INTERNATIONAL STANDARD

ISO 17089-2

First edition
2012-10-01

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

Part 2: Meters for industrial applications

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

Partie 2: Compteurs pour applications industrielles

Reference number
ISO 17089-2:2012(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 17089-2 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*

— *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. As well as offering 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 verify not only the functionality of a USM, but also 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.

This part of ISO 17089 focuses on meters for industrial gas applications (class 3 and class 4). Meters for custody transfer and allocation measurement are the subject of ISO 17089-1.

Typical performance factors of the classification scheme are:

Class	Typical applications	Typical uncertainty 95 % confidence level (volume flow rate)[a]	Reference
1	Custody transfer	±0,7 %	ISO 17089-1
2	Allocation	±1,5 %	ISO 17089-1
3	Utilities and process	±1,5 % to 5 % for $q_V > q_{V,\mathrm{t}}$[b]	This part of ISO 17089
4	Flare gas and vent gas	±5 % to 10 % for $q_V > q_{V,\mathrm{t}}$	This part of ISO 17089

[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 speed of sound, as well as meter timing repeatability.

[b]By specific flow conditioning or when multi-path meters are employed, lower uncertainties may be achieved.

The special application note(s) as presented in Clause 7 as well as information in parentheses are informative.

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

Part 2:
Meters for industrial applications

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 meters (USMs), which utilize acoustic signals to measure the flow in the gaseous phase in closed conduits.

This part of ISO 17089 is applicable to transit time USMs and is focused towards industrial flow measurement. Included are meters comprising meter bodies as well as meters with field-mounted transducers.

There are no limits on the size of the meter. It can be applied to the measurement of almost any type of gas; such as but not limited to air, hydrocarbon gases, and steam.

This part of ISO 17089 specifies performance, calibration (when required), and output characteristics of USMs 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*

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,[8] 4-30.

3.1.2.1.1
actual flow rate
volume of fluid per time at metering conditions

3.1.2.1.2
corrected flow rate
volume of fluid per time measured at metering conditions, but converted to equivalent volume at base conditions

3.1.2.2
indication
flow rate indicated by the meter

3.1.2.3
working range
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,[10] 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, $q_{V,\,\text{max}}$, and a minimum flow rate, $q_{V,\,\text{min}}$; the “given measuring instrument” is a meter.

NOTE 3 The terms “rangeability” and “turndown” can often be found in flowmeter data sheets in connection with the working range of the meter. These terms are sometimes used interchangeably although their exact meanings are different and may not mean the same as working range. For example, it is possible to find a stated flowmeter rangeability derived from the highest measurable flow divided by the minimum measurable flow (typically with flow expressed in terms of flow velocity).

3.1.2.4
metering pressure
p
absolute gas pressure in a meter at flowing conditions to which the indicated volume of gas is related

3.1.2.5
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.

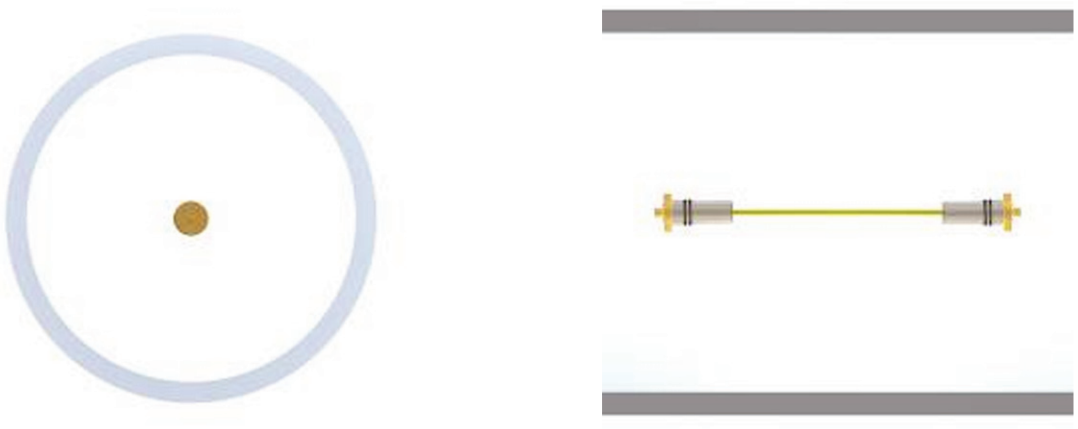


Figure 1 — Axial path

3.1.3.4
diametrical path
acoustic path whereby the acoustic wave travels through the centre-line or long axis of the pipe

See Figure 2.

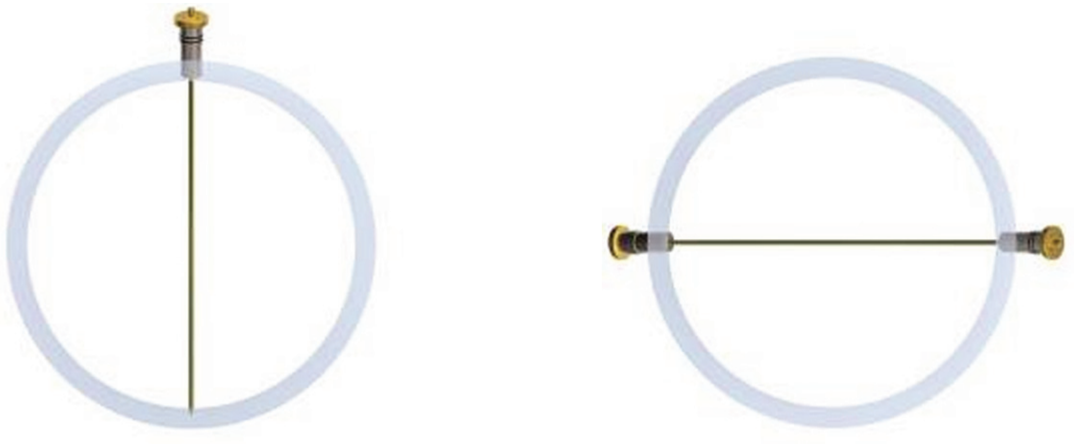


Figure 2 — Diametrical paths

3.1.3.5
chordal path
acoustic path whereby the acoustic wave travels parallel to the diametrical path

See Figure 3.

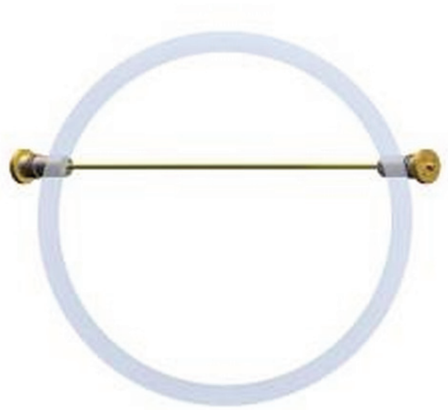


Figure 3 — Chordal paths

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 also known as uncorrected conditions.

NOTE 2 Adapted from ISO 9951:1993,[5] 3.1.6.

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

NOTE 1 Base conditions include base temperature and base pressure.

NOTE 2 Adapted from ISO 9951:1993,[5] 3.1.7.

NOTE 3 Preferred alternatives include reference conditions, standard conditions, normal conditions.

NOTE 4 Metering and base conditions relate only to the volume of the gas to be measured or indicated, and should not be confused with rated operating conditions and reference operating conditions (see ISO/IEC Guide 99:2007,[10] 4.9 and 4.11), which refer to influence quantities (see ISO/IEC Guide 99:2007,[10] 2.52).

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,[5] 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,[10] 2.16]

EXAMPLE Difference between the indication of the meter under test and the indication of the reference measurement.

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

3.1.5.4
repeatability
measurement precision under a set of repeatability conditions of measurement

[ISO/IEC Guide 99:2007,[10] 2.21]

EXAMPLE The closeness of agreement among a number of consecutive measurements of the output of the test meter for the same reference flow rate under the same metering conditions.

NOTE The repeatability corresponds to the 95 % confidence interval of the error.

3.1.5.5
resolution
smallest difference between indications of a meter that can be meaningfully distinguished

NOTE Adapted from ISO 11631:1998,[6] 3.28.

3.1.5.6
velocity sampling interval
time interval between two consecutive gas velocity measurements

3.1.5.7
zero flow reading
flowmeter indication when the gas is at rest, when both axial and non-axial velocity components are essentially zero

Figure 4 shows the flow rates in relation to the uncertainty budget.

