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Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits

Mesurage du débit de gaz humide au moyen d'appareils déprimogènes insérés dans des conduites de section circulaire

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.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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/TR 11583 was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 2, *Pressure differential devices*.

Introduction

ISO 5167-1:2003, ISO 5167-2:2003, and ISO 5167-4:2003 include specifications for Venturi tubes and orifice plates, but are applicable only where the fluid can be considered as a single phase and the conduit is running full.

If the fluid being measured is a wet gas there is an overreading which can be corrected using suitable wet-gas correction equations.

Measurement of wet gas flow by means of pressure differential devices inserted in circular cross-section conduits

1 Scope

This Technical Report describes the measurement of wet gas with differential pressure meters. It applies to two-phase flows of gas and liquid in which the flowing fluid mixture consists of gas in the region of 95 % volume fraction or more (the exact limits on the mixture are defined in 6.4.3, 6.4.5, 7.5.3 and 7.5.5). This Technical Report is an extension of ISO 5167. The ranges of gases and liquids from which the equations in this Technical Report were derived are given in 6.4.1 and 7.5.1. It is possible that the equations do not apply to liquids significantly different from those tested, particularly to highly viscous liquids.

Although the over-reading equations presented in this Technical Report apply for a wide range of gases and liquids at appropriate gas-liquid density ratios, evaluating gas flowrates depends on information in addition to that required in single-phase flow: under certain conditions, a measurement of the pressure loss is sufficient; tracers can be used to measure the liquid flow; the total mass flowrate may be known (this is more likely in a wet-steam flow than in a natural gas/liquid flow); in a wet-steam flow a throttling calorimeter can be used.

Wet-gas measurement using Venturi tubes or orifice plates is covered in this Technical Report.

This Technical Report is only applicable to wet gas flows with a single liquid and is not intended for the oil and gas industry.

2 Normative references

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

ISO 2186, *Fluid flow in closed conduits — Connections for pressure signal transmissions between primary and secondary elements*

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

ISO 5167-1:2003, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 1: General principles and requirements*

ISO 5167-2:2003, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 2: Orifice plates*

ISO 5167-4:2003, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full — Part 4: Venturi tubes*

ISO/TR 15377, *Measurement of fluid flow by means of pressure-differential devices — Guidelines for the specification of orifice plates, nozzles and Venturi tubes beyond the scope of ISO 5167*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 4006, ISO 5167-1 and the following apply.

3.1
stratified flow
common regime in horizontal pipes at low gas velocities (typically 5 m/s or less) in which the free liquid runs along the bottom of the pipe with the gas flowing at the top of the pipe

3.2
annular flow
flow regime that in horizontal pipes occurs at medium gas velocities (typically 5 m/s to 15 m/s) in which the liquid flows around the pipe wall with the gas flowing through the centre of the pipe

NOTE In horizontal pipes, annular flow is not uniform; owing to gravitational effects, the liquid is present in higher quantities around the wall at the bottom of the pipe than higher up the pipe wall.

3.3
mist flow
flow regime that in horizontal pipes requires high gas velocities (typically 15 m/s or higher) to keep the liquid suspended in the gas and describes liquid in the flow being carried along in small-droplet form within the body of gas

3.4
slug flow
flow regime in which liquid travels along the pipe intermittently but in significant quantity, often due to the liquid becoming trapped in the flow line, for example at the bottom of a vertical pipe or when the flow is started after shutdown

3.5
liquid volume fraction
LVF
ratio of the liquid volume flowrate to the total volume flowrate, where the total volume flowrate is the sum of the liquid volume flowrate and the gas volume flowrate, all volume flowrates being at actual (not standard) conditions

3.6
gas volume fraction
GVF
ratio of the gas volume flowrate to the total volume flowrate, where the total volume flowrate is the sum of the liquid volume flowrate and the gas volume flowrate, all volume flowrates being at actual (not standard) conditions

4 Symbols and subscripts

See Table 1.

5 Principle of the method of measurement and computation

5.1 Principle of the method of measurement

The principle of the method of measurement using differential-pressure meters is based on the installation of a primary device (such as an orifice plate or a Venturi tube) into a pipeline. The installation of the primary device causes a pressure difference between the upstream side and the throat or downstream side of the device. The flowrate can be determined from the measured value of this pressure difference and from the knowledge of the characteristics of the flowing fluid as well as the circumstances under which the device is being used. It is assumed that the device is geometrically similar to one on which calibration has been carried out and that the conditions of use are the same, i.e. that it is in accordance with ISO 5167-2 or ISO 5167-4.

