer, owner, calibration facility and meter being tested;

g) a report of the meter's software configuration parameters;

NOTE For clarification purposes, this might be with the post calibration final adjustment factor if this method of correction is employed.

h) the date(s) of the test;

i) the method of calibration (bell prover, sonic nozzles, other meters, etc.) and include the reference meter(s) identifier(s) and serial number(s);

j) the estimated uncertainty of the calibration results;

k) the position of the meter (i.e. horizontal, vertical flow upwards, vertical flow downwards);

l) the upstream and downstream piping configurations, including piping tag-numbers;

m) for a Class 3 or a Class 4 meter, where the individual meter has not been dynamically calibrated, the certificate should indicate how the meter factor has been obtained;

n) the nature (e.g. gas composition) and conditions, (pressure and temperature) of the test gas;

o) a description of any variations or deviations from the required test conditions;

p) the results of the zero flow test;

q) if applicable, the speed of sound of meter under test and also the velocity of sound as calculated from gas composition, pressure and temperature.

7.7 Meter factor adjustment

If a meter is dynamically flow calibrated, the meter factor(s) should normally be adjusted. Possible methods of applying meter factor(s) are:

a) by using weighted mean error (WME) over the meter's expected flow range (an example calculation of WME is shown in Annex B);

b) by using multi-point linearization algorithms over the meter's calibrated (operational) range;

c) polynomial algorithms over the meter's range of flow rates (least preferred option since they do not always fit the data well enough).

NOTE For bi-directional calibrations, a second set of factors can be used for reverse flow.

Where single point corrections are applied to Class 1 and Class 2 meters, the spread of the error points should be less than 0.1% across the operating range. If this condition cannot be met then an alternative correction algorithm should be used, e.g. linearization tables.

To optimize the meter's overall accuracy performance, if a zero offset was established during flow calibration, it might have to be revised based on the results of the flow calibration. The manufacturer should be asked to document such a change in this factor and alert the user that the zero flow output might have some intentional bias in order to improve the accuracy at q_{min}.

Any meter factors derived from the supplied dynamic calibration data should be entered in the flow computer, not the meter electronics, except for the first calibration which effectively removes the effects of manufacturing tolerances and incomplete theoretical assumptions from the meter's behaviour. This allows calibration repeatability to be easily tracked, thus any systematic bias being generated over time can be determined.

7.8 Calibration relaxation

Where a Class 1 or Class 2 meter is subjected to regular recalibration, consideration should be given to extending the period between calibrations.

Relaxing the calibration frequency has the added advantage of reducing meter handling and transportation which can lead to meter damage. Reducing calibration costs is not of itself a valid reason to relax calibration frequency as the potential increase in measurement uncertainty will have a far greater financial risk.

A relaxation might be appropriate when:

a) a meter has completed two successive recalibrations, i.e. three calibrations in total;

b) none of the individual calibration shifts have exceeded a predetermined tolerance;

c) no significant systematic trend is evident, i.e. calibration “drift” is not in the same direction;

d) there is a satisfactory performance as reported by a CBM system (where employed).

The first three conditions should be met, and the fourth should be met where CBM is employed.

If the meter recalibration shift does not exceed the predetermined tolerance at the next calibration, the meter might qualify for a further relaxation in the service period between calibrations.

If the shift at any future recalibration exceeds the predetermined tolerance, then the service period between calibrations should revert back to the initial service period. Relaxation is dependent on agreement by all interested parties.

7.9 In-situ verification (Class 3 and Class 4 meters)

7.9.1 General

Where no possibility exists for any viable form of dynamic testing, the functionality of the USM can be confirmed via several techniques.

7.9.2 Methods of in-situ verification

7.9.2.1 Velocity area method by means of pitot tubes, hot film/wire sensors or anemometers

The velocity area method is based on the approximate measurement of the velocity profile of the flow with suitable integration across the flow cross-section. As this technique involves effective sampling of the flowing velocity profile, a constant flow should be assured throughout the verification process. However, this might not be possible in some applications.

7.9.2.2 Optical method

The LDA (Laser–Doppler Anemometry) is based on a point-by-point measurement of the velocity profile by means of light scattering particles. Since sequential point-by-point measurement over the flow cross-section is required, this method can only be applied in applications on which a constant flow can be maintained for the period of the test.

7.9.2.3 Tracer method

The tracer method involves the injection of small amounts of a radioactive isotope into the gas line, where it mixes with the gas itself adopting the same flow profile, after which it passes two strap-on detectors. These detectors are located at a sufficient distance downstream of the injection point, and are spaced apart along the gas line at a known distance. It is essentially a tag time of flight technique measuring fluid flow velocity. A gas line where there is a shortage of suitable straight pipe run would not be a good candidate for this technique as many diameters of straight pipe run, typically ten to twenty depending upon flow conditions, are required for mixing, and then typically five to ten diameters for the measurement itself. Whilst acceptable uncertainty is possible, it requires that all stipulated installation conditions are satisfied, which can be difficult to achieve on larger diameter pipes, such as flare/vent gas lines. The technique can require extended straight pipe runs to maintain acceptable accuracy at low flow velocities. Consideration should also be given to the practical duration of the test, i.e. inclusive travel time to the location of the in-situ verification in addition to the work itself, as the radioactive isotope will have a finite half-life.

