INTERNATIONAL STANDARD

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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

Reference number
ISO 17089-1:2010(E)

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 17089-1 was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 5, *Velocity and mass methods*.

ISO 17089 consists of the following parts, under the general title *Measurement of fluid flow in closed conduits — Ultrasonic meters for gas*:

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

The following part is planned:

- *Part 2: Meters for industrial applications*

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 part of ISO 17089 advocates the addition and use of automated diagnostics instead of labour-intensive quality checks.

This part of ISO 17089 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, will be the subject of part 2.

Typical performance factors of the classification scheme are:

Class	Typical applications	Typical uncertainty	Reference
1	Custody transfer	<0,7 %	This part of ISO 17089
2	Allocation	<1,5 %	This part of ISO 17089
3	Utilities and process		ISO 17089-2[a]
4	Flare gas and vent gas		ISO 17089-2[a]

[a] Planned.

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.

INTERNATIONAL STANDARD **ISO 17089-1:2010(E)**

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

Part 1:
Meters for custody transfer and allocation measurement

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This part of ISO 17089 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 part of ISO 17089 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 part of ISO 17089 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 part of ISO 17089 specifies construction, performance, calibration, 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 part of ISO 17089.

2 Normative references

The following referenced documents are indispensable for the application 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/TR 7871, *Cumulative sum charts — Guidance on quality control and data analysis using CUSUM techniques*

ISO 12213 (all parts), *Natural gas — Calculation of compression factor*

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

3 Terms, definitions, and symbols

3.1 Terms and definitions

3.1.1 General

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

3.1.2 Quantities

3.1.2.1
volume flow rate
q_V

$$q_V = \frac{\mathrm{d}V}{\mathrm{d}t}$$

where

V is volume;

t is time.

NOTE Adapted from ISO 80000-4:2006[83], 4-30.

3.1.2.2
working range
rangeability
set of values of quantities of the same kind that can be measured by a given measuring instrument or measuring system with specified instrumental uncertainty, under defined conditions

NOTE 1 Adapted from ISO/IEC Guide 99:2007[33], 4.7, “working interval”.

NOTE 2 For the purposes of this part of ISO 17089, the “set of values of quantities of the same kind” are volume flow rates whose values are bounded by a maximum flow rate, $q_{V,\,\mathrm{max}}$, and a minimum flow rate $q_{V,\,\mathrm{min}}$; the “given measuring instrument” is a meter.

3.1.2.3
metering pressure
p
absolute gas pressure in a meter under flowing conditions to which the indicated volume of gas is related

3.1.2.4
average velocity
v
volume flow rate divided by the cross-sectional area

3.1.3 Meter design

3.1.3.1
meter body
pressure-containing structure of the meter

3.1.3.2
acoustic path
path travelled by an acoustic wave between a pair of ultrasonic transducers

3.1.3.3

axial path

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

NOTE 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

3.1.3.4

diametrical path

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

See Figure 2.

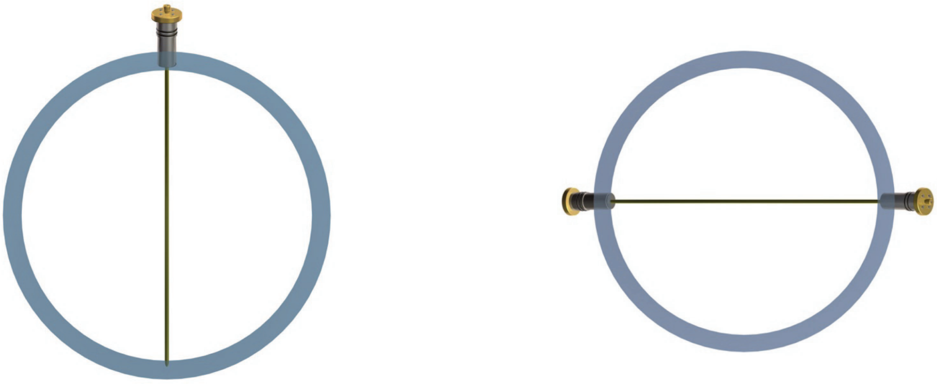


Figure 2 — Diametrical paths

3.1.3.5

chordal path

accoustic path whereby the acoustic wave travels parallel to the diametrical path

See Figure 3.

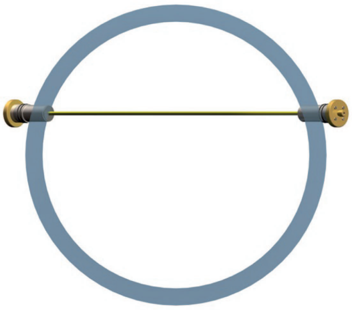


Figure 3 — Chordal paths

3.1.4 Thermodynamic conditions

3.1.4.1
metering conditions
conditions, at the point of measurement, of the fluid whose volume is to be measured

NOTE 1 Metering conditions include gas composition, temperature, and pressure.

NOTE 2 Adapted from ISO 9951:1993[2], 3.1.6.

3.1.4.2
base conditions
conditions to which the measured volume of the fluid is converted

NOTE 1 Base conditions include base temperature and base pressure.

NOTE 2 Adapted from ISO 9951:1993[2], 3.1.7.

3.1.4.3
specified conditions
conditions of the fluid at which performance specifications of the meter are given

NOTE Adapted from ISO 9951:1993[2], 3.1.8.

3.1.5 Statistics

3.1.5.1
measurement error
error of measurement
error
measured quantity value minus a reference quantity value

[ISO/IEC Guide 99:2007[33], 2.16]

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

3.1.5.2
error curve
interconnection of the curve (e.g. polynomial) fitted to a set of error data as a function of the flow rate of the reference meter

3.1.5.3
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

NOTE Adapted from ISO/IEC Guide 99:2007[33], 4.26.

3.1.5.4
maximum peak-to-peak error
maximum difference between any two error values

3.1.5.5
repeatability
measurement precision under a set of repeatability conditions of measurement

[ISO/IEC Guide 99:2007[33], 2.21]

3.1.5.6
measurement precision
closeness of agreement between output values of the test meter, obtained by replicate measurements on the same meter under specified conditions

NOTE Adapted from ISO/IEC Guide 99:2007[33], 2.15.

3.1.5.7
reproducibility
measurement precision under reproducibility conditions of measurement

[ISO/IEC Guide 99:2007[33], 2.25]

3.1.5.8
resolution
smallest difference between indications of a meter that can be meaningfully distinguished

NOTE Adapted from ISO 11631:1998[3], 3.28.

3.1.5.9
velocity sampling interval
interval between two consecutive gas velocity measurements, each being the set of true quantity values of a measurand with a stated probability, based on the information available

3.1.5.10
zero flow reading
datum measurement error where the gas is at rest, when both axial and non-axial velocity component values are zero

3.1.5.11
linearization
way of reducing the non-linearity of the ultrasonic meter, generally by applying corrections in the software

NOTE 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.

3.1.5.12
slope
gradient of a line joining data points

EXAMPLE Gradient of the best fitting straight line, determined by the least squares method, through the calibration points in an error curve.

3.2 Symbols and subscripts

The symbols and subscripts used in this part of ISO 17089 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	LT^{-1}	m/s
Outside pipe diameter	D	L	m
Inside diameter of the meter body	d	L	m
Modulus of elasticity; Young modulus	E	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	MPa
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
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	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
Pressure difference	Δp	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
Emitted acoustic pressure	p_n	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
Signal strength of the USM	P_s	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
Volume flow rate	q_V	$\mathrm{L}^3\mathrm{T}^{-1}$	m^3/s
Outside pipe radius	R	L	m
Inside pipe radius	r	L	m
Reynolds number (related to d)	Re_d	—	1
Absolute temperature of the gas	T	Θ	K
Temperature difference	ΔT	Θ	K
Transit time	t	T	s
Average velocity	v	LT^{-1}	m/s
Velocity of the acoustic path i	v_i	LT^{-1}	m/s
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	$\mathrm{L}^{-1}\mathrm{MT}^{-1}$	Pa·s
Wavelength of ultrasonic oscillation	λ	L	m
Poisson ratio	μ	—	1
Density of fluid	ρ	ML^{-3}	$\mathrm{kg/m}^3$
Path angle	ϕ	—	rad
Angular velocity	ω	T^{-1}	$\mathrm{rad{\cdot}s}^{-1}$

[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
$q_{V,\,\mathrm{max},\,20}$	Designed maximum flow rate, designed for maximum gas speed of 20 m/s
$q_{V,\,\mathrm{max},\,x}$	Designed maximum flow rate, designed for maximum gas speed of x m/s
$q_{V,\,\mathrm{max},\,\mathrm{op}}$	Operational maximum flow rate; defined only when smaller than designed maximum
$q_{V,\,\mathrm{max},\,\mathrm{cal}}$	Highest flow rate calibrated; defined only when smaller than operational maximum
$q_{V,\,\mathrm{min}}$	Designed minimum flow rate
$q_{V,\,\mathrm{t}}$	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
FRMM	flow reference meter method
FWME	flow-weighted mean error
HDF	historic difference footprint
HDH	historic difference histogram
M&R	metering and regulating stations
MDF	monthly difference footprint
MSOS	measured speed of sound
S/N	signal-to-noise ratio
SOS	speed of sound
TSOS	theoretical speed of sound
USM	ultrasonic flowmeter
USMP	USM package, including meter tubes, flow computer, 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 waves 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 pulses. These transducers transmit sound pulses 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 pulse from A to B decreases and the one from B to A increases, according to (ignoring second order effects, such as path curvature):

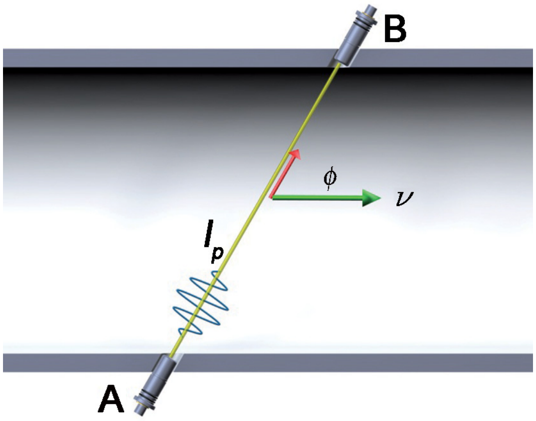
$$t_{\mathrm{AB}} = \frac{l_{\mathrm{p}}}{(c + v\cos\phi)} \tag{1}$$

and

$$t_{\mathrm{BA}} = \frac{l_{\mathrm{p}}}{(c - v\cos\phi)} \tag{2}$$

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 pulse.



Key

A, B	positions
l_{p}	path length
v	average velocity
ϕ	path angle

Figure 4 — Basic system setup

Equation (3) for the measured gas velocity can be derived by subtracting Equation (2) from Equation (1):

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

Note that the term for the SOS in the gas has been eliminated in Equation (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. However, if the transducers are recessed, there is an additional time delay component, which is SOS dependent.

In a similar way, the SOS can be derived by adding Equations (1) and (2) and rearranging:

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

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

$$v = f\left(v_1 \ldots v_n\right) \tag{5}$$

where n is the total number of paths. Due to variations in path configuration and different proprietary approaches to solving Equation (5), even for a given number of paths, the exact form of $f(v_1 \ldots v_n)$ 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:

$$q_V = A\ v \tag{6}$$

4.2 Factors affecting performance

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

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

a) the geometry of the meter body and ultrasonic transducer locations and the uncertainty with which these are known (including the temperature and pressure coefficient);

b) the accuracy and quality of the transducers and electronic components used in the transit time measurement circuitry (e.g. the electronic clock stability);

c) 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;

d) calibration (including proper compensation for signal delays in electronic components and transducers).

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

1) the flow velocity profile;

2) the temperature distribution;

3) flow pulsations;

4) the noise, both acoustic and electromagnetic;

5) solid and liquid contamination;

6) the dimensional integrity over time.

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 can be supplied in various forms. Typically, they comprise a piezoelectric element with electrode connections and a supporting mechanical structure with which the process connection is made. The 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, or threaded or may be more mechanically complex, e.g. to allow the removal of transducers from a pressurized line. The active element is usually isolated from the fluid by an acoustic coupling element. Once in operation, the active element transmits ultrasonic waves 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) close proximity to high pressure drop throttle valve (potential of in-pipe ultrasonic noise);

e) rapid or cyclic temperature or pressure changes;

f) corrosive or erosive gas (sour gas);

g) gas with traces of moisture or dirt.

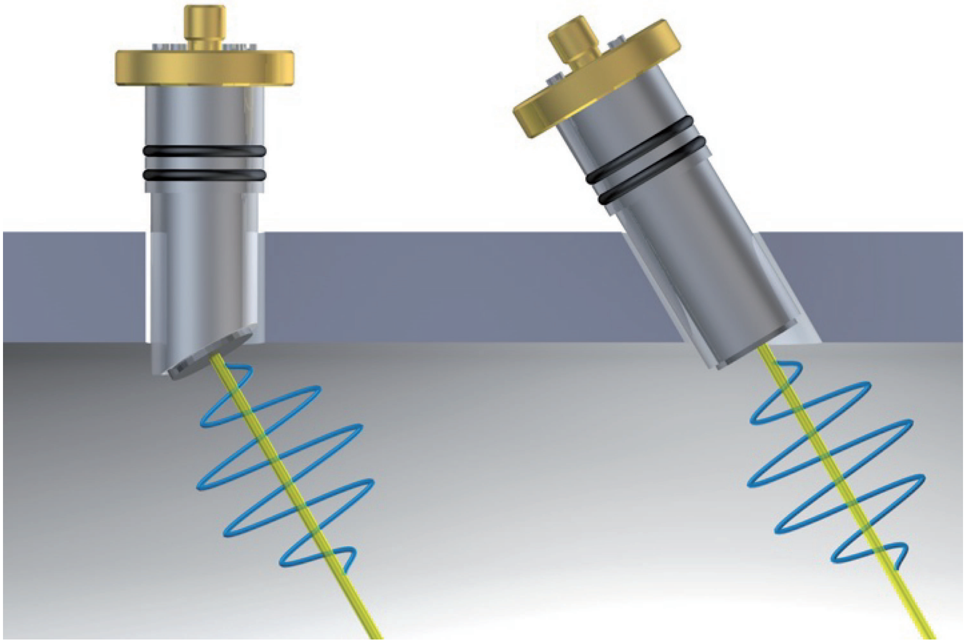


Figure 5 — Typical transducer arrangements

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 wave 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

The most common acoustic path types are illustrated in Figure 6.

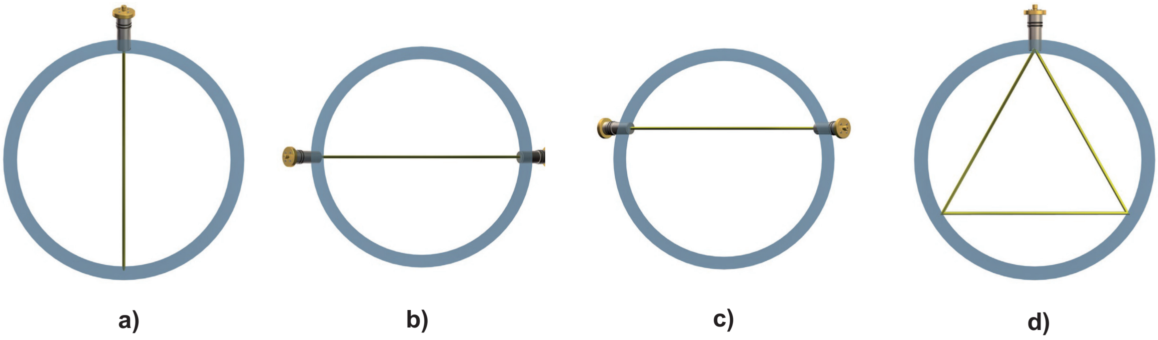


Figure 6 — Basic acoustic path types for multi-path meters

Velocity measurements made on a diametric path are more susceptible to changes in flow profile than off-centre paths such as the mid-radius path. Double traverses in a single plane are much less sensitive to non-axial velocity components than single traverse paths. Other configurations such as the triple traverse mid-radius path may be sensitive to non-axial components, but can be used in combination to eliminate or reduce the effects of swirl and cross-flow. Direct paths can be single, double or crossed.

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.

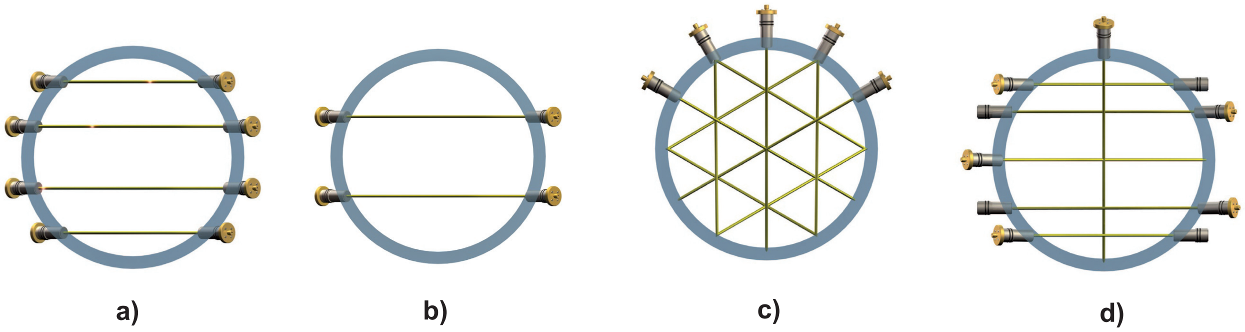


Figure 7 — Some typical cross-sectional acoustic path configurations

4.3.3.4 Meters with paths of equal radial displacement

Meters with paths of equal radial displacement [e.g. Figure 7 b)] 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.

$$v = k_\mathrm{h} \frac{\sum_{i=1}^{n} v_i}{n} \qquad (7)$$

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.

4.3.3.5 Meters with paths at off-diameter positions

In the case of these meters [e.g. Figure 7 a), c), 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.

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

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 Equation (11):

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

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

a) the uncertainty in the calibration factor, K;

b) the uncertainties in the measurements of the transducers and in the geometry of the meter body;

c) the uncertainty in the live input weighting factor or flow profile correction factor, f;

d) 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 t, 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. 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 USM classification

To aid the user in making a meter selection based on the overall uncertainty required for the measurement, a USM can be classified. This process involves dividing the meters available into classes of performance as outlined in Table 4. Other classes deal with other measurement applications.

Table 4 — USM classification

Class	Typical applications	Typical uncertainty 95 % confidence level (volume flow rate)[a]
1	Custody transfer	Within ±0,7 % for $q_V > q_{V,\mathrm{t}}$
2	Allocation	Within ±1,5 % for $q_V > q_{V,\mathrm{t}}$

[a] Meter performance, inclusive of total meter uncertainty, repeatability, resolution, and maximum peak-to-peak error, depends upon a number of factors which include pipe inside diameter, acoustic path length, number of acoustic paths, gas composition and associated SOS, and meter timing repeatability.

The two classes represent different 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.

4.6 Reynolds number

The flow profile is a function of the Reynolds number, for changes in which, most USMs correct. The Reynolds number is calculated from the known inside diameter of the body, d, the measured average velocity, v, a preset value of the actual density, ρ, and the dynamic viscosity, η.

$$Re = \frac{v\ d\ \rho}{\eta} \tag{12}$$

During calibration, as well as during operation, the actual values for the density and the dynamic viscosity should be entered in the USM computer. See also 5.8.3.

For values over 50 000, the impact of fluctuations in the Reynolds number is not large and ranges from approximately 1 % per decade for the path through the centre of the pipe to less than 0,3 % per decade for the half-radius path. For most ultrasonic multi-path meters, the impact on the measurement is less than 0,1 % for a change of a factor of 2 in the Reynolds number (to be confirmed by the manufacturer).

4.7 Temperature and pressure correction

4.7.1 Introduction

During dynamic (wet) calibration, all of the systematic errors are brought down to zero by determining and then applying the meter flow calibration factor. 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 4.7.2 to 4.7.5, 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 4.7.6. 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 4.7.2 to 4.7.6.

4.7.2 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:

$$\frac{q_{V,1}}{q_{V,0}} = \left(1+\alpha\Delta T\right)^3 = \left[1+3\alpha\Delta T+3\left(\alpha\Delta T\right)^2+\left(\alpha\Delta T\right)^3\right] \tag{13}$$

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 Equation (13) can be simplified to:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{\mathrm{b},T} = 1+3\alpha\Delta T \tag{14}$$

Or alternatively, expressed as a flow error:

$$\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},T} = 3\alpha\Delta T \tag{15}$$

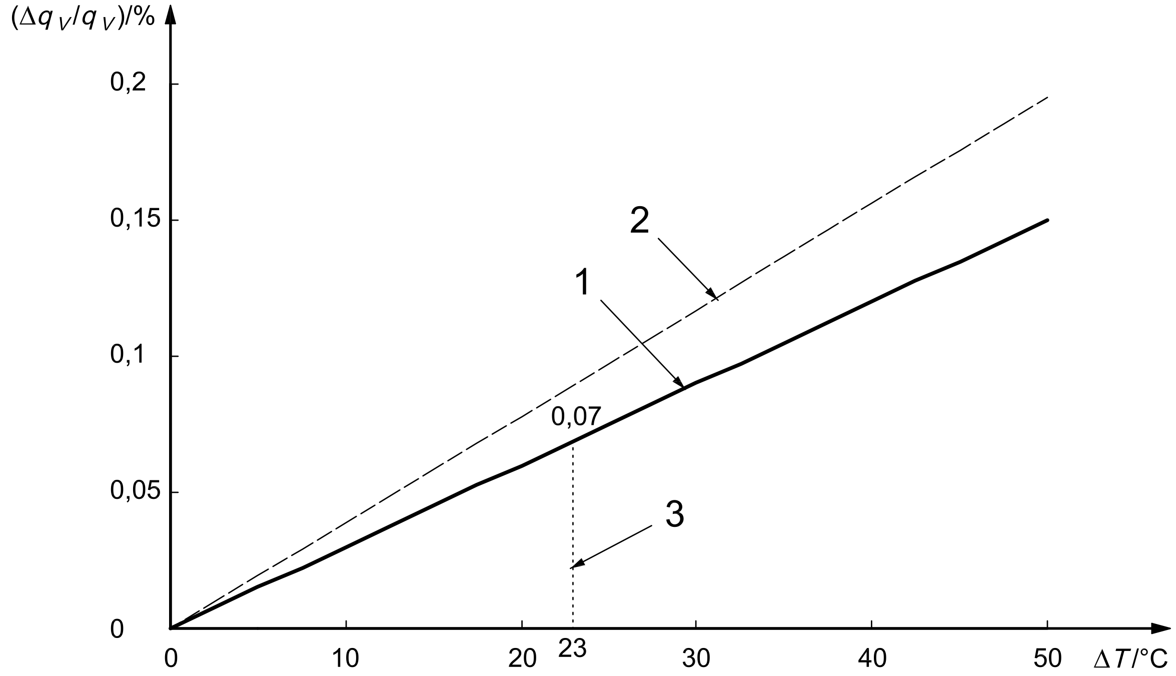
Table 5 gives typical coefficients of thermal expansion for common body materials.

