INTERNATIONAL STANDARD

ISO 5167-1

Third edition
2022-06

Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full —

Part 1:
General principles and requirements

Mesurage de débit des fluides au moyen d'appareils déprimogènes insérés dans des conduites en charge de section circulaire —

Partie 1: Principes généraux et exigences générales

Reference number
ISO 5167-1:2022(E)

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Published in Switzerland

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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 documents 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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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.

ISO 5167-1 was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, Subcommittee SC 2, *Pressure differential devices*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/SS F05, *Measuring instruments*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This third edition cancels and replaces the second edition (ISO 5167-1:2003), which has been technically revised

The main changes are as follows:

- improved consistency between ISO 5167-1 to ISO 5167-6 (some items that were new in ISO 5167-5 and ISO 5167-6 have been moved to this document);
- a primary element has been set as part of a differential pressure metering system;
- a short section on diagnostics and CBM (Condition Based Monitoring) has been included;
- a limitation on the use of the 5 % 2° rule for an acceptable profile has been noted;
- improved text about uncertainty calculation and an example in Annex E has been provided;
- annexes on turndown and permanent pressure loss have been included.

A list of all parts in the ISO 5167 series can be found on the ISO website.

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

ISO 5167, consisting of six parts, covers the geometry and method of use (installation and operating conditions) of orifice plates, nozzles, Venturi tubes, cone meters and wedge meters when they are inserted in a conduit running full to determine the flow rate of the fluid flowing in the conduit. It also gives necessary information for calculating the flow rate and its associated uncertainty.

ISO 5167 (all parts) is applicable only to pressure differential devices in which the flow remains subsonic throughout the measuring section and where the fluid can be considered as single-phase, but is not applicable to the measurement of pulsating flow. Furthermore, each of these devices can only be used uncalibrated within specified limits of pipe size and Reynolds number, or alternatively they can be used across their calibrated range.

ISO 5167 (all parts) deals with devices for which direct calibration experiments have been made, sufficient in number, spread and quality to enable coherent systems of application to be based on their results and coefficients to be given with certain predictable limits of uncertainty. ISO 5167 also provides methodology for bespoke calibration of differential pressure meters.

The devices introduced into the pipe are called primary devices. The term primary device also includes the pressure tappings. All other instruments or devices required to facilitate the instrument readings are known as secondary devices, and the flow computer that receives these readings and performs the algorithms is known as a tertiary device. ISO 5167 covers primary devices; secondary devices (see ISO 2186) and tertiary devices will be mentioned only occasionally.

Aspects of safety are not dealt with in ISO 5167-1 to ISO 5167-6. It is the responsibility of the user to ensure that the system meets applicable safety regulations.

Additional documents that may provide assistance include:

- ISO/TR 3313;
- ISO/TR 9464;
- ISO/TR 12767;
- ISO/TR 15377.

Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full —

Part 1:
General principles and requirements

1 Scope

This document defines terms and symbols and establishes the general principles for methods of measurement and computation of the flow rate of fluid flowing in a conduit by means of pressure differential devices (orifice plates, nozzles, Venturi tubes, cone meters, and wedge meters) when they are inserted into a circular cross-section conduit running full. This document also specifies the general requirements for methods of measurement, installation and determination of the uncertainty of the measurement of flow rate.

ISO 5167 (all parts) is applicable only to flow that remains subsonic throughout the measuring section and where the fluid can be considered as single-phase. It is not applicable to the measurement of pulsating 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*

ISO 5167 (all parts), *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full*

ISO 5168, *Measurement of fluid flow — Procedures for the evaluation of uncertainties*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the terms, definitions and symbols given in ISO 4006 and the following 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/

3.1 Pressure measurement

3.1.1

wall pressure tapping

annular slot or circular hole drilled in the wall of a conduit in such a way that the edge of the hole is flush with the internal surface of the conduit

Note 1 to entry: The pressure tapping is usually a circular hole but in certain cases may be an annular slot.