7.9.2.4 Zero flow box

This involves the removal of the transducers from the meter and placing them in a chamber, similar to that described in **7.4.4** and measuring the flow offset under no flow conditions. This offset is then applied to the flow computer configuration to correct the operation flow rates. This is included under the in-situ verification as the meter has not been removed from its installed location and the transducers remain connected to the transmitter.

7.9.2.5 Absolute speed of sound comparison

When the gas composition, temperature and pressure are known, the theoretical speed of sound (TSOS) can be compared with the measured speed of sound (MSOS) as indicated by the USM. For example, injecting nitrogen into a flare or vent line provides a relatively easy method of determining TSOS as the gas is well understood and not affected by process changes. The TSOS can be calculated from measured values of pressure, temperature and gas composition using an equation of state (see BS ISO 20765-1). Proprietary software is available to calculate TSOS.

In applications like flare gas, where gas composition can change dramatically and rapidly, the synchronization of the USM indication of MSOS and the sampling chronology for gas composition is critical to the validity of an absolute speed of sound comparison. A log of MSOS from USM with time and date stamp should be used.

An unacceptable difference between MSOS and TSOS values, e.g. >0.25%, should initially prompt checks of pressure and temperature data sources, but also investigation into the sampling technique and methodology for the gas composition. When these aspects of the comparison have all been validated, an inspection of the transducers should be made to ascertain whether deposition or fouling from gas-born contaminants has occurred.

7.9.2.6 Relative SOS comparison

A USM with two or more paths can be monitored by comparison of the SOS values per path.

The advantages are:

- it is independent of the gas composition;
- the measurement can be performed under flowing conditions; at high velocities acoustic path length might change, thereby increasing the discrepancy if the flow profile is seriously distorted;
- the calculation can be automatically done as part of a diagnostic package.

7.9.2.7 Velocity ratios

The individual path velocities of a multi-path USM have unique relationships reflecting the flow profile that is dominated by the pipe configuration. At velocities higher than 1 m/s to 2 m/s, these relationships do not change significantly over time in normal USM operating conditions, and therefore they can be monitored on-line as a diagnostic tool.

7.9.2.8 Other parameters

Although the speed of sound (SOS) is one of the most important parameters to be used in verification, there are many more parameters which can be indicated by the USM and these can be monitored in order to ensure optimum USM performance. Combinations of these might serve as the basis of an expert system.

7.9.2.9 Oscilloscope timing check

With transducer face to face dimension(s) and axial component of acoustic path dimension(s) confirmed, it is possible to validate the USM timing measurements through the use of an oscilloscope. The raw, unprocessed signals can be viewed by oscilloscope to establish upstream and downstream transit times and "delta t". The flow velocity can be calculated by hand and compared to the readings delivered by the USM after processing. This procedure should only be carried out by a skilled technician with an in-depth knowledge of the subject USM. The operator should almost certainly seek assistance from the manufacturer's service technician.

7.9.2.10 Computational fluid dynamics (CFD)

The use of CFD to verify meter performance of flow meters in Class 4 applications has been proven to provide a good assessment of flow rate.

7.9.2.11 In-situ verification report

A report should be generated following completion of the in-situ verification activities. This report should contain:

- the date(s) of the test;
- data of manufacturer such as meter size, meter serial number etc. for the meter being tested;
- a written description of the test procedure;
- the nature (e.g. gas composition, humidity) and conditions (pressure and temperature) of the test gas, inclusive of time and date for comparison with USM data log;
- MSOS from meter being tested and TSOS derived from gas composition, pressure and temperature of the test gas;
- source reference for TSOS;
- the log file containing all data taken during testing and/or calibration;
- a diagnostic report of the meter's software configuration parameters during testing;

- the values of adjustment-factors in the configuration of the USM before adjustment and the value after adjustment;
- a description of any variations or deviations from the test conditions required.

8 Condition-based maintenance (CBM)

8.1 General

In most cases, the current basis for maintenance activities is time in service. However, recent advances in USM technology and a greater understanding of the diagnostic capabilities inherent in gas USMs should allow a move to a risk based approach. To this end the use of condition-based maintenance (CBM) should be considered.

8.2 CBM – meter diagnostics

Gas USM meter diagnostics can be classified depending on the type of information that they provide:

- system performance (information pertaining to the overall measurement system);
- functional (information pertaining to the meter transducers and electronics);
- process (information pertaining to the fluid properties in the pipe, e.g. flow profile).