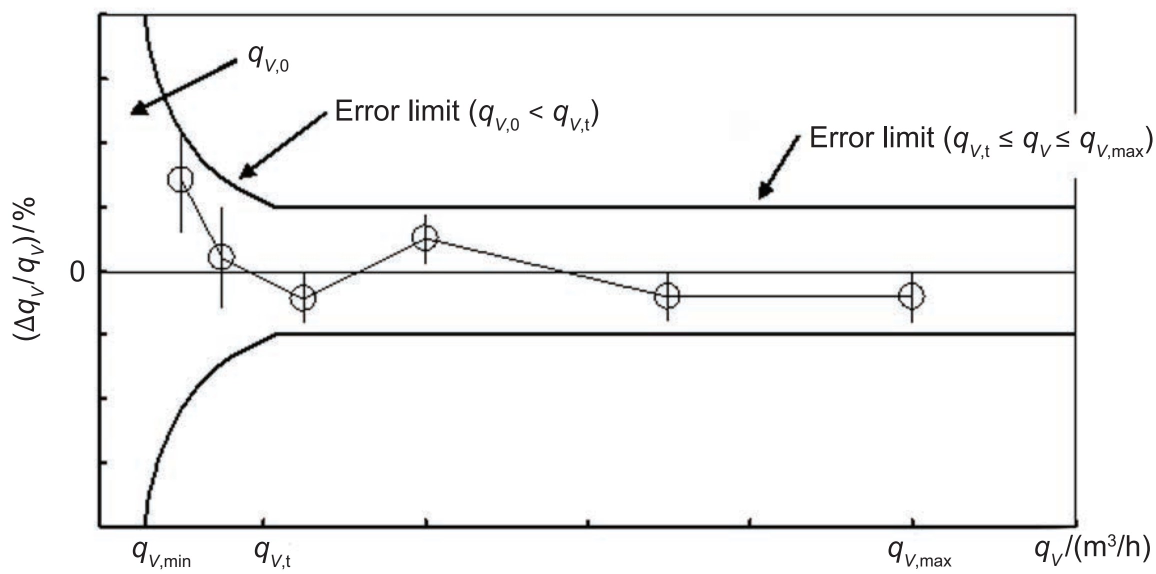


Figure 4 — Typical error curve as function of the flow rate

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
Inside diameter of the meter body	D	L	m
Weighting factors (live inputs)	f_i	1[b]	—
Integers (1,2,3, …)	i,n	1[b]	—
Calibration factor	K	1[b]	—
Flow profile correction factor	k_n	1[b]	—
Valve noise	$L_{p,\mathrm{N,v}}$	1[b]	dB
Path length	l_p	L	m
Attenuation factor	N_d	1[b]	—
Valve weighting factor	N_v	1[b]	—
Number of samples used in the signal processing.	n_s	1[b]	—
Absolute pressure	p	$ML^{-1}T^{-2}$	Pa
Emitted acoustic pressure	p_n	$ML^{-1}T^{-2}$	Pa
Pressure difference	Δp	$ML^{-1}T^{-2}$	Pa
Mass flow rate	q_m	MT^{-1}	kg/s
Volume flow rate	q_V	L^3T^{-1}	m^3/s
Transit time	t	T	s
Average velocity	v	LT^{-1}	m/s
Velocity of the acoustical path i	v_i	LT^{-1}	m/s
Weighting factors (fixed value)	w_i	1[b]	—
Path angle	ϕ	—	rad
Density of the fluid	ρ	ML^{-3}	kg/m^3

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

[b] "Dimensionless" quantity.

Table 2 — Subscripts

Subscript	Meaning
min	minimum
max	maximum
t	transition

Table 3 — Examples of flow rate symbols

Symbol	Meaning
$q_{V,\mathrm{max}}$	Designed maximum flow rate
$q_{V,\mathrm{min}}$	Designed minimum flow rate
$q_{V,\mathrm{t}}$	Transition flow rate for defining accuracy requirements

3.3 Abbreviations

ES	electronic system
FAT	factory acceptance test
FC	flow conditioner
MSOS	measured speed of sound
SNR	signal-to-noise ratio
SOS	speed of sound
TSOS	theoretical speed of sound
USM	ultrasonic flowmeter
USMP	USM package, including upstream pipe, flow conditioner and thermo-well when bi-directional

4 Principles of measurement

4.1 Transit time ultrasonic meters

Figure 5 outlines the basic system setup to demonstrate the transit time principle. A pair of transducers capable of transmitting and receiving ultrasonic pulses is located on both sides of the pipe at positions A and B. The transducers transmit and receive pulses sequentially. Under zero flow conditions, the time taken for an ultrasonic pulse to travel from A to B, t_{AB}, is equal to that from B to A, t_{BA}, and there is no difference in time.

When a flow is introduced, the ultrasonic pulse from A to B is assisted by the flow, and as a result the time taken decreases. In addition, the pulse from B to A is opposed by the flow and subsequently the time taken increases. The resulting measured difference in transit time is directly proportional to the axial velocity of the flowing gas. Providing that the distance between the transducers is known, the axial gas velocity passing between transducer A and B can be measured. Ignoring second order effects such as path curvature, the travel times of the acoustic pulse, t_{AB} and t_{BA}, can be shown to be given by:

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

and

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

where

l_{p} is the path length;

c is the speed of sound (SOS) in the gas;

v is the average velocity of the gas;

ϕ is the path angle.

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

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

It is important to note that, in Formula (3), the term for the SOS in the gas has been eliminated. This means that the measurement of the gas velocity is independent of the properties of the gas, such as pressure, temperature, and gas composition. Nonetheless, if the transducers are recessed, it is possible that there is an additional influence which is SOS dependent.

In a similar way, the SOS is derived by adding Formula (1) and Formula (2):

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

In multipath meters, the individual path velocity measurements are combined by a mathematical function to yield an estimate of the mean pipe velocity:

$$v = f\left(v_1 \ldots v_n\right) \quad (5)$$

where n is the total number of paths. Due to variations in path configuration and different proprietary approaches of solving Formula (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, the estimate of the mean pipe velocity, v, is multiplied by the cross-sectional area of the measurement section, A, as follows:

$$q_V = Av \quad (6)$$

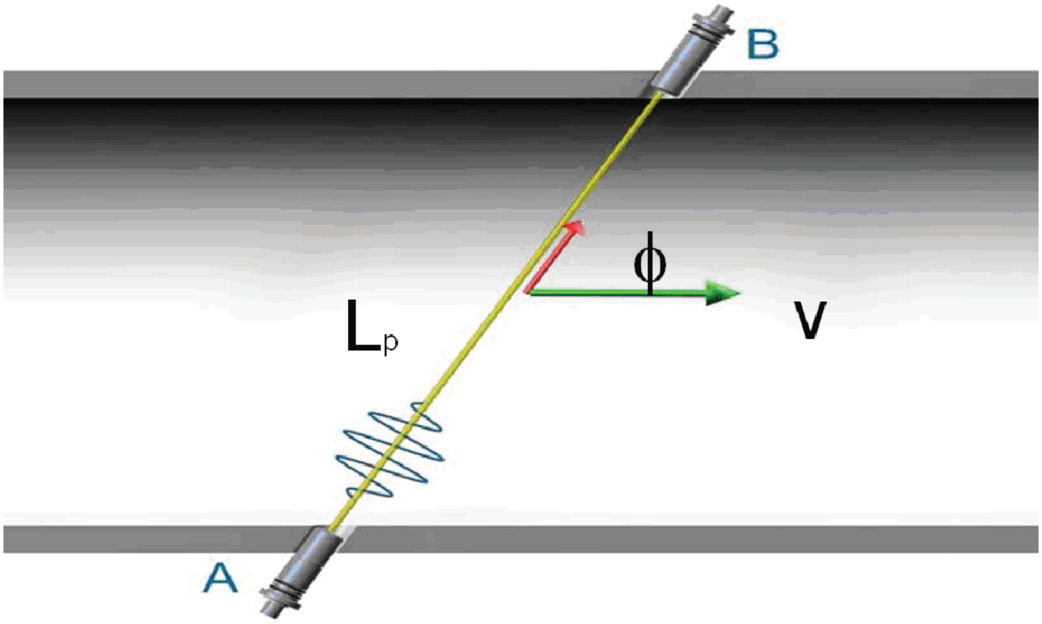


Figure 5 — Basic system setup

4.2 Flare or vent gas meters

In addition to class 1, 2, and 3 meters, ultrasonic transit time meters are also utilized extensively in class 4 measurement of flare or vent gas. Although the application is very different from that associated with class 1, 2 or 3 m, the transit time principle outlined above is still applicable.

The pipe sizes used for vent or flare systems within refineries, chemical plants or on production platforms can be very large in diameter, and the composition and process conditions of flare or vent gas often vary substantially between steady-state conditions and upset conditions. Rapid changes in pressure, temperature, gas composition, and flowing velocity frequently occur as a result of a plant or process upset. The user should ensure that a USM purchased for flare gas duty has been designed to accommodate such conditions. The addition of temperature and pressure inputs is also required to enable standard volume flow to be derived, and this may be a requisite for emissions reporting or even operational consent. A further requirement for plant mass balance and steam injection control for the flare stack tip is mass flow calculation. Some USMs may employ proprietary algorithms that utilize the MSOS, and absolute pressure and temperature inputs of the gas to infer the average molecular weight, and hence mass flow.

The user is advised to check with the USM manufacturer that the gas composition, process temperature and pressure remain compatible with any molecular weight or mass flow algorithms involved throughout the expected range of these process variables.

4.3 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 mean velocity (the latter of which determines the sensitivity of the meter to variations in the flow velocity distribution).

Extrinsic factors, i.e. those related to the process and ambient 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) temperature and pressure;

7) acoustic attenuation by specific gases (such as carbon dioxide);

8) acoustic effects by specific gases (such as hydrogen).

4.4 Description of generic types

4.4.1 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 be comprised of several components, namely:

a) transducers;

b) meter body with acoustic path configuration;

c) electronics;

d) a data-processing and presentation unit.

4.4.2 Transducers

Transducers for a USM function as pairs of known acoustic characteristics. Each individual transducer comprises an acoustic element with electrical connections and a supporting mechanical structure with which the process connection is made.

