
**Measurement of fluid flow in closed
conduits — Ultrasonic meters for gas —**

Part 1:
**Meters for custody transfer and
allocation measurement**

*Mesurage du débit des fluides dans les conduites fermées —
Compteurs à ultrasons pour gaz —*

Partie 1: Compteurs pour transactions commerciales et allocations

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the first edition (ISO 17089-1:2010), which has been technically revised. The main changes compared to the previous edition are as follows:

- Clause 3 has been revised;
- Formulae have been corrected throughout the document;
- editorial and terminological changes throughout the document;

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

Introduction

Ultrasonic meters (USMs) for gas flow measurement have penetrated the market for meters rapidly since 2000 and have become one of the prime flowmeter concepts for operational use as well as custody transfer and allocation measurement. Next to the high repeatability and high accuracy, ultrasonic technology has inherent features like: negligible pressure loss; high rangeability; and the capability to handle pulsating flows.

USMs can deliver extended diagnostic information through which it may be possible to demonstrate the functionality of an USM. Also, the measured speed of sound of the USM may be compared with the speed of sound calculated from pressure, temperature, and gas composition, to check the mutual consistency of the four instruments involved. Due to the extended diagnostic capabilities, this document advocates the addition and use of automated diagnostics instead of labour-intensive quality checks.

This document focuses on meters for custody transfer and allocation measurement (class 1 and class 2 meters). Meters for industrial gas applications, such as utilities and process, as well as flare gas and vent measurement, is the subject of ISO 17089-2.

Typical performance factors of the classification scheme are:

Class	Typical applications	Required accuracy class	Reference
1	Custody transfer	class 0.5 or class 1.0	This document
2	Allocation	class 1.5	This document
3	Utilities and process		ISO 17089-2
4	Flare gas and vent gas		ISO 17089-2

Typical configurations for class 1 and class 2 meters are multi-path meters with chords at different radial positions.

Typical configurations for class 3 and class 4 meters are single-path meters, meters with only diametrical paths, insertion type meters, household type, stack or chimney type, and flare type meters.

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Measurement of fluid flow in closed conduits — Ultrasonic meters for gas —

Part 1: Meters for custody transfer and allocation measurement

1 Scope

This document specifies requirements and recommendations for ultrasonic gas flowmeters (USMs), which utilize the transit time of acoustic signals to measure the flow of single phase homogenous gases in closed conduits.

This document applies to transit time ultrasonic gas flowmeters used for custody transfer and allocation metering, such as full-bore, reduced-area, high-pressure, and low-pressure meters or any combination of these. There are no limits on the minimum or maximum sizes of the meter. This document can be applied to the measurement of almost any type of gas, such as air, natural gas, and ethane.

Included are flow measurement performance requirements for meters of two accuracy classes suitable for applications such as custody transfer and allocation measurement.

This document specifies construction, performance, calibration, diagnostics for meter verification, and output characteristics of ultrasonic meters for gas flow measurement and deals with installation conditions.

NOTE It is possible that national or other regulations apply which can be more stringent than those in this document.

2 Normative references

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

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

ISO 5168, *Measurement of fluid flow — Procedures for the evaluation of uncertainties*

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

3 Terms, definitions and symbols

3.1 Terms and definitions

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

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

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1.1 Quantities

3.1.1.1 volume flow rate

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

where

V is volume

t is time

3.1.1.2 pressure

p
absolute gas pressure in a meter under flowing conditions to which the indicated volume of gas is related

3.1.1.3 average velocity

v
volume flow rate divided by the cross-sectional area

3.1.2 Meter design

3.1.2.1 meter body

pressure-containing structure of the meter

3.1.2.2 acoustic path

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

3.1.2.3 axial path

path travelled by an acoustic signal entirely in the direction of the main pipe axis

Note 1 to entry: An axial path can be both on or parallel to the centre-line or long axis of the pipe, see [Figure 1](#).

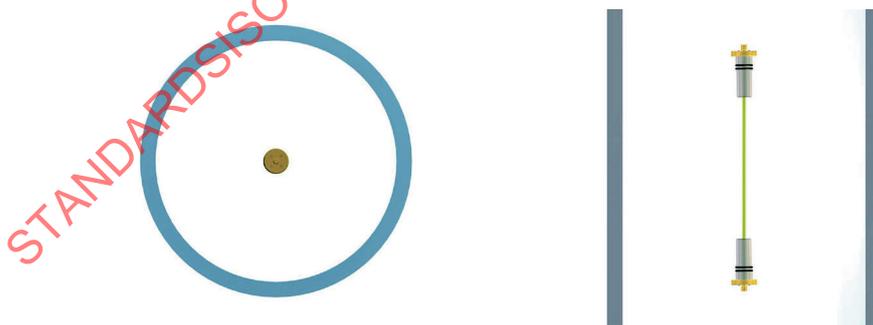


Figure 1 — Axial path

3.1.2.4 diametrical path

acoustic path whereby the acoustic signal travels through the centre-line or long axis of the pipe

Note 1 to entry: See [Figure 2](#) for a representation.

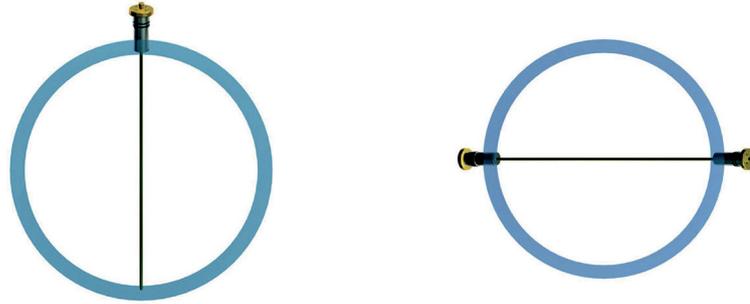


Figure 2 — Diametrical paths

3.1.2.5

chordal path

acoustic path whereby the acoustic signal travels parallel to the diametrical path

Note 1 to entry: See [Figure 3](#) for a representation.

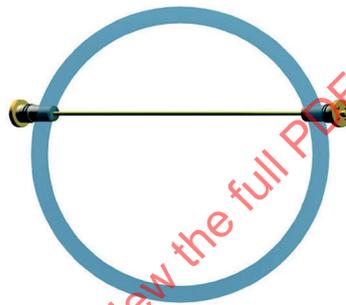


Figure 3 — Chordal paths

3.1.3 Thermodynamic conditions

3.1.3.1

metering conditions

conditions, at the point of measurement, of the fluid whose volume is to be measured

Note 1 to entry: Metering conditions include gas composition, gas temperature, and gas pressure.

[SOURCE: ISO 9951:1993, 3.1.6, modified — the term fluid is used instead of gas.]

3.1.3.2

base conditions

conditions to which the measured volume of the fluid is converted

Note 1 to entry: Base conditions include base temperature and base pressure.

[SOURCE: ISO 9951:1993, 3.1.7, modified — the term fluid is used instead of gas.]

3.1.4 Statistics

3.1.4.1

measurement error

the error of measurement is the measured quantity value minus a reference quantity value

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

EXAMPLE Measured quantity value of meter under test minus quantity value of reference meter.

3.1.4.2

calibration curve

set of measurement errors, at a number of different flow rates, with respect to a known reference quantity meter

3.1.4.3

maximum permissible error

extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given operational range of the meter

[SOURCE: ISO/IEC Guide 99:2007, 4.26, modified — the term measurement has been removed from the definition, thus the current term can be abbreviated by MPE.]

3.1.4.4

maximum peak-to-peak error

maximum difference between any two error values

3.1.4.5

repeatability

closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement

Note 1 to entry: The repeatability shall be calculated in absolute terms for the meter error as the type A uncertainty in a single measurement (U_{AS}) according to ISO 5168. The coverage factor k_{95} shall be derived from the Student's distribution for a 95,45 % confidence level depending on the number of measurements taken. See ISO 5168:2005, Table C.1.

$$r_p = U_{AS} = k_{95} \sqrt{\frac{\sum_{i=1}^n (E_i - \bar{E})^2}{(n-1)}}$$

Typical values of the coverage factor k_{95} are:

Measurements taken	3	5	7	10	100	∞
Coverage factor k_{95}	4,53	2,87	2,52	2,32	2,02	2,00

3.1.4.6

reproducibility

closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement

3.1.4.7

resolution

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

[SOURCE: ISO 11631:1998, 3.28, modified — the term meter has been replaced by flowmeter.]

3.1.4.8

zero flow reading

flow-velocity reading when the gas is assumed to be at rest, i.e. both the axial and non-axial velocity components are essentially zero

3.1.4.9 linearization

way of reducing the non-linearity and offset of the ultrasonic meter reading by applying corrections in the software

Note 1 to entry: The linearization can be applied to meter electronics or in a flow computer connected to the USM. The correction can be, for example, piece-wise linearization or polynomial linearization.

3.2 Symbols and subscripts

The symbols and subscripts used in this document are given in [Tables 1](#) and [2](#). Examples of uses of the volume flow rate symbol are given in [Table 3](#).

Table 1 — Symbols

Quantity	Symbol	Dimensions ^a	SI unit
Cross-sectional area	A	L^2	m^2
Speed of sound in fluid	c	$L T^{-1}$	m/s
Outside pipe diameter	D	L	m
Inside diameter of the meter body	d	L	m
Modulus of elasticity; Young modulus meter body	E	$ML^{-1}T^{-2}$	MPa
Modulus of elasticity; Young modulus transducer	E_t	$ML^{-1}T^{-2}$	MPa
Indicated flow error	E_f	—	1
Weighting factor (live inputs)	f_i	—	1
Integers (1, 2, 3, ...)	i, j, n	—	1
Impulse factor	I	L^{-3}	m^{-3}
Calibration factor	K	—	1
Body style factor	K_s	—	1
Body end correction factor	K_E	—	1
Velocity distribution correction factor	k_h	—	1
Flange stiffening factor	K_f	—	1
Minimum distance to a specified upstream flow disturbance	l_{min}	L	m
Typical averaging length in the ultrasonic flow meter	L_{AV}	L	m
Noise amplitude	L_p	—	dB
Path length	l_p	L	m
Attenuation factor	N_d	—	1
Valve-weighting factor	N_v	—	1
Absolute pressure	p	$ML^{-1}T^{-2}$	Pa
Pressure difference	Δp	$ML^{-1}T^{-2}$	Pa
Emitted acoustic pressure	p_n	$ML^{-1}T^{-2}$	Pa
Signal strength of the USM	P_s	$ML^{-1}T^{-2}$	Pa
Volume flow rate	q_V	$L^3 T^{-1}$	m^3/s
Outside pipe radius	R	L	m
Inside pipe radius	r	L	m
Reynolds number	Re	—	1
Repeatability	r_p	—	1
Repeatability during calibration	r_{cal}	—	1
Absolute temperature of the gas	T	θ	K

^a M ≡ mass; L ≡ length; T ≡ time; θ ≡ temperature.

Table 1 (continued)

Quantity	Symbol	Dimensions ^a	SI unit
Temperature difference	ΔT	Θ	K
Time	t	T	s
Standard deviation of the instantaneous turbulent scatter	u^*	—	1
standard deviation of the required turbulent scatter after averaging	u_d	—	1
Velocity	v	LT^{-1}	m/s
Average velocity	\bar{v}	LT^{-1}	m/s
Velocity of the acoustic path i	v_i	LT^{-1}	m/s
Volume	V	L^3	m^3
Weighting factor (fixed value)	w_i	—	1
Compressibility	Z	—	1
Coefficient of thermal expansion	α	Θ^{-1}	K^{-1}
Error at a flow rate $q_{V,i}$	Δ_i	—	%
Pipe wall thickness	δ	L	M
Dynamic viscosity	η	$L^{-1}MT^{-1}$	Pa·s
Wavelength of ultrasonic oscillation	λ	L	M
Poisson ratio	μ	—	1
Density of fluid	ρ	ML^{-3}	kg/m^3
Sensing point for pressure measurement	ϕ_m	—	—
Path angle	ϕ	—	rad

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

Table 2 — Subscripts

Subscript	Meaning
cal	calibration
min	minimum
max	maximum
op	operational
t	transition

Table 3 — Examples of flow rate symbols

Symbol	Meaning
$q_{V,max,20}$	Designed maximum flow rate, designed for maximum gas speed of 20 m/s
$q_{V,max,x}$	Designed maximum flow rate, designed for maximum gas speed of x m/s
$q_{V,max,op}$	Operational maximum flow rate; defined only when smaller than designed maximum
$q_{V,max,cal}$	Highest flow rate calibrated; defined only when smaller than operational maximum
$q_{V,min}$	Designed minimum flow rate
$q_{V,t}$	Transition flow rate for defining accuracy requirements

3.3 Abbreviations

CMC	calibration and measurement capability
ES	electronics system
FAT	factory acceptance test
FC	flow conditioner
FWME	flow-weighted mean error
M&R	metering and regulating stations
MPE	Maximum permissible error
MSOS	measured speed of sound
SAT	Site Acceptance Test
S/N	signal-to-noise ratio
SOS	speed of sound
TSOS	theoretical speed of sound
USM	ultrasonic flow meter
USMP	USM package, including meter tubes, flow conditioner, and thermowell
USM(P)	USM and USMP

4 Principles of measurement

4.1 Basic formulae

USMs are based on the measurement of the propagation time of acoustic signals in a flowing medium.

Figure 4 shows the basic system setup. On both sides of the pipe, at positions A and B, are mounted transducers capable of transmitting and receiving ultrasonic sound signals. These transducers transmit sound signals within such a short interval that the speed of sound (SOS) is identical for both measurements and their transit times are measured. With zero flow, the transit time from A to B, t_{AB} , is equal to the transit time from B to A, t_{BA} . However, if there is flow, the transit time of the sound signal from A to B decreases and the one from B to A increases, according to (ignoring second order effects, such as path curvature):

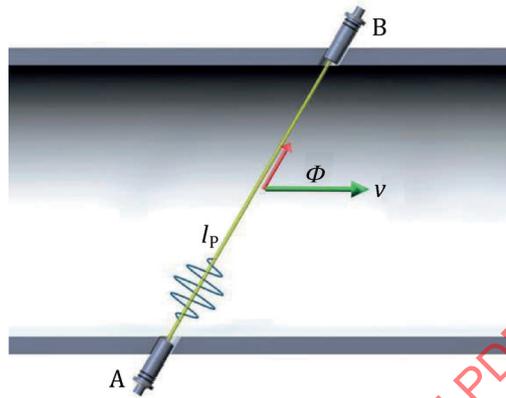
$$t_{AB} = \frac{l_p}{(c + v \cos \phi)} \quad (1)$$

and

$$t_{BA} = \frac{l_p}{(c - v \cos \phi)} \quad (2)$$

where

- l_p is the path length;
- c is the SOS;
- v is the average velocity;
- ϕ is the path angle;
- t_{AB}, t_{BA} are transit times of the acoustic signal.



Key

- A, B positions
- l_p path length
- v average velocity
- ϕ path angle

Figure 4 — Basic system set-up

[Formula \(3\)](#) for the measured gas velocity can be derived by subtracting [Formula \(2\)](#) from [Formula \(1\)](#):

$$v_i = \frac{l_p}{2 \cos \phi} \left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right) \tag{3}$$

Note that the term for the SOS in the gas has been eliminated in [Formula \(3\)](#). This means that the measurement of the gas velocity is independent of the properties of the gas, e.g. pressure, temperature, and gas composition.

In a similar way, the SOS can be derived by adding [Formulas \(1\)](#) and [\(2\)](#) and rearranging:

$$c = \frac{l_p}{2} \left(\frac{1}{t_{AB}} + \frac{1}{t_{BA}} \right) \tag{4}$$

In multi-path meters, the individual path velocity measurements are combined by a mathematical function to yield an estimate of the average velocity:

$$v = f(v_1 \dots v_n) \tag{5}$$

where n is the total number of paths. Due to variations in path configuration and different proprietary approaches to solving [Formula \(7\)](#), even for a given number of paths, the exact form of $f(v_1 \dots v_n)$ can differ.

To obtain the volume flow rate, q_V , multiply the estimate of the average velocity, v , by the cross-sectional area of the measurement section, A , as follows:

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

4.2 Factors affecting the performance

The performance of a USM is dependent on a number of intrinsic and extrinsic factors. Intrinsic factors (i.e. those related to the meter and its calibration prior to delivery) include:

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

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

- a) the flow velocity profile including swirl and skewness;
- b) change of wall roughness due to corrosion, solid and liquid contamination over time;
- c) the temperature distribution;
- d) flow pulsations;
- e) noise, both acoustic and electromagnetic;
- f) temporary or permanent buildup resulting in a reduction of the meter body cross sectional area.

4.3 Description of generic types

4.3.1 General

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

- a) transducers;
- b) a meter body with acoustic path configuration;
- c) electronics;
- d) a data-processing and presentation unit.

4.3.2 Transducers

Transducers are supplied in various forms. Typically, they comprise a piezoelectric element with electrode connections and a supporting mechanical structure with which the process connection is made. The transducers for custody transfer and allocation measurement are installed in a wetted (in direct contact with the fluid) mounting arrangement. Typical arrangements are shown in [Figure 5](#). The process connections for wetted transducers may be welded, flanged, threaded or may be more mechanically complex, e.g. to allow the removal of transducers from a pressurized line. The active

element is usually separated from the fluid by an acoustic coupling element housing. The transducers are orientated such that the active element transmits ultrasonic signals at an angle to the meter body axis in the direction of a second transducer or reflection point in the meter body interior.

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

- a) high and low temperature;
- b) high and low pressure;
- c) high gas velocities;
- d) high acoustic attenuation;
- e) close proximity to high pressure drop throttle valve (potential of in-pipe ultrasonic noise);
- f) rapid or cyclic temperature or pressure changes;
- g) corrosive or erosive gas (sour gas);
- h) gas with traces of moisture or dirt.

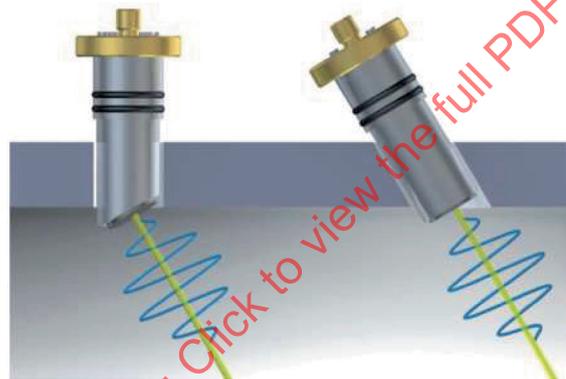


Figure 5 — Typical transducer arrangements

4.3.3 Meter body and acoustic path configurations

4.3.3.1 General

USMs are available in a variety of path configurations. The numbers of measurement paths are generally chosen based on a requirement with respect to variations in velocity distribution and required accuracy.

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

4.3.3.2 Basic acoustic paths types

Common acoustic path types are illustrated in [Figure 6](#).

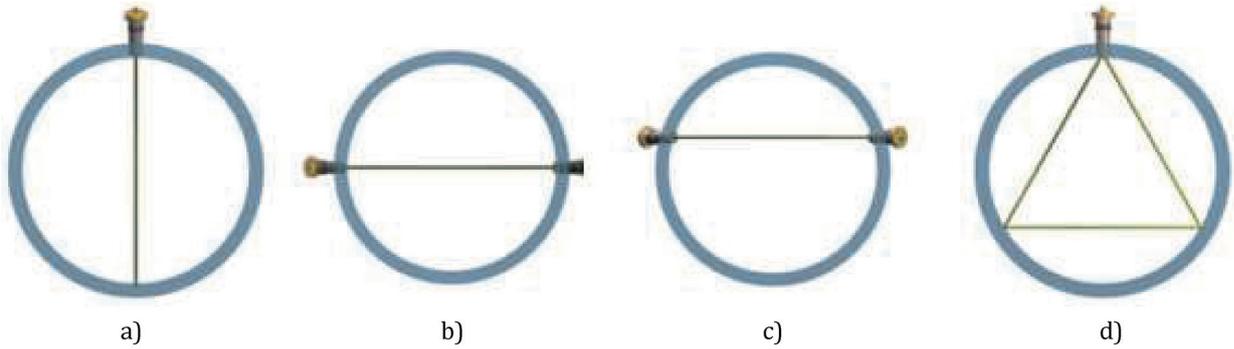
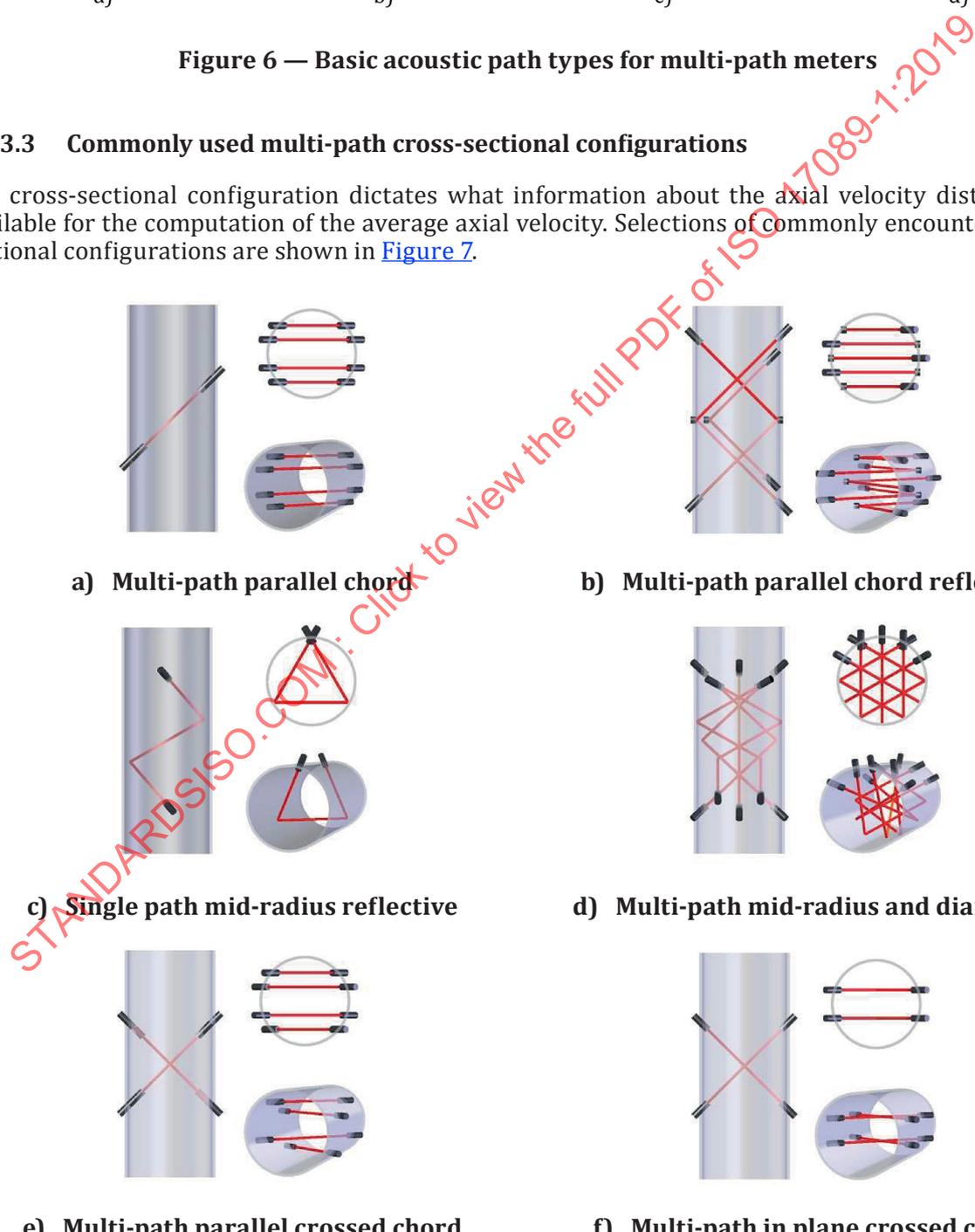


Figure 6 — Basic acoustic path types for multi-path meters

4.3.3.3 Commonly used multi-path cross-sectional configurations

The cross-sectional configuration dictates what information about the axial velocity distribution is available for the computation of the average axial velocity. Selections of commonly encountered cross-sectional configurations are shown in Figure 7.



a) Multi-path parallel chord

b) Multi-path parallel chord reflective

c) Single path mid-radius reflective

d) Multi-path mid-radius and diametric

e) Multi-path parallel crossed chord

f) Multi-path in plane crossed chord

Figure 7 — Selections of commonly encountered cross-sectional configurations

4.3.4 Average velocity calculation

Meters with paths of equal radial displacement [e.g. Figure 7 c) and f)] essentially make the same measurement with respect to velocity distribution if the flow is axisymmetric, regardless of the number of paths employed. In such cases, the average velocity, v , is determined by a simple arithmetic mean. In fully developed flow, a theoretical correction factor, k_h , can be introduced to account for the known variation in velocity profile. This, however, applies only to fully developed flow, not to disturbed flows.

$$v = k_h \frac{\sum_{i=1}^n v_i}{n} \tag{7}$$

where

- n is the total number of paths;
- v_i is the flow velocity measured on path i .

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

In the case of meters with paths at off-diameter positions [e.g. Figure 7 e) and d)], the velocity is measured at different radial positions. Several methods can be used when combining the velocities to obtain the average pipe velocity. These can be classified as follows.

Summation with constant weighting:

$$v = \sum_{i=1}^n w_i v_i \tag{8}$$

where the radial displacements of the paths and the constants, w_1 to w_n , are determined on the basis of documented numerical integration methods.

Or summation with variable weighting:

$$v = \sum_{i=1}^n f_i v_i \tag{9}$$

where the radial displacements of the paths are fixed at design and the variables, f_1 to f_n , may be determined from input parameters or measured variables (e.g. velocities).

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

$$q_V = K \cdot A \cdot v \tag{10}$$

The rules and tolerances for implementing corrections and linearization by calibration factor K are given in 5.8 and 6.3.3.

4.4 Contributions to the uncertainty in measurement

The total volume flow, q_V , measured by a USM can be calculated using [Formula \(11\)](#):

$$q_V = A \cdot K \sum_{i=1}^n f_i \frac{l_i}{2 \cos \phi_i} \left(\frac{1}{t_{AB,i}} - \frac{1}{t_{BA,i}} \right) \quad (11)$$

Considering this equation, the total uncertainty depends upon the individual uncertainties of all factors involved. Four sources can be distinguished:

- the uncertainty in the calibration factor, K , which is a function of both the calibration uncertainty and the correction method applied. K is a function of q_V ;
- the uncertainties in the measurements of the transducers and in the geometry of the meter body;
- the uncertainty in the live input weighting factor or flow profile correction factor, f ;
- the uncertainty in the transit time and transit time difference measurement.

After calibration and adjustment, the errors in indicated flow rate, q_V , caused by l , ϕ , A , and f are compensated for by multiplying the right-hand side by a calibration factor, K . The only remaining uncertainty at the calibration site is that of the calibration factor, K .