At the time of publication, due to lack of available data, none of the CBM diagnostics are able to provide a quantitive value for a shift in meter performance. They do, however, provide qualitive data that can form the basis of any decision made to remove a meter from service for recalibration.

8.3 CBM – speed of sound

Speed of sound (SOS) can be used to give an indication of the health of the measurement station as a whole. For an installation where an on-line gas chromatograph (OGC) is installed, the MSOS can be continually compared with that calculated from the gas composition derived by the OGC, together with an equation of state (see BS ISO 20765-1) and the measured temperature and pressure of the gas.

Deviation between the “measured” and “calculated” SOS greater than 0.21% might indicate errors in the measurement of temperature and/or pressure, in the operation of the OCG, or in the operation of the USM. Cross-checking with the other diagnostic features should enable the source of any discrepancy to be determined with relative ease. Conversely, where the deviation is at its minimal level (0.21% or less), there is a very clear indication that all the elements of the system (USM, OGC, temperature and pressure measurements) are operating satisfactorily. Intra-chordal comparisons of SOS against the average can provide an indication of a potential fault with any individual meter chord. Similarly, comparison of the average of the measured SOS against calculated SOS is possible, and the “footprint” of these, determined at the meter’s initial calibration, might usefully be compared with that produced by the meter throughout its time in service.

8.4 CBM – automatic gain control

Automatic gain control (AGC) is used to make the received signal amplitude the same, irrespective of operating conditions. The main purpose of AGC is to achieve consistent zero crossing detection for accurate timing, but the actual value of the gain is also a useful diagnostic, indicating the level of attenuation along the path. The gain depends on gas composition, pressure, velocity, path length and contamination. The AGC level should be compared against the AGC limit. As meter performance deteriorates the AGC level will increase until it reached its maximum permitted value. At this point the meter chord will no longer be able to make a measurement and will go into fault.

8.5 CBM – signal-to-noise ratio

Signal-to-noise ratio (SNR) provides limited data in use due to varying factors which can influence it. Generally however it can be used as an indication of the quality of the ultrasonic signals received. The distribution of SNRs among the transducers might indicate the source of some metering problems as they arise. For example, differences between the upstream and downstream SNR suggests the possible presence of an ultrasonic noise source, often a control valve with a large pressure drop. The receiving transducers facing the noise source will have a lower SNR than those facing away from it. The presence of a control valve or other source of ultrasonic noise can be confirmed by examining the physical layout of the metering station. If all transducers show a low SNR, the problem might be due to electrical noise. If only some transducer pairs show noise, and it appears on both up- and downstream signals, the transducers could be acoustically coupled to the meter body by liquid in the ports.

8.6 CBM – performance

Performance is defined as the simple arithmetic ratio of good pulses received to pulses rejected. Meter performance will generally decrease as the flow rate increases. Performance is also reduced by a decrease in line pressure.

8.7 CBM – flow profile

Depending on the meter path configuration, a number of techniques are possible whereby the flow profile at the meter can be determined. Measurements can include the shape and symmetry of the flow profile, the degree of “cross flow” and/or swirl, and a statistical estimation of the degree of turbulence of the flow. A change in the flow profile can indicate a change in the fluid viscosity, and/or a change in the pipe wall roughness. Cross-checking with other diagnostic features can enable the operator to determine the source of the change and to assess its significance. Where flow conditioning devices are installed, the flow profile will indicate any blockage or fouling of the profiling device.

8.8 CBM – temperature

For certain meter path configurations it is possible to carry out intra-chordal checks within the gas stream against the measured temperature. A difference between the measured and the average of the chordal temperatures can indicate a possible fault with the measured temperature. Variances in temperature between the meter chords can indicate stratification in the gas flow. This can have an effect on the calibration of USMs at the lowest flow point.

8.9 CBM strategy

Where it is proposed to adopt a condition-based maintenance strategy, users should contact the appropriate regulatory authority and the system/pipeline operator with details of the meter station under consideration. The following information should be presented for review:

- meter type (including details of transducer and electronics used);
- meter calibration history following the initial period of time-based intervention and calibration;
- details of the associated instrumentation (e.g. gas chromatograph) together with an indication of the historic stability of the relevant devices;
- typical throughput of the meter station;
- the typical cost of removal and recalibration of the meter.

Annex A (informative) Application of flow calibration results

A.1 General

Depending upon the use of the ultrasonic flow meter, particularly Class 1 and Class 2 applications, there might be a requirement to apply retrospective corrections to measurements made by the meters or, alternatively, seek an increase to the calibration period as detailed within **7.8**.

This Annex provides guidance to cover these elements of USM operation.

