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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 series

Mesurage du débit des fluides au moyen d'appareils déprimogènes — Lignes directrices pour la spécification des diaphragmes, des tuyères et des tubes de Venturi non couverts par la série de l'ISO 5167

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Foreword

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

This fourth edition cancels and replaces the third edition (ISO/TR 15377:2018), which has been technically revised.

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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 series

1 Scope

This document describes the geometry and method of use for conical-entrance orifice plates, quarter-circle orifice plates, eccentric orifice plates and Venturi tubes with 10,5° convergent angles. Information is also given for square-edged orifice plates and nozzles under conditions outside the scope of ISO 5167 series.

NOTE The data on which this document is based are limited in some cases.

2 Normative references

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

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

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

3 Terms and definitions

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

4 Symbols

For the purposes of this document, the symbols given in Table 1 apply.

Table 1 — Symbols

Symbols	Represented quantity	Dimensions M: mass L: length T: time	SI unit
a	Pressure-tapping hole diameter	L	m
C	Discharge coefficient	dimensionless	
d	Diameter of orifice (or throat) of primary device under working conditions[a]	L	m
d_k	Measured drain hole diameter	L	m

[a] In applications with drain holes, d is calculated from the measured values d_m and d_k [see Formulae (1) and (11)].

NOTE 1 Other symbols used in this documentt are defined at their place of use.

NOTE 2 Subscript 1 refers to the cross-section at the plane of the upstream pressure tapping. Subscript 2 refers to the cross-section at the plane of the downstream pressure tapping.

Table 1 *(continued)*

Symbols	Represented quantity	Dimensions M: mass L: length T: time	SI unit
d_m	Measured orifice or throat diameter (where the orifice or nozzle has a drain hole)	L	m
D	Upstream internal pipe diameter (or upstream diameter of a classical Venturi tube) under working conditions	L	m
d_{tap}	Diameter of pressure tappings	L	m
e	Thickness of bore	L	m
E, E_1	Thickness of orifice plate	L	m
F_E	Correction factor	dimensionless	
k	Uniform equivalent roughness	L	m
l	Pressure tapping spacing	L	m
L	Relative pressure tapping spacing: $L = l/D$	dimensionless	
p	Static pressure of the fluid	$ML^{-1} T^{-2}$	Pa
q_m	Mass flowrate	MT^{-1}	kg/s
r	Radius of profile	L	m
Ra	Arithmetical mean deviation of the (roughness) profile	L	m
Re	Reynolds number	dimensionless	
Re_D	Pipe Reynolds number	dimensionless	
Re_d	Throat Reynolds number	dimensionless	
$Re*$	Throat-tapping Reynolds number (= d_{tap} Re_d/d)	dimensionless	
β	Diameter ratio, $\beta = \dfrac{d}{D}$	dimensionless	
Δp	Differential pressure	$ML^{-1} T^{-2}$	Pa
ε	Expansibility (expansion) factor	dimensionless	
θ	Angle between the tappings used and the radius from the centre of the pipe to the centre of the drain hole	dimensionless	°
κ	Isentropic exponent	dimensionless	
λ	Friction factor	dimensionless	
ρ	Mass density of the fluid	ML^{-3}	kg/m^3
τ	Pressure ratio, $\tau = \dfrac{p_2}{p_1}$	dimensionless	

[a] In applications with drain holes, d is calculated from the measured values d_m and d_k [see Formulae (1) and (11)].

NOTE 1 Other symbols used in this documentt are defined at their place of use.

NOTE 2 Subscript 1 refers to the cross-section at the plane of the upstream pressure tapping. Subscript 2 refers to the cross-section at the plane of the downstream pressure tapping.

5 Square-edged orifice plates and nozzles: with drain holes, in pipes below 50 mm diameter, and as inlet and outlet devices

5.1 Drain holes through the upstream face of the square-edged orifice plate or nozzle

5.1.1 General

Square-edged orifice plates and nozzles with drain holes are used, installed and manufactured in accordance with the following guidelines.