3.1.2

static pressure

p

pressure which can be measured by connecting a pressure-measuring device to a *wall pressure tapping* (3.1.1)

Note 1 to entry: Only the value of the absolute static pressure is considered in ISO 5167 (all parts).

3.1.3

differential pressure

DP

Δp

difference between the (static) pressures measured at the wall pressure tappings, one of which is on the upstream side and the other of which is on the downstream side of a primary device [or in the throat for a throat-tapped nozzle, a *Venturi nozzle* (3.2.4) or a *Venturi tube* (3.2.5)], inserted in a straight pipe through which flow occurs, when any difference in height between the upstream and downstream tappings has been taken into account

Note 1 to entry: In ISO 5167 (all parts) the term "differential pressure" is used only if the pressure tappings are in the positions specified for each standard primary device.

3.1.4

pressure ratio

τ

ratio of the absolute (static) pressure at the downstream pressure tapping to the absolute (static) pressure at the upstream pressure tapping

3.1.5

vena contracta

location in a fluid stream where the diameter of the stream is smallest

3.2 Primary devices

3.2.1

orifice

throat opening of minimum cross-sectional area of a primary device

3.2.2

orifice plate

thin plate in which a circular opening has been machined

Note 1 to entry: Standard orifice plates are described as "thin plate" and "with sharp square edge", because the thickness of the plate is small compared with the diameter of the measuring section and because the upstream edge of the *orifice* (3.2.1) is sharp and square.

3.2.3

nozzle

device which consists of a convergent inlet connected to a cylindrical section generally called the "throat"

3.2.4
Venturi nozzle
device which consists of a convergent inlet which is a standardized ISA 1932 nozzle connected to a cylindrical part called the “throat”, which is itself connected to an expanding section called the “divergent” which is conical

3.2.5
Venturi tube
device which consists of a convergent inlet which is conical connected to a cylindrical part called the “throat”, which is itself connected to an expanding section called the “divergent” which is conical

3.2.6
cone meter
device which consists of a cone-shaped restriction held in the centre of the pipe with the nose of the cone upstream

3.2.7
wedge meter
device which consists of a wedge-shaped restriction

3.2.8
diameter ratio
β
<of a primary device used in a given pipe> square root of the ratio of the area of the throat of the primary device to the internal area of the measuring pipe upstream of the primary device

Note 1 to entry: In ISO 5167-2 and ISO 5167-3 the diameter ratio is the ratio of the diameter of the throat of the primary device to the internal diameter of the measuring pipe upstream of the primary device.

Note 2 to entry: In ISO 5167-4, where the primary device has a cylindrical section upstream, having the same diameter as that of the pipe, the diameter ratio is the ratio of the throat diameter to the diameter of this cylindrical section at the plane of the upstream pressure tappings.

3.2.9
carrier ring
device which is used to hold the primary element in the centre of the pipe and may incorporate the pressure tappings

3.3 Flow

3.3.1
flow rate
rate of flow
q
mass or volume of fluid passing through the primary device per unit time

3.3.1.1
mass flow rate
rate of mass flow
q_m
mass of fluid passing through the primary device per unit time

3.3.1.2
volume flow rate
rate of volume flow
q_V
volume of fluid passing through the primary device per unit time

Note 1 to entry: In the case of volume flow rate, it is necessary to state the pressure and temperature at which the volume is referenced.

3.3.2
Reynolds number

Re

dimensionless parameter expressing the ratio between the inertia and viscous forces

3.3.2.1
pipe Reynolds number

Re_D

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

$$Re_D = \frac{V_1 D}{\nu_1} = \frac{4 q_m}{\pi \mu_1 D}$$

3.3.2.2
throat Reynolds number

Re_d

dimensionless parameter expressing the ratio between the inertia and viscous forces in the orifice or throat of the primary device

$$Re_d = \frac{Re_D}{\beta}$$

Note 1 to entry: When an orifice plate is used the throat Reynolds number is sometimes called the orifice Reynolds number.