A.2 Setting predetermined tolerance

The predetermined tolerance applied to the results of the meter calibration is dependent on factors describing the meter and test centre performance together with any contract or commercial agreement applicable to the meter installation. In general terms, the predetermined tolerance is calculated as follows:

$$USM_{tol} = \sqrt{\left[\left(testcentrefactors\right)^2 + \left(USMfactors\right)^2\right]} \qquad (A.1)$$

where the factors in terms include elements relating to (but not limited to) repeatability and reproducibility.

A.3 Applying predetermined tolerance

Applying a “final daily correction (%)” based on a “predetermined tolerance” is unique to USMs. This method of correction challenges conventions applied to other measurement devices. The procedure is to apply Equation A.2 as part of the daily mismeasurement process.

$$\text{Final daily correction (\%)} = (\text{daily correction (\%)} - \text{USM}_{\text{tol}}) \qquad (A.2)$$

The application of the “final daily correction (%)” is dealt with in **A.5**.

The argument supporting the derivation and application of the final daily correction (%) is based on the premise that, without such a mechanism, a USM having a daily correction (%) marginally below the predetermined tolerance (USM_{tol}) is not subject to a mismeasurement correction, whilst a meter having a daily correction marginally above the USM_{tol} is subject to the full daily correction as part of a mismeasurement for that day. This is not considered fair, so the proposal is to apply the final daily correction which represents only that proportion of the daily correction that exceeds the predetermined tolerance.

A.4 Procedure for identifying a mismeasurement

A.4.1 General

The procedure starts before the meter is removed and is completed with a decision on whether a mismeasurement is present or not.

A.4.2 Perform full diagnostics check of meter

Prior to removal of the meter, perform a full diagnostic check and obtain a data log file. Complete this on-line at flowing and zero flow conditions prior to the meter being removed from service. This gives an indication of the state of the meter before it is depressurized, removed and shipped to the test centre.

A.4.3 Evaluate the meter operating range

Carry out an evaluation of the operating range of the meter during its most recent service period. This allows the calibration points that relate to the meter's operational range to be identified. It might also highlight a need to change the calibrated range. Present systems tend to be designed on a 10:1 turndown, so if the maximum velocity is, e.g. 20 ms^{-1}, then Q_{min} = 2 ms^{-1}. There might be no benefit in testing at 1 ms^{-1}, as this is outside the flow range.

A.4.4 Flow calibration of the USM

Perform the calibration in accordance with the recommendations of **7.6**.

A.4.5 Review meter performance curves

Assess the new and previous meter performance curves (i.e. the curve shapes) for acceptability or requiring further investigation. Generally, it is expected that the shape should be similar for successive calibrations.

A.4.6 Calculate meter shift or "drift"

Using the defined operating range (**A.4.3**), find the arithmetic average shift of the relevant calibration points between new curve values and old values. This determines the meter shift value. Compare this with the predetermined tolerance.

A.4.7 Mismeasurement determination

If the meter shift is greater than the predetermined tolerance and the calibration is deemed valid, then a mismeasurement determination is required (**A.5**). If the meter shift is less then the predetermined tolerance, then no mismeasurement is required. Return the meter to service and apply either a single point correction or full linearization data set using point error values from current calibration.

Two points to note are:

- the service period is taken as the meter when under flow, not the installed period;
- checks made on repeated calibrations enable retrospective correction for any long-term issues such as drift.

A.5 Procedure for the application of a mismeasurement

A.5.1 General

For Class 1 and Class 2 meters, it might be necessary to apply a retrospective mismeasurement. The procedure in this subclause can be used for this purpose.

Once it has been determined that a mismeasurement calculation is required, a number of steps are applied to calculate the overall mismeasured quantity.

A.5.2 Calculate daily correction (%)

The mismeasurement is derived from an assessment of the daily production through the meter. An average flow rate for each day of the service period is derived and a daily correction calculated. This daily correction is derived using linear interpolation between the two relevant error points from the new calibration certificate.

A.5.3 Calculate final correction (%)

The final correction (%) is the daily correction (%), from **A.5.2**, minus the predetermined tolerance (USM_{tol}). Equation A.3 states this mathematically:

$$\text{Final correction (\%)} = [\text{daily correction (\%)} - USM_{tol}] \qquad (A.3)$$

A.5.4 Calculate daily mismeasurement

A.5.4.1 Period of mismeasurement

The mismeasurement is based on the production the meter has measured during its service period since the start of the meter deficiency.

A.5.4.2 Known date of deficiency

If it is known when any shift occurred, then derive the mismeasurement for all of the affected production from that point.

A.5.4.3 Unknown date of deficiency

If the date when the deficiency occurred is unknown, then apply the shift to the affected production since the meter entered service, the last known good status, based on the commonly accepted "divide by two" rule. The difference in this procedure is that the daily production is divided by two, not the time (service) period.

NOTE This is contrary to a number of commercial agreements that explicitly state the latter condition.