Table 1 — Symbols

Symbol	Quantity	Dimension[a]	SI Unit
C	Coefficient of discharge	dimensionless	1
C_{Ch}	Chisholm coefficient	dimensionless	1
C_{fluid}	Concentration of tracer in fluid	dimensionless	1
d	Diameter of orifice or throat of Venturi tube at working conditions	L	m
D	Upstream internal pipe diameter (or upstream diameter of a Venturi tube) at working conditions	L	m
Fr_{gas}	Gas densiometric Froude number [see Equation (3)]	dimensionless	1
g	Acceleration due to gravity	LT^{-2}	$\mathrm{m/s}^2$
h	Specific enthalpy	$\mathrm{L}^2\mathrm{T}^{-2}$	J/kg
H	Function of the surface tension of the liquid (see 6.4.3)	dimensionless	1
L_{down}	Distance between the downstream end of the Venturi tube divergent section (measured from the end of the cone not the flange) and the downstream pressure tapping used to measure the pressure loss	L	m
p	Absolute static pressure of the fluid	$\mathrm{ML}^{-1}\,\mathrm{T}^{-2}$	Pa
q_m	Mass flowrate	MT^{-1}	kg/s
q_V	Volume flowrate	$\mathrm{L}^3\mathrm{T}^{-1}$	m^3/s
t	Temperature of the fluid	Θ	°C
X	Lockhart-Martinelli parameter [see Equation (2)]	dimensionless	1
β	Diameter ratio: $\beta = d/D$	dimensionless	1
Δp	Differential pressure	$\mathrm{ML}^{-1}\,\mathrm{T}^{-2}$	Pa
$\Delta \varpi$	Pressure loss (without correction for the pressure loss that would have taken place if the Venturi tube or orifice plate had not been present)	$\mathrm{ML}^{-1}\,\mathrm{T}^{-2}$	Pa
δ	Absolute uncertainty	—[b]	—[b]
ε	Expansibility [expansion] factor	dimensionless	1
κ	Isentropic exponent	dimensionless	1
ρ	Density of the fluid (subscript 1 denotes the value at the upstream tapping plane)	ML^{-3}	$\mathrm{kg/m}^3$
ϕ	Over-reading correction factor [see Equation (1)]	dimensionless	1

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

[b] The dimensions and units are those of the corresponding quantity.

In a wet gas flow the gas flowrate is determined by evaluating an over-reading. The over-reading is due to the mass of liquid passing through the primary device. The over-reading is affected by the flow regime, which in a wet gas flow is generally stratified, annular or mist, although, in practice, wet gas flows may be a combination of these flow regimes. Other flow regimes can occur intermittently, particularly the slug flow regime if liquid has become trapped in the flow line, for example at the bottom of a vertical pipe.

Combinations of line conditions, pipe orientations, and gas-liquid ratios influence the type of flow regime present. An appreciation of which, if any, flow regime is likely to prevail can be extremely useful. The application of the same wet-gas measurement technique can produce widely different results depending on which flow regime predominates, and knowledge of the likely flow regime can therefore influence the correct choice of measurement principle to be applied.

NOTE Even in a horizontal pipe, liquid can be held-up by gas flows of 1 m/s or less and can remain almost stationary rather than flow with the gas.

5.2 Computation

The gas mass flowrate, $q_{m,\text{gas}}$, is given by

$$q_{m,\text{gas}} = \frac{C}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \frac{\sqrt{2\Delta p \rho_{1,\text{gas}}}}{\phi} \quad (1)$$

where

C is given in 6.4.2 or 7.5.2 as appropriate;

ε is determined from the appropriate part of ISO 5167;

$\rho_{1,\text{gas}}$ is the upstream gas density;

ϕ is the over-reading correction factor.

NOTE In evaluating ε, the actual values of p_1 and p_2 measured in wet gas are used.

Factor ϕ depends on the primary device, on the gas-liquid density ratio, $\rho_{1,\text{gas}}/\rho_{\text{liquid}}$, where ρ_{liquid} is the density of the liquid, on the Lockhart-Martinelli parameter, X, as defined in Equation (2):

$$X = \left(\frac{q_{m,\text{liquid}}}{q_{m,\text{gas}}}\right) \sqrt{\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}} \quad (2)$$

and on the gas densiometric Froude number, Fr_{gas}, as defined in Equation (3):

$$Fr_{\text{gas}} = \frac{4 q_{m,\text{gas}}}{\rho_{1,\text{gas}} \pi D^2 \sqrt{gD}} \sqrt{\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}} - \rho_{1,\text{gas}}}} \quad (3)$$

where g is the acceleration due to gravity and $q_{m,\text{liquid}}$ is the liquid mass flowrate.

6 Venturi tubes

6.1 General

Venturi tubes are widely used for wet-gas applications. Among their advantages are:

a) they do not 'dam' the flow (unlike orifice plates);

b) they can be operated at higher differential pressures than orifice plates without incurring permanent meter damage [differential pressures up to and above 2 bar (200 kPa) can be contemplated; for a fixed gas mass flowrate the presence of liquid may greatly increase the differential pressure];

c) therefore, they have a relatively high turndown (typically 10:1) when used with suitably ranged differential pressure transmitters.

6.2 Design requirements

The design requirements for Venturi tubes are specified in ISO 5167-4. However, special attention should be paid to the following: the finish of the Venturi tube internal surface, which should be smooth and free from machining defects including burrs and ridges; the pressure tappings, which at the point of entry into the meter internal bore should have sharp edges and be free from burrs and wire edges; and the edge of the conical inlet, which should be sharp and free from manufacturing defects.

The equations in this Technical Report should only be applied to meters that have been installed horizontally. Installation of the Venturi tube at a low point of the piping configuration where liquid could collect should be avoided.

In respect of the number and location of the pressure tappings, the meter should not conform to ISO 5167-4; see 6.3.

In many situations, it is desirable that the Venturi tube be installed with suitable "double block and bleed" isolation valves so that the meter can be removed and inspected as required.

The presence of liquid in the flow line affects the flow profile as it enters the Venturi tube. This is a source of measurement uncertainty over and above that normally expected for dry-gas measurement. In order to minimize this additional uncertainty, upstream pipe work should be designed so that bends immediately upstream of the meter encourage any stratified liquid to flow at the bottom of the pipe. Moreover, it is not recommended that the reduced straight lengths outlined in ISO 5167-4 be used. Where possible, the longer lengths should be used in order to minimize measurement uncertainty. The use of flow conditioners in wet-gas applications is not recommended (see 12.1).

6.3 Pressure tappings

The meter should be installed horizontally with a single pair of pressure tappings. The recommended location for the tappings circumferentially is given in 12.3.