3.3.3
isentropic exponent

κ

ratio of the relative variation in pressure to the corresponding relative variation in density under elementary reversible adiabatic (isentropic) transformation conditions

Note 1 to entry: The isentropic exponent κ appears in the different formulae for the expansibility [expansion] factor ε and varies with the nature of the gas and with its temperature and pressure.

Note 2 to entry: There are many gases and vapours for which no values for κ have been published so far, particularly over a wide range of pressure and temperature. In such a case, for the purposes of ISO 5167 (all parts), the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume of ideal gases can be used in place of the isentropic exponent.

3.3.4
Joule Thomson coefficient

isenthalpic temperature-pressure coefficient

μ_{JT}

rate of change of temperature with respect to pressure at constant enthalpy:

$$\mu_{\mathrm{JT}} = \left.\frac{\partial T}{\partial p}\right|_H$$

Note 1 to entry: The Joule Thomson coefficient varies with the nature of the gas and with its temperature and pressure and can be calculated.

Note 2 to entry: An approximation for the Joule Thomson coefficient for some natural gases is given in ISO/TR 9464:2008, 5.1.5.4.4.

3.3.5
discharge coefficient

C

coefficient, defined for an incompressible fluid flow, which relates the actual flow rate to the theoretical flow rate through a device, and is given by the formula for incompressible fluids

$$C = \frac{q_m\sqrt{1-\beta^4}}{A_t\sqrt{2\Delta p\rho_1}}$$

Note 1 to entry: Calibration of standard primary devices by means of incompressible fluids (liquids) shows that the discharge coefficient is dependent only on the Reynolds number for a given primary device in a given installation.

The numerical value of C for any individual differential pressure meter is the same for different installations whenever such installations are geometrically similar and the flows are characterised by identical Reynolds numbers.

The formulae for the numerical values of C given in ISO 5167 (all parts) are based on data determined experimentally.

The uncertainty in the value of C can be reduced by flow calibration in a suitable laboratory.

Note 2 to entry: The quantity $1/\sqrt{1-\beta^4}$ is called the "velocity of approach factor", and $C\frac{1}{\sqrt{1-\beta^4}}$ is called the "flow coefficient".

3.3.6
expansibility [expansion] factor

ε

coefficient used to take into account the compressibility of the fluid

$$\varepsilon = \frac{q_m\sqrt{1-\beta^4}}{A_t C\sqrt{2\Delta p\rho_1}}$$

Note 1 to entry: Calibration of a given primary device by means of a compressible fluid (gas) shows that the following ratio is dependent on the value of the Reynolds number as well as on the values of the pressure ratio and the isentropic exponent of the gas:

$$\frac{q_m\sqrt{1-\beta^4}}{A_t\sqrt{2\Delta p\rho_1}}$$

The method adopted for representing these variations consists of multiplying the discharge coefficient, C, of the primary device considered, as determined by direct calibration carried out with liquids for the same value of the Reynolds number, by the expansibility [expansion] factor, ε.

The expansibility factor, ε, is equal to unity when the fluid is considered incompressible (liquid) and is less than unity when the fluid is compressible (gaseous).

This method is possible because experiments show that ε is practically independent of the Reynolds number and, for a given diameter ratio of a given primary device, ε only depends on the pressure ratio and the isentropic exponent.

The numerical values of ε for orifice plates given in ISO 5167-2 and for cone meters given in ISO 5167-5 are based on data determined experimentally. For nozzles (see ISO 5167-3), Venturi tubes (see ISO 5167-4) and wedge meters (see ISO 5167-6) they are based on the thermodynamic general formula applied to isentropic expansion.

3.3.7
arithmetical mean deviation of the roughness profile

Ra

arithmetical mean deviation from the mean line of the profile being measured

Note 1 to entry: The mean line is such that the sum of the squares of the distances between the effective surface and the mean line is a minimum. In practice, *Ra* can be measured with standard equipment for machined surfaces but can only be estimated for rougher surfaces of pipes. See also ISO 21920-3.

