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Measurement of fluid flow in closed conduits — Ultrasonic transit-time meters for liquid

Mesurage de débit des fluides dans les conduites fermées — Compteurs ultrasoniques pour liquides

Reference number
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Foreword

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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.

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Introduction

Ultrasonic meters (USMs) have become one of the accepted flow measurement technologies for a wide range of liquid applications, including custody-transfer and allocation measurement. Ultrasonic technology has inherent features such as no pressure loss and wide rangeability.

USMs can deliver diagnostic information through which it may be possible to demonstrate that an ultrasonic liquid flowmeter is performing in accordance with specification. Owing to the extended diagnostic capabilities, this International Standard advocates the addition and use of automated diagnostics instead of labour-intensive quality checks. The use of automated diagnostics makes possible a condition-based maintenance system.

Measurement of fluid flow in closed conduits — Ultrasonic transit-time meters for liquid

1 Scope

This International Standard specifies requirements and recommendations for ultrasonic liquid flowmeters, which utilize the transit time of ultrasonic signals to measure the flow of single-phase homogenous liquids in closed conduits.

There are no limits on the minimum or maximum sizes of the meter.

This International Standard specifies performance, calibration and output characteristics of ultrasonic meters (USMs) for liquid flow measurement and deals with installation conditions. It covers installation with and without a dedicated proving (calibration) system. It covers both in-line and clamp-on transducers (used in configurations in which the beam is non-refracted and in those in which it is refracted). Included are both meters incorporating meter bodies and meters with field-mounted transducers.

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 and definitions

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

3.1 Quantities

3.1.1
volume flowrate
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,[42] 4-30.

3.1.2
metering pressure
absolute fluid pressure in a meter under flowing conditions to which the indicated volume of liquid is related

3.1.3
mean velocity in the meter body
v
fluid flowrate divided by the cross-sectional area of the meter body

3.1.4
mean pipe velocity

v_p

fluid flowrate divided by the cross-sectional area of the upstream pipe

NOTE Where a meter has a reduced bore, the mean velocities in the upstream pipe and within the meter body itself differ.

3.1.5
path velocity

average fluid velocity on an ultrasonic path

3.1.6
Reynolds number

dimensionless parameter expressing the ratio between the inertia and viscous forces

3.1.7
pipe Reynolds number

Re_D

dimensionless parameter expressing the ratio between the inertia and viscous forces in the pipe

$$Re_D = \frac{\rho v_\mathrm{p} D}{\mu} = \frac{v_\mathrm{p} D}{v_\mathrm{kv}}$$

where

ρ is mass density;

v_p is the mean pipe velocity;

D is the pipe internal diameter;

μ is the dynamic viscosity;

v_kv is the kinematic viscosity

NOTE Where a meter has a reduced bore, it is possible also to define the throat Reynolds number, in whose definition the mean velocity in the meter body, the meter internal diameter and the kinematic viscosity are used.

3.2 Meter design

3.2.1
meter body

pressure-containing structure of the meter

3.2.2
ultrasonic path

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

3.2.3
axial path

path travelled by an ultrasonic signal either on or parallel to the axis of the pipe

3.2.4
diametrical path

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

3.2.5
chordal path

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

3.2.6
field mounted
external to the pipe, attached on site, not prior to a laboratory calibration

3.3 Thermodynamic conditions

3.3.1
metering conditions
conditions, at the point of measurement, of the fluid of which the volume is to be measured

NOTE Also known as operating conditions or actual conditions.

3.3.2
standard conditions
defined temperature and pressure conditions used in the measurement of fluid quantity so that the standard volume is the volume that would be occupied by a quantity of fluid if it were at standard temperature and pressure

NOTE 1 Standard conditions may be defined by regulation or contract.

NOTE 2 Not preferred alternatives: reference conditions, base conditions, normal conditions, etc.

NOTE 3 Metering and standard conditions relate only to the volume of the liquid to be measured or indicated, and should not be confused with rated operating conditions or reference conditions (see ISO/IEC Guide 99:2007,[44] 4.9 and 4.11), which refer to influence quantities (see ISO/IEC Guide 99:2007,[44] 2.52).