Any double block and bleed valve fitted to the tappings should be a full-bore valve.The use of compact or wafer double block and bleed valves introduces liquid traps into the impulse line.

In addition, a third pressure tapping may be located downstream of the Venturi conical expander outlet (the diffuser section) to facilitate the measurement of the fully recovered pressure. The optimum position for this third pressure tapping has not been definitively established, but is approximately $6D$ from the downstream end of the divergent section.

The ratio of the pressure loss to the differential pressure can be much higher than in a single phase flow. This ratio can be used under certain circumstances to determine the Lockhart-Martinelli parameter. Where the liquid mass flowrate is only measured discontinuously, significant variations in this ratio can help indicate when a new measurement of the liquid mass flowrate is required.

6.4 Computation of gas flowrate

6.4.1 General

The general model for the over-reading correction factor is reported in References [6] and [1]. Reference [3] includes an improved correlation. Extensive research (References [22] to [28]) includes the collection of data on which the equations in 6.4.2, 6.4.3 and 6.4.5 are based. Gas flowrate equations in this subclause appear in Reference [19].

Further research into the use of Venturi tubes in wet gas is still required.

The range of gases and liquids in the database from which the gas flowrate equations in this subclause have been derived is: nitrogen, argon, natural gas and steam; water (at ambient temperature and in a wet-steam flow), Exxsol D80[1)], Stoddard solvent (white spirit), and decane. It is possible that the equations do not apply to liquids significantly different from those tested, particularly to highly viscous liquids.

The wet gas flowrate is calculated from Equation (1) where C and ϕ are obtained from Equations (4) and (5), respectively.

Examples of how to perform the computations are given in Annex A.

6.4.2 Discharge coefficient

$$C = 1 - 0{,}046\,3\ \exp\left(-0{,}05 Fr_{\text{gas,th}}\right) \min\left(1, \sqrt{\frac{X}{0{,}016}}\right) \qquad (4)$$

where

$$Fr_{\text{gas,th}} = \frac{Fr_{\text{gas}}}{\beta^{2,5}}$$

6.4.3 Over-reading correction factor

$$\phi = \sqrt{1 + C_{\text{Ch}} X + X^2} \qquad (5)$$

where C_{Ch} is given by the following equation:

$$C_{\text{Ch}} = \left(\frac{\rho_{\text{liquid}}}{\rho_{1,\text{gas}}}\right)^n + \left(\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}\right)^n$$

where

$$n = \max\left[0{,}583 - 0{,}18\beta^2 - 0{,}578\ \exp\left(\frac{-0{,}8 Fr_{\text{gas}}}{H}\right), 0{,}392 - 0{,}18\beta^2\right]$$

H depends on the liquid and is equal to 1 for hydrocarbon liquid, 1,35 for water at ambient temperature, and 0,79 for liquid water in a wet-steam flow. It is a function of the surface tension of the liquid.

1) Product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

Limits of use:

$0,4 \leq \beta \leq 0,75$

$0 < X \leq 0,3$

$Fr_{\text{gas,th}} > 3$

$\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}} > 0,02$

$D \geq 50$ mm

6.4.4 Determination of X

To perform the flowrate computation, X is required. This can be obtained by one of the following methods:

a) by measuring the liquid flowrate using tracer techniques (see Clause 8);

b) by comparing the results from the wet-gas meter with those from gas and liquid meters downstream of a separator in series with the wet-gas meter;

c) by comparing the results with those from another wet-gas meter (see Clause 9);

d) by calculating from the known total mass flowrate (see Clause 10);

e) by using a throttling calorimeter in a steam/water flow (see Clause 11);

f) by using the third pressure tapping and applying an additional correlation (see 6.4.5).

6.4.5 Use of the pressure loss ratio to determine X

For a limited range of X, it is possible to use the pressure loss to determine the Lockhart-Martinelli parameter. The formulae given here are valid for a Venturi tube with divergent total angle in the range 7° to 8°.

The pressure loss, $\Delta\varpi$, from the upstream pressure tapping to a tapping a distance L_{down} downstream of the downstream end of the Venturi tube divergent section is measured. L_{down} should be such that

$$\max(5, 20\beta - 7) \leq \frac{L_{\text{down}}}{D} \leq 9$$

Then evaluate (this is an iterative procedure)

$$Y = \frac{\Delta\varpi}{\Delta p} - 0,089\,6 - 0,48\beta^9$$

and

$$Y_{\max} = 0,61 \exp\left[-11\left(\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}\right) - 0,045\left(\frac{Fr_{\text{gas}}}{H}\right)\right]$$

If $Y/Y_{\max} \geq 0,65$, it is not possible to use the pressure loss ratio to determine X.

If $Y/Y_{max} < 0,65$, X is evaluated from

$$\frac{Y}{Y_{max}} = 1 - \exp\left[-35X^{0,75}\exp\left(\frac{-0,28Fr_{gas}}{H}\right)\right]$$

Limits of use in addition to those in 6.4.3:

$$Fr_{gas,th} > 4$$

$$\frac{Fr_{gas}}{H} \leq 5,5$$

$$\frac{\rho_{1,gas}}{\rho_{liquid}} \leq 0,09$$

These limits reflect the available data: see Reference [19].

Then ϕ is obtained from 6.4.3 .