Equation A.4 states this mathematically:

$$\text{Daily mismeasurement} = \text{Final correction (\%)} \times (Q_{production} /2) \qquad (A.4)$$

Applying this method for the calculation of mismeasurements is considered fair and equitable; it obviates the need to question flowing periods when production is not continuous and does not adversely penalize a metering station for exceeding tolerance. An example calculation is given in **A.6**.

A.6 Worked example of a mismeasurement calculation based upon average daily data

Table A.1 gives some example flow calibration results.

Table A.1 **Sequential flow calibration results**

First calibration		**Second calibration**	
Flow rate m^3/h	Error %	Flow rate m^3/h	Error %
200	–0.46	200	–0.91
400	–0.37	400	–0.88
1 000	–0.52	1 000	–0.96
1 500	–0.48	1 500	–1.04
2 500	–0.24	2 500	–0.91
4 000	–0.56	4 000	–0.95

Range of daily production the meter has been subjected to during its period in service:

600 m/h – 2 100 m^3/h.

Average meter shift (using the pertaining flow points):

[Average (–0.37, –0.52, –0.48, –0.24)] – [Average (–0.88, –0.96, –1.04, –0.91)]

= –0.55%

Predetermined tolerance = ±0.30%

NOTE The predetermined tolerance percent is an estimate for illustrative purposes only and is subject to the accuracy associated with the calibration facilities and the uncertainty associated with the meter and its installation.

DECISION: A mismeasurement report is initiated, as the average meter shift is greater than the predetermined tolerance.

Quantify all days on an individual basis; an example of one day follows.

EXAMPLE

Day 1: Average flow rate = 1 250 m^3/h = 30 000 m^3/d

Average correction (%) from first calibration at 1 250 m^3/h: linear interpolation is applied to the two pertaining points –0.52% and –0.48% to give –0.50%

Average correction (%) from second calibration at 1250 m^3/h: linear interpolation is applied to the two pertaining points –0.96 and –1.04 to give –1.00%

Daily correction (%) to be applied = 0.5%

Final correction (%) = (0.5 – 0.30) = 0.20%

Day 1: Mismeasured quantity = final correction × (average daily flow rate/2)

= 0.20% × (30 000/2) m^3

= 30.0 m^3.

Annex B (informative) Methods for correcting a USM's flow measurement error at flow calibration

B.1 Introduction

The total flow measurement error of a USM consists of two parts:

- type A (or precision error) uncertainties; and
- type B (or bias error) uncertainties.

Type A uncertainties can be caused by various influences on a meter's operation. They normally, but not always, follow a certain statistical distribution. The magnitude of the random error can usually be reduced by acquiring multiple measurement samples and applying accepted statistical analysis principles to the data. Type B uncertainties normally cause repeated USM measurement readings to be in error by roughly the same amount. In most cases, flow calibration of a USM can help eliminate or, at least, minimize the Type B measurement error of the meter with respect to the reference used.

Due to machining tolerances, variations in component manufacturing processes, variations in the meter assembly process and other factors, each USM has its own unique operating characteristics. Thus, to absolutely minimize a particular USM's flow measurement uncertainty, the manufacturer can flow calibrate a USM and then use the calibration data to correct or compensate for the meter's measurement error. More than one error correction technique is available to the manufacturer depending on the meter application and the needs of the operator.

The following is a description of an error correction technique that uses a single meter correction factor: the flow weighted mean error (FWME) factor. If a USM's flow measurement output is very linear over the operational flow range of the meter, the FWME correction method is effective at minimizing the measurement uncertainty of the meter. Other meter-factor correction techniques are also available, such as linearization.

Before calculating FWME, it might be appropriate to determine the zero error from the flow calibration results and to apply this in such a way that the deviation curve becomes as flat as possible. After determining and applying the zero error, the FWME can be determined as detailed in **B.2**.

B.2 Example of a flow weighted mean error (FWME) calculation

The calculation of a meter's FWME from actual flow test data is an internationally agreed method of calibrating a meter, when only a single meter correction factor can be applied to the meter's output. Application of this factor to a USM's output is analogous to the use of an index gear ratio in a turbine or rotary flowmeter. As noted in **B.1**, use of the FWME factor is only one of several alternative methods of adjusting a USM's calibration to minimize the flow measurement uncertainty of the meter.

The following example demonstrates how to calculate the FWME.

EXAMPLE

A 200 mm diameter USM has been flow calibrated (see data set in Table B.1) under operating conditions similar to those that the meter would experience during field service. A calibration factor (a flow measurement error correction factor) is determined and then applied to the test results such that the resulting FWME is equal to zero.

