INTERNATIONAL STANDARD ISO 3966

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

Mesure 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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Annexes

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

1 SCOPE AND FIELD OF APPLICATION

This International Standard specifies a method for the determination in a closed conduit of the volume rate of flow of a regular flow (see 5.1) :

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

– with substantially uniform stagnation temperature across the measuring cross-section;

– running full in the conduit;

– 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.

The method of measurement and the requirements defined in this International Standard aim at reaching, at the 95 % confidence level, an uncertainty on 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 11. If any of the requirements of this International Standard are not fulfilled, this method may still be applied in special cases but the uncertainty on flow rate will be larger.

2 SYMBOLS AND DEFINITIONS

2.1 Symbols

Symbol	Quantity	Dimensions	Corresponding 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'	Stem 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 of the nose shape	–	–
k_t	Coefficient of turbulence correction	–	–
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
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	Molar constant of gas	$ML^2T^{-2}\Theta^{-1}$	$J \cdot mol^{-1} \cdot K^{-1}$
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	–	–
$(1-\epsilon)$	Compressibility correction factor	–	–

Symbol	Quantity	Dimensions	Corresponding SI unit
λ	Universal coefficient for head loss	–	–
μ	Dynamic viscosity of the fluid	$ML^{-1}T^{-1}$	Pa·s
ν	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	–	–

2.2 Definitions

The definitions in the following sub-clauses are given only for terms used with a special meaning or for terms the meaning of which might be usefully recalled.

2.2.1 Pitot static tube : A 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. It 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).

NOTE — Throughout this International Standard the expression "Pitot tube" is used without amplification to designate a "Pitot static tube" since no confusion is possible.

2.2.2 static pressure tapping : A group of holes for the measurement of fluid static pressure.

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

2.2.4 differential pressure : The difference between the pressures at the total and static pressure taps.

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

2.2.6 peripheral flow rate : The 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.

2.2.7 discharge velocity : The 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.

2.2.8 relative velocity : The 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 (for example, the centre of a circular conduit) or the discharge velocity in the measuring section.

2.2.9 straight length : A conduit section the axis of which is rectilinear and the surface and cross-section of which are constant.

NOTE — The shape of this section is usually circular, but it may be rectangular or annular.

2.2.10 irregularity : Any element or configuration of a conduit which makes it different from a straight length.

NOTE — For the purpose of this International Standard, those irregularities which create the most significant disturbances are bends, valves, gates and sudden widening of the section.

3 PRINCIPLE

3.1 General principle

The principle of the method consists of :

a) measuring the dimensions of the measuring section, which must be normal to the conduit axis; this measurement is necessary for defining the area of the cross-section (see 3.2);

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 3.3) 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 7);

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 12.

This International Standard presents three types of methods for determining the discharge velocity :

Graphical integration of the velocity area (see clause 8)

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.

Numerical integration of the velocity area (see clause 9)

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

Arithmetical methods (see clause 10)

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 10, 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.

3.2 Measurement of the measuring cross-section

3.2.1 *Circular cross-sections*

The mean diameter of the conduit is taken as equal to the arithmetical 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.

3.2.2 *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.

3.3 Measurement of local velocities

3.3.1 *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 at present available 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 International Standard.

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

3.3.2 *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.

It is essential that the shape of the velocity profile in the measuring cross-section remains stable and is not affected by possible variations of the flow rate whilst measurements are being taken.

When the curve of reference velocity variation 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 :

$$v_{i,o} = v_{i,t} \times \frac{v_{r,o}}{v_{r,t}}$$

NOTE — Where the reference measurement is a quantity directly proportional to the flow rate (for instance, the rotational speed 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 equation. Where the reference reading is in the form of a pressure difference (for instance 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 equation.

However, it must be noted 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 will relate to the differential pressure and not to the velocity.

3.3.3 *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 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.

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

3.4.1 *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 International Standard. These rules are given in clauses 8, 9 and 10 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 :

± 0,005 X, where X is the dimension of the duct parallel to the measurement of Pitot tube position, or

± 0,05 y, where y is the distance of the Pitot tube from the nearest wall, whichever is the smaller.

Sub-clauses 3.4.2 and 3.4.3 prescribe 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 must 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 systemetic error will then tend to cancel out on the two halves of the traverse.

3.4.2 *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 twelve 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 11.1.2).

3.4.3 *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 arithmetical method, their position shall be defined by the intersections of at least five straight lines running parallel to each wall of the conduit.

