TECHNICAL REPORT

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Guidelines for the use of ISO 5167:2022

Lignes directrices pour l'utilisation de l'ISO 5167:2022

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This third edition cancels and replaces the second edition (ISO/TR 9464:2008), which has been technically revised.

The main changes are as follows:

— this document has been revised to be consistent with ISO 5167:2022;

— this document is consistent with ISO/IEC Guide 98-3;

— the subclause on pressure transmitters has been updated.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The objective of this document is to assist users of ISO 5167, which was published in 2022 in six parts. Guidance on particular clauses of ISO 5167:2022 is given.

Some clauses of ISO 5167:2022 series are not commented upon and the corresponding clause numbers are therefore omitted from this document, except when it has been thought to be useful to keep a continuous numbering of paragraphs.

Guidelines for the use of ISO 5167:2022

1 Scope

The objective of this document is to provide guidance on the use of ISO 5167:2022 series. ISO 5167:2022 is an International Standard for flow measurement based on the differential pressure generated by a constriction introduced into a circular conduit (see ISO 5167-1:2022, 5.1). It presents a set of rules and requirements based on theory and experimental work undertaken in the field of flow measurement.

For a more detailed description of the scope, reference is made to ISO 5167-1:2022, Clause 1. Definitions and symbols applicable to this document are given in ISO 5167-1:2022, Clauses 3 and 4.

Neither ISO 5167-1:2022 nor this document gives detailed theoretical background, for which reference is made to any general textbook on fluid flow.

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*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

4 How the structure of this guide relates to the ISO 5167:2022 series

Clause 5 of this document sets out the guidance specific to each of the six parts of ISO 5167:2022:

— 5.1 covers part 1;

— 5.2 covers part 2;

— 5.3 covers part 3;

— 5.4 covers part 4;

— 5.5 covers part 5;

— 5.6 covers part 6.

Subsequent subclause numbering relates to the clauses in each of the parts. Hence, 5.1.1 covers Clause 1 in ISO 5167-1:2022; 5.2.6.4.3 covers 6.4.3 in ISO 5167-2:2022.

Guidance applicable to all six parts is given in Clause 6.

5 Guidance on the use of the ISO 5167:2022 series

5.1 Guidance specific to the use of ISO 5167-1:2022

5.1.1 Scope

No comments on this clause.

5.1.2 Normative references

No comments on this clause.

5.1.3 Terms and definitions

No comments on this clause.

5.1.4 Symbols and subscripts

No comments on this clause.

5.1.5 Principle of the method of measurement and computation

5.1.5.1 Principle of the method of measurement

No comments on this subclause.

5.1.5.2 Method of determination of the diameter ratio of the standard primary device

See Annex A.

5.1.5.3 Computation of flowrate

The formulae to be used to determine the flowrate of a metering system are given in ISO 5167-1:2022, Clause 5. Some results of these calculations will be fixed with installation dimensions and will only need to be computed once. Other calculations will need to be repeated for every flow measurement point. Annex A gives worked examples of the iterative computations shown in ISO 5167-1:2022, Annex A.

5.1.5.4 Determination of density, pressure and temperature

5.1.5.4.1 General

No comments on this subclause.

5.1.5.4.2 Density

For details on density measurement, see 6.4.

For details on density computation, see Annex B.

5.1.5.4.3 Static pressure

No comments on this subclause.

5.1.5.4.4 Temperature

The computation of temperature decrease resulting from expansion of the fluid through the primary device requires knowledge of the Joule-Thomson coefficient. The coefficient is a function of temperature, pressure and gas composition. The calculation can be carried out using an equation of state (see, in Annex B, the “detailed method” using molar composition analysis) or by the use of an approximation valid for natural gas mixtures that are not too rich, and when p and T are in the range given below. In the last case, the coefficient is a function of p and T alone.

Provided that, in the molar composition of the natural gas, methane is greater than 80 %, the temperature is in the range 0 °C to 100 °C and the absolute static pressure is in the range 100 kPa to 20 MPa (1 bar to 200 bar)

$$\mu_{JT} = 0{,}35 - 0{,}001\,42t + \left(0{,}231 - 0{,}002\,94t + 0{,}000\,013\,6t^2\right)\left(0{,}998 + 0{,}000\,41p - 0{,}000\,111\,5p^2 + 0{,}000\,000\,3p^3\right) \quad (1)$$

where

μ_{JT} is the Joule-Thomson coefficient, in kelvin per bar (K/bar);

t is the temperature of the fluid, in degrees Celsius (°C);

p is the absolute static pressure of the fluid, in bar.

The uncertainty was determined from the differences between this equation and the Joule-Thomson coefficient of 14 common natural gases and is given by

$$U = 0{,}066\left(1 - \frac{t}{200}\right) \quad \text{for } p \le 70 \text{ bar (7 MPa)} \quad (2)$$

and

$$U = 0{,}066\left(1 - \frac{t}{200}\right)\left[1 - \frac{(290 - t)}{4}\left(\frac{1}{70} - \frac{1}{p}\right)\right] \quad \text{for } p > 70 \text{ bar (7 MPa)} \quad (3)$$

where U is the expanded uncertainty in the Joule-Thomson coefficient (K/bar) at k = 2 (approximately 95 % confidence level).

NOTE If an orifice plate with β = 0,6 has a differential pressure Δp = 0,5 bar, the uncertainty in the Joule-Thomson coefficient corresponds to an expanded uncertainty in flowrate in the range from 0,001 % to 0,009 % at k = 2 (approximately 95 % confidence level), depending on the temperature, the pressure and the gas composition.

5.1.5.5 Differential pressure flow measurement system

No comments on this subclause.

5.1.5.6 Differential pressure flow measurement system design considerations

5.1.5.6.1 No comments on this subclause.

5.1.5.6.2 No comments on this subclause.

5.1.5.6.3 When comparing the permanent pressure loss with alternative differential pressure meter designs, it is important to compare meter designs that are sized to provide a similar range of differential pressure, rather than to compare different meter designs with the same value of β.

5.1.5.6.4 No comments on this subclause.

5.1.5.6.5 No comments on this subclause.

5.1.6 General requirements for the measurements

5.1.6.1 Primary device

5.1.6.1.1 No comments on this subclause.

5.1.6.1.2 No comments on this subclause.

5.1.6.1.3 Although not exhaustive, Table 1 lists materials most commonly used for the manufacture of primary devices.

Table 1 — Steels commonly used for the manufacture of primary devices

	ASTM/AISI	BS 970	AFNOR	DIN
Stainless steels	304	304-S15	Z6CN18-09	1.4301
	316	316-S16	Z6CND17-11	1.4401
High elastic limit stainless steel	420	420-S37	Z30C13	

Table 2 gives the mean linear expansion coefficient, elasticity moduli and yield stresses for the materials of Table 1 according to their ASTM/AISI designation.

Table 2 — Typical characteristics of commonly used steels

ASTM/AISI designation	Mean linear expansion coefficient between 0 °C and 100 °C K^{-1}	Elasticity modulus Pa	Yield stress Pa
304	17×10^{-6}	193×10^{9}	215×10^{6}
316	16×10^{-6}	193×10^{9}	230×10^{6}
420	10×10^{-6}	200×10^{9}	494×10^{6}

The values given in Table 2 vary with both temperature and the treatment process of the steel. For precise calculations, it is recommended that the data are obtained from the manufacturer.

When the primary device under operating conditions is at a different temperature from the one at which the diameter "d" was determined (this temperature is referred to as the reference or calibration temperature), it is necessary to calculate the expansion or contraction of the primary device. The corrected diameter "d" to be used in the computation of diameter ratio and flowrate is calculated using Formula (4), assuming there is no restraint due to the mounting:

$$d = d_0 [1 + \lambda_d (T - T_0)] \qquad (4)$$

where

d is the primary device diameter in flowing conditions;

d_0 is the primary device diameter at reference temperature;

λ_d is the mean linear expansion coefficient of the primary device material;

T is the primary device temperature in flowing conditions;

T_0 is the reference or calibration temperature.

Where automatic temperature correction is not required in the flow computer, the uncertainty for "*d*" included in the overall uncertainty calculations is increased for the change in "*d*" due to temperature variation (see ISO 5167-1:2022, 8.3.2.4). An initial calculation might show that this additional uncertainty is small enough to be considered negligible.

5.1.6.2 Nature of the fluid

No comments on this subclause.

5.1.6.3 Flow conditions

5.1.6.3.1 No comments on this subclause.

5.1.6.3.2 No comments on this subclause.

5.1.6.3.3 No comments on this subclause.

5.1.7 Installation requirements

5.1.7.1 General

The following list of inspection equipment is not exhaustive, but provides a basis for inspection control:

— calipers (thickness, diameters);

— internal micrometer (diameters);

— micrometer (thickness);

— gauge block, feeler gauge (relative position, absolute standard for checking micrometers);

— protractor (angles);

— profile measuring apparatus (edge);

— straight edge rule (flatness);

— three point bore gauge (internal diameter).

It is necessary only to use instruments that can be calibrated to primary standards if optimum accuracy is required.

5.1.7.1.1 No comments on this subclause.

5.1.7.1.2 No comments on this subclause.

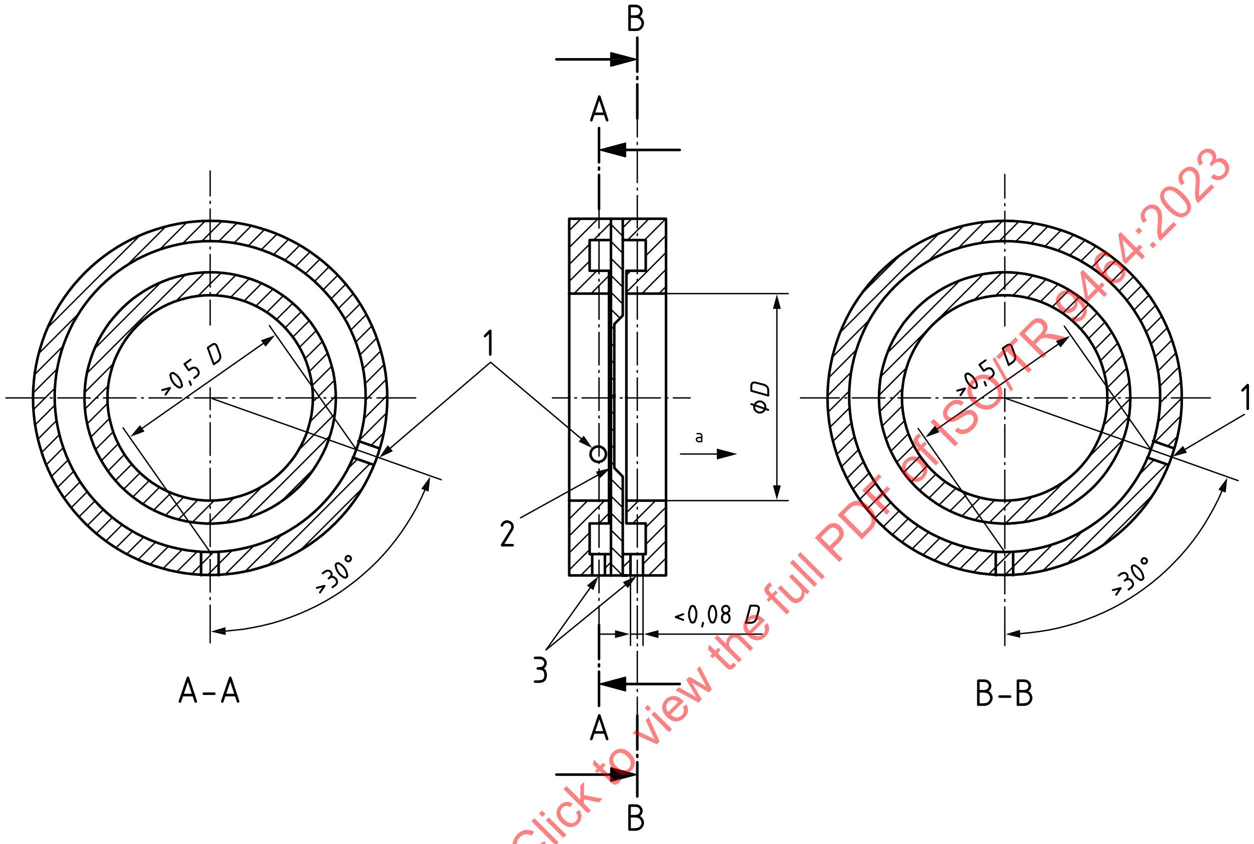
5.1.7.1.3 No comments on this subclause.

5.1.7.1.4 No comments on this subclause.

5.1.7.1.5 No comments on this subclause.

5.1.7.1.6 The requirements in this subclause of ISO 5167-1, where drain or vent holes are located near to the primary device, are illustrated in Figure 1. This figure illustrates the importance of placing the drain or vent hole in the annular chamber where one is used. The location of a drain or vent hole relative to a pressure tapping is of greater importance where there is no annular chamber and the drain or vent hole enters the pipe itself.

The flowing fluid might cause deposition, corrosion or erosion of the inner wall of the pipe. The installation might therefore not conform to the requirements of ISO 5167-1. Internal inspection of the pipe is carried out at intervals appropriate to the conditions of application.



Key

1 pressure tapping

2 orifice plate

3 drain holes and/or vent holes

[a] Flow direction.

Figure 1 — Location of drain holes and/or vent holes

5.1.7.1.7 This subclause is intended to ensure a reliable measurement of temperature. The flowing temperature is an important parameter since it is used in calculating the density of the flowing fluid and is used to calculate d and D. Furthermore, it is used to calculate critical process parameters under flowing conditions.

5.1.7.2 Minimum upstream and downstream straight lengths

5.1.7.2.1 No comments on this subclause.

5.1.7.2.2 When designing a metering pipe installation, it is recommended that the required minimum straight lengths are determined by the maximum diameter ratio that is expected in the life of the installation.

For diameter ratios not actually shown in ISO 5167-2:2022, Table 3, ISO 5167-3:2022, Table 3 or ISO 5167-4:2022, Table 1 but which are inside the limits of the standard, it is reasonable practice to interpolate linearly between the values obtained at the nearest two diameter ratios.

If an orifice meter is designed to measure the flowrate in either direction, the minimum requirements for upstream and downstream straight lengths as specified in ISO 5167-2:2022, 6.2 and Table 3 are applicable on both sides of the orifice plate.

5.1.7.3 General requirement for flow conditions at the primary device

No comments on this subclause.

5.1.7.4 Flow conditioners

Although swirl is generally not detectable in visual inspection of the pipe, swirl and asymmetry are sometimes visible in the coating, if present, on an orifice plate. A typical herring bone or chevron pattern that is seen on a plate that has been in service for some time might indicate that the flow at the orifice plate is swirling or asymmetrical. Swirl has a greater effect on measurement than any other fluid dynamic mechanism and, although straight lengths of pipe will eliminate swirl, decay occurs very slowly and the swirl persists over considerable distances.

Flow conditioners are strongly recommended where the upstream fittings or arrangement of fittings are not defined in the tables, e.g. a metering system header. They can also be useful to reduce the required upstream length. However, the additional permanent pressure loss induced by a flow conditioner is also a consideration.

ISO 5167-1:2022 describes compliance testing for flow conditioners.

5.1.8 Uncertainty on the measurement of flowrate

ISO/IEC Guide 98-3[12] and ISO 5168[9] are taken into account when performing uncertainty analyses.

Careful study of any manufacturer's specification of uncertainty helps to ensure that the metering system uncertainty is known at the measured value concerned. Some points to note include the following:

a) uncertainties are often expressed as a percentage of full scale or range;

b) uncertainties are often defined at specified reference conditions. Additional uncertainties might arise when operating conditions differ from reference conditions.

5.2 Guidance specific to the use of ISO 5167-2:2022

5.2.1 Scope

ISO 5167-2 is concerned solely with orifice plates and their geometry and installation. It is necessary to read ISO 5167-2 in conjunction with ISO 5167-1.