Note 2 to entry: For pipes, the uniform equivalent roughness k_a may also be used. This value can be determined experimentally (see 7.1.5) or taken from tables (see Annex B).

4 Symbols and subscripts

4.1 Symbols

Table 1 — Symbols

Symbol	Quantity	Dimension[a]	SI unit
A_t	Area of throat	$\mathrm{L^2}$	$\mathrm{m^2}$
C	Discharge coefficient	dimensionless	—
$C_{m,p}$	Molar-heat capacity at constant pressure	$\mathrm{ML^2T^{-2}\Theta^{-1}mol^{-1}}$	J/(mol·K)
d	Diameter of orifice (or throat) of primary device under working conditions	L	m
D	Upstream internal pipe diameter (or upstream diameter of a classical Venturi tube) under working conditions	L	m
H	Enthalpy	$\mathrm{ML^2T^{-2}mol^{-1}}$	J/mol
k	Coverage factor	dimensionless	—
k_a	Uniform equivalent roughness	L	m
K	Pressure loss coefficient (the ratio of the pressure loss, $\Delta\varpi$, to the dynamic pressure, $\rho V^2/2$), also known as the minor loss coefficient	dimensionless	—
l	Pressure tapping spacing	L	m
L	Relative pressure tapping spacing: $L = l/D$	dimensionless	—
p	Absolute static pressure of the fluid	$\mathrm{ML^{-1}T^{-2}}$	Pa
q_m	Mass flow rate	$\mathrm{MT^{-1}}$	kg/s
q_V	Volume flow rate	$\mathrm{L^3T^{-1}}$	$\mathrm{m^3/s}$
R	Radius	L	m
R_u	Universal gas constant	$\mathrm{ML^2T^{-2}\Theta^{-1}mol^{-1}}$	J/(mol·K)
Ra	Arithmetical mean deviation of the (roughness) profile	L	m
Re	Reynolds number	dimensionless	—
Re_d	Throat Reynolds number	dimensionless	—
Re_D	Pipe Reynolds number	dimensionless	—
t	Temperature of the fluid	Θ	°C
T	Absolute (thermodynamic) temperature of the fluid	Θ	K
u	Standard uncertainty	[c]	[c]

[a] M = mass, L = length, T = time, Θ = temperature

[b] γ is the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume. For ideal gases, the ratio of the specific heat capacities and the isentropic exponent have the same value (see 3.3.3). These values depend on the nature of the gas.

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

Table 1 *(continued)*

Symbol	Quantity	Dimension[a]	SI unit
u'	Relative standard uncertainty	dimensionless	—
U	Expanded uncertainty	[c]	[c]
U'	Relative expanded uncertainty	dimensionless	—
V	Mean axial velocity of the fluid in the pipe	$\mathrm{LT^{-1}}$	m/s
Z	Compressibility factor	dimensionless	—
β	Diameter ratio	dimensionless	—
γ	Ratio of specific heat capacities[b]	dimensionless	—
Δp	Differential pressure: $\Delta p = p_1 - p_2$	$\mathrm{ML^{-1}T^{-2}}$	Pa
Δp_c	Pressure loss across a flow conditioner	$\mathrm{ML^{-1}T^{-2}}$	Pa
$\Delta \varpi$	Pressure loss across a primary device	$\mathrm{ML^{-1}T^{-2}}$	Pa
ε	Expansibility [expansion] factor	dimensionless	—
κ	Isentropic exponent[b]	dimensionless	—
λ	Friction factor	dimensionless	—
μ	Dynamic viscosity of the fluid	$\mathrm{ML^{-1}T^{-1}}$	Pa·s
μ_{JT}	Joule Thomson coefficient	$\mathrm{M^{-1}LT^{2}\Theta}$	K/Pa
ν	Kinematic viscosity of the fluid: $\nu = \mu/\rho$	$\mathrm{L^{2}T^{-1}}$	$\mathrm{m^2/s}$
ξ	Relative pressure loss (the ratio of the pressure loss to the differential pressure)	dimensionless	—
ρ	Density of the fluid	$\mathrm{ML^{-3}}$	$\mathrm{kg/m^3}$
τ	Pressure ratio: $\tau = p_2/p_1$	dimensionless	—
ϕ	Total angle of the divergent section	dimensionless	rad