Table B.1 **Example flow calibration data table for 200 mm diameter USM**

Standard test rate	**Nominal test rate**	**Actual test rate from reference meter (q_i)**	**Actual rate from test meter (q_t)**	**USM error**
% q_{max}	m³/h	m³/h	m³/h	%
q_{min}	950	930	938.862 9	+0.953 0
10% q_{max}	1 900	1 870	1 877.031	+0.376 0
25% q_{max}	4 750	4 370	4 714.959	–0.318 0
50% q_{max}	9 500	9 450	9 420.233	–0.315 0
75% q_{max}	14 250	14 200	14 147.18	–0.372 0
100% q_{max}	19 000	18 500	18 437.84	–0.336 0

The FWME for the data set presented in Table B.2 is calculated as follows:

$$FWME = \frac{\sum_{i=1}^{n} \left(\frac{q_i}{q_{max}}\right) \times E_i}{\sum_{i=1}^{n} \left(\frac{q_i}{q_{max}}\right)} \qquad (B.1)$$

Where:

q_i/q_{max} is a weighting factor (Wf_i);

E_i is the indicated flow rate error (in percent) at the tested flow rate, q_i.

NOTE An alternate method for computing the FWME that decreases the contribution of the highest flow rate point can be calculated by using a reduced weighting factor, such as 0.4, when $q_i \geq 0.95\ q_{max}$. Different weighting factors, depending on whether the meter is run mostly in the lower, mid or upper range of flow may be used.

Applying this equation to the test data in Table B.1 (q_{max} = 19 000 m³/h) produces the results shown in Table B.2. Note that a column labelled Wf_i is used to show the weighting factor that is applied to each E_i value.

Table B.2 **Flow weighted mean error calculation**

q_i	$Wf_i = q_i/q_{max}$	E_i	$Wf_i \times E_i$
938.862 9	0.049 414	+0.953 0	0.047 091
1 877.031	0.098 791	+0.376 0	0.037 145
4 714.959	0.248 156	–0.318 0	–0.078 914
9 420.233	0.495 802	–0.315 0	–0.156 178
14 147.18	0.744 588	–0.372 0	–0.276 987
18 437.84	0.970 413	–0.336 0	–0.326 059
SUM =	2.607 163	SUM =	–0.753 9

As a result:

$$FWME = \frac{\sum_{i=1}^{n} (Wf_i \times E_i)}{\sum_{i=1}^{n} (Wf_i)} \tag{B.2}$$

= –0.7 539/2.607 163

= –0.289 165

The single calibration factor *F* to be applied to the USM's output can be calculated from the equation:

$$F = 100/(100 + \mathrm{FWME}) \tag{B.3}$$

Given a FWME equal to –0.289 165, the resulting calibration factor is calculated as 1.002 9. If this calibration factor of 1.002 9 is applied as a multiplier to the USMs output, the calculated FWME will then be equal to zero. This is shown in Table B.3, where each E_i has been adjusted to obtain a calibration-factor-adjusted value, E_{icf}, using the following equation:

$$E_{icf} = (E_i + 100) \times F - 100 \tag{B.4}$$

Table B.3 **FWME-corrected flow calibration data summary**

E_i	E_{icf}	$Wf_i \times E_{icf}$
+0.953 0	1.245 767	0.061 558
+0.376 0	0.667 094	0.065 903
–0.318 0	–0.028 919	–0.007 176
–0.315 0	–0.025 91	–0.012 846
–0.372 0	–0.083 075	–0.061 857
–0.336 0	–0.046 971	–0.045 581
	SUM =	0.000 00

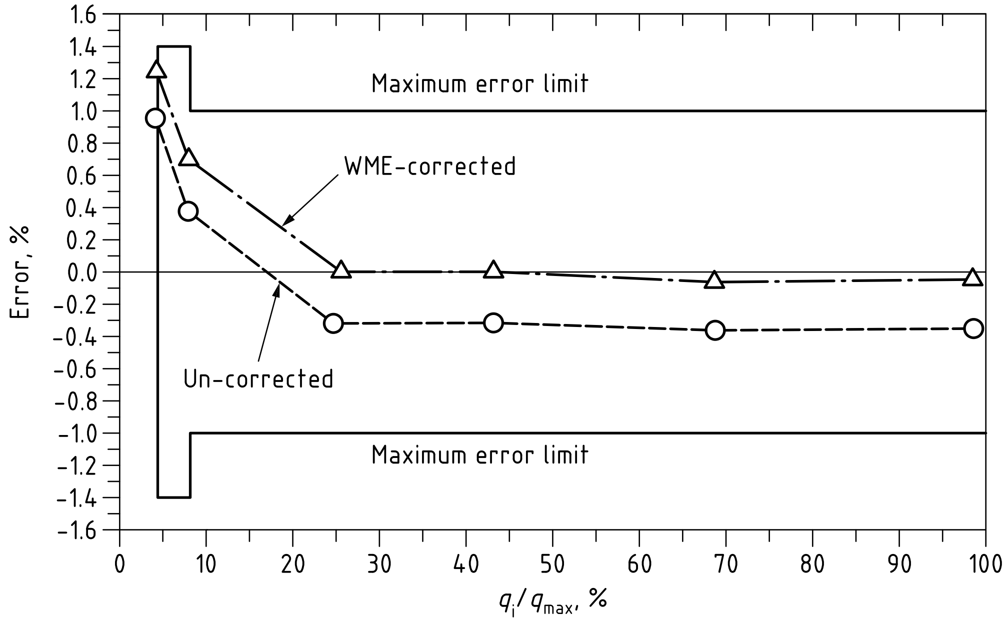
As a result:

$$\text{FWME} = 0.000\,0/2.607\,163 = 0.000 \qquad \text{(B.5)}$$

In Figure B.1, the FWME-corrected flow calibration data have been added to the test data presented in Table B.2. The triangles represent the meter's error after a FWME calibration factor of 1.002 9 has been applied to the original flow calibration data.