The transducers may be in contact with the process fluid (also termed invasive) as part of a meter body in a factory manufactured USM, but may also be field mounted as part of a retrofit installation to an existing pipe. Alternatively, transducers may be clamp-on (also termed non-invasive) with reference to a closed conduit (commonly termed: meter body; spool piece; process pipe; or parent pipe).

a) Wetted transducers are in direct contact with the fluid and may be supplied as an integral part of a meter body, or separately as part of a cold-tap or hot-tap field-mounting kit, to be fabricated on an existing process pipe.

b) A cold-tap installation requires that the process pipe is out of service, isolated, empty, and regarded as safe for cutting and welding.

c) A hot-tap installation is by contrast performed on a process pipe which is in active service and thus full of process fluid and at a pressure and/or temperature that are different to ambient and considered hazardous. Such an installation requires a special transducer insertion mechanism which achieves a leak- and pressure-tight seal of the process during the requisite hole-tapping operation.

d) Isolation valves are also employed on spool, hot-tap, and cold-tap installations to allow the transducer to be inserted or withdrawn with the valve opened.

It may be necessary for wetted transducers to be inserted into the bore of the meter body or parent pipe, possibly in conditions of atmospheric or very low pressure. In this situation, the transducer is termed intrusive in addition to being invasive.

Wetted transducers may also include a buffer which serves to isolate the transducer from aspects of the process fluid which may be harmful to it, such as cryogenic or very high temperature and/or high pressure. Such a buffer design typically also serves to maintain the pipe integrity in the event of transducer removal being necessary, and may even serve to enhance acoustic transmission by acting as a waveguide.

Clamp-on transducers may be made of metal or composite material and attached to the pipe by an appropriate clamping fixture. The pipe wall is an integral part of the flowmeter and the acoustic characteristics of the material, the thickness, the inside and the outside conditions as well as the position of the flanges need to be considered. The maximum angle of the acoustic path is limited and mostly determined by the ratio of the SOS between the pipe wall material and the fluid.

Typical diagrams of wetted, clamp-on and buffered transducers are given in Figure 6.

Due to the wide range of operating conditions within industry, there is no single design of transducer that is technically and commercially viable for all situations, and thus designs are many and varied. Accordingly, the user is advised to consult the USM manufacturer for correct transducer selection and application advice.

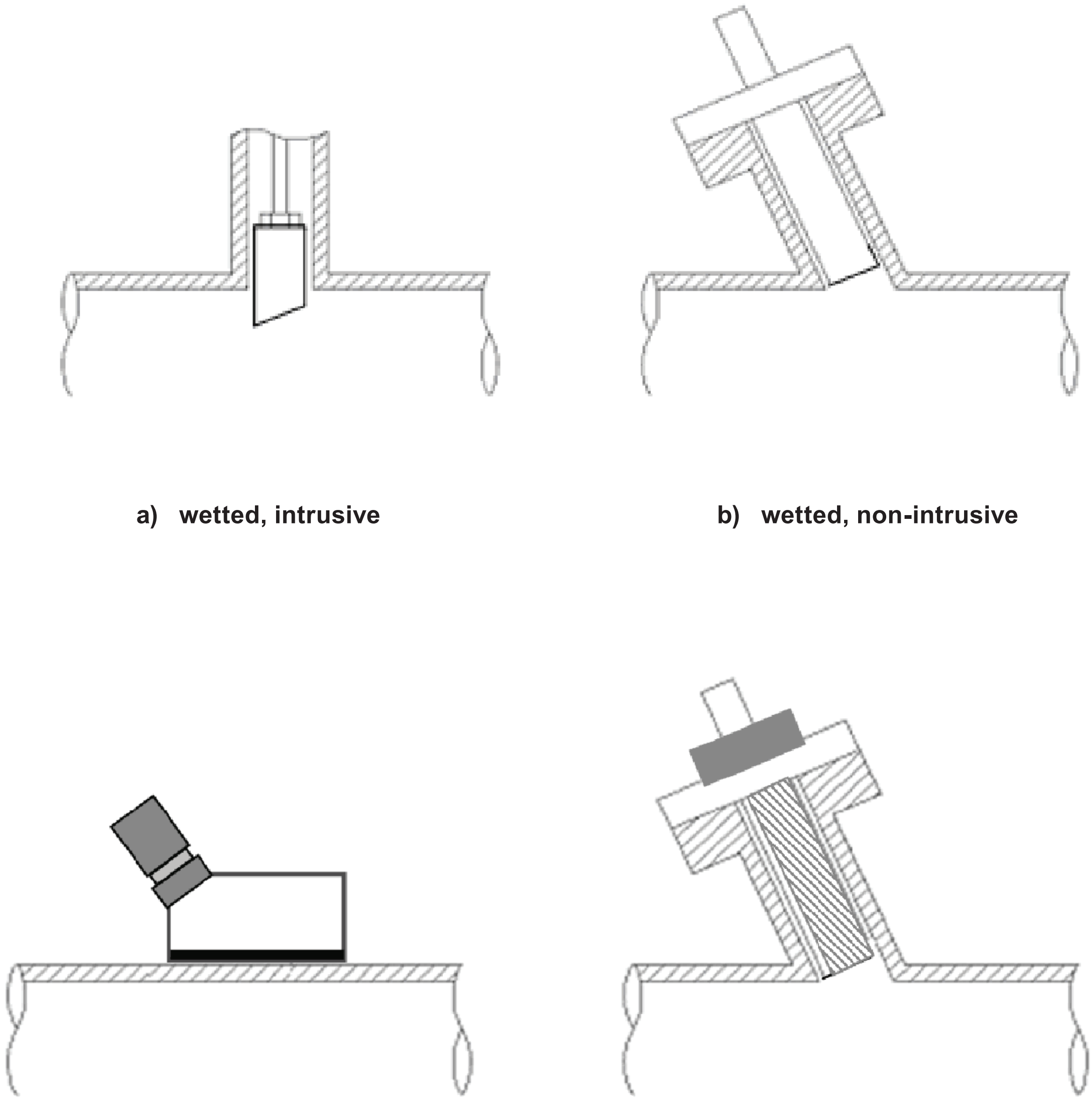
4.4.3 Meter body and acoustic path configurations

4.4.3.1 General

Clamp-on and wetted USMs for measurement of gases and vapours are available in a variety of single and multi-path configurations. The number of measurement paths required, and the configuration of those paths, may be influenced by the accuracy requirement or any potential variations in velocity distribution.

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.

Multi-path configurations may also offer redundancy of measurement paths, if so configured, to provide a safeguard if one path becomes inoperative. Alternatively, they may be utilized to offer reduced measurement uncertainty over the entire flow range, i.e. low-flow measurement paths and high-flow measurement paths (e.g. by pre-setting the angle of the sensor head).



a) wetted, intrusive **b) wetted, non-intrusive**

c) clamp-on **d) buffered**

Figure 6 — Typical transducer arrangements

4.4.3.2 Basic acoustic path configurations

Common acoustic path configurations are illustrated in Figure 7.

Path configurations may be described as shown in Figure 7 as:

a) diametric paths — paths that are across the diameter of the pipe;

b) chordal paths — paths that follow a chord of the pipe diameter;

c) bounced paths — paths with one reflection;

d) bounced paths — paths with more than one reflection;

e) partial path — path that partially follows a chord of the pipe diameter having intrusive transducers;

f) partial path — path that partially follows a chord of the pipe diameter, single probe mounted.

4.4.3.3 Flow profile correction factors, k_n

USMs are sensitive to velocity profile effects in both fully developed and disturbed flow conditions, since the devices estimate the average velocity across the whole of the pipe cross-section by measuring the average velocity along the path. Even in fully developed flow, the value of the profile correction factor, k_n, is not unity and depends on the Reynolds number and pipe wall roughness.

Depending on the path configuration, a correction based on the Reynolds number might or might not be incorporated by the manufacturer. Where used, effective correction normally depends upon the input during commissioning of relevant viscosity data for the process fluid, from which a Reynolds number can be calculated, and a correction factor established and applied.

The manufacturer should be asked whether there is a recommended meter orientation for upstream piping configurations and operational conditions which are known to produce flow profile distortions.

If profiles are disturbed, the profile correction factor for fully developed flow is no longer applicable. The flow profile can be disturbed by upstream pipe work configurations such as bends, expansions and contractions and the presence of valves and pumps.