Orifice plate meters with three arrangements of tappings are described and specified: flange tappings; corner tappings; and D and $D/2$ tappings.

5.2.2 Normative references

No comments on this clause.

5.2.3 Terms, definitions and symbols

No comments on this clause.

5.2.4 Principles of the method of measurement and computation

The density and viscosity of the fluid can be measured (see 6.4) or calculated (see Annex B) from the gas composition. A number of computer programs are available for carrying out the calculation of density and viscosity. In the case of a compressible fluid, the isentropic exponent at working conditions is necessary for the flow calculation and this can be calculated from gas composition.

5.2.5 Orifice plates

5.2.5.1 Description

5.2.5.1.1 General

No comments on this subclause.

5.2.5.1.2 General shape

5.2.5.1.2.1 No comments on this subclause.

5.2.5.1.2.2 No comments on this subclause.

5.2.5.1.2.3 Referring to Annex C, three rules need to be taken into consideration in designing an orifice plate to avoid excessive deformation:

— Firstly, that the mounting arrangements are such that no forces are imposed on the orifice plate which would cause the limit of 0,5 % slope given in ISO 5167-2:2022, 5.1.3.1 to be exceeded under the condition of no differential pressure.

— Secondly, that the thickness of the plate, E, is such that, taking account of the modulus of elasticity of the plate material, the differential pressure for the maximum design flowrate does not cause a 1 % slope to be exceeded. When the flowrate is reduced to zero, the plate will return to the original maximum 0,5 % slope.

— Thirdly, that, if it is possible for differential pressures in excess of those for maximum design flowrate to be applied, plastic buckling (i.e. permanent deformation) does not occur.

For the first point, great care is needed in both the design and the manufacture of the mounting arrangements. Single or double chamber mounting devices are satisfactory. When mounting orifice plates correctly between standard flanges, the flanges are at 90° ± 1° to the pipe axis. The pipe sections on both sides of the orifice plate are adequately supported to ensure that no undue strain is placed on the orifice plate.

For the second point, it is clear that elastic deformation of an orifice plate introduces an error in the flow measurement results. As long as the deformation does not exceed the 1 % slope required by ISO 5167-2:2022, 5.1.2.3, no additional uncertainty will result. Theoretical and experimental research (see Reference [21]) indicates that the maximum change in discharge coefficient for a 1 % slope is 0,2 %. Therefore, orifice plates that conform to the 0,5 % slope specified in ISO 5167-2:2022, 5.1.3.1 can deform an additional 0,5 % slope (i.e. 0,1 % change in discharge coefficient) while still conforming to the requirements of this subclause. Table 3 tabulates the plate thickness to plate support diameter ratios (E/D') for various values of β and differential pressures, valid for an orifice plate manufactured from ASTM/AISI stainless steel 304 or 316, and simply supported at its rim.

Table 3 — Minimum E/D' ratios for orifice plates manufactured in ASTM/AISI 304 or ASTM/AISI 316 stainless steel

β	**Δp for maximum flowrate** kPa						
	10	30	50	75	100	200	400
0,2	0,009	0,011	0,013	0,014	0,014	0,016	0,018
0,3	0,010	0,013	0,015	0,016	0,017	0,020	0,022
0,4	0,010	0,014	0,016	0,018	0,019	0,022	0,025
0,5	0,010	0,014	0,016	0,018	0,020	0,023	0,027
0,6	0,010	0,014	0,016	0,018	0,019	0,023	0,026
0,7	0,009	0,012	0,014	0,016	0,017	0,020	0,024
0,75	0,008	0,011	0,013	0,014	0,016	0,018	0,021

Table 3 is based on the use of Formula (5) when 100 $\Delta q_m/q_m$ is not to exceed 0,1 in magnitude and $Y = 193 \times 10^9$ Pa:

$$100\frac{\Delta q_m}{q_m} = -\frac{\Delta p}{Y}\left(\frac{D'}{E}\right)^2\left(\frac{aD'}{E} - b\right) \qquad (5)$$

where

a is equal to β (13,5 − 15,5β);

b is equal to 117 − 106 $\beta^{1,3}$;

Y is the modulus of elasticity of plate material;

D' is the plate support diameter (this might differ from pipe bore D);

E is the plate thickness.

For the third point, the maximum differential pressure (which can be greater than Δp in Table 3) that could be applied is determined by the designer. This could occur when the metering section is isolated and then vented to reduce it to atmospheric pressure to enable the orifice plate to be removed for inspection, or when pressurizing the metering section before putting into service.

To avoid plastic deformation (buckling), the orifice plate thickness is such that:

$$\frac{E}{D'} > \sqrt{\frac{\Delta p}{\sigma_y}(0{,}681 - 0{,}651\beta)} \qquad (6)$$

where

Δp is the maximum differential pressure determined by the designer, in Pa;

σ_y is the yield stress of the orifice plate material, in Pa.

NOTE 1 For stainless steel, σ_y = 300 MPa, but it is advisable to use a value of 100 MPa for design purposes.

The minimum thickness of the orifice plate is whichever is the greater when determined by Formulae (5) and (6). If the calculations indicate that the necessary E is greater than 0,05D (see ISO 5167-2:2022, 5.1.5.3), the designer either reduces Δp or else introduces a stronger material.

EXAMPLE

— Formula (5):

β = 0,2

Y = 193 GPa

Δp = 50 kPa (0,5 bar)

gives $E/D' > 0{,}013$ from Formula (5) or Table 3.

— Formula (6):

β = 0,2

σ_y = 300 MPa for stainless steel, but for design purposes it is advisable to use

σ_y = 100 MPa

Δp = 100 kPa (1 bar) (see NOTE 2)

gives $E/D' > 0{,}023$.

Consequently, E/D' is at least 0,023.

NOTE 2 100 kPa (1 bar) is the maximum anticipated differential pressure.

5.2.5.1.3 Upstream face A

Table 4 gives values of deflection of the inner edge of the orifice corresponding to the 0,5 % slope for various pipe diameters and diameter ratios, β, assuming the deformation is rectilinear.

Table 4 — Plate flatness tolerances

β	Nominal diameter of the measuring pipe in millimetres										
	50	100	200	300	400	500	600	700	800	900	1 000
	Maximum deflection h in millimetres for 0,5 % slope										
0,20	0,10	0,20	0,40	0,50	0,80	1,00	1,20	1,40	1,60	1,80	2,00
0,25	0,09	0,19	0,38	0,56	0,75	0,94	1,13	1,31	1,50	1,69	1,88
0,30	0,09	0,18	0,35	0,52	0,70	0,88	1,05	1,22	1,40	1,57	1,75
0,35	0,08	0,16	0,32	0,49	0,65	0,81	0,97	1,14	1,30	1,46	1,63
0,40	0,07	0,15	0,30	0,45	0,60	0,75	0,90	1,05	1,20	1,35	1,50
0,45	0,07	0,14	0,27	0,41	0,55	0,69	0,82	0,96	1,10	1,24	1,38
0,50	0,06	0,13	0,25	0,38	0,50	0,63	0,75	0,88	1,00	1,13	1,25
0,55	0,06	0,11	0,22	0,34	0,45	0,56	0,67	0,79	0,90	1,01	1,13
0,60	0,05	0,10	0,20	0,30	0,40	0,50	0,60	0,70	0,80	0,90	1,00
0,65	0,04	0,09	0,18	0,26	0,35	0,44	0,52	0,61	0,70	0,79	0,88
0,70	0,04	0,07	0,15	0,22	0,30	0,38	0,45	0,52	0,60	0,67	0,75
0,75	0,03	0,06	0,13	0,19	0,25	0,31	0,38	0,44	0,50	0,56	0,63
See Reference [21].											

5.2.5.1.3.2 The roughness criterion in this subclause might not be adequate to ensure that the edge sharpness requirements of ISO 5167-2:2022, 5.1.7.2 can be achieved. It is advised that $Ra \leq 10^{-5}d$ and that the roughness of the orifice bore conforms to the same criterion.

5.2.5.1.3.3 It is very important that the bevelled side of the plate (if applicable) is located downstream. If the plate is inserted with the bevel upstream, the flowrate can be as much as 20 % underestimated.

It is good practice to mark the plate, if practical, to indicate the upstream face in such a way that the marking can be seen when the plate is installed.

One common method of identifying the upstream face where the orifice plate is installed between flanges is to install a “paddle plate” where the critical details are engraved on the handle which extends from the flange joint.

The upstream face of the orifice plate within diameter “*D*” is never indented by any marking.

5.2.5.1.4 Downstream face B

No comments on this subclause.

5.2.5.1.5 Thicknesses *E* and *e*

No comments on this subclause.

5.2.5.1.6 Angle of bevel

No comments on this subclause.

5.2.5.1.7 Edges G, H and I

5.2.5.1.7.1 No comments on this subclause.

5.2.5.1.7.2 The last paragraph of this subclause requires the edge radius to be measured if there is any doubt that it conforms to the requirements of ISO 5167-2:2022, 5.1.7.1 and 5.1.7.2. In those exceptional cases, some suitable techniques are given below.

a) Casting method (see Reference [17])

A replica of the edge is produced using a casting technique. The casting is made in two stages, firstly with a coloured cold-forming plastic which takes up a negative form of the orifice plate edge, and then backed with a semi-transparent epoxy resin taking the place of the orifice plate. The completed casting is cut into two halves exposing the replica of the orifice plate edge, polished and photographed with magnification. The edge condition can then be measured.

b) Lead foil impression method (see Reference [17])

An impression of the edge is made by pressing lead foil, 0,1 mm thick, onto the orifice plate edge. The lead foil is held in a micrometer-controlled inspection gauge and pressed onto the edge to give an indentation 0,12 mm deep. The indentation is examined using a projection microscope or similar equipment where the image is magnified, and a tracing of the outline is drawn. The edge condition can then be measured.

c) Paper-recording roughness method (see Figure 2)

This instrument records on a magnified scale the movements of a tracing stylus. To obtain an enlarged reproduction of the orifice edge, the paper speed is chosen equal to the driving velocity times the magnification of the transverse movements. To establish the correct edge radius of the orifice, the tip radius of the stylus is subtracted from the edge radius measured from reproduction and divided by the degree of magnification. Note that the finite dimensions of the stylus, such as tip angle, tip radius and stylus length, can invalidate the measurement or conceal irregularities on the edge.

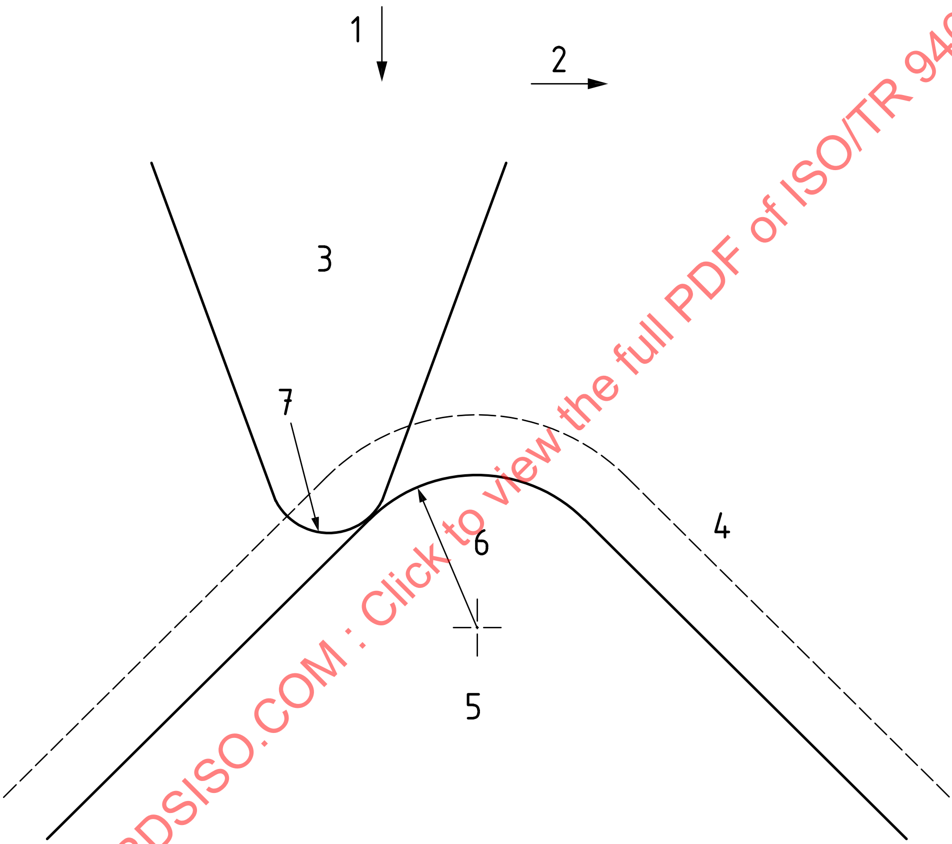
When edge sharpness is to be measured, at least 4 positions are used, equally spaced around the bore. When a defect is visible to the naked eye, the edge sharpness is also measured at this point.

Interpretation of the edge profile, whatever the reproduction technique, is a matter of expert judgement. Standard machining practice can cause the profile to be very irregular, even though the orifice plate conforms to all the requirements for dimensions and surface roughness.

All edges lying within the shaded region of Figure 3, with an additional margin for surface roughness, can be considered as acceptable. Some surface roughness is tolerable in accordance with ISO 5167-2:2022, 5.1.3.2, but very irregular edges are not acceptable.

A simple way of estimating the actual edge radius is by comparing the profile with curves (see examples in Figure 4) reproduced on a transparent foil.

Edge sharpness measurement is a specialist activity. There are laboratories in many countries that are capable of measuring edge sharpness to the standard required in ISO 5167-2:2022, 5.1.7.2. See Reference [17].



Key

1 recorded movement
2 driving movement
3 stylus
4 traced path
5 square edge
6 *R* = edge radius
7 radius

Figure 2 — Paper-recording roughness method

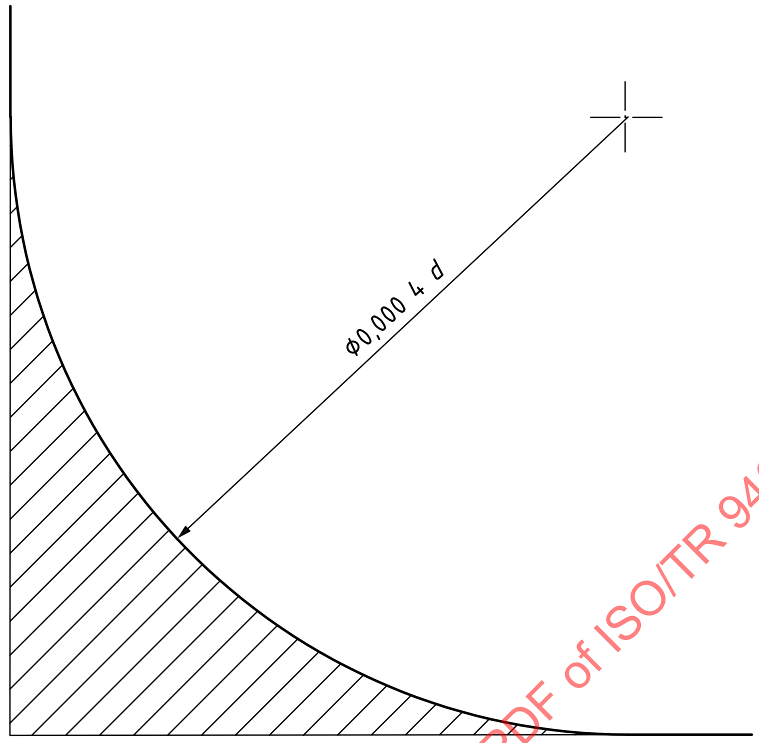


Figure 3 — Maximum edge radius

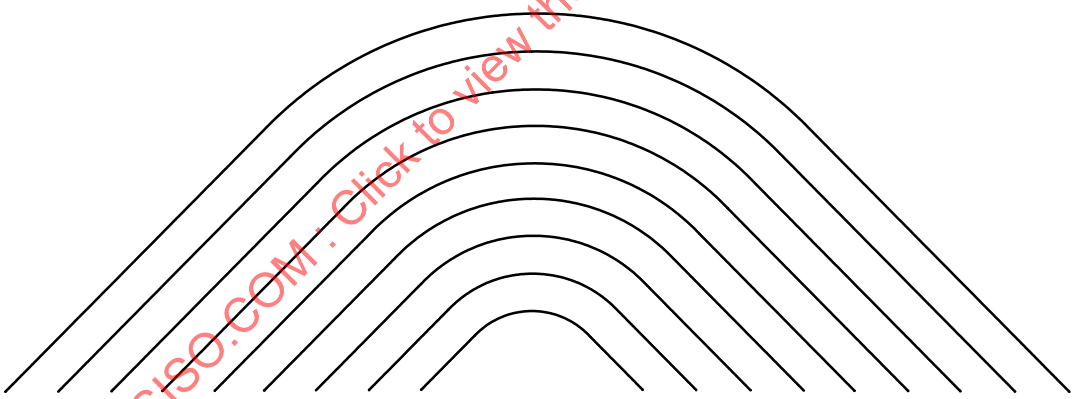


Figure 4 — Edge radius curves

5.2.5.1.7.3 No comments on this subclause.

5.2.5.1.7.4 No comments on this subclause.

5.2.5.1.8 Diameter of orifice, d

5.2.5.1.8.1 Because of the uncertainty of the discharge coefficient, and strict requirements on eccentricity, pipe roughness and upstream straight lengths, the user is advised to remain below a diameter ratio, β, of 0,6 for the most accurate measurements.