NOTE 1 The guidelines presented in this document are applicable to both drain holes for liquid in gas and vent holes for gas in liquid.

In a horizontal pipe, a drain hole is positioned at the bottom of the pipe. In a horizontal pipe, a vent hole is positioned at the top of the pipe.

NOTE 2 Use of drain or vent holes can help alleviate the problem of fluid hold-up, but will not resolve measurement errors arising from the presence of two-phase flow.

5.1.2 Square-edged orifice plates

If a drain hole is drilled through the orifice plate, the coefficient values specified in ISO 5167-2 are not used unless the following conditions are observed.

a) The diameter of the drain hole does not exceed 0,1d and no part of the hole lies within a circle, concentric with the orifice, of diameter (D – 0,2d). The outer edge of the drain hole is as close to the pipe wall as practicable. It is very important that neither the upstream nor the downstream pipe obscure the drain hole and that the hole is not so small that it blocks.

b) The drain hole is deburred and the upstream edge is sharp. Spark erosion is a good method of producing the drain hole.

c) Single pressure tappings are orientated so that they are between 90° and 180° to the position of the drain hole. Upstream and downstream pressure tappings are at the same orientation relative to the drain hole.

d) The measured orifice diameter, d_m, is corrected to allow for the additional orifice area represented by the drain hole of measured diameter d_k, as shown in Formula (1):

$$d = \frac{d_m}{\left\{ \left(1-\beta''^4\right) C_1{}^2 \frac{\left[1 + a\left(1-\frac{\theta}{180}\right)^n - a\left(1-\frac{\theta^*}{180}\right)^n\right]}{\left(1 + C_2 \frac{d_k{}^2}{d_m{}^2}\right)^2} + \beta_m{}^4 \right\}^{0,25}} \quad (1)$$

where

$$\beta_m = \frac{d_m}{D} \quad (2)$$

$a, n, \theta', C_2, \beta''$ and C_1 are given in Formulae (3) to (8):

$$a = 0,66 \beta_m{}^{4,6} \exp\left(-0,15 \frac{L_2' d_m}{\beta_m d_k}\right) \quad (3)$$

$$n=-0{,}45+7{,}3\beta_{\mathrm{m}}^{4{,}6}+0{,}117\frac{d_m}{d_{\mathrm{k}}} \tag{4}$$

$$\theta^*=92-62\beta_{\mathrm{m}}^{4{,}6} \tag{5}$$

$$C_2=\begin{cases}1{,}08 & \text{if} \quad E/d_{\mathrm{k}}\le 0{,}5\\ 0{,}7675+0{,}625E/d_{\mathrm{k}} & \text{if} \quad 0{,}5<E/d_{\mathrm{k}}<0{,}9\\ 1{,}33 & \text{if} \quad 0{,}9\le E/d_{\mathrm{k}}\end{cases} \tag{6}$$

$$\beta''=\beta_{\mathrm{m}}\sqrt{1+C_2\frac{d_{\mathrm{k}}^2}{d_{\mathrm{m}}^2}} \tag{7}$$

and

$$C_1=\frac{C(Re_D',\beta)}{C(Re_D',\beta'')} \tag{8}$$

where $C(Re_D',\beta^*)$ is the discharge coefficient given by the Reader-Harris/Gallagher (1998) equation[5] [ISO 5167-2:2022, Formula (4)] for an orifice plate of diameter ratio β^* and Reynolds number Re_D' (L_1 and L'_2 are determined for the actual orifice plate; β^* is either β or β'');

$$\beta=\frac{d}{D} \tag{9}$$

[d is given by Formula (1)]

Re_D'	is a fixed value of Reynolds number typical of the flow being measured. In high-pressure gas flows Re_D' might be taken as, say, 4×10^6 (the actual Reynolds number cannot be used in the calculation of d, since in that case for an orifice plate with a drain hole d would not have a fixed value);
$L_1\ (=l_1/D)$	is the quotient of the distance of the upstream tapping from the upstream face of the plate and the pipe diameter;
$L'_2\ (=l'_2/D)$	is the quotient of the distance of the downstream tapping from the downstream face of the plate and the pipe diameter;
θ	is the angle (in degrees) between the pressure tappings used and the radius from the centre of the pipe to the centre of the drain hole ($90° \le \theta \le 180°$);
E	is the thickness of the orifice plate.