4.4.3.4 Meters with paths at multiple radial displacements

In these meters, the velocity is measured at different radial positions. Several methods can be used when combining the velocities to obtain the mean pipe velocity. These can be classified as follows.

a) Summation with constant weighting:

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

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

b) Summation with variable weighting:

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

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

In any of the given configurations, a multiplying or meter factor, K (either constant or variable), may be applied after summation to correct for deviations due to manufacturing tolerances:

$$q_V = KAv \qquad (9)$$

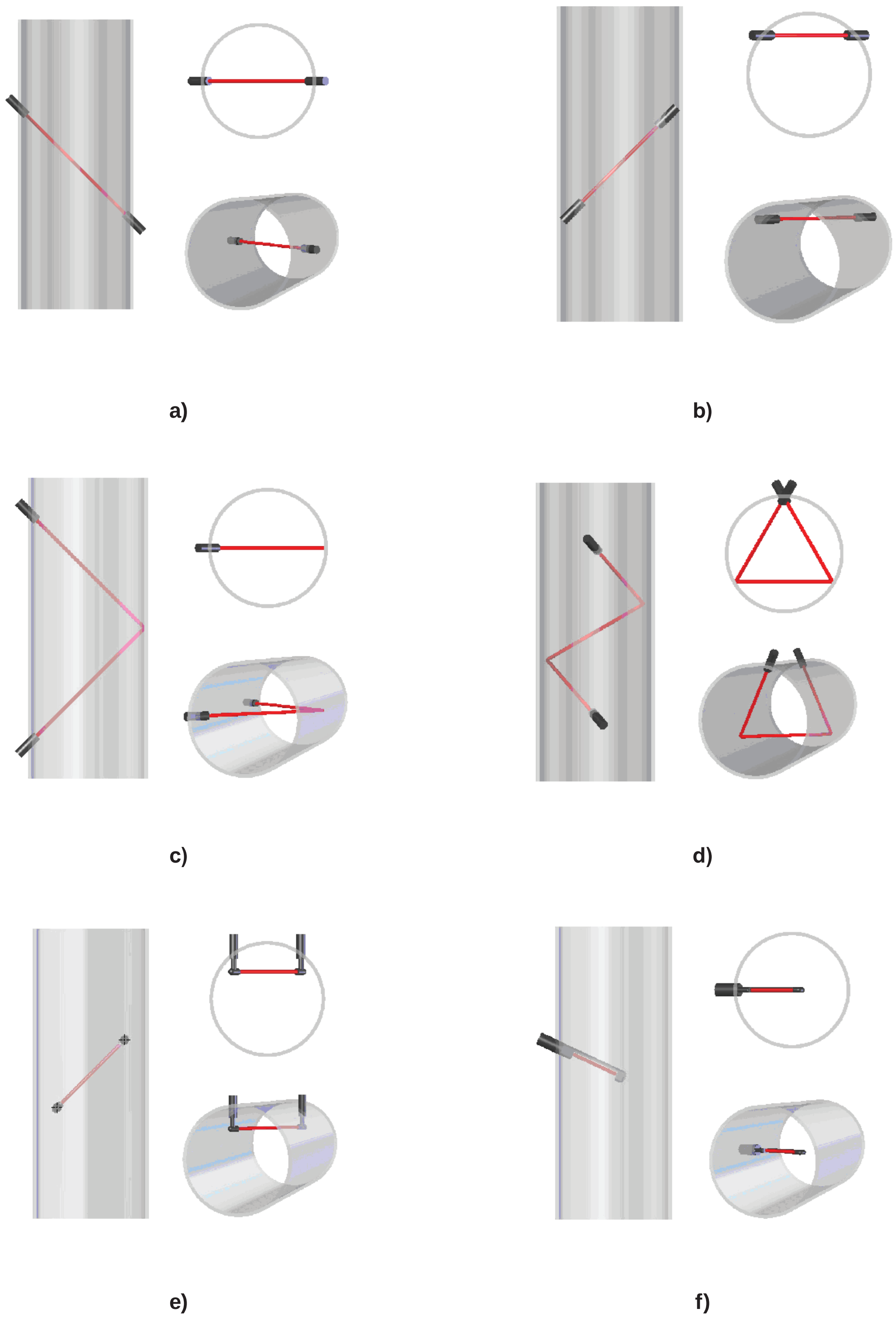


Figure 7 — Basic acoustic path types for USMs (front and top view)

NOTE The three-dimensional geometry cannot be depicted faithfully.

4.5 Impact of pressure and temperature on the flowmeter geometry

When a wide range of pressures and or temperatures are envisaged, the user should consult the manufacturer (If required the equations for this are given in ISO 17089-1).

4.6 USM measurement uncertainty determination

The *in situ* measurement uncertainty of systems based on USMs comprises:

a) verification uncertainties associated with the meter testing such as:

   1) timing verification,

   2) geometric verification;

b) uncertainties arising from differences between the process conditions and the conditions under which the meter was tested and or calibrated, including those which are a function of the pressure and temperature correction or compensation, flow conditions, fluid characteristics or contamination;

c) uncertainties associated with secondary instrumentation, such as pressure and temperature transmitters, gas composition measurement, and flow computers.

Additionally for clamp-on meters:

d) the pipe material and dimensions;

e) the mounting of the transducers;

f) the internal and external pipe wall surface conditions.

When a system uncertainty analysis is required, guidance can be found by reference to ISO 5168[3] and or ISO/IEC Guide 98-3.[9]

4.7 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 available meters into classes of performance as outlined in Table 4. Aside from this, there are also other classes dealing with other measurement applications (custody transfer or fiscal measurement and allocation) as detailed within ISO 17089-1.

Table 4 — USM classification

Class	Typical applications	Typical uncertainty 95 % confidence level (volume flow rate)[a]
3	Process, utilities or fuel gas	Within ±1,5 % to 5 % for $q_V > q_{V,\,\mathrm{t}}$ By specific flow conditioning or when multi-path meters are employed, lower uncertainties can be achieved
4	Emission monitoring as flare or vent gas	Within ±5 % to 10 % 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 SOS, and meter timing repeatability.

The classes detailed within this part of ISO 17089 represent two different measurement specifications commonly applied in industry. Depending on the importance of measurement with respect to operational demands, the total uncertainty budget for the complete measurement system is different (greater) than for the meter.

5 Meter characteristics

5.1 Performance indications

The manufacturer shall specify the repeatability and the maximum peak-to-peak error over the measurement range above $q_{V,\mathrm{t}}$.

5.2 Operating conditions

5.2.1 Volume flow rates and fluid velocities

The maximum volume flow rate and the minimum volume flow rate shall be specified.

5.2.2 Pressure classes

Ultrasonic transducers used in USMs require a minimum density to ensure acoustic coupling of the sound pulses to and from the fluid. Therefore, the expected minimum operating pressure as well as the maximum operating pressure shall be specified.

5.2.3 Temperature

The manufacturer or supplier shall specify the operating and ambient temperature ranges that can be met by the equipment being offered.

5.2.4 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 highly attenuating gases, such as carbon dioxide and hydrogen, can be present;

b) when the operational conditions are near the critical point of the gas mixture;

c) when non-hydrocarbon gases can be present and the sound velocity is being used to determine the molecular weight;

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

e) when there is the possibility of a liquid carry-over from separators or scrubbers;

f) salt deposits.

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

5.3 Meter body, materials, and construction

5.3.1 General

This subclause applies to meters delivered and installed with a meter body only. For field-mounted transducers, the manufacturer should be contacted to clarify the installation requirements.

5.3.2 Materials

The meter body shall be manufactured of materials suited to the service conditions including temperature, pressure, and gas composition of the fluid which the meter is to handle. Special care should be taken on corrosion resistance of the meter body. Exterior surfaces of the meter shall be protected as necessary against environmental corrosion. Insulation of the meter body is outside of the scope of this part of ISO 17089.

5.3.3 Meter body

The meter body and all other invasive or pressure- and/or force-loaded parts should be made in accordance with accepted International Standards or based on sound engineering practice agreed between the manufacturer and the user of the meter. Special care should be taken when meter bodies are to be welded into the pipeline.

5.4 Connections

The inlet and outlet connections of the meter shall conform to recognized standards e.g. ANSI/ASME (class 300, 600, 900, etc.), DIN, EN, and JIS. For a meter body that is to be welded into the pipeline, the welding ends shall conform to recognized standards (e.g. ANSI) or shall be agreed between the manufacturer and the user of the meter.

5.5 Dimensions

The inlet flange of the meter should have the same inside diameter to within 3 % compared with the adjacent pipeline. Any step change at the meter inlet beyond this should not prevent the meter from meeting the accuracy requirements of its performance class. In the case of bidirectional use of the meter, both flanges shall be considered as inlet flanges.

For welded-in meter bodies, the requirements of the welding procedure shall be considered.

The dimension of the measuring section (section of the meter body where the transducers are installed) shall be stated in the manufacturer's documentation.

5.6 Ultrasonic ports

Since the measured gas may contain impurities, transducer ports in connection with the transducer shall be designed so as to reduce the possibility of liquids or solids accumulating in the transducer ports or to ensure that the performance of the meter is not influenced by such conditions.

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. The manufacturer shall ensure that the operation of the replacement mechanism is safe under the design conditions of the meter.

5.7 Pressure tapping

Where a pressure measurement is required (i.e. for volume flow at standard conditions), at least one metering-pressure tapping shall be provided on the meter or on the piping adjacent to the meter. For a horizontal pipe, this shall be drilled perpendicular to the top ±85° of the meter body or pipe.

5.8 Anti-roll provision

For a USM constructed using a meter body, 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 of the meter during transportation and installation. Hoisting eyes or clearance for lifting straps shall be provided.

5.9 Flow conditioner

A flow-conditioning device may be delivered with the USM. In this case, the flow conditioner (FC) with its associated upstream pipe shall be considered as a part of the meter. The installation conditions (up and downstream runs) of the FC shall be agreed with the meter manufacturer. The additional pressure drop of the FC should be considered.

5.10 Markings

As a minimum, the following information shall be stated on the meter:

a) manufacturer, model number, serial number;

b) direction of forward flow;

c) minimum and maximum operating pressure and temperature;

Additionally, for wetted meters:

d) meter size, flange class, and mass;

e) meter body design code and material.

This information should be placed on a nameplate or stamped on the meter body. The legal requirements and/or requirements from codes and standards on marking of pressure bearing parts shall be considered.