3.3.3
specified conditions
conditions of the fluid at which performance specifications of the meter are given

3.4 Statistics

3.4.1
error
measured quantity value minus a reference quantity value

[ISO/IEC Guide 99:2007,[44] 2.16]

3.4.2
repeatability (of results of measurements)
closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement

NOTE 1 These conditions are called repeatability conditions.

NOTE 2 Repeatability conditions include:

- the same measurement procedure;
- the same observer;
- the same measuring instrument, used under the same conditions;
- the same location;
- repetition over a short period of time.

NOTE 3 Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

[ISO/IEC Guide 98-3:2008,[43] B.2.15]

3.4.3
reproducibility (of results of measurements)

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

NOTE 1 A valid statement of reproducibility requires specification of the conditions changed.

NOTE 2 The changed conditions may include:

- principle of measurement;
- method of measurement;
- observer;
- measuring instrument;
- reference standard;
- location;
- conditions of use;
- time.

NOTE 3 Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.

NOTE 4 Results are here usually understood to be corrected results.

[ISO/IEC Guide 98-3:2008,[43] B.2.16]

3.4.4
resolution

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

3.4.5
zero flow reading

flowmeter reading when the liquid is at rest, i.e. both axial and non-axial velocity components are essentially zero

3.4.6
linearization

way of reducing the non-linearity of an ultrasonic meter, by applying correction factors

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

3.4.7
uncertainty (of measurement)

parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

NOTE 1 The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

NOTE 2 Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.

NOTE 3 It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

[ISO/IEC Guide 98-3:2008,[43] B.2.18]

3.4.8
standard uncertainty

u

uncertainty of the result of a measurement expressed as a standard deviation

[ISO/IEC Guide 98-3:2008,[43] 2.3.1]

3.4.9
expanded uncertainty

U

quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand

[ISO/IEC Guide 98-3:2008,[43] 2.3.5]

NOTE 1 The large fraction is normally 95 % and is generally associated with a coverage factor $k = 2$.

NOTE 2 The expanded uncertainty is often referred to as the uncertainty.

3.4.10
coverage factor

numerical factor used as a multiplier of the standard uncertainty in order to obtain an expanded uncertainty

NOTE Adapted from ISO/IEC Guide 98-3:2008,[43] 2.3.6.

3.5 Calibration

3.5.1
flow calibration

calibration in which fluid flows through the meter

3.5.2
theoretical prediction procedure

procedure by which the performance of a meter is theoretically predicted, without liquid flowing through the meter

3.5.3
performance testing

testing of a representative sample of meters to determine, for example, reproducibility and installation requirements for meters geometrically similar to themselves

3.6 Symbols and subscripts

The symbols and subscripts used in this International Standard are given in Tables 1 and 2.

Table 1 — Symbols

Quantity	Symbol	Dimensions[a]	SI unit
Cross-sectional area of meter body	A	L^2	m^2
Speed of sound in fluid	c	LT^{-1}	m/s
Internal diameter of the meter body	d	L	m
Internal pipe diameter	D	L	m
Young's modulus	E	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
Function of path velocities	f	—	1
Integers (1,2,3, …)	i,j,n	—	1
Calibration factor	K	—	1
Body end correction factor	K_E	—	1
Path-geometry factor	K_g	L[b] or LT^{-1} [c]	m[b] or m/s [c]
Velocity profile correction factor	K_p	—	1
Body style correction factor	K_S	—	1
Minimum distance to a specified upstream flow disturbance	l_min	L	m
Path length	l_p	L	m
Absolute pressure	p	$\mathrm{ML}^{-1}\mathrm{T}^{-2}$	Pa
Volume flowrate	q_V	$\mathrm{L}^3\mathrm{T}^{-1}$	m^3/s
Internal pipe radius	r	L	m
External pipe radius	R	L	m
Throat Reynolds number	Re_d	—	1
Pipe Reynolds number	Re_D	—	1
Percentage maximum deviation in measured flowrate due to upstream fittings	S	—	1
Absolute temperature of the liquid	T	Θ	K
Transit time	t	T	s
Time delay	t_0	T	s
Mean axial fluid velocity in the meter body	v	LT^{-1}	m/s
Mean axial fluid velocity on ultrasonic path, i	v_i	LT^{-1}	m/s
Mean axial fluid velocity in the upstream pipe	v_p	LT^{-1}	m/s
Transducer axial separation	X	L	m
Thermal expansion coefficient	α	Θ^{-1}	K^{-1}
Pipe wall thickness	δ	L	m
Dynamic viscosity	μ	$\mathrm{ML}^{-1}\mathrm{T}^{-1}$	Pa s
Kinematic viscosity	ν_kv	$\mathrm{L}^2\mathrm{T}^{-1}$	m^2/s
Density of the liquid	ρ	ML^{-3}	$\mathrm{kg/m}^3$
Poisson's ratio	σ	—	1
Angle between ultrasonic path and pipe axis	ϕ	—	rad