Because of the presence of C_1 this is an iterative computation, but convergence is rapid.

When estimating the relative expanded uncertainty of the flow measurement the following additional percentage uncertainty is added arithmetically to the discharge-coefficient percentage relative expanded uncertainty given by ISO 5167-2:2022, 5.3.3.1:

$$2\frac{d_{\mathrm{k}}}{d_{\mathrm{m}}} \tag{10}$$

If $\beta_m \le 0{,}63$, or both $\beta_m \le 0{,}7$ and $\theta = 90°$, C_1 can be set equal to 1, with no increase in uncertainty; in this case there will be no need to iterate.

NOTE 1 There are very limited data for D smaller than 100 mm.

NOTE 2 The formulae given here are based on work described in Reference [10].

Because the formulae in this subclause are complex, there is an example in Annex A so that a computer program can be checked.

5.1.3 ISA 1932 nozzles

If a drain hole is drilled through the nozzle upstream face, the coefficient values specified in ISO 5167-3 are not used unless the following conditions are observed:

a) the value of β is less than 0,625;

b) the diameter of the drain hole does not exceed 0,1d and no part of the hole lies within a circle, concentric with the throat, of diameter (D – 0,2d);

c) the length of the drain hole does not exceed 0,1D;

d) the drain hole is deburred and the upstream edge is sharp;

e) single pressure tappings are orientated so that they are between 90° and 180° to the position of the drain hole;

f) the measured diameter, d_m, is corrected to allow for the additional throat area represented by the drain hole of diameter d_k, as shown in the following Formula (11):

$$d = d_\mathrm{m}\left[1 + 0{,}40\left(\frac{d_\mathrm{k}}{d_\mathrm{m}}\right)^2\right] \qquad (11)$$

NOTE Formula (11) is based on the assumption that the value for $C\varepsilon(1 - \beta^4)^{-0,5}$ for flow through the drain hole is 20 % less than the value for flow through the throat of the nozzle.

When estimating the overall uncertainty of the flow measurement, the following additional percentage uncertainty is added arithmetically to the discharge-coefficient percentage relative expanded uncertainty:

$$40\left(\frac{d_\mathrm{k}}{d_\mathrm{m}}\right)^2 \qquad (12)$$

5.1.4 Long radius nozzles

Drain holes through these primary elements are not used.

5.2 Square-edged orifice plates installed in pipes of diameter 25 mm ≤ D < 50 mm

5.2.1 General

Orifice plates are installed and manufactured according to ISO 5167-2.

5.2.2 Limits of use

When square-edged orifice plates are installed in pipes of bore 25 mm to 50 mm, it is essential to observe the following conditions:

a) The pipes have high-quality internal surfaces such as drawn copper or brass tubes, glass or plastic pipes or drawn or fine-machined steel tubes. The steel tubes are of stainless steel for use with corrosive fluids such as water. The roughness is according to ISO 5167-2:2022, 5.3.1.

b) Corner tappings are used, preferably of the carrier ring type detailed in ISO 5167-2:2022, Figure 4.

c) The diameter ratio, β, is within the range $0,5 \leq \beta \leq 0,7$.

NOTE It is possible to have $0,23 \leq \beta < 0,5$, but the uncertainty increases significantly if $d < 12,5$ mm.

5.2.3 Discharge coefficients and corresponding uncertainties

The Reader-Harris/Gallagher (1998) equation[5] for corner tappings given in ISO 5167-2:2022, 5.3.2.1 is used for deriving the discharge coefficients, provided the pipe Reynolds numbers are within the limits given in ISO 5167-2:2022, 5.3.1.