5.11 Transducers

5.11.1 Rate of pressure change

Rapid pressurization and 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 pressurized or 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. This does not apply to clamp-on transducers as they are located outside the pressure boundary.

5.11.2 Transducer characterization

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

5.11.3 Transducer cable

USMs may be sensitive to the characteristics of the individual transducer cable. Therefore the cable should be treated as an integral part of the meter and be marked, or a statement in the operator’s manual should be made, with a warning indicating that the length or type shall not be changed.

5.12 Electronics

5.12.1 General requirements

The ES of the USM usually includes power supply, microcomputer, signal-processing components, and ultrasonic transducer excitation circuits.

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

5.12.2 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.

5.12.3 Signal quality

The USM shall indicate as a minimum, the acoustic signal strength. An indication shall be given if the signal degrades such that the performance of the meter is affected. The meter shall be capable of rejecting invalid measurements.

5.12.4 Output

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

a) serial data interface, e.g. RS-232, RS-485, field bus or equivalent;

b) frequency;

c) analogue (4 mA to 20 mA).

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 (may not be applicable to serial data output).

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

5.12.5 Cable jackets and insulation

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

5.13 Firmware and software

5.13.1 General

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.

5.13.2 Discontinuity

Being an electronic meter, the firmware may introduce discontinuities that affect the performance of the meter. Therefore, the firmware shall be designed to avoid discontinuities.

5.13.3 Marking and version management

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

The firmware revision number and/or checksum shall be available for inspection.

The manufacturer may offer firmware upgrades from time to time to improve the performance of the meter or to add additional features.

5.13.4 Configuration and monitoring software

The meter may be supplied with a capability for configuring the ES and for monitoring the operation of the meter. Preferably, the ES shall be able to show all relevant parameters and settings.

5.14 Inspection and verification functions

5.14.1 General

It may be possible to view the flow measurement configuration parameters used by the ES, e.g. calibration constants, meter dimensions, time-averaging period, and sampling rate. Provisions can be made to prevent an accidental or undetectable alteration of those parameters that affect the performance of the meter. Suitable provisions include a software-based access control.

The following alarm status output shall be provided:

a) output invalid: when the indicated flow rate output is invalid;

Optionally, the following alarm status outputs can be provided:

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

c) partial failure with respect to multi-path meters: when one or more paths produce results that are not usable.

Ideally, it should be possible to verify all constants and parameters while the meter is in operation.

5.14.2 Diagnostics

The meter shall be able to provide and/or output the following diagnostics:

a) nonlinearized 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) signal-to-noise ratio or equivalent (gain control);

i) status and measurement quality indicators;

j) alarm and failure indicator.

For the diagnostic measurements, the meter may be supplied with an internal data logger for storing these values.

5.15 Operation and installation requirements

5.15.1 General

All influences from the USM installation, or the USM operating regime, that increase the measurement uncertainty shall be considered and where possible compensated for or eliminated. Minimum distances to sources of flow disturbance shall be specified.

It should be remembered that USM meter errors derived from an undeveloped or disturbed flow profile take the form of a bias in the absolute flow value. Provided that upstream flow disturbances do not adversely impact the ability of the USM to transmit pulses of ultrasound, and the measurement is thus robust and reliable with acceptable diagnostics, then measurement repeatability is unaffected, as this is merely a function of the known physical dimensions of the USM, the sound velocity of the gas medium, and the precision of the time measurement process of the USM.

5.15.2 Operational precautions

5.15.2.1 Sound, noise, pressure-regulating valves, and invasive USMs

The function and accuracy of a USM can be affected by noise generated from pressure-regulating valves; see Reference [33] and Annex A. In severe cases, the meter can become inoperable. The following recommendations are given in respect of valve-generated noise:

a) USMs should be positioned well away from throttling control valves, ideally with process equipment such as vessels or heat exchangers between them — positioning the meter upstream of the regulator is usually beneficial;

b) noise immunity of USMs can generally be improved 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, but consider the impact on flow profile and possible resulting meter error;

d) straight pipe is ineffective at attenuating ultrasonic noise;

e) decreasing the differential pressure across a valve reduces the noise generated at all frequencies.

The USM manufacturer should always be consulted in situations where throttling control valves or pressure regulators are intended for placement upstream of the proposed USM location. The general sensitivity of the USM to sound (noise) generated by pressure regulating valves and other sources shall be communicated by the manufacturer.

5.15.2.2 Sound, noise, pressure-regulating valves, and non-invasive USMs

In addition to gas-borne noise as discussed in 5.15.2.1, pipe-borne noise can also be a source of clamp-on USM performance problems where metal process pipes are involved. Plastics pipe is unlikely to carry pipe-borne noise. The signal-to-noise ratio (SNR) is very different for non-invasive versus invasive USMs. Consequently pipe-borne noise becomes significant. It is recommended that clamp-on USMs not be installed close to butt-welds within the process conduit, as pipe-borne noise can travel out from the measurement zone and then be reflected back from the weld, thus possibly adding to any SNR issues. A suitable separation is recommended. Furthermore, in low-pressure applications, it may be necessary to apply some form of acoustic damping to the pipe surface in the region of USM installation. The choice of material depends upon pipe temperature and noise severity. The manufacturer should be consulted in this regard.

5.15.2.3 Contamination

Deposits which can be present in gas pipelines affect the accuracy of the meter by reducing its cross-sectional area, by reducing the effective acoustic path length or by reducing the performance of an individual path.

Heavy accumulation of deposits due to a mixture of particles and/or liquid contaminants should be avoided. In such cases, a provision for the draining of the transducer pockets is recommended.

In process applications, it is expected that the gas may periodically be contaminated with particulate and/or liquid mist/droplets. The USM manufacturer should confirm that the meter is suitable for and proven in, such applications.

To avoid severe accumulation, a pipe configuration which reduces the potential for the deposition of particulate and/or liquid contamination within the meter should be adopted.

The acoustic signals are adversely affected by the presence of either or both gas-borne and pipe-borne droplets. Condensate running along the bottom of a horizontal pipe section may create no operational issues under certain flow rates, but as the rate increases a mist of droplets can form above the liquid condensate and create acoustic transmission difficulties. Vertical pipes may thus offer a preferred location.

5.15.2.4 Ambient temperature and pressure

The influence of the ambient temperature should be minimized by providing shade or by appropriate thermal insulation. For those class 4 applications where the process operates at or near atmospheric pressure, the effects of radiating heat from the sun or adjacent process activity, e.g. significant flaring, can be significant. Under very low flow conditions, eddy flows can be created which the USM may be sensitive enough to detect. Reverse flow in flare stacks which are not sealed from the atmosphere can also be observed, both due to the aforementioned eddy flows or as a result of certain atmospheric conditions such as high wind or where atmospheric pressure exceeds flare stack pressure.

5.15.2.5 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.

5.15.2.6 Non-steady flow

Class 4 applications in flare stacks are prone to pulsating flow. The manufacturer should be able to demonstrate that the performance of the meter is maintained in the presence of pulsations.

5.16 Installation requirements and flow profile considerations

5.16.1 General

A fully developed flow profile is the most desirable condition at the meter. In practice, undisturbed flow conditions may not be achievable.

5.16.2 Installation effects

Various combinations of upstream fittings, valves, bends, thermowells, and lengths of straight pipe can produce velocity profile distortions at the meter inlet that may result in flow rate measurement error. The magnitude of the meter error is dependent on the type and severity of the flow distortion as well as the ability of the meter to compensate for this distortion. This error may be reduced by increasing the length of upstream straight pipe or by using FCs.

Research work on installation effects is ongoing at the time of publication, so the installation-designer should consult the USM manufacturer to review the latest test results and evaluate how a specific USM design could 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 an FC as part of the meter run. Alternatively, carrying out flow calibrations under conditions similar to field conditions can compensate for the error.

The recommended minimum length of straight downstream pipe length is $2D$, where D is the nominal pipe inside diameter.

5.16.3 Thermowells

Thermowells should be positioned downstream of the meter.

For unidirectional flow, the thermowell and/or densitometer pocket shall be installed downstream of the USM and located between $2D$ and $5D$ 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 $D/3$.

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.

5.16.4 Flow conditioners

One of the main advantages of USMs is the absence of a pressure drop. The use of an FC introduces a pressure drop and partially 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 an FC at any position in the meter run upstream of the USM can cause a change in the flow rate indicated by the meter. This change depends on many factors (e.g. FC type, meter type, position relative to the USM or flow perturbation upstream of the FC). To avoid this additional uncertainty, when the USM is calibrated, then the actual FC and meter run should be calibrated as one package (USMP).

WARNING — Depending on its design, an FC may produce noise of significant levels that impact on the operation of the USM at certain gas velocities. Perforated plate-type conditioners are preferred; tube bundles and vane-type FCs only suppress the swirl, do not improve the flow profile, and can even cause additional profile distortions.

5.16.5 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, affect the accuracy of the meter. The same effects can be experienced from rusting of untreated internal surfaces or defective internal coating.

5.16.6 Bidirectional use

For bidirectional use, both upstream and downstream piping shall be regarded as “upstream” piping.

5.17 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/or cable of removal.

6 Test and calibration

6.1 Flow test and calibration

A USM of class 3 or 4 can be fundamentally characterized as being either:

a) a USM with field-mounted transducers;

b) a USM with a meter body.

