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MEASUREMENT OF FLUID FLOW BY MEANS OF ORIFICE PLATES AND NOZZLES

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BRIEF HISTORY

The ISO Recommendation R 541, *Measurement of Fluid Flow by Means of Orifice Plates and Nozzles*, was drawn up by Technical Committee ISO/TC 30, *Measurement of Fluid Flow in Closed Conduits*, the Secretariat of which is held by the Association Française de Normalisation (AFNOR).

Work on this question by the Technical Committee began in 1948, taking into account the studies which had been made by the former International Federation of the National Standardizing Associations (ISA), and led in 1962 to the adoption of a Draft ISO Recommendation.

In February 1963, this Draft ISO Recommendation (No. 532) was circulated to all the ISO Member Bodies for enquiry. It was approved, subject to a few modifications of an editorial nature, by the following Member Bodies:

Australia
Austria
Belgium
Chile
Czechoslovakia
France
Germany
Hungary
India
Iran
Italy
Japan
Netherlands
Portugal
Sweden
Switzerland
United Kingdom
U.S.A.
U.S.S.R.

No Member Body opposed the approval of the Draft.

The Draft ISO Recommendation was then submitted by correspondence to the ISO Council, which decided, in January 1967, to accept it as an ISO RECOMMENDATION.

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MEASUREMENT OF FLUID FLOW BY MEANS OF ORIFICE PLATES AND NOZZLES

1. GENERAL

1.1 Principle of the method of measurement

A device such as an orifice plate or a nozzle is placed in a pipe-line through which a fluid is flowing.

A static pressure difference then exists between the upstream side and the downstream side of the device and whenever the device is geometrically similar to one on which direct calibration has been made, the conditions of use being the same, the rate of flow can be determined from the measured value of this pressure difference and from a knowledge of the circumstances under which the device is being used.

This ISO Recommendation describes the shape and method of use of certain of these devices, on which direct calibration experiments have been made, sufficient in number and quality to enable coherent systems of application to be based on their results.

The devices introduced in the pipe are called " primary elements ", which term includes the pressure taps; all other instruments or devices required for measuring are known as " secondary devices ". This ISO Recommendation covers the primary elements; secondary devices will be mentioned only occasionally.

1.2 Standard primary elements

The standard primary elements are the following:

1.2.1 *Orifice plate*, a sharp square-edged orifice in a thin plate, with which are used various arrangements of pressure tappings, known as

- Corner taps,
- *Vena contracta* taps,
- Flange taps.

1.2.2 *Nozzles*, which differ in shape and/or in position of the pressure taps and are known as either

- ISA 1932 nozzle,
- Long-radius nozzle.

2. GENERAL REQUIREMENTS FOR VALIDITY OF THE MEASUREMENTS

It is necessary to ensure that all the following requirements, some of which are explained in detail in the following sections, are completely fulfilled during the period of measurement.

2.1 Primary element

2.1.1 The primary element should be manufactured, installed and used in accordance with this ISO Recommendation.

2.1.2 The condition of the primary element should be checked after each measurement or each series of measurements.

2.1.3 The primary element should be manufactured from material the coefficient of thermal expansion of which is known.

2.2 Type of fluid

2.2.1 The fluid may be either compressible (gas) or considered as incompressible (liquid).

2.2.2 The fluid should be physically and thermally homogeneous and of single (gas or liquid) phase.

Colloidal solutions with a high degree of dispersion (such as milk), and those only, are considered to behave as a single phase fluid.

2.3 Installation

2.3.1 The measuring process applies only to fluids flowing through a pipe-line.

2.3.2 The primary element is fitted between two sections of straight cylindrical pipe of constant cross-sectional area, in which there is no obstruction or branch connection (whether or not there is flow into or out of such connections during measurement) other than those specified in this ISO Recommendation.

The pipe is considered straight when it appears so by mere visual inspection.

The required minimum straight lengths of pipe, which conform to the description above, vary according to the nature of the fittings and are indicated in Table 1, on page 7.

The pipe bore is truly circular over the entire minimum lengths of straight pipe required.

The cross-section is taken to be circular if it appears so by mere visual inspection. The circularity of the outside of the pipe may be taken as a guide, except in the immediate vicinity of the primary element.

Over an upstream length of at least 2 D measured from the upstream face of the primary element, the pipe should be cylindrical. The value of the diameter D of the pipe should be taken as the mean of the measurements of several diameters situated in meridian planes at approximately even angles to each other and in several planes normal to the pipe centre line within the specified length of 2 D. Four diameters at least should be measured.

The pipe is said to be cylindrical when no diameter in any plane differs by more than 0.3 per cent from the value of D obtained as a mean of all measurements.

Attention is called to the fact that it is possible to check circularity of a pipe bore, within the accuracy required, without measuring the mean diameter of the pipe bore itself.