[a] M = mass, L = length, T = time, Θ = temperature

[b] γ is the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume. For ideal gases, the ratio of the specific heat capacities and the isentropic exponent have the same value (see 3.3.3). These values depend on the nature of the gas.

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

5 Principle of the method of measurement and computation

5.1 Principle of the method of measurement

The principle of the method of measurement is based on the installation of a primary device into a pipeline in which a fluid is running full. The installation of the primary device causes a static pressure difference between the upstream side and the throat or downstream side of the device. The flow rate can be determined from the measured value of this pressure difference and the knowledge of the thermodynamic conditions, fluid properties, meter geometry and meter characteristics. It is assumed that an uncalibrated differential pressure meter is within the geometric and Reynolds number range required for the ISO discharge coefficient prediction to be valid. Alternatively, it is assumed that a bespoke calibrated differential pressure meter is to be used within its calibration range.

The mass flow rate can be determined, since it is related to the differential pressure within the uncertainty limits stated in ISO 5167, using Formula (1):

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \varepsilon A_t \sqrt{2 \Delta p \rho_1} \tag{1}$$

NOTE For practical implementation, this formula is expanded upon as Formula (1) of ISO 5167-2, ISO 5167-3, ISO 5167-4, ISO 5167-5 and ISO 5167-6.

Similarly, the value of the volume flow rate can be calculated using Formula (2):

$$q_V = \frac{q_m}{\rho} \tag{2}$$

where ρ is the fluid density at the temperature and pressure for which the volume is stated.

5.2 Method of determination of the required diameter ratio for the selected standard primary device

In practice, when determining the diameter ratio of a primary element to be installed in a given pipeline, C and ε used in Formula (1) are, in general, not precisely known. Hence the following shall be selected *a* priori:

- the type of primary device to be used;
- a flow rate and the corresponding desired value of the differential pressure.

The related values of q_m and Δp are then inserted in Formula (1), rewritten in the form of Formula (3):

$$\frac{C\varepsilon\beta^2}{\sqrt{1-\beta^4}} = \frac{4q_m}{\pi D^2\sqrt{2\Delta p\rho_1}} \tag{3}$$

in which the diameter ratio of the selected primary device can be determined by iteration (see Annex A).

For a given flow rate, the uncertainty of the discharge coefficient and that of the predicted differential pressure are directly linked, because the discharge coefficient is proportional to the reciprocal of the square root of the differential pressure. Consequently, care shall be taken when determining β that the maximum differential pressure does not exceed the upper range limit of the transmitter. This is of particular importance where the uncertainty of the discharge coefficient is large.

5.3 Computation of flow rate

Computation of the flow rate, which is a purely arithmetic process, is performed by replacing the different terms on the right-hand side of Formula (1) by their numerical values.

C may be dependent on Re, which is itself dependent on q_m. In such cases the final value of C, and hence of q_m, is obtained by iteration. See Annex A for guidance regarding the choice of the iteration procedure and initial estimates.

The dimensions used in the formulae are the values of the dimensions at the working conditions. Measurements taken at any other conditions should be corrected for any possible expansion or contraction of the primary device and the pipe due to the values of the temperature and pressure of the fluid during the measurement.

NOTE For corrections due to thermal expansion or contraction see ISO/TR 9464:2008 5.1.6.1.3 and 5.2.6.4.2.

It is necessary to know the density and the viscosity of the fluid at working conditions. In the case of a compressible fluid, it is also necessary to know the isentropic exponent of the fluid at working conditions.