4 DESIGN OF PITOT TUBES

4.1 General description

The use of one of the types of Pitot tube described in annex A, all of which fulfil the requirements of 4.2, 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 4.2 is permitted provided that its calibration is known.

The Pitot static tubes dealt with in this International Standard 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 15 and 25 times 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.

4.2 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 law 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;

2) at least six, and sufficient in number for the damping in the static pressure circuit to be as nearly as possible equal to that in the total-pressure circuit; if necessary, on Pitot tubes the diameter of which is small, the orifices may be placed in two planes;

3) placed not less than six head-diameters from the tip of the nose;

4) placed not less than eight head-diameters from the axis of the stem.

e) If the stem is enlarged to a diameter d', there shall be a length of stem not less than $7\,d'$, between the axis of the head and the commencement of the enlargement, for which the stem-diameter is equal to the head-diameter.

f) The junction between the head and stem shall be either mitred or curved to a mean radius equal to 3 ± 0,5 times the head-diameter.

g) An alignment arm shall be fitted to the end of the stem away from the head, to ensure precise alignment and positioning within a conduit.

Three types of Pitot tubes which are currently used and which comply with these criteria are described as examples in annex A.

5 REQUIREMENTS FOR USE OF PITOT TUBES

5.1 Selection of the measuring cross-section

5.1.1 The cross-section selected for measurements shall be located in a straight pipe length and shall be perpendicular to the direction of flow. It shall be of simple shape, for example either circular or rectangular. It shall be located in an area where the measured velocities fall within the normal working range of the apparatus used (see 5.3.2).

5.1.2 Close to the measuring cross-section, flow shall be substantially parallel to and symmetrical about the conduit axis and contain neither excessive turbulence nor swirl; the measuring cross-section shall thus be chosen far enough away from any disturbances that could create asymmetry, swirl or turbulence (see 5.1.4).

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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.

The length of straight pipe that may be required to achieve these conditions will vary with the flow velocity, upstream disturbances, level of turbulence and the degree of swirl, if any.[1]

5.1.3 Although measurements with the Pitot tube in oblique or converging flow should as far as possible be avoided, these may however be carried out provided that the maximum flow deviation with respect to the Pitot tube axis does not exceed 3°.

For guidance, it can also be considered that a swirl is small enough not to increase the confidence limits given in this International Standard on the measured flow rate if the resulting gradient of local velocities to the pipe axis is less than 3°.

5.1.4 Preliminary traverse tests shall be made to ascertain the regularity of flow.

If these traverses show that flow is not satisfactory, this can sometimes be remedied using one of the devices described in 5.2.

Once these devices are in place it shall be checked that the flow complies with the requirements of this International Standard. If not, a more detailed traverse of the measuring cross-section is necessary, and reference shall then be made to a separate document which will be published later.

5.2 Devices for improving flow conditions

5.2.1 If swirl is present in the flow, it can often be suppressed by means of an anti-swirl device consisting either of several adjacent pipes parallel to the flow direction or of a honeycomb with square or hexagonal cells. Whichever type is used the whole device shall be rigorously symmetrical and the following requirements shall be met :

- the maximum transverse dimension a of a channel shall be less than 0,25 D;
- length shall be greater than 10 a.

5.2.2 If the velocity distribution is unacceptably irregular, it can often be remedied by means of a profile developer consisting of, for example, one or more screens, grids or perforated plates. It must be noted, however, that such devices are only effective at the price of a rather high head loss.

5.2.3 The devices described in 5.2.1 and 5.2.2 shall be located at the greatest possible distance upstream of the measuring cross-section and in any case at a distance of at least five diameters of a circular cross-section (or 20 times the hydraulic radius of a conduit of any cross-section shape). Furthermore they shall not be located immediately downstream of a disturbance.

5.2.4 If the velocity distribution is unacceptably irregular or if the flow is not parallel enough, but if it has been possible to check that no swirl is present, it is sometimes possible to remedy the situation by means of a provisional guiding installation. The latter will consist of a slightly converging entrance, connected in such a way as to ensure that no separation occurs, to a straight pipe length, the length of which shall be at least twice the larger dimension of the conduit.

5.3 Limits of use

5.3.1 *Nature of the fluid*

The fluid shall be a continuous single-phase fluid or shall behave as if it were such a fluid. Liquids shall be Newtonian and shall not exhibit anomalous viscosity or thixotropic behaviour.