NOTE Transferring the meter to the field, there is an additional uncertainty due to the specific operating conditions and installation conditions in the field, which differ from those at the calibration site.

4.5 Reynolds number

The flow profile is a function of the Reynolds number. The Reynolds number is calculated from the known inside diameter of the body, d , the measured average velocity, v , density, ρ , and the dynamic viscosity, η .

$$Re = \frac{v \cdot d \cdot \rho}{\eta} \quad (12)$$

The instant average velocity and the density, for which pressure is the dominant factor, are the main contributors in changes of the Reynolds number for a specific gas.

The impact of changes in the Reynolds number on the calibration factor of a single path depends on the path configuration of the USM. For Reynolds numbers greater than 10 000, the impact ranges from approximately 1 % per decade for a diametrical path to less than 0,3 % per decade for a chordal path at a half-radius position. For high Reynolds numbers for instance at high pressures and/or high flow velocity, the change of the flow profile becomes insignificant and the calibration factor will become a constant number.

The path configurations of most ultrasonic multi-path meters are designed to reduce the impact to a negligible amount per decade.

Nevertheless the calibration factor may change with respect to Reynolds number changes due to the working pressure especially for flow rates below $q_{V,t}$. The manufacturer shall specify the applicable pressure range and whether during calibration, as well as during operation, the actual values for the density and the viscosity shall be entered in the ES of the USM. See also [5.8.3](#).

4.6 USM classification

To aid the user in making a meter selection based on the demanded accuracy, a USM can be classified by application. This process involves dividing the meters available into classes of performance as outlined in [Table 4](#). Only classes 1 and 2 are suitable for custody transfer and allocation duties. Other classes deal with other measurement applications and are covered by ISO 17089-2.

Table 4 — USM classification

Class	Typical applications	Required accuracy class
1	Custody transfer	class 0.5 or class 1.0
2	Allocation	class 1.5 or better

The two classes are intended to represent typical measurement specifications commonly applied in industry. Depending on the importance of measurement with respect to regulatory or custody transfer demands, the total uncertainty budget for the system differs.

5 Meter characteristics

5.1 Operating conditions

5.1.1 Flow rates and gas velocities

The maximum flow rate and the minimum flow rate shall be specified by the manufacturer for the gas densities for which the meter operates within the specifications of the meter performance defined in 5.8. The maximum flow rate, in cubic metres per hour, of the meter depends on the maximum gas velocity the meter is designed for.

The flow range for bidirectional applications is: $-q_{V,\max} < q_V < -q_{V,\min}$ and $q_{V,\min} < q_V < q_{V,\max}$.

5.1.2 Pressure

Ultrasonic transducers used in USMs require a minimum gas density to ensure acoustic coupling of the sound signals to and from the gas where pressure is the predominant factor of gas density. Therefore, the gas composition and the minimum operating pressure as well as the maximum operating pressure shall be specified.

5.1.3 Temperature

The manufacturer or supplier shall specify the operating and ambient temperature ranges for the equipment being offered, inclusive of meter body, field-mounted electronics, and its associated peripherals and cabling as well as ultrasonic transducers.

5.1.4 Gas quality

The meter shall operate within the relevant accuracy limits for all gases for which the meter is intended to be used.

The presence of some components in the gas can impact on the performance of a meter. In particular, 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.

Deposits which may be present in a process (e.g. condensates, glycol, amines, inhibitors, water or traces of oil mixed with mill scale, dirt or sand) may affect the accuracy of the meter by reducing its cross-sectional area, by reducing the effective acoustic path length and by obstructing the emitted and received ultrasonic signals.

The manufacturer should be consulted if any of the following are expected:

- a) when the acoustic-signal-attenuating carbon dioxide levels are above 3 % molar fraction or the occurrence of carbon dioxide in large meters (>12");
- b) when the hydrogen levels are above 10 % molar fraction;

- c) when the operation is near the critical density of the natural gas mixture (crossing a phase boundary causing retrograde condensation resulting in 2 phase flow);
- d) when the total sulfur level, from materials such as hydrogen sulfide, mercaptans (thiols), and elemental sulfur, exceeds 320 $\mu\text{mol/mol}$ (which is corrosive and may require resistant materials or additional wall thickness allowance);
- e) deposits.

5.2 Meter body, materials, and construction

5.2.1 Materials

The meter body and the internal mechanism shall be manufactured from materials suited to the service conditions and resistant to attack by the fluid which the meter is to handle. Exterior surfaces of the meter shall be protected as necessary against corrosion. Internal surfaces of the meter shall be designed to resist changes to the internal cross-sectional area and the wall roughness to the extent required so that meter accuracy is not endangered.

5.2.2 Meter body

The meter body and all other parts comprising the fluid-containing structure of the meter shall be constructed of sound materials and designed to handle the pressures and temperatures for which they are rated.

5.2.3 Connections

The inlet and outlet connections of the meter shall conform to recognized standards, e.g. ANSI (class 300, 600, 900, etc.), DIN, and JIS.

5.2.4 Dimensions

5.2.4.1 General

The flanges of the USM shall both have the same inside diameter to within 1 % of each other. An USM with an inside diameter equal to the flange diameter shall be indicated as "full bore". An USM of inside diameter smaller than the flange diameter shall be indicated as "reduced bore". Any measurement of the bore of the meter should be within 0,5 % of the average over the length of the meter or, in the case of reduced bore meters, the measurement zone.

5.2.4.2 Geometrical parameters of the measuring section

The manufacturer shall measure and document:

- a) the average inside diameter representative for the measuring section of the meter;
- b) the length of each acoustic path between transducer faces;
- c) the inclination angle of each acoustic path or the axial (meter body axis) distance between transducer pairs;
- d) the uncertainty of measurements a) to c);
- e) the meter body material;
- f) the meter body coefficients for pressure and temperature expansion.

The meter body temperature shall be measured and documented at the time these measurements are made. The individual lengths shall be reported to the smallest practicable uncertainty. All instruments

used to perform these measurements shall have valid calibrations traceable to internationally recognized standards.

5.2.5 Ultrasonic transducer ports

Since the measured gas may contain some impurities (e.g. light oils or condensates), transducer ports shall be designed to reduce the possibility of liquids or solids accumulating in the transducer ports. The USM transducer ports may also be equipped with devices to allow safe draining of any accumulated fluids (e.g. double block and bleed).

The USM may be equipped with valves or necessary additional devices, mounted on the transducer ports, in order to make it possible to replace the ultrasonic transducers without depressurizing the meter run. In that case, a bleed valve shall be required in addition to the isolation valve to ensure that no excess pressure exists behind a transducer before releasing the extraction mechanism.

Note the conditions for exchange of components (5.6).

5.2.6 Pressure tapplings

At least one metering-pressure tapping, drilled perpendicular in the top $\pm 85^\circ$, shall be provided on the meter body or on the piping adjacent to the meter for the full bore flow meter to enable direct measurement of the static pressure under metering conditions.

For a reduced bore flow meter, the metering pressure tapping shall be provided on the meter body in the reduced bore section.

The connection of the pressure tapping shall be marked " p_m " to be used at both the installation and calibration. If more than one " p_m " tapping is provided, the difference in pressure readings shall not exceed 100 Pa at maximum flow rate at ambient conditions.

Meters have the option of utilising tapplings in the pipework adjacent to the meter providing the difference in pressure readings does not exceed 100 Pa at maximum flow rate at ambient conditions.

Depending of the end user piping standards the pressure connection shall be either a screwed or flanged type design.

A meter may be equipped with other pressure tapplings in addition to the p_m tapping. These may serve to determine the pressure drop over a part of the meter or for other purposes. The other pressure tapping shall be marked " p ".

The centre-line of the tapping shall meet the pipe centre-line and be at an angle of 90° to it. At the point of breakthrough, the hole shall be circular. The edges shall be flush with the internal surface of the pipe wall and as sharp as possible. To ensure the elimination of all burrs or wire edges at the inner edge, rounding is permitted, but shall be kept as small as possible and, where it can be measured, its radius shall be less than one-tenth of the pressure tapping diameter. No irregularity shall appear inside the connecting hole, on the edges of the hole drilled in the pipe wall, or on the pipe wall close to the pressure tapping. Conformity of the pressure tapplings with the requirements specified may be judged by visual inspection. The diameter of the pressure tapping shall have a minimum bore diameter of 3 mm and a maximum bore of 12 mm. The pressure tapping shall be circular and cylindrical over a length of at least $2,5d_1$, where d_1 is the inside diameter of the tapping hole, measured from the inner wall of the pipeline. The centre-line of the pressure tapping may be located in any axial plane of the pipeline.

The installation of a pressure tapping in close proximity to a transducer port should be avoided.

5.2.7 Anti-roll provision

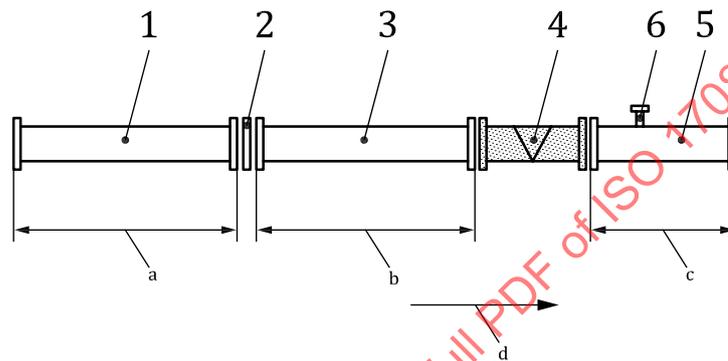
The meter shall be designed so that the meter body does not roll when resting on a smooth surface with a slope of up to 10 %. This is to prevent damage to the protruding transducers and electronic system (ES) when the USM is temporarily set on the ground during installation or maintenance work.

The meter shall be designed to permit easy and safe handling during transportation and installation; however, the anti-roll provision alone is not sufficient during transportation. Hoisting eyes or clearance for lifting straps shall be provided.

5.2.8 Flow conditioner

A flow conditioner irremovably attached to the meter is deemed to be part of the meter.

A USMP package is formed when the flow conditioner is positioned at a distance less than L_{\min} . The package consists of the flow conditioner, inlet spool and the meter. In a bidirectional setup, a thermowell is also part of the USMP. Calibration shall always be done with the whole measurement package or a simulated package consisting of a upstream pipe and the same make and model flow conditioner (all of the same exact dimensions, inner wall conditions and type) may be considered.



Key

- 1 upstream spool
- 2 flow conditioner
- 3 inlet spool
- 4 ultrasonic flowmeter (USM)
- 5 outlet spool
- 6 temperatur sensor (TS)
- a $\geq 2D$ (preferably $3D$).
- b $\geq XD$ (Specified by the manufacturer).
- c TS $2D$ to $5D$ (Outlet spool $3D$ to $\geq 6D$).
- d Flow primary direction (Forward).

Figure 8 — Typical drawing of USMP

For the USMP and the simulated USMP, it shall be guaranteed that all components are mounted in correct direction and orientation as in the field situation. For this purpose the direction and orientation should be permanently marked on these components.

Any other flow conditioner upstream of a USMP is regarded as part of the “installation” or of the “calibration facility”.

5.2.9 Markings

Nameplates shall include the following:

- a) manufacturer, model number, serial number, and month and year of manufacture;
- b) meter size, flange class, and total mass;
- c) meter body design code and material, flange design code and material;

- d) maximum and minimum operating pressure, and operating temperature range;
- e) the nominal maximum and minimum actual volume flow rate per hour over the calibrated range;
- f) direction of positive or forward flow;

Nameplates may include the following:

- g) purchase order number or shop order number;
- h) legal metrology approval identification;
- i) transition actual volume flow rate per hour.

Each transducer port shall be permanently marked with a unique designation for easy reference.

5.2.10 Corrosion protection

Immediately after production, the inner surface of the meter, spool pieces, and flow conditioners should be protected from corrosion.

5.3 Transducers

5.3.1 Specification

The acoustic frequency shall be specified.

5.3.2 Rate of pressure change

Rapid depressurization of a USM may cause damage to the transducer or the coating on the inner wall, resulting in a change of the characteristics of the meter. It shall therefore be ensured that the meter runs are depressurized as slowly as possible and, in the absence of information from the manufacturer, a rate of no greater than 0,5 MPa/min is recommended.

5.3.3 Transducer characterization

If the flowmeter electronics system (ES) requires specific transducer characterization parameters, documentation of all parameters which are unique to each transducer, or transducer pair, shall be provided.

5.3.4 Path configuration

In a multi-path arrangement, the number of chords, their positioning and the integration technique used affects the measurement uncertainty as well as its sensitivity to changes in the flow profile. The number of transducer pairs, the number of reflections per path and the attachment method into the conduit (protruding, retracted flush or wall-mounted) shall be specified.

5.3.5 Marking

Each transducer shall be permanently marked with a unique serial number.

5.3.6 Cable

If the USM is sensitive to the characteristics of the individual transducer cable, then the cable shall be treated as an integral part of the meter and it shall be marked with a warning indicating the characteristic not to be changed, e.g. length.

5.3.7 Robustness

The wetted part of the transducer shall be manufactured of materials suited for the service conditions and resistant to attack by the fluid which the meter is exposed to.

5.4 Electronics

5.4.1 General requirements

The ES of a USM usually include power supply, microcomputer, signal processing components, and ultrasonic transducer excitation circuits.

It shall be verified that the ES operates over its specified range of environmental conditions without a significant change in meter performance. The ES operating the transducers shall be capable of withstanding electromagnetic discharge as specified in 7.5. Intrinsically safe designs and explosion-proof enclosure designs shall comply with national requirements.

The ES shall contain a self-monitoring function to ensure automatic restart in the event of a program lock-up.

5.4.2 Display

The meter shall have the capability for local and/or remote display.

5.4.3 Power supply

The manufacturer shall specify the necessary power supply, the tolerance on the voltage variation, and the power consumption. The reaction of the USM to power interruptions and voltage drops shall be specified.

5.4.4 Signal detection method

The signal detection method shall be designed to ensure reliable time measurement; this implies accurate detection of start and stop triggers, use of a precision clock, and resistance to systematic errors like "peak-switching", etc.

5.4.5 Sampling or pulsating flow

The meter shall cope with non-steady flow. For that purpose, acoustic signals may be fired at a non-constant rate. The manufacturer shall specify the maximum flow fluctuation frequency.

5.4.6 Signal-to-noise ratio

The USM shall indicate the S/N ratio per transducer or per acoustic path.

5.4.7 Alarm signal

The meter shall trigger an alarm when the performance of the meter deteriorates due to for low S/N or signal acceptance rate for example.

5.4.8 Processing of data

The processing section shall, in addition to determining the volume flow rate from the measured transit times, be capable of rejecting invalid measurements. The indicated volume flow rate may be the result of one or more individual velocity determinations. The percentage of valid measurements to performed measurements may be indicated for every acoustic path by the USM.

5.4.9 Output

The meter shall be equipped with at least one of the following outputs:

- a) serial data interface; e.g. RS-232, RS-485, or fieldbus;
- b) a frequency output representing flow rate at metering conditions;
- c) a digital status output.

The time-integrated values of outputs a) and b) shall match better than 0,02 % in every arbitrary interval of 100 s for flow rates above $q_{V, \min}$.

The meter may be equipped with the following outputs:

- a) additional frequency outputs;
- b) additional status outputs;
- c) additional data interfaces (e.g. Ethernet, read-only serial port);
- d) analogue (4 mA to 20 mA) outputs.

Flow rate outputs shall function up to 120 % of the maximum flow rate, $q_{V, \max, \text{cal}}$, of the meter. A low flow cut-off function may be provided that sets the flow rate output to zero when the indicated flow rate is below a minimum value.

NOTE Setting the output to zero at low flow can cause problems if the USM output is used to control valve settings.

Two separate flow rate outputs or serial data values may be provided for bidirectional applications to facilitate the separate accumulation of volumes by the associated flow computer(s).

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

For control purposes, output signal(s) of the measured flow shall be updated at a frequency of not less than 1 Hz.

5.4.10 Cable jackets and insulation

Cable jackets, rubber, plastic, and other exposed parts shall be resistant to ultraviolet light, water, oil, and grease.

5.4.11 Marking

Each electronic assembly shall be permanently marked with a unique version number for easy reference. A list of electronic assemblies, including version number, shall be kept up to date by the manufacturer as part of version management.

5.5 Software

5.5.1 Firmware

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

It shall be possible to verify all constants and parameters while the meter is in operation. A firmware check-sum and event log shall be provided to validate that no unauthorized changes have been made to the firmware.

5.5.2 MODBUS communication data specification

The USM shall provide a defined data structure (see [Annex F](#)) for serial communication to simplify the data communication to a communication system (e.g. flow computer or data acquisition system).

The data communication protocol is based on the publicly available specifications of the "Modbus Organization, Inc." [83].

5.5.3 Discontinuity

When exposed to a continuous increase or decrease of flow, the firmware shall be designed to avoid a step change in the calculated output flow rate.

5.5.4 Marking and version management

The manufacturer shall maintain a record of all firmware revisions including the revision serial number, date of revision, applicable meter models and circuit board revisions, and description of changes to firmware performed by them or by their representative.

The firmware revision number, revision date, serial number, and checksum shall be available for inspection of the firmware chip, display or digital communications port.

The manufacturer may offer firmware upgrades from time to time to improve the performance of the meter or add additional features. The manufacturer shall notify the user if the firmware revision affects the accuracy of a flow-calibrated meter.

5.5.5 Monitoring and recording of measuring and diagnostic data

The meter shall have the capability to monitor and record as a minimum the following data:

- a) actual volume flow rate;
- b) totalizers;
- c) average velocity;
- d) average SOS;
- e) individual path velocity;
- f) individual path SOS;
- g) percentage of accepted signals for each acoustic path;
- h) S/N ratio or equivalent (gain control);
- i) status and measurement quality indicators;
- j) alarm and failure indicator.

5.5.6 Correction functions and parameters

Both at operation and calibration, correct parameter settings for Reynolds correction, body expansion correction and calibration curve correction should be used. This is valid either when these parameters are inside the USM or inside the flow computer attached to the USM. This is valid either when actual pressure and actual temperature are entered as fixed values or from live inputs.

Reynolds correction parameters are density and viscosity.

Body expansion correction parameters are actual pressure, calibration pressure, actual temperature, calibration temperature, thermal expansion coefficient, Young modulus, Poisson ratio and dimensional measurements.

Calibration curve correction parameters are either a set of flow rates and deviations, or a set of parameters that determine polynomial correction according to the design of the calibration curve correction mechanism.

The software of the USM and/or the flow computer attached to the USM should allow the operator to enter the correct settings of these parameters. Care should be given not to activate a correction mechanism twice, both in the USM and in the flow computer attached to the USM.

5.5.7 Inspection and verification functions

It shall be possible to view and print the flow measurement configuration parameters used by the ES, e.g. calibration constants, meter dimensions, time averaging period, and sampling rate. Provisions shall be made to prevent an accidental or undetectable alteration of those parameters that affect the performance of the meter. Suitable provisions include a sealable switch or jumper, or a permanent programmable read-only memory chip with verifiable checksum/event log alarms.

Provide the following alarm status output:

- a) output invalid: when the indicated flow rate output is invalid (required);
- b) partial failure: when one or more of the multiple ultrasonic path results is not usable (required);
- c) warning: when any of several monitored parameters fall outside normal operation for a significant length of time (optional).

5.6 Exchange of components

It should be possible to replace or relocate similar types of transducers, electronic parts and software without a significant change in meter performance. The fault due to the interchange of such a component shall not be more than one third of the MPE for the corresponding meter class. Otherwise the meter shall be recalibrated.

The above statements shall be made clear in the meter metrological approval.

Procedures to be used when such components have to be exchanged, including possible mechanical, electrical or other measurements and adjustments, shall be specified.

From every event with the ultrasonic flowmeter (calibration, repair, etc.), a full list of the relevant “as-found”, “as-calibrated” and “as-left” parameters shall be available.

If parts are replaced by newer or different versions, advantages and disadvantages shall be specified.

The manufacturer shall provide a reputable method of version management.

5.7 Secondary measurements

5.7.1 General

For the conversion of volume flow under metering conditions to mass flow or volume flow under base conditions, secondary measurements are required.

5.7.2 Pressure measurement

The pressure tapping marked “ p_m ” shall be used as the pressure sensing point (see [5.2.6](#)).

5.7.3 Temperature measurement

For unidirectional flow, the thermowell shall be installed $2D \leq x \leq 5D$ downstream of the USM, but upstream of any outlet valve, diameter steps or flow restrictions. It is important that the thermowell be correctly installed to ensure the heat transfer from the piping and the thermowell attachment and

radiation effects of the sun do not influence the temperature reading. The recommended insertion length for thermowells shall be such that the tip protrudes between $D/10$ and $D/3$. Special probe designs may be required for insertion lengths greater than $D/3$.

In case of density meters are used, the same installation rules for the pockets apply.

Some installations require the installation of two or even three thermowells (back-up measurement or validation measurement). Additionally, safety regulations may prescribe large well dimensions. The thermowell shall be installed such that the ambient temperature does not influence the gas temperature measured.

For applications where the ambient temperature can be significantly different ($>5\text{ }^{\circ}\text{C}$) from the gas temperature, thermal insulation or shading of the upstream pipe section, the USM assembly and the downstream section, as far as $1D$ beyond the furthest thermowell, shall be installed, unless the meter is operating above $q_{V,t}$.

For bidirectional use with two USMs in series, it is possible for the thermowell to be installed in between the two meters. An example of a bidirectional flow installation where two USMs are employed with the thermowell located in the centre section is given in [Figure 11](#). Both the number and sizes of the thermowells or densitometer pockets exacerbate the flow perturbation.

The thermowell vortex shedding frequency at high gas velocities shall not excite the natural vibration frequency of the thermowell to the point of failure; conical thermowells are advised. With the thermowell(s) upstream of the USM, they shall be positioned such that it is not in line with one of the acoustic paths. Also they should not be placed in line with each other in order to avoid the amplification of the vortex generated by the thermowell.

In [Figure 9](#) an example is shown whereby 2 thermowells are used in combination with an ultrasonic flow meter having horizontal paths.

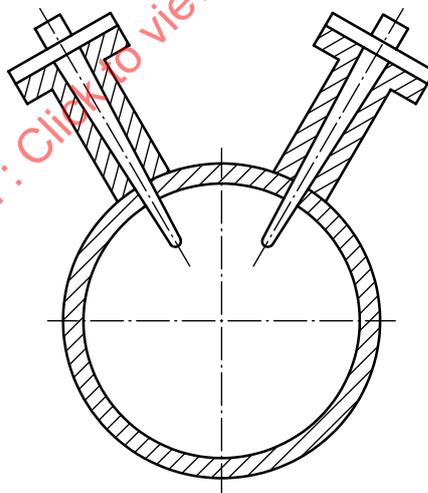


Figure 9 — Thermowells positioned not in line with any of the ultrasonic paths

For smaller pipe diameters ($<6''$) alternatives to intrusive thermowell-based technologies, like surface mounted temperature measurement elements, may be considered where it can be demonstrated that both the accuracy and the response time of the temperature measurement device are such that it does not compromise the overall uncertainty of the calculated flow rate. This may be particularly advantageous when considering bidirectional metering systems where flow disturbances are to be minimized.

5.8 Performance requirements

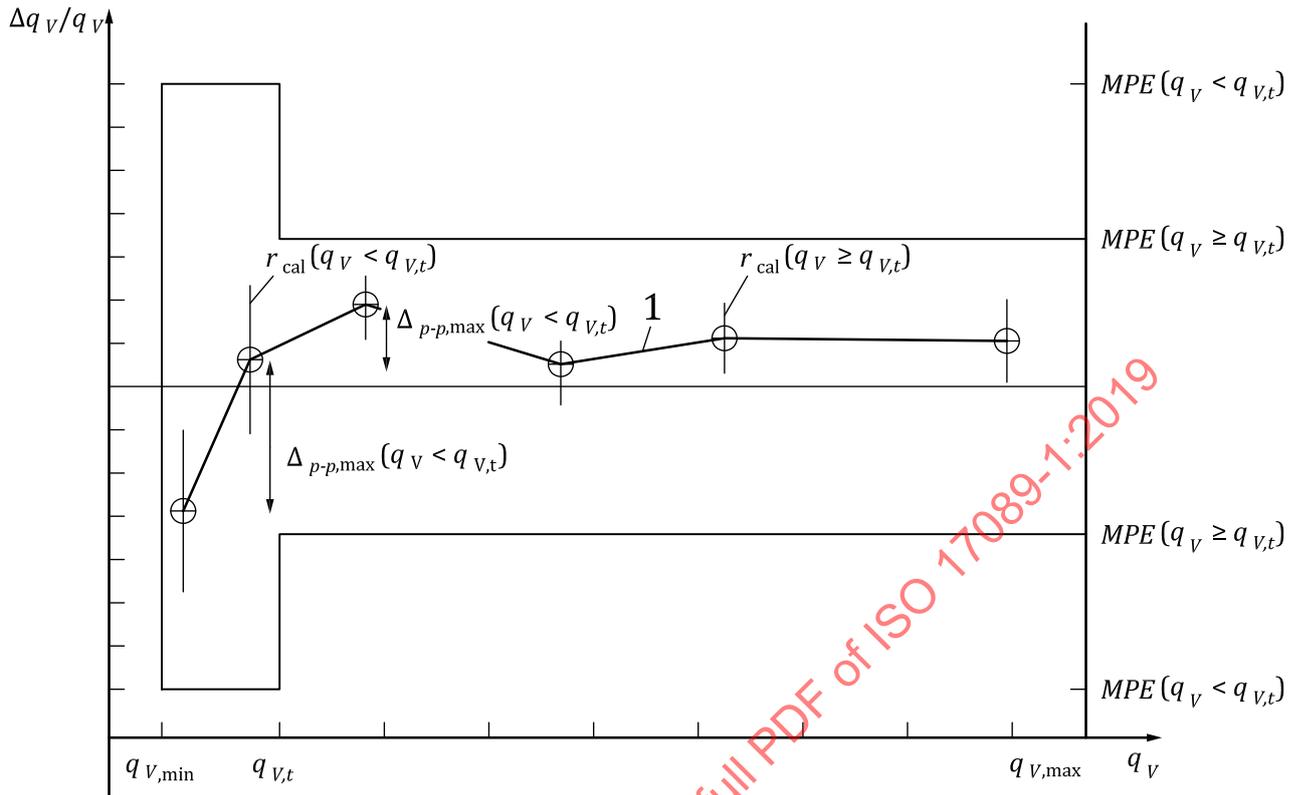
5.8.1 General

The USM shall be designed and manufactured such that its errors do not exceed the applicable MPE over the full operating pressure, temperature, and gas composition ranges, with inputs or a correction algorithm, if necessary. The necessary correction algorithms and inputs shall be specified. If a correction algorithm is not necessary, an additional uncertainty due to pressure, temperature, and composition changes shall be specified. If the USM requires a manual input to characterize the flowing gas condition, e.g. gas density and viscosity, the sensitivity of the USM to these parameters shall be specified so that the operator can determine the need to change these parameters as operating conditions change. The concerning parameter settings shall be documented both during calibration and in operation.