5.4 Determination of density, pressure and temperature

5.4.1 General

Any method of determining reliable values of the density, static pressure and temperature of the fluid is acceptable if it does not interfere with the distribution of the flow in any way at the cross-section where measurement is made.

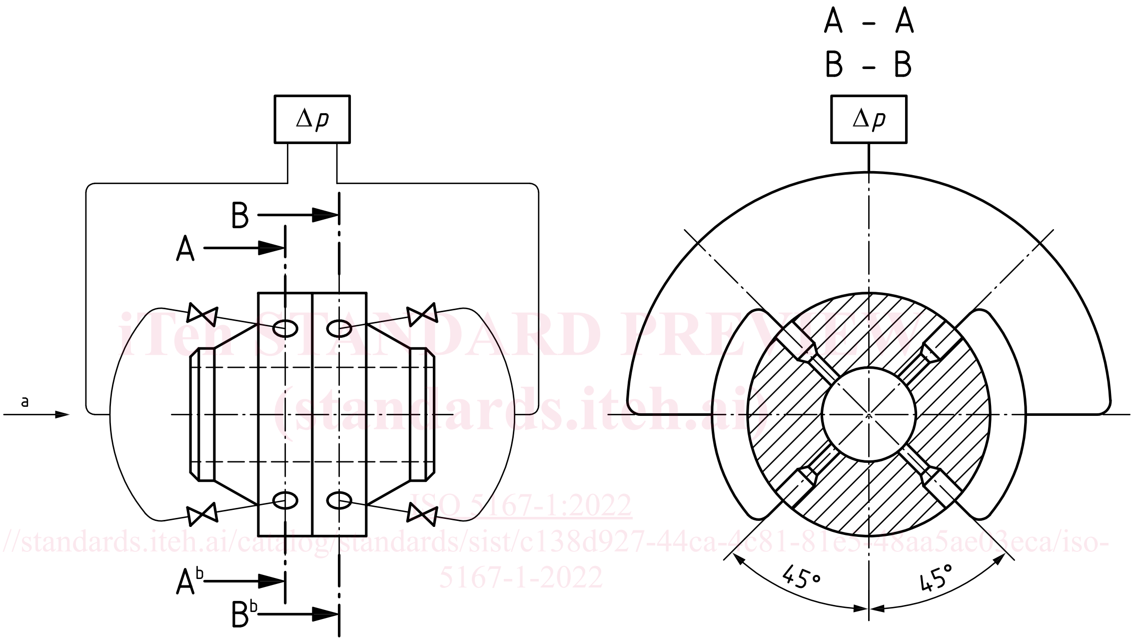
5.4.2 Density

It is necessary to know the density of the fluid at the upstream pressure tapping; it can either be measured directly or be calculated from an appropriate equation of state from a knowledge of the absolute static pressure, absolute temperature and composition of the fluid at that location.

NOTE ISO/TR 9464:2008, 6.4.2 provides a method for correcting density measured downstream of a device to upstream conditions.

5.4.3 Static pressure

The static pressure of the fluid shall be measured by means of an individual wall pressure tapping, or several such tappings interconnected, or by means of carrier ring tappings if they are permitted for the measurement of differential pressure in that tapping plane for the particular primary device.



[a] Flow.

[b] Section A-A (upstream) also typical for section B-B (downstream).

Figure 1 — “Triple-T” arrangement

Where four pressure tappings are connected together to give the pressure upstream, downstream or in the throat of the primary device, it is best that they should be connected together in a “triple-T” arrangement as shown in Figure 1. The “triple-T” arrangement is often used for measurement with large Venturi tubes.

It is permissible to link simultaneously one pressure tapping with differential pressure measuring device(s) and static pressure measuring device(s), provided that these connections do not lead to any distortion of the differential pressure measurement.

5.4.4 Temperature

5.4.4.1 Temperature measurement requires particular care. The thermometer well or pocket shall take up as little space as possible to avoid reducing the cross-sectional area of the pipe. Thermometer probes should have adequate immersion depth to ensure the fluid temperature is measured accurately.