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Measurement of fluid flow in closed conduits — Velocity area method using Pitot static tubes

Mesurage du débit des fluides dans les conduites fermées — Méthode d'exploration du champ des vitesses au moyen de tubes de Pitot doubles

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Foreword

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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).

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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 5, *Velocity and mass methods*.

This third edition cancels and replaces the second edition (ISO 3966:2008), which has been technically revised.

The main changes compared to the previous edition are as follows:

— All the mathematical formulae have been numbered;

— The essential Formula 4 has been corrected from $\Delta\rho/p$ to $\Delta p/p$;

— The related Table 2 is corrected likewise;

— The last sentence in 8.2 “for selected values of g and the $\Delta\rho/p$.....” was corrected accordingly;

— In 11.2.2 in the 2nd paragraph *ef* is corrected by *e* or *f*.

— Figure A.5 was changed editorially, the millimetre-grid has been removed.

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.

Measurement of fluid flow in closed conduits — Velocity area method using Pitot static tubes

1 Scope

This document specifies a method for the determination in a closed conduit of the volume rate of flow of a regular flow

a) of a fluid of substantially constant density or corresponding to a Mach number not exceeding 0,25,

b) with substantially uniform stagnation temperature across the measuring cross-section,

c) running full in the conduit, and

d) under steady flow conditions.

In particular, it deals with the technology and maintenance of Pitot static tubes, with the calculation of local velocities from measured differential pressures and with the computation of the flow rate by velocity integration.

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

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

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

3.1.1
Pitot static tube
"Pitot tube"
tubular device consisting of a cylindrical head attached perpendicularly to a stem allowing measurement of a differential pressure from which the flow rate of the fluid in which it is inserted can be determined, and which is provided with static pressure tapping holes (drilled all around the circumference of the head at one or more cross-sections) and with a total pressure hole (facing the flow direction at the tip of the axially symmetrical nose of the head)

3.1.2
static pressure tapping
group of holes for the measurement of fluid static pressure

3.1.3
total pressure tapping
hole for the measurement of fluid stagnation pressure (the pressure produced by bringing the fluid to rest without change in entropy)

3.1.4
differential pressure
difference between the pressures at the total and static pressure taps

3.1.5
stationary rake
set of Pitot tubes, mounted on one or several fixed supports, which explore the whole diameter or measuring section simultaneously

3.1.6
peripheral flow rate
volume flow rate in the area located between the pipe wall and the contour defined by the velocity measuring points which are the closest to the wall

3.1.7
discharge velocity
ratio of the volume rate of flow (integral of the axial component of local velocities with respect to the cross-sectional area) to the area of the measuring cross-section

3.1.8
relative velocity
ratio of the flow velocity at the considered point to a reference velocity measured at the same time and being either the velocity at a particular point (e.g. the centre of a circular conduit) or the discharge velocity in the measuring section

3.1.9
straight lenght
conduit section, the axis of which is rectilinear and the surface and cross-section of which are constant

Note 1 to entry: The shape of this section is usually circular, but it may be rectangular or annular.

3.1.10
irregularity
any element or configuration of a conduit which makes it different from a straight length

Note 1 to entry: For the purpose of this document, those irregularities which create the most significant disturbances are bends, valves, gates and sudden widening of the section.

3.2 Symbols

Symbol	Quantity	Dimensions	SI unit
A	cross-sectional area of the conduit	L^2	m^2
a, a'	distance of the extreme measuring point to the nearest wall	L	m
D	pipe diameter	L	m
d	head diameter	L	m
d'	steam diameter	L	m
d_i	total pressure tapping hole diameter	L	m
H	rectangular conduit height	L	m
h	height of a particular point above the bottom	L	m
k_b	blockage coefficient of a cylindrical stem	—	—
k_g	coefficient depending on the nose shape	—	—
k_t	coefficient of turbulence correction	—	—