6.5 Uncertainties

The uncertainty, $\delta q_{m,gas}$, of the gas mass flowrate is given by

$$\frac{\delta q_{m,gas}}{q_{m,gas}} = \sqrt{\left[\frac{\delta(C/\phi)}{C/\phi}\right]^2 + \left[\frac{\delta(\phi q_{m,gas}/C)}{\phi q_{m,gas}/C}\right]^2}$$

where

$$\frac{\delta(C/\phi)}{C/\phi}$$

the relative uncertainty of C/ϕ, is as given in Table 2 and

$$\frac{\delta(\phi q_{m,gas}/C)}{\phi q_{m,gas}/C}$$

is obtained by considering Equation (1). The denominator, $\phi q_{m,gas}/C$, consists of the terms of Equation (1) excluding the factor C/ϕ, and thus the uncertainty of each term can be estimated either from ISO 5167 or from calibration (see ISO 5167-1:2003, 8.2.2.1).

Table 2 — The relative uncertainty of C/ϕ in Equation (1) for a Venturi tube using the equations in 6.4

	Range of X or of Y/Y_{max}	Relative uncertainty of C/ϕ in Equation (1)
X known without error	$X \leq 0,15$	3%
	$X > 0,15$	2,5 %
X obtained from the formulae in 6.4.5	$Y/Y_{max} < 0,6$	4%
	$0,6 \leq Y/Y_{max} < 0,65$	6%

There are very limited data for wet-steam flow. Because of the uncertainty in the value of H, both $\phi_{0,94}$, the value of ϕ given H = 0,94, and $\phi_{0,79}$, the value of ϕ given H = 0,79, should be calculated and

$$100\left(\frac{\phi_{0,79}-\phi_{0,94}}{\phi_{0,79}}\right)\%$$

added to the relative uncertainty of C/ϕ.

7 Orifice plates

7.1 General

Orifice plates have been historically used for a wide range of applications including wet gas. Provided that the orifice plate remains undamaged, orifice plates perform well in wet gas. There is a risk that a slug of liquid could bend an orifice plate.

7.2 Design requirements

The design requirements for orifice plate assemblies are contained within ISO 5167-2.

The equations in this Technical Report should only be applied to meters that have been installed horizontally. Installation of the orifice plate assembly at a low point of the piping configuration where liquid could collect should be avoided.

In many situations it is desirable that the orifice plate be installed with suitable double block and bleed isolation valves, so that the orifice plate can be removed and inspected as required.

The presence of liquid in the flow line affects the flow profile as it enters the orifice plate. This is a source of measurement uncertainty over and above that normally expected for dry gas measurement. In order to minimize this additional uncertainty, upstream pipe work should be designed so that bends immediately upstream of the meter encourage any stratified liquid to flow at the bottom of the pipe. Moreover, it is not recommended that the reduced straight lengths outlined in ISO 5167-2 be used. Where possible, the longer lengths should be used in order to minimize measurement uncertainty. The use of flow conditioners in wet-gas applications is not recommended (see 12.1).

7.3 Use of orifice plates with drain holes

The use of orifice plates fitted with drain holes is covered by ISO/TR 15377. Where the liquid flow only occurs infrequently for brief periods, orifice plates with drain holes may be sufficient without any correction for over-reading. There are insufficient data to provide general formulae for ϕ and C for the orifice plate with a drain hole.

The drain hole should be located at the bottom of the orifice plate (corresponding to the 6 o'clock position).

7.4 Pressure tappings

The meter should be installed horizontally with a single pair of pressure tappings. The recommended location for the tappings circumferentially is given in 12.3.

In addition, a third pressure tapping may be located downstream of the orifice plate to facilitate the measurement of the fully recovered pressure. A distance of 6D from the plate is regarded as reasonable.

The ratio of the pressure loss to the differential pressure can be significantly higher than in a single-phase flow. This ratio can be used under certain circumstances to determine the Lockhart-Martinelli parameter. Where the liquid mass flowrate is only measured discontinuously, significant variations in this ratio can help indicate when a new measurement of the liquid mass flowrate is required.

7.5 Computation of gas flowrate

7.5.1 General

The general model for the over-reading correction factor is reported in References [6] and [1]. Research is included in References [20], [21], and [29]. The equations in 7.5.3 appear in Reference [30].

The range of gases and liquids in the database from which the gas flowrate equations in this subclause have been derived is: nitrogen and natural gas; Exxsol D80[1)] and decane. It is possible that the equations do not apply to liquids significantly different from those tested, particularly to highly viscous liquids. The over-reading is smaller in cold water than in a light hydrocarbon liquid: determining the magnitude of this difference requires further work.

The wet gas flowrate is calculated from Equation (1) where C and ϕ are obtained in 7.5.2 and 7.5.3, respectively.

7.5.2 Discharge coefficient

C is given by the Reader-Harris/Gallagher equation (see ISO 5167-2:2003, 5.3.2.1). The Reynolds number used is that which would be obtained if only the gas were flowing.

7.5.3 Over-reading correction factor

$$\phi = \sqrt{1 + C_{\text{Ch}} X + X^2} \qquad (6)$$

where C_{Ch} is given by:

$$C_{\text{Ch}} = \left(\frac{\rho_{\text{liquid}}}{\rho_{1,\text{gas}}}\right)^n + \left(\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}}\right)^n$$

where

$$n = 0{,}214 \quad \text{for} \quad 0{,}2 \le Fr_{\text{gas}} < 1{,}5$$

and

$$n = \left(\frac{1}{\sqrt{2}} - \frac{0{,}3}{\sqrt{Fr_{\text{gas}}}}\right)^2 \quad \text{for} \quad Fr_{\text{gas}} > 1{,}5$$

Limits of use:

$0{,}24 \le \beta \le 0{,}73$

$0 < X \le 0{,}3$

$Fr_{\text{gas}} \ge 0{,}2$

$\frac{\rho_{1,\text{gas}}}{\rho_{\text{liquid}}} > 0{,}014$

$D \ge 50$ mm

7.5.4 Determination of X

To perform the flowrate computation, X is required. This can be obtained by one of the following methods:

a) by measuring the liquid flowrate using tracer techniques (see Clause 8);

b) by comparing the results from the wet-gas meter with those from gas and liquid meters downstream of a separator in series with the wet-gas meter;

c) by comparing the results with those from another wet-gas meter (see Clause 9);

d) by calculating from the known total mass flowrate (see Clause 10);

e) by using a throttling calorimeter in a wet-steam flow (see Clause 11);

f) or by using the third pressure tapping and applying an additional correlation (see 7.5.5).