5.2.5.1.8.2 No comments on this subclause.

5.2.5.1.8.3 To enable the requirements of this subclause (i.e. 0,05 % difference) to be shown to have been met, it is necessary to measure or compare with an expanded uncertainty of at most 0,02 %.

5.2.5.1.9 Bidirectional plates

5.2.5.1.9.1 A symmetrical plate is intended to be used for the measurement of a fluid that flows in either direction. Such a plate is not bevelled.

The thickness, *E*, of the plate is then not greater than 0,02*D*. As a consequence, symmetrical plates are only used with low values of differential pressure to prevent deformation (see ISO 5167-2:2022, 5.1.2.3).

5.2.5.1.9.2 The appropriate tappings for the direction of flow are used.

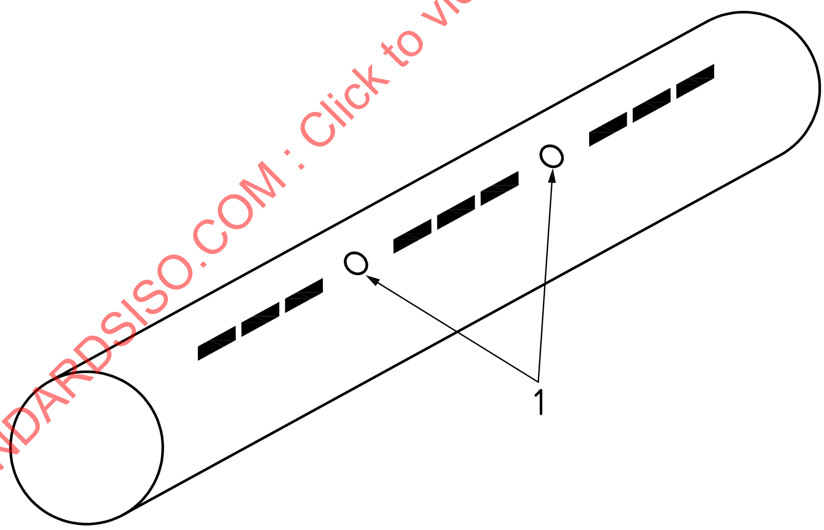
5.2.5.1.10 Material and manufacture

Subclause 5.1.6.1.3 gives some information on the most commonly used materials and their characteristics.

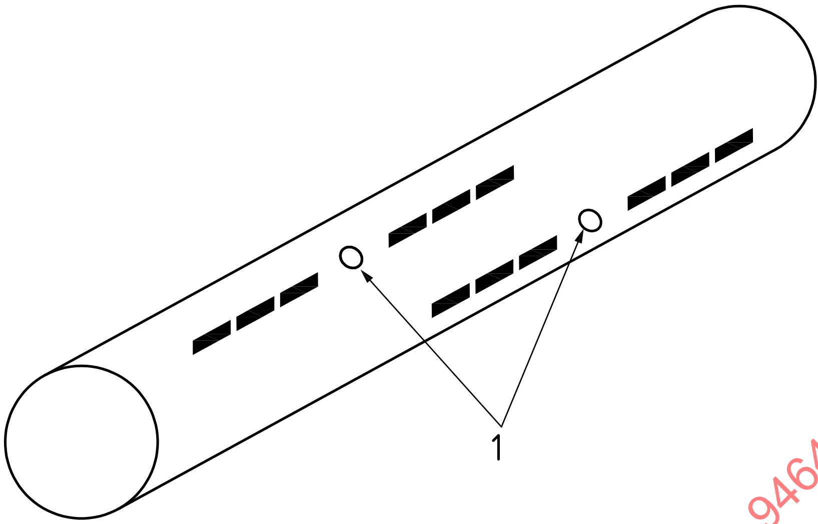
5.2.5.2 Pressure tappings

This subclause means that pressure tappings are installed as follows: at least one upstream tapping and one downstream tapping of the same type, i.e. *D* and *D*/2, flange or corner (see ISO 5167-2:2022, 5.2.1). It is possible to install tappings of several types at the same location. In such cases, each type of tapping (each "set") is designed to be totally independent of the others: the various sets are designed not to interfere in any way, and failure to comply with this results in an inaccurate measurement.

For correct design this implies that, on the same side of the orifice plate, several tappings do not lie on the same axial plane (see Figure 5). Moreover, if they are of different types (e.g. flange and *D* and *D*/2), they are offset by at least 30°. If they are of the same type (e.g. all flange), then no guidance on the acceptable offset in terms of angle is given. Good design means that no tappings affect the readings of any other tappings.



a) Example of incorrect positioning



b) Example of correct positioning

Key

1 pressure tappings

Figure 5 — Relative position of pressure tappings of different types

5.2.5.3 Coefficients and corresponding uncertainties of orifice plates

No comments on this subclause.

5.2.5.4 Pressure loss, $\Delta\varpi$

ISO 5167-2:2022, Figure 5 does not take account of frictional pressure losses in the pipe.

ΔT, as shown, is appropriate for a gas metering system.

5.2.6 Installation requirements

5.2.6.1 General

No comments on this subclause.

5.2.6.2 Minimum upstream and downstream straight lengths for installation between various fittings and the orifice plate

No comments on this subclause.

5.2.6.3 Flow conditioners

No comments on this subclause.

5.2.6.4 Circularity and cylindricality of the pipe

NOTE To conform to the given specifications, the pipe lengths adjacent to the primary device might have to be specially machined. To ensure that no significant diameter difference exists between the various lengths of the measuring pipe (ISO 5167-2), it is wise that the ones adjacent to the primary device be made of a thicker pipe so that the correct internal diameter can be obtained after machining a length of 2 pipe diameters upstream of the primary device. This method results in a measuring pipe having homogeneous dimensions.

5.2.6.4.1 A check is made that, over a length of $2D$ upstream of the primary device, any diameter measured in any plane does not vary by more than 0,3 % from the mean diameter previously obtained by ISO 5167-2:2022, 6.4.2.

In addition to the diameters measured in three cross-sections to establish "D", additional diameters are measured in at least each of two different cross sections at locations dependent on the device to be installed:

— $0{,}5D$ and $2D$ for orifice plates with D and $D/2$ pressure tappings;

— D and $2D$ for orifice plates with corner and flange tappings.

In those cases where few cross-sections are used, a check is made that no systematic variation of the measured diameters can be found.

5.2.6.4.2 The value of "D", corrected for thermal expansion (see below), is that used for the computation of the diameter ratio. This value of "D" is also used as the basis for establishing the circularity of the pipe over a length of at least $2D$ upstream and downstream of the primary device (see ISO 5167-2:2022, 6.4).

The distance to each of the measurement locations is expressed in terms of "D", which is not known before taking measurements at the prescribed locations. For the purpose of establishing the position of these locations, it is permissible to take "D" as equal to the nominal bore of the pipe.

Figure 6 gives an example for orifice meters where diameters are measured in only three different cross-sections:

— A_1, B_1, C_1 for orifice plates with corner tappings;

— A_2, B_2, C_2 for orifice plates with flange tappings;

— A_3, B_3, C_3 for orifice plates with D and $D/2$ tappings.

In any case, good practice is that individual diameters are measured with an expanded uncertainty of at most 0,1 % at $k = 2$ (approximately 95 % confidence level), as the overall tolerance is 0,3 % (see ISO 5167-2:2022, 6.4.1).

When the measuring pipe under flowing conditions is at a significantly different temperature from the one at which diameter D_0 was determined (this temperature is referred to as the reference or calibration temperature), the expansion or contraction of the pipe is taken into account in the computation of diameter ratio and flowrate, using Formula (7):

$$D = D_0 [1 + \lambda_D (T - T_0)] \quad (7)$$

where

D is the diameter of the pipe in flowing conditions;

D_0 is the diameter of the pipe at reference temperature;

λ_D is the mean linear expansion coefficient of the pipe material;

T is the pipe temperature in flowing conditions;

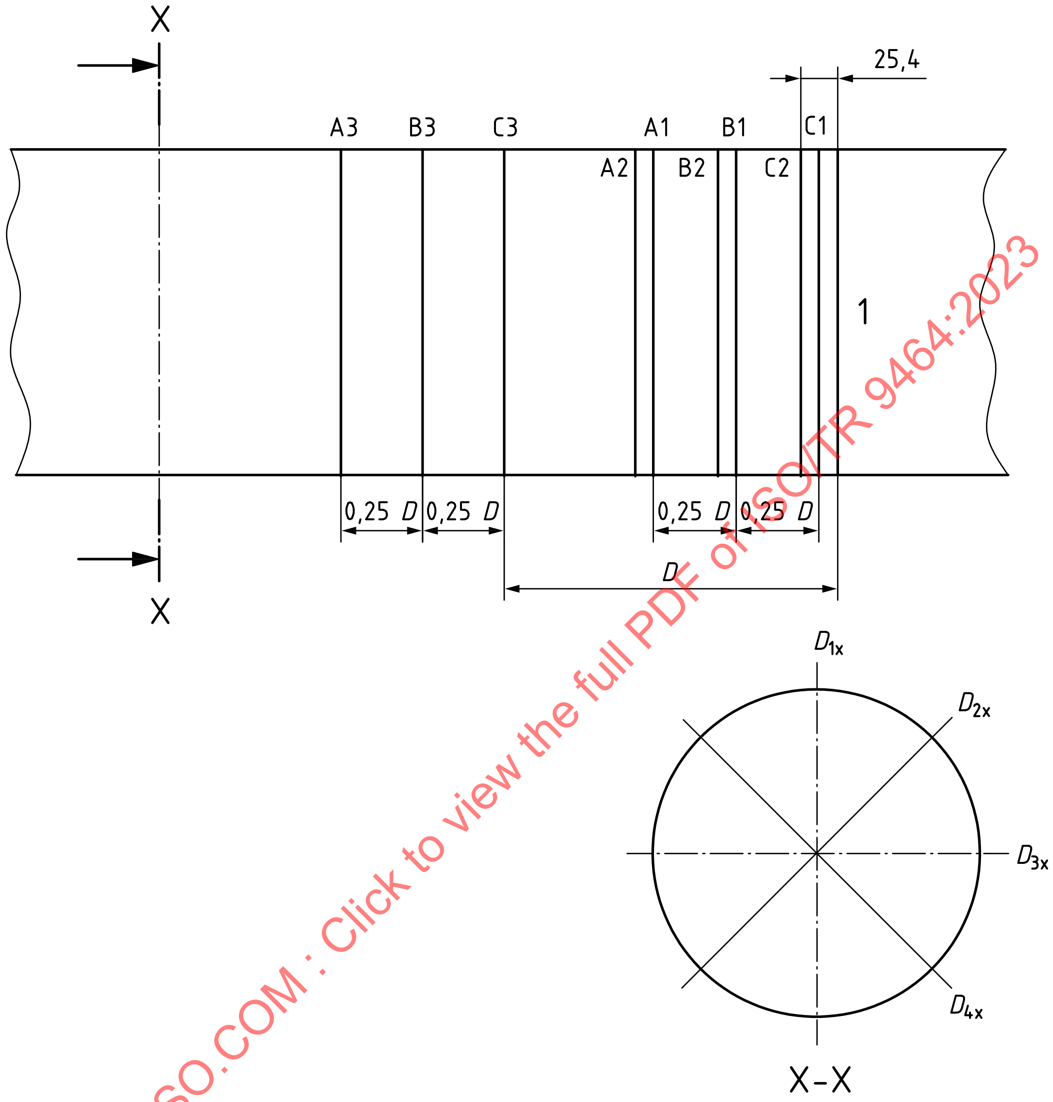
T_0 is the reference or calibration temperature.

The value for λ_D is obtained from the manufacturer of the measuring pipe.

Where automatic temperature correction is not required in the flow computer, the uncertainty for "D" included in the overall uncertainty is increased for the change in "D" due to temperature variation (see

ISO 5167-1:2022, 8.2.2.4). An initial calculation might show that this additional uncertainty is small enough to be considered negligible.

Dimensions in millimetres



Key

1 plate upstream face

Internal diameter D to be used in flowrate computation:

$$D = \frac{1}{12}\left[\sum_{i=1}^{4} D_{iA_n} + \sum_{i=1}^{4} D_{iB_n} + \sum_{i=1}^{4} D_{iC_n}\right]$$

n = 1 for corner tappings

n = 2 for flange tappings

n = 3 for D and $D/2$ tappings

Figure 6 — Measurement of internal diameter, *D*

5.2.6.4.3 Measuring the internal diameter at the ends of each section of pipe is not sufficient to ensure conformity with ISO 5167-2:2022, 6.4.3. In addition, a check is undertaken to determine that the different sections of pipe are properly mounted and do not have a step in excess of the limits given in ISO 5167-2 when connected together. See Figure 7.

The use of self-centring pipe joints is recommended. Good options are the use of tongue and groove flanges, male and female flanges, dowel pins or spigot and recess.

Check that the maximum internal step "*e*" between any two adjacent sections of pipe (A and B) more than two pipe diameters upstream of the primary device does not exceed the required value in ISO 5167-2:2022, 6.4.3, where D is the mean pipe diameter computed over $0{,}5D$ (see Figure 6).