Both forms of USM should be functionally static tested by the manufacturer to establish the final pre-delivery settings of the ES. This is also a recommended part of any factory acceptance test (FAT). Similarly both forms of USM can be later and periodically verified in the field.

However, only for a meter of type b) is a traceable, dynamic (flowing gas) calibration under reference conditions possible.

6.2 Static testing for leakage and pressure

For a USM with a meter body, it is a safety prerequisite that all parts exposed to pressure shall be properly leak and pressure tested in accordance with the intended duty and applicable national or international regulations, e.g. Reference [16].

For insertion devices, care should be taken in respect of leakage potential and pressure rating of those field-mounted devices.

Pressure and leak testing is not applicable for clamp-on devices.

6.3 Dimensional measurements

6.3.1 USM with field-mounted transducers

6.3.1.1 Non-invasive or clamp-on

This form of USM requires accurate transducer positioning, whereby the dimensions involved are normally derived from the ES of the USM once all necessary application data have been correctly entered. Commercially available ultrasonic devices can be used to verify the pipe schedule or otherwise establish the accurate pipe wall thickness. On larger pipes, where it can become impractical for a clamping fixture design that controls transducer spacing to be employed, careful measurement and marking out of the pipe are required. It is typically sufficient to employ standard tools for this activity, such as liquid levels and welder's pipe-wraps. The same tools are used both to mark out the pipe for intended transducer locations and to verify the markings. Alternatively, it is possible to verify intended transducer locations using a proven dimensional survey method employing a proprietary system of theodolite and custom-designed prisms.

6.3.1.2 Insertion

For this form of USM, it is normally required that items of mounting hardware are initially welded to the process or "parent" pipe. The hardware might typically comprise angled and contour-cut pipe stubs with flanges, whose three-dimensional position relative to the parent pipe impacts USM performance. During the welding process, movement of the hardware can result from thermal forces and thus the final post-welding position, considered both linearly and angularly, can be different from that prescribed and assumed. Here, it has been found that a dimensional survey method employing a proprietary system of theodolite and custom-designed prisms can assist during the initial tack-welding operation to ensure the hardware does not adopt an early out-of-specification orientation, and it later assists the welder in making small adjustments at each stage of the welding process. The final "as-built" dimensions can also be accurately determined and reported in order to optimize the programming of the ES in respect of critical transducer and parent pipe coordinates.

6.3.2 USM with meter body

6.3.2.1 General

Where the transducers of the USM have been mounted into a meter body, then simpler and potentially more accurate methodology can be employed, whereby meter body designs can be individually tested under static conditions. This comprises the measurement of the critical meter body dimensions wherein the following parameters shall be recorded (either by the user or manufacturer):

a) the geometrical dimensions;

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.

Depending on the application:

e) the meter body material;

f) the meter body pressure and temperature expansion coefficients;

g) the wall thickness.

6.3.2.2 Zero flow verification test

To verify the transit time measurement system of a meter, a zero flow verification test can be performed for which the manufacturer shall specify the procedure and tolerances. Such a test can be expected at the manufacturer's facility as part of normal quality control procedure, or as part of a customer FAT, but it can also be performed in the field during the commissioning activity for the USM. However, the user is advised that for such a test, certain precautions shall be observed. A USM is sensitive to even minimal changes in transit time, which may be due not to USM zero instability, but movement of the gaseous medium being used for the test, itself resulting from small leaks or thermal gradients. Therefore, the transducers of USM shall be completely isolated from ambient air movement, and where the test is being conducted at pressure above atmospheric, a sufficiently sensitive pressure-monitoring device should be employed to confirm that no gaseous movement is created from leakage to ambient. Furthermore, the test shall be conducted such that the meter body, or other apparatus used to position field-mounted transducers in a simulated installation configuration, is isolated from radiant heat emanating from some adjacent process or the sun.

6.3.2.3 Adjustment for time delay and dimensional tolerance

When reliable static conditions prevail, i.e. where pressure is absolutely stable, complete isolation from gas movement is assumed and temperature influence is eliminated, the value of SOS indicated by the USM (MSOS) can be compared to the TSOS for the prevailing test gas conditions. A fine and often iterative adjustment for timing may thus be made to compensate for mechanical and electrical tolerances within the USMP, to achieve exact agreement between MSOS and TSOS. For a class 3 or class 4 USM, the USMP may essentially comprise no more than transducers, cables, and ES. If such an adjustment is made before the USM leaves the manufacturer, there should be no need to make any further adjustment of this type, provided that none of the aforementioned items are later exchanged or replaced.

6.3.2.4 Static test report

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

a) the date(s) of the test;

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

c) a written description of the test procedure;

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

e) MSOS from the meter being tested and the TSOS derived from gas composition, pressure, and temperature of the test gas;

f) source reference for TSOS;

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

h) a record and parameter setting report;

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

6.4 Dynamic testing (testing and calibration, adjustment under flowing conditions)

6.4.1 General

Depending upon the application, either an individual USM or a USMP may be dynamically tested and calibrated. Two principal methods are used:

a) dynamic flow testing and/or calibration of a USM with individual meter body under fully traceable reference conditions in a dedicated calibration facility;

b) dynamic field flow testing and adjustment for agreement with an installed reference meter or other form of comparison, typically reserved for a USM with field-mounted transducers.

6.4.2 Dynamic testing under flowing reference conditions

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

The measurement uncertainty of the complete test setup used for the calibration shall not be larger than the specified or agreed error limits of the USM to be tested; and preferably not exceed one-third of these error limits.

6.4.3 Dynamic testing in the field

Where a USM is being installed as a second technology on the same process line as an existing meter of a different measurement principle, e.g. to alleviate common mode failure issues, then a dynamic calibration performed beforehand under reference conditions in a dedicated calibration facility, would have limited value unless the USM is being introduced as the primary reference or new master meter of the pair, with the existing meter thus being adjusted to agree with the USM.

When dynamic testing is attempted in the field, great care shall be taken in considering the comparative uncertainties of the USM and the reference, including the calibration validity of any reference meter, along with the installation conditions and the influence these will have on the validity of the comparison. Certainly, the installation conditions of a reference meter shall be confirmed as acceptable, or the methodology of any other form of reference for comparison shall be validated, before such testing can be expected to yield a useful result. Should a combination of installed process meters be considered as a means to dynamically test a USM, where, for example, some form of combined gas injection is attempted to a common line containing the USM, e.g. a flare line, the reliability depends upon static conditions across several areas of a process plant, and this is a challenging concept with a complex uncertainty.

Furthermore, remember that the different forms of USM have differing levels of susceptibility to upstream and downstream flow profile disturbances. For example, a multi-path USM has less flow profile susceptibility than a single-path USM, and an insertion-type field-mounted USM is probably less affected than a clamp-on USM. The choice of USM technology shall be specified to suit the application and the performance requirements as defined within the list in the introduction. It is recommended that the USM operations manual or the USM manufacturer be consulted in this regard.

6.4.4 Report

Results of dynamic testing shall be available on request, together with a statement of conditions under which the dynamic testing took place. The test data provided as a result of the dynamic testing shall include:

a) meter identification and description of the test:

   1) manufacturer's data such as meter size and meter serial number,

   2) the estimated uncertainty of the testing and/or calibration results,

   3) a written description of the test procedure, typically including:

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

      ii) the upstream and downstream piping configurations involved in the qualification of undisturbed flow profile, including inside diameters

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

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

b) results:

   1) the determined deviations at the investigated flow rates,

   2) the date(s) of the test,

   3) in case of bidirectional meters: forward flow or reverse flow,

   4) the MSOS of the meter being tested and the TSOS from gas composition, pressure and temperature, and compressibility,

   5) the log file containing all data taken during testing and/or calibration,

   6) a report of the configuration parameters of the meter during testing and/or calibration.

6.5 Meter diagnostics

6.5.1 General

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 gas USM, but also several other components within the system. 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.

Available USM diagnostic information can be utilized to infer any necessity for re-calibration, thus potentially reducing the cost and inconvenience of process line shutdown to allow flowmeter removal for that purpose.

For applications where an audit trail is required, ISO 17089-1 shall be reviewed.

6.5.2 Absolute speed of sound comparison

When the gas composition, temperature, and pressure are known, the TSOS can be compared with the MSOS as indicated by the USM. The TSOS can be calculated from measured values of pressure, temperature and gas composition using an equation of state, such as the AGA 10[11] or equivalent. Proprietary software is available to calculate TSOS.

The SOS is an excellent tool to monitor not only the health and functionality of the USM itself, but possibly also any other components in the USMP, such as the pressure and temperature transmitters.

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

An unacceptable difference between MSOS and TSOS values should initially prompt not only checks of pressure and temperature data sources, but also investigation into the sampling technique and methodology for the gas composition. When these aspects of the comparison have all been validated, an inspection of the transducers should be made to ascertain whether deposition or fouling from gas-borne contaminants has occurred.

6.5.3 Relative speed of sound comparison

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

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 changes thereby increasing the discrepancy should the flow profile be seriously distorted;

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

6.5.4 Velocity ratios

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

6.5.5 Other parameters

Although the SOS is one of the most important parameters to be used in verification, there are many more parameters which are indicated by the USM, and these can be monitored in order to ensure optimum USM performance.