7.5.5 Use of the pressure loss ratio to determine X

If $0{,}5 \le \beta \le 0{,}68$, it may be possible to use the pressure-loss ratio to determine X.

The pressure loss, $\Delta\varpi$, from the upstream pressure tapping to a tapping between $5D$ and $7D$ downstream of the orifice plate is measured. Then evaluate (this is an iterative procedure)

$$Y = \frac{\Delta\varpi}{\Delta p} - \left.\frac{\Delta\varpi}{\Delta p}\right|_{\text{dry}}$$

where

$$\left.\frac{\Delta\varpi}{\Delta p}\right|_{\text{dry}}$$

is obtained using ISO 5167-2: 2003, Equation (7).

$$X = \frac{6{,}41Y}{\beta^{4{,}9}}\left(\frac{\rho_{\text{l,gas}}}{\rho_{\text{liquid}}}\right)^{0{,}92} .$$

Limits of use in addition to those in 7.5.3:

$$0{,}5 \le \beta \le 0{,}68$$

$$X < 0{,}45\left(\frac{\rho_{1\text{,gas}}}{\rho_{\text{liquid}}}\right)^{0{,}46}$$

$$\frac{\rho_{1\text{,gas}}}{\rho_{\text{liquid}}} \le 0{,}21\beta - 0{,}09 .$$

Then ϕ is obtained from 7.5.3.

7.6 Uncertainties

The uncertainty, $\delta q_{m,\text{gas}}$, of the gas mass flowrate is given by

$$\frac{\delta q_{m,\text{gas}}}{q_{m,\text{gas}}} = \sqrt{\left[\frac{\delta(C/\phi)}{C/\phi}\right]^2 + \left[\frac{\delta\left(\phi q_{m,\text{gas}}/C\right)}{\phi q_{m,\text{gas}}/C}\right]^2}$$

where

$$\frac{\delta(C/\phi)}{C/\phi}$$

is as given in Table 3 and

$$\frac{\delta(\phi q_{m,\text{gas}}/C)}{\phi q_{m,\text{gas}}/C}$$

is obtained by considering Equation (1). The denominator, $\phi q_{m,\text{gas}}/C$, consists of the terms of Equation (1) excluding the factor C/ϕ and thus the uncertainty of each term can be estimated either from ISO 5167 or from calibration (see ISO 5167-1:2003, 8.2.2.1).

Table 3 — The relative uncertainty of C/ϕ in Equation (1) for an orifice plate using the equations in 7.5

	Liquid in the wet gas flow	Relative uncertainty of C/ϕ in Equation (1)
X known without error	A light hydrocarbon liquid or water in a wet-steam flow	2 %
	Water at ambient temperature	3 %
X obtained from the formulae in 7.5.5	A light hydrocarbon liquid or water in a wet-steam flow	6 %
	Water at ambient temperature	7 %

8 Tracer techniques

8.1 General

Where 6.4.5 or 7.5.5 is not undertaken or is impossible, tracer techniques may be a satisfactory alternative (Reference [11]). They are especially useful in a natural-gas/liquid flow verifying Venturi tubes when there is no possible means of routing the flow to a test separator.

Where there is more than one liquid in the pipeline, different tracers may be used to distinguish the flow of different liquids, e.g. hydrophobic and hydrophilic tracers may be used to distinguish condensate and water flows. However, this Technical Report only covers flows with a single liquid.

If it is decided at the outset that tracer techniques are to be used, the installation should be designed and constructed with the needs and requirements of these techniques in mind. Specifically, the points listed in the following need to be taken into account.

a) The injection point should be located so that good mixing occurs between the tracer fluid and the line fluids before sampling.

b) The required mixing distance generally depends on the availability of bends or other devices that introduce additional mixing. The pipe does not need to be straight; e.g. it may contain bends and valves, since mixing is desirable. If the pipe is straight, 150D of pipe between the tracer injection and sampling points should be sufficient. However, the pipe layout and flow design data should be closely examined in order to perform mixing calculations and make detailed recommendations (see References [31] and [32]).

c) The sampling point should be located at the bottom of a horizontal pipe to ensure that an adequate amount of liquid can be obtained for analysis purposes: it is generally necessary to collect at least 50 ml.

Tracer techniques are essentially ‘spot checks’, and therefore there is a degree of inherent uncertainty from fluctuations in the presence of liquid.

8.2 Technique

The tracer technique is used to determine the volume flowrate of a liquid within a pipe using the following equation:

$$q_{V,\text{liquid}} = q_{V,\text{injected}} \frac{C_{\text{injected}}}{C_{\text{sample}}}$$

where

$q_{V,\text{injected}}$ is the injection volume flowrate;

C_{injected} is the concentration of tracer in the injection fluid;

C_{sample} is the concentration of tracer in the sampled fluid.

Reasonable effort should be made to avoid slug flow in the pipeline since the tracer injection method assumes a constant liquid flow.