Figure B.1 shows that for gas flow rates above about 25% of the capacity of the meter, the measurement error has been virtually eliminated by applying a single FWME correction factor to all of the test flow data. However, for flow rates below about 25% of the meter's capacity, the FWME correction does not completely eliminate the measurement error because the USM has a non-linear characteristic over this portion of its operating range. Therefore, the user needs to either accept the higher measurement error on the low end of the meter's operational range, or apply a more sophisticated correction scheme such as linearization to reduce or eliminate the measurement error on the low end of the meter's range.

Figure B.1 **Un-corrected and FWME-corrected flow calibration**



B.3 Application of the linearization method

This section details the application of a linearization method. The linearization method attempts to remove the errors identified at a flow calibration. In practice, applications of this method vary slightly depending on different equipment and calibration methodologies. However, the basics of the method are common throughout and involve implementing the results from a flow (wet) calibration into a flow computer of some kind to allow on-line corrections of the metered flowrates in the field.

Table B.4 shows example results from a typical flow calibration of a 4 in nb (nominal bore) USM.

Table B.4 **Example results from a typical flow calibration**

Reference flowrate (m^3/hr)	USM indicated flowrate (m^3/hr)	USM correction factors
650	649.11	1.001 371
450	448.53	1.003 277
300	298.57	1.004 789
200	199.25	1.003 764
100	99.72	1.002 808
65	64.5	1.007 752

There will always be a difference between the reference flowrate, provided by a flow laboratory or master meter, and the indicated flowrate from the USM on test. Since the uncertainty in the reference is much lower than that of the test USM, the flowrate difference is denoted as the error in the response of the USM on test from the true flowrate. Therefore in the field, the test USM output is corrected to account for this error. At the indicated flowrates the USM correction factors are shown in Column 3 of Table B.4.

$$\text{Correction factor} = \text{reference flowrate} / \text{indicated flowrate} \tag{B.6}$$

So, for example, at a USM indicated flowrate of 448.53 m^3/hr, a correction factor of 1.003277 can be used to correct the indicated flowrate to account for the error the USM has at that flowrate. Therefore in the field:

$$\text{Corrected flowrate} = 448.53 \times 1.003277 = 450\text{m}^3/\text{hr} \tag{B.7}$$

To account for flowrates in between the test flowrates derived at the flow calibration, an interpolation method is used. So for example at an indicated flowrate of 325 m^3/hr by the USM in the field, a linearization correction is applied as follows based on the corrections at the test flowrates immediately above and below the indicated flowrate:

$$\text{Corrected flowrate} = 325 \times [[((325 - 300)/(450 - 300)) \times (1.003277 - 1.004789)] + 1.004789] = 326.4745\text{m}^3/\text{hr} \tag{B.8}$$

A general form of this equation can be written as follows:

$$\text{Corrected flowrate} = Q_{ind} \times [[((Q_{ind} - Q_{below})/(Q_{above} - Q_{below})) \times (CF_{above} - CF_{below})] + CF_{below}] \tag{B.9}$$

Where:

Q_{ind}	is the flowrate indicated by the USM in the field without any correction
Q_{below}	is the test flowrate from the calibration immediately below the indicated flowrate
Q_{above}	is the test flowrate from the calibration immediately above the indicated flowrate
CF_{below}	is the correction factor corresponding to Q_{below}
CF_{above}	is the correction factor corresponding to Q_{above}

If the USM flowrate is above or below the maximum or minimum test indicated flowrates (in this example those would be 649.11 and 64.5 m³/hr respectively) the correction factors used will be those of the maximum and minimum flowrates (1.001371 and 1.007752 in this example) respectively, although operating outside the calibrated range of the USM will usually be avoided.

Another common method is to use the errors derived from a calibration certificate. Table B.5 shows example results from a typical flow calibration of a 18 in nb USM.

Table B.5 **Example calibration results**

Reference flowrate (m³/hr)	USM indicated flowrate (m³/hr)	USM error (%)
17 918	17 981.25	0.352 996 99
13 780	13 815.63	0.258 563 13
7 650	7 654.11	0.053 725 49
3 945	3 945.89	0.022 560 2
1 972	1 963.12	–0.450 304 26
1 050	1 042.99	–0.667 619 05

Often the error information is provided to a smaller number of decimal places owing to the system measurement uncertainty making numerous decimal places superfluous. However they have been included here for completeness.