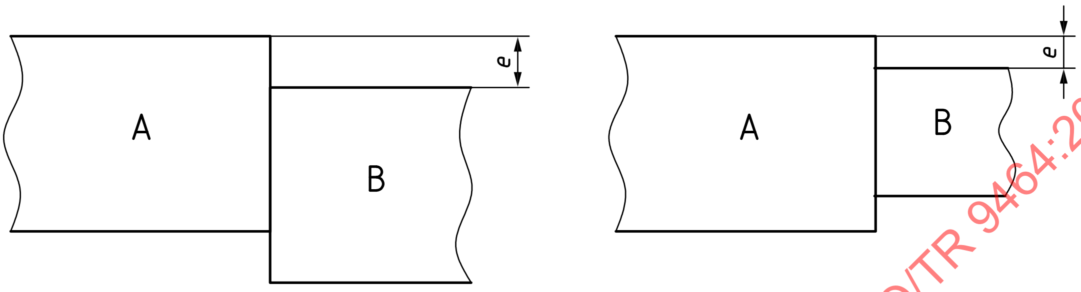


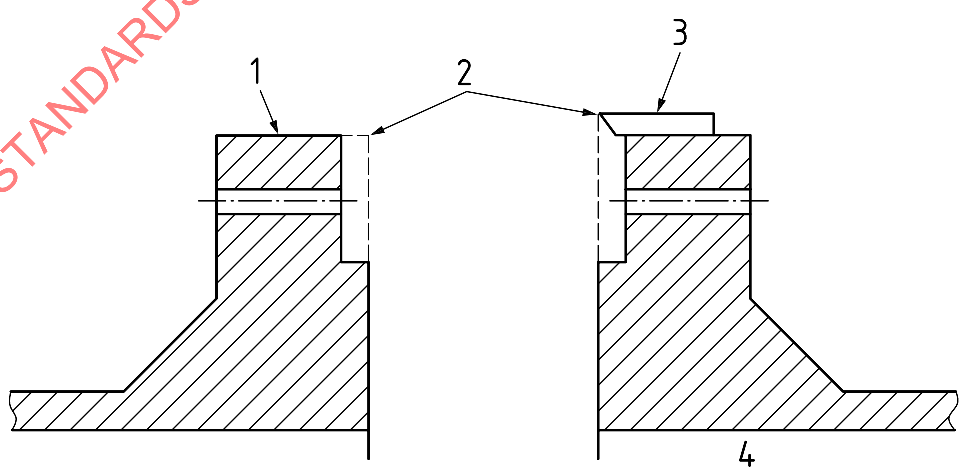
Figure 7 — Inspection of measuring pipe sections

It is possible to determine the step between coupled pipe lengths with sufficient accuracy by fixing external reference points while the pipe is uncoupled. The tolerances of the pipe and flanges are to be accounted for. Reference points can be on the extension of a matching piece or plane and are constructed in pairs, just over the joint, one on each side of it. Four or six pairs of reference points equally spaced around the circumference of the pipe joint will usually be adequate.

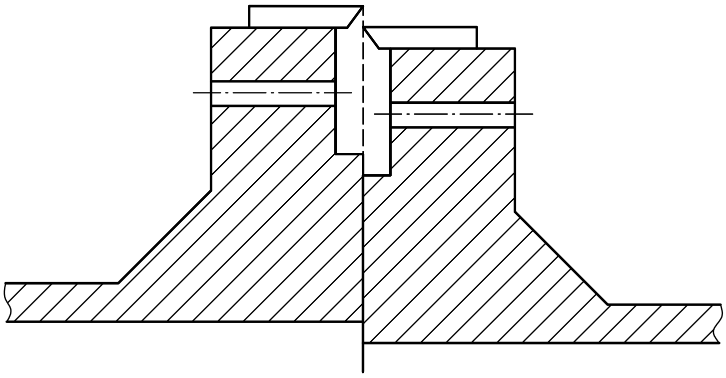
The distance from the pipe wall to the reference point is measured while uncoupled. To determine the position of a reference point in space on the extension of a plane [Figure 8 a), left hand side], the plane is extended by a sliding reference piece.

Once coupled, the distance between two reference points of a pair is measured with a micrometer. To bridge the gap, the micrometer is best fixed in a smooth plane fitting piece sliding over an equally smooth plane. Two or more measurements are then needed to determine the distance between reference points.

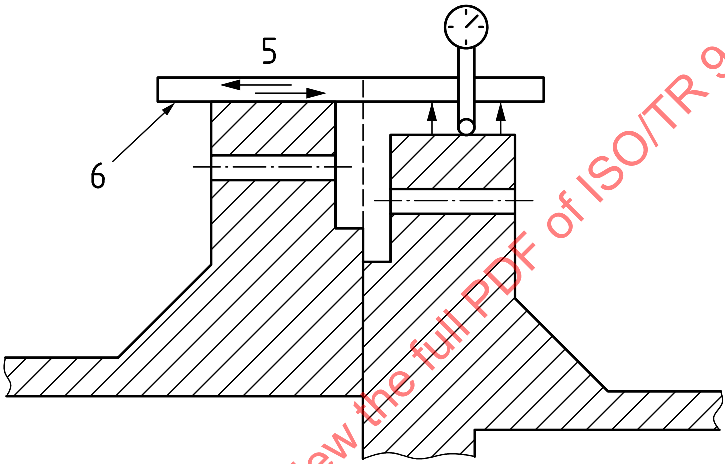
If the pipe joints are self-centring, then the external reference points are not needed. Careful measurement of the pipe bore and centring device will produce equally accurate results. Examples are given in Figure 8.



a) Some possible constructions of reference points



b) Direct measurement of distance between reference points



c) Indirect measurement of distance between reference points

Key

1 smooth plane
2 reference points
3 fixed reference piece
4 inside pipe wall
5 sliding reference piece
6 smooth plane

Figure 8 — Measurement of steps between pipe lengths

If a flow conditioner is included upstream of the orifice plate, then in an acceptable installation the pipes on either side of the conditioner are in conformity with ISO 5167-2:2022, 6.4.3 and a method of aligning the pipes and centring the flow conditioner is used.

5.2.6.4.4 No comments on this subclause.

5.2.6.4.5 No comments on this subclause.

5.2.6.4.6 No comments on this subclause.

5.2.6.5 Location of orifice plate and carrier rings

5.2.6.5.1 No specific comments on this subclause.

Table 5 and Figure 9 show the maximum distance e_c between the centre-line of the orifice and the centre-line of the pipe on the upstream and downstream sides, in the direction parallel to the axis of the pressure tappings, as a function of a diameter ratio, β, and of the pipe diameter, D, for no additional error.

Table 5 — Maximum distance e_c between the orifice centre-line and the centre-lines of upstream and downstream pipe sections in the direction parallel to the axis of the pressure tappings, in millimetres

β	D mm							
	100	150	200	300	400	500	600	700
0,20	2,41	3,62	4,82	7,23	9,65	12,06	14,47	16,88
0,25	2,29	3,44	4,59	6,88	9,18	11,47	13,76	16,06
0,30	2,11	3,16	4,21	6,32	8,43	10,54	12,64	14,75
0,35	1,86	2,79	3,72	5,58	7,43	9,29	11,15	13,01
0,40	1,57	2,36	3,15	4,72	6,29	7,87	9,44	11,01
0,45	1,29	1,93	2,57	3,86	5,15	6,43	7,72	9,01
0,50	1,03	1,54	2,05	3,08	4,10	5,13	6,15	7,18
0,55	0,81	1,21	1,61	2,42	3,22	4,03	4,83	5,64
0,60	0,63	0,94	1,26	1,88	2,51	3,14	3,77	4,40
0,65	0,49	0,73	0,98	1,47	1,96	2,45	2,94	3,43
0,70	0,38	0,57	0,77	1,15	1,53	1,92	2,30	2,68
0,75	0,30	0,45	0,60	0,91	1,21	1,51	1,81	2,11

5.2.6.6 Method of fixing and gaskets

To avoid flow measurement errors due to incorrect centring, the design of the system holding the primary element in the pipe requires care.

To conform to the requirements of centring and fixing the primary device, it is necessary, in many practical situations, to design a special fitting to suit the line size, type of fluid, pressure and temperature fluctuations of the fluid, ease of maintenance and operation, required accuracy and the system already in existence.

If the primary device can be made an integral part of the measuring pipe, the resulting installation can be defined precisely, enabling flow measurements to be highly reproducible.

Other arrangements use pairs of flanges (slip-on or weld-neck) or special proprietary fittings. Annex C illustrates recommended arrangements for orifice plates, which are equally valid for nozzles. When using flanges, it is good practice to provide a pair of jacking screws in diametrically opposite positions.

Gaskets are cheap and easy to produce but in acceptable installations they do not protrude into the pipe at any point. It is advised that gaskets are not thicker than 0,03D. It is inevitable therefore that a recess is formed at this point. The depth of the recess does not affect flow measurement, but it is necessary to maintain adequate gasket material to ensure a leak-proof joint.

O-ring seals are easy to use and give a tight, smooth joint if manufactured correctly.

Ring joints (self-centring and sealing) might produce a gap, depending upon the standard employed, and a recess between sections. Provided the gap does not exceed 13 mm, tests have shown that flow measurement will not be affected.

It is always important to avoid unacceptable flexibility of the primary device mounting with respect to the eccentricity and tapping point location tolerance (ISO 5167-2:2022, 6.5.3).

Good metering depends on maintenance of the primary device within the tolerances of the standard, thus necessitating inspection of the device from time to time. With some types of mounting for orifice plates, it is impracticable to inspect the device and the installation without dismantling the pipework. Devices enabling easy withdrawal and re-insertion of orifice plates to known tolerances might be the only practicable solution.

See Reference [26].

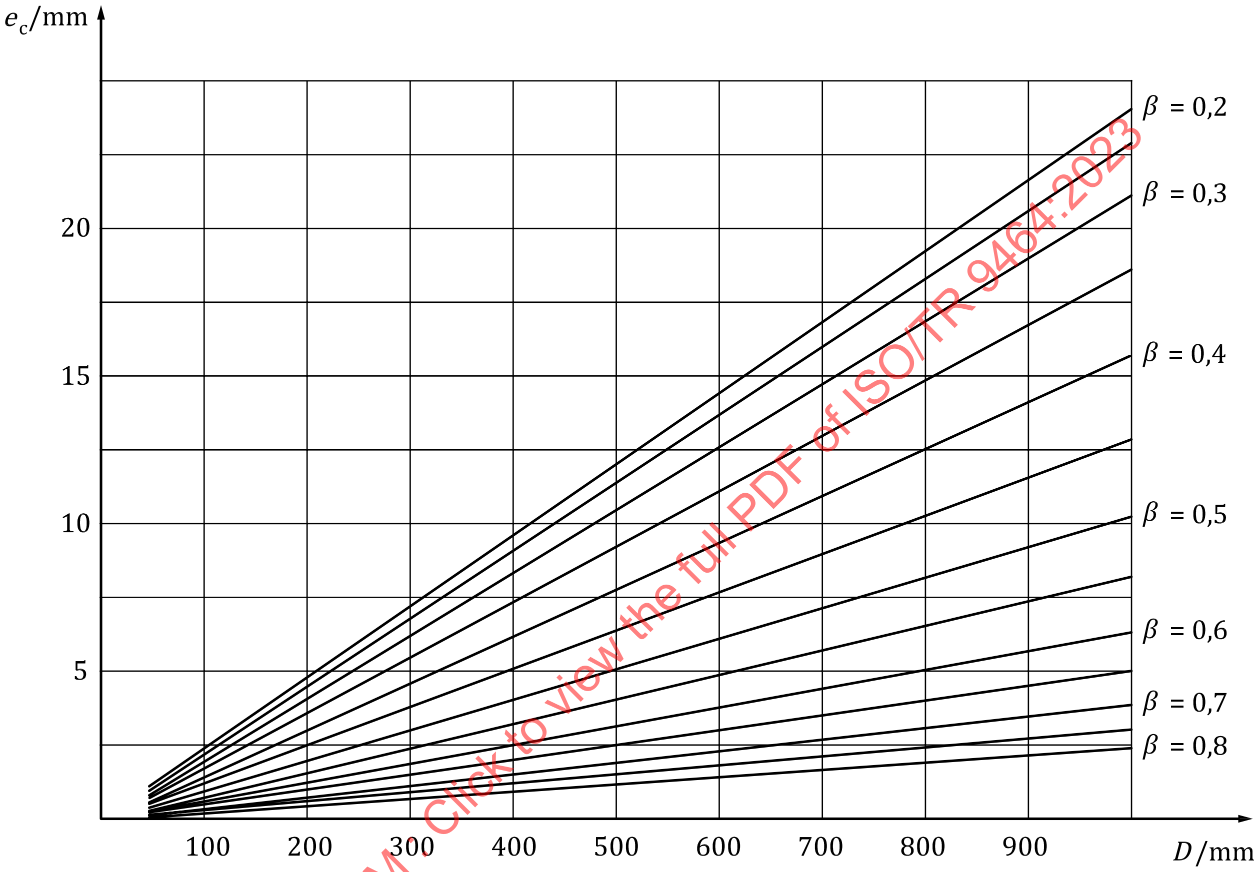


Figure 9 — Maximum distance e_c between orifice centre-line and the centre-lines of upstream and downstream pipe sections in the direction parallel to the axis of the pressure tappings, as a function of the pipe diameter, D, and the diameter ratio, β

5.2.7 Flow calibration of orifice meters

No comments on this clause.

5.3 Guidance specific to the use of ISO 5167-3:2022

5.3.1 Scope

No comments on this clause.

5.3.2 Normative references

No comments on this clause.

5.3.3 Terms and definitions

No comments on this clause.

5.3.4 Principles of the method of measurement and computation

No comments on this clause.

5.3.5 Nozzles and Venturi nozzles

5.3.5.1 ISA 1932 nozzle

No comments on this subclause.

5.3.5.2 Long radius nozzles

See Reference [23] for six low-ratio nozzles with $Ra \approx 10^{-5}\,d$, where C as given by ISO 5167-3:2022, 5.2.6.2 fits the discharge coefficient data with twice the r.m.s. deviation equal to 0,4 %.

5.3.5.3 Throat-tapped nozzles

No comments on this subclause

5.3.5.4 Venturi nozzles

5.3.5.4.1 General shape

No comments on this subclause.

5.3.5.4.2 Material and manufacture

No comments on this subclause.

5.3.5.4.3 Pressure tappings

5.3.5.4.3.1 No comments on this subclause.

5.3.5.4.3.2 No comments on this subclause.

5.3.5.4.3.3 There are equal angles between the centre-lines of adjacent tapping points.

5.3.6 Installation requirements

No comments on this clause.

5.3.7 Flow calibration of nozzles

No comments on this clause.

5.4 Guidance specific to the use of ISO 5167-4:2022

No comments on this document.

5.5 Guidance specific to the use of ISO 5167-5:2022

No comments on this document.

5.6 Guidance specific to the use of ISO 5167-6:2022

No comments on this document.

6 Information of a general nature relevant to the application of ISO 5167:2022 (all parts)

6.1 Secondary instrumentation

6.1.1 General

The definition of primary/secondary devices is stated in the Introduction to ISO 5167-1:2022.