NOTE Tracer techniques can also be used to give a direct measurement of the flowrate of the gas fraction. However, at present the most effective technique for this purpose involves the use of radioactive tracers, which limits their use in many applications. This technique is outside the scope of this Technical Report.

8.3 Measuring the gas flowrate using tracer techniques

The gas mass flowrate can be determined using the following procedure.

a) Perform tracer flow technique to determine liquid flowrate.

b) If necessary, analyse liquid to determine density.

c) If necessary, sample gas to determine gas density.

d) Calculate total uncorrected gas mass flowrate from the differential-pressure meter from Equation (1) using $\phi = 1$ during tracer flow technique (Use $C = 1$ for a Venturi tube; use $C = 0,6$ for an orifice plate).

e) Determine X from Equation (2) and Fr_{gas} from Equation (3).

f) Use Equation (5) or (6) as appropriate to determine ϕ; use Equation (4) or the Reader-Harris/Gallagher equation (see ISO 5167-2:2003, 5.3.2.1) as appropriate to determine C.

g) Calculate gas mass flowrate from Equation (1).

h) Iterate through e) to g) until converged $q_{m,\text{gas}}$ is obtained.

i) Until the tracer technique is used again it is necessary to make an assumption about the liquid content.

NOTE Under certain circumstances where a third pressure tapping is available, it is possible to combine 6.4.5 or 7.5.5 with Clause 8 by measuring the pressure loss ratio at one or more values of X and using the measured values of pressure loss ratio together with 6.4.5 or 7.5.5 to give an improved estimate of pressure loss ratio as a function of X for the particular installation.

9 Comparison method

An alternative method to 6.4.5, 7.5.5 or Clause 8 is the comparison method. This method can be used to verify meters in remote locations (e.g. subsea or on unmanned platforms). Essentially, the meter under test is compared with a reference measurement. A common method is to make measurements downstream of a separator (see Reference [33]). Until the comparison method is used again it is necessary to make an assumption about the liquid content.

NOTE There will almost certainly be a difference between the results of distant meters, and therefore it is possible that flow testing over a considerable time is necessary in order to clear or cater for liquids and to allow integration over a sufficient period. Consideration should be given to transit times and liquid hold-up. It is extremely important to clear a subsea flow line and to determine the gas-to-liquid ratio over the flowing period. It is possible that the gas-to-liquid ratio is the link to variable flow measurement factors over time (perhaps as much as a few years).

The flow test can also be used to produce a sample of the gaseous portion of the wet gas at the topsides for a subsea meter.

The corrections to be applied to the meter under test for liquid volume fraction can be determined from the information gained from the reference measurement. The measurements may need to be adjusted for partial phase changes between the fluids at the meter under test and those at the reference measurement. The use of a proprietary process engineering package can be used to calculate the phase fractions at the meter. The accuracy of this method is dependent on the accuracy of the conversion factors used.

In order to minimize measurement uncertainty, gas and liquid sampling points should be provided on the topsides, since corrections may be required for partial phase changes.

10 Total mass flowrate known

Where the total mass flowrate is known, for example in a wet-steam flow, proceed as in the following.

a) Calculate total uncorrected gas mass flowrate from the differential-pressure meter from Equation (1) using $\phi = 1$. (Use $C = 1$ for a Venturi tube; use $C = 0,6$ for an orifice plate).

b) Calculate liquid mass flowrate by subtraction of the gas mass flowrate from the total mass flowrate.

c) Determine X from Equation (2) and Fr_{gas} from Equation (3).

d) Use Equation (5) or (6) as appropriate to determine ϕ; use Equation (4) or the Reader-Harris/Gallagher equation (see ISO 5167-2:2003, 5.3.2.1) as appropriate to determine C.

e) Calculate gas mass flowrate from Equation (1).

f) Iterate through b) to e) until converged $q_{m,\text{gas}}$ is obtained.

11 Using a throttling calorimeter

In a wet-steam flow it may be possible to pass some of the wet steam from the pipe through a small orifice into a sampling chamber. Provided that the conditions in the sampling chamber are such that the steam is superheated and that the expansion into the sampling chamber is isenthalpic it is possible to determine the steam quality:

$$\frac{q_{m,\text{gas}}}{q_{m,\text{gas}} + q_{m,\text{liquid}}} = \frac{h_{\text{chamber}} - h_{\text{liquid}}}{h_{\text{gas}} - h_{\text{liquid}}}$$

where

h_{chamber} is the specific enthalpy of the superheated steam in the chamber;

h_{gas} is the specific enthalpy of the (saturated) steam in the pipe;

h_{liquid} is the specific enthalpy of the liquid water in the pipe.

Using this equation and Equation (2), X can be determined. This method only works at low X.

Further details may be obtained from ASME MFC-19G-2008 (Reference [14]), 6.1.4.2 and Appendix I.

12 Installation

12.1 Flow conditioners

The use of ‘thick plate’ flow conditioners that are designed for use with orifice plates to correct the flow profile is not recommended in wet gas flow applications. Liquids can easily build up in front of the flow conditioners producing a skewed flow profile that results in measurement error.

NOTE In certain conditions, hydrates can even form in the flow conditioner, restricting the flow and producing highly distorted exit profiles. Practical experience (e.g. in References [9], [10]) highlights this and other problems associated with the use of flow conditioners.

There may be scope for the use of flow conditioners that are specially designed for use in wet-gas applications, their primary aim being to redistribute liquids evenly across the flow, but such flow conditioners might change the over-reading correction factor and should not be used without testing.