An additional uncertainty of 0,5 % is added arithmetically to the relative expanded uncertainty derived from ISO 5167-2:2022, 5.3.3.1.

5.3 No upstream or downstream pipeline

5.3.1 General

This subclause applies where there is no pipeline on either the upstream or the downstream side of the device or on both the upstream and the downstream sides of the device, that is for flow from a large space into a pipe or vice versa, or flow through a device installed in the partition wall between two large spaces.

5.3.2 Flow from a large space (no upstream pipeline) into a pipeline or another large space

5.3.2.1 Upstream and downstream tappings

The space on the upstream side of the device is considered large if

a) there is no wall closer than $4d$ to the axis of the device or to the plane of the upstream face of the orifice or nozzle,

b) the velocity of the fluid at any point more than $4d$ from the device is less than 3 % of the velocity in the orifice or throat, and

c) the diameter of the downstream pipeline is not less than $2d$.

NOTE 1 The first condition implies, for example, that an upstream pipeline of diameter greater than $8d$ (that is where $\beta < 0,125$) can be regarded as a large space. The second condition, which excludes upstream disturbances due to draughts, swirl and jet effects, implies that the fluid is to enter the space uniformly over an area of not less than 33 times the area of the orifice or throat. For example, if the flow is provided by a fall in level of a liquid in a tank, the area of the liquid surface needs to be not less than 33 times the area of the orifice or throat through which the tank is discharged.

In an acceptable installation the distance of the upstream tapping (i.e. the tapping in the large space) from the orifice or nozzle centreline is greater than $4d$.

The upstream tapping is preferably located in a wall perpendicular to the plane of the orifice and within a distance of $0,5d$ from that plane. The tapping does not necessarily need to be located in any wall; it can be in the open space. If the space is very large, for example a room, the tapping is shielded from draughts.

The downstream tapping is located as specified for corner tappings in ISO 5167-2. If the downstream side also consists of a large space, the tapping is located as for the upstream tapping, except for Venturi nozzles where the throat tapping is used.

NOTE 2 When the upstream and downstream tappings are at different horizontal levels, it might be necessary to make allowance for the difference in hydrostatic head. This is usually done by reading the differential-pressure transmitter with no fluid flow and making an appropriate correction.

5.3.2.2 Square-edged orifice plates with corner tappings

5.3.2.2.1 Square-edged orifice plates with corner tappings are manufactured according to ISO 5167-2:2022, Clause 5.

5.3.2.2.2 The limits of use for square-edged orifice plates with corner tappings where there is a flow from a large space are as follows:

— $d \geq 12{,}5$ mm;

— downstream there is either a large space or a pipeline whose diameter is not less than $2d$;

— $Re_d \geq 3\,500$.

NOTE 1 It is possible to have 12,5 mm > d > 6 mm, but the uncertainty increases significantly if $d < 12{,}5$ mm.

NOTE 2 Provided that $\beta \leq 0{,}2$ and $d \geq 12{,}5$ mm, the Reader-Harris/Gallagher (1998) equation[5] given in ISO 5167-2:2022, 5.3.2.1 can be used in a pipeline for $Re_d \geq 3\,500$ with a relative expanded uncertainty of the value of C at $k = 2$ (approximately 95 % confidence level) of 1 % (if $Re_D < 5\,000$).

5.3.2.2.3 The discharge coefficient, C, is given by Formula (13):

$$C = 0{,}596\,1 + 0{,}000\,521 \left(\frac{10^6}{Re_d} \right)^{0{,}7} \tag{13}$$

The relative expanded uncertainty of the value of C at $k = 2$ (approximately 95 % confidence level) is 1 %.