6.1.2 General requirements concerning installation of secondary instruments

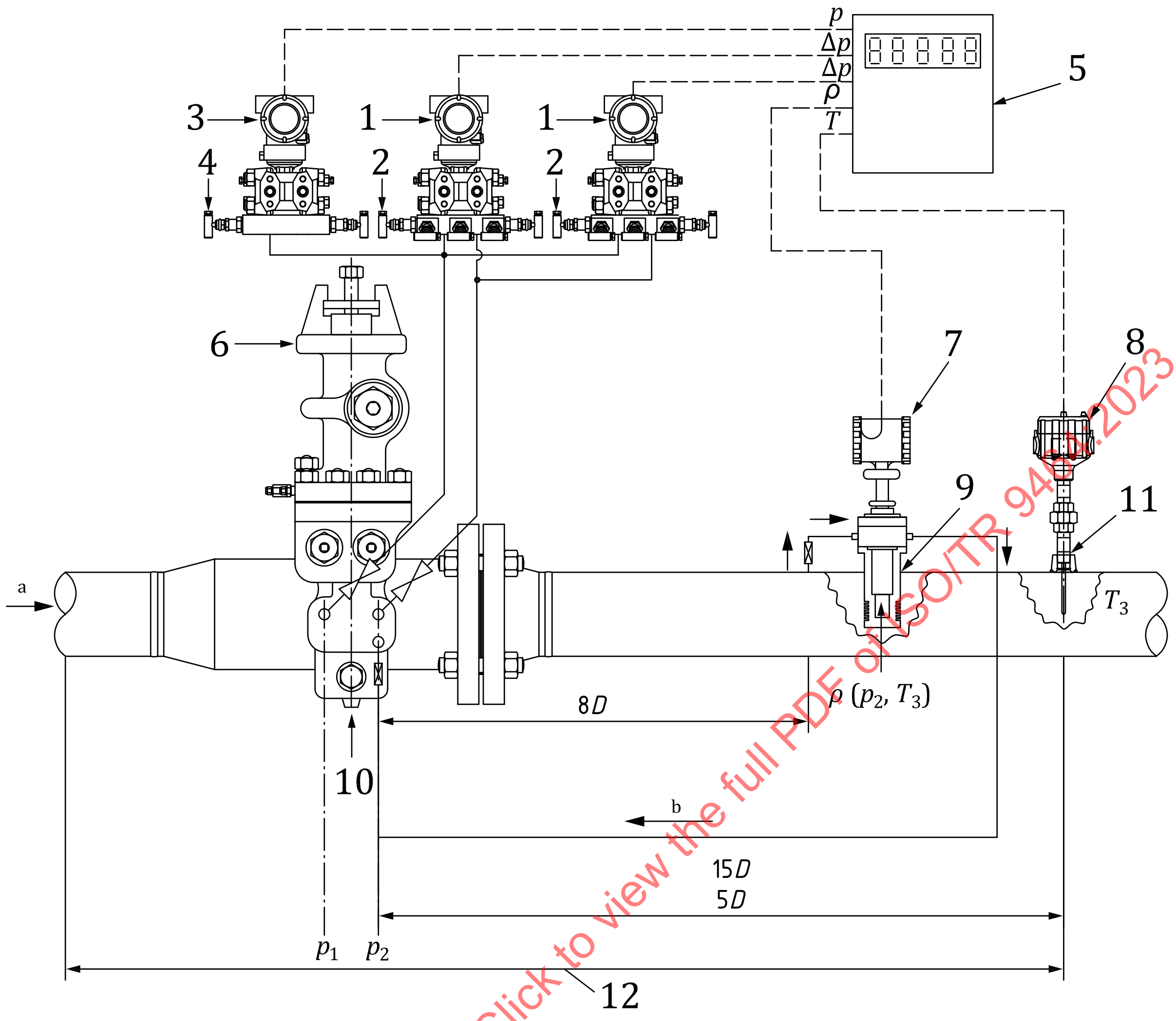
An example of an orifice-plate metering system is shown in Figure 10. When installing the instruments, the manufacturer's specifications are very important. The following general rules are followed to avoid significant errors in the performance of the secondary instrumentation close to the primary element.

a) The instrumentation is installed so that no mechanical stress is imparted by the method of mounting or the connection to the impulse pipes.

b) The installation is free from mechanical vibration within the limits of the manufacturer's specification.

c) The pressure signal connection line does not have a resonant frequency within the band width of pipeline noise (see ISO 5167-1:2022, 6.3.1).

d) If the environmental conditions are sufficiently variable to introduce significant errors into the secondary instrumentation, then the instruments are placed in an enclosure where the temperature is controlled.



Key

1 differential pressure transmitter
2 5-valve manifold
3 pressure transmitter
4 2-valve manifold
5 flow computer
6 orifice fitting
7 density meter
8 temperature transmitter
9 pocket
10 orifice plate
11 temperature sensor connection
12 meter tube per international standard
a Flow direction.
b Sample flow.

Figure 10 — Example of a metering device installation

6.2 Measurement of pressure and differential pressure

6.2.1 General

For a complete treatment of the subject of pressure-signal transmission, reference is made to ISO 2186. However, some of the problems that demand special care are briefly mentioned below.

6.2.2 Connections for pressure signal transmissions between primary and secondary elements

6.2.2.1 General

The impulse lines connecting the tappings of the primary device to the differential pressure transmitter are arranged so that no back pressure or false pressure difference is set up by the following:

a) a temperature difference between the two impulse lines;

b) the presence of gas bubbles, liquid droplets or solid deposits in either or both impulse lines;

c) the congealing or freezing of the liquid in the impulse lines.

These requirements are met by the following:

— attending to the location of the meter and the size and run of the impulse lines;

— providing gas vents and liquid catchpots or water seals;

— employing diaphragm seals (remote seals).

6.2.2.2 Isolating valves (see ISO 2186)

In general:

— It is advised that suitable isolating valves are provided in the impulse lines. The choice and location of the valves is the responsibility of the designer.

— A ball valve is used for fluids liable to form a sediment.

6.2.2.3 Condensation chambers

For specific fluids and conditions, such as steam, special connection arrangements, condensation chambers, etc. might be required. See ISO 2186 for details.

6.2.3 Pressure measurement devices

6.2.3.1 General

The accurate measurement of the differential pressure generated across a primary element is fundamental to the calculation of flowrate in a circular cross-section conduit.

In the case of orifice plates, for the measurement of gas or where higher accuracy is required for liquids, it is necessary to determine the absolute static pressure of the fluid at the upstream pressure tappings. In addition to the calculation of the expansibility factor, the static pressure is required to determine, as appropriate, the downstream to upstream corrections for process parameters such as temperature and measured density.

When density is calculated using an equation of state, the sensitivity of the static pressure measurement is greater and the need to measure this parameter accurately becomes more acute. In many instances, gauge pressure transmitters are employed to measure the pressure of the fluid at the upstream pressure tappings. The absolute static pressure of the fluid is required for the flowrate calculations and can be calculated from gauge and ambient pressure measurements. Instead of measuring the ambient barometric pressure it is common to add the conventional reference pressure of 101,325 kPa (1,013 25 bar) to the measured gauge pressure. However, when variations in atmospheric pressure result in a 0,1 % change in mass flow, it is recommended that gauge pressure instruments are replaced with absolute pressure instruments.

6.2.3.2 Pressure transmitters

The differential pressure across the primary device is most commonly measured using a differential pressure transmitter connected via the impulse lines to the upstream and downstream pressure tappings. It is acceptable that the connection to the upstream tapping be routed to the differential pressure and the static pressure transmitters when both units are installed as part of a metering device as illustrated in Figure 10; the use of multivariable transmitters is also acceptable.

The choice of pressure transmitter depends upon a number of factors which include the following:

a) the required accuracy of the measurement system;

b) the characteristics of the flowing fluid;

c) the data acquisition system including the computation device;

d) the required mounting and location for the transmitter.

6.2.3.3 Pressure calibrators

As with all secondary instrumentation, the pressure transmitters (differential and static pressure) are calibrated as appropriate for optimum accuracy. There are a number of devices currently available for this function; an acceptable device has a lower uncertainty than the pressure transmitter being calibrated.

6.2.3.4 Calibration of pressure transmitters

To reduce the effects of ambient temperature changes to a minimum, it is advised that the differential and static pressure transmitters be installed in temperature-controlled enclosures.

Static pressure transmitters are usually calibrated *in situ* against an appropriate pressure calibrator selected for the specific function.

Differential pressure transmitters are often calibrated at atmospheric pressure, again using a calibrator which is deemed suitable for the purpose. For optimum accuracy, a transmitter is ideally calibrated at operating pressure. It is common practice to use a high-static deadweight tester for this application.

As previously stated, a high-static calibration might not be possible due to less than ideal environmental conditions or background vibration at the worksite. If this is the case, a correction for static pressure shift effect is applied either mathematically or via an interim calibration option such as “footprinting”.

The “footprinting” method referred to above involves the off-line calibration of the transmitter in a controlled environment and the subsequent production of an atmospheric “footprint” which is used as a datum at the worksite for the periodic checking of the transmitter against test equipment which is less environmentally sensitive than a high-static deadweight tester.

6.2.3.5 Damping of pressure signals

See ISO/TR 3313:2018, Annex B.

6.3 Measurement of temperature

6.3.1 General

The temperature at the upstream pressure tapping is needed in order to determine the density and viscosity of the fluid and to apply correction for thermal expansion of the device and the pipe.

The temperature of the fluid is preferably measured downstream of the primary device.

6.3.2 Fundamentals of measuring the temperature of a moving fluid

Since any immersion temperature probe only measures its own temperature, the problem is to ensure that the representative temperature in the fluid is the same as the temperature at the measuring probe. Heat can be transferred by conduction, convection and radiation.

Except for great temperature differences, most of the heat is transferred from the fluid to the temperature probe by conduction and convection.

When the probe is inserted into the moving fluid, the boundary layer will tend to resist the transfer of heat to the probe and, at the same time, heat will be lost to the surroundings via the probe. The latter effect can be reduced by using thin wire leads and applying thermal insulation.

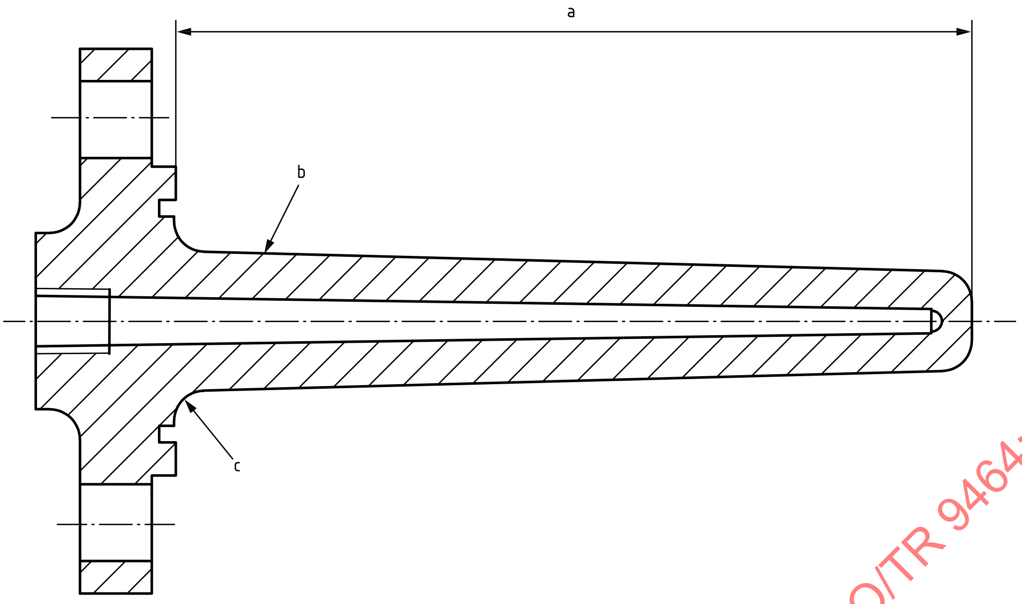
It might be necessary to mount the thermometer probe in a thermowell to protect the probe from the adverse effects of "corrosion", vibration and excessive pressures, as well as to insulate it from electrically conductive liquids. The use of thermowells gives easy access to the probe unit. See Figure 11.

Temperature measurement in gases is more difficult than in liquids because of

— the relativity poor heat transfer between the gas and the probe, as compared with the transfer of heat between the probe and its surroundings, and

— the possibility of rapid fluctuations in temperature within the gas.

If it is not practical to insert the thermometer probe into a thermowell and if the heat transfer from the gas to the pipe wall is good, then it is possible to use a sensing device clamped to the wall. This arrangement is not recommended for high-accuracy applications.



a As this length is important, it is essential that it is checked.

b Thermowell body.

c Radius carefully designed to minimize stresses.

Figure 11 — Example of thermowell design

6.3.3 Sensor installation

See ISO 5167-1:2022, 5.4.4.1.

6.3.4 Precautions for accurate measurement

6.3.4.1 Sensor position and installation configuration

In general, the sensor or thermometer is mounted perpendicular to the pipe wall, as illustrated in Figure 12 a). Severe vibration of the probe can result from the fluid flow around the inserted probe, using this installation.

This insertion depth of the sensor (*N* in Figure 12, measured from the inner wall) is such that the sensor is in the middle third of the pipe. This is not always possible for smaller and larger pipes.

6.3.4.2 Use of radiation shield

The effect of thermal radiation can be reduced by developing a piping arrangement to move the thermowell out of the direct sight line of the radiating body. A highly polished thermowell will reflect a maximum of radiant energy.

6.3.4.3 Electrical isolation of the temperature transducer

Electrical isolation prevents disturbances due to variations in the insulation resistance of the sensing elements. These are caused by high temperature in the case of thermocouples, and by moisture and other electrolytic impurities penetrating into the junction box in the case of resistance bulbs. The choice between an isolated transducer and one without isolation is determined by the operating conditions. If exceptional reliability and accuracy are required from the measurement, isolation is recommended. If the conditions remain reasonably constant and the measuring point is not particularly critical, transducers, without isolation, can be used with a considerable saving in cost.

6.3.5 Restrictions on thermowells

When positioning and installing thermowells, the following provisions are observed.

a) Where a number of thermowell pockets are to be found in close proximity to each other, care is taken not to install them in line. This is to prevent the downstream probes being subjected to unduly high stresses as a result of vortex shedding and vibrations. The problems of vortex shedding can be minimized by spacing the thermowell pockets radially around the pipe.

b) The immersion length of the well is at least ten times the diameter of the well to minimize the risk of conduction error.

c) For smaller pipes, where dimension *N* [in Figure 12 a)] becomes larger than 3/4 of the nominal inside diameter of the pipe, the positions illustrated in Figure 12 b) and Figure 12 c) are used.

d) For larger diameter pipes, where thermowell lengths exceed 100 mm, strength and vibration calculations are required if high density fluids are being measured. Air between the element and well is a very poor conductor of heat and results in measurement errors due to stem conduction. The second effect is an increase in the response time of the element. Liquid filling has been used to fill the empty space. Some heat transfer greases have been used; these materials are widely used in the electronics industry. Problems are associated with the fact that these greases have little or no lubricating effects and in fact are reported to cause threaded connections to seize together. The greatest improvement in heat transfer between the thermowell and the sensitive element is obtained by closely controlling the tolerances of the element's outside diameter and the well's inside diameter, ensuring the minimum extra clearance. Another method is to use a spring-loaded contact between the sensor and the well.

e) Undue projection of the well outside the pipe is avoided.

f) The part of the thermometer projecting outside the pipe is insulated if the temperature of the fluid differs from that of the ambient air. The adjacent pipe walls are insulated; see ISO 5167-1:2022, 7.1.7.

g) The mouth of the well is closed to minimize loss of heat by convection, especially at high temperature.

h) Care is taken regarding external temperature conditions including heat transfer due to radiation and ambient temperature.

6.3.6 Additional precautions in the case of fluctuating temperatures

If the temperature of the fluid is not constant, the accuracy of measurement depends also on the rate of heat transfer from the fluid to the temperature-sensitive element. The following precautions are taken to reduce the time lag in response:

— the wall of the well has a moderately high thermal conductivity and the surface in contact with the fluid is kept clean;

— the temperature-sensitive portion of the thermometer is small in size and of low mass and of low heat capacity.

6.3.7 Devices for temperature measurement

There are a wide variety of temperature-measuring devices based on different operating principles. Among the most common are liquid-in-glass thermometers, thermocouples and resistance thermometers.

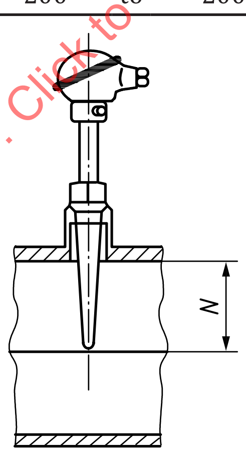
The choice of thermometer is based on knowledge of the measured media, the temperature range and the accuracy and reliability required. Some of the main characteristics of various thermometers are summarized in Table 6.

NOTE 1 Table 6 is not complete, but a simple guide. Quoted values are orders of magnitude. See also IEC 60584 for thermocouples and IEC 60751 for industrial platinum resistance thermometer sensors.

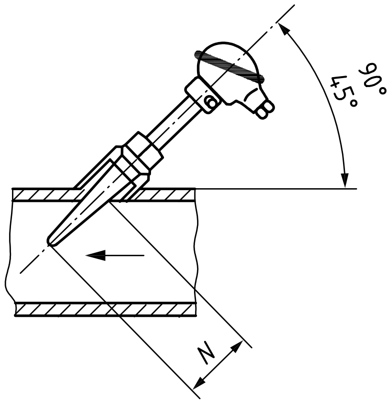
NOTE 2 Temperature sensors tend to be sensitive to mechanical vibration.