Table 5 — Common coefficients of thermal expansion in the 0 °C to 100 °C range

Material	Thermal expansion coefficient α K^{-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 Equation (15) is shown in Figure 8 for two materials from Table 5.



Key

$\Delta q_V/q_V$	flow measurement error
ΔT	temperature difference
1	austenitic stainless steel
2	ferritic stainless steel
3	example

Figure 8 — Temperature related flow error for two example material types

Figure 8 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).

4.7.3 Pressure correction

4.7.3.1 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:

a) welded-in cylindrical body designs;

b) meter bodies consisting of a pipe with welded-on flanges;

c) non cylindrical meter body designs, for example those based on casting.

In 4.7.3.2 to 4.7.3.4, a means of making an initial estimate of the flow error for any body type is provided.

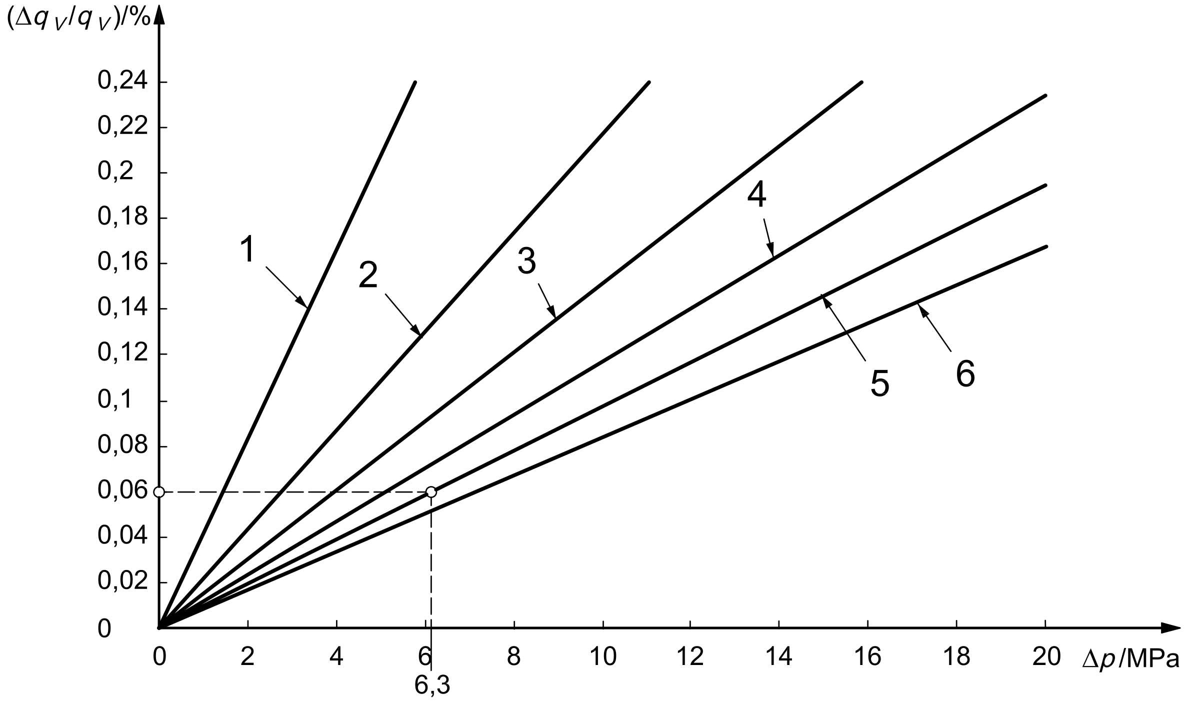
4.7.3.2 General simplified expression for any body type

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:

$$\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p,\mathrm{max}} = 4\,\frac{\Delta r}{r} = 4\left(\frac{R^2+r^2}{R^2-r^2}+\mu\right)\frac{\Delta p}{E} \qquad (16)$$

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.

Equation (16) can be presented in graphical form as shown in Figure 9 for a range of values of δ/r, i.e. the ratio of wall thickness to internal radius.



Key

	δ/r
1	0,050
2	0,100
3	0,150
4	0,200
5	0,250
6	0,300

Δp	pressure difference
$\Delta q_V/q_V$	flow measurement error
r	inside pipe radius
δ	pipe wall thickness

Figure 9 — Maximum expected pressure-related flow error for different δ/r ratios

Figure 9 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 Equation (16) and Figure 9 provide a maximum expected error, the reader can, if desired, go straight to 4.7.5 (taking $K_\mathrm{E} = K_\mathrm{s} = 1$) to assess the significance of the error without the need of the refinement in the initial estimate provided in 4.7.3.3 and 4.7.3.4 since these result in a lower value for the flow error.

4.7.3.3 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 4.7.3.2. Consequently, the body expansion and resulting flow error is less than that given by Equation (16) and Figure 9. 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:

$$\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p,\,\mathrm{rev1}} = K_\mathrm{s}\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p\,,\mathrm{max}} \qquad (17)$$

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, $K_\mathrm{s} = 1$, 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;

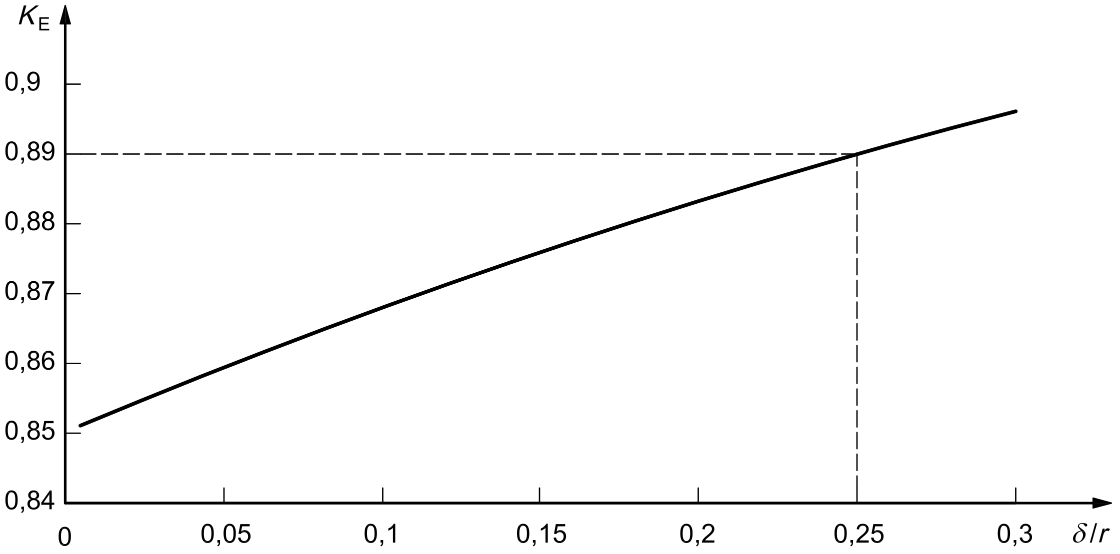
c) for irregularly shaped meter bodies, for example cast bodies, K_s is obtained as follows based on an average flow error:

    1) Equation (16), or Figure 9, 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, $K_\mathrm{s} = 0{,}5 \times (1 + y/x)$ where x is the initial estimate based on the thinnest wall section.

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

Equation (16) and Figure 9 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, given in Figure 10 for a Poisson ratio of 0,3.



Key

K_E	end correction factor
r	inside pipe radius
δ	pipe wall thickness

$K_\mathrm{E} = -0{,}122\,9(\delta/r)^2 + 0{,}191\,3(\delta/r) + 0{,}850\,1$

Figure 10 — End loading and support correction factor, K_E

The end correction factor is derived simply from the ratio of Equations (E.12) and (E.14). In the example in Figure 10, $K_\mathrm{E} = 0{,}89$ 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:

$$\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p} = K_\mathrm{E}\,K_\mathrm{s}\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p,\,\mathrm{max}} \tag{18}$$

Note, Equation (18) gives an estimate of the expected minimum flow error. It can therefore be used in combination with the maximum flow error (i.e. with $K_\mathrm{E} = K_\mathrm{s} = 1$) to provide an initial estimate of the range or tolerance in expected flow error.

4.7.4 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).

4.7.5 Total metering error

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

$$\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{c,\,est}} = \left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,T} + K_\mathrm{E}\,K_\mathrm{s}\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p,\,\mathrm{max}} \tag{19}$$

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 4.7.6 needs to be performed to obtain a more precise flow correction factor.

NOTE If calculations in 4.7.3.3 and 4.7.3.4 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.

4.7.6 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:

$$\frac{q_{V,1}}{q_{V,0}} = \left(\frac{d_1}{d_0}\right)^2\left(\frac{l_1}{l_0}\right)^2\left(\frac{x_0}{x_1}\right) \tag{20}$$

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

$$q_{V,\,1}/q_{V,\,0} = \text{x,xxxx} \pm \text{x,xxxx} \tag{21}$$

$$\Delta q_V/q_V = (\text{x,xx} \pm \text{x,xx})\ \% \tag{22}$$

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 Equations (21) and (22).

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 Equation (20) 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 Equations (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. Equation (20) is still used to predict the flow error along each path based on the changes in physical dimensions between conditions.

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: $-q_{V,\,\mathrm{max}} < q_V < -q_{V,\,\mathrm{min}}$ and $q_{V,\,\mathrm{min}} < q_V < q_{V,\,\mathrm{max}}$

5.1.2 Pressure

Ultrasonic transducers used in USMs require a minimum gas pressure (density) to ensure acoustic coupling of the sound pulses to and from the gas. Therefore, the expected 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.

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

a) when the acoustic-wave-attenuating carbon dioxide levels are above 3 % volume fraction or the occurrence of carbon dioxide in large meters (⩾12″);

b) when the operation is near the critical density of the natural gas mixture;

c) when the total sulfur level, from materials such as hydrogen sulfide, mercaptans (thiols), and elemental sulfur, exceeds 320 µmol/mol;

d) salt deposits.

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 sound waves.

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

The flanges of the USM shall both have the same inside diameter to within 1 % of each other. A USM with an inside diameter equal to the flange diameter shall be indicated as “full bore”. A 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.

5.2.5 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 tappings

At least one metering-pressure tapping, drilled perpendicular in the top ± 85°, shall be provided on the meter or on the piping adjacent to the meter to enable direct measurement of the static pressure under metering conditions. For a reduced bore meter, the tapping shall be in the reduced bore section. The connection of this pressure tapping shall be marked “pm”. If more than one pm tapping is provided, the difference in pressure readings shall not exceed 100 Pa at maximum flow rate with an air density of 1,2 kg/m^3.

A meter may be equipped with other pressure tappings in addition to the pm 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 tapings 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 (a device intended to improve both the stability and the shape of the flow profile) irremovably attached to the meter is regarded as part of the equipment. For purposes of this part of ISO 17089, the combination of flow conditioner and meter is regarded as the USM.

A flow conditioner, not attached to the meter but intended to be connected permanently to it, plus the linking meter tube, forms a USM package (USMP). In a bidirectional setup, a thermowell may also be part of the USMP.

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) maximum and minimum actual volume flow rate per hour;

f) direction of positive or forward flow;

g) orientation of the meter (“this side up”);

Nameplates may include the following:

h) purchase order number or shop order number;

i) legal metrology approval identification.

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

If markings are stamped on the meter body, low stress stamps may be used which produce a rounded-bottom impression.

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 (range) shall be specified.

5.3.2 Rate of pressure change

Rapid depressurization of a USM may cause damage to the transducer or change the characteristics of the meter. Meter users should therefore ensure that the transducers 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.

5.4 Electronics

5.4.1 General requirements

The ES of a USM usually includes 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 6.4.2. 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 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.

5.4.3 Pulse detection method

The pulse 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.

5.4.4 Sampling or pulsating flow

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

5.4.5 Signal-to-noise ratio

The USM shall indicate the S/N ratio per transducer or per acoustic path. An alarm shall be triggered when the signal is lost. An alarm may also be given at low performance.

5.4.6 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.

5.4.7 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) frequency representing non-linearized flow rate.

The time-integrated values of these outputs shall match better than 0,02 % in every arbitrary interval of 100 s under flowing conditions above $q_{V,\text{min}}$.

The meter may be equipped with the following output:

c) frequency, representing linearized flow rate;

d) an analogue (4 mA to 20 mA) output for flow rate at line conditions.

Flow rate outputs shall function up to 120 % of the maximum flow rate, $q_{V,\text{max}}$, 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 (not applicable to serial data output).

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.

The USM may be equipped with a display for presenting measured and other values.

For control purposes, the update frequency of the output signal(s) to the measured flow shall be specified and be at least 1 Hz.

5.4.8 Cable jackets and insulation

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

5.4.9 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 a 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 checksum and event log shall be provided to validate that no unauthorized changes have been made to the firmware.

5.5.2 Discontinuity

Being an electronic meter, the firmware may introduce discontinuities due, for example, to level settings. Therefore, the firmware shall be designed to avoid discontinuities.

5.5.3 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.

5.5.4 Configuration and monitoring software

The meter shall be specified to have a capability for local or remote configuration of the ES and for monitoring the operation of the meter. As a minimum, the ES shall be able to display and record the following measurements:

a) actual volume flow rate;

b) average velocity;

c) average SOS;

d) individual path velocity and SOS per path;

e) ultrasonic acoustic signal quality received by each transducer.

As an option, these functions may be provided as part of the embedded software of the meter.

5.5.5 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) warning: when any of several monitored parameters fall outside normal operation for a significant length of time (optional);

c) partial failure: when one or more of the multiple ultrasonic path results is not usable (optional).

5.5.6 Diagnostic parameters

As a minimum, the following measurements shall be provided for diagnostic purposes:

a) non-linearized average velocity through the meter;

b) flow velocity for each acoustic path (or equivalent for evaluation of the flowing velocity profile);

c) SOS along each acoustic path;

d) average SOS;

e) velocity sampling interval;

f) averaging time interval;

g) percentage of accepted pulses for each acoustic path;

h) S/N ratio or equivalent (gain control);

i) status and measurement quality indicators;

j) alarm and failure indicator.

The provision of the linearized average flow velocity is optional.

The meter shall be supplied with a facility for storing these values in a data file.

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 (i.e. within the repeatability specification).

If it is not possible to replace or relocate transducers, electronic parts, and software without a significant change in meter performance (i.e. within the repeatability specification), the meter shall be recalibrated.

Procedures to be used when such components have to be exchanged, including possible mechanical, electrical or other measurements and adjustments, shall be specified. Any change of parts without recalibration of the meter may lead to additional uncertainties which have to be specified by the manufacturer.

From every event with the ultrasonic flowmeter (calibration, repair, etc.), a full list of the relevant “as-found” 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 version management.

5.7 Determination of density

5.7.1 General

For the conversion of volume flow under metering conditions to mass flow or volume flow under base conditions, gas density shall be determined.

Gas density may be determined by:

a) direct measurement;

b) calculation from pressure, temperature and gas composition;

c) inferential measurement.

5.7.2 Pressure measurement

The pressure tapping marked “pm” shall be used as the pressure sensing point (see 5.2.6).

5.7.3 Temperature measurement and density measurement

For unidirectional flow, the thermowell or densitometer pocket shall be installed downstream of the USM and located between $2D$ and $5D$, where D is the outside pipe diameter, from the downstream flange 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 and pockets is between $D/10$ and $D/3$. Special probe designs may be required for insertion lengths greater than $D/3$.

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 is significantly different 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 $q_{V,\mathrm{t}}$.

For bidirectional use with two USMs in series, the thermowell or densitometer pocket shall 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 13. Both the number and sizes of the thermowells or densitometer pockets exacerbate the flow perturbation.

In practical application, there are protrusions upstream of the meter into the flow, like thermowells, density pockets, and sampling probes. The meter shall be calibrated in combination with these.

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. Also, when using multiple thermowells, these should not be in line. The manufacturer or supplier shall give the optimal (rotational) position of the wells in relation to the acoustic paths.

Alternatives to intrusive thermowell-based technologies 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 Accuracy requirements for class 1 meters

Prior to making any adjustment, aside from those described in 6.3.3 and 6.3.5 a), or any linearization of the output, the USM or the USMP shall meet the accuracy requirements specified in Table 6 for flow rates between $q_{V,\,\mathrm{min}}$ and $q_{V,\,\mathrm{max,\,op}}$.

Table 6 — Accuracy requirements for class 1 meters

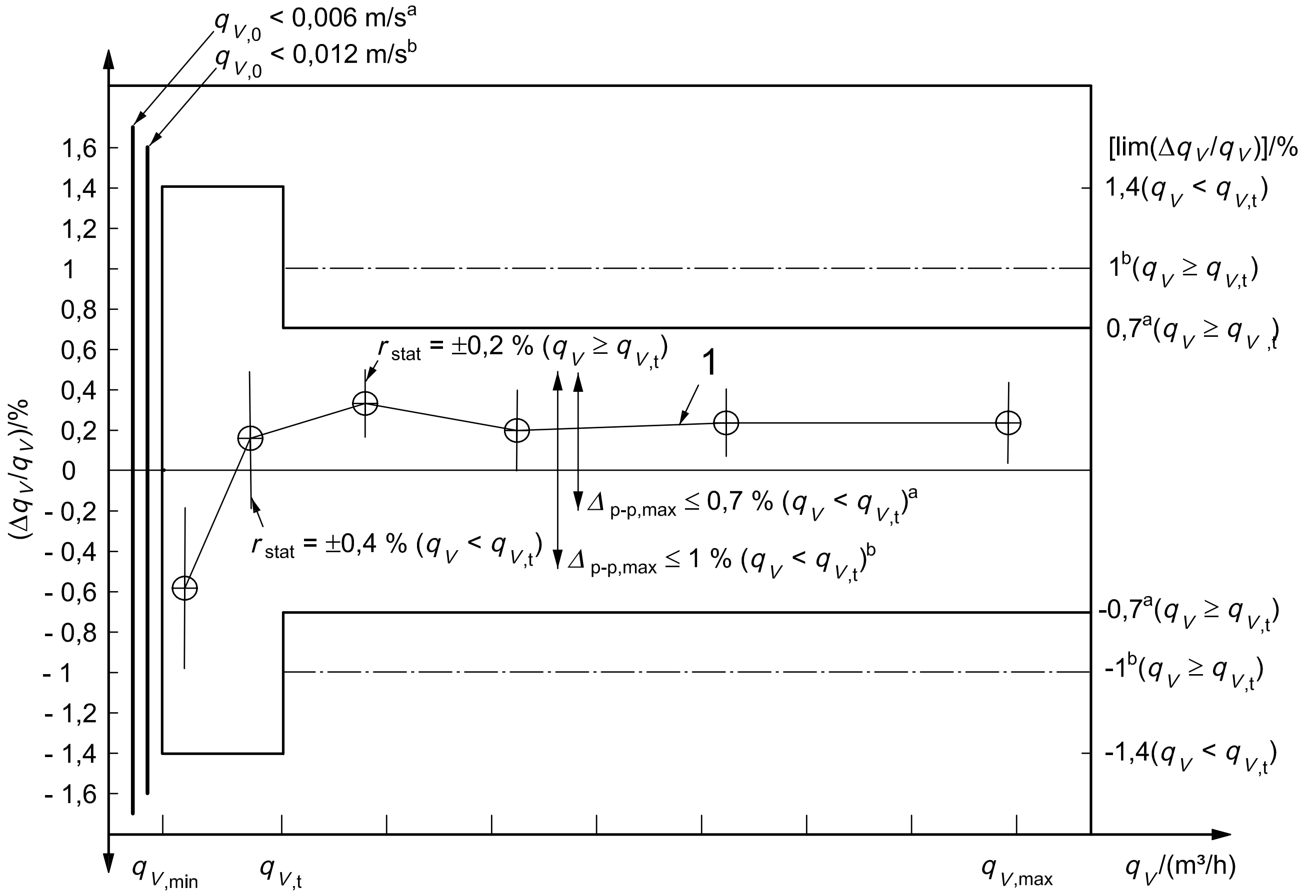
Subject	Requirement
Repeatability	Within ±0,2 % of measured value for $q_V \geqslant q_{V,\,\mathrm{t}}$ Within ±0,4 % of measured value for $q_{V,\,\mathrm{min}} < q_V < q_{V,\,\mathrm{t}}$
Reproducibility	Within ±0,3 % of measured value for $q_V \geqslant q_{V,\,\mathrm{t}}$ Within ±0,6 % of measured value for $q_{V,\,\mathrm{min}} < q_V < q_{V,\,\mathrm{t}}$
Resolution	0,001 m/s
Zero flow reading for meters ⩾12″ [a]	<0,006 m/s for each acoustic path
Zero flow reading for meters <12″ [a]	<0,012 m/s for each acoustic path
Maximum permissible error for meters ⩾12″ [a]	Within ±0,7 % of measured value for $q_V \geqslant q_{V,\,\mathrm{t}}$ Within ±1,4 % of measured value for $q_{V,\,\mathrm{min}} < q_V < q_{V,\,\mathrm{t}}$
Maximum permissible error for meters <12″ [a]	Within ±1,0 % of measured value for $q_V \geqslant q_{V,\,\mathrm{t}}$ Within ±1,4 % of measured value for $q_{V,\,\mathrm{min}} < q_V < q_{V,\,\mathrm{t}}$
Maximum peak-to-peak error for meters ⩾12″ [a]	<0,7 % for $q_V \geqslant q_{V,\,\mathrm{t}}$
Maximum peak-to-peak error for meters <12″ [a]	<1 % for $q_V \geqslant q_{V,\,\mathrm{t}}$
$q_{V,\,\mathrm{t}}$ for meters ⩾12″ [a]	$q_{V,\,\mathrm{t}}$ at $\bar{v} = 1{,}5$ m/s
$q_{V,\,\mathrm{t}}$ for meters <12″ [a]	$q_{V,\,\mathrm{t}}$ at $\bar{v} = 3$ m/s

[a] 1″ = 25,4 mm

Reproducibility includes the behaviour of the USM over time (drift), and includes additional contributions from calibration, handling and operational conditions; for total operational uncertainty calculation, see 7.7.