6.6 *In situ* verification

6.6.1 General

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

6.6.2 Methods of *in situ* verification

6.6.2.1 Velocity area method by means of Pitot tubes, hot film, and wire sensors or anemometers

This method is based on the approximate measurement of the velocity profile of the flow with suitable integration across the flow cross-section. Application of the velocity area method should always take the relevant regulations into consideration. As this technique involves effective sampling of the flowing velocity profile, ensure a constant flow throughout the verification process.

6.6.2.2 Optical method

The LDA (laser–Doppler anemometry) method is based on a point-by-point measurement of the velocity by means of light-scattering particles. Since only sequential point-by-point measurement can be made over the flow cross-section, this method is applicable only where a constant flow can be maintained for the duration of the test.

6.6.2.3 Tracer methods

This technique involves the injection of small amounts of a radioactive isotope into the gas line, where it mixes with the gas itself adopting the same flow profile, after which it passes two strap-on detectors. These detectors are located at a sufficient distance downstream of the injection point and are spaced apart along the gas line at a known distance. It is essentially a tag time of flight technique measuring fluid flow velocity. A gas line where there is a shortage of suitable straight pipe run is not a good candidate for this technique, as many diameters of straight pipe run, typically $10D$ to $20D$ depending upon flow conditions, are required for mixing, and then typically $5D$ to $10D$ for the measurement itself. While acceptable uncertainty is possible, it requires that all stipulated installation conditions are satisfied, which can be difficult to achieve on larger diameter pipes, such as flare gas lines. The technique may require extended straight pipe runs to maintain acceptable accuracy at low flow velocities. Also consider the practical duration of the test, i.e. inclusive travel time to the location of the *in-situ* verification, in addition to the work itself, as the radioactive Isotope has a finite half-life. This consideration applies particularly for remote or offshore facilities where severe delays can be experienced through transportation and weather difficulties.

6.6.2.4 *In-situ* verification report

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

a) the date(s) of the test;

b) data supplied by the manufacturer, e.g. meter size and meter serial number, for the meter being tested;

c) a written description of the test procedure;

d) the nature (e.g. gas composition, humidity) and conditions (pressure and temperature) of the test gas, inclusive of time and date for comparison with the USM data log;

e) the MSOS from the meter being tested and the TSOS derived from gas composition, pressure, and temperature of the test gas;

f) source reference for the TSOS;

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

h) a report of the configuration parameters of the meter during testing;

i) the values of the adjustment factors in the ES of the USM before adjustment and the value after adjustment;

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

Annex A
(normative)

Special application note on valve characterization and noise

A.1 Introduction

Since the successful introduction of USMs for measuring gas flow, such flow meters have been operating satisfactorily in an increasing number of applications and are becoming the default standard of high accuracy measurement.

However, with the increase in the number of meters installed, some applications have been encountered where ultrasonic noise created by pressure or flow regulators has caused problems. When the research to investigate this problem was started, it became apparent that hardly any information on noise was available, especially noise in the ultrasonic range and in high-pressure pipelines. Although models were available describing noise generation for the audible range, extensions of these models to the ultrasonic range were hardly supported by any experimental data and most of them proved useless.

Due to this, a test programme was established to obtain:

— basic data and information needed for designing USMs with improved noise immunity;

— data for building a model that can be used to predict, firstly, the noise levels generated and, secondly, the performance of a USM subject to the ultrasonic noise levels thus predicted.

Therefore, a theoretical approach was initially formulated to determine the dominating factors that influence the generation of noise. Then a practical model was developed based on the actual measurements gathered from the field.

A.2 The model

A.2.1 Theory of noise generation

Pressure control valves are the main source of ultrasonic noise, and their noise generation is dependent on operational conditions such as pressure drop and flow rate.

For the characterization, a good starting point is the model described in Reference [47]. The acoustic power produced by a control valve, W_a, can be described as:

$$W_\mathrm{a} \propto q_m c_1^2 \left\{ \frac{2}{\gamma - 1} \left[\left(\frac{p_1}{p_\mathrm{vc}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \right\}^{5/2} \left(\frac{p_1}{p_\mathrm{vc}} \right)^{\gamma + \frac{1}{\gamma} - 1} \tag{A.1}$$

where

q_m	is the mass flow rate;
c_1	is the speed of sound upstream of the control valve;
$\gamma = C_p/C_V$	the Poisson constant (for natural gases mostly of the order of 1,3);
p_1	is the pressure upstream of the control valve;
p_vc	is the pressure in the vena contracta.

The pressure in the vena contracta is related to the valve characteristics and can be described by the pressure recovery coefficient, F_L (see Figure A.1):

$$F_L = \frac{p_1 - p_2}{p_1 - p_{vc}} \tag{A.2}$$

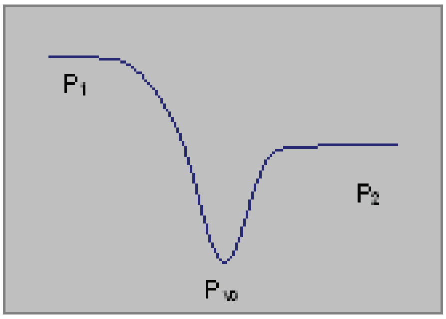


Figure A.1 — Pressure drop across a control valve

Remarks:

— when $p_1 = p_2$ (high recovery), then $F_L = 0$

— when $p_2 = p_{vc}$ (no recovery), then $F_L = 1$

— F_L can be related to the opening the valve

The acoustic power generated by the control valve can now be calculated according to Formulae (A.1) and (A.2).

However, for a USM it is not the acoustic power but the emitted acoustic pressure that is of importance. Based on Reference [46], the relation between the acoustic energy and the emitted acoustic pressure, p_n, can be written as:

$$p_n = 2 \times \sqrt{\frac{W_a \rho c}{A}} \tag{A.3}$$

where

ρ is the gas density;

c is the speed of sound;

A is the cross-sectional area of the pipe.

A.2.2 A practical indicator

One of the difficulties in using Formulae (A.1) to (A.3) is the determination of the value of p_{vc}, the pressure in the vena contracta. Expressions can be found for p_{vc}, but they relate to the opening of the control valve and other process parameters. Trying to solve this problem leads to a vast number of other equations with a series of unknown coefficients. Therefore it is necessary to adopt an empirical approach.

Not only is the noise level of the valve of interest, but also a method that enables the prediction of whether the meter can perform satisfactory in a given installation at a certain operating range is sought. Therefore, in addition to the noise level (emitted acoustic pressure) generated by the valve, the characteristics of the USM and piping properties, e.g. as elbows and T-joints, as well as silencers (if applicable), need to be taken into account.

Therefore, the Reethof and Ward equation (Reference [47]) is used only to determine the important factors; measurement data are used to derive an empirical equation.

Limiting its validity to natural gas, the combination of Formulae (A.1) to (A.3) leads to an expression for valve noise, $L_{p,\mathrm{N,v}}$, in which the emitted acoustic pressure approximates to the ratio of p_1/p_{vc} and the square root of the mass flow.

$$L_{p,\mathrm{N,v}} \approx p_1/p_{\mathrm{vc}} \sqrt{q_m} \quad \text{(A.4)}$$

Looking at the relationship between these components, based on the measurement data for natural gas, Formula (A.4) can be simplified to:

$$L_{p,\mathrm{N,v}} \approx \Delta p \sqrt{q_V} \quad \text{(A.5)}$$

where q_V is the actual volume flow rate, not the mass flow rate.

The valve weighting, N_{v}, is then added to take account of the dependence on the valve construction and the kind of trim used, giving:

$$L_{p,\mathrm{N,v}} \approx N_{\mathrm{v}} \Delta p \sqrt{q_V} \quad \text{(A.6)}$$

The valve weighting determines how noisy a valve is. A high value indicates a noisy valve, a low value a quiet one. The valve factor can differ for upstream and downstream conditions and is also a function of the frequency. In practice very low noise valves have been found possessing a valve weighting N_{v} of only 0,02. The noisiest valve tested had a factor of 2. This means that the choice of the right valve is extremely important.

A.2.3 Piping elements

Based on linear systems theory, the effects from piping elements can be represented by a number indicating the attenuation of the ultrasonic sound in the relevant frequency band. The effect of several piping elements is represented by a number N_{d}, which is the multiplication of all the contributions of all the individual piping elements. The N_{d} value is between 0 and 1; the better the acoustic attenuation of the pipe work, the closer the N_{d} value is to 0.

With this, the noise level at the position of the USM is given by:

$$L_{p,\mathrm{N,v}} \approx N_{\mathrm{d}} N_{\mathrm{v}} \Delta p \sqrt{q_V} \quad \text{(A.7)}$$

A.2.4 Acoustic signal strength

With all the ultrasonic transducers being based on piezoceramics, the sensitivity of all the transducers is quite similar.

Key factors in the received signal strength are:

— the pressure;

— the density;

— the acoustic path length or meter pipe inside diameter.

Next to this, if averaging techniques are applied in the signal processing, the square root of the number of samples has also to be taken into account.

For natural gas, this leads to the simple formula for the signal, P_s:

$$P_\mathrm{s} = \frac{p}{l_\mathrm{p}\sqrt{n_\mathrm{s}}} \qquad \text{(A.8)}$$

where

n_s is the number of samples averaged;

l_p is the acoustic path length.