5.8.2 Accuracy requirements

Table 5 — Accuracy requirements

Subject	Accuracy class		
	0.5	1.0	1.5
Maximum permissible error (MPE)			
for $q_V \geq q_{V,t}$	±0,5 %	±1,0 %	±1,5 %
for $q_{V,min} < q_V < q_{V,t}$	±1,0 %	±2,0 %	±3,0 %
Maximum peak-to-peak error			
for $q_V \geq q_{V,t}$	<0,5 %	<1,0 %	<1,0 %
for $q_{V,min} < q_V < q_{V,t}$	<1,0 %	<2,0 %	<2,0 %
Maximum permissible flow weighted mean error prior any adjustment (see 6.3.3)			
FWME	0,5 %	1,0 %	1,5 %
Repeatability under flowing conditions during calibration r_{cal}			
for $q_V \geq q_{V,t}$	0,17 %	0,33 %	0,5 %
for $q_{V,min} < q_V < q_{V,t}$	0,33 %	0,66 %	1,0 %
Reproducibility			
for $q_V \geq q_{V,t}$	0,17 %	0,33 %	0,5 %
Transition flow rate			
$q_{V,t}$	$q_{V,t} \leq 0,1 q_{V,max,cal}$		
Speed of Sound deviation			
MSOS deviation from TSOS	≤±0,2 %		
MSOS spread between acoustic paths	≤0,5 m/s		

**Key**

- q_V volume flow rate
- $\Delta q_V/q_V$ flow rate measurement error, in %
- 1 unadjusted meter curve calibration results
- MPE* maximum permissible error
- $q_{V,0}$ zero flow rate limit
- $q_{V,t}$ transition flow rate
- $q_{V,max}$ designed maximum flow rate
- $q_{V,min}$ designed minimum flow rate
- r_{cal} uncertainty in the mean meter error, see chapter 6.3.2.2
- $\Delta_{p-p,max}$ maximum peak-to-peak error for meters

Figure 10 — Performance requirements envelope

5.8.3 Influence of pressure, temperature, and gas composition

The USM shall meet the above accuracy requirements over the full operating pressure, temperature, and gas composition ranges, with inputs or a correction algorithm, if necessary. The necessary correction algorithms and inputs shall be specified. If a correction algorithm is not necessary, an additional uncertainty due to pressure, temperature, and composition changes shall be specified. If the USM requires a manual input to characterize the flowing gas condition, e.g. gas density and viscosity, the sensitivity of the USM to these parameters shall be specified so that the operator can determine the need to change these parameters as operating conditions change. The concerning parameter settings shall be documented both during calibration and in operation.

5.9 Operation and installation requirements

5.9.1 General

All influences from the installation, or the way the installation is operated, that increase the uncertainty of the USMP shall either be neutralized or compensated. Minimum distances to flow disturbing objects shall be specified. Subclause 5.9 applies to calibration (see Clause 6) as well as to operation (see Clause 8).

Various combinations of upstream fittings, valves, bends, and lengths of straight pipe can produce velocity profile distortions at the meter inlet that may result in flow rate measurement errors. The magnitude of the meter error is dependent on the type and severity of the flow distortion and the ability of the meter to compensate for it. This error can be reduced by increasing the length of upstream straight pipes or by using flow conditioners. Alternatively, carrying out flow calibrations under conditions similar to field conditions is the most effective way to compensate for this error. Research work on installation effects is ongoing, so the installation designer may consult with the USM manufacturer to review the latest test results and evaluate how a specific USM design may be affected by the upstream piping configuration of the planned installation. In order to achieve the desired meter performance, it may be necessary for the installation designer to alter the original piping configuration or include a flow conditioner as part of the meter run.

5.9.2 Operational requirements

5.9.2.1 Sound, noise, and pressure-regulating valves

The function and accuracy of an USM can be adversely affected by noise generated by pressure-regulating valves; see also Reference [55] and 8.1. As the acoustic signal of the meter is stronger at higher pressures and as the noise transmitted by single trim valves is lower upstream, it is strongly recommended to locate the control valve downstream of the USM. (See Annex D).

In the worse cases, the meter can become inoperable under certain conditions. The following recommendations are given in respect of valve-generated noise:

- a) position USMs well away from throttling control valves, ideally with process equipment such as vessels or heat exchangers between them, upstream of the regulator;
- b) improve noise immunity of USMs by:
 - 1) increasing meter transducer frequency,
 - 2) increasing meter transducer power,
 - 3) using signal processing techniques for signal detection, e.g. signal averaging (stacking), digital correlation, or signal coding;
- c) by the installation of blind tees, heat exchangers, out-of-plane bends and/or a flow conditioner between the USM and the valve (i.e. by blocking the line of sight) is the most effective use of standard pipe fittings for attenuating ultrasonic noise;

NOTE 1 A straight pipe is not considered effective for the attenuation of ultrasonic noise.

NOTE 2 Potential operational issues may occur associated with blind tees, which have the potential to introduce undesirable installation effects that distort flow profiles (see 5.9.3.2), collect liquids and become difficult to purge.

- d) lowering the differential pressure across a valve reduces the noise generated at all frequencies.

Note that it is essential that the upstream straight length of the meter is not compromised in following these recommendations. The general sensitivity of the USM to sound (noise) generated by pressure-regulating valves and other sources shall be described.

5.9.2.2 Contamination

Accumulation of deposits due to a mixture of particles and liquid contaminants should be avoided.

Filtration of the gas flow upstream is recommended and in bidirectional applications, filtration both upstream and downstream is recommended. The potential for flow profile disturbance caused by filtration equipment, however, should be recognized.

To avoid severe accumulation, a pipe configuration having a low point downstream of the meter is recommended.

5.9.2.3 Ambient temperature

The influence of the ambient temperature should be minimized as described in 5.7.3. Stratification, especially at low flow velocities, may occur when the temperature difference between the outside temperature and that of the gas is more than 5 °C^[87]. The USM diagnostics may be utilized to determine the presence of stratification.

Also, at least a shade should over the full length of the measurement section be supplied to protect the meter run and electronics against direct sun radiation. The best way to protect from ambient temperature is thermal insulation of the upstream pipe (until 10D), the USM and the downstream pipe including the temperature measurement.

5.9.2.4 Vibration

USMs shall not be exposed to vibration levels or vibration frequencies that might excite the natural frequencies of ES boards, components, or ultrasonic transducers.

5.9.2.5 Electrical noise

Even though a USM design has been tested to withstand the electrical noise influences described in 7.5, the USM or its connected wiring shall not be exposed to any unnecessary electrical noise, including alternating current, solenoid transients or radio transmissions.

5.9.2.6 Non-steady flow

Pulsations and non-steady flow beyond the manufacturer's specifications shall be avoided (see 5.4.4).

5.9.3 Installation requirements

5.9.3.1 General

A fully developed flow profile is the most desirable condition at the meter. In practice, undisturbed flow conditions may be the highest achievable.

Due to the large variety of USM types, upstream piping configurations, and flow conditioners, it is practically impossible to standardize upstream lengths. Furthermore, USM technology continues to improve, which makes standardization on this point even more difficult. The lengths between the USM and the flow conditioner and upstream of the flow conditioner shall be specified in the manufacturer instructions.

5.9.3.2 Distance to perturbations, upstream and downstream straight pipe length requirements

Typical upstream piping conditions (operating conditions), e.g. bends, headers, T-joints, flow conditioners, filtration equipment, diameter changes (steps, expanders or reducers), and valves, introduce swirl, an asymmetric flow profile, a flat flow profile, a peaked flow profile or combinations of these. Research has demonstrated that asymmetric profiles may require a length measuring 50D of straight pipe without a flow conditioner, and swirling profiles may require 200D of straight pipe

without a flow conditioner before a fully developed flow profile can be expected. Installing such lengths of upstream straight pipe is impractical. The current ability of USMP to compensate for disturbed flow profiles allows shorter lengths of straight upstream pipe.

It is recommended to utilize the USM diagnostics to determine if the flow conditions in operation are not severely disturbed. Secondly it should be determined if the flow conditions are representative with the calibration conditions of the USM by comparing the diagnostics of the USM during calibration and in operation.

The minimum length of straight upstream pipe, l_{\min} , shall be such that the addition of an extra straight length measuring $10D$ alters the reading of the USM (FWME) by not more than the combined reproducibility of the calibration facility and the USM. The value of l_{\min} differs in accordance with the upstream piping configuration and can only be found using a set of reference standards. Determination of the values of l_{\min} for a standard set of upstream piping configurations is a major task during type testing; see 7.3. Determine l_{\min} such that the maximum additional error due to flow perturbations is less than one third of the MPE for the corresponding meter class. The manufacturer shall specify the values of l_{\min} for the different flow perturbations defined in 7.3.

A configuration for which l_{\min} is unknown:

- requires a length of $50D$ of straight upstream piping the application of a USM, or
- requires a length of $10D$ for the application of a USMP.

The minimum length of straight downstream pipe is $3D$.

5.9.3.3 Protrusions and diameter step

Changes in inside diameters (D) and protrusions should be avoided at the USM inlet to avoid the disturbance of the velocity profile.

The flanges and adjacent upstream pipe shall be straight, cylindrical, and have the same inside diameter throughout as the inside diameter of the inlet of the meter, at maximum of 1 %. These components shall be carefully aligned to minimize flow disturbances, especially at the upstream flange. 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°.

NOTE This value can only be considered as a guide to estimate the additional uncertainty due to diameter steps.

For a minimum upstream length of $2D$, there shall be no flow disturbances from flanges, flow straighteners, etc. Over a length of at least $10D$ or l_{\min} upstream of the meter, whichever is smaller, the pipe section(s) shall fulfil the following requirements:

- a) the pipe shall be straight, i.e. have no bends $>5^\circ$;
- b) two pipes are said to be aligned when local diameter steps are $<3\%$;
- c) the internal weld of the downstream flange of the upstream piping shall be ground smooth and no part of the upstream gasket or flange face edge shall protrude into the flow stream;
- d) the pipe is said to be cylindrical when no diameter in any plane differs by more than 3 % from the average inside diameter, D , obtained from the measurements specified;
- e) The USM manufacturer shall prove that the additional bias due to the diameter steps greater than 1 % is below one third of the MPE for the corresponding meter class within type testing, see 7.3.

5.9.3.4 Thermowells and density cells

For thermowells and density cells, see 5.7.2.

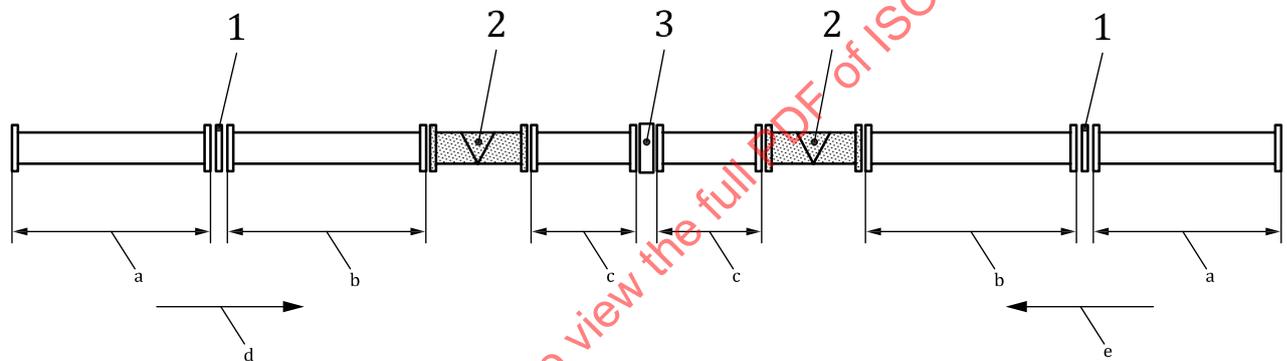
5.9.3.5 Flow conditioners

One of the main advantages of USMs is the absence of a pressure drop. The use of a flow conditioner introduces a pressure drop and negates this advantage. Lack of available space for sufficient upstream length or unquantifiable effects of upstream pipe work configuration are the most common reasons for their use.

Installing a flow conditioner at any position in the meter run upstream of the USM causes a change of the flow rate indicated by the meter. This change depends on many factors (e.g. flow conditioner type, meter type, position relative to the USM, and flow perturbation upstream of the flow conditioner). To avoid this additional uncertainty, the USM shall be calibrated with the actual flow conditioner and meter tube as one package (USMP) or simulated (with the same make and model).

For USMs, perforated plate-type conditioners are preferred. Tube bundles and vane-type flow conditioners only suppress the swirl, do not improve the flow profile, and may even cause additional profile distortions.

An example of a bidirectional flow installation where two USMs and flow conditioners are employed with the thermowell located in the centre section is given in the next Figure.



Key

- 1 flow conditioner
- 2 ultrasonic flowmeter (USM)
- 3 temperature annulus
- a $\geq 2D$ (Preferably $\geq 3D$).
- b $10D$.
- c $5D$.
- d Flow primary direction (Forward).
- e Flow secondary direction (Reverse).

Figure 11 — Example of a bidirectional installation

WARNING — A flow conditioner may produce noise of severe levels depending on its design and the gas velocity.

5.9.3.6 Internal surface and wall roughness

Deposits due to normal gas transmission conditions, e.g. condensates or traces of oil mixed with mill-scale, dirt or sand, may affect the accuracy of the meter. The same effects may be experienced from rusting of untreated internal surfaces or a defective internal coating. The internal surface and the wall roughness should therefore be monitored for changes using the meter diagnostics as well as optical (visual) methods. The monitoring interval chosen should be dependent on the sensitivity of the USM as well as the expected changes in wall roughness.

5.9.3.7 Bidirectional use

For bidirectional use, both upstream and downstream piping shall be regarded as “upstream” piping. The sensitivity of the USM to the thermowell or the density cell shall be specified.

5.9.3.8 Orientation of meter

The requirement of [5.8.1](#) shall also be met when orienting the USM into a position different to that for which it was designed.

5.9.4 Manual handling and transportation

Regulations covering manual handling shall apply. The possibility of damage to the USM during handling and transportation shall be recognized and all reasonable steps taken to minimize its likelihood. For example, consider:

- a) the use of an indication device such as a shock detector during transportation;
- b) the use of appropriate lifting and transport cases or frames;
- c) the use of flange covers to avoid the internal contamination of the meter;
- d) the minimization of transducer and cable removal;
- e) the implementation of procedures described in [8.2](#);
- f) post-production protection of the meter and spools against corrosion by purging with inert gas prior to transport.

5.10 Documentation

5.10.1 General

All documentation shall be dated and the manufacturer shall provide a list of all documents submitted.

5.10.2 Generic meter documentation

The manufacturer shall provide or make available at least the following documents:

- a) a description of the meter giving the technical characteristics and the principle of its operation;
- b) a dimensioned drawing and/or photograph of the meter;
- c) a nomenclature of parts with a description of constituent materials of such parts;
- d) an assembly drawing with identification of the component parts listed in the nomenclature;
- e) a dimensioned drawing;
- f) a drawing showing the location of verification marks and seals;
- g) a drawing or picture of the data plate or face plate and of the arrangements for inscriptions;
- h) a drawing of any auxiliary devices;
- i) instructions for installation, operation, and periodic maintenance and troubleshooting;
- j) a field verification test procedure as described in [Clause 8](#);
- k) maintenance documentation including third party drawings for any field repairable components;
- l) a recommended spare parts list;

- m) a description of the electronic signal processing unit, arrangement, and general description of operation;
- n) a description of the available output signals and any adjustment mechanisms;
- o) a list of electronic interfaces and user wiring termination points with their essential characteristics;
- p) a description of software functions and operating instructions.

5.10.3 Particular meter documentation

The manufacturer shall provide or make available at least the following documents of the particular meter:

- a) specific meter outline drawings including overall flange face-to-face dimensions, inside diameter, maintenance space clearances, conduit connection points, and estimated mass;
- b) documentation that the design and construction comply with applicable safety codes and regulations;
- c) documentation that the performance of the meter meets the requirements of [5.8](#) and [Clause 7](#);
- d) documentation of the dimensional measurements as required in [5.2.4.2](#);
- e) copies of hydrostatic test certificates, material certificates, weld radiographic reports and other quality tests as specified by the designer;
- f) documentation that the design of the meter successfully passed the tests described in [Clause 6](#).

6 Test and calibration

6.1 Pressure testing and leakage testing

The meter body shall be pressure tested before the FAT and in accordance with the applicable design code.

The meter shall be properly leak checked to ensure tightness at any design conditions of the meter.

6.2 Individual testing — Static testing

6.2.1 General

Static testing comprises the measurement of the meter body dimensions (see [5.2.4](#)) and the time delays of the electronics and the transducers as well as a zero flow verification test.

6.2.2 Timing and time delays

Transducer, electronics and cable time delays can cause velocity-offset errors if they are not correctly defined in the parameter list of the USM. The manufacturer shall measure and document the time delay(s) of electronics, cable and transducers, if applicable. The uncertainty of the measurement shall be specified. Test gas and all calibration instruments used to perform these measurements shall have calibration certificates traceable to internationally recognized standards. Any time delay effects emerging from differences between calibration conditions and operating conditions shall be specified and compensated for as required to comply with the specified uncertainty.

6.2.3 Zero flow verification test

To verify the transit time measurement system of each meter, a zero flow verification test shall be performed. The manufacturer shall specify procedure and tolerances.

The test procedure shall include the following elements as a minimum:

- a) blind flanges have to be attached to the ends of the meter body;
- b) the acoustic properties of the test gas or gas mixture, whose selection shall be the responsibility of the manufacturer, shall be documented;
- c) gas shall be homogeneously mixed with stable pressure and temperature, especially for tests at high pressure. The test conditions shall be considered stable if the relative standard deviation of the average speed of sound value is not greater than 0,05 %;
- d) gas velocity and speed of sound for each acoustic path shall be recorded for at least 300 s from which the average values and their standard deviation for each acoustic path shall then be calculated;
- e) the zero flow reading and absolute SOS deviation for each acoustic path shall fulfil the requirements of [5.8](#);
- f) the uncertainty of the test gas pressure measurement shall be better than 0,1 % and the uncertainty of the test gas temperature measurement shall be better than 0,2 K;
- g) the theoretically determined values for the SOS shall be computed using a complete compositional analysis of the test gas using internationally recognized algorithms. The theoretical speed of sound of the test gas shall be calculated with an uncertainty better than 0,05 %.

6.3 Individual testing — Flow calibration

6.3.1 General

All class 1 meters shall be flow calibrated meeting the requirements of a flow laboratory. For class 2 meters, this flow calibration is highly recommended.

The flow calibration of meters may also be required because of:

- national legal requirements;
- high accuracy requirements;
- the application for custody transfer.

The calibration shall be carried out with a representative test gas. Where practicable calibrate as close as possible to the operating conditions. Where this not possible this standard provides equations and guidance for situations where the operating pressure is significantly different from the calibration pressure (see chapter 9).

The flow calibration delivers a set of systematic errors, as a function of flow rate or Reynolds number. This set is usually presented as a “calibration curve” and shall be used to correct the meter output as documented in [6.3.4](#). The manufacturer shall provide a calibration and adjustment procedure.

It is recommended to calibrate the meter to the maximum flow rate of the application ($q_{V, \max, \text{op}}$) and not lower than the minimum technical flow rate of the meter ($q_{V, \min, \text{design}}$), see also [5.1.1](#).

While USM's can be sensitive for flow disturbances by welding seams, these shall be avoided in the upstream pipe. See also [5.9.3.3](#).

6.3.2 Laboratory flow calibration

6.3.2.1 General

To minimize the uncertainty of the calibration, the calibration shall be conducted at a laboratory having a quality control in accordance with the ISO/IEC 17025 and having a stated CMC table (combined uncertainty of the calibration rig U_{CMC}) determined according to ISO/IEC GUIDE 98-3 (GUM).

The calibration shall be performed:

- a) under undisturbed, i.e. non-swirling, non-pulsating and symmetrically developed flow conditions (see 6.3.2.4);
- b) under steady flow conditions (see 6.3.2.4);
- c) over a statistically significant duration of time (see 6.3.2.2);
- d) over the appropriate range of flow rates to describe the in-service response of the meter; a minimum of six, but preferably seven, points should be taken, e.g. for a seven point calibration: 100 %, 70 %, 40 %, 25 %, 10 %, 5 % of $q_{V, \max, op}$ and $q_{V, \min}$;
- e) whenever applicable, by using the upstream and downstream meter spools and flow conditioner or dedicated calibration spools;
- f) if there are protrusions upstream of the meter in the flow path, such as thermowells and/or sample probes the meter shall be calibrated in combination with these components at the same distance and orientation as in the field;
- g) the user shall make sure that there is no degradation and/or contamination of the USMP (flow conditioner and the upstream pipe);
- h) The calculation of the uncertainty shall be done in accordance with the ISO 5168.

6.3.2.2 Duration of the calibration

The duration of a measurement (one single flow rate) shall be large enough to reduce the effects of random processes and displays with limited resolution to negligible proportions.

Two methods are given.

- 1) Running standard deviation: During the measurement the samples taken are processed into a running standard deviation in order to calculate the uncertainty in the mean meter error. When the running standard deviation evolves into a stable value, the required duration and repeatability as stated in 5.8 is reached.
- 2) Fixed measurement time: A mean measurement of one flow rate is calculated from several measurements. Three measurements at each test flow rate should be taken at a minimum. These three measurements shall not have a trend for deviation in one direction greater than the stated repeatability. At least one more measurement is necessary until three succeeding measurement repeats fulfill this requirement. Take as many measurements as necessary until the uncertainty in the mean meter error of the measurement is in agreement with the repeatability requirements from 5.8.

The repeatability during the calibration shall be calculated as the uncertainty in the mean meter error of a measurement according to Formula given in 3.1.4.5:

$$r_{\text{cal}} = U_{\text{AM}} = \frac{U_{\text{AS}}}{\sqrt{n}} \quad (13)$$

Based on the uncertainty in a single measurement U_{AS} (see definition of repeatability) and the number n of measurements taken.

NOTE If the uncertainty in the mean meter error exceeds the limit, this can also be caused by too few observations and/or instable conditions. To verify this, more measurements in a stable condition should be taken, to determine if the meter calibration can fulfil the repeatability requirement.

Practice has shown that the total duration of one measurement shall be at least 300 s (e.g. 3 repeats of 100 seconds and at least 3 300 counted impulses each). In the event this is not achieved in reasonable time than the averaging time as stated in Annex D shall be used.

6.3.2.3 Uncertainty of the calibration facility

Choosing a suitable calibration lab is essential for achieving a low uncertainty. Depending on the pressure and flow there exists large differences between the calibration measurement capabilities (CMC) of the various laboratories; some are more appropriate for smaller meters, others are more appropriate for large meters. The uncertainty of the calibration and measurement capability U_{CMC} reflect the variations in operating temperature and pressure during the calibration and any uncertainties arising from the calculation procedure used to derive the meter error of the flowmeter under calibration.

The uncertainty of measurements performed at the test facility shall be sufficiently low to enable the overall metering system uncertainty budget to be met. The stated U_{CMC} of the flow calibration laboratory used for the calibration shall be better than one third of the MPE for the corresponding meter class.

6.3.2.4 Flow conditions

The upstream piping conditions in the laboratory shall be chosen such that no additional errors are introduced. The calibration facility shall deliver a fully developed and undisturbed flow profile upstream of the USM/USMP. The requirements and recommendations given in 5.9.2 and 5.9.3 have to be taken into account. The conditions during the calibration or test on the calibration facility, such as pipe inside diameters, upstream pipe configurations, condition of the inner surfaces of the USM and the pipes, shall be accurately documented.

The stability of pressure, temperature and flow shall be in accordance with the maximum acceptable variations which have formed the basis of the certified U_{CMC} .

The reference turbine meter will shift by pulsations in the flow when it cannot follow the rapid flow changes any more. This occurs when the frequency of the pulsations is higher than $0,2 \times 1/T_T$, where T_T is the time constant of the turbine meter. This time constant is depending of the ratio between the mass of the turbine wheel and the mass flow through the meter. The manufacturer of the turbine meter shall provide this information.

Pulsations with an amplitude of $\Delta q/q > 3,2 \%$ a frequency above $0,2 \times 1/T_T$ shall be avoided. Also to minimize the impact of pulsations for the ultrasonic meter pulsation frequencies higher than half of the sample rate of the ultrasonic meter should be avoided as well.

A correction of line pack effects shall be applied and the effect of the line pack errors shall be properly accounted for in the calibration result.

Any measurement shall be rejected when any of the following situations is encountered:

- a) $\Delta_{LP} > 0,2 \%$ per measurement (line pack);
- b) $\Delta T > 0,25 \text{ K}$ per 100 s (temperature drift);
- c) $\Delta p > 0,002p$ per 100 s (pressure drift);
- d) $\Delta q_V > 0,03q_V$ per 100 s (flow rate drift);

The flow conditions for the specific quantities a) to d) listed above shall be monitored and documented during calibrations.

6.3.2.5 Thermal stratification at a calibration facility

During calibration, especially at low flow velocities, stratification can occur when the temperature difference between the outside temperature and that of the gas is more than 5 °C.

To detect the presence of thermal stratification, the speed of sound of the upper most and the lower most horizontal measuring paths of a chordal path meter can be used. For flow rates above $q_{V,t}$ the speed of sound of the upper path shall not differ greater than 0,2 % from the lower path. Otherwise the calibration point shall be repeated.

Adequate thermal insulation in the upstream, the USM(P), and the temperature measurement section prevents stratification.

6.3.2.6 Bidirectional calibration

A class 1 USM / USMP used for a bidirectional application shall be calibrated in both directions including the thermowells.

6.3.3 Judging the measurement performance of the meter

The judgement of the measurement performance of the meter shall be based on the combination of the calibration curve and a linear offset related to the flow-weighted mean error (FWME) only. Other corrections, such as curve fittings or linearization's, may not be used to judge the performance of the meter as they might mask hidden design effects. They shall only be applied after approving the meter performance curve.

The FWME shall be calculated according to [B.2](#) and verified against the corresponding accuracy class requirement.

The USM or the USMP shall meet the accuracy requirements specified in [5.8](#) for flow rates between $q_{V, \min, \text{cal}}$ and $q_{V, \max, \text{cal}}$.

NOTE If the uncertainty of the calibration facility cannot meet the U_{CMC} criteria stated in [6.3.2.3](#), the measurement performance of the meter can be judge alternatively by reducing the applied maximum permissible error with the excess of the uncertainty. In this case the USM or the UMSP shall meet the following acceptance criteria:

$$\pm \left(\frac{4}{3} \cdot \text{MPE} - U_{\text{CMC}} \right)$$

while $U_{\text{CMC}} \leq \text{MPE}$.