12.2 Insulation

In order to promote temperature stability, and to ensure that the measured temperature is representative of that at the meter, insulation of the meter run from the upstream straight pipe length to the downstream temperature measurement device is recommended.

The use of trace heating can help to minimize the presence of liquid.

NOTE It is possible that the use of trace heating is necessary to prevent the formation of hydrates in extreme conditions.

12.3 Pressure tappings and impulse lines

12.3.1 General

Requirements for impulse lines are given in ISO 2186. The arrangement of impulse lines depends on whether the gas is a condensing vapour, e.g. steam.

12.3.2 Gas in condensing conditions, e.g. steam

If the gas is a condensing vapour, e.g. steam, the pressure tappings should be on the horizontal centreline of the primary device.

If the gas is a condensing vapour, the impulse lines should slope downwards from the pressure tappings, and the fluid in the impulse lines is then liquid condensed from the vapour.

12.3.3 Gas in non-condensing conditions

If the gas is not a condensing vapour, the pressure tappings should be at the top of the pipe (the 12 o'clock position). In this way, the potential for liquid becoming entrained in the tapping or impulse lines is minimized, and the tappings are kept as far as possible from the bulk of the liquid if stratified or annular flow regimes are present. Other positions for the tappings between the 10 o'clock and 2 o'clock positions may be satisfactory, but the uncertainty may increase.

It is important to recognize that liquid drop-out in pressure impulse lines is likely to occur, as the temperature of the gas tends towards ambient once it leaves the meter stream. In extreme cases, hydrates may even form. The presence of liquids (or hydrates) in impulse lines introduces errors into the measurement of differential or static pressure. Pressure impulse lines connecting the pressure tappings of the meter to a differential- or static-pressure transmitter should therefore be as short as possible and inclined towards the vertical in order to drain entrained liquids.

Liquid (or hydrate) accumulation can be further countered by the insulation of the impulse lines and the application of trace heating. To minimize cooling by ambient conditions, the pressure transmitters, and even the impulse lines if possible, may be placed in a heated, sealed enclosure. Alternatively, consideration could be given to the use of diaphragm (or remote) seals to minimize the risk of hydrates.

Condensate pots located in the impulse lines may be effective at catching liquids. These should be drained frequently to avoid excessive liquid build-up and therefore they may not be effective in use on unmanned installations that experience significant liquid drop-out in impulse lines.

12.4 Gas composition

The use of on-line gas chromatographs is obviously problematic in applications where large quantities of liquids are present.

Gas sampling points, if properly designed, should be capable of providing representative gas samples, even where the liquid-to-gas ratio is relatively high.

It is recommended that, where gas composition needs to be measured in wet-gas applications, it is obtained through the analysis of samples obtained from an appropriately designed sample point, in conjunction with an off-line gas chromatograph (see Clause 13).

12.5 Densitometers

Densitometers should not be used in wet-gas applications, even when the liquid volume fraction is relatively low. Contamination occurs, requiring manual intervention.

Except in the case of steam, the density of the gas and of the liquid should be determined from the analysis of representative samples (see Clause 13).

13 Sampling

13.1 General

Sampling is a potentially critical part of a system for wet-gas measurement. This is especially so in situations where a test separator is not provided for verifying wet-gas meter performance and tracer techniques are used. If a sample is at different temperature and/or pressure conditions from those in the line, a process simulation package may be required to determine values at line conditions.

This sampling clause presents some guidance that may help to minimize mis-measurement resulting from poor design and/or operation of sampling systems.

Sampling is included here for completeness, but further details can be found in the documents to which reference is made in this clause and in other references in the bibliography.

The aim of sampling in wet gas flows is to obtain the compositions of the gaseous, the aqueous and the hydrocarbon-liquid portions of the flow. It is not to obtain the relative proportions of these components.

13.2 Sampling points at the wet-gas meter

If sampling is to be carried out from the flow line itself, where significant amounts of liquid may be present, two sampling points may be installed, one each for gas and for liquid.

Sampling probes may not be advisable in certain applications in view of the high risk of sample contamination.

13.3 Sampling points at test separators

13.3.1 General

Test separators should be provided with suitable sampling points. Sampling probes may be used.

13.3.2 Gas sampling

For gas sampling the standard IP 345/80 (Reference [12]) should be followed.

13.3.3 Liquid sampling

For liquid sampling and analysis, reference should be made to the recommendations of the standard GPA 2165 (Reference [13]).

Annex A
(informative)

Calculations

A.1 Example 1

A.1.1 Inputs

The following measurements are made using a Venturi tube for which d = 60 mm and D = 100 mm

Δp = 0,5 bar = 50 000 Pa

p = 60 bar = 6 000 000 Pa

t = 20 °C

From these, it is known for the particular gas in use that κ = 1,3, $\rho_{1,\text{ gas}}$ = 50 kg/m^3.

The liquid is hydrocarbon with density ρ_{liquid} = 800 kg/m^3; so H = 1.

The Venturi tube is located in a place where g = 9,81 m/s^2.

From the most recent use of a separator it is assumed that

$$\frac{q_{m,\text{liquid}}}{q_{m,\text{gas}}} = 0{,}5$$

There is assumed to be an uncertainty of 0,05, i.e. 10% in this ratio.

A.1.2 Calculations

A.1.2.1 Initial calculations

From ISO 5167-4:2003, 5.6,

ε = 0,994 236

From Equation (2)

$$X = 0{,}5\sqrt{\frac{50}{800}} = 0{,}125$$

Iteration is required.