A.2.5 Operating range of an ultrasonic flow meter

To determine the operating range of a USM, the parameter δ(S/N) is defined, reflecting the ratio between the valve noise at the position of the meter and the signal strength.

$$\delta(\mathrm{S/N}) = P_{\mathrm{s,USM}} / L_{p,\mathrm{N,USM}} \qquad \text{(A.9)}$$

Using Formulae (A.7) and (A.8), this leads to:

$$\delta(\mathrm{S/N}) \approx \frac{p\sqrt{n_\mathrm{s}}}{l_\mathrm{p} N_\mathrm{d} N_\mathrm{v} \Delta p \sqrt{q_V}} \qquad \text{(A.10)}$$

NOTE In ISO 17089-1:2010, Equations (27) and (28), for q_m, read q_V. This small error will be corrected in the next edition.

At a certain signal-to-noise level, a USM ceases to function. This is a manufacturer-specific parameter, called δ_critical.

For $\delta > \delta_\mathrm{critical}$, the meter functions (i.e. there is sufficient signal strength).

For $\delta \leq \delta_\mathrm{critical}$, the meter fails (there is too much noise).

Due to the stochastic nature of noise, in many cases a safety factor of 2 is put into the equation, to ensure that measurement performance is still at a very high level, despite the noise. With this safety factor, the value of δ is reduced by a factor of 2.

Table (A.1) lists values for a sample calculation using Formula (A.10).

Table A.1 — Calculation example

Calculation of δ (S/N) in natural gas		
p_min	3,41	MPa
n_s	1	number of samples used in the signal processing.
l_p	0,21	m
N_d	0,01	
N_v	0.4	
Δp	4,65	MPa
$q_{V,\mathrm{max}}$	19 000	Nm^3/h
Safety factor	2	
	δ (S/N)	**3,17**

Practical measures to reduce the noise level.

In noisy environments, there are in principle three ways to overcome the problems of excessive noise:

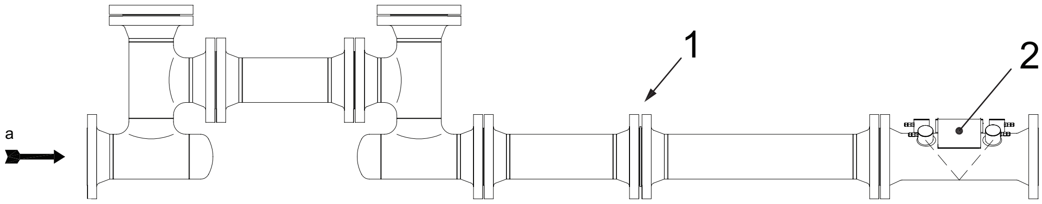
a) by mechanical attenuation of the noise;

b) by selecting a different transducer frequency;

c) by applying advanced signal processing.

A.2.6 Mechanical attenuation

There are different types of silencers, most of which suffer from drawbacks as the sensitivity to fouling or large pressure drops. The latter can be significant as it can interfere with the regulation of the entire system. One of the few exceptions to this is the so-called pipe element silencer (see Figure A.2, normally referred to as the “Brandenburger Tor” [Brandenburg Gate] configuration) having an excellent attenuation of approximately 40 dB combined with a relatively low pressure loss.



Key

1 flow conditioner

2 USM

a noise

Figure A.2 — Typical pipe element silencers with flow conditioner and ultrasonic meter

The inlet length in front of the meter is dependent upon the flow conditioner design and the USM acoustic path configuration; for this the user should consult the manufacturer.

In combination with coded pulse compression (CPC) technology, this results in approximately 55 dB to 60 dB attenuation. This combination is able to cope with almost any noise interference.

A.2.7 Piping elements

The most common pipe elements are 90° bends, T-joints, and double out-of-plane bends. The attenuation as mentioned in Table A.1 is a general guideline and depends on operating frequency, gas density, and liquid fraction. For a 200 kHz transducer frequency, the attenuation is presented in Table A.2.

Table A.2 — The attenuation of piping elements (at 200 kHz)

Piping element	Typical attenuation
Elbow	5 dB
Tee	9 dB to 10 dB
Double out-of-plane bend	12 dB
Straight length 100 m	5 dB

A.2.8 Other elements in the pipe

Every element that obstructs the flow also scatters sound and thereby attenuates noise. In gas transmission pipelines, there is a large variety of “obstruction type” elements like filters, heat exchangers, perforated plate flow straighteners, and other flow meters like orifice plates or turbine meters. The attenuation of these, at 200 kHz, is presented in Table A.3.

Table A.3 — The attenuation of other elements (at 200 kHz)

Other elements	**Typical attenuation**
Filter	10 dB to 20 dB
Heat exchanger	10 dB to 20 dB
Turbine meter	10 dB to 20 dB
Orifice plate	6 dB ($\beta \leq 0{,}5$)
4-Tee pipe element silencer	35 dB
Perforated plate (flow straightener)	6 dB

A.2.9 Transducer frequency

Depending on its design and the throttling, the noise produced by the valve usually has its highest amplitude between 30 kHz and 80 kHz and falls off at higher frequencies (see Figure 3). Depending on the valve, it might be advantageous to measure the acoustic signals at higher frequencies, where the noise level is substantially lower. The latest USMs employ transducers operating at frequencies in the 300 kHz range. Figure A.3 shows a typical sound pressure distribution that is created by a pressure control valve. At 80 kHz, the noise pressure is around 1 300 Pa; at 300 kHz, it is only 115 Pa.

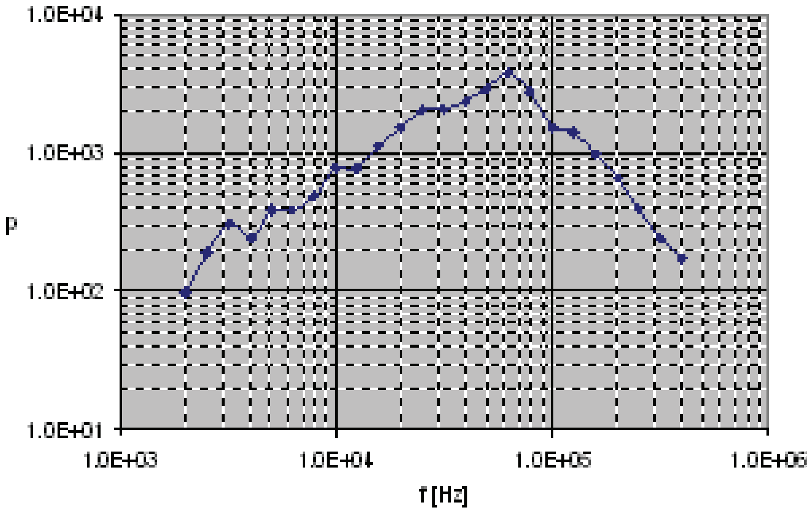


Figure A.3 — Spectral distribution of the sound pressure

A.2.10 Signal processing

A.2.10.1 General

For signal processing, there are numerous options, depending on the centre frequency and bandwidth of the transducers. Looking at the meters available on the market at the time of publication, in principle there are three methods applied:

— correlation;

— stacking;

— coded pulse compression.

A.2.10.2 Correlation method

The correlation method is a widespread filtering method using frequency domain algorithm. The disadvantage is the lack of accuracy of the measurement, and therefore this method is not usually used for meters for custody transfer.

A.2.10.3 Stacking

Stacking is a method that is also widely used in, for instance, digital oscilloscopes. Hereby a number of received signals are stacked on top of each other. Assuming that the ultrasonic signals are in phase and the associated noise is not, the signal-to-noise ratio increases with the number of stacked signals.

Stacking typically improves the signal-to-noise ratio by the square root of the stack size, e.g. a stack of nine received signals increases the signal-to-noise ratio by a factor of 3 or 10 dB.

A prerequisite for success is the time stability in the receiving signals, and that is the weakness of this method for ultrasonic flow measurement. Due to turbulence, the ultrasonic transit times are prone to fluctuations, denoted as jitter. In situations where the time jitter is relatively small, stacking can be applied successfully. However, at higher flow velocities, the time jitter increases to such a level that a measurement is no longer possible.

A.2.10.4 Coded pulse compression

CPC is an advanced signal processing technology designed to overcome the time jitter-related problems of stacking. In order to reconstruct the original signal and eliminate the time jitter component, instead of a single signal, a complex burst is generated consisting of a large number of individual pulses transmitted in certain time coded pattern (see Figure A.4). At the receiving site, this transmitted time code is used to reconstruct the original signal

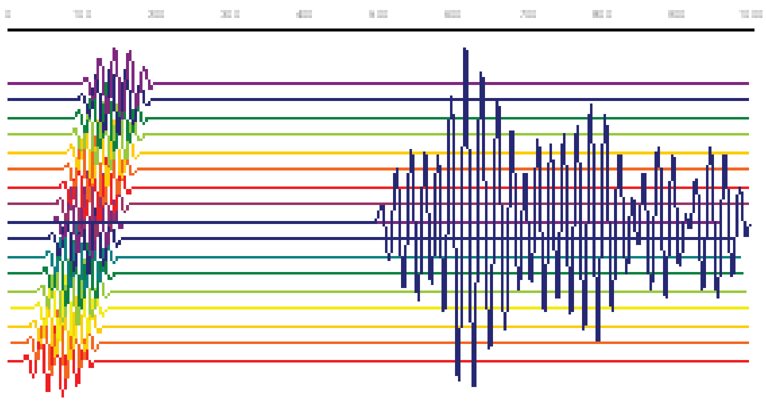


Figure A.4 — Transmission of a burst of multiple pulses

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ICS 17.120.10
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