6.3.4 Adjustment and records

6.3.4.1 General

Adjustment factors and calibration curve correction (linearization) may be applied within the flow computer or within the meter. Care shall be taken to ensure that the same correction is not applied in multiple locations.

Possible methods of applying adjustment factors are by using:

- FWME over the expected flow range of the meter (an example of the calculation of FWME is shown in [B.2](#));
- multi-point linearization algorithms over the calibrated (operational) range of the meter;
- polynomial algorithms over the calibrated range of flow rates of the meter. When using polynomial algorithms strict adherence to mathematical data fitting rules shall be applied.

The correction shall be fixed to the respective last valid correction of the calibrated $q_{V, \min}$ respective $q_{V, \max}$ if the meter operates outside the calibrated range. The uncertainty of the measurement in that region is unknown.

For bidirectional calibrations, a second set of factors shall be used for reverse flow.

Where linearization curves are applied, the following correction algorithm may be used:

$$q_{V, \text{true}} = q_{V, \text{actual}} \frac{100}{100 + E(q_{V, \text{actual}})} \quad (14)$$

where

$q_{V, \text{actual}}$ is the raw metered quantity;

$E(q_{V, \text{actual}})$ is the error, as a percentage, associated with the flow rate;

$q_{V, \text{true}}$ is the value the meter should return with insignificant error, i.e. the reference meter quantity.

After adjustment of the meter any corrections shall be verified.

For a FWME correction a single verification point taking around 40 % is recommended.

When using a polynomial correction or multi-point linearization a minimum of two verification points are necessary which are preferably chosen in a flow rate range of 10 %..25 % $q_{V, \text{max}}$ and 70..100 % $q_{V, \text{max}}$. At least one verification point shall be chosen between two different as-found flow rates.

6.3.4.2 Results

Record:

- a) the date(s) of the test;
- b) in case of bidirectional meters: “forward flow” or “reverse flow”;
- c) the determined errors As found and As left, the total uncertainty U_{tot} , U_{CMC} values and repeatability at the investigated flow rates;
- d) to indicate whether an adjustment factor had been updated on the meter, in the case of a single point correction, the value of both the adjustment factor and FWME before adjustment and the value after adjustment shall be indicated;
- e) to facilitate a multi-point calibration curve correction in the field (linearization), the individual adjustment factors, e.g. frequency and impulse factor, of the calibration points;
- f) the calibration checkpoints if an adjustment was applied to the meter;
- g) the density and viscosity of the gas or/and the gas composition;
- h) the check of the MSOS against the TSOS calculated by AGA-8 or GERG-2004^[61];
- i) the log file containing all diagnostics data taken during calibration to be used in the audit trail with as a minimum:
 - MSOS as a function of flow;
 - MSOS fingerprint;
 - Flow dependent signal waveforms;
 - Flow dependent S/N values and ratios;
 - Flow dependent AGC values;
 - Standard deviation and velocity values per path and ratios;

- j) the report of the meter configuration parameters and checksums during calibration and after adjustment.

6.3.4.3 Meter identification and description of the facility

Record:

- a) data supplied by the manufacturer, such as:
- meter size
 - Serial numbers of meter, electronics and transducers
 - the firmware version
- b) of the meter being tested;
- c) the calibration facility, the method of calibration (bell prover, sonic nozzles, other meters, etc.).

6.3.4.4 Conditions of the test

Record and verify against the applicable requirements:

- a) the upstream and downstream piping configurations involved in the qualification of “undisturbed flow profile”, including flow conditioners, piping tag numbers and inside diameters;
- b) the position of the meter (horizontal, vertical flow upwards, vertical flow downwards) as well as the meter orientation;
- c) the position, orientation and flow direction of the piping components (such as pipes, flow conditioners, used pressure sensing point and thermowells) if calibrating an USMP;
- d) a description of the condition of the inner surface of the meter and the upstream pipes (dirt, corrosion) — where necessary, add a photograph;
- e) the nature (e.g. gas composition) and conditions (pressure and temperature) of the test gas.

A description of any variations or deviations from the required test conditions.

7 Type testing

7.1 General

A meter calibration curve without the guarantee that the meter behaves the same way in the field as in the calibration laboratory is meaningless and real-world circumstances are generally more complex than those encountered at a calibration facility. In order to ensure that the quality of the calibration curve is transferable to the field, type testing of the model/family design is introduced. Here real-world circumstances are simulated by a series of perturbations tests and the meter has to prove that it can deal with these. Only then is the calibration curve transferable.

Every USM model/family design requires a compliance testing to this document.

Type testing shall be conducted by recognized bodies or independent certified laboratories.

The meters used for type testing shall be equipped with all characteristic parts (electronics, transducers, software, etc.). Meters of different design shall play no part in the type approval. The validity of the type approval shall be clearly defined. It is recommended that the type testing be carried out on at least one of the smaller meter sizes of the USM type in order to evaluate the largest influence of the geometrical parameters and the time delays on meter performance.

These test requirements shall apply to the design of all circuit boards, ultrasonic transducers, interconnecting wiring, and customer wiring terminals. The electronics shall be in operation, measuring zero flow, and remain 100 % functional during the tests. In the case of high-voltage transient and electrostatic discharge tests, the meter may temporarily stop functioning, but shall automatically recover within 30 s.

All signal outputs representing the same measurement value shall represent with the same accuracy.

During these tests, the ultrasonic transducers may be operated in a smaller and lighter test cell (or test cells) instead of a full meter body. However, the transducers shall actually be measuring zero flow and exposed to the same test conditions as other parts of the electronics.

7.2 Accuracy

The accuracy limits of [5.8.2](#) shall be met within $q_{V, \max, \text{design}}$ and $q_{V, \min}$.

The tests shall be conducted under undisturbed flow conditions with the following flow rates: 120 %, 100 %, 70 %, 40 %, 25 %, 10 %, 5 % of $q_{V, \max, \text{design}}$.

The duration of one measurement shall comply with the requirements of [6.3.2.2](#).

Due to the nature of the more disturbed flow conditions during the test of the installation conditions a longer measurement time or increased number of repeats might be required to achieve an acceptable uncertainty in the mean meter errors at these tests.

The repeatability test shall be conducted for at least one flow rate below $q_{V, t}$ and at least one flow rate above $q_{V, t}$. For each of these flow rates, 10 single measurements shall be taken with the duration of the measurement as given above.

For the reproducibility test, the same meter shall be tested under exactly the same installation conditions. The reproducibility shall be derived from at least three test results for flowrates above or equal to $q_{V, t}$.

7.3 Installation conditions

The minimum length of straight upstream pipe, l_{\min} , shall be such that the addition of an extra straight length measuring 10D alters the reading of the USM (FWME) by not more than the combined repeatability of the calibration facility and the USM.

For a standardized set of perturbations, the l_{\min} of every perturbation shall be determined:

- a) under reference flow conditions according to [6.3.2.1](#);
- b) with a single 90° bend (radius of curvature of 1,5D):
 - with the USM in normal position;
 - with the USM rotated by 90°;
- c) with two 90° bends in perpendicular planes (radius of curvature of 1,5D, without spacer between bends):
 - with the USM in normal position;
 - with the USM rotated by 90°;
- d) an expander with a diameter increase of at least one pipe size [typically 2¹];
- e) a reducer with a diameter decrease of at least one pipe size [typically 2¹];

1) 1" = 25,4 mm.

- f) a diameter step on the upstream flange of the USM with magnitude of at least +3 % and –3 %;
- g) a flow conditioner chosen and positioned by the manufacturer in combination with perturbations above.

The single tests shall be conducted for at least one flow rate below $q_{V,t}$ and for at least two different flow rates above $q_{V,t}$, according to 6.4.2. Relevant are the mean values of the three single measurements at each flow rate. Above $q_{V,t}$, all calculated mean additional errors shall be within one third of the MPE for the corresponding meter class.

Instead of the perturbation tests described in a) to g), similar tests with different perturbation-producing devices are allowed, such as perturbation plates (e.g. swirl generators). In that case, it shall be clearly shown that the velocity fields produced are similar to the perturbations presented in a) to g), for instance via the measurement of the three-dimensional velocity field.

7.4 Path failure simulation and exchange of components

Where a class 1 or 2 meter remains in service in the event of path failure, the effect of the failure shall be determined by simulating the failure of one or more paths.

The test should be carried out at a flow velocity of 15 m/s. During the test, the flow rate should be varied to a value of 10 m/s and 20 m/s. For all three tests the additional error shall be not more than one third of the MPE for the corresponding meter class.

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

- a) the electronics;
- b) transducers of different path types.

When components are exchanged, the resulting shift in the mean error of the meter shall not be more than as laid down in [5.6](#).

7.5 Electronics design testing

The design of the electronics shall be tested to demonstrate that the USM continues to meet the performance requirements of [5.8.2](#), while operating under the influences and disturbances specified in [Annex G](#).

[Table G.1](#) shows the minimum severity level for each test to fulfil the requirements of the instrument classifications used in:

- a) open locations with average climatic conditions, thus excluding polar and desert environments;
- b) locations where the level of vibration and shock is high or very high, e.g. for instruments mounted directly on machines or conveyor belts;
- c) locations with electromagnetic disturbances corresponding to those likely to be found in industrial buildings.

During these tests, the ultrasonic transducers may be operated in a smaller and lighter test cell (or test cells) instead of a full flow-meter body. However, the transducers shall actually be measuring zero flow and be exposed to the same test conditions as other parts of the electronic system.

If the meter performance is monitored at no-flow conditions the cut-off for low flow rates shall be switched off so that the flow rate output corresponds to the unsuppressed flow rate.

The flow rate output has to be monitored and evaluated according to [5.8](#) and the fault limit and test condition as stated in [Annex G](#).

8 Audit trail and diagnostics for meter verification

8.1 General

This clause is directed at the operator, to ensure that the USM, once in service, continues to meet the expected performance requirements after installation.

USMs can deliver extended diagnostic information through which it may be possible not only to verify the functionality of a USM, but also of several other components within the system, such as the gas chromatograph and the pressure and temperature transmitters. Due to the extended diagnostic capabilities, this document advocates the addition and use of automated diagnostics instead of labour-intensive quality checks.

Ultrasonic flow meters for custody transfer generate a comprehensive and beneficial diagnostic suite, however the amount of data and the way that it is presented differs from manufacturer to manufacturer. It is complex, and in all cases will be far too much to be handled by most of the operators, often resulting in the information being disregarded or lost.

For many operators, there is no structure available to help them present the data in, or to enable them to easily make comparisons. This problem has been recognized and addressed by this document and a two-step approach has been chosen so that the health of the USM and associated instrumentation that make up the measurement are monitored. By selecting just a small group of diagnostic parameters and using them as key indicators, it is possible to ensure the health of the meter and the overall measurement system.

In the first mandatory step there is a simple check on the maximum deviations of those key parameters. As long as those are within the tolerance bands as presented, there is no need for further action.

Only as a trend is monitored and/or the deviation passes the alarm values service actions need to be started. In those service actions the diagnostic parameters can then be compared with their historical values determined at various stages during manufacturing, calibration and the commissioning of the ultrasonic flow meter and stored in the audit trail.

The use of diagnostics shall be used in conjunction with operational best practice.

8.2 USM Lifecycle Process

For class 1 and class 2 meters the operator shall set up an audit trail. The audit trail files are key documents and key characteristics of the USM throughout its life cycle (see [Figure 12](#)).

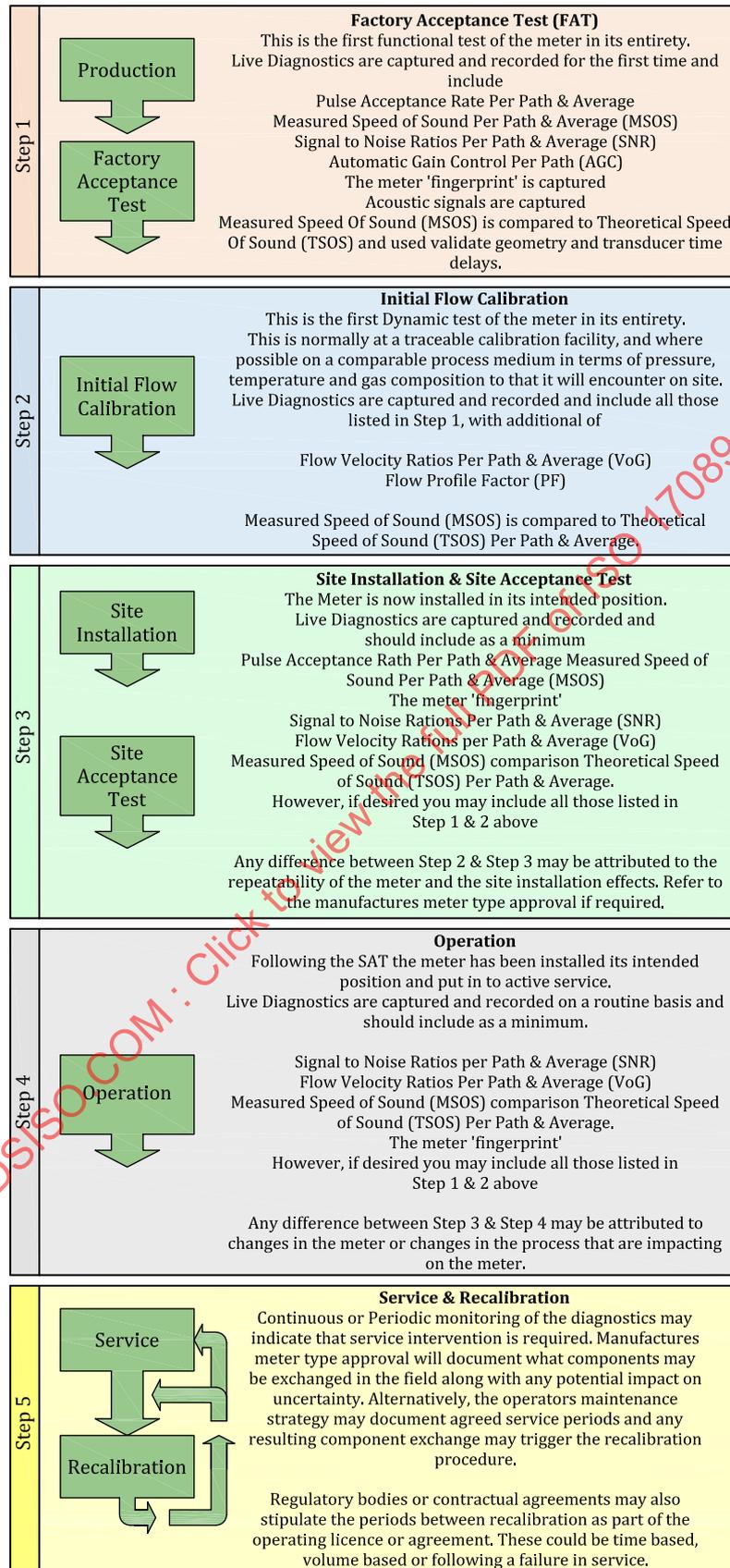


Figure 12 — Audit trail

The audit trail reflects the total history of a meter. It starts at the manufacturing plant with the design of the meter and goes all the way up to the diagnostic tests during operation. Also when applicable, service reports and recalibration results have to be included.

In each of these phases specific tests are done and data is gathered which forms the basics of the audit trail. That data is vital to judge the performance in situ and needs to be delivered to the customer together with the ultrasonic flow meter.

8.3 Production and Factory Acceptance Test

During manufacturing, a manufacturing handbook is created containing the required production and material certificates for each individual meter, including the pressure and other test certificates.

During production a Factory Acceptance Test (FAT) is conducted, checking the behavior of the meter under controlled zero flow conditions. In the FAT, typically the meter is filled and pressurized to a pressure of approximately 1 MPa to 2 MPa with a gas of which the acoustic properties have to be known with an uncertainty in the speed of sound that is better than 0,05 %.

During the FAT the P & T are accurately measured and the Theoretical Speed of Sound (TSOS) is determined and compared to the measured Speed of Sound (MSOS).

Based on the TSOS the properties of the acoustic paths are determined and set to the correct value.

A relationship between each of the acoustic paths is established and the resulting meter fingerprint which is used for future reference and comparison is obtained.

Deliverables from manufacturing:

- a) Manufacturing handbook;
- b) FAT performance and diagnostic test results should be captured and as a minimum should include:
 - Zero flow path gas velocity measurement;
 - MSOS values per path and the MSOS ratios (fingerprint);
 - Signal acceptance rate shall be 100 %;
 - Acoustic signal waveforms;
 - S/N values;
 - Gain values;
 - A configuration report including software and firmware version;
 - Recording of the actual temperature, pressure and gas composition.

Following the FAT the meter is sent to the calibration facility where it will undergo a flow calibration. For details see [6.3](#).

8.4 Initial Flow Calibration

During calibration the meter is subjected to flow for the first time. Therefore, next to the calibration result itself, it is vital to record the flow dependent behavior of all the diagnostic parameters. These records can later be used to validate the performance in the field. The non-flow dependent diagnostics should be comparable to those obtained during the FAT. The piping configuration implemented at the calibration may influence the diagnostics produced by the meter, therefore it is important to document the conditions and record the layout according to [6.3](#).

Deliverables at the calibration:

- Flow dependent diagnostic parameters to be captured at calibration shall include as a minimum:
 - MSOS as a function of flow (check against the AGA-8 / GERG-2004);
 - MSOS fingerprint;
 - Flow dependent signal waveforms;
 - Flow dependent S/N values and ratios;
 - Flow dependent AGC values;
 - Standard deviation and velocity values per path and ratios.

From the above individual values, the Average, Minimum, Maximum and Standard Deviation values can be determined.

- The calibration report shall document the results of the calibration, together with a statement of conditions under which the calibration took place as documented in [6.3.4.1](#).

8.5 Site installation and site acceptance test

Once the meter has been installed, connected up and pressurized, it is important to conduct an initial functional verification to ensure that no damage has occurred in transit or during installation. The meter fingerprint should be captured and compared to that obtained at the FAT and also the calibration laboratory. The commissioning process shall also include a Site Acceptance Test (SAT) where flow tests across the operational range are an inherent part. Diagnostic log files should be captured as this will become the 'first gas' fingerprint against which future comparison can be made.

- SAT performance and diagnostic test results should be captured and as a minimum shall include:
 - A log-file of the diagnostic data captured across the achievable flow range, including MSOS values per path and the MSOS ratios (fingerprint), S/N values and gain values;
 - A record of the individual acoustic signal waveforms;
 - Comparison report of the actual meter parameters with those used during calibration;
 - A record of the individual path gas velocities;
 - An in-situ TSOS comparison to the average MSOS value using an internationally recognized algorithm;
 - A check of the MSOS ratios of the various paths;
 - Recording of the actual temperature, pressure and gas composition.

8.6 Operation

Following completion of the commissioning process and subsequent acceptance of the meter, the metering system is then put in to commercial operation. If the commissioning or SAT process did not include a full functional flow test then it is important that an operational diagnostic log file is captured as soon as possible after the system is put in to operation. Ideally the meter should be initially operated across its full range so that the profile related diagnostics are captured correctly. If that is not possible due to operational or seasonal constraints then it should be performed as soon as practically possible. This will become the installed reference data against which future comparisons are made so it becomes an essential part of the audit trail.

During operation the operator shall periodically compare the actual data from the meter with that collected during the previous steps to determine the following three vital points remain within acceptable limits:

- The accuracy of the timing.
- The stability of the flow profile.
- The quality of the acoustic signal detection.

In practice:

- The check on the timing accuracy is done by checking the MSOS and the MSOS ratios.
- The check on the stability of the flow profile is done by checking the flow velocity ratios.
- The check on the quality of the signal detection is done by checking the S/N ratios.

When the meter is installed in a situation where no contamination occurs the user can then be assured with a very high confidence level that the meter is operating within specification.

Data that shall be periodically generated and reported:

- MSOS comparison of the measured MSOS versus the one calculated based on the AGA-8/GERG-2004;
- MSOS ratios (SOS fingerprint);
- Velocity ratios;
- S/N ratios.

For each of these the maximum deviations need to be given for a warning and an alarm level. These are described below. In case of a warning, the meter may require attention. In case of an alarm, intervention and corrective action may be required.

8.7 Diagnostic warning and alarm levels in operation

8.7.1 MSOS and MSOS ratios warning & alarm levels

Comparing the MSOS from the UFM with TSOS calculated using an internationally recognized algorithm, allows the timing of the ultrasonic flow meter can be checked. Here there are two checks, one on the average MSOS and one on the MSOS ratios. The latter is used to check if all the acoustic paths are still in line with each other and whether stratification occurs.

The accuracy with which the comparison of the average MSOS against the TSOS can be done depends on the quality of the calculation, and the quality, suitability and condition of the equipment used to measure the gas composition, pressure and temperature. The more representative the sample is to the bulk gas composition, then the more accurate the TSOS will be.

For pressures above 12 MPa the GERG-2004 equation may provide lower calculated uncertainty for the calculated TSOS, but in most practical applications where the operating pressure is below 12 MPa, and within a temperature range of -8 to 62 °C, the AGA-8 will be a suitable internationally recognized calculation.

The sensitivity for small deviations is much lower for the pressure than for the temperature, e.g.:

- An uncertainty of 0,1 % in the pressure has corresponding uncertainty on the MSOS of 0,005 %;
- An uncertainty of 0,1 % in the temperature has an 0,05% corresponding uncertainty in MSOS.

Based on this, the warning and alarm limits for the MSOS comparison can be defined, allowing also a small tolerance of 0,1 % for the uncertainty of the temperature measurement and also an additional small uncertainty of 0,1 % in case air is used during the FAT.

For a meter operating below 12 MPa and within a temperature range of -8 to 62 °C:

- The MSOS to TSOS comparison is acceptable when the differences are $\leq 0,25$ %;
- Warning level: when the differences are between 0,25 % and 0,35 %;
- Alarm level: when the differences are $> 0,35$ %.

As the MSOS ratios are only affected by the turbulence level, the warning and alarm values can be slightly reduced to:

- The MSOS ratio comparison is acceptable when the differences are $\leq 0,2$ %;
- Warning level: when the differences are between 0,2 % and 0,3 %;
- Alarm level: when the differences are $> 0,3$ %.

The temperature sensors should be regularly calibrated so that the tight tolerances can be maintained. Otherwise, when the deviations of the temperature sensor can be larger than $0,3$ °K a larger uncertainty band has to be applied.

8.7.2 Velocity ratios warning & alarm levels

Setting generic levels for velocity ratios is more difficult as those are dependent on the acoustic path position. Meters with acoustic paths closer to the wall show a larger variation than meters with their paths positioned closer to the centerline of the pipe. Therefore these are values that shall be submitted by the manufacturer.

8.7.3 S/N ratios warning & alarm levels

During the Site acceptance test (8.5) records of the S/N values and Gain values are made. These values serve as reference for the warning and alarm levels.

For operating conditions whereby the pressure does not change more than approximately 15 %, for the difference between the actual S/N ratios and those recorded S/N during the SAT of the following warnings and alarms can be set:

- The measurement is ok when the difference between the actual S/N ratios and the recorded S/N during the SAT are ≤ 6 dB;
- A warning is given when these are > 6 dB and < 9 dB;
- An alarm is given when when these are ≥ 9 dB.

In case the operating pressure is lower than than the approximately 85 % of the pressure during the SAT, the above mentioned values are relaxed with the ratio of both pressures in dB. ($20 \log P/PSAT$). So for instance when the operating pressure is half of the pressure during the SAT, the values are relaxed with an additional 6 dB, provided that the relaxed limit fulfills still the minimum requirement for S/N set by the manufacturer.

8.8 Service and recalibration

8.8.1 General

The time between the initial calibration and subsequent recalibrations can vary as it can be dependent on the legal rules, local legislation, contractual agreements, measurement circumstances and the

financial impact. For a single meter run the recalibration time varies between 1 and 8 year in most countries.

The meter is normally in full working order when it is required to be taken out of service to be returned for re-calibration. The flow diagram in [Figure 13](#) outlines the recommended procedure for meters being returned for recalibration under different circumstances.

8.8.2 Service Related Diagnostics

During normal operation the USM may be subject to routine maintenance, preventative maintenance or essential intervention. During these events it is recommended that diagnostic log files and signal waveform captures are obtained both for reference and assistance in diagnosing any meter or process related issues. In addition, it is also recommended that the following is obtained (where possible) prior to the USM being taken out of service/operation:

- Complete diagnostic log file capture prior to removal from service in preparation for repair/recalibration
- Complete signal waveform capture prior to removal from service in preparation for repair/recalibration
- Configuration file capture prior to removal from service in preparation for repair/recalibration
- Visual inspection (Photographs) following removal from service in preparation for repair/recalibration
- Report any contamination, degradation or material failure

Identification of the above will determine the route that the USM should follow on the flow chart in [Figure 13](#).

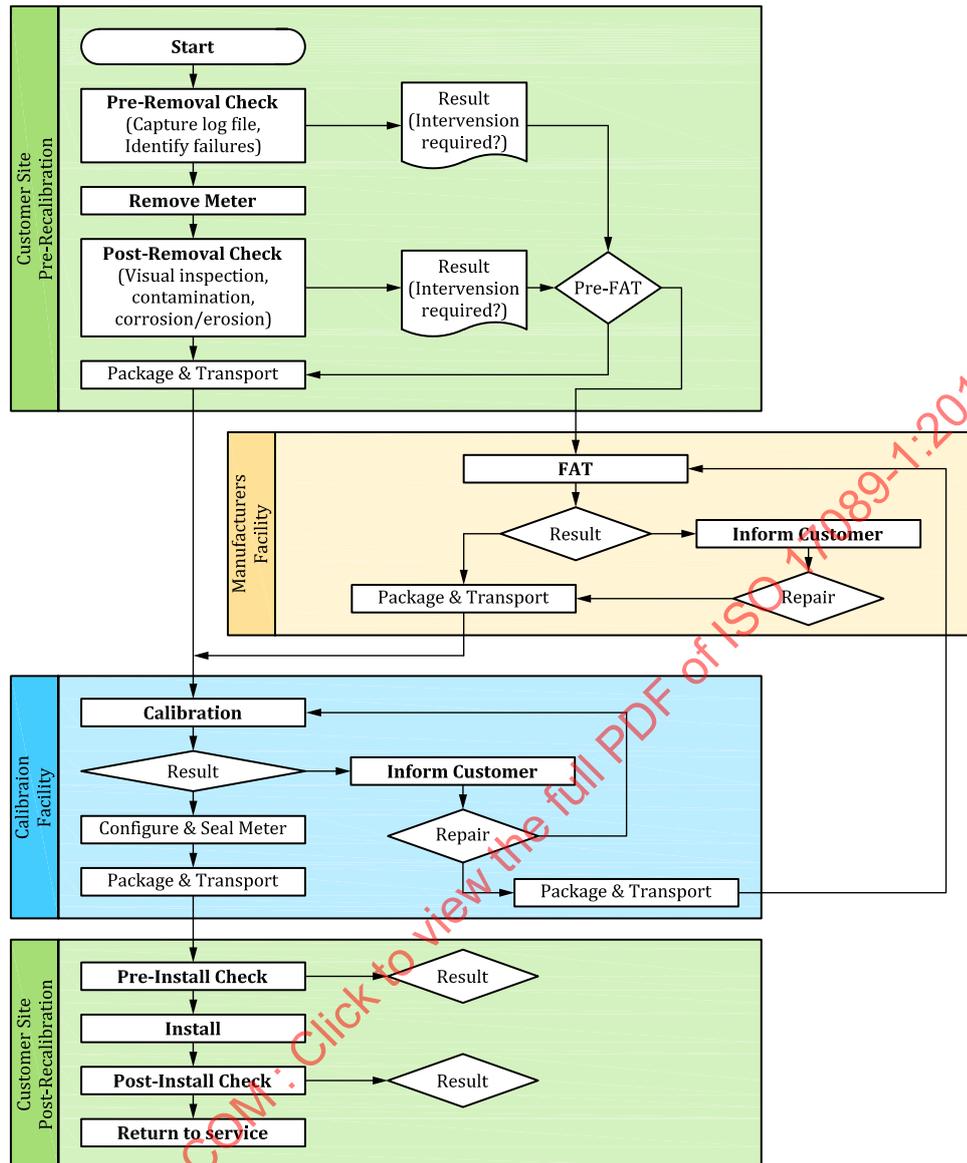


Figure 13 — Recalibration process

8.9 Diagnostic parameters

8.9.1 Speed of sound

8.9.1.1 Measured speed of sound (MSOS)

Speed of sound (SOS) is one of the most important diagnostics associated with the USM. It is a physical measurement of the speed at which the ultrasonic signal travels between the transducer pair. This is defined as the measured speed of sound (MSOS).