Also, the user and calibration body shall ensure that the USM(P) complies with the reproducibility requirement during operation and during calibration, respectively, by providing undisturbed flow conditions, providing steady flow conditions, avoiding contamination, avoiding damage, etc. according to 5.9.

See Figure 11.



Key

q_V	volume flow rate
$\Delta q_V/q_V$	flow rate measurement error
1	unadjusted meter curve calibration results
lim ($\Delta q_V/q_V$)	flow rate measurement error limit
$q_{V,0}$	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_{stat}	repeatability
$\Delta_{p-p,max}$	maximum peak-to-peak error for meters

[a] for meters ⩾ 12″

[b] for meters < 12″

Figure 11 — Permissible uncertainty envelope for class 1 meters

5.8.2 Accuracy requirements for class 2 meters

Prior to making any adjustment, aside from those described in 6.3.3 and 6.3.5 a), or any linearization of the output, the USM or the USMP shall meet the accuracy requirements specified in Table 7 for flow rates between $q_{V,\ \mathrm{min}}$ and $q_{V,\ \mathrm{max,\ op}}$.

Table 7 — Accuracy requirements for class 2 meters

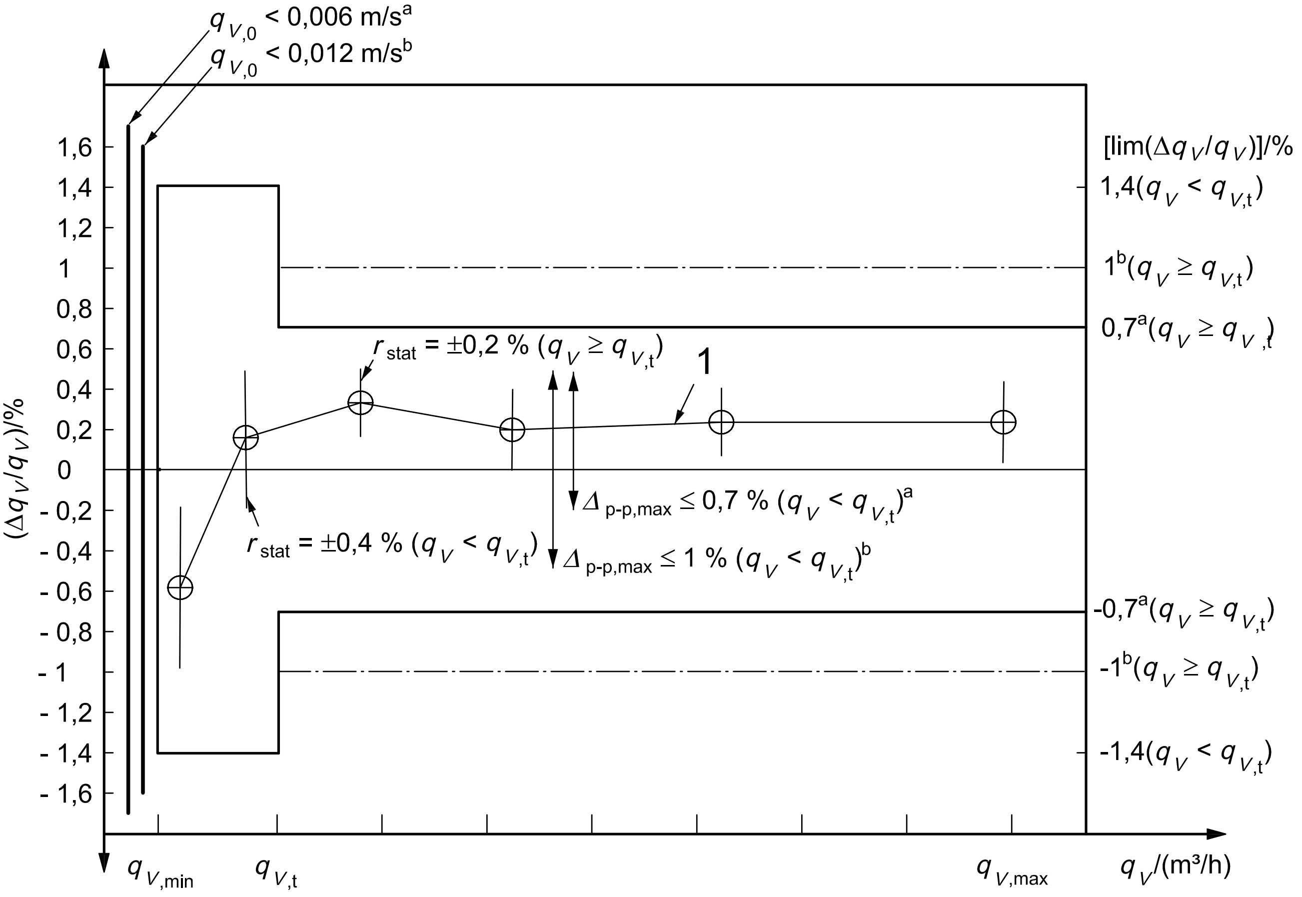
Subject	Requirement
Repeatability	Within ±0,25 % of measured value for $q_V \geqslant q_{V,\ \mathrm{t}}$ Within ±0,5 % of measured value for $q_{V,\ \mathrm{min}} < q_V < q_{V,\ \mathrm{t}}$
Reproducibility	Within ±0,6 % of measured value for $q_V \geqslant q_{V,\ \mathrm{t}}$ Within ±1,2 % of measured value for $q_{V,\ \mathrm{min}} < q_V < q_{V,\ \mathrm{t}}$
Resolution	0,002 m/s
Zero flow reading for meters ⩾12″[a]	<0,012 m/s for each acoustic path
Zero flow reading for meters <12″[a]	<0,024 m/s for each acoustic path
Maximum permissible error for meters ⩾12″[a]	Within ±1 % of measured value for $q_V \geqslant q_{V,\ \mathrm{t}}$ Within ±2,0 % of measured value for $q_{V,\ \mathrm{min}} < q_V < q_{V,\ \mathrm{t}}$
Maximum permissible error for meters <12″[a]	Within ±1,5 % of measured value for $q_V \geqslant q_{V,\ \mathrm{t}}$ Within ±2,0 % of measured value for $q_{V,\ \mathrm{min}} < q_V < q_{V,\ \mathrm{t}}$
Maximum peak-to-peak error for meters ⩾12″[a]	<1 % for $q_V \geqslant q_{V,\ \mathrm{t}}$
Maximum peak-to-peak error for meters <12″[a]	<1,4 % for $q_V \geqslant q_{V,\ \mathrm{t}}$
$q_{V,\ \mathrm{t}}$ for meters ⩾12″[a]	$q_{V,\ \mathrm{t}}$ at $\bar{v} = 1{,}5$ m/s
$q_{V,\ \mathrm{t}}$ for meters <12″[a]	$q_{V,\ \mathrm{t}}$ at $\bar{v} = 3$ m/s

[a] 1″ = 25,4 mm.

Reproducibility includes the behaviour of the USM over time (drift), and includes additional contributions from calibration, handling and operational conditions; for the total operational uncertainty calculation, see 7.7.

Also, the user and calibration body shall undertake their responsibilities to make the USM(P) comply with the reproducibility requirement during operation and during calibration, respectively, by providing undisturbed flow conditions, avoiding contamination, avoiding damage, etc. according to 5.9.

See Figure 12.



Key

q_V	volume flow rate
$\Delta q_V/q_V$	flow rate measurement error
1	unadjusted meter curve calibration results
lim $(\Delta q_V/q_V)$	flow rate measurement error limit
$q_{V,0}$	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_{stat}	repeatability
$\Delta_{p\text{-}p,max}$	maximum peak-to-peak error for meters

[a] for meters ⩾ 12″

[b] for meters < 12″

Figure 12 — Permissible uncertainty envelope for class 2 meters

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.

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 7).

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 may 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 compensates 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 strongly affected by noise generated by pressure-regulating valves; see also Reference [55] and 8.1. 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) blind tees and out-of-plane bends are the most effective standard pipe fittings for attenuating ultrasonic noise;

d) straight pipe is very poor at attenuating ultrasonic noise;

e) 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 a few degrees. The USM diagnostics may be utilized to determine the presence of stratification.

Also, a shade should be supplied to protect the electronics.

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 8.2, 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 and flow profile considerations

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. To find out whether undisturbed flow conditions are reached, a practical definition is introduced: a USM is found to be in undisturbed flow conditions when the addition of a length measuring $10D$ of straight pipe at the upstream side alters the reading of the USM (FWME) by not more than the combined repeatability of the facility and the USM.

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 assumed. 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.

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. 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 6.4. Determine l_{min} such that the maximum additional error due to flow perturbations is $<0{,}3$ %. The manufacturer shall specify the values of l_{min} for the different flow perturbations defined in 6.4.3.

Determination of l_{min} of an upstream piping configuration for which l_{min} is not yet known is the responsibility of the user. Application of the USM in a configuration for which l_{min} is unknown requires a length of $50D$ of straight upstream piping; for the USMP, the corresponding value is $30D$.

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

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.

5.9.3.3 Protrusions and diameter step

Changes in inside diameters and protrusions should be avoided at the USM inlet to avoid the disturbance of the velocity profile, unless the meter is classified as “reduced bore”, see 5.2.4.

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, preferably within 1 % but at maximum within 3 %. 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 $>5°$;

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.

The value for D shall be the average of the pipe inside diameters over a length of $0,5D$ upstream of the USM. The average inside diameter can be determined by various methods which shall be supported by an adequate quality control system. The instruments shall be traceable to internationally recognized standards.

When determining D by hand-held instruments, this diameter shall be the arithmetic average of at least 12 measurements, namely four diameters positioned at approximately equal angles to each other, distributed in each of at least three cross-sections evenly distributed over a length of $0,5D$, two of these sections being at distance 0 and $0,5D$ from the USM and one being in the plane of the weld.

Diameter steps larger than 3 % within $10D$ upstream of the meter are allowed exclusively in exceptional cases, in which the USM manufacturer shall prove that the additional bias due to the diameter steps is below 0,2 %, e.g. within type testing, see 6.4.2.

5.9.3.4 Thermowells and density cells

For thermowells and density cells, see 5.7.3.

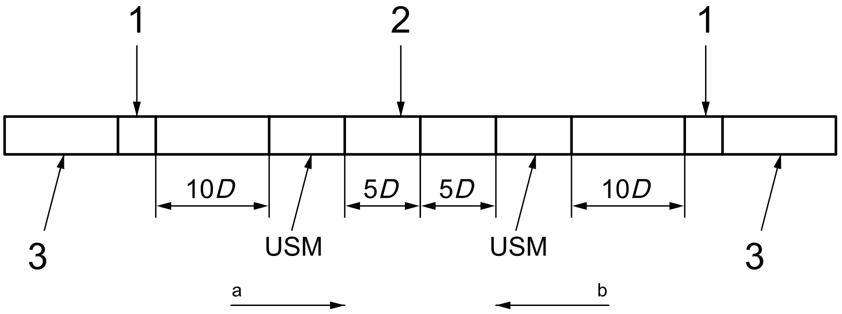
5.9.3.5 Flow conditioners

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).

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 Figure 13.



Key

1	flow conditioner
2	thermowell
3	pipe
D	pipe inside diameter
USM	ultrasonic flowmeter

[a] Flow primary direction (forward).

[b] Flow primary direction (reverse).

Figure 13 — 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 7.6.4;

f) post-production protection of the meter and spools against corrosion by purging with inert gas prior to transport.

6 Test and calibration

6.1 Pressure testing and leakage testing

The meter body shall be properly leak tested and pressure tested.

6.2 Individual testing — Static testing

6.2.1 General

Static testing comprises the measurement of the meter body dimensions and of time delays of electronics and transducers as well as a zero flow verification test.

6.2.2 Geometrical parameters

The manufacturer shall document:

a) the average inside diameter of the meter;

b) the cross-sectional area of the meter;

c) the length of each acoustic path between transducer faces;

d) the inclination angle of each acoustic path or the axial (meter body axis) distance between transducer pairs;

e) the uncertainty of measurements a) to d);

f) the meter body material;

g) the meter body pressure and coefficients of thermal expansion;

h) the wall thickness;

i) the wall roughness.

The meter body temperature shall be measured at the time these measurements are made. The individual corrected lengths shall then be averaged and reported to the nearest 0,000 $1d$.

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

6.2.3 Timing and time delays

Transducer 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 and transducers. The uncertainty of the measurement shall be specified. All calibration instruments used to perform these measurements shall have calibration certificates traceable to internationally recognized standards.

One method involves mounting two transducers in a pressurized test cell, filled with a gas, for which the SOS is accurately known. Actual transit time of the signals in the gas can be calculated from the ratio of path length and SOS. Because transit times are equal (zero flow), t_{AB} and t_{BA} can be calculated. The ultrasonic system measures times that include time delays in the electronics, transducers, cables, etc. Time delays are calculated from the measured values. Any errors in the SOS in the test cell affect meter performance, just as errors in geometrical parameters l_{p} and d do.

Another method requires a set-up in which the transit times of a pair of transducers can be measured at two known and different path lengths under zero flow conditions. The measurement shall be performed under the same gas conditions for both path lengths.

6.2.4 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) after blind flanges are attached to the ends of the meter body, the meter may be purged of all air and pressurized with a pure test gas or gas mixture, whose selection shall be the responsibility of the manufacturer and whose acoustic properties shall be documented;

b) gas pressure and temperature shall be allowed to stabilize — gas velocities for each acoustic path shall be recorded for at least 300 s from which the average gas velocity and standard deviation for each acoustic path shall then be calculated;

c) if the measured SOS values are compared with theoretical values, the theoretically determined values shall be computed using a complete compositional analysis of the test gas — 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 — for the theoretical determination, the equations in ISO 12213 shall be used (Reference [34] contains equivalent equations);

d) the SOS values shall be within 0,1 % of the theoretical value given by ISO 12213.

6.3 Individual testing — Flow calibration

6.3.1 General

All class 1 meters shall be calibrated under flowing conditions during which the meter shall not generate any critical alarms. For class 2 meters, this flow calibration is highly recommended. The calibration of meters under flowing conditions (flow or flow calibration) may also be required because of:

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

Generally, USMs can be operated at much higher flow velocities (up to 30 m/s average velocity or even higher) than turbine meters or orifice meters of the same diameter. This leads to high turn-down ratios. Very often these large velocities are not used in the metering facility (e.g. due to serial installation with turbine meters or noise emission limits). In that case it is recommended not to choose the calibration flow rates in accordance with the $q_{V,\,\text{max, design}}$ of the meter, but in accordance with the maximum flow rate of the application ($q_{V,\,\text{max, op}}$), see also 5.1.1. In such a case, the limits given in 5.8.1 have to be recalculated for the new $q_{V,\,\text{max}} = q_{V,\,\text{max, op}}$.

Both individual USMs and USMPs may be calibrated, as described in 5.9.3.5.

Two principal methods of calibration under flowing conditions are used:

a) laboratory flow calibration;

b) field flow calibration (not recommended for class 1 type meters) (see 7.6.3).

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

Where possible, calibrate at a similar pressure and temperature to meter operating conditions. Differences in dimensions due to pressure and temperature differences between calibration and operation may be corrected as described in 4.7.

6.3.2 Laboratory flow calibration

6.3.2.1 General

To minimize the uncertainty of the calibration, the calibration shall be conducted:

a) according to good laboratory practice;

b) in accordance with methods recognized by International Standards;

c) at a laboratory accredited according to ISO/IEC 17025;

d) under undisturbed flow conditions (see 6.3.2.4);

e) under steady flow conditions (see 6.3.2.4);

f) over a statistically significant duration of time (see 6.3.2.2);

g) 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 $q_{V,\,\text{max, op}}$, $q_{V,\,\text{min}}$ or the minimum flow as specified by the end user;

h) whenever possible, by using the upstream and downstream meter spools or dedicated calibration spools and flow conditioners (when applicable).

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.

a) Running standard deviation: During the measurement the samples taken are processed into a running standard deviation. When the running standard deviation evolves into a stable value, the required duration is reached.

b) Fixed measurement time: A mean measurement of one flow rate is calculated from several measurements. Normally three, but preferably five measurements per rate are taken and valid only if no trend in one direction is observed. Take as many measurements as necessary until the standard deviation of the determined measurements is <0,3 % for $q_V \geqslant q_{V,\,\text{t}}$.

Practice has shown that the duration of one measurement shall be at least 300 s or 400 × r/v, where r is the inside pipe radius of the meter and v is the average flow velocity, whichever is larger.

6.3.2.3 Uncertainty of the calibration facility

The uncertainty of measurements performed at the test facility shall be sufficiently low to enable the overall metering system uncertainty budget to be met. Typically, this is in the region of ±0,3 % of the reading.

6.3.2.4 Flow conditions

The upstream piping conditions in the laboratory shall be chosen such that no additional errors are introduced. The upstream straight length of the meter package shall be greater than or equal to l_{min}. 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.

Random variations and trends in pressure, temperature and flow rate shall be negligible during the calibration or test run. The additional error due to line pack, $\varDelta_{\text{LP}}$, shall be calculated using:

$$\varDelta_{\text{LP}} = \frac{\Delta m_{\text{buff\_}V}}{q_{m,\text{ref}}\, t} \times 100\ \% \tag{23}$$

and the line pack mass flow rate, $q_{m,\text{ LP}}$, in kilograms per second, using

$$q_{m,\text{LP}} = \frac{\Delta m_{\text{buff\_}V}}{t} \tag{24}$$

where

$\Delta m_{\text{buff\_}V}$	is the increase or decrease in mass, in kilograms, inside the buffer volume during the measurement;
t	is the duration, in seconds, of the measurement;
$q_{m,\text{ ref}}$	is the reference mass flow rate, in kilograms per second.

NOTE Instead of calculating line pack based on mass and mass flow, volume and volume flow at any chosen base condition can be utilized.

The line pack effect shall be taken into account when $\varDelta_{\text{LP}} > 0{,}02\ \%$; $q_{V,\text{ LP}}$ shall be determined with a maximum uncertainty of 5 % at $q_V > q_{V,\text{ t}}$ and 10 % for $q_{V,\text{ min}} < q_V \leqslant q_{V,\text{ t}}$.

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

a) $\varDelta_{\text{LP}} > 0{,}2$ % per measurement (line pack);

b) $\Delta T > 0{,}25$ K per 100 s (temperature drift);

c) $\Delta p > 0{,}002p$ per 100 s (pressure drift);

d) $\Delta q_V > 0{,}03 q_V$ per 100 s (flow rate drift);

e) pulsations inside the calibration facility give rise to an error larger than 0,05 % on the reading of the reference meter(s) and the meter(s) under test.

6.3.2.5 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 a few degrees. To detect the presence of stratification, the temperature measurement of the gas should be performed both at the bottom and at the top of the pipe. If the temperature difference inside the pipe is more than 0,5 K, the calibration point should be rejected; diagnostics may also indicate the presence of stratification. Special attention shall be paid to the quality of the temperature probes.

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

6.3.2.6 Traceability of the calibration facility

Measurements carried out at the calibration facility shall be traceable to international standards. Also, the calibration laboratory should be accredited to ISO/IEC 17025.

6.3.2.7 Limited calibration range at initial calibration

It is recognized that it may not be possible to test large USMs up to their maximum capacity because of the limitations of currently available test facilities. Therefore, a $q_{V,\text{ max, cal}}$ (lower than $q_{V,\text{ max, op}}$) may be specified for flow calibration. The USM shall be regarded as class 1 only for flow rates up to $q_{V,\text{ max, cal}}$.

6.3.2.8 Limited calibration range at recalibration

It is recognized that it may not be possible to test large USMs up to their maximum capacity because of the limitations of currently available test facilities. Therefore, for recalibration, a $q_{V,\text{ max, cal}}$ (lower than $q_{V,\text{ max, op}}$) may be specified for flow calibration: $q_{V,\text{ max, cal}} \geqslant 0{,}4 q_{V,\text{ max, op}}$. The deviations at $q_V > q_{V,\text{ max, cal}}$ may be calculated from previous flow calibration results at $q_V > q_{V,\text{ max, cal}}$, taking into account the shift of the points already calibrated.

When $q_{V,\text{ max, cal}} = 0{,}7 q_{V,\text{ max, op}}$, an additional uncertainty of 0,15 % shall be added to the deviation at 100 % of $q_{V,\text{ max, op}}$. When $q_{V,\text{ max, cal}} = 0{,}4 q_{V,\text{ max, op}}$, an additional uncertainty of 0,15 % shall be added to the deviation at 70 % of $q_{V,\text{ max, op}}$ and 0,3 % shall be added to the deviation at 100 % of $q_{V,\text{ max, op}}$; otherwise, the additional uncertainty shall be calculated for the particular application.

Optionally, the tests specified in 6.4.4 covering meter performance in partial failure mode may be conducted during initial calibration of the meter.

6.3.2.9 Bidirectional calibration

A flow calibration is only valid for the direction in which the meter is calibrated. A valid flow calibration for a bidirectional application requires calibration of the meter in each direction.

6.3.2.10 Report

6.3.2.10.1 General

Results of calibration shall be available on request, together with a statement of conditions under which the calibration took place. The calibration data provided shall include those listed in 6.3.2.10.2 to 6.3.2.10.4.