Table 6 — Main characteristics of different types of temperature sensors

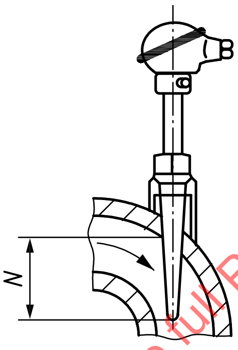
Type	Materials	Range °C			Expanded uncertainty at $k = 2$ (approximately 95 % confidence level) °C	Comments
Liquid-in-glass	Mercury	−39	to	600	0,05	Toxic; fragile
Liquid-in-glass	Alcohol	−100	to	50	0,1	Fragile
Thermocouples	Pt-Rh/Pt	0	to	1 500	1	
Thermocouples	Cu/Const	−200	to	350	0,5	
Thermocouples	Fe/Const	−200	to	600	1,5	
Thermocouples	Chromel/Alum	−200	to	1 000	1,5	
Resistance	Pt	−200	to	600	<0,2	
Resistance	Ni	−100	to	200	0,5	
Resistance	Cu	−100	to	200	0,5	
Thermistor	Semi-conduct	−200	to	200	0,2	



a)



b)



c)

Figure 12 — Installation of immersion temperature probe

6.4 Determination of density

6.4.1 General

The density of the fluid can be either measured directly or calculated from the knowledge of static pressure, temperature and characteristics of the fluid using an equation of state at the chosen reference plane.

The density of liquid at flowing conditions is determined from measurement or from reference sources and corrected to the temperature at flowing conditions. The variation with pressure is so slight that it is usually acceptable for it to be neglected, depending on the application. Special care is taken when working with fluids near the point of vaporization.

The density of gas varies with temperature, pressure and composition. For moist gas, the density also varies with the amount of water vapour present. Large errors can occur if sampling is used and the gas composition changes or the temperature drops below the saturation temperature, causing the formation of liquids.

The most common techniques used for density measurement are the force balance and vibrating element density meters. The fundamental characteristics of different density meters are given in Table 7.

NOTE Table 7 is a simple guide. Quoted values are orders of magnitude.

Table 7 — Characteristics of densitometers

Type	Range kg/m^3	Span kg/m^3	Expanded uncertainty at $k = 2$ (approximately 95 % confidence level) %
Continuous weighing	400 to 2 500	250 (max.)	0,1 % to 0,3 % of measured value
Centrifugal (gas only)	1 200 (max.)	Variable	0,5 % of span
Vibration vane	0 to 400 (gases)	0,01 (min.)	0,1 % of span
		0,1 (max.)	
	300 to 1 200 (liquid)	0,1 (min.)	
		0,3 (max.)	
Vibrating tube	0 to 400 (gases)	as range	0,1 % of span
	600 to 1 600		

6.4.2 Installation of density transducers

Most of the factors relevant to the satisfactory installation of density transducers are identical to those for other field instruments; however, as the density transducer is essentially a sampling system, good installation also ensures that:

a) the pressure and temperature of the fluid in the density cell are as similar as possible to conditions at the metering device;

b) the sample fluid is as clean as possible, free from particles and single-phase;

c) the conditions in the sample cell are not significantly affected by ambient temperature, solar radiation or wind;

d) there is a sufficient flow through the density cell to enable an adequate response to be made to changes in composition, pressure and temperature;

e) there are suitable facilities for maintenance and calibration of the transducer.

As with the installation of the temperature sensor, there is a conflict between the aim of knowing the density at the plane of the upstream pressure tapping and the installation requirements of the relevant part of ISO 5167. It is suggested that the density cell is installed downstream of the primary device either as an in-line probe or in a sample bypass. If the first alternative is chosen, the distance from the primary device to the point of installation is in accordance with ISO 5167-2:2022, Table 3 and ISO 5167-4, Table 1. For a nozzle or Venturi nozzle, the density cell is located in accordance with ISO 5167-3:2022, Table 3. Figure 13 illustrates this type of installation.

The other installation method consists of bypassing or venting the fluid through the density cell. In this case the high-pressure tapping is located at least 8*D* downstream of the primary device. The low-pressure return tapping is located just behind the downstream face of the orifice plate. It is essential that the density measurement does not interfere with the flowrate measurement. Figure 14 illustrates this type of installation method. In this illustration, valve V_1 is a needle valve, adjusted to control the flow through the densitometer in accordance with the manufacturer's instructions. Valve V_2 is a full flow valve, such as a ball valve, fully open to ensure that there is no pressure drop between the densitometer and the low-pressure return tapping. In this "bypass" mode of operation, the density of the gas (ρ_m) is measured at p_2 (downstream tapping pressure) and T_3 (downstream recovered temperature). Formula (8) is an example of an equation that is used to calculate the upstream density:

$$\rho_1 = \frac{\rho_m p_1 T_3 Z_{(p_2, T_3)}}{p_2 T_1 Z_{(p_1, T_1)}} \quad (8)$$

where

ρ_1 is the upstream density (at p_1,T_1);

ρ_m is the measured density (at p_2,T_3) from the densitometer in bypass mode;

p_1 is the upstream pressure;

p_2 is the pressure at the downstream pressure tapping;

T_1 is the upstream temperature;

T_3 is the measured temperature at the downstream recovery point;

$Z_{(p_1, T_1)}$ is the compressibility at p_1, T_1;

$Z_{(p_2, T_3)}$ is the compressibility at p_2, T_3.

Listed below are some advantages and disadvantages of both installations.

Advantages of an in-line probe:

a) Temperature and pressure are always at flowing conditions at the point of measurement, but temperature and pressure still need correction.

b) The method is suitable for both large and small pipelines.

c) The probe can be removed while the line is in service if fitted with an isolating valve.

d) The method minimizes contamination by condensates.

Disadvantages of an in-line probe:

a) There is always the danger of the seal not holding with the result that the probe could be ejected from the line or leakage around the housing might develop. Added safety precautions are taken to ensure safe operation.

b) A relatively long response time to changes in gas density occurs at low flowrates or static pressure changes.

c) The probe is not easily removed from or inserted into the line when under pressure, if not fitted with an isolating valve.

d) Main flow might be affected, causing a change in the orifice discharge coefficient.

e) There is no check facility on sample flow through the transducer.

Advantages of a sample bypass probe:

a) Filtering or maintaining a filter in the stream if needed is easy.

b) The flowrate can be adjusted to comply with the accuracy of the instrumentation needed.

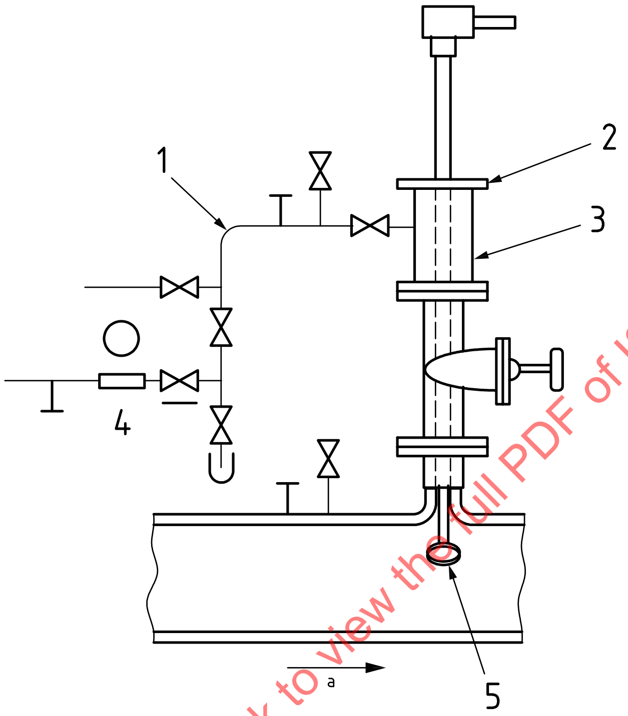
c) Access for maintenance and testing is easy.

Disadvantages of a sample bypass probe:

a) Large thermal mass might cause poor response time to temperature changes.

b) Temperature and pressure could vary from flowing conditions, resulting in measurement error. It is important to provide both side stream and transducers with thermal insulation.

c) Condensation can occur in the instrumentation and affect the accuracy of the density reading. A condensate trap might be necessary.



Key

1 sampling system for proving purposes only

2 seal

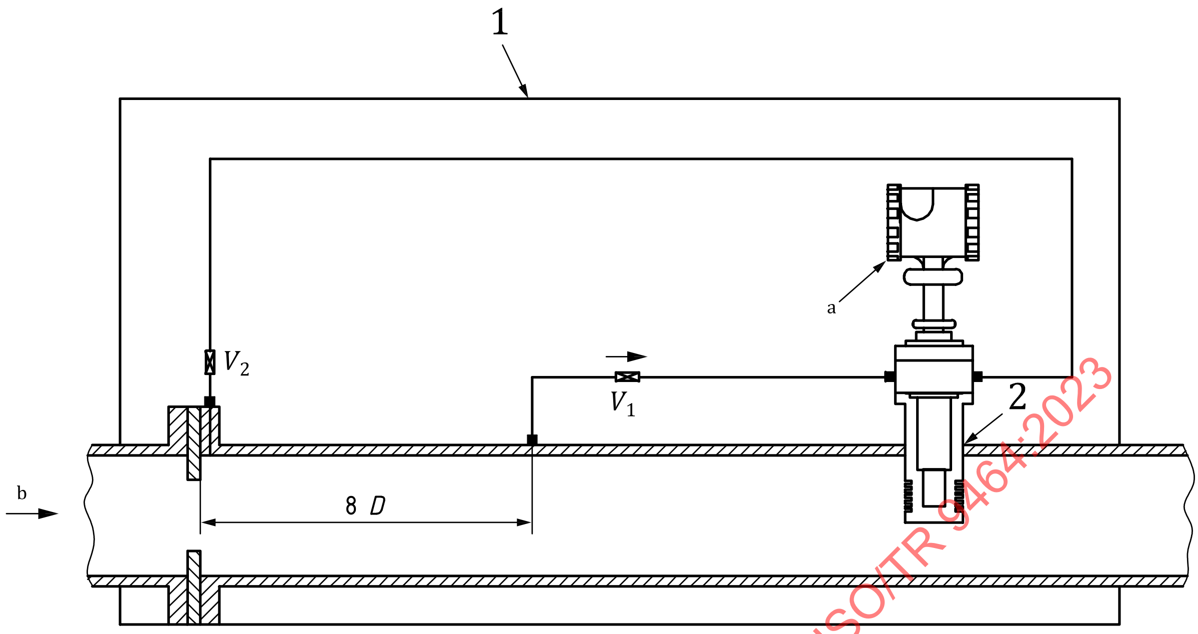
3 seal housing

4 flow meter

5 retractable probe

[a] Flow.

Figure 13 — Direct-insertion-type density meter



Key

1 thermal lagging

2 top of pipe

a To readout electronics.

b Flow.

Figure 14 — Installation showing density meter installed in sample bypass meter mounted in pocket

6.4.3 Additional method for the determination of the density of gas

The density of the gas can be computed from the real gas equation of state [see ISO 5167-1:2022, 5.4.2].

When the composition and the temperature and pressure of the gas are known, the only unknown variable is the compressibility factor. When the compressibility factor of the gas is not known from published tables, the value is found from experiments. The more common techniques used are the expansion method and the weighing method. Expanded uncertainty of the compressibility factor in the range 0,1 % to 0,2 % can be obtained at $k = 2$ (approximately 95 % confidence level) (see Annex B).

6.4.4 Special consideration concerning gas density

If high accuracy is required, introduce a correction to compensate for the fact that the fluid entering the density transmitter is not at the condition of the upstream pressure tapping. This correction is made from knowledge of the density variation caused by a change in pressure and/or temperature. An estimate of the correction can be made from the real gas equation of state (see Annex B) and use of the Joule-Thomson coefficient.

6.4.5 Special considerations concerning liquid density

Pressure has limited influence on the liquid density. It is normally accurate enough to measure the temperature of flowing conditions (see 6.3) and find the density at that temperature from tables. This is satisfactory as long as the composition is constant and within the specification in the tables.

When the liquid contains dissolved solids or gases, it is necessary to determine the specific gravity if accurate results are required.

The pyknometer method can be used for checking continuous density measurements.

6.5 Electrical supply and electrical installations

6.5.1 Potentially explosive atmospheres

Reference is made to IEC 60079-0 for general requirements.

NOTE It is possible that other parts of the IEC 60079 series are also required.

6.5.2 Cabling

The specification for the cabling of electrical instrumentation will be defined by the instrumentation design engineer and will be influenced by the type of instrument in question. Nevertheless, the following simple rules can be given:

a) signal cables are as short as possible;

b) shielded cables which are earthed only at one point are used;

c) weak signals are amplified before they are transmitted through the cables;

d) power cables are separated from instrument cables and only cross instrumentation lines at right angles;

e) signal lines are shielded from electrical lines.

6.5.3 Electronic equipment

The installation of electronic equipment is carried out in accordance with the Code of Practice appropriate for the intended use.

Annex A
(informative)

Principles of measurement and computation

A.1 Formulae

A.1.1 General

In all formulae, d, D and β refer to actual flowing conditions. In particular, when the flowing temperature differs from the temperature at which these dimensions were measured (usually 20 °C), the values are corrected for thermal expansion (see ISO 5167-1:2022, 5.4.4.1).

An explanation of the symbols used can be found in ISO 5167-1:2022, Clause 4.

A.1.2 Formulae common to all devices

Mass flowrate:
$$q_m = [1-\beta^4]^{-0,5} C\varepsilon \frac{\pi}{4} d^2 [2\Delta p \rho_1]^{0,5} \quad \text{(A.1)}$$

Volume flowrate:
$$q_{V1} = \frac{q_m}{\rho_1} \quad \text{or} \quad q_{VR} = \frac{q_m}{\rho_R} \quad \text{(A.2)}$$

where
$$\rho_1 = \rho_R \frac{p_1 T_R Z_R}{p_R T_1 Z_1} \quad \text{(A.3)}$$

Subscript “1” refers to the flow condition at the upstream pressure tapping cross-section.

Subscript “R” refers to given conditions of pressure and temperature.

Reynolds number:
$$Re_D = \frac{V_1 D}{\nu_1} = \frac{4 q_m}{\pi D \mu_1} = \frac{4 q_{V1}}{\pi D \nu_1} \quad \text{(A.4)}$$

A.1.3 Limits of use of primary devices

The formulae given for C and ε in all parts of ISO 5167 for the various primary devices can be applied only when certain quantities lie within given limits.

These limits of use are recalled in Table A.1.

A.2 Example of computation

A.2.1 General

Four detailed examples are shown below which deal with a compressible fluid and the discharge coefficient depending on β and Re_D.

As will be seen later, it might be convenient to consider the discharge coefficient C as the sum of two terms, $C = C_\infty + C_{Re}$, where C_∞ is the discharge coefficient obtained for an infinite Reynolds number. Table A.2 shows the formulae giving C_∞ and C_{Re} for each type of device.

Reference is made to the table of iterative computations in ISO 5167-1:2022, Annex A.

Depending on the quantity which is to be calculated, additional equations derived from Formula (A.1) might be useful. Table A.3 shows the equation needed in the four types of problem usually encountered together with the quantities which have to be known to perform the calculations.

In all examples, 10-digit numbers are listed which is much more accurate than can be justified for practical purposes, but which can be helpful when checking the accuracy of the computer programs.

In each case, the aim is to solve an equation $f(X) = X$; so if X_i is the ith approximation to the true answer δ_I can be defined as $f(X_i) - X_i$ and the iterative algorithm in Annex A of ISO 5167-1:2022 becomes

$$X_{n+1} = X_n - \frac{[f(X_n) - X_n](X_n - X_{n-1})}{f(X_n) - X_n - f(X_{n-1}) + X_{n-1}} \tag{A.5}$$

An initial value, X_1, is required; then $X_2 = f(X_1)$; then the above equation can be used for $n = 2$, ...