5.3.2 *Range of velocities*

Pitot tubes shall not be used with flow velocities less than the velocity corresponding to the lower limit of the Reynolds number (see 7.1) or greater than the velocity corresponding to a Mach number of 0,25.

5.3.3 *Nature of the flow*

The formulae given (see 7.1 and 7.2) are accurate only for steady flow without transverse velocity gradient or turbulence. In practice both are always present in closed conduits. Clause 11 and annexes B and C give indications of the magnitude of the corresponding errors.

5.3.4 *Dimensional limitations*

The ratio d/D of the Pitot tube diameter d to the conduit diameter D shall not exceed 0,02 with a view to keeping negligible the error on the rate of flow resulting from the velocity gradient and from the stem blockage effect (see clause 11). In difficult flow conditions, a ratio of up to 0,04 may be admissible provided that the necessary corrections for blockage effect and velocity gradient are made; this limit value may indeed be necessary to avoid vibration of the tube in very high velocity flows. On the other hand the requirements mentioned in clause 4 shall be satisfied.

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[1] For guidance it is normally assumed that to comply with these conditions there should be a length of upstream conduit between the beginning of the working section and any significant upstream irregularity (see 2.2.10) of at least 20 diameters of a circular cross-section (or 80 times the hydraulic radius of a conduit of any cross-section shape). Similarly there should be at least 5 diameters of a circular cross-section (or 20 times the hydraulic radius of a conduit of any cross-section shape), between the measuring cross-section and any significant downstream irregularity.

5.3.5 *Influence of turbulence*

Turbulence has a twofold influence in the case of an exploration by means of a Pitot tube, i.e. :

a) on the total pressure reading;

b) on the static pressure reading.

Turbulence of flow leads to an overestimation in the determination of velocity, which is a function of the degree of turbulence.

Detailed study of the turbulence correction is given in annex C.

5.4 Performance of measurements

5.4.1 *Measurement of differential pressure*

The device chosen for the measurement of differential pressure shall be capable of measurement of a steady differential pressure equal to the maximum value recorded during the traverse with an uncertainty not exceeding 1 % (at 95 % confidence level).

5.4.2 *Differential pressure fluctuations*

In order to obtain, from the measurements, time-averaged values which are representative in spite of random fluctuations of the flow rate, it is necessary :

a) that the differential pressure fluctuations be damped by applying to the measuring apparatus the minimum damping allowing easy reading without concealing longer-term fluctuations. The damping of the apparatus shall be symmetrical and linear; this can be achieved by means of a capillary tube located in the manometric limb in accordance with the requirements of annex D;

b) that readings at each measuring point shall be repeated a certain number of times, preferably at unequal time intervals. A sufficient number of readings is reached when suppressing any one of them (except those which present an abnormally high error and are excluded automatically) does not modify the mean by more than ± 1 %.

However, if damping condition a) has been satisfied sufficiently well so that the instantaneous readings of differential pressure do not fluctuate by more than ± 2 % of the mean differential pressure over a sufficiently long period of time (for example ten maximum and ten minimum values to be observed), then a visual averaging of the measurement is permissible.

NOTE — The final tolerance applicable to the rate of flow on account of random fluctuations of the readings will be a function of the total number of readings made during an exploration. Consequently if the total number of measuring points is high, the number of readings at each point may be comparatively small.

5.4.3 *Determination of fluid density*

The fluid density shall be determined in such a way as to ensure that the uncertainty in the value obtained does not exceed ± 0,5 % (at 95 % confidence level).

When the fluid density is obtained from the absolute static pressure and static temperature, these quantities may generally be taken from single readings made at a point located at 0,75 times the pipe radius from the wall. Nevertheless, for measurements in a compressible fluid where the ratio of the maximum differential pressure to the absolute static pressure in the plane of the traverse is greater than 0,01, the procedure described in 7.2 and in E.3 of annex E shall be followed.

5.5 Inspection and maintenance of the Pitot tube

The Pitot tube does not require any special maintenance, but it shall be ensured, before and after the measurements, that the tube used complies with the criteria specified in clause 4.

The following points in particular shall be checked :

- the pressure sensing holes and their connecting tubes are not blocked;
- there is no leakage between the chambers inside the Pitot tube which receive the total pressure and the static pressure;
- the tube has not been strained, or its nose damaged;
- the tube is clean;
- the head of the Pitot tube is truly perpendicular to the supporting stem.