The MSOS indicated by the USM is influenced by:

- the temperature;
- the gas composition;
- the pressure;

- the geometry of the measurement section;
- the transit time measurement (by the meter);
- Stratification under low flow conditions (non homogeneous temperature distribution).

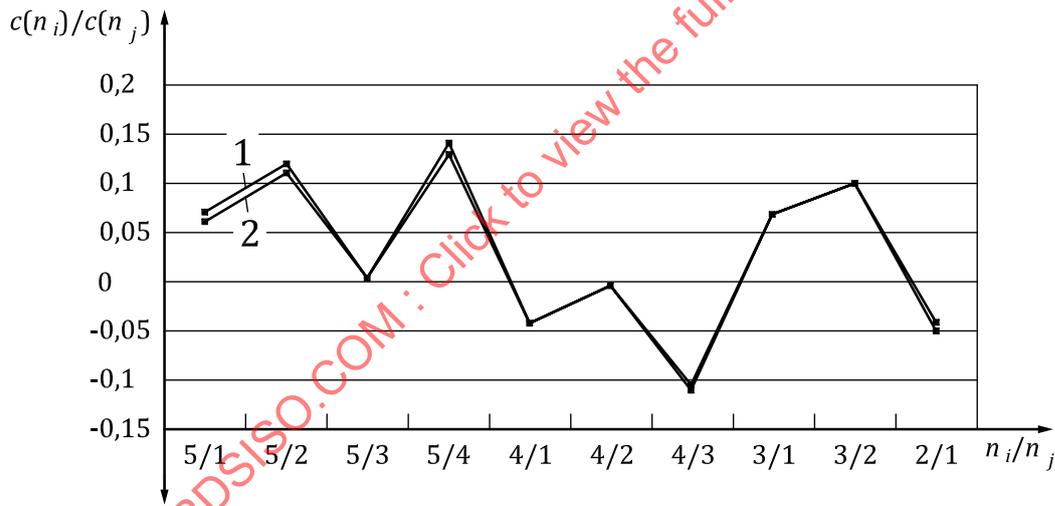
When the USM is equipped with three or more measurement paths, it is possible to use the individual MSOS of each individual path to perform a relative SOS comparison. This comparison is used to establish a ‘fingerprint’ of the USM.

The advantages are:

- It is independent of the gas composition;
- the measurement can be performed under flowing conditions;
- the calculation comparison can be automatically performed as part of a diagnostic package.

NOTE At high velocities, acoustic path length may change due to curving of the acoustic signal (mach effect), thereby increasing the uncertainty.

The fingerprint comparison may be displayed graphically as shown in Figure 14. This is the fingerprint from a five-path USM. The ordinate shows the SOS ratios measured during static testing and flow calibration. The plots show the different ratios of the MSOS from the various paths. The abscissa gives the numbers of the paths from which MSOS is obtained, e.g. 5/1 means the result from path 5 divided by that of path 1.



Key

- n_i/n_j designation of paths
- $c(n_i)/c(n_j)$ SOS ratio, in %
- 1 static test
- 2 flow calibration
- $c(n_i)$ SOS on path n_i
- $c(n_j)$ SOS on path n_j
- n_i one path, $i = 1 \dots 5 (i \neq j)$
- n_j another path, $j = 1 \dots 5 (j \neq i)$

Figure 14 — Fingerprint: ratio pattern determined during static testing with nitrogen and during the flow calibration at the calibration facility

[Figure 14](#) is just an example. Note that different graphs may be generated depending on the meter configuration and number of acoustic paths. However, the same principle can be applied across all USM types with three or more paths.

The relative SOS fingerprint should be unaffected by time, gas composition, temperature and pressure. During operation, the deviation between paths should be within a band of 0,2 % above $q_{V,t}$. Below $q_{V,t}$ at very low flowrates and/or if thermal insulation is insufficient, temperature gradients in the flowing gas may cause additional path SOS deviation.

A change in the shape of the fingerprint over time may indicate malfunction of a path of the USM with a resulting potential for mis-measurement. Fingerprints from FAT, SAT, flow calibration, and field testing may be compared in order to monitor changes in the behavior of the USM.

8.9.1.2 Theoretical speed of sound (TSOS)

In addition to the MSOS, it is also possible to calculate the theoretical speed of sound (TSOS) if the gas composition, temperature and pressure is known. This requires additional input from an online gas chromatograph (OGC), the process temperature and the process pressure transmitters. Using these inputs and applying the equation of state, the GERG-2004 equation or the AGA-8 equation will determine a value for the TSOS.

When the MSOS and TSOS are available it is then possible to make a continuous comparison between the two. The MSOS to TSOS comparison is acceptable when the differences are $\leq 0,25$ %.

Differences between MSOS and TSOS may indicate:

- asynchronous determination of MSOS and TSOS due to fluctuations in gas composition and analysis time lag;

or a malfunction of:

- gas composition measurement;
- temperature measurement;
- pressure measurement;
- USM, including parameter setting, path lengths, time delay and signal detection and processing depositions on the transducer(s) or meter body which change the path length;
- the calculation method used and its operational dependant uncertainties.

Statistical techniques may be helpful for monitoring MSOS and TSOS over time.

8.9.2 Automatic gain control

Automatic gain control (AGC) is used to make the amplified receive signal amplitude the same, irrespective of operating conditions. The main purpose of AGC is to maintain sufficient amplitude and S/N ratio for accurate timing of the receive signal, 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 degree of contamination. The amplification level should be compared against the amplification limit. As the transducer's ability to generate ultrasonic sound deteriorates, the AGC level will increase. At this point the meter path will no longer provide a valid MSOS or an accurate path velocity and the measurement and will go into fault.

8.9.3 Signal-to-noise ratio (S/N)

Signal-to-noise ratio (S/N) 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 S/N suggests the possible

presence of an ultrasonic noise source, often a control valve or flow conditioner device with a large pressure drop. The receiving transducers facing the noise source will have a lower S/N than those facing away from it. The presence of a control valve or other source of ultrasonic noise can normally be confirmed by examining the physical layout of the metering station. If all transducers show a low S/N, the problem might be due to electrical noise, contamination on the transducers, or excessive gas velocity. 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.

8.9.4 Acoustic signal acceptance

Signal acceptance is defined as the simple arithmetic ratio of the signals transmitted to the signals accepted. Signal acceptance will generally decrease as the flow rate increases beyond the rated capacity, and may also reduce with decreased line pressure, or from the presence of dirt and moisture.

8.9.5 Flow profile

The individual path velocities of the meter have unique relationships reflecting the flow profile that is dominated by the upstream pipe configuration. At velocities higher than Q_v , these relationships should not change significantly over time. 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 non-axial flow components such as “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 diagnostics can enable the operator to determine the source of the change and to assess its significance. Where flow conditioning devices are installed, a change in the flow profile may indicate a blockage or fouling of the profiling device.

8.9.6 Standard deviation/turbulence

For a variety of occasions and especially when fouling is present, the increase in the standard deviation of the major diagnostic parameters such as the speed of sound, the AGC, path velocities and pulse acceptance are good indicators to detect problems in an early stage. Table 6 shows an example of such a relational diagram.

Table 6 — Relational diagnostic diagram

Relational diagnostic	Per path					
	Signal Acceptance	Automatic gain control	S/N	MSOS	Flow velocity	Standard Deviation
Transducer failure	x	x	—	x	x	x
Detection problems	x	x	x	x	x	x
Ultrasonic noise	x	x	x	—	—	—
Process conditions pressure	—	x	x	—	—	—
Process conditions temperature	—	—	—	x	—	—
Fouling	x	x	x	x	x	x
Changes in the flow profile	—	—	—	—	x	x
High velocity	x	x	x	—	—	x

9 Operational practice

9.1 Temperature and pressure correction

The output of the USM shall be corrected for the effect of thermal expansion. Whether a correction for pressure is necessary depends highly on the pressure difference and the meter body construction; the manufacturer shall inform the operator about the effects.

As a result of the flow calibration, systematic errors are reduced by determining and then applying the meter flow calibration factor, resulting in a FWME as close as possible to zero and/or linearization resulting in an error curve as close as possible to zero. From that moment onwards, the pressure and temperature reference conditions of the meter are those encountered during the dynamic calibration. Any subsequent change in temperature or pressure alters the physical dimensions of the meter and, if not corrected for, introduces a systematic flow measurement error. In general, the pressure and temperature during calibration differ from those encountered under operating conditions.

In [9.1.2](#), a simple approach is given to allow an initial estimate to be made of the flow error caused by temperature and pressure conditions that differ from the calibration reference condition. If this error is significant relative to the uncertainty required for custody transfer or allocation purposes, a more detailed assessment of flow error has to be performed as described in [9.1.2.7](#). [Annex E](#) provides an extensive and detailed explanation of the process which readers are advised to consult for the background to many of the statements made in [9.1.2](#).

The calculation method and the correct configuration of the parameters shall be described in the manufacturer instructions, specifically with regards to the calibration and afterwards when the meter is taken into operation in a measuring station.

9.1.1 Correction for the temperature

For all meter types, the geometry-related temperature correction can be given as a straightforward analytical solution (see [E.2](#)). In consequence, the correction has a very high precision and the only uncertainties related to this correction are the uncertainties related to the material constants.

The flow correction factor due to a body temperature change, ΔT , is given by:

$$\frac{q_{V,1}}{q_{V,0}} = (1 + \alpha \Delta T)^3 = \left[1 + 3\alpha \Delta T + 3(\alpha \Delta T)^2 + (\alpha \Delta T)^3 \right] \quad (15)$$

where

$q_{V,1}$ is the volume flow rate under operating conditions;

$q_{V,0}$ is the volume flow rate under the conditions at which the meter was calibrated; ΔT is $T_1 - T_0$.

in which

T_1 is the temperature under operating conditions,

T_0 is the temperature under the conditions at which the meter was calibrated.

Other than in extreme situations, $\alpha\Delta T$ is generally very small and [Formula \(15\)](#) can be simplified to:

$$\left(\frac{q_{V,1}}{q_{V,0}} \right)_{b,T} = 1 + 3\alpha\Delta T \tag{16}$$

Or alternatively, expressed as a flow error:

$$\left(\frac{\Delta q_V}{q_V} \right)_{b,T} = 3\alpha\Delta T \tag{17}$$

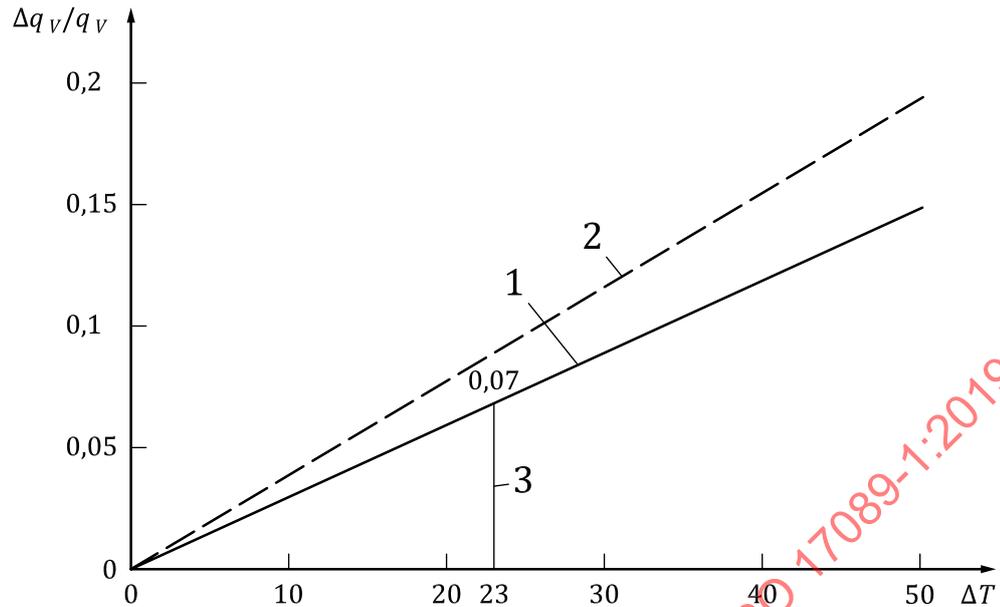
[Table 7](#) gives typical coefficients of thermal expansion for common body materials.

Table 7 — Common coefficients of thermal expansion in the 0 °C to 100 °C range

Material	Thermal expansion coefficient
	αK^{-1}
Carbon steel	12×10^{-6}
Stainless steel AISI 304	17×10^{-6}
Stainless steel AISI 316	16×10^{-6}
High elastic-limit stainless steel AISI 420	10×10^{-6}

The thermal expansion coefficients for a given material vary with temperature and the treatment process of the steel. The values given in [Table 5](#) and used in the example in [Figure 8](#) are for illustrative purposes only. It is consequently recommended that, for more precise calculations, the coefficient of thermal expansion data be obtained from the material manufacturer.

A graphical presentation of [Formula \(19\)](#) is shown in [Figure 15](#) for two materials from [Table 8](#).

**Key**

ΔT	temperature difference, in °C
$\Delta q_V/q_V$	flow measurement error, in %
1	austenitic stainless steel
2	ferritic stainless steel
3	example

Figure 15 — Temperature related flow error for two example material types

This figure can be used to quickly estimate the percentage correction required for a given temperature change. The example point for a +23 °C temperature change with an austenitic stainless steel body shows a +0,07 % correction (i.e. the meter would underestimate the flow by 0,07 % without the correction). If ΔT is negative, $\Delta q_V/q_V$ is negative (i.e. the meter will overestimate the flow).

9.1.2 Correction for the pressure

9.1.2.1 General

The geometry-related pressure correction is complex and depends on the design of the meter body, its end connections and the way the meter ends are supported in operation. Looking at the market, the various meter designs offered can be grouped into three broad categories:

- welded-in cylindrical body designs;
- meter bodies consisting of a pipe with welded-on flanges;
- non cylindrical meter body designs, for example those based on casting.

In [9.1.2.2](#) to [9.1.2.4](#), a means of making an initial estimate of the flow error for any body type is provided.

9.1.2.2 General simplified expression for any body type

As a first stage in estimating the pressure effects, a general basic expression can be derived assuming the meter body consists simply of a cylindrical pipe. An estimate of the maximum expected flow error due to a body pressure change, Δp , is (as described in E.5) given by:

$$\left(\frac{\Delta q_V}{q_V}\right)_{b,p,max} = 4 \frac{\Delta r}{r} = 4 \left(\frac{R^2 + r^2}{R^2 - r^2} + \mu\right) \frac{\Delta p}{E} \tag{18}$$

where

R is the outside radius;

r is the inside radius;

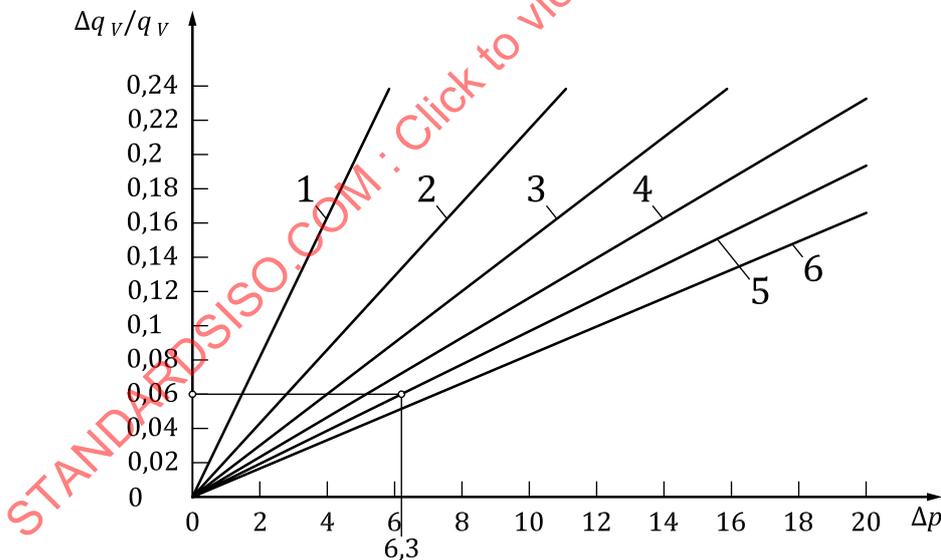
μ is the Poisson ratio;

E is the Young modulus, in MPa;

Δp is the operational pressure minus calibration pressure, in MPa.

If the meter body is irregular or non-cylindrical (e.g. as might be the case for a cast body), then, for the purposes of this initial estimate, the outside radius value, R , should be taken as the point where the wall is thinnest since this gives the largest estimate of flow error.

Formula (20) can be presented in graphical form as shown in Figure 16 for a range of values of δ/r , i.e. the ratio of wall thickness to internal radius.



Key

	δ/r		
1	0,050	Δp	pressure difference, in MPa
2	0,100	$\Delta q_V/q_V$	flow measurement error, in %
3	0,150	r	inside pipe radius
4	0,200	δ	pipe wall thickness
5	0,250		
6	0,300		

Figure 16 — Maximum expected pressure related flow error for different δ/r ratios

[Figure 16](#) provides a rapid means of estimating the maximum expected flow error due to body pressure changes. The figure is plotted for a body material with a Young modulus of 2×10^{11} Pa and a Poisson ratio of 0,3. The example of $\Delta p = 6,3$ MPa shows the maximum expected pressure-induced error to be 0,06 % for a $\delta/r = 0,25$. If Δp is negative, $\Delta q_V/q_V$ is negative (i.e. the meter will overestimate the flow).

Since [Formula \(16\)](#) and [Figure 16](#) provide a maximum expected error, the reader can, if desired, go straight to [9.1.2.6](#) (taking $K_E = K_S = 1$) to assess the significance of the error without the need of the refinement in the initial estimate provided in [9.1.2.3](#) and [9.1.2.4](#) since these result in a lower value for the flow error.

9.1.2.3 Refinement in initial estimate to account for different meter body designs

Flanged ends or irregular shape to the body stiffen the body compared to the simple cylindrical pipe approach used in [9.1.2.1](#) consequently, the body expansion and resulting flow error is less than that given by [Formula \(19\)](#) and [Figure 16](#). To compensate for this local stiffening effect, a body style correction factor, K_S , is used to give a revised estimate of the flow error:

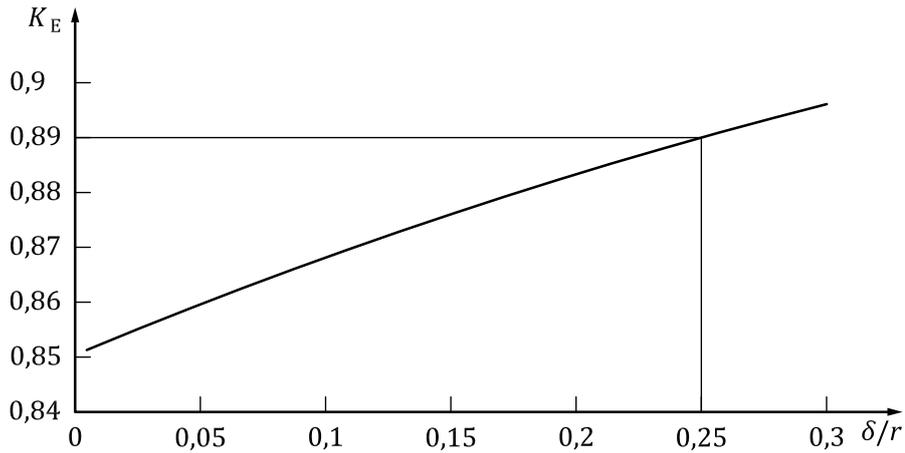
$$\left(\frac{\Delta q_V}{q_V} \right)_{b,p,rev1} = K_S \left(\frac{\Delta q_V}{q_V} \right)_{b,p,max} \quad (19)$$

K_S is always less than or equal to 1; the value of K_S to be used for a given body type is as follows:

- a) for a welded-in body with no flanges within $2R$, where R is the outside pipe radius, of the ultrasonic transducer locations, $K_S = 1$, i.e. the meter body behaves as a simple pipe;
- b) for a flanged meter body (e.g. consisting of two flanges welded to a pipe) or welded-in design where neighbouring flanges are within $2R$ of the transducer positions, the value of K_S has to be calculated as described in [E.2.3](#);
- c) for irregularly shaped meter bodies, for example cast bodies, K_S is obtained as follows based on an average flow error:
 - 1) [Formula \(20\)](#) or [Figure 17](#), are used to obtain a second flow error, y , but this time based on the thickest wall section,
 - 2) K_S is then calculated as, $K_S = 0,5 \times (1 + y/x)$ where x is the initial estimate based on the thinnest wall section.

9.1.2.4 Refinement in initial estimate for effects of end loading and end support or constraint

[Formula \(16\)](#) and [Figure 17](#) are based on the worst-case conditions for radial body expansion (no end loads and free ends). The effect of the best-case conditions (pressure end loads and free ends) for minimal radial body expansion can be taken into account by introducing an end correction factor, K_E (see [Annex E](#)), given in [Figure 17](#) for a Poisson ratio of 0,3.



Key

K_E end correction factor

r inside pipe radius

δ pipe wall thickness

$$K_E = -0,122\ 9(\delta/r)^2 + 0,191\ 3(\delta/r) + 0,850\ 1$$

Figure 17 — End loading and support correction factor, K_E

The end correction factor is derived simply from the ratio of [Formulas \(E.12\)](#) and [\(E.14\)](#). In the example in [Figure 17](#), $K_E = 0,89$ for $\delta/r = 0,25$. Note that the smallest value K_E can have is 0,85.

The flow error $\Delta q_V/q_V$ then becomes:

$$\left(\frac{\Delta q_V}{q_V}\right)_{b,p} = K_E K_S \left(\frac{\Delta q_V}{q_V}\right)_{b,p,max} \tag{20}$$

NOTE [Formula \(22\)](#) gives an estimate of the expected minimum flow error. It can therefore be used in combination with the maximum flow error (i.e. with $K_E = K_S = 1$) to provide an initial estimate of the range or tolerance in expected flow error.

9.1.2.5 Effects of transducer ports

The combined impact of the transducer and the transducer port are normally an order of magnitude smaller than the effect on the meter body and can be neglected for most cases. However, for reference, in [E.2.5](#), a simple calculation method is provided that includes an estimate of port effects. In these equations, the transducer material coefficients have to be known (obtainable from the manufacturer).

9.1.2.6 Total metering error

The initial estimate of the combined flow error, $(\Delta q_V/q_V)_{c, est}$ due to a temperature and a pressure difference is given by:

$$\left(\frac{\Delta q_V}{q_V}\right)_{c,est} = \left(\frac{\Delta q_V}{q_V}\right)_{b,T} + K_E K_S \left(\frac{\Delta q_V}{q_V}\right)_{b,p,max} \tag{21}$$

If the flow error is deemed not significant, then it can be dismissed.

If, however, the flow error is deemed significant and hence requires correction, the detailed calculation described in [9.1.2.6](#) needs to be performed to obtain a more precise flow correction factor.

NOTE If calculations in [9.1.2.3](#) and [9.1.2.4](#) were omitted in the estimate for pressure effect, a repeat estimate can be performed using those sections to provide a lowered estimate before reassessing the need for the more detailed calculation.

9.1.2.7 Detailed calculation procedure

[Annex E](#) describes the detailed calculation and includes the pressure and temperature effects on the transducer ports as well as on the meter body, effects of body style, and end loading.

The ratio between $q_{V,0}$ at a reference calibration condition and $q_{V,1}$ at different conditions can be written (see [E.1](#)) as a flow correction factor, $q_{V,1}/q_{V,0}$, given by:

$$\frac{q_{V,1}}{q_{V,0}} = \left(\frac{d_1}{d_0}\right)^2 \left(\frac{l_1}{l_0}\right)^2 \left(\frac{x_0}{x_1}\right) \quad (22)$$

The detailed calculation contains estimates of extremes and allows the flow error to be described in either of the following equivalent forms:

$$\frac{q_{V,1}}{q_{V,0}} = x, \text{xxxx} \mp x, \text{xxxx} \quad (23)$$

$$\frac{\Delta q_V}{q_V} = (x, \text{xx} \mp x, \text{xx}) \% \quad (24)$$

Stating the final flow correction factor, $q_{V,1}/q_{V,0}$, to four decimal places and the flow error, $\Delta q_V/q_V$, to two decimal places is representative of the general level of accuracy of the calculation method. Since there is always some uncertainty as to the actual end-loading conditions on the meter, the flow estimates are never more precise than the tolerance magnitudes given in [Formulae \(23\)](#) and [\(24\)](#).

For meter bodies that are generally cylindrical in shape and either welded in or have attached flanges, [Annex E](#) provides a simple procedure based on direct calculation from the physical characteristics of the meter. [Annex E](#) provides a worked example of such a direct calculation.

Where the meter body is such that the body shape is not a simple cylinder, flanges take up a significant proportion of the total body length or ports are not simple tubes, a finite element (FE) model provides a more accurate estimate of the body and port dimensions, and consequent flow error obtained from [Formula \(18\)](#) than that given by the direct calculations of [E.2.2](#) to [E.2.5](#). [E.3](#) provides guidance on the use of FE modelling to predict the temperature and pressure expansion effects.