6.3.2.10.2 Results

Record:

a) the determined errors at the investigated flow rates;

b) the date(s) of the test;

c) in case of bidirectional meters: “forward flow” or “reverse flow”;

d) if the error at $q_{V,\,\max}$ has not been determined, the “restricted calibration range”, $q_{V,\,\max,\,\mathrm{cal}}$;

e) in the case of a single point correction, the value of the adjustment factor and FWME before adjustment and the value after adjustment;

f) 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;

g) SOS both from the meter being tested and calculated from gas composition, pressure, and temperature;

h) the log file containing all data taken during calibration;

i) a diagnostic report of the software configuration parameters of the meter during calibration.

6.3.2.10.3 Meter identification and description of the facility

Record:

a) data supplied by the manufacturer, such as meter size, meter serial number, and transducer S/N ratio of the meter being tested;

b) the calibration facility, the method of calibration (bell prover, sonic nozzles, other meters, etc.);

c) the estimated uncertainty of the calibration results;

d) a written description of the test procedure;

e) a description of the condition of the inner surface of the meter and the upstream pipes (dirt, corrosion) — where necessary, add a photograph.

6.3.2.10.4 Conditions of the test

Record:

a) the position of the meter (horizontal, vertical flow upwards, vertical flow downwards) as well as the meter orientation;

b) the upstream and downstream piping configurations involved in the qualification of “undisturbed flow profile”, including flow conditioners, piping tag numbers and inside diameters;

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

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

6.3.3 Judging the measurement quality of the meter

Fundamentally, the USM is based on a linear measurement principle. Theoretically, after correcting for a possible Reynolds effect, the meter curve is a combination of an offset term (dominant at the low flow velocities) and a bias term. The judgement of the measurement quality of the meter should therefore be based on the combination of the calibration curve and a linear offset only. Other corrections, such as curve fittings or linearizations, may not be used to judge the quality of the meter as they might mask hidden design effects. They shall only be applied after approving the meter performance curve (see also 5.8).

NOTE Correction of Reynolds number effects is included in either the k_h factor or the f_i factor given in Equations (7) and (9), respectively.

6.3.4 Calculation of flow-weighted mean error (FWME)

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

$$\overline{E}(q_V) = \frac{\sum\left[\left(q_{V,i} / q_{V,\ \text{max, op}}\right) E_i\right]}{\sum\left(q_{V,i} / q_{V,\ \text{max, op}}\right)} \tag{25}$$

where

$q_{V,i}$ is the tested flow rate;

$q_{V,\ \text{max, op}}$ 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: $q_{V,\ \text{min}} \leqslant q_{V,i} \leqslant q_{V,\ \text{max, op}}$ when $q_{V,\ \text{max, cal}} \geqslant q_{V,\ \text{max, op}}$,

$q_{V,i}$ ranges: $q_{V,\ \text{min}} \leqslant q_{V,i} \leqslant q_{V,\ \text{max, cal}}$ when $q_{V,\ \text{max, cal}} < q_{V,\ \text{max, op}}$.

In OIML R 137-1[37] the so-called “reduced weighting factor” of 0,4 is used when the actual flow rate, $q_{V,i}$, is higher than $0{,}9 q_{V,\ \text{max}}$.

In other documents, other weighting factors are used above different flow rates.

To avoid confusion and because USMs are supposed to be linear, in this part of ISO 17089, all weighting factors shall be based on the ratio of the actual flow rate, $q_{V,i}$, over the maximum flow rate, $q_{V,\ \text{max}}$, only.

6.3.5 Adjustment factors

Adjustment factors and calibration curve correction (linearization) may be applied within the flow computer or within the meter. Possible methods of applying adjustment factors are by using:

a) FWME over the expected flow range of the meter (an example of the calculation of FWME is shown in B.2);

b) multi-point linearization algorithms over the calibrated (operational) range of the meter;

c) polynomial algorithms over the calibrated range of flow rates of the meter (polynomial corrections outside the calibrated range may lead to instabilities).

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

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

$$q_{V,\ \text{true}} = q_{V,\ \text{actual}} \frac{100}{100 + E\left(q_{V,\ \text{actual}}\right)} \tag{26}$$

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.

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

6.4 Type testing, ensuring measurement quality in the field

6.4.1 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 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.

Type testing, however, is interpreted differently. In some countries, it is used as a waiver for the need for an individual calibration. Here this is not the case. Type testing is not meant to replace the required individual flow calibration.

Also, when a meter is not type tested, the user has no guarantee of the final performance in the field. In such cases, a minimum upstream straight pipe length of $50D$ is recommended, but this does not give any guarantee.

When no type approval is present, every individual USM requires a compliance testing to this part of ISO 17089 as described in 6.4.2 in addition to the tests of 6.1, 6.2 and 6.3.

6.4.2 Type testing

Type testing includes extensive tests in order to verify the compliance to all requirements of this part of ISO 17089. A USM having a type approval shall be tested as in 6.1, 6.2 and 6.3. 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.

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 ES.

6.4.3 Accuracy

The accuracy limits of 5.8.1 shall be met within $q_{V,\,\mathrm{max,\,design}}$ and $q_{V,\,\mathrm{min}}$.

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

The duration of one measurement shall be at least 300 s, 3 times 100 s or $800r/v$, whichever is larger.

The repeatability test shall be conducted for at least one flow rate below $q_{V,\,\mathrm{t}}$ and at least one flow rate above $q_{V,\,\mathrm{t}}$. 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 with a time difference of at least one month.

6.4.4 Installation conditions

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

a) under reference flow conditions;

b) with a single 90° bend (radius of curvature of 1,5D):

  1) with the USM in normal position,

  2) with the USM rotated by 90°;

c) with two 90° bends in perpendicular planes (radius of curvature of 1,5D, without spacer between bends):

  1) with the USM in normal position,

  2) with the USM rotated by 90°;

d) an expander with a diameter increase of at least one pipe size [typically 2″1)];

e) a reducer with a diameter decrease of at least one pipe size [typically 2″1)];

f) a diameter step on the upstream flange of the USM with magnitude of +3 % and −3 % (or larger values if the manufacturer allows for larger steps);

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 $q_{V,\,\mathrm{t}}$ and for at least two different flow rates above $q_{V,\,\mathrm{t}}$, according to 6.4.2. Relevant are the mean values of the three single measurements at each flow rate. Above $q_{V,\,\mathrm{t}}$, all calculated mean additional errors shall be within 0,3 %.

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.

6.4.5 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 during meter calibration by simulating the failure of one or more paths. The test should be carried out at or around the mid-point of the expected operating range of the meter. During the test, the flow rate should be varied by 20 % of the flow rate to ensure that the meter responds appropriately.

The manufacturer 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 0,2 %.

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1) 1″ = 25,4 mm

6.4.6 Electronics design testing

The design of the electronics shall be tested to demonstrate that the USM continues to meet the performance requirements of 5.8.1, while operating under the influences and disturbances specified in Annex F, disturbance tests.

Table F.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.

The low-flow cut-off shall be switched off for all tests if the meter under test or the test cell, containing electronics and transducers, is set up for no-flow conditions.

The flow rate output has to be monitored and evaluated according to 5.8.

7 Audit trail and operational practice

7.1 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.

In contrast to many other meters, 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 part of ISO 17089 advocates the addition and use of automated diagnostics instead of labour-intensive quality checks.

The re-certification method selected by the operator should be appropriate for the application, thus for applications of class 1 and class 2 meters where high potential financial risks are matched by greater accuracy expectations, it is necessary to incorporate a number of advanced diagnostic and audit trail procedures within the re-certification package. Optional diagnostic information systems or diagnostic programs embedded within the database computer or distributed control system provide a continuous verification of the functionality of the USM.

7.2 Verification process

For class 1 and class 2 meters an audit trail shall be set up. The audit trail files key documents and key characteristics of the USM throughout its life cycle (see Figure 14).

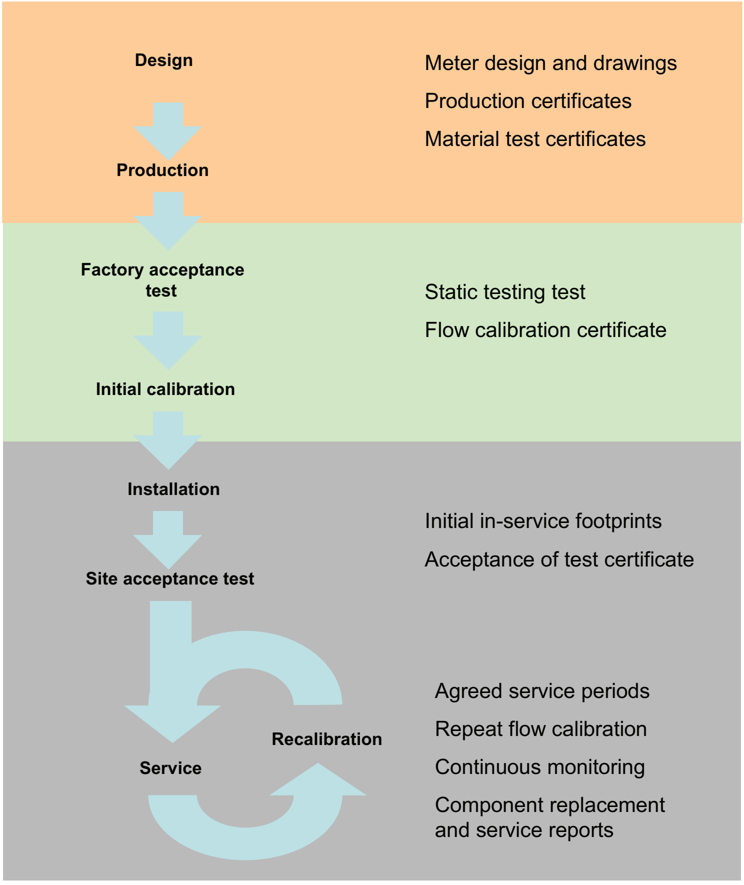


Figure 14 — Audit trail

An audit trail contains some or all of the following processes:

a) manufacture;

b) factory acceptance testing (FAT);

c) calibration;

d) field operation and condition-based monitoring;

e) recalibration.

Documents produced by the above processes are:

1) production certificates;

2) test certificates;

3) calibration certificates;

4) parameter change certificates or reports;

5) component replacement certificates/reports;

6) inspection reports.

Characteristic indicators are deduced from measurement and diagnostic data as specified in 5.5.6:

i) SOS footprints;

ii) trends in gain settings and other diagnostic data;

iii) inter-comparison results;

iv) log files.

7.3 Into operation

Installation of the USM shall comply with 5.9.

Parameters characterizing actual gas conditions, e.g. viscosity, shall be set to average operating conditions if the effect of the difference between calibration conditions and average operating conditions exceeds 0,05 %.

The output of the USM shall be corrected for the effect of meter body expansion if the effect exceeds 0,05 %. Meter body expansion plays a role when operating conditions of pressure and temperature differ to a large extent from calibration conditions. The magnitude of the effect shall be calculated using Equations (13) to (22).

7.4 Operational diagnostics

7.4.1 Speed of sound

When the gas composition, temperature and pressure are measured, the theoretical speed of sound (TSOS) can be compared with the measured value. The SOS is an excellent tool to monitor not only the USM, but also the other components in the system, such as the gas chromatograph and the pressure and temperature transmitters.

The SOS measured by a USM, the measured SOS (MSOS), is influenced by:

a) the gas composition;

b) the pressure;

c) the temperature;

d) the geometry of the measurement section;

e) the transit time measurement (by the meter).

The TSOS can be calculated from measured values of pressure, temperature, and gas composition using an equation of state, the AGA Report No. 10[35] or equivalent.

7.4.1.1 Absolute speed of sound comparison

If both MSOS and TSOS are available, they may be compared: absolute comparison.

Differences between MSOS and TSOS may indicate:

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

b) malfunction of:

  1) USM,

  2) pressure measurement,

  3) temperature measurement,

  4) gas composition measurement;

c) depositions on the transducer(s) or meter body which change the path length.

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

7.4.1.2 Relative speed of sound comparison; footprint

A USM with three or more paths may be monitored by comparison of the SOS values per path: “relative comparison”.

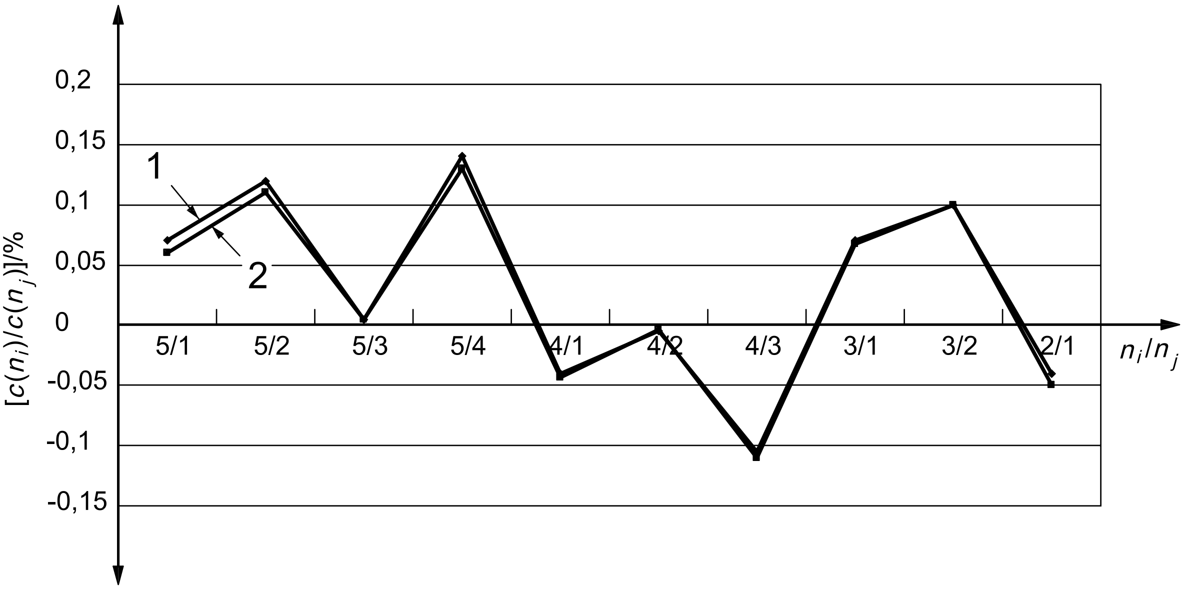
The advantages are:

a) it is independent of the gas composition;

b) the measurement can be performed under flowing conditions — at high velocities, acoustic path length may change, thereby increasing the discrepancy;

c) the calculation can be automatically done as part of a diagnostic package.

The comparison may be displayed graphically as a “footprint”. As an example, in Figure 15, the footprint is shown from a five-path USM, showing on the ordinate the SOS ratios measured during static testing and flow calibration. The plots show the different ratios of the SOS from the various paths. The abscissa gives the numbers of the paths on which SOS is measured, 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
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, $i = 1 \ldots 5$ $(i \neq j)$
n_j	another path, $j = 1 \ldots 5$ $(j \neq i)$

Figure 15 — Footprint: Ratio pattern determined during static testing with nitrogen and during the flow calibration at the calibration facility

Figure 15 is just an example. Note that different graphs may be generated, depending on the meter configuration, to serve as a footprint.

A change in the shape of the footprint over time may indicate malfunction of a path of the USM with a resulting potential for mismeasurement. Footprints from FAT, static testing, flow calibration, and field testing may be compared in order to monitor changes in the behaviour of the USM.

7.4.1.3 Velocity ratios

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

7.4.1.4 Profile factor number

The profile factor number describes the shape of the gas velocity profile entering the meter, which is a function of the entire metering assembly including meter, piping, and flow conditioning components as well as their location. It can be estimated as a ratio between raw gas velocities of dissimilar paths and a result is independent of any manufacturer coefficients. A constant profile factor is an indication that the meter maintains a close correlation between individual path velocities and hence the quality of the measurement.

7.4.1.5 Other parameters

Although the SOS is one of the most important parameters to be used in verification, there are many more parameters which may be monitored in order to ensure optimum performance and combinations of these may serve as the basis of an expert system. Table 8 shows an example of such a relational diagram.

Table 8 — Relational diagnostic diagram

Relational diagnostic diagram	Performance	Automatic gain control per path	S/N per path	SOS per path	Flow velocity per path
Transducer failure	×	×	—	×	×
Detection problems	×	×	—	×	×
Ultrasonic noise	×	×	×	—	—
Process conditions pressure	—	—	×	—	—
Process conditions temperature	—	—	—	×	—
Fouling	×	×	—	×	×
Changes in the flow profile	—	—	—	—	×
High velocity	×	×	×	—	—

7.5 Audit trail during operation; inter-comparison and inspection

7.5.1 Inter-comparison checks of multiple meters in series

If the USM is operated with another meter in series, e.g. via permanent serial installation or short-term serial installation, the output and key parameters from each meter can be monitored and compared to confirm agreement between the meters. If necessary, where 100 % redundancy has been provided as part of the system design, one of the meters can be designated the “check” meter and only introduced into service for this inter-comparison activity.

Where provision has been made for USMs to operate in series, either continually or for short periods, differences between the meters shall be confirmed at start-up and verified regularly during operation, using the integrated volume flow rate differences at metering conditions or reference conditions. As with all situations where meters of similar technology are used to verify one another, the potential for common-mode error shall be recognized.

The differences in integrated volume flow rate shall be evaluated according to control limits established for the specific inter-comparison method. If these differences exceed the control limits, prior to any action being taken, troubleshooting shall be performed to determine, if possible, which meter is faulty and whether any external effects may have impacted on the performance of the meters.

Where Z-configuration piping is being utilized for the check meter allowing both operational and check meters to be in series, ensure that the upstream straight length requirements for the check meter are strictly followed. This is to guarantee that the integrated volume difference between these two meters is due to the performance of these meters and is independent of the meter installation effects.

Annex C presents an example of the reference meter method with two USMs in series.

7.5.2 Inspections

7.5.2.1 General

Monitoring based on measurement data (see Annex C) leaves the USM undisturbed. However, there may be reasons to internally inspect the depressurized meter body and its transducers. It may be possible to remove insertion-type transducers for inspection independent of process line conditions.

7.5.2.2 Zero flow checks

The USM is separated from the gas flow and the gas velocity checked to confirm that the registration of that variable on all n_i/n_j acoustic path combinations is zero. A zero flow check may only be attempted in the field if full isolation and temperature stability can be maintained. If either are suspect, then the check shall be aborted.

When possible, the operator may verify that the USM displays values at or near zero when no gas is flowing through the meter. When performing this test, the operator may bypass any low flow cut-off function. The operator should be aware that temperature differences cause thermal convection currents in the gas to circulate inside the meter which the USM may measure as a flow rate. With some types of meter, the SOS vertical gradient is an indicator of temperature gradient and convection problems.

A zero offset may be indicative of a more fundamental problem with the USM or the operator may wish to perform additional diagnostic checks as part of a static test re-certification package.

7.5.2.3 Visual inspection

Visual checks can often provide initial indications of dimensional changes resulting from erosion or particulate depositions; see 5.9.2.2 (contamination) and 5.9.3.6 (wall roughness). If the meter bore is clean and the original machining marks clearly visible, there may not be a need or requirement to re-gauge.

The bore of the USM may be inspected for contamination by either removing the meter from service or by employing a “bore-scope” or similar device to ensure that there has not been a particulate build-up or changes in surface finish which could impact on the performance of the meter. Access for the inspection device may be through the line pressure tapping or via purpose-built inspection ports in the upstream and downstream pipe spools adjacent to the meter. If the latter are employed, ensure that they do not produce local disturbances in the flowing medium.

7.6 Recalibration

7.6.1 General

Depending on the outcome of diagnostics and internal company regulations or rules set forward by the authorities, USMs may need to be recalibrated.

7.6.2 Recalibration interval

The interval between successive recalibrations depends upon a number of issues including:

a) the stability of the meter;

b) the long-term repeatability of the meter;

c) commercial risk;

d) accuracy requirements;

e) the interpretation of diagnostic information as proposed in 7.4 and 7.5.

Once an initial recalibration interval has been adopted, new recalibration results may influence the length of the interval. Helpful statistical techniques are given in ISO/TR 7871.

7.6.3 Field recalibration

As an alternative to recalibration at an approved test facility, a master meter may be incorporated into the metering system during the build stage and used to periodically “prove” the duty meter(s). It may be recognized that the adoption of this flow recalibration option may result in a larger system uncertainty in comparison to the laboratory calibration.

The effects of the actual installations in the field on the meter output can be corrected with a field calibration. A master meter shall be installed in series with the meter being calibrated. The performance of the master meter shall not be influenced by the conditions of the installation. To ensure that this is achieved, the master meter may be isolated when not used for verification, thus avoiding common-mode error. The duration of one measurement shall comply with 6.3.2.2.

7.6.4 As-found laboratory recalibration

Recalibrations at an approved test facility require the meter to be removed from service and transported to the test facility. Guidance on manual handling and transportation is given in 5.9.4. If production is to be maintained, there may also be a requirement to hold a spare meter in the field in order to maximize availability.

7.6.4.1 Handling in the field

Proceed as follows:

a) record a log file at flowing conditions (prior to zero flow and zero pressure conditions);

b) record zero flow reading as in 7.3;

c) remove the USM(P);

d) inspect, internally, the USM and adjacent meter spools as in 7.3 and keep a photographic record;

e) replace the USM with either a spare meter, a spool piece or blind flanges;

f) do not clean the USM(P) unless applicable health and safety regulations require it — record any cleaning performed in the event log;

g) prepare the USM for transportation — to prevent changes in wall roughness and contamination, pressurize the blind-flanged USM with nitrogen or use equivalent techniques, where practical.

7.6.4.2 Handling in the laboratory

Proceed as follows:

a) inspect the USM and record the situation photographically, if necessary;

b) do not clean the USM;

c) mount the USM in accordance with 6.3 — if the USM has been calibrated before, use identical upstream piping;

d) use preferably the same upstream pipe spools as in the original calibration;

e) ensure alignment;

f) avoid changing the USM parameters;

NOTE Make no changes to the adjustment factor or linearization parameters.

g) calibrate in accordance with 6.3 using equal flow set points if the USM has been calibrated before.