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

[b] Non-refracting configuration.

[c] Refracting configuration.

Table 2 — Subscripts

Subscript	Meaning
cal	under calibration conditions
meas	measured (uncorrected)
op	under operational conditions
true	actual (corrected)

3.7 Abbreviated terms

AGC	automatic gain control
FAT	factory acceptance test
MSOS	measured speed of sound
SNR	signal to noise ratio
SOS	speed of sound
RSOS	reference speed of sound
USM	ultrasonic meter
USMP	USM package, including meter tubes, flow conditioner, flow computer and thermowell

4 Principles of measurement

4.1 Description

The ultrasonic transit-time flowmeter is a sampling device that measures discrete path velocities using one or more pairs of transducers. Each pair of transducers is located a known distance, l_{p}, apart such that one is upstream of the other (see Figure 1). The upstream and downstream transducers send and receive pulses of ultrasound alternately, referred to as contra-propagating transmission, and the times of arrival are used in the calculation of average axial velocity, v. At any given instant, the difference between the apparent speed of sound in a moving liquid and the speed of sound in that same liquid at rest is directly proportional to the instantaneous velocity of the liquid. As a consequence, a measure of the average axial velocity of the liquid along a path can be obtained by transmitting an ultrasonic signal along the path in both directions and subsequently measuring the transit time difference.

The volume flowrate of a liquid flowing in a completely filled closed conduit is defined as the average velocity of the liquid over a cross-section multiplied by the area of the cross-section. Thus, by measuring the average velocity of a liquid along one or more ultrasonic paths (i.e. lines, not the area) and combining the measurements with knowledge of the cross-sectional area and the velocity profile over the cross-section, it is possible to obtain an estimate of the volume flowrate of the liquid in the conduit.

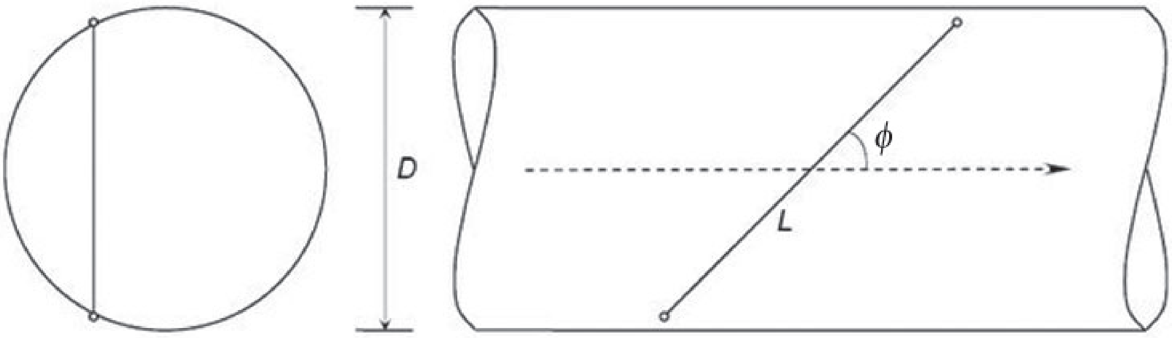

Figure 1 — Measurement principle

Several techniques can be used to obtain a measure of the average effective speed of propagation of an ultrasonic signal in a moving liquid in order to determine the average axial flow velocity along an ultrasonic path line. However, the normal technique applied in modern USMs is the direct time differential technique.