Regardless of the complexity of the meter, an FE model of the body and ports can be used. It is recommended that [Formulas \(E.12\)](#) to [\(E.15\)](#), including any body style correction effects ([E.2.3](#)) where relevant, can be used as a means of checking the predicted dimensions from the FE model to provide added confidence in the FE model. [Formula \(18\)](#) is still used to predict the flow error along each path based on the changes in physical dimensions between conditions.

Annex A (informative)

Registration of error bands

A.1 General

The magnitude of the shift between flow recalibration results may be of specific interest where retrospective reconciliation or calibration repeatability tolerances are required. A method for deriving mismileasurements based on sequential flow recalibration results employing registration error limits is presented in this annex, together with a guide to the determination of a representative registration error band or “trigger point”.

The registration error band or trigger point, $\Delta(\text{reg})$, should be derived from:

$$\Delta(\text{reg}) = \left[u(\text{USM})^2 + u(\text{TF})^2 \right]^{1/2} \quad (\text{A.1})$$

where

$u(\text{USM})$ is the USM primary component of uncertainty (USM factor);

$u(\text{TF})$ is the test facility primary component of uncertainty (test facility factor).

Included within $u(\text{USM})$ shall be those sub-components of uncertainty as detailed in [4.4](#).

The facility used to perform the recalibration shall provide $u(\text{TF})$, which varies from centre to centre.

Annex B (informative)

Derivation and correction of USM errors

B.1 Methods for correcting flow measurement error of a USM

The total flow measurement error of a USM consists of two components: random error and bias (or systematic error). The random error can be caused by various influences, generally not dependent on each other, on operation of a meter. It usually follows a certain statistical distribution (and is often expressed in terms of measurement uncertainty). The magnitude of the random error can usually be reduced by acquiring multiple measurement samples and applying accepted statistical analysis principles to the data. The bias usually causes 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 systematic measurement error of the meter with respect to the reference used. For a detailed description of uncertainties and errors in flow metering, see ISO 5168.

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 flow measurement error, a particular USM can be flow calibrated and the calibration data used to correct or compensate for the measurement error of the meter. 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 utilizes a single meter correction factor: the flow-weighted mean error (FWME) factor. If the flow measurement output of a USM is very linear over the operational flow range of the meter, the FWME correction method is effective at minimizing the bias of the meter. Other single meter-factor correction techniques are also available. If the flow measurement output of a USM is non-linear over the operational range of the meter, more sophisticated error correction techniques can be applied. For instance, a higher-order curve fit algorithm, such as a second-order or third-order polynomial equation, can be used to characterize the output of the meter, based on the available test data.

Before calculating the FWME, it may be appropriate to determine the zero error from the flow calibration results and to apply this so 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 Calculation of flow-weighted mean error (FWME)

B.2.1 General

The FWME, $\bar{E}(q_V)$, is calculated as follows:

$$\bar{E}(q_V) = \frac{\sum \left[(q_{V,i} / q_{V,\max,op}) E_i \right]}{\sum (q_V / q_{V,\max,op})} \quad (\text{B.1})$$

where

- $q_{V,i}$ is the tested flow rate;
- $q_{V,max,op}$ is the maximum rated operational capacity of the meter;
- E_i is the error, as a percentage, indicated at the tested flow rate, $q_{V,i}$:
 - $q_{V,i}$ ranges: $q_{V,min} \leq q_{V,i} \leq q_{V,max,op}$ when $q_{V,max,cal} \geq q_{V,max,op}$
 - $q_{V,i}$ ranges: $q_{V,min} \leq q_{V,i} \leq q_{V,max,cal}$ when $q_{V,max,cal} < q_{V,max,op}$

B.2.2 Example of a flow-weighted mean error calculation

The calculation of the FWME from actual flow test data is an internationally agreed calibration method, when only a single correction factor can be applied to the output of the meter. Application of this factor to the output of a USM 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 the calibration of a USM to minimize the flow measurement uncertainty of the meter.

The following example demonstrates how to calculate the FWME.

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. An adjustment 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 — Flow calibration data table for 200 mm diameter USM

Standard test rate	Nominal test rate	Actual test rate from reference meter $q_{V,ref}$	Actual rate from test meter $q_{V,i}$	USM error %
$q_{V,min}$	950	930	938,862 9	+0,953 0
0,10 $q_{V,max}$	1 900	1 950	1 957,332 0	+0,376 0
0,25 $q_{V,max}$	4 750	4 780	4 764,799 6	-0,318 0
0,40 $q_{V,max}$	7 600	7 650	7 625,902 5	-0,315 0
0,70 $q_{V,max}$	13 300	13 250	13 200,710 0	-0,372 0
$q_{V,max}$	19 000	18 950	18 880,643 0	-0,366 0

The FWME for the data set presented in Table B.1 is calculated as follows:

$$\bar{E}(q_V) = \frac{\sum \left[(q_{V,i} / q_{V,max}) E_i \right]}{\sum (q_V / q_{V,max})} \tag{B.1}$$

where

- $q_{V,i}/q_{V,max}$ is a weighting factor, f_i ;
- E_i is the indicated flow rate error, expressed as a percentage, at the tested flow rate, $q_{V,i}$.

Applying Formula (B.1) to the test data in Table B.1 ($q_{V,max} = 19\ 000$) produces the results shown in Table B.2.

Table B.2 — Flow-weighted mean error calculation summary for 200 mm diameter USM

Indicated flow rate q_i	Weighting factor $i = q_{V,i}/q_{V,max}$	Indicated flow rate error E_i	Weighted flow rate error $f_i E_i$
938,862 9	0,049 414	0,953 0	0,047 091
1 957,332 0	0,103 017	0,376 0	0,038 735
4 764,799 6	0,250 779	-0,318 0	-0,079 748
7 625,902 5	0,401 363	-0,315 0	-0,126 429
13 200,710 0	0,694 774	-0,372 0	-0,258 456
18 880,643 0	0,993 718	-0,366 0	-0,363 701
	$\sum f_i = 2,493 066$		$\sum f_i E_i = -0,742 508$

As a result:

$$\begin{aligned}\bar{E}(q_V) &= \frac{\sum f_i E_i}{\sum f_i} \\ &= -0,742 508 / 2,493 066 \\ &= -0,297 829 28\end{aligned}$$

The single adjustment factor, F , to be applied to the output of a USM can be calculated from [Formula \(B.2\)](#):

$$F = \frac{100}{100 + \bar{E}(q_V)} \quad (\text{B.2})$$

Given a FWME equal to $-0,297 829 28$, the resulting adjustment factor, F , is calculated as 1,002 987. If this adjustment factor of 1,002 987 is applied as a multiplier to the output of the USM, the calculated FWME then equals zero. This is shown in [Table B.3](#), where each E_i has been adjusted to obtain a calibration factor-adjusted value, $E_{i,cf}$ using [Formula \(B.3\)](#):

$$E_{i,cf} = (E_i + 100)F - 100 \quad (\text{B.3})$$

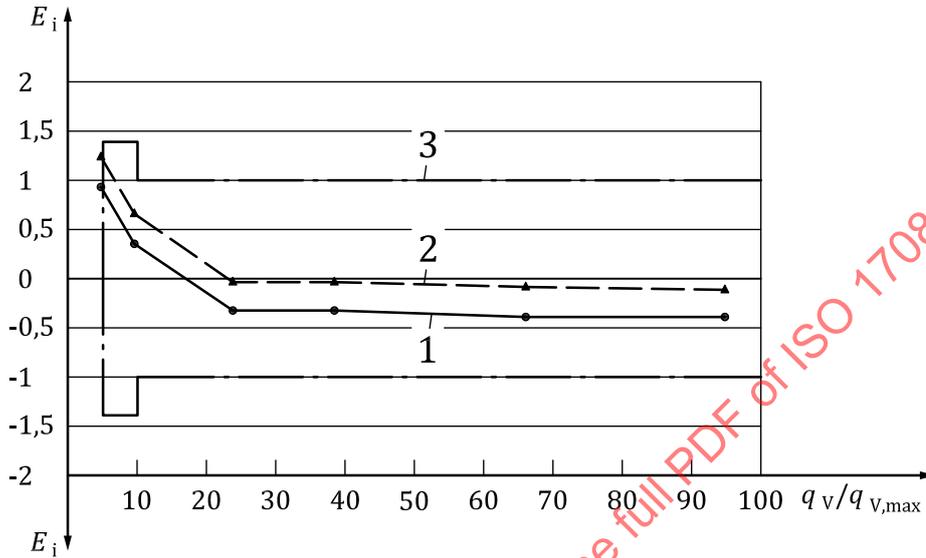
Table B.3 — FWME-corrected flow calibration data summary for a 200 mm diameter USM

Indicated flow rate error E_i	Calibration factor-adjusted flow rate error $E_{i,cf}$	Weighted calibration factor-adjusted flow rate error $f_i E_{i,cf}$
0,953 0	1,254 566	0,061 993
0,376 0	0,675 842	0,069 624
-0,318 0	-0,020 23	-0,005 074
-0,315 0	-0,017 22	-0,006 912
-0,372 0	-0,074 39	-0,051 686
-0,366 0	-0,068 37	-0,067 945
$\sum f_i E_{i,cf} = 0,000 0$		

As a result:

$$\bar{E}(q_V) = \frac{0,000\ 0}{2,493\ 066} = 0,000$$

In [Figure B.1](#), the FWME-corrected flow calibration data have been added to the test data presented in [Table B.1](#). The triangular data points represent the error of the meter after a FWME adjustment factor of 1,002 987 has been applied to the original flow calibration data.



Key

- $q_V/q_{V,max}$ ratio of volume flow rate to maximum volume flow rate, in %
- E_i error
- 1 uncorrected data
- 2 FWME corrected data
- 3 maximum error limit

Figure B.1 — Uncorrected and FWME-corrected flow calibration data plot for 200 mm diameter USM

This figure 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 the entire set of flow test data. However, for flow rates below about 25 % of the capacity of the meter, 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 operational range of the meter, or apply a more sophisticated correction scheme to reduce or eliminate the measurement error at the low end of the range of the meter.

Annex C (informative)

Valve characterization and noise in a metering and regulating station

C.1 Introduction

In order to estimate in advance if a USM performs satisfactorily in a given application, the following is provided as guidance.

Pressure-regulating valves produce noise within the audible and also in the ultrasonic range. The amount of noise depends on the process conditions, such as pressure drop and flow. When a control valve (pressure-regulating valve) is installed in the vicinity of a USM, the acoustic noise levels emitted can interfere with the acoustic signal and loss of flow measurement is imminent. The emission and the spectral distribution of the noise are valve and trim dependent. The emission of acoustic noise at a specific frequency is characterized by a valve-weighting factor, N_v . Next to the characterization of the valve, a model is defined that comprises the USM as well as the piping installation, such as elbows, tees, and silencers (if applicable). Also, the method for the determination of the valve-weighting factor is given.

In order to be sure that the meter performs well within the operating envelope, it is advised to contact the valve manufacturer as well as the manufacturer of the USM in the early planning stage of a metering and regulating (M&R) station.

C.2 Calculation method

C.2.1 General

In order to be able to make an assessment of the functionality of a USM in a given application, the following items have to be investigated:

- the generation of the noise by the control valve within the M&R station as a function of the pressure drop across the valve dP and normalised flowrate through valve q_n ;
- the attenuation of noise while propagating from the valve to the USM (attenuation factor, N_d);
- the signal strength, P_s , of the USM;
- the outcome of this is the S/N ratio at the USM — together with the minimum required S/N ratio (error critical) of a meter, a prediction of the performance of the meter can be made.

C.2.2 Generation of noise by the control valve

The emitted acoustic pressure, p_n , in Pascals [Pa], of a valve is proportional to the pressure drop, Δp , in pascals, p across the valve and the square root of the normalised flow rate, q_n , in normal cubic meters per hour [Nm³/h], i.e.

$$p_n \sim \Delta p \sqrt{q_n} \tag{C.1}$$

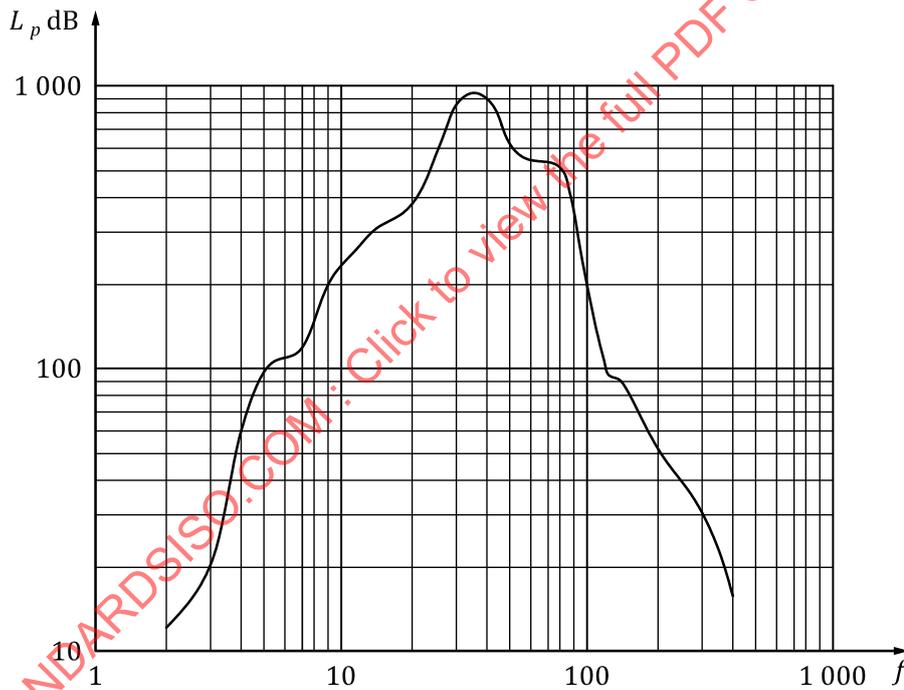
In addition to this, a valve-weighting factor, N_v is defined which is a function of the acoustic pressure and the value of $\Delta p \sqrt{q_n}$:

$$p_n = N_v \cdot \Delta p \sqrt{q_n} \tag{C.2}$$

This valve-weighting factor describes how noisy a valve is at a certain frequency and in a certain direction (up or downstream). The higher the N_v value, the noisier the valve.

Remark: The metric unit of the valve-weighting factor N_v is: [m^{-1,5}]^{0,5}

Analysing the frequency spectrum of the noise generated by valves, it can be concluded that most valves have a broad bandwidth with a maximum somewhere between 30 kHz and 90 kHz (see [Figure C.1](#)).

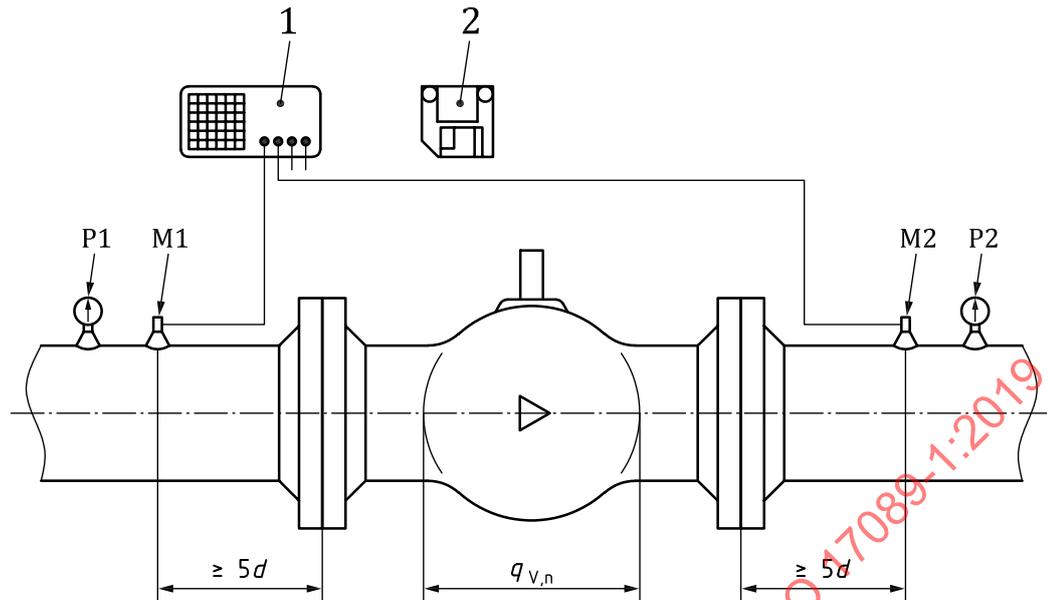


Key
 f Frequency, in kHz
 L_p noise amplitude

Figure C.1 — A typical spectrum of the acoustic noise generated by a valve

C.2.3 Practical determination of the valve weighting factor N_v

To determine the valve-weighting factor in a practical way, N_v , of a valve and trim combination for each operational condition, the pressure drop, the flow rate, and the acoustic pressure need to be measured. [Figure C.2](#) depicts an installation for determination of the valve-weighting factor.

**Key**

1	oscilloscope
2	data storage for binary data capture
M1, M2	microphones
P1, P2	pressure gauges
d	pipe inside diameter
$q_{V,n}$	flow rate

Figure C.2 — Installation set-up

Note that:

- distance between microphone and regulating valve may be $5D$ or longer;
- there are no obstructions in the pipeline between the microphone and the regulating valve;
- there are no U-bends, T-bends, etc. between the microphone and the regulating valve;
- installation of microphone is flush with the inner wall of the pipeline;
- before starting a test, the background noise shall be measured — during this measurement, Δp shall be 0 Pa, the gas flow 0 m³/h, and the pipeline pressurized at line pressure;
- The noise is calculated over a one third octave (tertz) bandwidth;
- each noise measurement at a specific operational condition may consist of three to five measurements;
- measurements may be done under stable process conditions;
- at the end of the test, the background noise levels may be measured again;
- in most cases the N_v value is different for the upstream or downstream side.

C.2.4 Theoretical determination of the valve weighting factor N_v

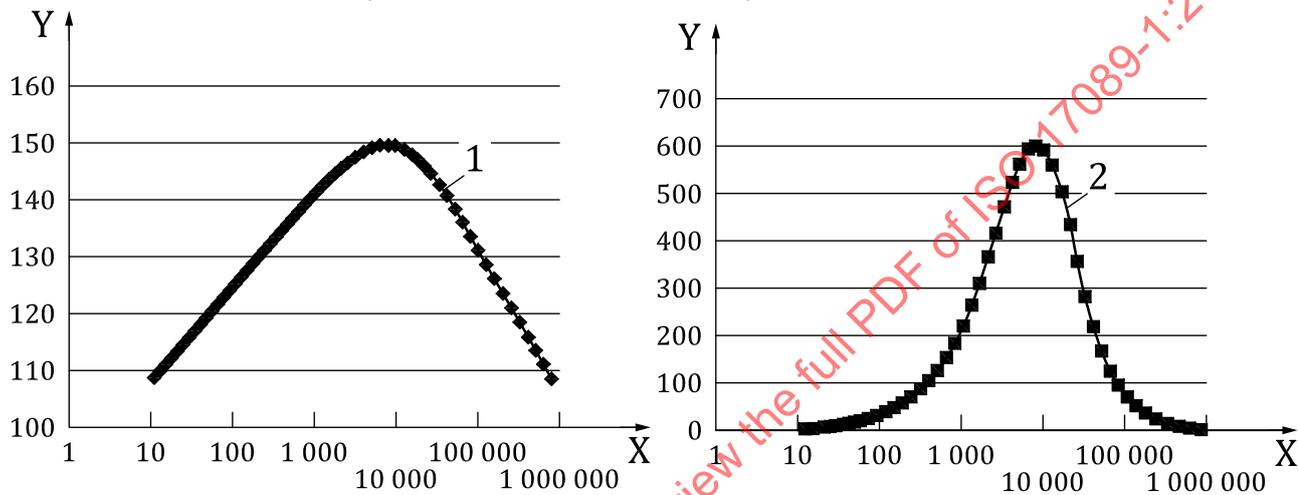
If practical determination of the valve weighting factor is not done, the next best guess would be using IEC 60534-8-3. This standard describes a control valve aerodynamics noise prediction method. It is used to calculate the audible noise produced by a control valve, outside of a pipe at 1 m distance from the pipe. To do so, the noise spectrum inside the pipe is also calculated. The model however only

calculates the spectrum up to 20 kHz (audible range). By extrapolation into the ultrasonic noise region the IEC 60534-8-3 can also be used for ultrasonic noise. For a certain combination of flow rate (q_n) and pressure drop (ΔP) the spectrum of the emitted noise of a control valve is defined by:

- L_{pi} = Overall internal sound-pressure level at pipe wall
- f_p = Generated peak frequency

The spectrum is calculated by:

$$L_{pi}(f) = L_{pi} - 8 - 10 \cdot \log \left\{ \left[1 + \left(\frac{f}{2f_p} \right)^{2,5} \right] \cdot \left[1 + \left(\frac{f_p}{2f} \right)^{1,7} \right] \right\} \quad (C.3)$$



Key

- X frequency, in Hz
- Y acoustic level
- 1 $L_{pi}(f)$
- 2 $Pi(f)$

Figure C.3 — Typical peak frequency plots, acoustic level as function of frequency

For each combination of ΔP and q_n the noise level can be calculated for a specific frequency and by using [Formula \(C.3\)](#) the valve weighting factor N_v can be calculated.

The preferred method of course is measuring the N_v ; using the IEC 60534-8-3 should be regarded as a back-up method.

C.2.5 Propagation of noise from the valve to the USM using attenuation factor, N_d

The USM operates in the high-frequency range where, unfortunately, the noise propagates easily. To reduce the intensity of these high ultrasonic noise frequencies, it is necessary to obstruct the acoustic noise (eliminating the line of sight) or to let the acoustic noise interact with the pipe wall, thereby attenuating the acoustic energy. Therefore, piping elements like elbows and tees or special developed silencers can be used to attenuate the ultrasonic noise.

The reduction of the ultrasonic noise, propagating from the valve to the USM, is presented as the attenuation factor, N_d .

All piping elements present in an installation attenuate acoustic noise, an attenuation which is frequency dependent.

Based on linear systems theory, piping elements can be represented by a number indicating the attenuation of ultrasonic sound in the relevant frequency band.

As an example, [Table C.1](#) shows the attenuation of different piping elements at 200 kHz.

Table C.1 — Attenuation of piping elements at 200 kHz

Piping element	Factor N_d	Attenuation dB
Bend 90°	0,56	5
Bend 45°	0,79	2
Tee	0,32	10
Two bends out of plane	0,20	14
100 m pipeline	0,56	5
NOTE Values differ for other frequencies.		

Whereas bends and tees show significant attenuation of ultrasonic noise, straight pipe has little to almost no effect. If the noise level exceeds acceptable limits, additional bends or tees can be installed to act as silencer or silencers specifically designed for this purpose. Such a silencer has to be engineered for a specific kind of application (e.g. dependent of frequency).

C.2.6 Signal strength of the USM, P_s

For the signal strength of a USM, the following rules apply:

- $P_s \propto p$: the higher the pressure at the USM, the stronger the signal;
- $P_s \propto 1/l_p$: the longer the path length, the weaker the signal;
- $P_s \propto \sqrt{t}$: the longer the integration time or number of samples, the stronger the signal (or more accurately averaging data improves S/N ratio by \sqrt{n}).

So:

$$P_s \sim \frac{p\sqrt{t}}{l_p} \quad (\text{C.4})$$

The above used parameters are all manufacturer independent. To truly determine the signal strength of an USM, manufacturer specific parameters like e.g. transducer efficiency, excitation voltage should be used as well. A specific manufacturer parameter α_{mf} can be defined which incorporates all additional manufacturer specific parameters and which transfers [Formula \(C.4\)](#) into:

$$P_s = \alpha_{mf} \cdot \frac{p\sqrt{t}}{l_p} \quad (\text{C.5})$$

Remark: The metric unit of α_{mf} is meter [m]

C.2.7 Signal-to-noise ratio at the USM

The combination of the attenuation factor, N_d , with the amount of noise produced by the control valve [[Formula \(C.2\)](#)] results in the levels of acoustic noise pressure at the USM:

$$p_{n, \text{USM}} = N_d N_v \Delta P \sqrt{q_n} \quad (\text{C.6})$$

Combining this with [Formula \(C.4\)](#), describing the signal strength, [Formula \(C.5\)](#) results in [Formula \(C.7\)](#), which describes the SNR, P_s/p_n , USM:

$$SNR = \frac{P_s}{P_{n, USM}} = \frac{\alpha_{mf} p \sqrt{t}}{l_p N_d N_v \Delta P \sqrt{q_n}} \tag{C.7}$$

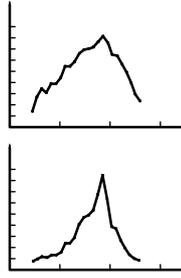
Having established the SNR at the USM, the last remaining item to be determined is the required minimum SNR at which the meter still operates. This SNR is manufacturer specific:

$$SNR > SNR_{mf} \Rightarrow \text{the USM functions} \tag{C.8}$$

$$SNR < SNR_{mf} \Rightarrow \text{the USM fails} \tag{C.9}$$

Calculation example 1: metric

Frequency [Hz]	Noise level	
	[Pa]	dB
2 000	100	40
2 520	200	46
3 175	300	50
4 000	250	48
5 040	380	52
6 350	380	52
8 000	500	54
10 079	880	59
12 699	880	59
16 000	1 100	61
20 159	1 700	65
25 398	2 000	66
32 000	2 100	66
40 317	2 300	67
50 797	3 000	70
64 000	3 800	72
80 635	2 800	69
101 594	1 600	64
128 000	1 500	64
161 270	1 000	60
203 187	680	57
256 000	400	52
322 540	230	47
406 375	170	45



$$\Delta P = 2,5 \text{ MPa}$$

$$P = 6,0 \text{ MPa}$$

$$q = 20\,000 \text{ m}^3/\text{h}$$

$$l_p = 0,5 \text{ m}$$

$$t = 1$$

Operating frequency of the transducer is 200 kHz,

Noise levels measured at 200 kHz is approx. 680 Pa, So:

$$P_n = 680 \text{ Pa}$$

Instead of calculating noise levels linearly the noise levels can also be calculated logarithmically in this case

$$P_{n, \text{dB}} = 57 \text{ dB} (= 20 \cdot 10 \log(680))$$

The normalised flowrate (q_n) can be simply be estimated using pressure (P) times line flow rate (q). For calculating the normalised flow officially also the effect of temperature (T) and compressibility (Z) needs to be taken account for. However the uncertainty of this model (in the range of a factor 2) is much larger than the correction by temperature and compressibility. So the simplified formula for the normalised flow rate, $q_n = \frac{P}{P_0} q$ can be used with in this case $P_0 = 0,1 \text{ MPa}$.

$$q_n = 1,200,000 \text{ Nm}^3/\text{h}$$

The valve weighting factor can be calculated according to:

$$N_v = \frac{P_n}{\Delta P \sqrt{q_n}}$$

$$\Delta P = 25 \text{ bar} = 2,500,000 \text{ Pa}$$

$$N_v = \frac{680}{2,500,000 \sqrt{1,200,000}} = 2,5 \cdot 10^{-7} \text{ m}^{-1,50,5}$$

If between the pressure control valve and the UFM 2 bends in plane are present then according table they will create an attenuation of:

$$N_d = 2 \times 5 \text{ dB} = 10 \text{ dB (factor 3,2)}$$

The acoustic noise at the UFM would then be:

$$P_{n, \text{USM}, \text{dB}} = P_{n, \text{dB}} - N_d = 57 \text{ dB} - 10 \text{ dB} = 47 \text{ dB}$$

or

$$P_{n, \text{USM}} = \frac{P_{n, \text{dB}}}{N_d} = \frac{680}{3,2} = 215 \text{ Pa}$$

To determine the signal strength of the UFM the manufacturer specific parameter α_{mf} is required.

$$\alpha_{mf} = 2,2 \cdot 10^{-4} \text{ m}$$

$$p = 60 \text{ bar} = 6,000,000 \text{ Pa}$$

$$l_p = 0,5 \text{ m}$$

$$t = 1$$

$$P_s = \alpha_{mf} \cdot \frac{p\sqrt{t}}{l_p}$$

$$P_s = 2,2 \cdot 10^{-4} \cdot \frac{6,000,000\sqrt{1}}{0,5} = 2640 \text{ Pa}$$

$$P_{s, \text{dB}} = 20 \cdot \log(2640) = 68 \text{ dB}$$

The signal to noise ratio is:

$$SNR = \frac{P_s}{P_{n, \text{USM}}} = \frac{2640}{215} = 12,3$$

$$SNR_{\text{dB}} = P_{s, \text{dB}} - P_{n, \text{USM}, \text{dB}} = 68 \text{ dB} - 47 \text{ dB} = 21 \text{ dB}$$

It is assumed that the UFM the $SNR_{mf} = 20 \text{ dB}$ (factor 10) this means there is no additional attenuation required.