If a USM has to be modified, it is recommended that an as-found calibration be performed prior to modification. After modification, a new full calibration may not be necessary if the type approval permits; but verify at least one flow rate.

7.6.5 Consequences and aftercare

Under ideal conditions, the adjustment factor or the FWME from subsequent recalibrations, when expressed as a percentage, may not exceed the component of uncertainty limits ascribed to the meter at the designated test facility. Typically, the acceptable changes of the FWME between sequential recalibrations lie between ±0,3 % and ±0,5 %. The actual value depends upon which type of meter is recalibrated and where this activity is performed.

After each recalibration it is recommended that a reality check be carried out on the new calibration curve derived from the individual registration errors recorded at the designated flow points. These curves, if plotted historically on the same axis, provide a good visual indicator of potential operational issues such as longterm drift, which if not addressed could become a problem impacting on the performance of the meter.

While recalibration results may be within the designated registration limits for the meter, the shape of the curves may provide valuable information concerning “test centre effects”.

The magnitude of the shift between the current and previous recalibration results may be of specific interest where a retrospective reconciliation to metered quantities is required in order to comply with contractual or governmental obligations. A method for deriving mismeasurements based on sequential flow recalibration results employing registration error limits is presented in Annex B.

7.7 Total operational uncertainty

For a formal calculation of the operational uncertainty, the user is referred to the ISO 5168.

The components of uncertainty require combination. The main components are:

a) the reproducibility of the USM as specified by the manufacturer and as listed in 5.8.1 — this contribution includes all intrinsic factors as listed in 4.2, except for calibration, and is $\leqslant 0,3$ %;

b) the CMC of the calibration facility; value $\leqslant 0,3$ % — on the basis of the dry calibration only, the contribution is assumed to be 2 %;

c) contributions from handling and operational circumstances, such as:

    1) consideration of l_{min}:

        i) if l_{min} is not determined, the contribution is 0,5 %,

        ii) if l_{min} is respected, the contribution is 0 %,

        iii) if detailed research shows that the USM performance under simulated operational circumstances differs by less than 0,3 % from calibration, the contribution to the uncertainty may be lowered to the determined value ($\leqslant 0,3$%),

    2) if a calibration curve correction or linearization is not applied, the contribution is 0,3 %,

    3) other extrinsic factors as listed in 4.2 and specified in 5.9 and in Clause 7; the contribution is $\geqslant 0,1$ %.

For the calculation of the total operational uncertainty, all contributions shall be added by the root sum of squares method.

EXAMPLE 1

a) USM: 0,2 %
b) CMC: 0,2 %
c) Operational
    1) l_{min} is “respected”: 0 %
    2) calibration curve correction “on”: 0 %
    3) handling: 0,1 %

Total uncertainty on volume is equal to
$\sqrt{(0,2^2 + 0,2^2 + 0,1^2)} = 0,3$ %

EXAMPLE 2

a) USM: 0,3 %
b) CMC: 0,3 %
c) Operational
    1) l_{min} needs “detailed research”: 0,3 %
    2) calibration curve correction “off”: 0,3 %
    3) handling: 0,1 %

Total uncertainty on volume is equal to
$\sqrt{[(4 \times 0,3^2) + 0,1^2]} = 0,6$ %

8 Valve characterization and noise in a metering and regulating station

8.1 Introduction

In order to know 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 an metering and regulating (M&R) station.

8.2 Calculation method

8.2.1 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:

a) the generation of the noise by the control valve as a function of the operating envelope of the M&R station;

b) the propagation of noise from the valve to the USM, using attenuation factor, N_d;

c) the signal strength, P_s, of the USM;

d) 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.

8.2.2 Generation of noise by the control valve

The emitted acoustic pressure, p_n, in pascals, of a valve is proportional to the pressure drop, Δp, in pascals, across the valve and the square root of the mass flow rate, q_m, in newton cubic metres per hour, i.e.

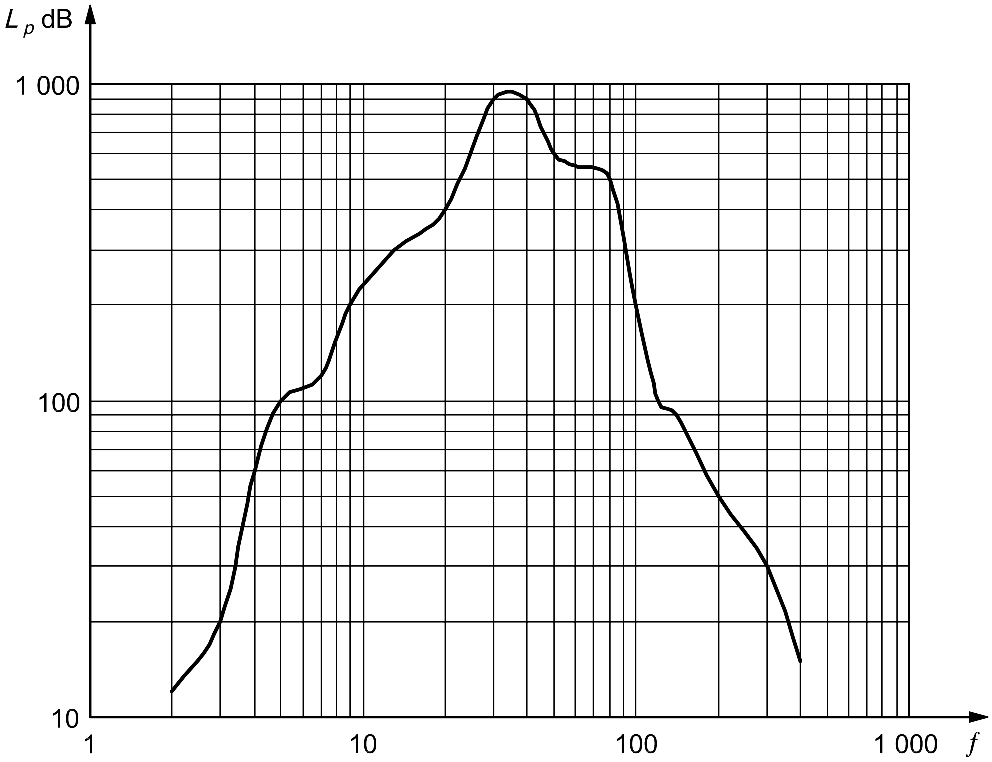
$$p_n \propto \Delta p \sqrt{q_m} \tag{27}$$

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

$$p_n = N_\mathrm{v} \, \Delta p \sqrt{q_m} \tag{28}$$

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.

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 16).



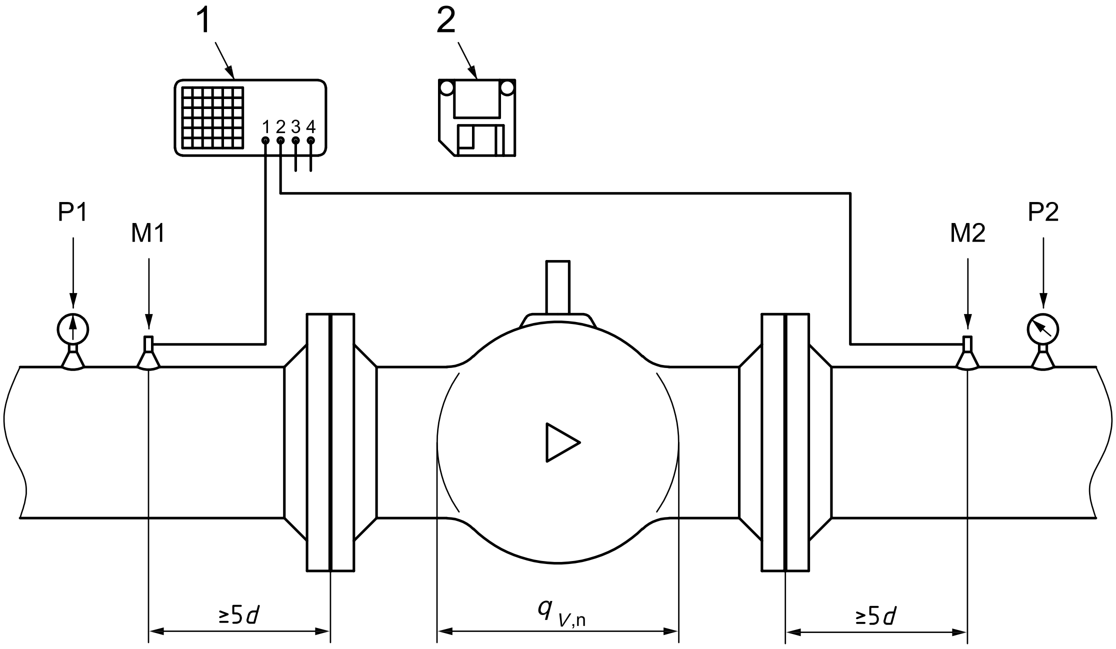
Key

f frequency

L_p noise amplitude

Figure 16 — A typical spectrum of the acoustic noise generated by a valve

To determine the valve-weighting factor, 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 17 depicts an installation for determination of the valve-weighting factor.



Key

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

Figure 17 — Installation set-up

Note that:

a) distance between microphone and regulating valve may be 5D or longer;

b) there are no obstructions in the pipeline between the microphone and the regulating valve;

c) there are no U-bends, T-bends, etc. between the microphone and the regulating valve;

d) installation of microphone is flush with the inner wall of the pipeline;

e) before starting a test, the background noise shall be measured — during this measurement, Δp shall be 0 MPa, the gas flow 0 m^3/h, and the pipeline pressurized at line pressure;

f) each noise measurement at a specific operational condition may consist of three to five measurements;

g) measurements may be done under stable process conditions;

h) at the end of the test, the background noise levels may be measured again;

i) in most cases the N_v value is different for the upstream or downstream side.

8.2.3 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 wave (eliminating the line of sight) or to let the acoustic wave 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 9 shows the attenuation of different piping elements at 200 kHz.

Table 9 — 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).

8.2.4 Signal strength of the USM, P_s

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

a) $P_s \propto p$: the higher the pressure at the USM, the stronger the signal;

b) $P_s \propto 1/l_p$: the longer the path length, the weaker the signal;

c) $P_s \propto \sqrt{t}$: 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:

$$P_s \propto \frac{p\,\sqrt{t}}{l} \tag{29}$$

8.2.5 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 [Equation (28)] results in the levels of acoustic noise pressure at the USM:

$$p_{n,\text{USM}} = N_d\ N_v\ \Delta p\ \sqrt{q_m} \tag{30}$$

Combining this with Equation (29), describing the signal strength, Equation (30) results in Equation (31), which describes the S/N ratio, $P_\mathrm{s}/p_\mathrm{n}$:

$$\frac{P_\mathrm{s}}{p_\mathrm{n}} \propto \frac{p\sqrt{t}}{N_\mathrm{d}\, N_\mathrm{v}\, l\, \Delta p \sqrt{q_\mathrm{m}}} \tag{31}$$

Based on this, a new S/N parameter, $\delta_\mathrm{S/N}$, is defined:

$$\delta_\mathrm{S/N} = \frac{p\sqrt{t}}{N_\mathrm{d}\, N_\mathrm{v}\, l\, \Delta p \sqrt{q_\mathrm{m}}} \tag{32}$$

Having established the S/N ratio at the USM, the last remaining item to be determined is the required minimum value, $\delta_\mathrm{S/N,\,min}$, at which the meter still operates:

$$\delta_\mathrm{S/N} \geqslant \delta_\mathrm{S/N,\,min} \quad \Rightarrow \text{the USM functions} \tag{33}$$

$$\delta_\mathrm{S/N} < \delta_\mathrm{S/N,\,min} \quad \Rightarrow \text{the USM fails} \tag{34}$$

The required minimum S/N parameter, $\delta_\mathrm{S/N,\,min}$ is meter specific, and is determined by the meter manufacturer.

8.2.6 M&R station design

From 8.2.2 to 8.2.5, it is clear that the successful operation of an M&R station comprising a USM system is dependent on:

a) 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;

b) the required operating envelope, as selected and determined by the user;

c) the pipe configuration, which may be modified to include silencers in the design;

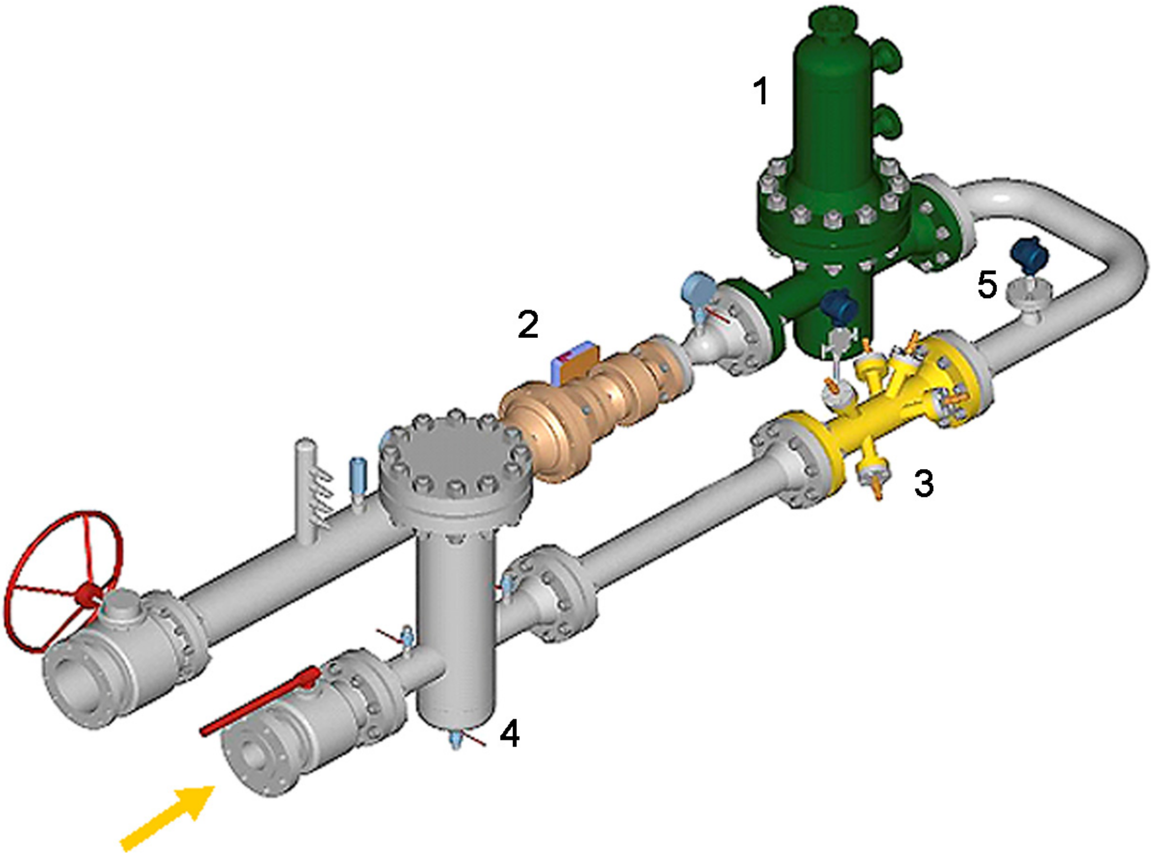
d) the level of noise immunity of the USM for which the manufacturer has to present the value of $\delta_\mathrm{S/N,\,min}$.

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 18). 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 18 — M&R station optimized for ultrasonic measurement

Annex A
(informative)

Registration of error bands

A.1 General

As detailed in Clause 7, 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 mismeasurements 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:

$$\Delta(\text{reg}) = \sqrt{[u(\text{USM})^2 + u(\text{TF})^2]}$$

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).

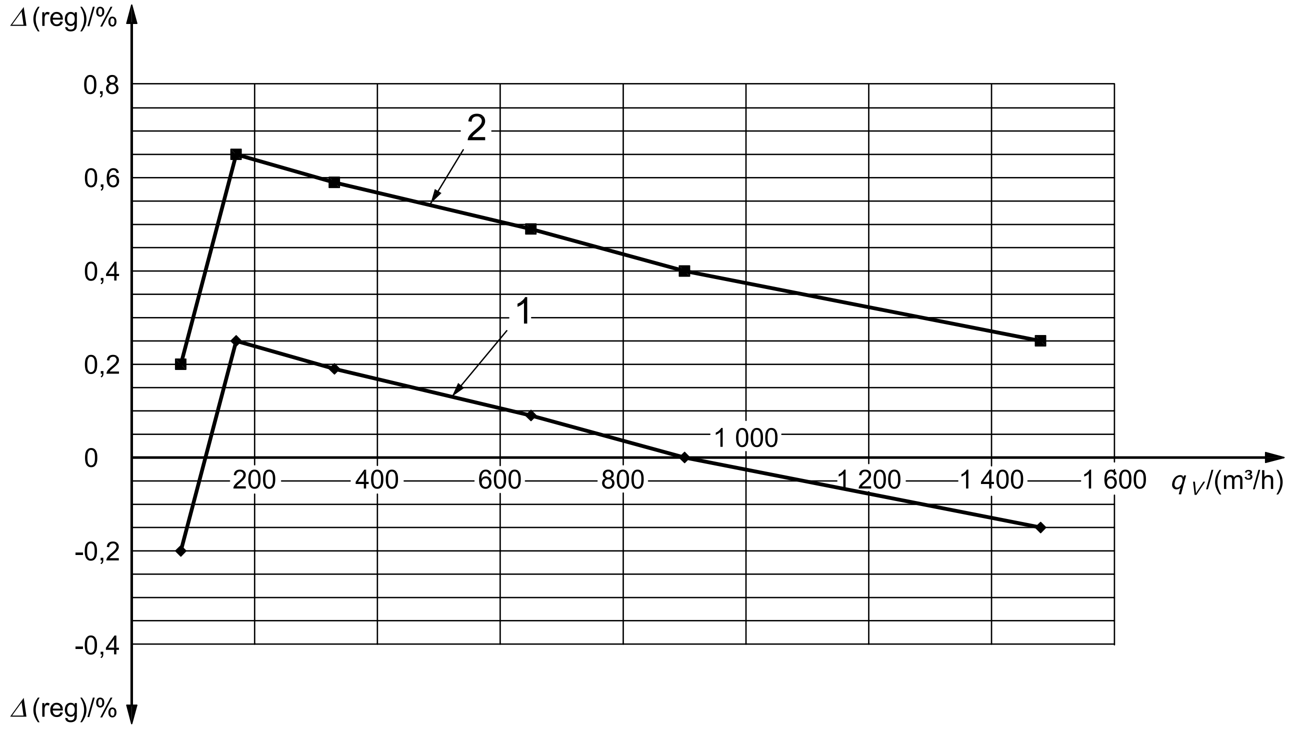
Included within $u(\text{USM})$ shall be those sub-components of uncertainty as detailed in 4.4.

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

A.2 Mismeasurement example

Figure A.1 illustrates an example of a set of results recorded during the initial comparative calibration and subsequent recalibration of a USM. A calibration “offset” has been applied to the initial results and entered into the meter electronics. The registration error band and hence the trigger point for mismeasurement is taken to be ±0,35 %. As can be seen from this example, the first sequential recalibration has produced results that appear to be outside this error band, thus leading to a possible mismeasurement issue.

The period nominated for the mismeasurement depends upon a number of factors, predominant among which is previous service history. If it can be established from log files or comparative checks when the shift occurred, then this may be taken as the start date for any mismeasurements. If not, a start date shall be agreed based on available data or contractual agreements, possibly employing the latter half of the previous service period, during which actual flow was registered, for a mismeasurement review.



Key

q_V	volume flow rate
Δ(reg)	registered error
1	initial calibration (post-offset)
2	recalibration

Figure A.1 — USM recertification history mismeasurement example

Having established a potential mismeasurement period, the next stage is to determine if the registration error band was exceeded over the associated operating range of the meter. For this, the daily average flow rates are required and from these the flow range for the period can be determined, i.e. minimum and maximum flow rates based on these daily averages.

To determine if the registration error band has been exceeded, the error values on either side and within the area of the curve bounded by the flow profile are averaged. If this average value exceeds the error band, then a mismeasurement is triggered. As an example and with reference to Figure A.1, if the flow range is established from historic records to be within the region 400 m^3/h to 800 m^3/h, then the percentage errors at three flow points (320 m^3/h, 640 m^3/h, 960 m^3/h) are used to determine if the trigger point has been exceeded. Note that a minimum of two flow points should be used to establish the average percentage error value.

Once it has been established that the registration error band has been exceeded, as in this example where all three points have a 0,4 % error, a mismeasurement procedure may be implemented. The mismeasurement may be calculated on a day by day basis with the mismeasurement error for each day being derived from the calibration and recalibration results plus the associated performance charts. The actual mismeasurement for a day is based on the difference between sequential calibration errors derived at each of the daily average flow rates, by linear interpolation between respective flow point percentage errors. In the example at 640 m^3/h, the difference in recorded errors between sequential calibrations is +0,4 %, resulting in an overregistration of flow on the day by 2,56 m^3/h.