Furthermore, since the determination of the velocity is related to the differential pressure, it shall also be checked that :

- the connections to the pressure gauge are as short as possible and that they are absolutely leak-tight (porous or cracked rubber tubes, etc., are not permissible);
- they are in general in accordance with ISO 2186, *Fluid flow in closed conduits — Connection for pressure signal transmissions between primary and secondary elements;*
- where damping of the differential pressure gauge is necessary, it is symmetrical and linear (see annex D).

6 POSITIONING OF PITOT TUBE

The axis of the Pitot tube head shall be set parallel to the pipe axis; an alignment arm shall be provided to assist in doing this.

The Pitot tube shall be rigidly fixed during the measurements.

The Pitot tube shall be positioned in the pipe in accordance with the requirements of 3.4.1 and clause 8 or 10.

The device which holds the Pitot tube in the pipe shall be such that no leak can occur into or out of the pipe.

7 VELOCITY COMPUTATION

7.1 Verification of conditions for a measurement

Provided that the Reynolds number based on the diameter of the total pressure hole of the Pitot tube is in excess of 200, and that the local Mach number (for measurements in a compressible fluid) does not exceed 0,25, the local velocity may be calculated. However, annex E gives indications on the method of carrying out velocity measurements in the case of a compressible fluid at a higher Mach number.

The first condition is equivalent to a requirement that Δp is never less than

$$\frac{2 \times 10^4}{\rho} \left(\frac{\mu}{\alpha d_i} \right)^2$$

where

Δp is the differential pressure measured by the Pitot tube;

ρ is the density of the fluid;

μ is the dynamic viscosity of the fluid;

d_i is the diameter of the total pressure hole of the Pitot tube;

α is the calibration factor of the Pitot tube : to be taken as 1 for this calculation.

The second condition requires that, for measurement in a compressible fluid, the ratio of the differential pressure to the absolute value of the pressure recorded by the static pressure tapping of the Pitot tube shall never exceed a limiting value, which varies with γ (the ratio of the specific heat capacities of the gas) according to table 1.

TABLE 1

γ	1,1	1,2	1,3	1,4	1,5	1,6	1,7
$\left(\frac{\Delta p}{p}\right)_{\text{max.}}$	0,035	0,038	0,042	0,046	0,048	0,052	0,054

7.2 Formulae for velocity computation

The local velocity of a fluid in a steady flow without transverse velocity gradient or turbulence at Reynolds numbers, based on the internal diameter of the total pressure tapping, greater than 200 is given by the expression

$$v = \alpha(1 - \epsilon) \sqrt{\frac{2\Delta p}{\rho}}$$

in which $(1 - \epsilon)$ is a compressibility correction factor. In a liquid, $\epsilon = 0$ so that no compressibility correction is required, but in a compressible fluid at low Mach numbers the factor $(1 - \epsilon)$ may be determined by the relationship

$$(1 - \epsilon) \approx \left[1 - \frac{1}{2\gamma} \frac{\Delta p}{p} + \frac{\gamma - 1}{6\gamma^2} \left(\frac{\Delta p}{p} \right)^2 \right]^{1/2}$$

where

γ is the ratio of specific heat capacities;

p is the local statio pressure;

ρ is the local density of the fluid;

Δp is the differential pressure indicated by the Pitot tube;

α is the calibration factor of the Pitot tube (under the above-mentioned conditions and for Pitot tubes described in this International Standard, it is practically equal to 1,00).

The density of the compressible fluid is determined from the following equation :

$$\rho = \frac{pM}{ZRT}$$

where

$R = 8{,}314\,3\ \text{J·mol}^{-1}\text{·K}^{-1}$, the molar mass being expressed in kilograms per mole and having a value 0,028 95 for air;

Z is the gas law deviation factor; it is insignificantly different from unity for air at absolute pressures less than ten times atmospheric and temperatures between 273 and 373 K (it should be distinguished from $(1 - \epsilon)$, the compressibility correction factor);

T is the local static temperature given by the formula[1]

$$\frac{T_o}{T} = \left[1 + \frac{\gamma - 1}{\gamma} \frac{\Delta p}{p} \right]$$

T_o being the total temperature measured on the axis of the duct using an ideal total temperature probe. The effect of using any non-ideal temperature probe is discussed in annex D.

For selected values of γ and $\Delta p/p$, values of $(1 - \epsilon)$, together with T/T_o, are shown in table 2.