Calculation example 2: Imperial

Frequency [Hz]	[psi]	dB
2 000	0,015	-37
2 520	0,029	-31
3 175	0,044	-27
4 000	0,036	-29
5 040	0,055	-25
6 350	0,055	-25
8 000	0,073	-23
10 079	0,128	-18
12 699	0,128	-18
16 000	0,160	-16
20 159	0,247	-12
25 398	0,290	-11
32 000	0,305	-10
40 317	0,334	-10
50 797	0,435	-7
64 000	0,551	-5
80 635	0,406	-8
101 594	0,232	-13
128 000	0,218	-13
161 270	0,145	-17
203 187	0,099	-20
256 000	0,058	-25
322 540	0,033	-30
406 375	0,025	-32

To perform the same calculation with imperial units all parameters should be transferred.

$$1 \text{ bar} = 14,50 \text{ psi}$$

$$1 \text{ m} = 3,28 \text{ ft}$$

$$1 \text{ h} = 0,0417 \text{ day as a result} \quad 1 \text{ m}^3/\text{h} = 8,47 \cdot 10^{-4} \text{ mmcfd}$$

$$1 \text{ m} = 39,37 \text{ inch}$$

The α_{mf} and N_v also needed to be transferred.

$$\alpha_{mf} = 2,2 \cdot 10^{-4} \text{ m} \quad \text{so} \quad \alpha_{mf} = 8,7 \cdot 10^{-3} \text{ inch}$$

$$N_v = 2,5 \cdot 10^{-7} \text{ m}^{-1,50,5} \quad \text{so} \quad N_v = 8,5 \cdot 10^{-6} \text{ mmscf}^{-1,50,5}$$

The used values are:

- $\Delta P = 363 \text{ psi}$ (25 bar)
- $P = 870 \text{ psi}$ (60 bar)
- $q = 16,9 \text{ mmcfd}$ (20,000 m^3/h)

- $l_p = 19,7''$ (0,5 m)
- $t = 1$
- $f = 200$ kHz so $P_n = 0,099$ psi (-20 dB)

$$q_n = \frac{P}{P_0} q = 1\,016 \text{ mmscfd} \quad (P_0 = 14,5 \text{ psi})$$

$$N_v = \frac{P_n}{\Delta P \sqrt{q_n}}$$

$$N_v = 8,5 \cdot 10^{-6} \text{ mmscf}^{1/2} \text{d}^{1/2}$$

$$N_d = 10 \text{ dB (factor 3,2)}$$

$$P_{n, \text{USM}} = \frac{P_n}{N_d} = \frac{0,099}{3,2} = 0,031 \text{ psi} \quad \text{or} \quad P_{n, \text{USM, dB}} = -20 \text{ dB} - 10 \text{ dB} = -30 \text{ dB}$$

$$P_s = \alpha_{mf} \cdot \frac{p \sqrt{t}}{l_p} = 0,383 \text{ psi} \quad \text{or} \quad P_{s, \text{dB}} = -8 \text{ dB}$$

$$SNR = \frac{0,383}{0,031} = 12,3 \quad \text{or} \quad SNR_{\text{dB}} = -8 \text{ dB} - (-30 \text{ dB}) = 22 \text{ dB}$$

$SNR_{mf} = 20$ dB (factor 10) so no additional attenuation required.

C.3 M&R station design

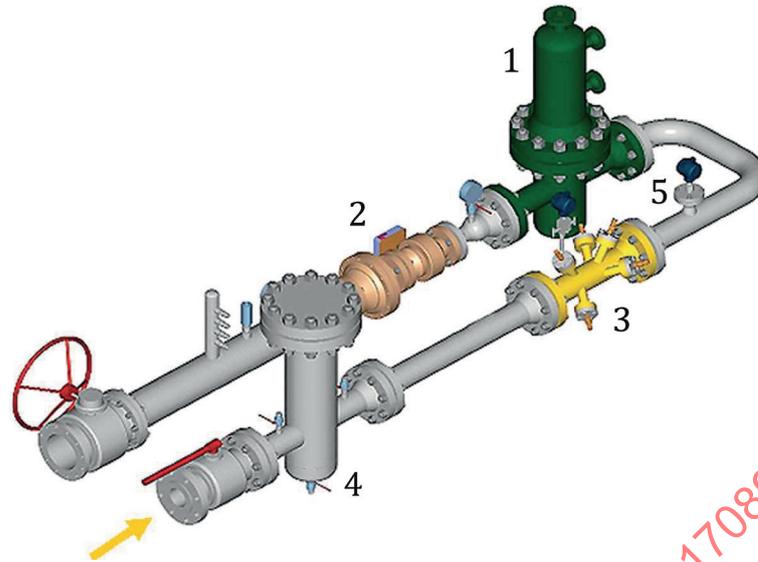
From [C.2.2](#) to [C.2.5](#), it is clear that the successful operation of an M&R station comprising a USM system is dependent on:

- the noise characteristics of the source of the noise, the valve, with the responsibility of the valve manufacturer to present the valve factors, N_v , for both the upstream and downstream side;
- the required process operating envelope defined by $\frac{P}{\Delta P \sqrt{q_n}}$, as selected and determined by the user;
- the pipe configuration, which may be modified to include silencers in the design;
- the level of noise immunity of the USM for which the manufacturer has to present the value of $\delta S/N$, min.

To provide an optimal solution, these issues need to be addressed in the early design stage of an M&R station. In contrast to the design of a turbine meter station, where the meter is normally positioned after the regulating valve, for a USM station, the meter may be placed before the regulating valve and heat exchanger (see [Figure C.4](#)). The obvious advantages of this set-up are:

- the USM is placed in the high-pressure area that improves the ultrasonic signal strength;
- the heat exchanger is placed between the noise-generating valve, acting as a silencer (in many cases a heat exchanger attenuates more than 20 dB).

In most cases, the N_v value is 3 dB to 6 dB lower for the upstream side than for the downstream side (to be confirmed by the valve manufacturer).



Key

- 1 heat exchanger
- 2 control valve
- 3 USM
- 4 filter
- 5 thermowell

Figure C.4 — M&R station optimized for ultrasonic measurement

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Annex D (informative)

The calibration time of ultrasonic flow meters

D.1 Introduction

In most of the calibration stations, ultrasonic flow meters are compared with turbine meters which are acting as the prime standard. As turbine meters behave differently on turbulence and flow perturbations the utmost care has to be taken to ensure a correct calibration. Hence stable pressure and temperature conditions during the calibration period are required and pulsations shall be avoided. Requirements for those are presented in [6.3](#).

Also in [6.3.2](#) of the first version the minimum calibration time is defined as: "the duration of one measurement shall be at least 300 s or $400 \times r/v$, where r is the inside pipe radius of the meter and v is the average flow velocity, whichever is larger.

The background of his requirement is explained in this paper and expanded for the new OIML class 0,5 and OIML class 1 requirements and an enhanced criterion is proposed.

D.2 Comparing turbine meters and ultrasonic meters

Turbine meter have been in the calibration labs for years and were there long before the ultrasonic flow meter technology appeared. Being a conservative market, turbine meters are still dominating the calibration labs but that situation is now slightly changing. In the new and the most advanced labs already both meter technologies are used, making the best of each technology.

One of the main reasons that turbine meters are still used as reference meters is that those meters are relatively insensitive to the turbulent fluctuations in the flow. In turbine meters the turbulent fluctuations are averaged over the length of the turbine wheel and the vortices themselves are reduced by the acceleration in the internals of the turbine meter. As a result, turbine meters have a reduced bandwidth and are not capable of measuring rapid flow fluctuations. Also turbine meters are not able to cope with fluctuating flows as they over speed in such situations and large measurement errors occur. (for that reason during calibration pulsations in the flow may not occur).

Ultrasonic meters in contrast to that have a much greater bandwidth and are able to detect much higher frequencies. As a result ultrasonic meters will measure the actual fluctuations in the flow and can excellently deal with the accurate measurement of fluctuating flows.

Whereas in a calibration the outcome of both meters are compared, it shall be ensured that both the impact of the turbulent fluctuations and that of the pulsations are reduced to such a level it that does not impact the quality of the calibration. Dependent on the OIML classification of the meter run, the final additional uncertainty due to the turbulent fluctuations may therefore not be larger than 1/3 of the respected uncertainty band of their category.

D.3 The minimum calibration time

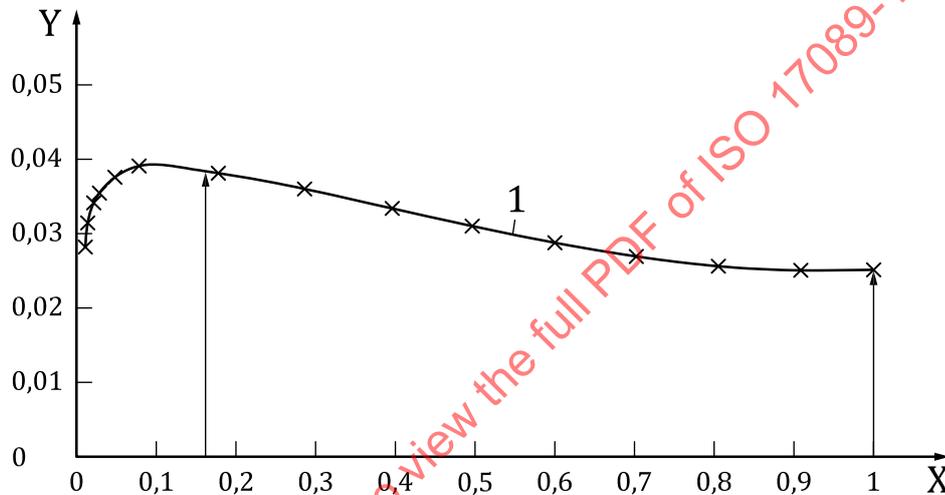
In a calibration lab, the operator has to ensure that the flow and turbulence conditions are identical to those as encountered in an infinitely long and straight pipe. From the meter it is assumed that the measurement sampling rate is high enough that it can be regarded as a continuous measurement.

In a long straight pipe the fluctuations in the flow are due to the natural occurring turbulence which are generated by the friction at the pipe wall. There at the pipe wall, the shear stress creates a gradient in the flow velocity profile which is the main cause for the generation of turbulence.

The turbulence intensity is a function of both the gradient in the flow velocity profile and the distance to the pipe wall (the free space in which the vortex can be generated). For pipes with a standard wall roughness, this leads to the situation where:

- the dominant vortices have a characteristic size of approximately 0,2 D – 0,3 D. for pipe flows with $Re > 8\ 000$
- the turbulent intensity level is approximately 4 % close to the pipe wall and approximately 3 % in the middle of the pipe; 3,5 % as an average. (see also: Hinze “Turbulence”^[84])

This is shown in the next figure, taken from ch. 7.13^[84].



Key

- 1 $\frac{u_r}{u_{x,max}}$
- Y $\frac{u^*}{v} \cong 0,035$
- X $\frac{2x_2}{D}$

Figure D.1 — turbulent intensity in a standard pipe ($Re > 8\ 000$)

There are 2 ways to determine the turbulence level u^* :

- a) When the meter run can be regarded as a straight pipe, the graph from Hinze can be used for accessing the turbulence level at the position of the ultrasonic paths.
- b) By logging the one second values of one of the outer paths and calculate its standard deviation.

Measuring the turbulence level is preferred for situations where a much higher turbulence level than normal is expected, such as for instance in cases where a flow conditioner is positioned close to the ultrasonic flow meter.

Turbulence is a stochastic process and the impact of it can be reduced by averaging. Being a naturally occurring process, a classical Gaussian probability distribution can be expected and the impact of the turbulence will then be reduced with a factor equal to the root of the number of samples.

To reduce the instantaneous fluctuations for example of a level of 4 % to a level of 0,1 % the measurement has to be averaged over a total number $(4/0,1)^2 = 1\ 600$ vortices. (at a 1σ confidence level).

With a characteristic vortex size of $1/4 \cdot D$ this means that for a point measurement, the measurement shall be averaged over a length of $1\ 600 \cdot 1/4 \cdot D = 400 \cdot D$; or in time over a period of $400 \times D / v$; where v is the average flow velocity.

More generic the equation for the measurement at a single point in the pipe is:

$$T_{\min} = (u^*/u_d)^2 \cdot 0,25 \cdot D / v \tag{D.1}$$

where

u^* the turbulence level (defined as the standard deviation of the instantaneous turbulent scatter);

u_d is the required standard deviation after averaging;

T_{\min} is the required minimum averaging time.

Whereas ultrasonic flow meters also average the flow over the length of the acoustic path, the total averaging length can be reduced by the internal total path length L_{AV} over which the turbulence is already averaged.

This factor is shown in the following table where the typical averaging length of various meters is presented. (Please note that these are typical values which may vary slightly for different designs.)

Table D.1 — Internal averaging lengths L_{AV} of various meter designs

Number of paths	Typical averaging length in D
3	3,5
4	4,5
5	5,5

In this calculation only the length of the single straight path length is used. Crossed path and reflective designs theoretically should have a higher value but whereas the turbulent scatter is identical for both paths forming the cross, the information from both paths together cannot be treated anymore as being completely independent with a random scatter. Conservatively for those designs the same value is used as the one for the straight paths designs.

With that the minimum averaging time T_{\min} from [Formula \(D.2\)](#), at a 1σ confidence level, is reduced to a value of:

$$T_{\min} = (u^*/u_d)^2 \cdot 0,25 \cdot D / (v \cdot L_{AV}) \tag{D.2}$$

Please note that these are not exact equations; this is statistics.

Dealing with statistics, also the confidence level comes into play. For a random Gaussian distribution the confidence level at 1σ is about 68 % (see also [Figure D.2](#)). In case a lower uncertainty is required the minimum averaging time has to be multiplied with a coverage factor. The coverage factors for different levels of confidence are shown in the following table.

Table D.2 — Gaussian coverage factors

	Coverage factors for the normal, Gaussian distribution					
Confidence level, %	68,27	90,00	95,00	95,45	99,00	99,73
Coverage factor, k	1,000	1,645	1,960	2,000	2,576	3,000

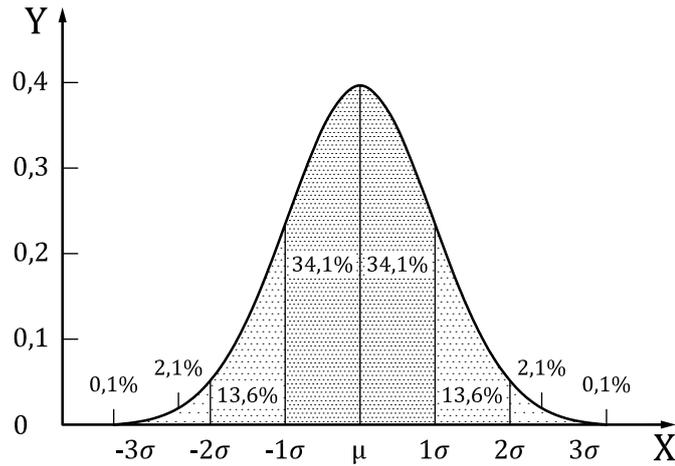


Figure D.2 — Gaussian probability distribution

In the Oil & Gas industry, in most cases a confidence level of 95 % is used resulting in a coverage factor $k = 2$. With that, the minimum averaging time T_{\min} from [Formula \(D.2\)](#), now at a 2σ confidence level is:

$$T_{\min} = (u^*/u_d)^2 \cdot 0,5 \cdot D / (v \cdot L_{AV}) \quad (D.3)$$

where

- u^* is the standard deviation of the instantaneous turbulent scatter;
- u_d is the standard deviation of the required turbulent scatter after averaging;
- v is the flow velocity;
- L_{AV} is the typical averaging length in the ultrasonic flowmeter.

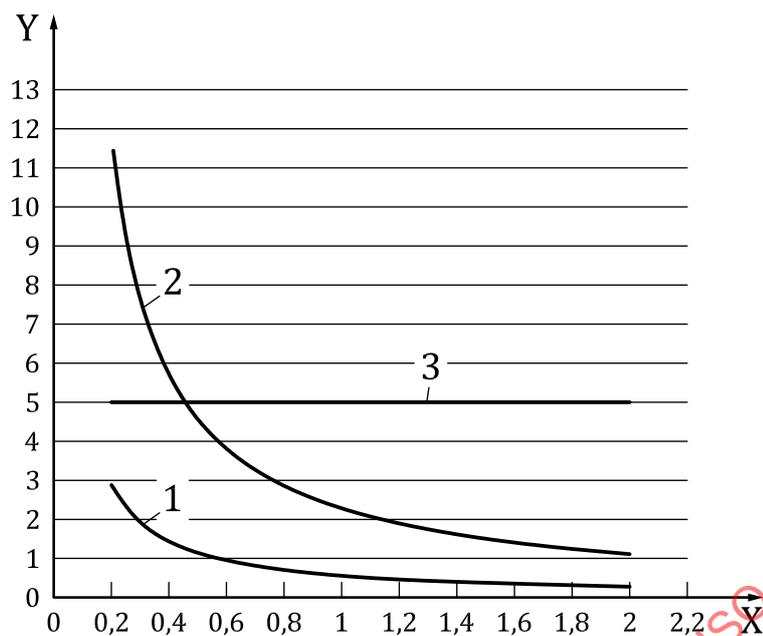
D.4 Determining the value of u_d

The value of additional uncertainty due to the occurring turbulence depends on the required accuracy. For an OIML 0.5 classification, the maximum allowable deviation is 0,167 % (1/3 of the classification). Similarly, the final scatter due to the turbulence, after averaging, should therefore also be less than 1/3 of the allowable total uncertainty in its class.

That results in:

- $u_d = 0,05$ % for a OIML class 0.5 meter run;
- $u_d = 0,1$ % for a OIML class 1 meter run.

The results of the calculations for a 12"meter is shown in [Figure D.3](#), using a turbulence level of 3,5 % and a L_{AV} of 4,5:

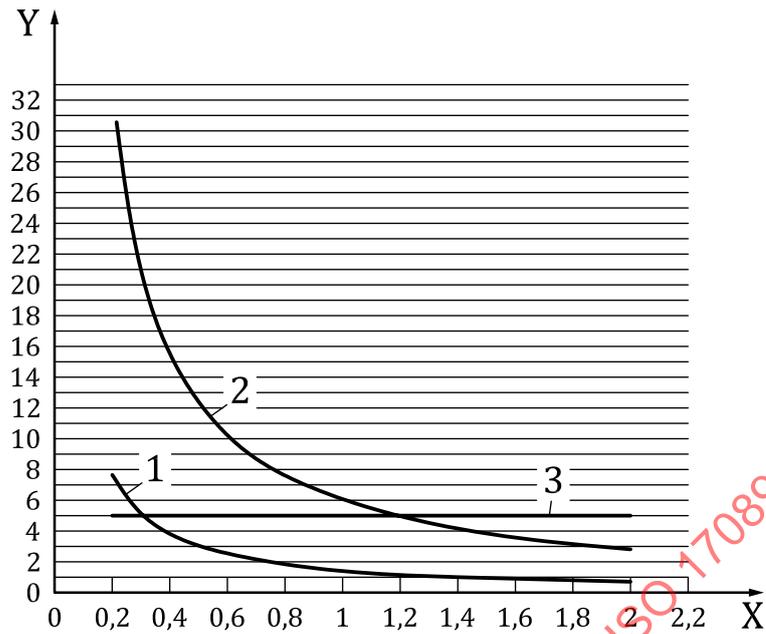


Key

- 1 T_{\min} OIML class 1
- 2 T_{\min} OIML class 0.5
- 3 T_{\min} 300 seconds rule
- Y minutes
- X m/s

Figure D.3 — Minimum averaging time for a 12 “meter

The results of the calculations for a 32”meter is shown in figure 31, using a turbulence level of 3,5 % and a L_{AV} of 4,5:

**Key**

- 1 T_{\min} OIML class 1
- 2 T_{\min} OIML class 0.5
- 3 T_{\min} 300 seconds rule
- Y minutes
- X m/s

Figure D.4 — Minimum averaging time for a 32 "meter

From these figures can be seen that the "old" 300 seconds rule is ok for all the OIML Class 1 meters up to 32" with a V_{\min} of around 30 cm/s or 1 ft/s.

However, for the new generation of high accurate OIML Class 0.5 meters the 300 seconds rule is not adequate anymore and longer averaging times at the lowest calibration points should be applied.

Annex E (informative)

Detailed calculation of geometry-related temperature and pressure corrections

E.1 General background

This annex provides a method of estimating the systematic errors due to meter geometry changes regardless of the particular type, make or model of time-of-flight meter or of the fluid being used.

Geometry change causes two primary effects:

- a) it changes the actual acoustic path length and path angle between a given transducer pair and consequently, if uncorrected, introduces a path velocity error and hence gives rise to a flow error;
- b) any diameter change results in an area change and, if ignored, introduces a further flow error.

For any given path, [Formula \(11\)](#) can be rewritten in the following form in terms of the meter inside diameter of the meter body, d , the path-length, l_p , and the transducer axial separation, x , rather than path angle, ϕ :

$$q_V = \frac{\pi d^2}{4} \frac{l^2}{2x} \left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right) \quad (\text{E.1})$$

For the simple meter arrangement shown in [Figure 4](#), x is obtained from simple trigonometry as:

$$x = l_p \cos \phi$$

The ratio between $q_{V,0}$ at a reference calibration condition and $q_{V,1}$ at different conditions can therefore be written as a flow correction factor, $q_{V,1}/q_{V,0}$, given by:

$$\frac{q_{V,1}}{q_{V,0}} = \left(\frac{d_1}{d_0} \right)^2 \left(\frac{l_1}{l_0} \right)^2 \left(\frac{x_0}{x_1} \right) \quad (\text{E.2})$$

This form is useful since it separates the flow area effect, d^2 , from the path-length effect, l^2 , from the axial extension effect (or path angle effect), x .

Alternatively, an equation equivalent to [Formula \(E.2\)](#), but expressed as a relative flow error, $\Delta q_V/q_V$, can be used:

$$\frac{\Delta q_{V,1,0}}{q_V} = \frac{q_{V,1}}{q_{V,0}} - 1 \quad (\text{E.3})$$

In a multi-path flowmeter, the effect has to be calculated for each of the individual paths and the effect on total flow obtained after integrating the flows once the path weightings have been applied.

The results for a single diametral path are used to provide an estimate of magnitude of the required geometry corrections.

The temperature and pressure are independent effects that need to be evaluated separately, but both effects need to be taken into account for a given situation. The respective effects can work either in the same direction or in opposition to each other. For example, a pressure increase associated with a temperature decrease partly cancel each other out while a pressure increase in combination with a

temperature increase (or pressure reduction in association with a temperature reduction) reinforce the correction effect needed.

Since the physical dimensions of the meter are most likely to have been measured under static calibration conditions, the flow calibration carried out under dynamic calibration conditions, and the meter used under field conditions, the calculation of the flow correction required between dynamic calibration and field conditions can be carried out as a three stage process.

First, calculate the flow correction from static calibration to dynamic calibration using:

$$\frac{q_{V,1}}{q_{V,0}} = \left(\frac{d_1}{d_0}\right)^2 \left(\frac{l_1}{l_0}\right)^2 \left(\frac{x_0}{x_1}\right) \quad (\text{E.4})$$

Second, calculate the flow correction from static calibration to field conditions using:

$$\frac{q_{V,2}}{q_{V,0}} = \left(\frac{d_2}{d_0}\right)^2 \left(\frac{l_2}{l_0}\right)^2 \left(\frac{x_0}{x_2}\right) \quad (\text{E.5})$$

Third, calculate the difference between dynamic calibration and field conditions using:

$$\frac{q_{V,2}}{q_{V,1}} = \frac{q_{V,2}}{q_{V,0}} \frac{q_{V,0}}{q_{V,1}} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{l_2}{l_1}\right)^2 \left(\frac{x_1}{x_2}\right) \quad (\text{E.6})$$

or alternatively:

$$\frac{\Delta q_{V,2,1}}{q_V} = \frac{q_{V,2}}{q_{V,1}} - 1 \quad (\text{E.7})$$

This three stage approach is useful if a check on the actual physical dimensions at intermediate stages within the calculations is required as, for example, might be the case if specific dimensions are to be compared against FE modelling. However, as can be seen in [Formula \(E.6\)](#), the calculation can be carried out in a direct single stage (from dynamic calibration to field operation conditions) rather than in the more lengthy three stage process since the actual flow correction between these two conditions involves the relative change in dimensions, not the absolute values.

[E.6.4](#) and [E.6.5](#) provide a worked example of a direct single stage calculation and a three stage calculation.

For meter bodies that are generally cylindrical in shape and either welded in or have attached flanges, a direct calculation from the physical characteristics of the meter can be performed. The direct calculation method is described in [E.2](#) and is based on a six step process.