Symbol	Quantity	Dimensions	SI unit
L	rectangular conduit width	L	m
l	distance from a particular point to the side-wall	L	m
M	molar mass of fluid	M	kg/mol
m	roughness coefficient	—	—
Ma	Mach number	—	—
p	absolute static pressure of the fluid	$ML^{-1}T^{-2}$	Pa
q_V	volume flow rate	L^3T^{-1}	m^3/s
R_g	molar constant of gas	$ML^2T^{-1}\Theta^{-1}$	J/mol·K
R	pipe radius	L	m
r	measuring circle radius	L	m
Re	Reynolds number	—	—
S	frontal projected area of the stem inside the conduit	L^2	m^2
T	absolute temperature	Θ	K
U	discharge velocity	LT^{-1}	m/s
u	mean velocity along a circumference or a measurement line	LT^{-1}	m/s
v	local velocity of the fluid	LT^{-1}	m/s
X	pipe dimension	L	m
y	distance of a measuring point to the wall	L	m
Z	gas law deviation factor	—	—
α	calibration factor of the Pitot tube	—	—
γ	ratio of the specific heat capacities	—	—
Δp	differential pressure measured by the Pitot tube	$ML^{-1}T^{-2}$	Pa
ε	expansibility factor	—	—
$(1 - \varepsilon)$	compressibility correction factor	—	—
λ	universal coefficient for head loss	—	—
μ	dynamic viscosity of the fluid	$ML^{-1}T^{-1}$	Pa·s
ν_{kv}	kinematic viscosity of the fluid	L^2T^{-1}	m^2/s
ξ	head loss	$ML^{-1}T^{-2}$	Pa
ρ	density of the fluid	ML^{-3}	kg/m^3
φ	Pitot tube inclination	—	—

4 Principle

4.1 General principle

The principle of the method consists of:

a) measuring the dimensions of the measuring section, which shall be normal to the conduit axis — this measurement is necessary for defining the area of the cross-section (see 4.2);

b) defining the position of the measuring points in the cross-section, the number of measuring points having to be sufficient to permit adequate determination of the velocity profile;

c) measuring the differential pressure existing between the total and static pressures of the Pitot tube placed at these measuring points (see 4.3) and determining the density of the fluid in the test conditions;

d) determining the local velocity of the flow, from given formulae, on the basis of previous measurements (see Clause 8);

e) determining the discharge velocity from these values;

f) calculating the volume rate of flow equal to the product of the cross-sectional area and the discharge velocity.

Errors in the techniques described in a) to f) contribute to the error in the flow-rate measurement; other sources of error (such as the shape of the velocity distribution and the number of measuring points) are discussed in Clause 13.

The method of measurement and the requirements defined in this document aim at reaching, at the 95 % confidence level, an uncertainty in flow rate not greater than ±2 %. To attain this result, it may be necessary, according to measurement conditions, to take into account the corrections given in Clause 12. If any of the requirements of this document are not fulfilled, this method may still be applied in special cases but the uncertainty on flow rate will be larger.

This document presents three types of methods for determining the discharge velocity.

4.1.1 Graphical integration of the velocity area (see Clause 9)

This method consists in plotting the velocity profile on a graph and evaluating the area under the curve which is bounded by the measuring points closest to the wall. To the value thus obtained is added a calculated term which allows for the flow in the peripheral zone (the area between the wall and the curve through the measuring positions closest to the wall) on the assumption that the velocity profile in this zone satisfies a power law.

For this method, the measuring points may be located at whichever positions are required in order to obtain a satisfactory knowledge of the velocity profile.

4.1.2 Numerical integration of the velocity area (see Clause 10)

The difference between this method and 4.1.1 lies in the fact that the graphical velocity profile is replaced by an algebraic curve and the integration is carried out analytically.

4.1.3 Arithmetical methods (see Clause 11)

The arithmetical methods assume that the velocity distribution follows a particular law and the mean velocity in the conduit is then given by a linear combination of the individual velocities measured at the locations specified by the method.

For the arithmetical methods described in Clause 11, the assumption is made that in the peripheral zone the velocity distribution follows a logarithmic law as a function of the distance from the wall.

4.2 Measurement of the measuring cross-section

4.2.1 Circular cross-sections

The mean diameter of the conduit is taken as equal to the arithmetic mean of measurements carried out on at least four diameters (including the traverse diameters) at approximately equal angles to each other in the measuring section. Should the difference between the lengths of two consecutive diameters be greater than 0,5 %, the number of measured diameters shall be doubled.