5.3.2.2.4 The expansibility factor, ε, is given by the following Formula (14) and is only applicable if $p_2/p_1 > 0{,}75$:

$$\varepsilon = 1 - 0{,}351 \left[1 - \left(\frac{p_2}{p_1} \right)^{1/\kappa} \right] \tag{14}$$

When $\Delta p/p_1$ and κ are assumed to be known without error, the relative expanded uncertainty of the value of ε at $k = 2$ (approximately 95 % confidence level) is equal to $3{,}5 \frac{\Delta p}{\kappa p_1}$ %.

Test results for the determination of ε are known for air, steam and natural gas only. However, there is no known objection to using the same formula for other gases and vapours whose isentropic exponent is known.

5.3.2.3 ISA 1932 nozzles

5.3.2.3.1 ISA 1932 nozzles are manufactured according to ISO 5167-3:2022, 5.1.

5.3.2.3.2 The limits of use for ISA 1932 nozzles where there is flow from a large space are as follows:

— $d \geq 11{,}5$ mm;

— downstream there is either a large space or a pipeline whose diameter is not less than $2d$;

— $Re_d \geq 100\,000$.

5.3.2.3.3 The discharge coefficient, C, is equal to 0,99. The relative expanded uncertainty of the value of C at $k = 2$ (approximately 95 % confidence level) is expected to be no better than 1 %.

5.3.2.3.4 The expansibility factor, ε, is given by the following Formula (15) and is only applicable if $p_2/p_1 \geq 0{,}75$:

$$\varepsilon = \left[\left(\frac{\kappa \tau^{2/\kappa}}{\kappa - 1} \right) \left(\frac{1 - \tau^{(\kappa-1)/\kappa}}{1 - \tau} \right) \right]^{0,5} \quad (15)$$

The relative expanded uncertainty of the value of ε at k = 2 (approximately 95 % confidence level) is equal to $2\Delta p/p_1$ %.

5.3.2.4 Venturi nozzle

5.3.2.4.1 Venturi nozzles are manufactured according to ISO 5167-3:2022, 5.4.

5.3.2.4.2 The limits of use for Venturi nozzles where there is flow from a large space are as follows:

— $d \geq 50$ mm;

— downstream there is either a large space or a pipeline whose diameter is not less than $2d$;

— $3 \times 10^5 \leq Re_d \leq 3 \times 10^6$.

5.3.2.4.3 The discharge coefficient, C, is equal to 0,985 8. The relative expanded uncertainty of the value of C at k = 2 (approximately 95 % confidence level) is expected to be no better than 1,5 %.

5.3.2.4.4 The expansibility factor, ε, is given by the following Formula (16) and is only applicable if $p_2/p_1 \geq 0{,}75$:

$$\varepsilon = \left[\left(\frac{\kappa \tau^{2/\kappa}}{\kappa - 1} \right) \left(\frac{1 - \tau^{(\kappa-1)/\kappa}}{1 - \tau} \right) \right]^{0,5} \quad (16)$$

The relative expanded uncertainty of the value of ε at k = 2 (approximately 95 % confidence level) is equal to $4\ \Delta p/p_1$ %.

5.3.3 Flow into a large space (no downstream pipeline)

5.3.3.1 General

The space on the downstream side of the device is considered large if there is no wall closer than $4d$ to the axis of the device or to the downstream face of the orifice plate or nozzle.

The upstream tapping is located as specified for corner tappings in ISO 5167-2 and in ISO 5167-3 for orifice plates and nozzles respectively.

The distance of the downstream tapping (i.e. the tapping in the large space) from the orifice or nozzle centreline is greater than $4d$.

For Venturi nozzles, the throat tapping is used.

The downstream tapping is preferably located in a wall perpendicular to the plane of the orifice and within a distance of $0{,}5d$ from that plane. The tapping does not necessarily need to be located in any wall; it can be in the open space. If the space is very large, for example a room, the tapping is shielded from draughts.

NOTE Where the upstream and downstream tappings are at different horizontal levels, it might be necessary to make allowance for the difference in hydrostatic head.