Formula (A.5) can be rewritten as

$$X_{n+1} = (1 - E_n) f(X_n) \tag{A.6}$$

where

$$E_n = \frac{(f(X_n) - X_n)[f(X_{n-1}) - f(X_n)]}{f(X_n)[X_n + f(X_{n-1}) - f(X_n) - X_{n-1}]} \tag{A.7}$$

Then, given an initial value, X_1, Formula (A.6) can be used for subsequent iterations with $E_1 = 0$ and Formula (A.7) for $n = 2$, ...

Table A.1 — Limits of use

Type of device	d mm	D mm	β	Re_D	Roughness criteria
Corner tappings orifice plate D and $D/2$ tappings orifice plate	≥12,5	$50 \le D \le 1\,000$	$0{,}10 \le \beta \le 0{,}75$	$Re_D \ge 5\,000$ for $0{,}10 \le \beta \le 0{,}56$ $Re_D \ge 16\,000\beta^2$ for $\beta > 0{,}56$	See ISO 5167-2:2022, Tables 1 and 2
Flange tappings orifice plate	≥12,5	$50 \le D \le 1\,000$	$0{,}10 \le \beta \le 0{,}75$	$Re_D \ge 5\,000$ and $Re_D \ge 170\beta^2 D$ [a]	See ISO 5167-2:2022, Tables 1 and 2
ISA 1932 nozzle	—	$50 \le D \le 500$	$0{,}30 \le \beta \le 0{,}80$	$70\,000 \le Re_D \le 10^7$ for $0{,}30 \le \beta \le 0{,}44$ $20\,000 \le Re_D \le 10^7$ for $0{,}44 \le \beta \le 0{,}80$	See ISO 5167-3:2022, Table 1
Long-radius nozzle	—	$50 \le D \le 630$	$0{,}20 \le \beta \le 0{,}80$	$10^4 \le Re_D \le 10^7$	$Ra/D \le 3{,}2 \times 10^{-4}$
Throat-tapped nozzle	—	$100 \le D \le 630$	$0{,}40 \le \beta \le 0{,}50$	$8 \times 10^5 \le Re_d \le 2 \times 10^7$	$Ra \le 14\, Re_d^{-0{,}92}\, d$ [d] $Ra \le 28\, Re_D^{-0{,}92}\, D$ [e]
Venturi nozzle	≥50	$65 \le D \le 500$	$0{,}316 \le \beta \le 0{,}775$	$1{,}5 \times 10^5 \le Re_D \le 2 \times 10^6$	See ISO 5167-3:2022, Table 2
"as cast" convergent Venturi tube	—	$100 \le D \le 800$	$0{,}30 \le \beta \le 0{,}75$	$2 \times 10^5 \le Re_D \le 2 \times 10^6$	$Ra < 10^{-4}\, d$ [b] $Ra < 10^{-4}\, D$ [c]
Machined convergent Venturi tube	—	$50 \le D \le 350$	$0{,}40 \le \beta \le 0{,}75$	$2 \times 10^5 \le Re_D$	$Ra < 10^{-4}\, d$ [b, c]
Fabricated convergent Venturi tube	—	$200 \le D \le 1\,200$	$0{,}40 \le \beta \le 0{,}70$	$2 \times 10^5 \le Re_D \le 2 \times 10^6$	$Ra < 10^{-4}\, d$ [b] $Ra \approx 5 \times 10^{-4}\, D$ [c]

[a] D is in millimetres.

[b] Throat roughness criterion.

[c] Convergent section roughness criterion.

[d] Nozzle roughness criterion.

[e] Upstream pipe roughness criterion.

NOTE For all devices, $\Delta p/p_1 \le 0{,}25$ when used with compressible fluids.

Table A.2 — C_∞ and C_{Re} for orifice plates for D > 71,12 mm: $C = C_\infty + C_{Re}$

Type of device	Formulae	Formula number
Orifice plates	$C_\infty = C_{\infty,\text{corner}} + C_{\infty,L}$ $C_{\infty,\text{corner}} = 0{,}596\,1 + 0{,}026\,1\beta^2 - 0{,}216\beta^8$ $C_{\infty,L} = (0{,}043 + 0{,}080\text{e}^{-10L_1} - 0{,}123\text{e}^{-7L_1})\dfrac{\beta^4}{1-\beta^4}$ $-0{,}031(M'_2 - 0{,}8M'^{1,1}_2)\beta^{1,3}$	(A.8)
	$C_{Re} = 0{,}000\,521\left(\dfrac{10^6\beta}{Re_D}\right)^{0,7} + (0{,}018\,8 + 0{,}006\,3A)\beta^{3,5}\left(\dfrac{10^6}{Re_D}\right)^{0,3}$ $-0{,}11A(0{,}043 + 0{,}080\text{e}^{-10L_1} - 0{,}123\text{e}^{-7L_1})\dfrac{\beta^4}{1-\beta^4}$	(A.9)
	L_1, M'_2 and A are as defined in ISO 5167-2:2022, 5.3.2.1.	

Table A.3 — Iteration formulae

Known parameters	Quantities to be computed	Formulae	Formula number
d D Δp	q_m	$f(q_m) = CK_q$	(A.10)
		$K_q = \left(1-\beta^4\right)^{-0,5}\varepsilon\dfrac{\pi}{4}d^2\sqrt{2\Delta p\rho_1}$	(A.11)
q_m Δp D	β	$f(\beta) = (1 + C^2\varepsilon^2K_\beta)^{-0,25}$	(A.12)
		$K_\beta = \dfrac{\Delta p\rho_1}{8}\left(\dfrac{\pi D^2}{q_m}\right)^2$	(A.13)
d D q_m	Δp	$f(\Delta p) = K_{\Delta p}\varepsilon^{-2}$	(A.14)
		$K_{\Delta p} = \dfrac{8\left(1-\beta^4\right)}{\rho_1}\left(\dfrac{q_m}{\pi Cd^2}\right)^2$	(A.15)
q_m Δp β	D	$f(D) = K_DC^{-0,5}$	(A.16)
		$K_D = \left[\dfrac{8\left(1-\beta^4\right)}{\Delta p\rho_1\beta^4}\left(\dfrac{q_m}{\pi\varepsilon}\right)^2\right]^{0,25}$	(A.17)

A.2.2 Determination of D — Example

See Figure A.1 for an example of a flowchart.

Assume an orifice plate metering facility using flange tappings is designed for the following conditions:

- fluid: steam
- maximum flowrate: 1 kg·s^{-1}
- maximum diameter ratio: 0,65
- maximum pressure differential: 0,5 × 10^5 Pa (500 mbar)
- pressure: 10 × 10^5 Pa (10 bar)

— temperature: 773,15 K (500 °C)

— $\lambda_d = 16 \times 10^{-6}$ K^{-1}

— $\lambda_D = 11 \times 10^{-6}$ K^{-1}

Use the following typical data:

— $\rho_1 = 2{,}825\,1$ kg·m^{-3}

— $\mu_1 = 28{,}5 \times 10^{-6}$ Pa·s

— $\kappa = 1{,}276$

The exit criterion chosen is 10^{-6} (0,000 1 %). The calculation procedure is then:

Assessing starting values

a) ε, applying equation for expansibility [ISO 5167-2:2022, 5.3.2.2]:

$$\varepsilon = 1 - \left(0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8\right)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$$

$\varepsilon = 0{,}983\,201\,997\,0$.

For manual calculations using a calculator with a memory, it is useful to store the value of β^4, since it is required in a number of the subsequent formulae.

b) K_D, applying Formula (A.17): $K_D = \left[\frac{8\left(1-\beta^4\right)}{\Delta p \rho_1 \beta^4}\left(\frac{q_m}{\pi\varepsilon}\right)^2\right]^{0{,}25}$

$K_D = 0{,}072\,295\,778\,11$

In each case, p_1, T_1, ρ_1, μ_1 and κ are also required.

c) Applying Formula (A.8) for corner tappings:

$$C_{\infty,\text{corner}} = 0{,}596\,1 + 0{,}026\,1\beta^2 - 0{,}216\beta^8$$

$C = C_{\infty,\text{ corner}} = 0{,}600\,244\,522\,0$

For all the other devices, C_∞ could be readily calculated at this stage.

d) The starting value of D is obtained from Formula (A.16): $f(D) = K_D\, C^{-0{,}5}$

$D_1 = f(D) = 0{,}093\,314\,435\,6$

e) Reynolds number from Formula (A.4):

$Re_D = 478\,758{,}419\,9$

NOTE For most practical purposes, it is possible to stop the calculation here, since the final result will not be significantly different from D_1 and will be eventually rounded up to the next commercially available pipe diameter.

The final result obtained by the complete computation would be:

D = 0,092 707 108 61

From the previous calculation of D, the nearest commercially available pipe diameter, D = 0,102 m, would be selected by the designer of the metering station.

A.2.3 Computation of β — Example

Refer to Figure A.2 for an example of a flowchart.

It is now necessary to calculate the orifice diameter d for the same conditions as in A.2.2, i.e.

— fluid: steam

— maximum flowrate: 1 kg·s^{-1}

— maximum pressure differential: 0,5 × 10^5 Pa (500 mbar)

— pressure: 10 × 10^5 Pa (10 bar)

— temperature: 773,15 K (500 °C)

— pipe diameter at ambient: D_0 = 0,102 m

— $\lambda_d = 16 \times 10^{-6}$ K^{-1}

— $\lambda_D = 11 \times 10^{-6}$ K^{-1}

— ρ_1 = 2,825 1 kg · m^{-3}

— $\mu_1 = 28{,}5 \times 10^{-6}$ Pa·s

— κ = 1,276

The exit criterion being still 10^{-6}, the calculation would be:

Assessing starting values:

a) D is obtained from Formula (7): $D = D_0\,[1 + \lambda_D\,(T - T_0)]$

D = 0,102 538 560 0

b) Re_D, from Formula (A.4): $Re_D = \dfrac{4q_m}{\pi D \mu_1}$

Re_D = 435 690,453 9

c) β being unknown, it is convenient and reasonable to use ε = 0,97 as the starting value, except in the case of incompressible fluids, for which ε = 1.

d) β being unknown, it is convenient either

— to use a fixed starting value of C, e.g. 0,60 for orifice plates and 0,99 for all types of nozzles, or

— to use as a starting value $C = C_\infty$ (in the case of some classical Venturi tubes C is a constant).

The second method is preferable when the diameter ratio β (and D for orifice plates using flange tappings) is a known parameter; in such a case, C is calculated from $C = C_\infty + C_{Re}$ in the iteration steps, where C_∞ has already been calculated.

In the case of orifice plates using flange tappings where D is not known and β is known, the starting value of C can be taken as equal to $C_{\infty,\text{corner}}$, i.e. the value of C_∞ that would be obtained for corner tappings. In the iteration steps, C is computed as:

$$C = C_{\infty,\text{corner}} + C_{\infty,L} + C_{Re}$$

where the last two terms have to be recalculated at each step.

In most practical cases however, it will be sufficient to assume $C = C_\infty$ and make no iteration.

e) K_β, from Formula (A.13): $K_\beta = \dfrac{\Delta p \rho_1}{8}\left(\dfrac{\pi D^2}{q_m}\right)^2$

K_β = 19,264 708 61

f) Starting value of β from Formula (A.12): $f(\beta) = (1 + C^2 \varepsilon^2 K_\beta)^{-0,25}$

$\beta_1 = f(\beta)$ = 0,603 764 155 8

First iteration step

a) $$\varepsilon = 1 - \left(0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8\right)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$$

ε = 0,984 182 761 4

b) C, from Formulae (A.8) and (A.9):

$$C = C_\infty + C_{Re}$$

C = 0,607 261 036 6

c) Next value of β from Formula (A.12): $f(\beta) = (1 + C^2 \varepsilon^2 K_\beta)^{-0,25}$

$\beta = f(\beta_1)$ = 0,596 831 560 9

No correction being made at the first step ($E_1 = 0$), the starting value for the second step is:

$\beta_2 = f(\beta_1)$ = 0,596 831 560 9

Second iteration step

a) $$\varepsilon = 1 - \left(0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8\right)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$$

ε = 0,984 300 372 0

b) C, from Formulae (A.8) and (A.9):

C = 0,607 076 664 5

c) Next value of β from Formula (A.12): $f(\beta) = (1 + C^2 \varepsilon^2 K_\beta)^{-0,25}$

$\beta = f(\beta_2)$ = 0,596 879 546 2

d) Deviation in $f(\beta_2)$ is given by: $E_2 = -\frac{1}{f(X_2)}\frac{[f(X_2)-X_2]^2}{[2X_2-f(X_2)-X_1]}$

E_2 = 5,526 344 567 × 10^{-7}

which is less than the exit criterion. The iteration is then stopped.

$d = \beta D$ d = 0,061 203 169 16 m

d_0 from Formula (4): $d = d_0\,[1 + \lambda_d(T - T_0)]$ d_0 = 0,060 736 711 22 m

A.2.4 Computation of q_m — Example

Refer to Figure A.3 for an example of a flowchart.

Assume the metering station is now used to measure a flowrate with a plate of diameter d_0 = 0,061 m in the following conditions:

— fluid: steam

— pressure differential: 0,481 × 10^5 Pa (481 mbar)

— pressure: 10 × 10^5 Pa (10 bar)

— temperature: 773,15 K (500 °C)

— ρ_1 = 2,825 1 kg·m^{-3}

— d_0 = 0,061 m

— D_0 = 0,102 m

— μ_1 = 28,5 × 10^{-6} Pa·s

— λ_d = 16 ×10^{-6} K^{-1}

— λ_D = 11 ×10^{-6} K^{-1}

— κ = 1,276

The exit criterion being 10^{-6}, the calculation would be:

Assessing starting values:

a) d is obtained from Formula (4): $d = d_0\,[1 + \lambda_d\,(T - T_0)]$

d = 0,061 468 480 00

b) D, from Formula (7): $D = D_0\,[1 + \lambda_D\,(T - T_0)]$

D = 0,102 538 560 0

c) β, from $\beta = d/D$

β = 0,599 466 971 3

d) $$\varepsilon = 1 - \left(0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8\right)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$$

ε = 0,984 857 929 9

e) K_q, from Formula (A.11): $K_q = (1-\beta^4)^{-0,5} \varepsilon \frac{\pi}{4} d^2 (2\Delta p \rho_1)^{0,5}$

K_q = 1,632 671 123

f) C, from Formula (A.8):

$C = C_\infty$ = 0,602 425 043 2

g) The starting value for q_m from Formula (A.10): $f(q_m) = CK_q$

$q_{m,1} = f(q_m)$ = 0,983 561 971 8

First iteration step

a) Reynolds number from Formula (A.4): $Re_D = \frac{4q_m}{\pi D \mu_1}$

Re_D = 428 528,561 9

b) New estimate of C, from $C = C_\infty + C_{Re}$

C = 0,607 176 725 2

c) New estimate of q_m, from Formula (A.10): $f(q_m) = CK_q$

$q_m = f(q_{m,1})$ = 0,991 319 905 8

No correction being made at the first step (E_1 = 0), the starting value for the second step is:

$q_{m,2} = f(q_{m,1})$ = 0,991 319 905 8

Second iteration step

a) New Reynolds number from Formula (A.4): $Re_D = \frac{4q_m}{\pi D \mu_1}$

Re_D = 431 908,619 7

b) New value of C, from $C = C_\infty + C_{Re}$

C = 0,607 163 108 8

c) New value of q_m, from Formula (A.10): $f(q_m) = CK_q$

$q_m = f(q_{m,2})$ = 0,991 297 674 7

d) Deviation of $f(q_{m,2})$: $E_2 = -\frac{1}{f(X_2)} \frac{[f(X_2) - X_2]^2}{[2X_2 - f(X_2) - X_1]}$

E_2 = − 6,408 057 577 × 10^{-8}

which is less than the exit criterion. The iteration is then stopped and the result is:

q_m = 0,991 297 674 7 kg·s^{-1}

A.2.5 Determination of Δp — Example

Refer to Figure A.4 for an example of a flowchart.