4.2.2 Rectangular cross-sections

The conduit width and height shall both be measured at least on each straight line (at least four) passing through the measuring points. Should the difference between the widths (or heights) corresponding to two successive measuring lines be greater than 1 %, the number of measured widths (or heights) shall be doubled.

4.3 Measurement of local velocities

4.3.1 Method of exploring traverse section

It is sometimes proposed that several Pitot tubes be mounted on a stationary rake in order to explore simultaneously the whole measuring cross-section. However, the experimental data available at the time of publication are insufficient to allow the design of certain details (such as shape of head and of stem) which would ensure that measurements by a rake would achieve the accuracy required by this document.

Therefore, this document deals only with velocity area methods using a single Pitot tube placed successively at each measuring point.

4.3.2 Reference measurement

Reference measurements shall be made in order to check the steadiness of flow and to correct individual velocity measurements for slight changes in flow rate during traversing; any reference measuring device inserted in the conduit shall be placed in such a way that there is no interaction with the traversing Pitot tube. The reference measurement shall be made as far as possible simultaneously with each velocity measurement.

However, if only one measuring device is available, the steadiness of the flow shall be checked by repeating measurements at the reference point after each local velocity measurement.

The shape of the velocity profile in the measuring cross-section shall remain stable and shall not be affected by possible variations of the flow rate whilst measurements are being taken.

When the curve of reference velocity, v_r, has been plotted against time, this curve is used to relate all traverse measurements to the same reference flow rate, q_o (preferably that which corresponds to the mean of velocity measurements at the fixed point). For comparatively small changes of the reference velocity, the velocity, $v_{i,t}$, measured at any point, i at time, t can be transposed by multiplication by the ratio of velocity, $v_{r,o}$, at the reference point corresponding to flow rate, q_o, at velocity, $v_{r,t}$, at this reference point at time t is given by Formula (1):

$$v_{i,o} = v_{i,t} \left(\frac{v_{r,o}}{v_{r,t}} \right) \quad (1)$$

NOTE Where the reference measurement is a quantity directly proportional to the flow rate (e.g. the rotational frequency of a shaft driving a fan or a pump), this measurement can be substituted directly for $v_{r,o}$ and $v_{r,t}$ in the above formula. Where the reference reading is in the form of a pressure difference (e.g. across a fixed feature of the flow circuit, or the differential pressure of a reference Pitot tube), the square root of each reference reading can be substituted for $v_{r,o}$ and $v_{r,t}$ in the above formula.

However, note that velocity profile fluctuations may occur without creating flow rate fluctuations. In such a case, the use of reference point velocity may lead to errors and it is preferable to check steadiness of flow by means of any pressure difference device (standardized pressure difference flow meter, piezometric control on a convergent, bend, spiral casing, peculiar pressure loss, etc.), even if it is not calibrated, provided that its reliability and adequate sensitivity have been ascertained. In this case, the above-mentioned proportional correction relates to the differential pressure and not to the velocity.

4.3.3 Checking of velocity distribution

It is recommended that the regularity of the velocity distribution be checked either by plotting or by other means, regardless of whether or not the plotting is necessary for calculating the discharge velocity.

In the same way, when several measurements are made on the same cross-section at different flow rates, it is recommended that the velocity profiles be plotted in a non-dimensional manner (i.e. by using the relative velocities; see 3.2.8) to check their consistency with each other and hence to ensure that there are no abnormal features at particular flow rates (thus, the profiles shall not change erratically as the flow rate varies over a wide range of Reynolds numbers).

It may also be useful to plot the velocity distribution curves as indicated above in order to detect any error in the measurement of a local velocity. The doubtful measurement shall be repeated whenever possible; when this cannot be done, it shall be ignored and the velocity profile drawn on the basis of the previously obtained profiles provided there are independent reasons for believing the doubtful measurement is false.

4.4 Location and number of measuring points in the cross-section

4.4.1 General requirements

The rules to be followed for locating the measuring points differ according to the methods of determination of the discharge velocity as specified in this document. These rules are given in Clauses 9, 10 and 11, respectively.

Whatever method is used, the distance between the axis of the head of the Pitot tube and the wall shall not be less than the head diameter, *d*.