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 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 $q_{V,\,\mathrm{ref}}$	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:

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

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 Equation (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:

$$\overline{E}(q_V) = \frac{\sum f_i\ E_i}{\sum f_i}$$

$$= -\ 0{,}742\ 508/2{,}493\ 066$$

$$= -\ 0{,}297\ 829\ 28$$

The single adjustment factor, F, to be applied to the output of a USM can be calculated from Equation (B.2):

$$F = \frac{100}{100 + \overline{E}(q_V)} \tag{B.2}$$

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, $E_{i,\,\mathrm{cf}}$, using Equation (B.3):

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

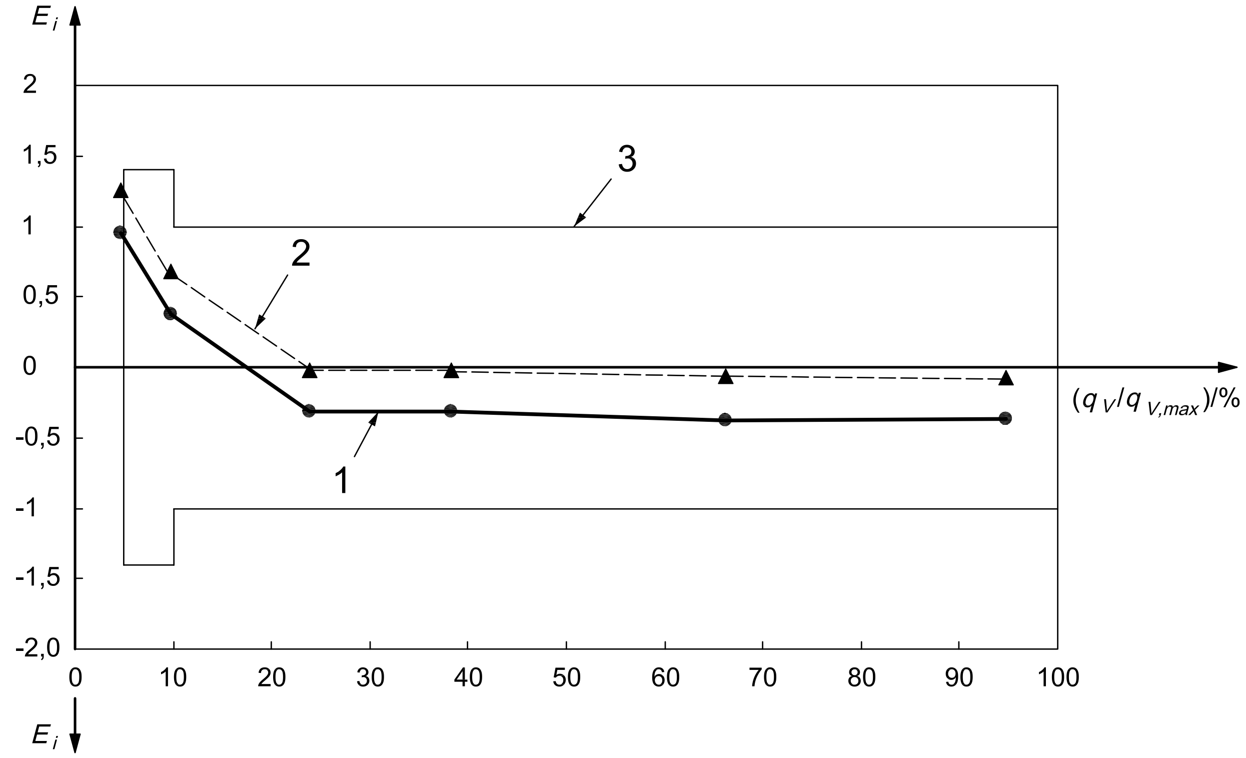
Table B.3 — FWME-corrected flow calibration data summary for a 200 mm diameter USM

Indicated flow rate error E_i	**Calibration factor-adjusted flow rate error** $E_{i,\,\mathrm{cf}}$	**Weighted calibration factor-adjusted flow rate error** $f_i\,E_{i,\,\mathrm{cf}}$
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
		$\sum f_i\ E_{i,\mathrm{cf}} = 0{,}000\ 0$

As a result:

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

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.



E_i	error
$q_V/q_{V,\max}$	ratio of volume flow rate to maximum volume flow rate
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

Figure B.1 shows that, for gas flow rates above about 25 % of the capacity of the meter, the measurement error has been virtually eliminated by applying a single FWME correction factor to 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)

The flow reference meter method for USMs in series

C.1 General

With two USMs operating in series, a systematic approach, the flow reference meter method (FRMM), may be employed to monitor the quality of the meters (with the exception of common-mode errors).

The purpose of the FRMM is to provide:

a) means to re-establish traceability *in situ* after having repaired one of two meters in series;

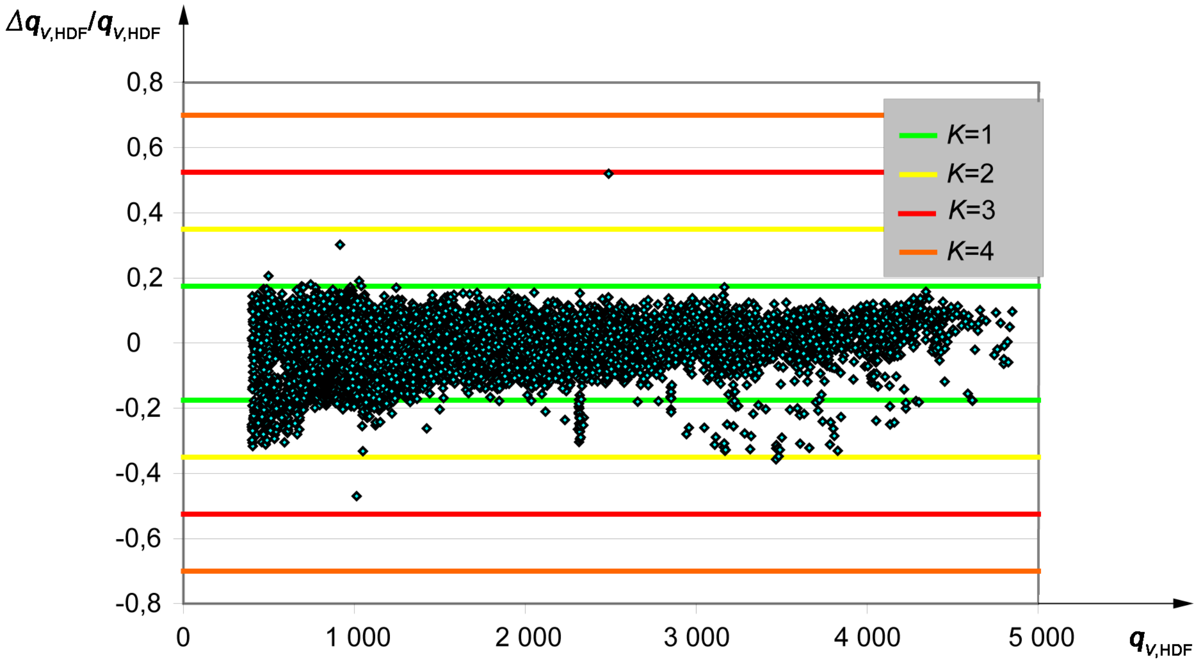
b) control limits for evaluation of meter performance of two meters in series during normal operation, providing an extremely efficient means of demonstrating compliance with custody transfer requirements.

Examples of the use of the FRMM can be found in Reference [53].

C.2 Systematic approach to the flow reference meter method

C.2.1 Step 1

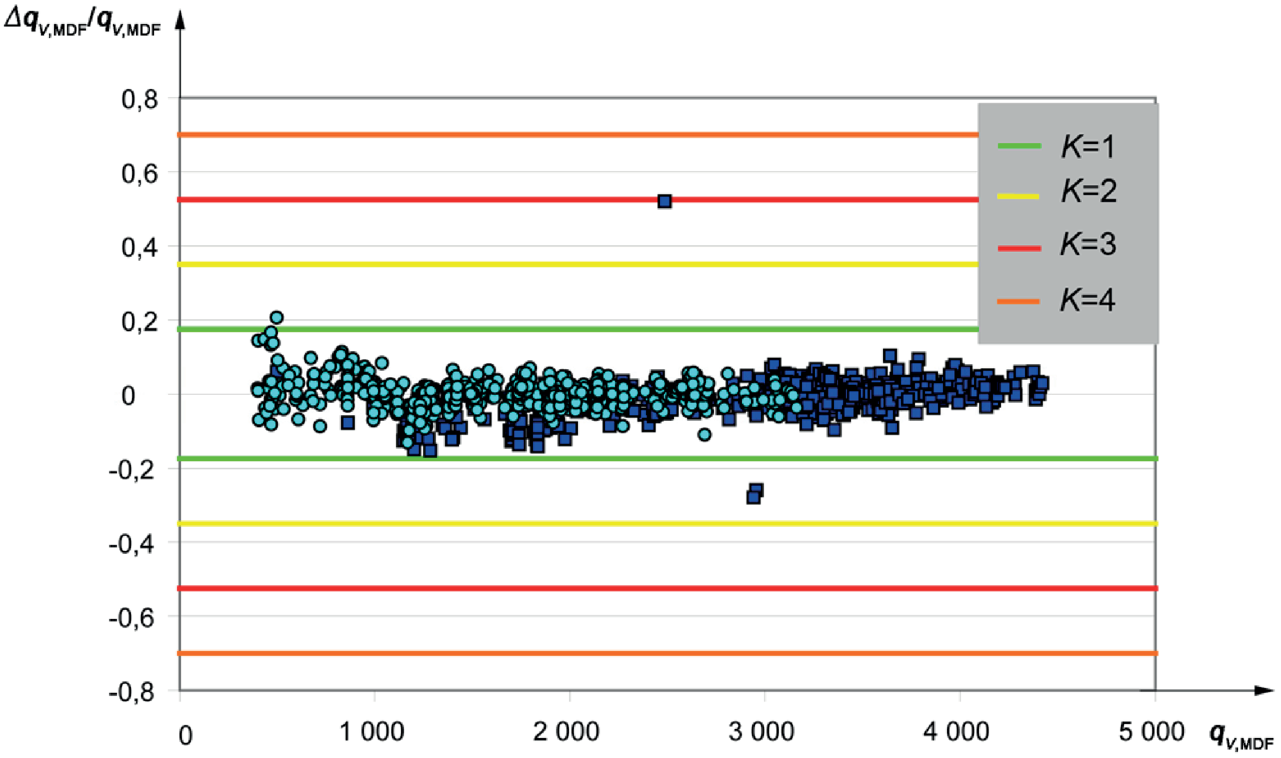
Establish and maintain the historic difference footprint (HDF), the difference between hourly volume totals at metering conditions for various flow rates within working range, since first start-up (see Figure C.1). Establish monthly difference footprints (MDF) at regular intervals during operation (every month for the last month) (see Figure C.2). Only hours containing stable flow conditions may be included. Hours containing start-up, shutdown, wet gas or other instabilities may be disregarded.



Key

$q_{V,\text{ HDF}}$	mean volume flow rate (HDF data), in cubic metres per hour
$\Delta q_{V,\text{ HDF}} / q_{V,\text{ HDF}}$	ratio of difference between hourly volume totals to mean volume flow rate (HDF data), as a percentage
K	calibration factor

Figure C.1 — Historic difference footprint (HDF)

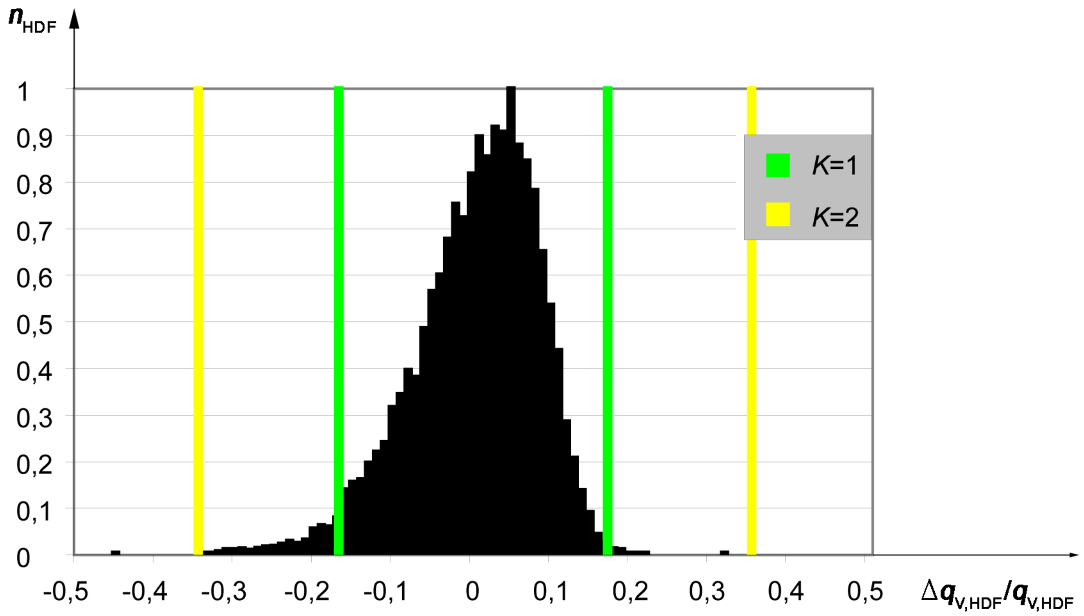


Key

$q_{V,\ \mathrm{MDF}}$	mean volume flow rate (MDF data), in cubic metres per hour
$\Delta q_{V,\ \mathrm{MDF}}/q_{V,\ \mathrm{MDF}}$	ratio of difference between hourly volume totals to mean volume flow rate (MDF data), as a percentage
■	month 1
○	month 2
K	calibration factor

Figure C.2 — Monthly difference footprints (MDF)

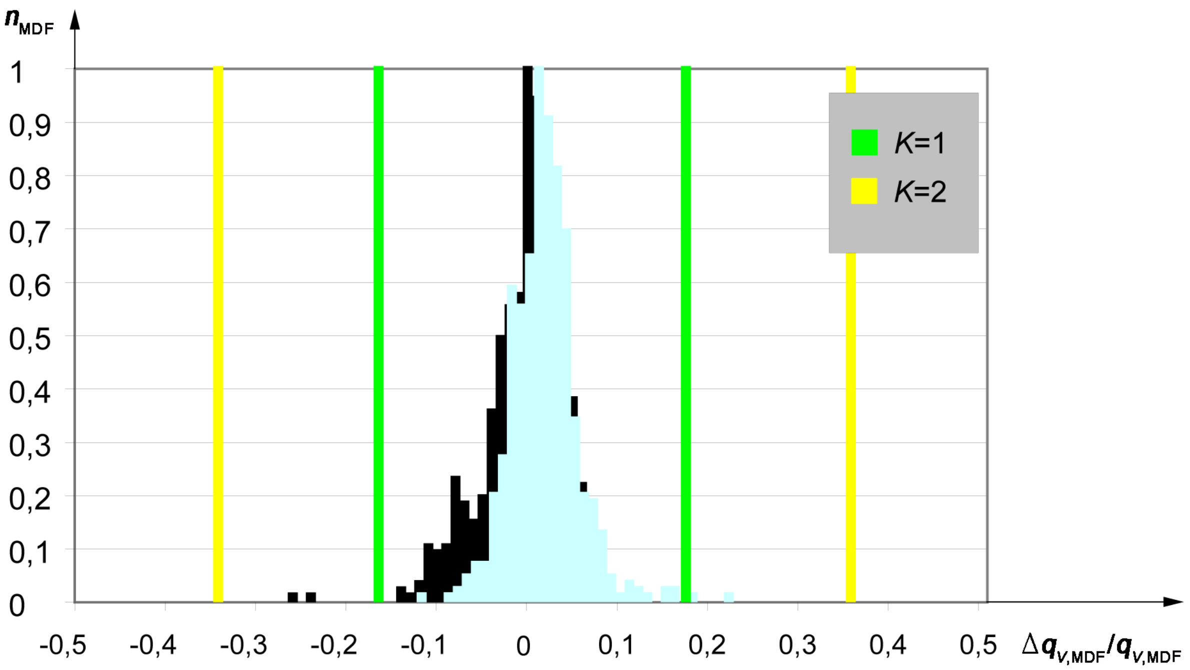
It is also useful to establish historic and monthly difference histograms (HDH and MDH) (see Figures C.3 and C.4).



Key

n_{HDF}	normalized frequency (HDF data)
$\Delta q_{V,\,\mathrm{HDF}}/q_{V,\,\mathrm{HDF}}$	ratio of difference between hourly volume totals to mean volume flow rate (HDF data), as a percentage
K	calibration factor

Figure C.3 — Historic difference histogram (HDH)



Key

n_{MDF}	normalized frequency (MDF data)
$\Delta q_{V,\,\mathrm{MDF}}/q_{V,\,\mathrm{MDF}}$	ratio of difference between hourly volume totals to mean volume flow rate (MDF data), as a percentage
K	calibration factor

NOTE The dark bars denote month 1 data while the light bars denote those of month 2.

Figure C.4 — Monthly difference histograms (MDH)

C.2.2 Step 2

Determine control limits for the change, Δ, of the MDF or MDH from the HDF or HDH or from the MDF or MDH of the previous month. The control limits may be based on the uncertainty of the USMs ($\pm 2\sigma$, where σ is the standard deviation, relative expanded uncertainty with coverage factor $k = 2$).

The actions that are valid when re-establishing traceability and for evaluation of meter performance are listed in Table C.1 for each control limit. The control limits are valid in the working range (20:1) (The FRMM uses similar control limits to those in API MPMS 13.2:1996[34], Table 14).

Table C.1 — Control limits with corresponding actions for the FRMM

Control limits	**Actions** (when re-establishing traceability after having repaired a meter)	**Evaluation** (of meter performance)
$\lvert\Delta\rvert \leqslant 1\sigma (k = 1)$	Original calibration certificate is considered still valid.	**OK**
$\lvert\Delta\rvert \leqslant 2\sigma (k = 2)$	Adjust calibration curve to match reference meter values. Traceability through reference meter calibration certificate.	**Warning:** Look for systematic shifts in footprint.
$\lvert\Delta\rvert \leqslant 3\sigma (k = 3)$	Adjust calibration curve to match reference meter values. Traceability through reference meter calibration certificate. Evaluate the need for recalibration in an accredited calibration laboratory based on maintenance history for both ultrasonic gas meters, i.e. number of transducer replacements and number and size of previous adjustments of calibration curves.	**Action:** Look for signs of wet gas, unusual process conditions, evaluate sound velocity profile, etc.
$\lvert\Delta\rvert \leqslant 4\sigma (k = 4)$	Recalibrate in an accredited calibration laboratory.	**Tolerance:** Consider recalibration.
$4\sigma < \lvert\Delta\rvert$	Service and check to be performed by supplier. Recalibrate in an accredited calibration laboratory.	**Fault:** Consider service and recalibration.

C.2.3 Step 3

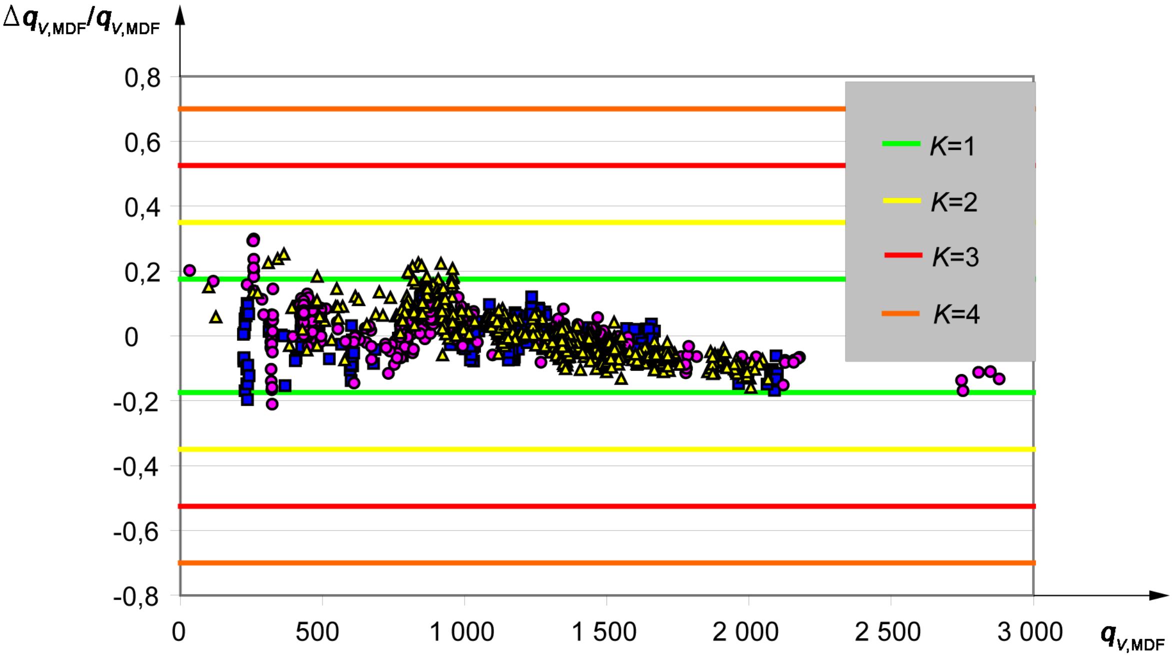
If an error occurs, the faulty meter may be repaired and put back in operation as a check meter. The other ultrasonic gas meter is a duty meter and is used as the reference meter in the FRMM.

C.2.4 Step 4

The two USMs are then compared using the MDF or MDH. Sufficient basis may be established before conclusions are drawn and comparing the two meters for at least one month may be considered.

C.2.5 Step 5

The established HDF or HDH and the MDF or MDH prior to the error occurring may be compared with the MDF or MDH established after the error was corrected (see Figure C.5). Changes in MDF shape, shift in MDF, and size of Δ shall be considered. Determine actions based on the control limit criteria.



Key

$q_{V,\ \mathrm{MDF}}$	mean volume flow rate (MDF data), in cubic metres per hour
$\Delta q_{V,\ \mathrm{MDF}}/q_{V,\ \mathrm{MDF}}$	ratio of difference between hourly volume totals to mean volume flow rate (MDF data), as a percentage
■	before error situation
○	during error situation
△	after error situation
K	calibration factor

Figure C.5 — Comparing monthly difference footprints (MDF) before, during and after error situation

If the size of Δ exceeds the action limit when evaluating meter performance, prior to any action being taken, troubleshooting should be performed to determine, if possible, which meter is drifting.

Annex D
(informative)

Documents

In other clauses of this part of ISO 17089, documentation has been required on accuracy, installation effects, electronics, ultrasonic transducers, and zero flow verification. In addition to the above mentioned documentation, the manufacturer should provide all necessary data, certificates and documentation for a correct configuration, set-up, and use of the particular meter to operate correctly. This includes an operator's manual, pressure test certificates, material certificates, measurement report on all geometrical parameters of the meter body, and certificates specifying the zero flow verification parameters used.