A.1.2.2 Iterations

A.1.2.2.1 First iteration

Assume:

$C = 1$

$\phi = 1$

From Equation (1)

$$q_{m,\text{gas}} = \frac{1}{\sqrt{1-0{,}6^4}} 0{,}994\,236 \,\frac{\pi}{4} 0{,}06^2 \,\frac{\sqrt{2 \times 50\,000 \times 50}}{1} = 6{,}737\,63 \text{ kg/s}$$

From Equation (3)

$$Fr_{\text{gas}} = \frac{4 \times 6{,}737\,63}{50\pi 0{,}1^2 \sqrt{9{,}81 \times 0{,}1}} \sqrt{\frac{50}{800-50}} = 4{,}472\,68$$

From 6.4.2

$$Fr_{\text{gas,th}} = \frac{4{,}472\,68}{0{,}6^{2{,}5}} = 16{,}039\,4$$

From Equation (4), assuming $X > 0{,}016$

$$C = 1 - 0{,}046\,3 \exp\left(-0{,}05 \times 16{,}039\,4\right) = 0{,}979\,237$$

From 6.4.3

$$n = \max(0{,}583 - 0{,}18 \times 0{,}6^2 - 0{,}578 \exp\left(-0{,}8 \times 4{,}472\,68 / 1\right), 0{,}392 - 0{,}18 \times 0{,}6^2) = 0{,}502\,058$$

From 6.4.3

$$C_{\text{Ch}} = \left(\frac{800}{50}\right)^{0{,}502\,058} + \left(\frac{50}{800}\right)^{0{,}502\,058} = 4{,}271\,47$$

From Equation (5)

$$\phi = \sqrt{1 + 4{,}271\,47 \times 0{,}125 + 0{,}125^2} = 1{,}244\,813$$

A.1.2.2.2 Second iteration

From Equation (1)

$$q_{m,\text{gas}} = \frac{0{,}979\,237}{\sqrt{1-0{,}6^4}} 0{,}994\,236 \,\frac{\pi}{4} 0{,}06^2 \,\frac{\sqrt{2 \times 50\,000 \times 50}}{1{,}244\,813} = 5{,}300\,19 \text{ kg/s}$$

From Equation (3)

$$Fr_{\text{gas}} = \frac{4 \times 5{,}300\ 19}{50\pi 0{,}1^2 \sqrt{9{,}81 \times 0{,}1}} \sqrt{\frac{50}{800 - 50}} = 3{,}518\ 45$$

From 6.4.2

$$Fr_{\text{gas,th}} = \frac{3{,}518\ 45}{0{,}6^{2{,}5}} = 12{,}617\ 5$$

From Equation (4)

$$C = 1 - 0{,}046\ 3 \exp\left(-0{,}05 \times 12{,}617\ 5\right) \min\left(1, \sqrt{\frac{0{,}125}{0{,}016}}\right) = 0{,}975\ 363$$

From 6.4.3

$$n = \max(0{,}583 - 0{,}18 \times 0{,}6^2 - 0{,}578 \exp\left(-0{,}8 \times 3{,}518\ 45 / 1\right), 0{,}392 - 0{,}18 \times 0{,}6^2) = 0{,}483\ 567$$

From 6.4.3

$$C_{\text{Ch}} = \left(\frac{800}{50}\right)^{0{,}483\ 567} + \left(\frac{50}{800}\right)^{0{,}483\ 567} = 4{,}083\ 49$$

From Equation (5)

$$\phi = \sqrt{1 + 4{,}083\ 49 \times 0{,}125 + 0{,}125^2} = 1{,}235\ 339$$

This method is repeated, and on the sixth iteration the values in A.1.2.3 are obtained.

A.1.2.3 Final results

$q_{m,\text{gas}}$ = 5,319 26 kg/s

Fr_{gas} = 3,531 11

$Fr_{\text{gas,th}}$ = 12,662 9

C = 0,975 418

n = 0,483 916

C_{Ch} = 4,086 94

ϕ = 1,235 513

Further iterations do not change the values quoted.

A.1.3 Uncertainty

The uncertainty is obtained from 6.5. In practice it is likely that

$$\frac{\delta(C/\phi)}{C/\phi}$$

is much larger than

$$\frac{\delta(\phi q_m / C)}{\phi q_m / C}$$

So, if the latter is negligible in comparison with the former and X is known without error, the uncertainty is 3,0 % in the gas mass flowrate. However, since there is an uncertainty of 10 % in X, this causes additional uncertainty. If X were reduced by 10 %, the gas mass flowrate (calculated by the method above) would increase to 5,414 099 kg/s, an increase of 1,8 %. Thus the overall uncertainty in the gas mass flowrate is

$$\sqrt{3{,}0^2 + 1{,}8^2} = 3{,}5\ \%$$

A.2 Example 2

A.2.1 Input

The following measurements are made using a Venturi tube for which d = 60 mm and D = 100 mm

Δp = 0,5 bar = 50 000 Pa

$\Delta\varpi$ = 0,125 bar = 12 500 Pa

p = 60 bar = 6 000 000 Pa

t = 20 °C

From these, it is known for the particular gas in use that κ = 1,3, $\rho_{1,\ \mathrm{gas}}$ = 50 kg/m^3.

The liquid is water with density ρ_{liquid} = 1 000 kg/m^3; so H = 1,35.

The Venturi tube is located in a place where g = 9,81 m/s^2.

A.2.2 Calculations

A.2.2.1 Initial calculations

From ISO 5167-4:2003, 5.6,

ε = 0,994 236.

From 6.4.5

$$Y = \frac{12\ 500}{50\ 000} - 0{,}089\ 6 - 0{,}48 \times 0{,}6^9 = 0{,}155\ 56$$

Iteration is required.