The basis of this technique is the measurement of the transit time of ultrasonic signals as they propagate between a transmitter and a receiver. The velocity of propagation of the ultrasonic signal is the sum of the speed of sound, c, and the flow velocity in the direction of propagation. Therefore the transit time upstream and downstream can be expressed as:

$$t_{\mathrm{fl\_up/dn}} \approx \int_{l=0}^{l_\mathrm{p}} \frac{1}{c + \boldsymbol{v}_l \bullet \boldsymbol{n}} . \mathrm{d}l \qquad (1)$$

where

c is the speed of sound in the fluid;

$\boldsymbol{n}$ is the unit normal vector to the wave front;

v_l is the flow velocity vector at location, l, on the path l_p.

NOTE This is correct whether the transmitter is upstream or downstream.

With the assumptions that the flow velocity is in the axial direction only and that $v_i \ll c$, where v_i is the mean axial flow velocity on ultrasonic path line i, then the upstream and downstream transit times can be written as

$$t_{\mathrm{fl\_up}} = \frac{l_\mathrm{p}}{c - v_i \cos\phi} \qquad (2)$$

$$t_{\mathrm{fl\_dn}} = \frac{l_\mathrm{p}}{c + v_i \cos\phi} \qquad (3)$$

Rearranging terms and solving for v_i gives

$$\frac{1}{t_{\mathrm{fl\_dn}}} - \frac{1}{t_{\mathrm{fl\_up}}} = \frac{t_{\mathrm{fl\_up}} - t_{\mathrm{fl\_dn}}}{t_{\mathrm{fl\_up}} t_{\mathrm{fl\_dn}}} = \frac{2 v_i \cos\phi}{l_\mathrm{p}} \qquad (4)$$

$$v_i = \frac{l_\text{p}}{2\cos\phi}\frac{\Delta t}{t_\text{fl\_up}t_\text{fl\_dn}} \tag{5}$$

where

l_p is the distance between the transducers;

Δt is the difference in transit times;

ϕ is the angle of inclination of the ultrasonic signal with respect to the axial direction of the flow.

The speed of sound can be calculated as follows:

$$\frac{1}{t_\text{fl\_dn}} + \frac{1}{t_\text{fl\_up}} = \frac{t_\text{fl\_up} + t_\text{fl\_dn}}{t_\text{fl\_up}t_\text{fl\_dn}} = \frac{2c}{l_\text{p}} \tag{6}$$

$$c = \frac{l_\text{p}}{2}\frac{\left(t_\text{fl\_up} + t_\text{fl\_dn}\right)}{t_\text{fl\_up}t_\text{fl\_dn}} \tag{7}$$

4.2 Volume flow

The individual path velocity measurements are combined by a mathematical function to yield an estimate of the mean velocity in the meter body:

$$v = f(v_1, \ldots, v_n) \tag{8}$$

where n is the total number of paths.

Owing to variations in path configuration and different proprietary approaches of solving Formula (8), even for a given number of paths, the exact form of $f(v_1, \ldots, v_n)$ can vary.

The relationship between the mean pipe velocity and the measured path velocities depends on the flow profile. In fully developed flow, the flow profile depends only on the Reynolds number and the pipe roughness.

One possible solution is to calculate the mean velocity as a weighted sum of the path velocities and to apply a velocity profile factor, K_p, to compensate for profile changes. The value of K_p is calculated by an algorithm that takes into account flow regime (laminar, transitional, and turbulent), as well as other process variables, as required.

$$v = K_\text{p}\sum_{i=1}^{n} w_i v_i \tag{9}$$

The volume flowrate, q_V, is given by:

$$q_V = Av \tag{10}$$

where

v is the estimate of the mean pipe velocity;

A is the cross-sectional area of the measurement section.

Note that increasing n may reduce the uncertainty associated with flow profile variations.