The manufacturer should provide at least the following documents:

a) a description of the meter giving the technical characteristics and the principle of its operation;

b) a perspective drawing 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 dimensioned drawing of essential metrological components;

h) a drawing of the data plate or face plate and of the arrangements for inscriptions;

i) a drawing of any auxiliary devices;

j) instructions for installation, operation, and periodic maintenance;

k) maintenance documentation including third party drawings for any field repairable components;

l) a description of the electronic signal processing unit, arrangement, and general description of operation;

m) a description of the available output signals and any adjustment mechanisms;

n) a list of electronic interfaces and user wiring termination points with their essential characteristics;

o) a description of software functions and operating instructions;

p) documentation that the design and construction comply with applicable safety codes and regulations;

q) documentation that the performance of the meter meets the requirements of 5.8;

r) documentation that the design of the meter successfully passed the tests in 6.2;

s) minimum upstream piping configurations which do not create an additional error of more than 0,3 %;

t) maximum allowable flow profile disturbance which does not create an additional error of more than 0,3 %;

u) a field verification test procedure as described in Clause 7;

v) a list of the documents submitted.

All documentation shall be dated.

After receipt of order, the manufacturer shall furnish specific meter outline drawings including overall flange face-to-face dimensions, inside diameter, maintenance space clearances, conduit connection points, and estimated mass.

The manufacturer shall provide a recommended list of spare parts.

The manufacturer shall also furnish meter-specific electrical drawings showing customer wiring termination points, and associated electrical schematics for all circuit components back to the first isolating component; e.g. optical isolator, relay, and operational amplifier. This enables the designer to properly design the interfacing electronic circuits.

Prior to shipment of the meter, the manufacturer shall make the following available for review by an inspector: metallurgy reports, weld inspection reports, pressure test reports, and final dimensional measurements as required in 6.2.1.

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, Equation (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:

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

For the simple meter arrangement shown in Figure 4, x is obtained from simple trigonometry as:

$$x = l_\text{p} \cos\phi$$

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:

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

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 Equation (E.2), but expressed as a relative flow error, $\Delta q_V/q_V$, can be used:

$$\frac{\Delta q_{V,1,0}}{q_V} = \frac{q_{V,1}}{q_{V,0}} - 1 \tag{E.3}$$

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:

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

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

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

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

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

or alternatively:

$$\frac{\Delta q_{V,2,1}}{q_V} = \frac{q_{V,2}}{q_{V,1}} - 1 \tag{E.7}$$

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 Equation (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 Equation (E.2) than is given by the direct calculations of Equations (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:

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

Substituting the Equations (E.8) into Equation (E.2) gives:

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

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

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

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

$$\frac{\Delta q_V}{q_V} = 3\,\alpha\,\Delta T \qquad \text{(E.11)}$$

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:

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

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

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:

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

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

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 ($\delta / r \leqslant$ 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:

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

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

For the purposes of this part of ISO 17089, 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 Equations (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 [Equations (E.12) to (E.15)] is the preferred approach since this is more general than thin-shell theory [Equations (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 part of ISO 17089, 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 Equations (E.12) and (E.14) [or (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.

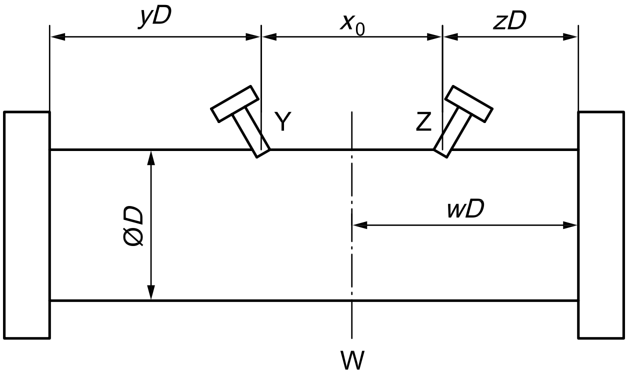
K_s is always less than or equal to 1. The value of K_s to be used for a given body type is as follows:

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 part of ISO 17089, it is assumed that the diametral expansion varies linearly from zero at the flange to the value given by Equations (E.12) and (E.14) [or (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.



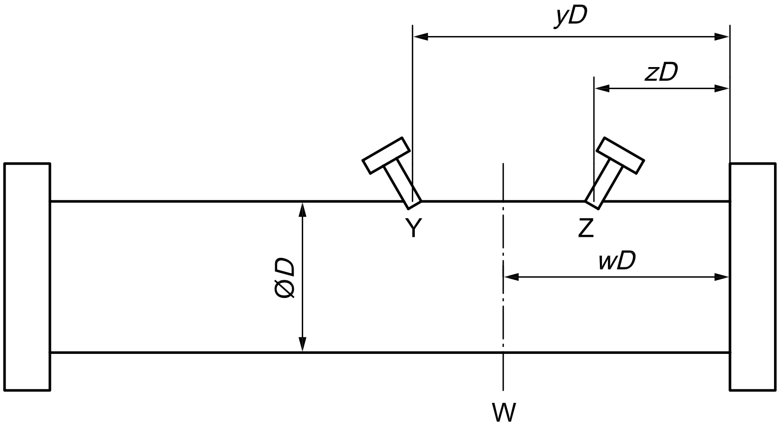
Key

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:

$$w_a\ D = \left\{\frac{w+y+z}{3}\right\} D \tag{E.20}$$

The style correction, K_s, is obtained using:

$$K_\mathrm{s} = \frac{w_a}{1} \tag{E.21}$$

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:

$$d_1 = d_0\left(1 + K_\mathrm{s}\frac{\Delta d}{d_0}\right) = d_0\left(1 + K_\mathrm{s}\frac{\Delta r}{r}\right) \Rightarrow \frac{d_1}{d_0} = 1 + K_\mathrm{s}\frac{\Delta r}{r} \tag{E.22}$$

The path length is calculated from:

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

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

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 Equations (E.22) to (E.24).

The flow correction factor is then calculated using:

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

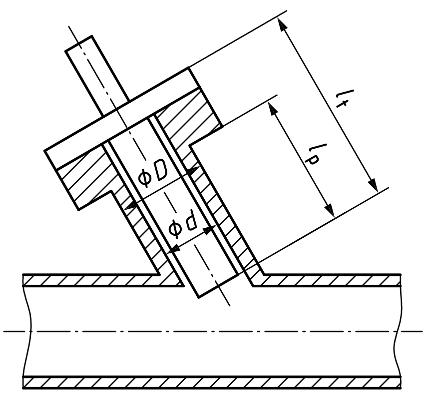
where “b, p” denotes body pressure.

The error correction obtained from Equation (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. Figure E.3 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:

$$\Delta l_\mathrm{t} = l_\mathrm{t}\left(\alpha_\mathrm{p}\,\Delta T - \alpha_\mathrm{t}\,\Delta T\right) = l_\mathrm{t}\left(\alpha_\mathrm{p} - \alpha_\mathrm{t}\right)\Delta T \qquad \text{(E.26)}$$

This is the change in face position in each port, so the effect on a given ultrasonic path is $2\,\Delta l_\mathrm{t}$. Assuming there is no diameter change or axial change, Equation (E.2), solely for the port expansion, simplifies to:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{\mathrm{p},\,T} = \left(\frac{l_1}{l_0}\right)^2 = \left(\frac{l_0 + 2\,\Delta L_\mathrm{t}}{l_0}\right)^2 = \left[1 + \frac{2 l_\mathrm{t}\left(\alpha_\mathrm{p} - \alpha_\mathrm{t}\right)\Delta T}{l_0}\right]^2 \qquad \text{(E.27)}$$

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

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{\mathrm{p},\,T} = \left[1 + \frac{4\,l_\mathrm{t}\left(\alpha_\mathrm{p} - \alpha_\mathrm{t}\right)\Delta T}{l_0}\right] \qquad \text{(E.28)}$$

or alternatively to:

$$\frac{\Delta q_V}{q_V} = 4\left(\alpha_\mathrm{p} - \alpha_\mathrm{t}\right)\frac{l_\mathrm{t}}{l_0}\,\Delta T \qquad \text{(E.29)}$$

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:

$$\Delta l_\mathrm{p} = l_\mathrm{t}\,\frac{\Delta p}{E_\mathrm{t}} + l_\mathrm{p}\,\frac{\Delta p}{E_\mathrm{p}}\left(\frac{d_\mathrm{p}^2}{D_\mathrm{p}^2 - d_\mathrm{p}^2}\right) = \Delta p\left[\frac{l_\mathrm{t}}{E_\mathrm{t}} + \frac{l_\mathrm{p}}{E_\mathrm{p}}\left(\frac{d_\mathrm{p}^2}{D_\mathrm{p}^2 - d_\mathrm{p}^2}\right)\right] \qquad \text{(E.30)}$$

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

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

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

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

or alternatively to:

$$\frac{\Delta q_V}{q_V} = 4\,\frac{\Delta l_\mathrm{p}}{l_0} \qquad \text{(E.33)}$$

E.2.5.4 Combined port correction

This is calculated using:

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

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:

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

which can be expressed as:

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

For small values of correction this simplifies to:

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

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 Equations (21) and (22):

$$q_{V,x}/q_{V,0} = \mathrm{x{,}xxx\ x} \pm \mathrm{x{,}xxx\ x} \tag{E.38}$$

$$\Delta q_{V,x}/q_V = (\mathrm{x{,}xx} \pm \mathrm{x{,}xx})\ \% \tag{E.39}$$

E.3 Guidance on the use of finite element models

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. Equation (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 Equations (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 Equations (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 Equation (E.4);

b) static calibration to operating conditions as in Equation (E.5);

c) comparison of the relative change between the two as in Equations (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 Equation (E.2). This allows the flow error to be expressed in either of the forms given by Equations (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.4 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 Equations (E.12), (E.14), (E.16) and (E.18)] for different δ/r ratios.

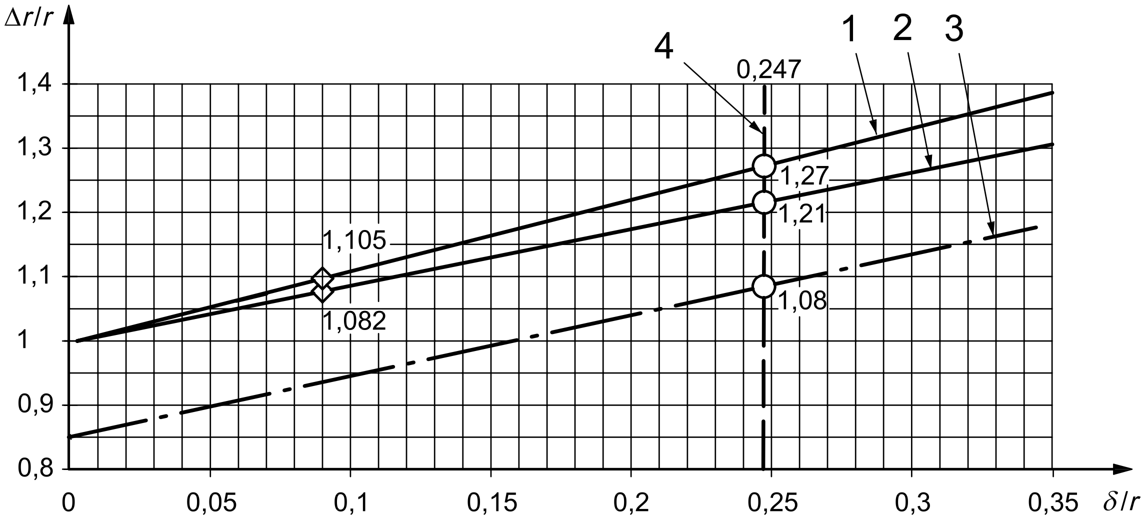
As can be seen from Figure E.4, δ/r ratios higher than 0,1 give differences in $\Delta r/r$ of more than 10 % compared with the thick-shell theory for the same end-loading conditions. If, for example, $\delta/r = 0{,}247$, the differences are in the region of 21 % to 27 % depending on which loading configuration 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.5 Calculation of an initial estimate for the body pressure effect

To provide the initial estimate of the body pressure effects used in 4.7.3.2, the axial change in x and any flange proximity or body style effect, K_s, are neglected for simplicity. Using Equations (E.23) and (E.24), Equation (E.25) reduces to:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{\mathrm{b},\,p,\,\mathrm{est}} = \left(\frac{d_1}{d_0}\right)^2 \left(\frac{l_1}{l_0}\right)^2 = \left(\frac{d_1}{d_0}\right)^2 \left(\frac{d_1}{d_0}\right)^2 = \left(\frac{d_1}{d_0}\right)^4 = \left(1 + \frac{\Delta r}{r}\right)^4 \tag{E.40}$$

For small values of $\Delta r/r$, this reduces further, by ignoring higher order terms, to:

$$\left(\frac{q_{V,1}}{q_{V,0}}\right)_{\mathrm{b},\,p,\mathrm{est}} = \left(1 + \frac{\Delta r}{r}\right)^4 \approx 1 + 4\,\frac{\Delta r}{r} \tag{E.41}$$

or in terms of $\Delta q_V/q_V$ gives:

$$\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p,\mathrm{est}} = \frac{q_{V,1}}{q_{V,0}} - 1 = 4\,\frac{\Delta r}{r} \tag{E.42}$$

The no-ends, thick-wall Equation (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:

$$\left(\frac{\Delta q_V}{q_V}\right)_{\mathrm{b},\,p,\mathrm{max}} = 4\,\frac{\Delta r}{r} = 4\left(\frac{R^2 + r^2}{R^2 - r^2} + \mu\right)\frac{\Delta p}{E} \tag{E.43}$$

E.6 Worked example

E.6.1 Meter details

A flanged-body spool meter has the following details which form the input data for the flow correction calculation.

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.

Parameter		Value	Implication
Wall thickness ratio, δ/r		0,247 5	⇒ thick wall
Meter external diameter		$2 \times 228{,}6 = 457{,}2 = D_\mathrm{p}$	
Flange proximity	closest	$366/457{,}2 = 0{,}8D_\mathrm{p}$	$\Rightarrow z = 0{,}8$
	furthest	$(366 + 267)/457{,}2 = 1{,}38D_\mathrm{p}$	$\Rightarrow y = 1$
	mid-path	$[366 + 0{,}5 \times 267]/457{,}2 = 1{,}09D_\mathrm{p}$	$\Rightarrow w = 1$
Body style correction factor		$(w + y + z)/3 = 2{,}8/3 = 0{,}93 = K_\mathrm{s}$	

E.6.2 Initial flow error estimate

Using the simple estimates from Figures 8 and 9, the expected $\Delta q_V/q_V$ flow errors from dynamic calibration to field operating conditions are +0,13 % for ΔT = 33 °C, and +0,16 % × 0,93 = +0,15 % for Δp = 16,7 MPa.

From Figure 10, for $\delta/r = 0{,}247$, the end correction $K_\mathrm{E} = 0{,}89$, and this gives a lower estimate of 0,13 % (i.e. 0,89 × 0,15 %) for the pressure term.

This gives a combined initial estimate for the flow error of +0,26 % to +0,28 % [or (0,27 ± 0,01) %] which is significant and therefore a detailed calculation is needed.

E.6.3 Common elements to detailed calculation

Common elements to the detailed calculation for any Δp and E ratio are given in the following.

Port pressure length change from Equation (E.30):

$$\Delta l_\mathrm{p} = \Delta p \left[\frac{230}{1{,}9E+11} + \frac{220}{2E+11}\left(\frac{32^2}{50^2-32^2} \right) \right] = 1{,}973\ 67 \times 10^{-9} \times \Delta p$$

Equations (E.12) to (E.15) give:

For no-ends:

$$\frac{\Delta r}{r} = \left(\frac{228{,}6^2 + 183{,}25^2}{228{,}6^2 - 183{,}25^2} + 0{,}3 \right) \frac{\Delta p}{E} = 4{,}895\ 85\ \frac{\Delta p}{E}$$

$$\frac{\Delta x}{x} = -0{,}3 \left(\frac{2 \times 183{,}25^2}{228{,}6^2 - 183{,}25^2} \right) \frac{\Delta p}{E} = -1{,}078\ 76\ \frac{\Delta p}{E}$$

and for capped-ends:

$$\frac{\Delta r}{r} = \left(\frac{1{,}3 \times 228{,}6^2 + 0{,}4 \times 183{,}25^2}{228{,}6^2 - 183{,}25^2} \right) \frac{\Delta p}{E} = 4{,}356\ 47 \frac{\Delta p}{E}$$

$$\frac{\Delta x}{x} = \left(\frac{0{,}4 \times 183{,}25^2}{228{,}6^2 - 183{,}25^2} \right) \frac{\Delta p}{E} = 0{,}719\ 17 \frac{\Delta p}{E}$$

NOTE The ratio between capped-ends and no-ends for $\Delta r/r$ is = 4,356 47/4,895 85 = 0,89 as would be obtained from Figure 10.

The thin-walled pipe Equations (E.16) to (E.19) give:

For no-ends:

$$\frac{\Delta r}{r} = \frac{183{,}25}{45{,}35} \frac{\Delta p}{E} = 4{,}040\ 79\ \frac{\Delta p}{E}$$

$$\frac{\Delta x}{x} = -0{,}3\ \frac{183{,}25}{45{,}35} \frac{\Delta p}{E} = -1{,}212\ 24\ \frac{\Delta p}{E}$$

For capped-ends:

$$\frac{\Delta r}{r} = 0{,}85\ \frac{183{,}25}{45{,}35}\frac{\Delta p}{E} = 3{,}434\ 67\ \frac{\Delta p}{E}$$

$$\frac{\Delta x}{x} = 0{,}2\ \frac{183{,}25}{45{,}35}\frac{\Delta p}{E} = 0{,}808\ 16\ \frac{\Delta p}{E}$$

The thin-wall results are only shown here as an example, since the actual δ/r ratio being used is 0,247. Note, however, that the thick-wall to thin-wall ratio $\Delta r/r = 4{,}895\ 85/4{,}040\ 79 = 1{,}21$ for $\delta/r = 0{,}247$ for no-ends and $\Delta r/r = 4{,}356\ 47/3{,}434\ 67 = 1{,}27$ for capped-ends. These were the values used in the example in Figure E.4.

E.6.4 Direct single stage detailed calculation

From the example, the temperature and pressure difference between dynamic calibration and field operation is:

$\Delta T = 40 - 7 = +33$ °C $\qquad \Delta p = 23{,}0 - 6{,}3 = +16{,}7$ MPa

This gives:

$\Delta p/E = 16{,}7 \times 10^{6}/2 \times 10^{11} \qquad = 83{,}5 \times 10^{-6}$

$\Delta l_\mathrm{p} = (16{,}7 \times 10^{6}) \times (1{,}973\ 67 \times 10^{-9}) = 0{,}032\ 95$

a) Body temperature effect from Equation (E.10):

$q_{V,\,1}/q_{V,\,0} = 1 + (3 \times 1{,}26 \times 10^{-5} \times 33{,}0) = 1{,}001\ 247$

b) Body pressure effect from Equations (E.12) to (E.15) and Equation (E.43) is given for the following two cases.