The location of the Pitot tube shall be calculated from the actual dimension of the conduit along each traverse line (rather than from the mean dimension) and shall be measured to:

a) $\pm 0{,}005 \cdot X$, where X is the dimension of the duct parallel to the measurement of the Pitot tube position;

or

b) $\pm 0{,}05 \cdot y$, where y is the distance of the Pitot tube from the nearest wall, whichever is the smaller.

4.4.2 and 4.4.3 specify a minimum number of measuring points applying in particular to small dimension conduits. As it is necessary to define the velocity profile as accurately as possible, the number of measuring points can be advantageously increased provided that this is allowed by the operating conditions and steadiness of the flow.

When a single Pitot tube is traversed across the duct, the distance between a reference point (from which each position is measured) and the wall of the duct shall first be obtained. This may introduce a relatively large systematic error in all position measurements. In such instances, it is recommended that complete diameters be traversed (rather than opposite radii on each diameter) since the systematic error will then tend to cancel out on the two halves of the traverse.

4.4.2 Circular cross-sections

The measuring points shall be located at every point of intersection between a prescribed number of circles concentric with the pipe axis and at least two mutually perpendicular diameters.

The measurements shall be carried out in at least three points per radius, so that there is a minimum of 12 points in the cross-section. An additional measuring point at the centre of the conduit is desirable to check the shape of the velocity profile and is necessary for the calculation of the stem blockage correction, where applicable (see 12.1.2).

4.4.3 Rectangular cross-sections

The minimum number of measuring points shall be 25. Unless a special layout of measuring points is required for the use of an arithmetic method, their position shall be defined by the intersections of at least five straight lines running parallel to each wall of the conduit.

5 Design of Pitot tubes

5.1 General description

The use of one of the types of Pitot tube described in Annex A, all of which fulfil the requirements of 5.2, is recommended; this avoids the necessity of making several corrections to the measurements. The use of any other Pitot tube which fulfils the requirements of 5.2 is permitted provided that its calibration is known.

The Pitot static tubes dealt with in this document consist of a cylindrical head attached perpendicularly to a stem which usually passes through the wall of a conduit. The length of the head is generally between 15d and 25d, where d is the head diameter.

At one or two cross-sections along the head, static-pressure holes are drilled around the circumference, so that, in the absence of leakage, the registered pressure is transferred through the head and stem to a point outside the conduit.

A smaller tube, concentric with the head and stem, transfers the total pressure, registered by a hole facing the flow direction at the tip of an axially symmetrical nose integral with the head, to a point outside the conduit.

An alignment arm, fitted to the end of the stem, facilitates alignment of the head when this is obscured by the conduit wall.

5.2 Criteria to be fulfilled by the Pitot tube

The nose (including the total pressure hole) shall be designed in such a way as to comply with the following requirements.

a) The response of the differential pressure to inclination of the head relative to the flow shall meet one of the following two conditions according to the circumstances (in both cases it is necessary to know the response curve of the Pitot tube):

   1) if precise alignment of the Pitot tube with the conduit axis is not possible but there is no swirl, the differential pressure should be as independent as possible of the yaw of the head in uniform flow[1)];

   2) if precise alignment of the Pitot tube with the conduit axis is possible but swirl is present, the variation of the differential pressure recorded by the tube in uniform flow with yaw angle, φ, shall be approximately proportional to $\cos^2\varphi$. If the head is perfectly aligned axially and if swirl is less than ±3°, the differential pressure shall not deviate from this relationship by more than 1 %.

   It should be noted that misalignment and swirl can occur simultaneously and efforts shall be made to minimize each of them.

b) The calibration factors for different specimens of tubes to a particular specification shall be identical, to within ±0,25 %, and shall remain so for the working life of any such tube. If the user has any doubt upon this point, an individual calibration of each Pitot tube should be made.

c) When used in a liquid, any cavitation from the nose shall not cause a significant error in the static pressure reading of the tube.

d) The static-pressure holes shall be:

   1) not larger than 1,6 mm in diameter;

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1) The Pitot tubes described in Annex A allow independence of the differential pressure to within ±1,5 % up to 14° yaw in uniform flow.