Where the meter body is such that the body shape is not a simple cylinder, flanges take up a significant proportion of the total body length or ports are not simple tubes, an FE model provides a more accurate estimate of the body and port dimensions and consequent flow error obtained from [Formula \(E.2\)](#) than is given by the direct calculations of [Formulas \(E.3\)](#) to [\(E.6\)](#). [E.3](#) provides guidance on the use of FE modelling to predict the temperature and pressure expansion effects.

E.2 Direct calculation

E.2.1 Step 1 — Body temperature effect

The effect of a temperature difference, ΔT , is relatively easy to account for since it expands the dimensions according to:

$$\begin{aligned}
 l_1 &= l_0 (1 + \alpha \Delta T) \\
 x_1 &= x_0 (1 + \alpha \Delta T) \\
 d_1 &= d_0 (1 + \alpha \Delta T)
 \end{aligned}
 \tag{E.8}$$

Substituting the [Formulas \(E.8\)](#) into [Formula \(E.2\)](#) gives:

$$\frac{q_{V,1}}{q_{V,0}} = (1 + \alpha \Delta T)^3 = \left[1 + 3\alpha \Delta T + 3(\alpha \Delta T)^2 + (\alpha \Delta T)^3 \right]
 \tag{E.9}$$

Since $\alpha \Delta T$ is generally small, this can be simplified to:

$$\left(\frac{q_{V,1}}{q_{V,0}} \right)_{b,T} = 1 + 3\alpha \Delta T
 \tag{E.10}$$

where “b, T” denotes body temperature, or alternatively,

$$\left(\frac{\Delta q_V}{q_V} \right)_{b,T} = 3\alpha \Delta T
 \tag{E.11}$$

E.2.2 Step 2 — Body pressure expansion

The effect of a pressure change is to alter the diameter and length of the meter body, but the actual change in dimensions depends on a number of factors including:

- a) the thickness/inside radius ratio of the meter walls (i.e. the ratio δ/r);
- b) the way the meter is supported and attached to, or constrained by, adjacent pipework;
- c) the rigidity of the adjacent pipework;
- d) any axial loading;
- e) the general geometry of the meter body and whether it has flanges;
- f) the slenderness ratio of the meter (i.e. the overall body length/body diameter).

For generally cylindrical bodies, the equations of Roark (see Reference [\[74\]](#)) are used as the basis of the analysis. These have for many years been taken as the fundamental basis for stress analysis of pressure vessels and are derivations from the basic Lamé-Clapeyron equations of 1833.

For a thick-wall body (i.e. $\delta / r > 0,1$) with only radial internal pressure but no end loads (this is referred to as the “no-ends” condition) and positions well away from ends, Reference [\[74\]](#) gives:

$$\frac{\Delta r}{r} = \frac{\Delta p}{E} \left(\frac{R^2 + r^2}{R^2 - r^2} + \mu \right)
 \tag{E.12}$$

$$\frac{\Delta x}{x} = \frac{-\Delta p \mu}{E} \left(\frac{2r^2}{R^2 - r^2} \right) \quad (\text{E.13})$$

And for radial internal pressure plus pressure end load (this is referred to as the “capped-ends” condition) and positions well away from ends, Reference [74] gives:

$$\frac{\Delta r}{r} = \frac{\Delta p}{E} \left(\frac{R^2(1+\mu) + r^2(1-2\mu)}{R^2 - r^2} \right) \quad (\text{E.14})$$

$$\frac{\Delta x}{x} = \frac{\Delta p}{E} \left(\frac{r^2(1-2\mu)}{R^2 - r^2} \right) \quad (\text{E.15})$$

where

μ is the Poisson ratio, equal to 0,3 for steel;

R is the outside radius in the same units as r .

For a thin-wall body ($\delta / r \leq 0,1$) for only radial internal pressure (no-ends) and positions well away from ends, Reference [74] gives simpler equations:

$$\frac{\Delta r}{r} = \frac{\Delta p r}{E \delta} \quad (\text{E.16})$$

$$\frac{\Delta x}{x} = \frac{-\Delta p r \mu}{E \delta} \quad (\text{E.17})$$

And, for capped-ends:

$$\frac{\Delta r}{r} = \frac{\Delta p r}{E \delta} \left(1 - \frac{\mu}{2} \right) \quad (\text{E.18})$$

$$\frac{\Delta x}{x} = \frac{\Delta p r}{E \delta} (0,5 - \mu) \quad (\text{E.19})$$

For the purposes of this document, for all meter types, the meter ends are assumed to be unconstrained and free to move axially.

It should be noted that for positions away from ends, the thick-wall [Formulas \(E.12\) to \(E.15\)](#) are the more exact since they also cover the simpler case of thin-wall pipe.

Consequently, for all meter body types, thick-shell theory [[Formulas \(E.12\) to \(E.15\)](#)] is the preferred approach since this is more general than thin-shell theory [[Formulas \(E.16\) to \(E.19\)](#)]. Essentially, the choice of whether to use thin- or thick-shell theory is based on the ratio δ / r . In practice, this effectively means that the choice of equations is related to the pressure rating of the body since meters for high-pressure systems have thicker walls than meters for low-pressure systems. When designing a meter spool calculated in accordance with the ASME rules and using one of the most common steel types (A333 steel), all meters up to ANSI 900 fall in the range that can be handled by thin-walled pipe equations; this is also true for many of the ANSI 1500 meters made from high tensile steel.

Thin-wall equations are generally not used where $\delta / r > 0,1$ but can be used as described in [E.4](#), for the purposes of this document, for thick-walled vessels in combination with FE modelling ([E.3](#)) if the limitations are understood as an alternative to applying the style correction given in [E.2.3](#).

E.2.3 Step 3 — Correction for body style effect or proximity to flanges

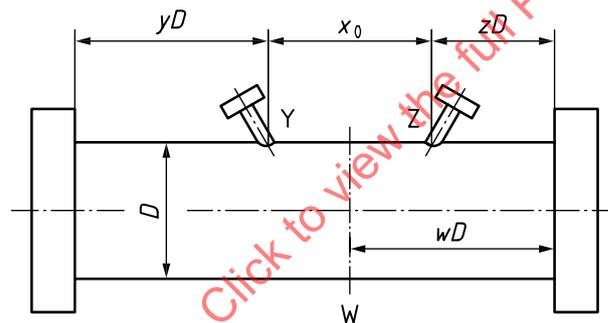
If portions of the ultrasonic path are closer than one outside pipe diameter to flanges or the body is of irregular shape, the radial expansion is, due to local stiffening effects, less than that indicated by [Formulas \(E.12\)](#) and [\(E.14\)](#) [or [Formulas \(E.16\)](#) and [\(E.18\)](#) for a thin-walled body]. To compensate for this local stiffening effect, a “style correction factor”, K_s , is used.

K_s is always less than or equal to 1. The value of K_s to be used for a given body type is as follows:

- a) for a welded-in body with no flanges within $2R$ of the ultrasonic transducer locations, $K_s = 1$, i.e. the meter body behaves as a simple pipe;
- b) for a flanged meter body (e.g. consisting of two flanges welded to a pipe) or welded-in design where neighbouring flanges are within $2R$ of the transducer positions, the value of K_s is calculated as in the next paragraph.

For the purpose of this document, it is assumed that the diametral expansion varies linearly from zero at the flange to the value given by [Formulas \(E.12\)](#) and [\(E.14\)](#) [or [Formulas \(E.16\)](#) and [\(E.18\)](#) for thin-wall] at one outside diameter of the meter body, D , or greater from the flange. It is also assumed that the flange correction only affects the radial expansion of the body, not the linear expansion in the vicinity of the ultrasonic paths.

The transducer port positions are shown in [Figure E.1](#) in terms of the outside diameter of the meter body, D .



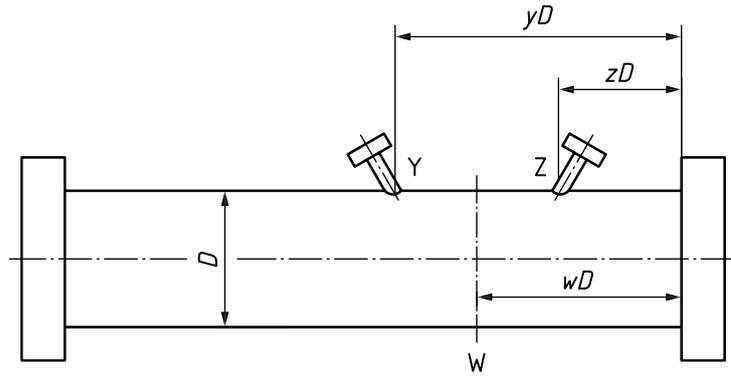
Key

- D outside diameter of the meter body
- W mid-path position
- w factor to express the distance from flange to mid-path position in terms of D
- x_0 distance between transducers Y and Z
- Y transducer location
- y factor to express the distance from flange to transducer Y location in terms of D
- Z transducer location
- z factor to express the distance from flange to transducer Z location in terms of D

Figure E.1 — Transducer port proximity to flanges

Since the ultrasonic path covers a range in axial distance from a flange, the average path distance, $w_a D$, is calculated from three positions on a given path; W , at the mid-path position and Y and Z , at the actual transducer locations. The distances to the nearest flange are measured from positions W , Y , and Z .

Where the transducers of the meter are clearly all closer to one flange than the other, the alternative arrangement shown in [Figure E.2](#) is used.

**Key**

D outside diameter of the meter body

W mid-path position

w factor to express the distance from flange to mid-path position in terms of D

Y transducer location

y factor to express the distance from flange to transducer Y location in terms of D

Z transducer location

z factor to express the distance from flange to transducer Z location in terms of D

Figure E.2 — Transducer port proximity to flanges — Long meter with offset transducer

If any of the values of w , y or z are greater than 1, then the value used for that parameter in the calculation shall be limited to a value of 1.

The average path distance from a flange is calculated from:

$$w_a D = \left\{ \frac{w + y + z}{3} \right\} D \quad (\text{E.20})$$

The style correction, K_s , is obtained using:

$$K_s = \frac{w_a}{1} \quad (\text{E.21})$$

A stiffening effect also occurs near any part of the body which has features such as branches or welds. These generally create less of an effect than proximity to flanges since they typically occupy only a small portion of the body circumference.

E.2.4 Step 4 — Combined pressure correction effect

The radial expansion of the body, including flange correction, is calculated from:

$$d_1 = d_0 \left(1 + K_s \frac{\Delta d}{d_0} \right) = d_0 \left(1 + K_s \frac{\Delta r}{r} \right) \Rightarrow \frac{d_1}{d_0} = 1 + K_s \frac{\Delta r}{r} \quad (\text{E.22})$$

The path length is calculated from:

$$l_0^2 = (N + 1)^2 d_0^2 + x_0^2 \quad (\text{E.23})$$

$$l_1^2 = (N+1)^2 d_1^2 + x_1^2 \tag{E.24}$$

where N is the number of bounces along a given path (for a single traverse path).

Hence, for a given meter with a known wall thickness, δ , and initial geometry x_0 , d_0 , and l_0 at dry-calibration conditions, the revised dimensions x_1 , d_1 , and l_1 can be calculated for the pressure difference using [Formulas \(E.22\)](#) to [\(E.24\)](#).

The flow correction factor is then calculated using:

$$\left(\frac{q_{V,1}}{q_{V,0}} \right)_{b,p} = \left(\frac{d_1}{d_0} \right)^2 \left(\frac{l_1}{l_0} \right)^2 \left(\frac{x_0}{x_1} \right) \tag{E.25}$$

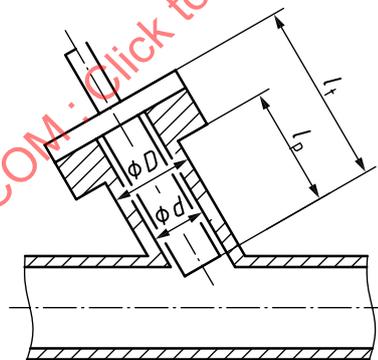
where “ b, p ” denotes body pressure.

The error correction obtained from [Formula \(E.25\)](#) for the no-ends case and for the capped-ends cases should be calculated to give a range of correction factors. This range should generally be small and the process sufficient to provide an indication of the flow correction required.

E.2.5 Step 5 — Expansion effects in the transducer ports

E.2.5.1 General

In addition to the effects that pressure and temperature changes have on the meter body they also alter the lengths of the transducer ports. This actually moves the position of the transducer face and hence affects the acoustic path length. Although this effect is generally small, a simple procedure is included here to allow the effects on the ports to be estimated. The next figure shows the port geometry dimensions used for this assessment.



Key

- D outside diameter of the meter body
- d inside diameter of the meter body
- l_p path length
- l_t length to the transducer face

Figure E.3 — Transducer port dimensions

Temperature and pressure corrections are treated separately and, for both, the only effect that is considered here is the path length change.

E.2.5.2 Port temperature correction

Due to the way the transducer is secured into the port, it is generally held at the end of the port. The consequence of this is that any expansion of the port itself occurs in the opposite direction to the expansion of the transducer; hence the expansions to some extent cancel depending on the relative coefficient of thermal expansion of the port material, α_p , and the transducer material, α_t . The change in transducer face position, Δl_t , due to temperature is given by:

$$\Delta l_t = l_t (\alpha_p \Delta T - \alpha_t \Delta T) = l_t (\alpha_p - \alpha_t) \Delta T \quad (\text{E.26})$$

This is the change in face position in each port, so the effect on a given ultrasonic path is $2 \Delta l_t$. Assuming there is no diameter change or axial change, [Formula \(E.2\)](#), solely for the port expansion, simplifies to:

$$\left(\frac{q_V}{q_{V,0}} \right)_{p,T} = \left(\frac{l_1}{l_0} \right)^2 = \left(\frac{l_0 + 2\Delta l_t}{l_0} \right)^2 = \left[1 + \frac{2l_t (\alpha_p - \alpha_t)}{l_0} \right]^2 \quad (\text{E.27})$$

where p, T denotes port temperature, which for small values gives:

$$\left(\frac{q_V}{q_{V,0}} \right)_{p,T} = \left[1 + \frac{4l_t (\alpha_p - \alpha_t)}{l_0} \right] \quad (\text{E.28})$$

or alternatively to:

$$\frac{\Delta q_V}{q_V} = 4(\alpha_p - \alpha_t) \frac{l_t}{l_0} \Delta T \quad (\text{E.29})$$

E.2.5.3 Port pressure correction

The pressure effect on the port and the transducer act in the same direction; the port is stretched whilst the transducer is compressed. For this simple approach, the port and transducer are assumed to act as simple linear elastic materials. The linear strain in the port walls is given by:

$$\Delta L_p = l_t \frac{\Delta p}{E_t} + l_p \frac{\Delta p}{E_p} \left(\frac{d_p^2}{D_p^2 - d_p^2} \right) = \Delta p \left[\frac{l_t}{E_t} + \frac{l_p}{E_p} \left(\frac{d_p^2}{D_p^2 - d_p^2} \right) \right] \quad (\text{E.30})$$

This is the change in face position in each port. Assuming there is no diameter change or axial change, [Formula \(E.2\)](#), solely for the port pressure expansion, simplifies to:

$$\left(\frac{q_V}{q_{V,0}} \right)_{p,p} = \left(\frac{l_1}{l_0} \right)^2 = \left(\frac{l_0 + 2\Delta L_p}{l_0} \right)^2 = \left[1 + \frac{2\Delta L_p}{l_0} \right]^2 \quad (\text{E.31})$$

where p, p denotes port pressure, which for small values gives:

$$\left(\frac{q_V}{q_{V,0}} \right)_{p,p} = \left[1 + \frac{4\Delta L_p}{l_0} \right] \quad (\text{E.32})$$

or alternatively to:

$$\frac{\Delta q_V}{q_V} = 4 \frac{\Delta L_p}{l_0} \quad (\text{E.33})$$

E.2.5.4 Combined port correction

This is calculated using:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_p = \left(\frac{q_{V,1}}{q_{V,0}}\right)_{p,p} + \left(\frac{q_{V,1}}{q_{V,0}}\right)_{p,T} \tag{E.34}$$

As an alternative to this simple assessment, the transducer port effects can be built into an FE model of the meter as described in [E.3](#).

E.2.6 Step 6 — Combined flow correction

The combined flow correction factor for a given set of pressure and temperature conditions is obtained from:

$$\frac{q_{V,x}}{q_{V,0}} = \left(\frac{q_{V,x}}{q_{V,0}}\right)_{b,p} + \left(\frac{q_{V,x}}{q_{V,0}}\right)_{b,T} + \left(\frac{q_{V,x}}{q_{V,0}}\right)_p \tag{E.35}$$

which can be expressed as:

$$\frac{\Delta q_{V,x,0}}{q_V} = \frac{\Delta q_{V,x}}{q_{V,0}} - 1 \tag{E.36}$$

For small values of correction this simplifies to:

$$\frac{q_{V,x}}{q_{V,0}} = \left(\frac{q_{V,x}}{q_{V,0}}\right)_{b,p} + \left(\frac{q_{V,x}}{q_{V,0}}\right)_{b,T} + \left(\frac{q_{V,x}}{q_{V,0}}\right)_p \tag{E.37}$$

Two values for the combined flow correction are obtained; one using the no-ends pressure correction and one using the capped-ends pressure correction. This allows the flow error to be expressed in either of the equivalent forms as in [Formulas \(21\)](#) and [\(22\)](#):

$$\frac{q_{V,1}}{q_{V,0}} = x,xxxx \mp x,xxxx \tag{E.38}$$

$$\frac{\Delta q_V}{q_V} = (x,xx \mp x,xx) \% \tag{E.39}$$

E.3 Guidance on the use of finite element models

E.3.1 General

Where the meter body is such that transducer ports are close to end flanges or the body shape is not a simple cylinder, an FE model of the body and ports can be run to predict the pressure and temperature expansion effects on *d*, *x*, *l*, and port and transducer length. [Formula \(E.2\)](#) is still used to predict the flow error along each path.

As a means of checking the values from the FE model, the results for *d*, *x*, *l*, and port lengths can be compared against those obtained from [Formulas \(E.12\)](#) to [\(E.15\)](#) including any flange or body style correction effect described in [E.2.3](#), where relevant, and port effects described in [E.2.5](#). If the meter body wall is irregular or non-cylindrical (e.g. as might be the case for a cast body), then, for the purposes of checking against the FE model, the direct calculations can be run for two scenarios: one where the outside radius, *R*, used in [Formulas \(E.12\)](#) to [\(E.15\)](#), is taken as the point where the wall is thinnest and one for the case where the outside radius is based on the point where the wall is thickest.

Since FE analysis deals with absolute change in physical dimensions, closer agreement with the direct calculation method of [E.2](#) is obtained for actual metre dimensions at given conditions if the calculation and FE runs are carried out as a three stage process as described in [E.1](#) namely:

- a) static calibration to dynamic calibration conditions as in [Formula \(E.4\)](#);
- b) static calibration to operating conditions as in [Formula \(E.5\)](#);
- c) comparison of the relative change between the two as in [Formulas \(E.6\)](#) and [\(E.7\)](#).

Care, however, needs to be taken in choice of the boundary conditions used for the FE model since these are often not easy to estimate for a given installation. It is recommended that models be run with a number of different boundary conditions so that the sensitivity to the boundary conditions can be assessed. This is essentially similar to including the no-ends and capped-ends cases in the direct calculation approach of [E.2](#).

For each run, the flow error is calculated using [Formula \(E.2\)](#). This allows the flow error to be expressed in either of the forms given by [Formulas \(21\)](#) or [\(22\)](#). [E.6.4](#) and [E.6.5](#) provide worked examples of a direct single stage approach and the more lengthy three stage approach.

[E.4](#) provides additional guidance on the use of thin-walled pipe theory to check the results of FE analysis carried out on a thick-wall meter body.

E.3.2 Note on intentional use of thin-wall equations beyond their normal limit

In the fields of stress analysis and pressure vessel design, it is generally accepted that thin-wall theory is only applied where $\delta/r < 0,1$. The reasons for this are that as δ/r increases, the difference with the more exact thick-shell theory grows unacceptably large, at least as far as prediction of wall stress levels are concerned. [Figure E.4](#) shows the effect on $\Delta r/r$ of the various approaches [as given in [Formulas \(E.12\)](#), [\(E.14\)](#), [\(E.16\)](#) and [\(E.18\)](#)] for different δ/r ratios.

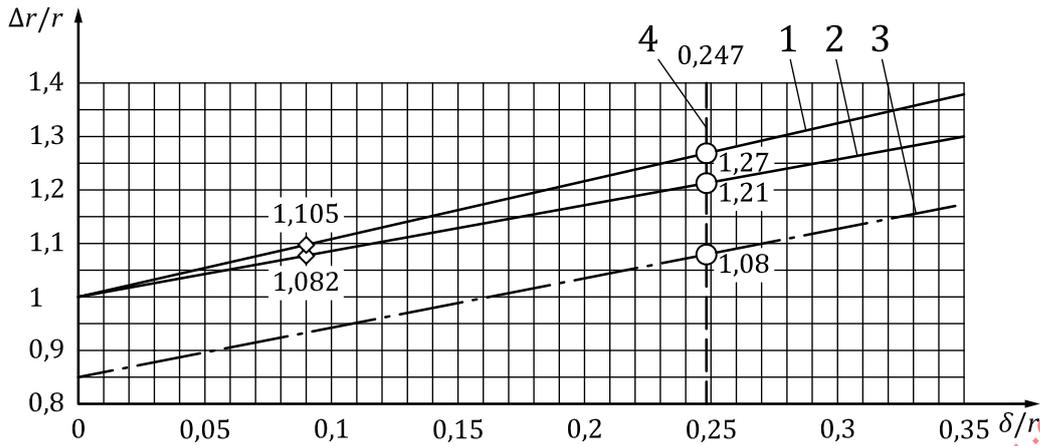
As can be seen from [Figure E.4](#), δ/r ratios higher than 0,1 give differences in $\Delta r/r$ of more than 10 % compared with the thick-shell theory for the same end-loading conditions. If, for example, $\delta/r = 0,247$, the differences are in the region of 21 % to 27 % depending on which loading configuration is applied.

If one mixes the loading cases and uses the thin-wall no-ends equations for a thick-wall capped-ends situation, then one overestimates $\Delta r/r$ for $\delta/r < 0,16$ and underestimates it for $\delta/r > 0,16$. For the example of $\delta/r = 0,247$, the underestimate in $\Delta r/r$ is 8 %.

[Figure E.4](#) shows that the thin-wall equations predict lower values of $\Delta r/r$ than the thick-shell theory for the same load conditions. This produces a similar effect to using thick-shell theory plus a flange proximity or body style correction as in [E.2.3](#), although how similar depends on the actual geometry, flange proximity and end-loading conditions for a given meter.

Consequently, in combination with FE modelling ([E.3](#)), it may, for the above reasons, be found that a simple thin-shell theory gives adequate agreement to FE results for a given meter geometry and can subsequently be used as a valid means of estimating metering error at other conditions.

CAUTION — This only applies to the specific meter on which the FE analysis was shown to give agreement and should not be taken as a general rule that can be applied to all meters.



Key

- $\Delta r/r$ thick-wall/thin-wall ratio
- δ/r pipe thickness to inside pipe radius ratio
- 1 capped ends
- 2 no ends
- 3 thick capped/thin no ends
- 4 example

Figure E.4 — Comparison of thick-shell with thin-shell theory for different δ/r ratios

E.4 Calculation of an initial estimate for the body pressure effect

To provide the initial estimate of the body pressure effects used in 9.1.2.2, the axial change in x and any flange proximity or body style effect, K_s , are neglected for simplicity. Using Formulas (E.23) and (E.24), Formula (E.25) reduces to:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{b,p,est} = \left(\frac{d_1}{d_0}\right)^2 \left(\frac{l_1}{l_0}\right)^2 = \left(\frac{d_1}{d_0}\right)^2 \left(\frac{d_1}{d_0}\right)^2 = \left(\frac{d_1}{d_0}\right)^4 = \left(1 + \frac{\Delta r}{r}\right)^4 \tag{E.40}$$

For small values of $\Delta r/r$, this reduces further, by ignoring higher order terms, to:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{b,p,est} = \left(1 + \frac{\Delta r}{r}\right)^4 \approx 1 + 4 \frac{\Delta r}{r} \tag{E.41}$$

or in terms of $\Delta q_V/q_V$ gives:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{b,p,est} = \frac{q_{V,1}}{q_{V,0}} - 1 = 4 \frac{\Delta r}{r} \tag{E.42}$$

The no-ends, thick-wall Formula (E.12) is used for $\Delta r/r$ to give a worst-case estimate since it produces the largest change in $\Delta r/r$ for a given applied Δp . Hence the maximum expected $\Delta q_V/q_V$ due to body pressure change effects is given by:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{b,p,max} = 4 \frac{\Delta r}{r} = 4 \left(\frac{R^2 + r^2}{R^2 - r^2} + \mu\right) \frac{\Delta p}{E} \tag{E.43}$$

E.5 Worked example

E.5.1 Meter details

A flanged-body spool meter has the following details which form the input data for the flow correction calculation.

Table E.1 — Meter parameters

Parameter	Symbol	Value
Body inside radius ^a	r_b	183,25 mm
Body outside radius ^a	R_b	228,6 mm
Wall thickness ^a	δ	45,35 mm
Transducer port length	l_{tp}	230 mm
Port outside diameter	D_p	50 mm
Port inside diameter	d_p	32 mm
Proximity to left-hand flange ^a	—	366 mm
Proximity to right-hand flange ^a	—	686 mm
Single bounce path	N	1
Path angle	ϕ	70°
Path length	l_o	780,117 mm
Transducer separation	x_o	267,007 mm
Body material Young modulus ^a	E	$2,00 \times 10^2$ GPa
Poisson ratio ^a	μ	0,3
Coefficient of thermal expansion ^a	α	$1,26 \times 10^{-5}$ K ⁻¹
Port length excluding flange	l_{pxf}	220 mm
Transducer diameter	d_t	32 mm
Transducer length	l_t	230 mm
Transducer coefficient of thermal expansion (estimated)	α_t	$1,5 \times 10^{-5}$ K ⁻¹
Transducer Young modulus (estimated)	E_t	$1,9 \times 10^2$ GPa
Static calibration conditions	—	0 MPa (gauge), 20 °C
Dynamic calibration conditions ^a	—	6,3 MPa (gauge), 7 °C
Field operation conditions ^a	—	23,0 MPa (gauge), 40 °C
^a Needed for the initial estimate.		

These are first used to calculate some common basic parameters.

Table E.2 — Meter basic parameters

Parameter	Value	Implication	
Wall thickness ratio, δ / r	0,247 5	⇒ thick wall	
Meter external diameter	$2 \times 228,6 = 457,2 = D_p$		
Flange proximity	closest	$366/457,2 = 0,8D_p$	⇒ $z = 0,8$
	furthest	$(366 + 267)/457,2 = 1,38D_p$	⇒ $y = 1$
	mid-path	$[366 + 0,5 \times 267]/457,2 = 1,09D_p$	⇒ $w = 1$
Body style correction factor	$(w + y + z)/3 = 2,8/3 = 0,93 = K_s$		