It is also important to note the definition for USM error (%) used by the flow calibration laboratory. The method used here is common and is derived as:

$$\text{USM error (\%)} = 100 \times (Q_{ind} - Q_{ref}) / Q_{ref} \tag{B.10}$$

Each USM indicated flowrate would be entered into the flow computer system but this time the errors would also be entered from the calibration certificate.

The corrected flowrate is derived in this example as follows:

$$\text{Corrected flowrate (m}^3\text{/hr)} = Q_{ind} / [(\text{error (\%)} / 100) + 1] \tag{B.11}$$

A general form of the interpolation equation can be written as follows:

$$\text{Corrected flowrate} = Q_{ind} \times [[((Q_{ind} - Q_{below})/(Q_{above} - Q_{below})) \times (E(\%)_{above} - E(\%)_{below})] + E(\%)_{below}] \tag{B.12}$$

Another option commonly experienced is the requirement to enter the indicated flowrate in terms of a percentage of the maximum theoretical flowrate (Q_{max}) so for example:

If Q_{max} = 19 000 m^3/hr

Then in this example, the results shown in Table B.6 are seen.

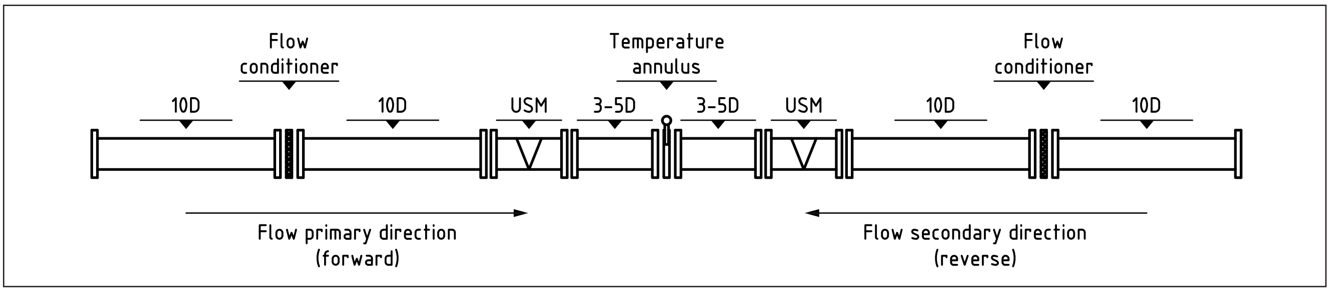
Table B.6 **Calculation of percentage flowrate**

USM indicated flowrate (m^3/hr)	% of Q_{max}
17 918	94.638 157 9
13 780	72.713 842 1
7 650	40.284 789 5
3 945	20.767 842 1
1 972	10.332 210 5
1 050	5.489 421 05

Annex C (informative) Thermowell installations in bi-directional flow installations incorporating flow-conditioners

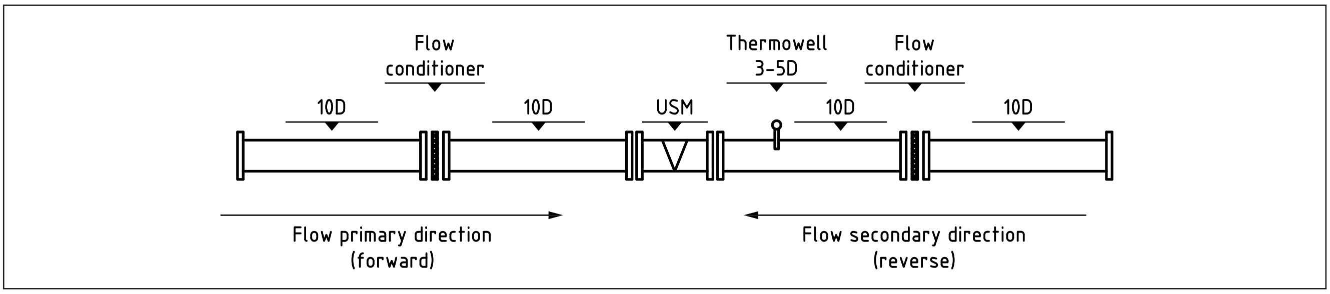
An example of a bi-directional flow installation where two USMs and flow-conditioners are employed with the thermowell located in the centre section is given in Figure C.1.

Figure C.1 **Bi-directional flow installation employing two USMs**



An example of a bi-directional flow installation where one USMs and two flow-conditioners are employed with the thermowell located 3D to 5D downstream of the USM when the flow is in the primary (forward) direction is given in Figure C.2.

Figure C.2 **Bi-directional flow installation employing one USM**



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