No-ends:

$\Delta r/r = 4{,}895\ 85 \times 83{,}5 \times 10^{-6} = 4{,}088\ 03 \times 10^{-4}$

$\Delta x/x = -1{,}078\ 76 \times 83{,}5 \times 10^{-6} = -0{,}900\ 76 \times 10^{-4}$

The initial body pressure estimate is $4\Delta r/r$ = 0,164 %

Capped-ends:

$\Delta r/r = 4{,}356\ 47 \times 83{,}5 \times 10^{-6} = 3{,}637\ 66 \times 10^{-4}$

$\Delta x/x = 0{,}719\ 17 \times 83{,}5 \times 10^{-6} = 0{,}600\ 51 \times 10^{-4}$

c) Flange proximity from Equation (E.21):

$K_\mathrm{s} = 0{,}93$

d) Combined body pressure effect from Equations (E.22) to (E.25):

No-ends:

$d_1/d_0 = 1 + (0{,}93 \times 4{,}088\ 03 \times 10^{-4}) = 1{,}000\ 380$

$d_1 = 1{,}000\ 380 \times 366{,}5 = 366{,}639\ 3$

$x_1/x_0 = 1 - (0{,}900\ 76 \times 10^{-4}) = 0{,}999\ 910$

$x_1 = 0{,}999\ 910 \times 267{,}007 = 266{,}983\ 0$

$l_1 = (2^2 \times 366{,}639\ 3^2 + 266{,}983\ 0^2)^{0{,}5} = 780{,}370\ 1$

$l_1/l_0 = 780{,}370\ 1/780{,}117 = 1{,}000\ 324$

$q_{V,\,1}/q_{V,\,0} = 1{,}000\ 380^2 \times 1{,}000\ 324^2/0{,}999\ 910 = \mathbf{1{,}001\ 499}$

Capped-ends:

$d_1/d_0 = 1 + (0{,}93 \times 3{,}637\ 66 \times 10^{-4}) = 1{,}000\ 338$

$d_1 = 1{,}000\ 338 \times 366{,}5 = 366{,}623\ 9$

$x_1/x_0 = 1 + (0{,}600\ 51 \times 10^{-4}) = 1{,}000\ 060\ 1$

$x_1 = 1{,}000\ 060\ 1 \times 267{,}007 = 267{,}023\ 04$

$l_1 = (4 \times 366{,}623\ 9^2 + 267{,}023\ 04^2)^{0{,}5} = 780{,}354\ 8$

$l_1/l_0 = 780{,}354\ 8/780{,}117 = 1{,}000\ 305$

$q_{V,\,1}/q_{V,\,0} = 1{,}000\ 338^2 \times 1{,}000\ 305^2/1{,}000\ 060\ 1 = \mathbf{1{,}001\ 226}$

e) Port effects from Equations (E.29), (E.32), and (E.34):

Temperature $q_{V,\,1}/q_{V,\,0} = 1 + [4 \times 230 \times (1{,}25 - 1{,}5) \times 10^{-5} \times 33]/780{,}117 = 0{,}999\ 903$

Pressure $q_{V,\,1}/q_{V,\,0} = 1 + 4 \times 0{,}032\ 95/780{,}117 = 1{,}000\ 169$

Combined $q_{V,\,1}/q_{V,\,0} = 0{,}999\ 903 \times 1{,}000\ 169 = \mathbf{1{,}000\ 072}$

f) Overall combined flow correction from Equation (E.35):

No-ends:

$q_{V,\,1{,}0}/q_{V,\,0} = 1{,}001\ 247 \times 1{,}001\ 499 \times 1{,}000\ 072 = \mathbf{1{,}002\ 820}$

Capped-ends:

$q_{V,\,1{,}0}/q_{V,\,0} = 1{,}001\ 247 \times 1{,}001\ 226 \times 1{,}000\ 072 = \mathbf{1{,}002\ 547}$

$= \mathbf{1{,}002\ 684 \pm 0{,}000\ 136}$

$= \mathbf{1{,}002\ 7 \pm 0{,}000\ 1}$

In terms of $\Delta q_V/q_V$ from Equation (E.36) this is:

$\Delta q_{V,\,1{,}0}/q_{V,\,0} = +\mathbf{0{,}282\ 0\ \%}$ for no-ends

$= +\mathbf{0{,}254\ 7\ \%}$ for capped-ends

$= +\mathbf{(0{,}268\ 4 \pm 0{,}013\ 6)\ \%}$

$= +\mathbf{(0{,}27 \pm 0{,}01)\ \%}$

E.6.5 Three stage detailed calculation

E.6.5.1 Stage 1: Static calibration to dynamic calibration

$\Delta T = -13\ °\mathrm{C}\quad \Delta p = 6{,}3\ \mathrm{MPa}$

$\Delta p/E = 6{,}3 \times 10^6/2 \times 10^{11} = 3{,}15 \times 10^{-5}$

$\Delta l_\mathrm{p} = (6{,}3 \times 10^6) \times (1{,}973\ 67 \times 10^{-9}) = 0{,}012\ 43$

a) Body temperature effect from Equation (E.10):

$q_{V,\,1{,}0}/q_{V,\,0} = 1 + (3 \times 1{,}26 \times 10^{-5} \times -13{,}0) = \mathbf{0{,}999\,509}$

b) Body pressure effect from Equations (E.12) to (E.15) and Equation (E.43):

No-ends:

$\Delta r/r = 4{,}895\,85 \times 31{,}5 \times 10^{-6} = 1{,}542\,19 \times 10^{-4}$

$\Delta x/x = -1{,}078\,76 \times 31{,}5 \times 10^{-6} = -0{,}339\,81 \times 10^{-4}$

The initial body pressure estimate is 4 $\Delta r/r$ = **0,062 %**

Capped-ends:

$\Delta r/r = 4{,}356\,47 \times 31{,}5 \times 10^{-6} = 1{,}372\,29 \times 10^{-4}$

$\Delta x/x = 0{,}719\,17 \times 31{,}5 \times 10^{-6} = 0{,}226\,54 \times 10^{-4}$

c) Flange proximity from Equation (E.21):

$K_\mathrm{s} = 0{,}93$

d) Combined body pressure effect from Equations (E.22) to (E.25):

No-ends:

$d_1/d_0 = 1 + (0{,}93 \times 1{,}542\,19 \times 10^{-4}) = 1{,}000\,143$

$d_1 = 1{,}000\,143 \times 366{,}5 = 366{,}552\,6$

$x_1/x_0 = 1 - (0{,}339\,81 \times 10^{-4}) = 0{,}999\,967$

$x_1 = 0{,}999\,967 \times 267{,}007 = 266{,}997\,9$

$l_1 = (2^2 \times 366{,}552\,6^2 + 266{,}997\,9^2)^{0{,}5} = 780{,}212\,2$

$l_1/l_0 = 780{,}212\,2/780{,}117 = 1{,}000\,122$

$q_{V,\,1}/q_{V,\,0} = (1{,}000\,14^2 \times 1{,}000\,122^2)/0{,}999\,967 = \mathbf{1{,}000\,557}$

Capped-ends:

$d_1/d_0 = 1 + (0{,}93 \times 1{,}372\,29 \times 10^{-4}) = 1{,}000\,128$

$d_1 = 1{,}000\,128 \times 366{,}5 = 366{,}546\,8$

$x_1/x_0 = 1 + (0{,}226\,54 \times 10^{-4}) = 1{,}000\,022\,7$

$x_1 = 1{,}000\,022\,7 \times 267{,}007 = 267{,}013\,05$

$l_1 = (4 \times 366{,}546\,8^2 + 267{,}013\,05^2)^{0{,}5} = 780{,}206\,5$

$l_1/l_0 = 780{,}\ 206\,5/780{,}117 = 1{,}000\,115$

$q_{V,\,1}/q_{V,\,0} = (1{,}000\,128^2 \times 1{,}000\,115^2)/1{,}000\,022\,7 = \mathbf{1{,}000\,463}$

e) Port effects from Equations (E.29), (E.33), and (E.34):

Temperature $q_{V,\,1}/q_{V,\,0} = 1 + [4 \times 230 \times (1{,}25 - 1{,}5) \times 10^{-5} \times -13]/780{,}117 = 1{,}000\,038$

Pressure $q_{V,\,1}/q_{V,\,0} = 1 + (4 \times 0{,}012\,43)/780{,}117 = 1{,}000\,064$

Combined $q_{V,\,1}/q_{V,\,0} = 1{,}000\,038 \times 1{,}000\,064 = \mathbf{1{,}000\,102}$

f) Overall combined flow correction from Equation (E.35):

No-ends:

$$q_{V,\,1{,}0}/q_{V,\,0} = 0{,}999\,509 \times 1{,}000\,557 \times 1{,}000\,102 = \mathbf{1{,}000\,168}$$

Capped-ends:

$$q_{V,\,1{,}0}/q_{V,\,0} = 0{,}999\,509 \times 1{,}000\,463 \times 1{,}000\,102 = \mathbf{1{,}000\,074}$$

$$= \mathbf{1{,}000\,121 \pm 0{,}000\,047}$$

In terms of $\Delta q_{V0}/q_V$ from Equation (E.36) this is:

$\Delta q_{V,\,1{,}0}/q_{V,\,0} = +\mathbf{0{,}016\,8\ \%}$ for no-ends

$= +\mathbf{0{,}007\,4\ \%}$ for capped-ends

$$= +\mathbf{(0{,}012\,1 \pm 0{,}004\,7)\ \%}$$

E.6.5.2 Stage 2: Static calibration to field operation

$\Delta T = +20$ °C, $\Delta p = +23{,}0$ MPa

$$\Delta p/E = 230 \times 10^5/2 \times 10^{11} = 115 \times 10^{-6}$$

$$\Delta l_\text{p} = (230 \times 10^5) \times (1{,}973\,67 \times 10^{-9}) = 0{,}045\,39$$

a) Body temperature effect from Equation (E.10):

$$q_{V,\,1{,}0}/q_{V,\,0} = 1 + (3 \times 1{,}26 \times 10^{-5} \times 20{,}0) = \mathbf{1{,}000\,756}$$

b) Body pressure effect from Equations (E.12) to (E.15) and Equation (E.43):

No-ends:

$$\Delta r/r = 4{,}895\,85 \times 115 \times 10^{-6} = 5{,}630\,23 \times 10^{-4}$$

$$\Delta x/x = -1{,}078\,76 \times 115 \times 10^{-6} = -1{,}240\,57 \times 10^{-4}$$

The initial body pressure estimate is $4 \times \Delta r/r = 4 \times 5{,}630\,23 \times 10^{-4} = \mathbf{0{,}23\ \%}$

Capped-ends:

$$\Delta r/r = 4{,}\ 356\,47 \times 115 \times 10^{-6} = 5{,}009\,94 \times 10^{-4}$$

$$\Delta x/x = 0{,}719\,17 \times 115 \times 10^{-6} = 0{,}827\,05 \times 10^{-4}$$

c) Flange proximity from Equation (E.21):

$K_\text{s} = 0{,}93$

d) Combined body pressure effect from Equations (E.22) to (E.25):

No-ends:

$$d_2/d_0 = 1 + (0{,}93 \times 5{,}630\,23 \times 10^{-4}) = 1{,}000\,524$$

$$d_2 = 1{,}000\,524 \times 366{,}5 = 366{,}691\,9$$

$$x_2/x_0 = 1 - (1{,}240\,57 \times 10^{-4}) = 0{,}999\,876$$

$$x_2 = 0{,}999\,876 \times 267{,}007 = 266{,}973\,9$$

$$l_2 = (2^2 \times 366{,}691\,9^2 + 266{,}973\,9^2)^{0{,}5} = 780{,}465\,8$$

$l_2/l_0 = 780{,}465\ 8/780{,}117 = 1{,}000\ 448$

$q_{V,\,2}/q_{V,\,0} = (1{,}000\ 524^2 \times 1{,}000\ 448^2)/0{,}999\ 876 = \mathbf{1{,}002\ 070}$

Capped-ends:

$d_2/d_0 = 1 + (0{,}93 \times 5,\ 009\ 94 \times 10^{-4}) = 1{,}000\ 466$

$d_2 = 1{,}000\ 466 \times 366{,}5 = 366{,}670\ 8$

$x_2/x_0 = 1 + (0{,}827\ 05 \times 10^{-4}) = 1{,}000\ 082\ 7$

$x_2 = 1{,}000\ 082\ 7 \times 267{,}007 = 267{,}029\ 08$

$l_2 = (4 \times 366{,}670\ 8^2 + 267{,}029\ 08^2)^{0{,}5} = 780{,}445\ 0$

$l_2/l_0 = 780{,}445\ 0/780{,}117 = 1{,}000\ 420$

$q_{V,\,2}/q_{V,\,0} = (1{,}000\ 466^2 \times 1{,}000\ 420^2)/1{,}000\ 082\ 7 = \mathbf{1{,}001\ 690}$

e) Port effects from Equations (E.29), (E.33), and (E.34):

Temperature $q_{V,\,2}/q_{V,\,0} = 1 + [4 \times 230 \times (1{,}25 - 1{,}5) \times 10^{-5} \times 20]/780{,}117 = 0{,}999\ 941$

Pressure $q_{V,\,2}/q_{V,\,0} = (1 + 4 \times 0{,}045\ 39)/780{,}117 = 1{,}000\ 233$

Combined $q_{V,\,2}/q_{V,\,0} = 0{,}999\ 941 \times 1{,}000\ 233 = \mathbf{1{,}000\ 17}$

f) Overall combined flow correction from Equation (E.35):

No-ends:

$q_{V,\,2{,}0}/q_{V,\,0} = 1{,}000\ 756 \times 1{,}002\ 070 \times 1{,}000\ 17 = \mathbf{1{,}002\ 998}$

Capped-ends:

$q_{V,\,2{,}0}/q_{V,\,0} = 1{,}000\ 756 \times 1{,}001\ 690 \times 1{,}000\ 17 = \mathbf{1{,}002\ 618}$

$= 1{,}002\ 808 \pm 0{,}000\ 19$

In terms of $\Delta q_V/q_V$ from Equation (E.36), this is:

$\Delta q_{V,\,2{,}0}/q_{V,\,0} = \mathbf{+0,\ 299\ 8\ \%}$ for no-ends

$= \mathbf{+0,\ 261\ 8\ \%}$ for capped-ends

$= \mathbf{+(0{,}280\ 8 \pm 0{,}001\ 9)\ \%}$

E.6.5.3 Stage 3: Dynamic calibration to field operation flow correction factor

The overall flow correction is obtained from Equation (E.6):

No-ends:

$$\frac{q_{V,\,2{,}1}}{q_{V,\,1}} = \frac{q_{V,\,2{,}0}}{q_{V,\,0}} \frac{q_{V,\,0}}{q_{V,\,1{,}0}} = \frac{1{,}002\ 998}{1{,}000\ 168} = 1{,}002\ 830$$

Capped-ends:

$$\frac{q_{V,\,2{,}1}}{q_{V,\,1}} = \frac{q_{V,\,2{,}0}}{q_{V,\,0}} \frac{q_{V,\,0}}{q_{V,\,1{,}0}} = \frac{1{,}002\ 618}{1{,}000\ 074} = 1{,}002\ 544$$

$= \mathbf{1{,}002\ 687 \pm 0{,}000\ 143}$

In terms of $\Delta q_V/q_V$ this is:

$\Delta q_{V,\,2,1}/q_{V,\,1}$ $= +$**0, 283 0 %** for no-ends
$= +$**0, 254 4 %** for capped-ends
$= +$**(0,268 7 ± 0,014 3) %**

Expressed to the precision of Equations (21) and (22), this gives:

$q_{V,\,2}/q_{V,\,1}$ $=$ **1,002 7 ± 0,000 1**

$\Delta q_{V,\,2}/q_{V,\,1}$ $=$ **(0,27 ± 0,01) %**

E.7 Observations on the example calculation

E.7.1 General

Note that, for the sake of calculation accuracy, individual values during the calculations have generally been quoted to six significant figures, but it should be realized that this does not reflect the implied accuracy of the prediction method. It is felt that, as stated in 4.7.6, the final overall flow correction factor, $q_{V,\,2}/q_{V,\,1}$, should be quoted to four decimal places and $\Delta q_V/q_V$ to two decimal places.

In terms of final flow correction error between the dynamic calibration conditions and operating conditions, the difference between the direct single stage calculation of E.6.4 and the more complex three stage approach of E.6.5 are negligible. As mentioned in E.1, the three stage approach may, however, be more useful to compare intermediate results and specific dimensions with those from an FE model.

It is also noticeable that the initial flow error estimate made in E.6.2 using the simple approach outlined in 4.7 is the same as the result of the more detailed calculation of E.6.4 or E.6.5. This is most probably a feature of the example chosen since a minor difference would be expected.

The intermediate stages in the calculation are useful to gauge the relative sizes, and hence importance, of the flow correction effects due to the causes described in E.7.2 to E.7.7.

E.7.2 Initial body pressure estimate

The initial body pressure effect estimates were 0,062 % and 0,23 % for the two cases examined and these compare with values of 0,056 % and 0,21 % from the more detailed calculation in Step 4 for each case. In both cases, as expected, the initial estimate is higher than the more detailed calculation.

E.7.3 Meter end-loading conditions

The variation in end loading only affects the change in body dimensions due to pressure effects. The use of the no-ends condition and the capped-ends condition provides an indication of the sensitivity of the correction to the end-loading conditions. In the two cases looked at, the variation between the no-ends and capped-ends cases is only +0,05 % to +0,06 % in case 1 and +0,17 % to +0,21 % in case 2. This would indicate that the end-loading conditions are of secondary importance.

E.7.4 Body pressure effect

For the two cases considered, the body pressure was of the order of +0,05 % in case 1 (6,3 MPa) and +0,2 % in case 2 (23,0 MPa). Of that, the area effect, due to $(d_1/d_0)^2$, was of the order of 0,027 % and 0,09 %, respectively, for the two cases; hence the area effect accounts for roughly half of the flow correction.

E.7.5 Body temperature effects

For the two cases considered, the body temperature effects were −0,05 % for case 1 (−13 °C) and +0,08 % for case 2 (+20 °C). This would indicate that temperature effects are equally important to pressure effects. Note that in case 1, because ΔT was negative, its effect partly cancelled the pressure effect whereas in case 2, ΔT was positive and its effect added to the pressure effect.

E.7.6 Port effects

Due to the way transducers are held in the port, it is possible for the temperature effects to cancel (i.e. port extension is cancelled by transducer growth). The combined pressure and temperature effect in case 1 is +0,01 % and in case 2 +0,02 %. This indicates that transducer port effects are an order of magnitude smaller than either the temperature or pressure effects on the meter body itself.

E.7.7 Comparison against the results of an FE model

The pressure and temperature conditions and meter dimensions used in the worked examples have been based on conditions that have also been used in an FE model. Results from this show flow errors of +0,003 % to +0,006 % for single bounce diametral paths for case 1 and combined flow error for the difference between case 2 and case 1 of +0,264 % to +0,272 %. These compare very favourably with the +0,007 % to +0,017 % for case 1 and +0,25 % to + 0,28 % for the combined case 2 and case 1 calculated in E.6.5. Agreement is to within 0,01 % on overall percentage flow error.

E.7.8 Conclusion

These observations are made on the particular cases examined in this specific example. Consequently, some variation between the magnitude of various effects with different metering models and operating conditions can be expected. However, the relative size of specific effects can still be expected to be consistent with the observations made in the example calculations.

Annex F
(informative)

Disturbance tests

Table F.1 — Disturbance tests

No	Test (applicable standard)	Subclause	I/D	Requirement		Severity
1	Dry heat IEC 60068-2-2[5], IEC 60068-3-1[13]	10.1.1	I[a]	MPE[c]		rated temperature
2	Cold IEC 60068-2-1[4], IEC 60068-3-1[13]	10.1.2	I[a]	MPE[c]		rated temperature
3	Damp heat, steady state (non-condensing) IEC 60068-2-78[12], IEC 60068-3-4[14]	10.2.1	I[a]	MPE[c]	1	+30 °C 85 % r.h.[h] 2 days
4	Damp heat, cyclic (condensing) IEC 60068-2-30[8], IEC 60068-3-4[14]	10.2.2	D[b]	NSFa[d]	2	+25 °C to 55 °C 95 % r.h.[h] during change 93 % r.h.[h] upper phase two cycles of 24 h
5	Water IEC 60068-2-18[7], IEC 60512-14-7[16], IEC 60529[17]	10.3	D[b]	NSFa[d]	2	0,07 l/min 10 min ±180°
6	Vibration (random) IEC 60068-2-47[10], IEC 60068-2-64[11], IEC 60068-3-8[15]	11.1.1	I[a]	MPE[c]	2	10 Hz to 150 Hz 7 m^2/s 3 axes 2 min
7	Vibration (sinusoidal) IEC 60068-2-6[6], IEC 60068-2-47[10], IEC 60068-3-8[15]	11.1.2	I[a]	MPE[c]	2	10 Hz to 150 Hz 10 m^2/s 3 axes $\geqslant$2 min
8	Mechanical shock IEC 60068-2-31[9]	11.2	D[b]	NSFa[d]	2	two times each bottom edge 50 mm height
9	Radiated, radio-frequency, electromagnetic fields IEC 61000-4-3[23]	12.1.1	D[b]	NSFd[e]	3	general origin 26 MHz to 800 MHz, 10 V/m 80 % AM[i], 1 kHz, sine wave digital radio telephones 800 MHz to 960 MHz, 10 V/m 1 400 MHz to 2 000 MHz, 10 V/m 80 % AM[i], 1 kHz, sine wave
10	Conducted radio-frequency fields IEC 61000-4-6[26]	12.1.2	D[b]	NSFd[e]	3	0,15 MHz to 80 MHz 10 V (e.m.f. [j]) 80 % AM[i], 1 kHz sine wave
11	Electrostatic discharge IEC 61000-4-2[22]	12.2	D[b]	NSFa[d]	3	contact discharge 6 kV air discharge 8 kV 10 discharges
12	Power frequency magnetic field IEC 61000-4-8[27]	12.3	D[b]	NSFd[e]	5	continuous field 100 A/m short duration 1 000 A/m
13	Bursts (transients) on signal, data and control lines IEC 61000-4-1[21], IEC 61000-4-4[24]	12.4	D[b]	NSFd[e]	3	amplitude 1 kV repetition rate 5 kHz

Table F.1 (*continued*)

No	Test (applicable standard)	Subclause	I/D	Requirement		Severity
14	Surges on signal, data and control lines IEC 61000-4-5[25]	12.5	D[b]	NSFa[d]	3	unsymmetrical: — line to line 1 kV — line to ground 2 kV symmetrical: — line to line N.A. — line to ground 2 kV
15	DC mains voltage variation IEC 60654-2[18]	13.1	I[a]	MPE[c]	1	U_{min} U_{max}
16	AC mains voltage variation IEC/TR 61000-2-1[19], IEC 61000-4-1[21]	13.2	I[a]	MPE[c]	1	$U_{\text{nom}}{}^{+10\ \%}_{-15\ \%}$
17	AC mains frequency variation IEC/TR 61000-2-1[19], IEC 61000-2-2[20], IEC 61000-4-1[21]	13.3	I[a]	MPE[c]	1	f_{nom} ±2 %
18	AC mains voltage dips, short interruptions and voltage variations IEC 61000-4-11[28], IEC 61000-6-1[31], IEC 61000-6-2[32]	13.4	D[b]	NSFd[e]	3	Test a: 0 % 0,5 cycles Test b: 0 % 1 cycle Test c: 40 % 10 cycles /12 cycles Test d: 70 % 25 cycles /30 cycles Test e: 80 % 250 cycles /300 cycles
19	Bursts (transients) on AC and DC mains IEC 61000-4-1[21], IEC 61000-4-4[24]	13.5	D[b]	NSFd[e]	3	amplitude 2 kV repetition rate 5 kHz
20	Voltage dips, short interruptions and voltage variations on DC mains power IEC 61000-4-29[30]	13.6	D[b]	NSFa[d,f] NSFd[e,g]	1	voltage dips 40 % and 70 % for 0,01 s; 0,03 s; 0,1 s; 0,3 s; 1 s short interruptions 0 % for 0,001 s; 0,003 s; 0,01 s; 0,03 s; 0,1 s; 0,3 s; 1 s voltage variation 85 % to 120 % of rated voltage for 0,1 s; 0,3 s; 1 s; 3 s; 10 s
21	Ripple on DC mains power IEC 61000-4-17[29]	13.7	D[b]	NSFd[e]	1	2 % nominal voltage
22	Surges (transients) on AC and DC mains lines IEC 61000-4-5[25]	13.8	D[b]	NSFa[d]	3	line to line 1 kV line to earth 2 kV

[a] Influence factor.

[b] Disturbance.

[c] Maximum permissible error.

[d] No significant fault shall occur after the disturbance.

[e] No significant fault shall occur during the disturbance.

[f] For integrating instruments.

[g] For non-integrating instruments.

[h] Relative humidity.

[i] Amplitude modulation.

[h] Electromotive force.

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