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[1] This formula is an approximation which is adequately precise for the purposes of this International Standard.

TABLE 2

γ / $\frac{\Delta p}{p}$	1,1		1,2		1,3		1,4		1,5		1,6		1,7	
	T/T_o	$(1-\epsilon)$	T/T_o	$(1-\epsilon)$	T/T_o	$(1-\epsilon)$	T/T_o	$(1-\epsilon)$	T/T_o	$(1-\epsilon)$	T/T_o	$(1-\epsilon)$	T/T_o	$(1-\epsilon)$
0,01	0,999	0,998	0,998	0,998	0,998	0,998	0,997	0,998	0,997	0,998	0,996	0,998	0,996	0,999
0,02	0,998	0,996	0,997	0,996	0,995	0,996	0,994	0,997	0,993	0,997	0,993	0,997	0,992	0,997
0,03	0,997	0,993	0,995	0,994	0,993	0,994	0,992	0,995	0,990	0,995	0,989	0,995	0,988	0,996
0,04	0,996	0,991	0,994	0,992	0,991	0,993	0,989	0,993	0,987	0,994	0,985	0,994	0,984	0,994
0,05	–	–	–	–	0,989	0,991	0,986	0,991	0,984	0,992	0,982	0,992	0,980	0,993

8 DETERMINATION OF THE DISCHARGE VELOCITY BY GRAPHICAL INTEGRATION OF THE VELOCITY AREA

The general principle of this method is specified in 3.1.

The measuring points shall be located along straight lines, and in order to determine m accurately, two measuring points shall be placed on each straight line as close as possible to the wall (see annex F).

The number and position of the other points shall be selected in such a manner that the velocity profile can be determined satisfactorily. They will usually be distributed in the cross-section in such a way as to divide it into areas, each of which has the same flow rate in order to attach approximately the same importance to all measuring points.

Reference should be made to 3.4 when determining the number and location of measuring points, and to clause 11 when it is considered necessary to make some correction to local velocity measurements or to the position of measuring points.

8.1 Circular cross-section

If v is the flow velocity at a point of polar co-ordinates r and θ, and if R is the mean radius of the measuring section, the discharge velocity is

$$U = \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R v(r,\theta)\, r\, \mathrm{d}r\, \mathrm{d}\theta = \int_0^1 u\, \mathrm{d}\left(\frac{r}{R}\right)^2$$

$$= \int_0^{(r_n/R)^2} u\, \mathrm{d}\left(\frac{r}{R}\right)^2 + \int_{(r_n/R)^2}^1 u\, \mathrm{d}\left(\frac{r}{R}\right)^2$$

where

u is the spatial mean velocity along the circumference of radius r;

r_n is the radius of the circle defined by the measuring points closest to the wall.

The method used consists in :

a) taking u_c (arithmetical mean of the velocities at the measuring points located on one circle of radius r_c) as the value of u;

b) plotting u_c against $(r_c/R)^2$ between $r = 0$ and $r = r_n$ (see figure 1)[1];

c) graphically determining the value of the included area below this curve (see figure 1);

d) adding to this value a calculated term[2] corresponding to the peripheral zone and equal to :

$$\frac{m}{m+1} u_n \left(1 - \frac{r_n{}^2}{R^2}\right)$$

where

u_n is the value of the arithmetical mean of the velocities at the measuring points located on the circle of radius r_n (i.e. the closest to the wall);

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[1] To facilitate plotting in the vicinity of the measuring point closest to the wall, the tangent line to the curve for $r = r_n$ will be drawn with a slope equal to :

$$\left(\frac{\mathrm{d}u_c}{\mathrm{d}x}\right)_{r = r_n} = \frac{-u_n}{2m\frac{r_n}{R}\left(1 - \frac{r_n}{R}\right)}$$

denoting $(r/R)^2$ as x.

The slope of the curve is derived from Karman's conventional law, for the variation of the fluid velocities in the peripheral zone :

$$u = u_n \left(\frac{R - r}{R - r_n}\right)^{1/m}$$

[2] This simplified expression omits the other term

$$\frac{-m}{(m+1)(2m+1)} u_n \left(1 - \frac{r_n}{R}\right)^2$$

in the result of the integration (within the peripheral zone) derived from Karman's conventional law : this latter term only represents about

$$\frac{1 - (r_n/R)}{4m + 2}$$

times the flow in the peripheral zone.