Assume the pressure differential is required for the maximum flowrate of the same facility if the plate has a diameter of d_0 = 0,050 m.

— fluid: steam

— flowrate: 1 kg·s^{-1}

— pressure: 10 × 10^5 Pa (10 bar)

— temperature: 773,15 K (500 °C)

— density: 2,825 1 kg·m^{-3}

— d_0 = 0,050 m

— D_0 = 0,102 m

— μ_1 = 28,5 × 10^{-6} Pa·s

— λ_d = 16 × 10^{-6} K^{-1}

— λ_D = 11 × 10^{-6} K^{-1}

— κ = 1,276

10^{-6} being the exit criterion, the calculation would be:

Assessing starting values

a) d is obtained from Formula (4): $d = d_0\,[1 + \lambda_d\,(T - T_0)]$

d = 0,050 384 000 00

b) D, from Formula (7): $D = D_0\,[1 + \lambda_D\,(T - T_0)]$

D = 0,102 538 560 0

c) β, from $\beta = d/D$

β = 0,491 366 369 9

d) Re_D from Formula (A.4): $Re_D = \dfrac{4q_m}{\pi D \mu_1}$

Re_D = 435 690,453 9

e) C, from Formulae (A.8) and (A.9): $C = C_\infty + C_{Re}$

C = 0,603 572 933 9

f) $K_{\Delta p}$, from Formula (A.15): $K_{\Delta p} = \frac{8(1-\beta^4)}{\rho_1}\left(\frac{q_m}{\pi C d^2}\right)^2$

$K_{\Delta p}$ = 115 091,115 8

g) ε is taken as equal to 0,97.

h) Starting value for Δp, from Formula (A.14): $f(\Delta p) = K_{\Delta p}\,\varepsilon^{-2}$

$\Delta p_1 = f(\Delta p)$ = 122 320,242 1

First iteration step

a) $\varepsilon = 1 - \left(0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8\right)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$

ε = 0,964 125 846 1

b) Next value of Δp, from Formula (A.14): $f(\Delta p) = K_{\Delta p}\,\varepsilon^{-2}$

$\Delta p = f(\Delta p_1)$ = 123 815,310 0

No correction being made at the first step (E_1 = 0), the starting value for the second step is:

$\Delta p_2 = f(\Delta p_1)$ = 123 815,310 0

Second iteration step

a) New value of ε: $\varepsilon = 1 - \left(0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8\right)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$

ε = 0,963 680 936 9

b) Next value of Δp, from Formula (A.14): $f(\Delta p) = K_{\Delta p}\,\varepsilon^{-2}$

$\Delta p = f(\Delta p_2)$ = 123 929,661 7

c) Deviation of $f(\Delta p_2)$: $E_2 = -\frac{1}{f(X_2)}\frac{[f(X_2) - X_2]^2}{[2X_2 - f(X_2) - X_1]}$

$E_2 = -7{,}641\ 976\ 350 \times 10^{-5}$

For manual computation, one would stop here. The calculation is carried on to show the effect of the rapid scheme.

Third iteration step

a) The starting value for step 3 is obtained from: $\Delta p_{n+1} = (1 - E_n)\, f(\Delta p_n)$

Δp_3 = 123 939,132 4

NOTE If substitution iteration was continued [$\Delta p_{n+1} = f(\Delta p_n)$ for all steps], a total of 5 iteration steps would be necessary to conform to the exit criterion.

b) New value of ε: $\varepsilon = 1 - \left(0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8\right)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]$

ε = 0,963 644 081 9

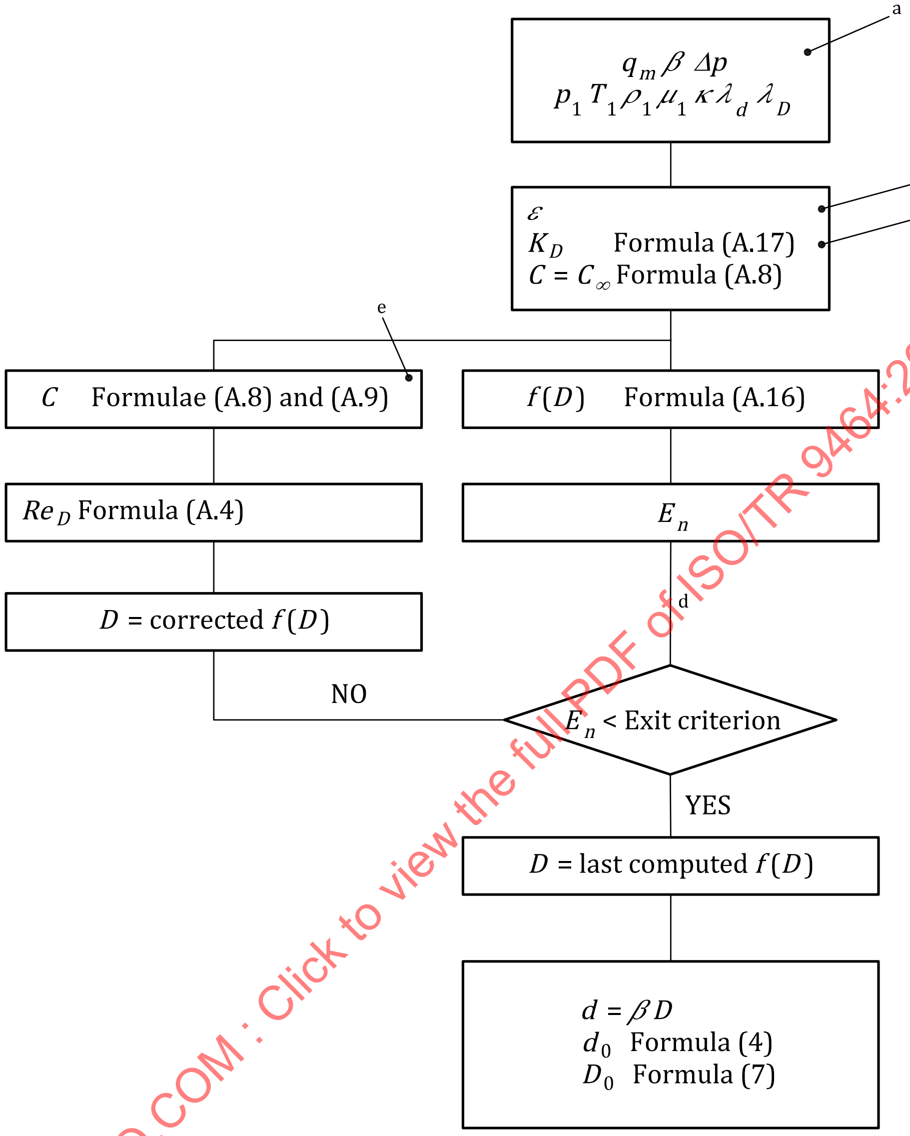
c) Next value of Δp, from Formula (A.14): $f(\Delta p) = K_{\Delta p}\,\varepsilon^{-2}$

$\Delta p = f(\Delta p_3)$ = 123 939,141 4

d) Deviation on $f(\Delta p_3)$: $E_n = \dfrac{1}{f(X_n)} \dfrac{[f(X_n) - X_n][f(X_{n-1}) - f(X_n)]}{[X_n + f(X_{n-1}) - f(X_n) - X_{n-1}]}$

$E_3 = -\,6{,}017\ 524\ 711 \times 10^{-9}$

The iteration is then stopped, the exit criterion being met. The result is Δp = 123 939,141 4 Pa.



a ε and p_1 have to be known for compressible fluids only.

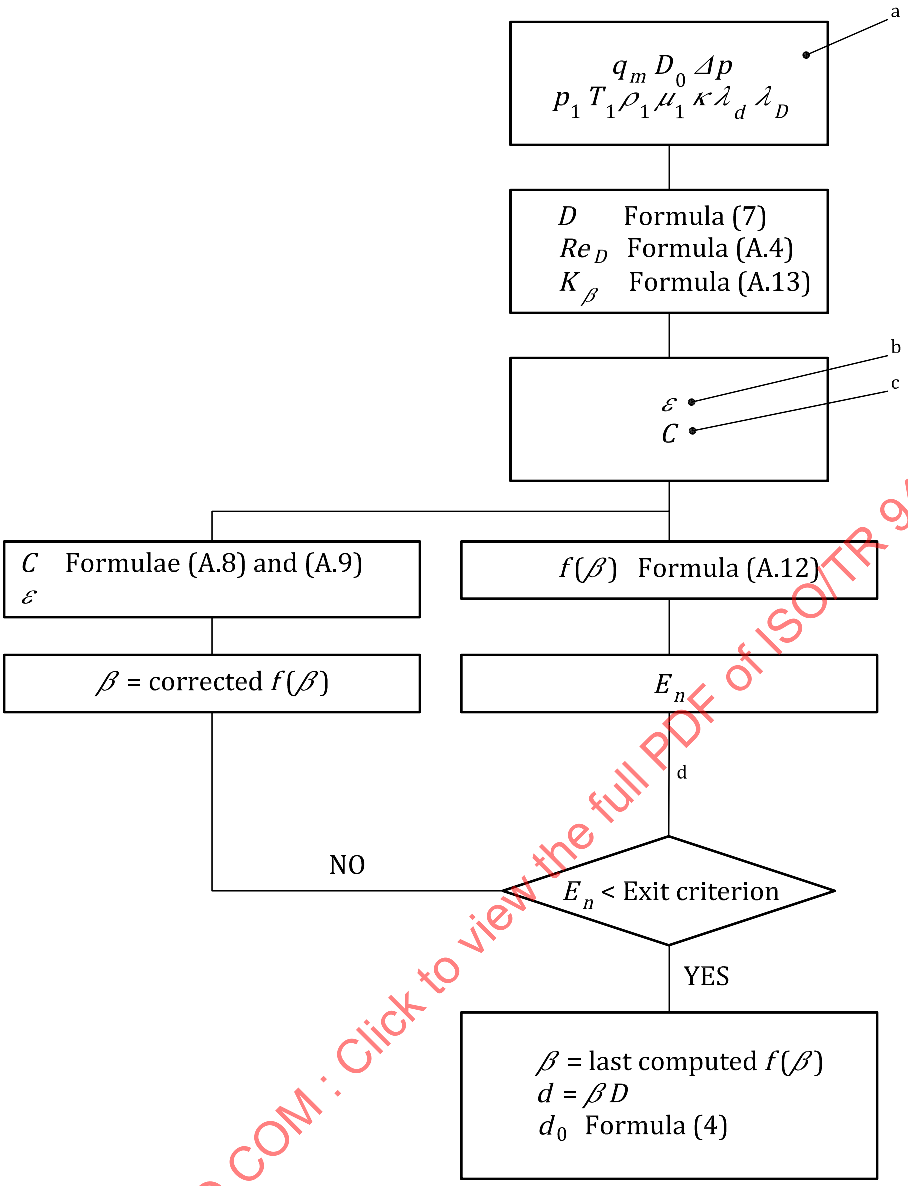
b For incompressible fluids, $\varepsilon = 1$.

c For Venturi nozzles and some classical Venturi tubes $C = C_\infty$, and no loop is necessary.

d For the first step, $E_1 = 0$ but proceed to "NO", except for Venturi nozzles and some classical Venturi tubes.

e Except for flange tapping orifice plates, only C_{Re} has to be computed here, then it is added to previously computed C_∞.

Figure A.1 — Flowchart example — Computation of pipe diameter *D*



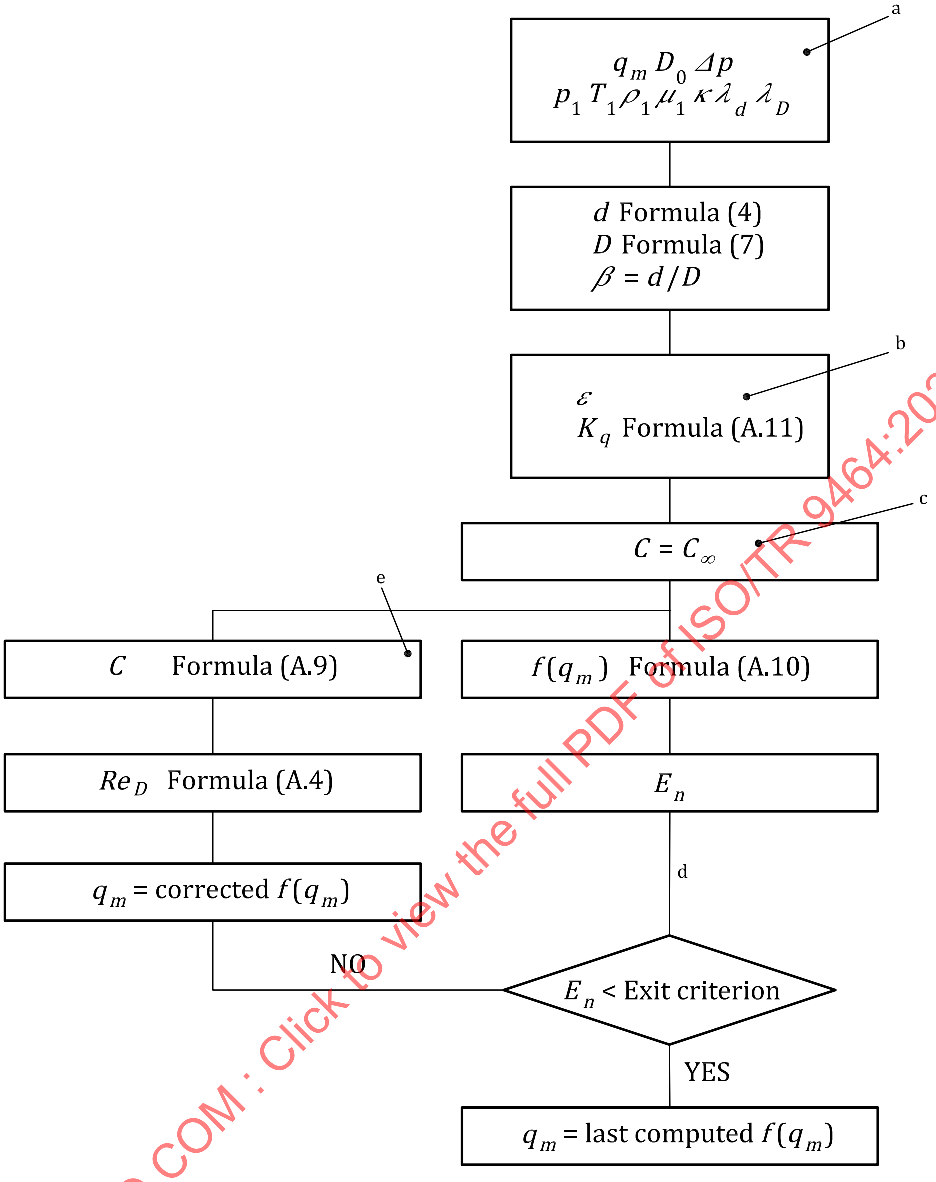
a ε and p_1 have to be known for compressible fluids only.

b For incompressible fluids, $\varepsilon = 1$ and need not be computed further again.

c For classical Venturi tubes, *C* is a constant and need not be computed further again. If in addition the fluid is incompressible, no iteration is necessary.

d For the first step, $E_1 = 0$ but proceed to "NO", except for Venturi tubes operated with incompressible fluids.

Figure A.2 — Flowchart example — Computation of diameter *d* and diameter ratio *β*



a ε and p_1 have to be known for compressible fluids only.

b For incompressible fluids, $\varepsilon = 1$ and need not be computed further again.

c For Venturi nozzles and some classical Venturi tubes, $C = C_\infty$ and no iteration is necessary.

d For the first step, $E_1 = 0$ but proceed to "NO", except for Venturi nozzles and some classical Venturi tubes.

e Only C_{Re} has to be computed here, then added to already computed C_∞.

Figure A.3 — Flowchart example — Computation of flowrate q_m