The mean diameter of the downstream straight length, considered along a length of at least 2 D from the upstream face of the primary element, should not differ from the mean diameter of the upstream straight length by more than ± 2 per cent, this being judged by the check of a single diameter of the downstream straight length.

2.3.3 The inside diameter of the pipe should be equal to or more than 2 in (50 mm) and equal to or less than the maximum diameters specified for each device.

2.3.4 The inside surface of the measuring pipe should be clean, free from pitting and deposit and not encrusted. However, it may be either “ smooth ” or “ rough ”.

2.3.5 The pipe should run full at the measuring section.

2.3.6 The rate of flow should be constant or, in practice, vary only slightly and slowly with time. This ISO Recommendation does not provide for the measurement of pulsating flow.

2.3.7 The flow of fluid through the primary element should not cause any change of phase. To determine whether there is a change of phase, the computation of flow should be carried out on the assumption that the expansion is isentropic if the fluid is a gas, or isothermal if the fluid is a liquid.

2.3.8 If the fluid is a gas, the ratio of the downstream to the upstream absolute pressures should be greater than 0.75.

2.4 Straight lengths

2.4.1 The minimum straight lengths to be installed upstream and downstream of any primary element, according to clause 2.3.2, are the same regardless of the actual type of the primary element, as described in clauses 1.2.1 and 1.2.2.

The minimum upstream and downstream straight lengths required for installation between various fittings and the primary element are given in Table 1 below.

TABLE 1. — **Minimum straight lengths required between various fittings located upstream or downstream of the primary element and the primary element itself**

β	**On upstream (inlet) side of the primary element**						**On downstream (outlet) side**
	Single 90° bend or tee (flow from one branch only)	Two or more 90° bends in the same plane	Two or more 90° bends in different planes	Reducer (2 D to D over a length of 3 D). Expander (0.5 D to D over a length of 1.5 D)	Globe valve fully open	Gate valve fully open	All fittings included in this Table
$\leqslant$0.20	10 (6)	14 (7)	34 (17)	16 (8)	18 (9)	12 (6)	4 (2)
0.25	10 (6)	14 (7)	34 (17)	16 (8)	18 (9)	12 (6)	4 (2)
0.30	10 (6)	16 (8)	34 (17)	16 (8)	18 (9)	12 (6)	5 (2.5)
0.35	12 (6)	16 (8)	36 (18)	16 (8)	18 (9)	12 (6)	5 (2.5)
0.40	14 (7)	18 (9)	36 (18)	16 (8)	20 (10)	12 (6)	6 (3)
0.45	14 (7)	18 (9)	38 (19)	18 (9)	20 (10)	12 (6)	6 (3)
0.50	14 (7)	20 (10)	40 (20)	20 (10)	22 (11)	12 (6)	6 (3)
0.55	16 (8)	22 (11)	44 (22)	20 (10)	24 (12)	14 (7)	6 (3)
0.60	18 (9)	26 (13)	48 (24)	22 (11)	26 (13)	14 (7)	7 (3.5)
0.65	22 (11)	32 (16)	54 (27)	24 (12)	28 (14)	16 (8)	7 (3.5)
0.70	28 (14)	36 (18)	62 (31)	26 (13)	32 (16)	20 (10)	7 (3.5)
0.75	36 (18)	42 (21)	70 (35)	28 (14)	36 (18)	24 (12)	8 (4)
0.80	46 (23)	50 (25)	80 (40)	30 (15)	44 (22)	30 (15)	8 (4)

Fittings	**Minimum upstream (inlet) straight length required**
Abrupt symmetrical reduction having a diameter ratio $\geqslant$ 0.5	30 (15)
Thermometer pocket of diameter $\leqslant$ 0.03 D	5 (3)
Thermometer pocket of diameter between 0.03 D and 0.13 D	20 (10)

NOTE.—Table 1 is valid for all primary elements defined in this ISO Recommendation.

The unbracketed values are " zero additional tolerance " values (see clause 2.4.3).

The bracketed values are "± 0.5 per cent additional tolerance " values (see clause 2.4.4).

All straight lengths are expressed as multiples of the diameter D. They should be measured from the upstream face of the primary element.

2.4.2 The straight lengths given in Table 1 are minimum values, and it is always recommended to have straight lengths longer than those indicated. For research work especially, it is recommended to double at least the upstream values given in Table 1 for " zero additional tolerance ".*

2.4.3 When the straight lengths comply with the requirements of Table 1 and when they are longer than or equal to the values given for " zero additional tolerance ",* there is no need to add any additional deviation to the flow measurement error to take account of the effect of such installation conditions.

2.4.4 When the upstream or downstream straight lengths are shorter than the " zero additional tolerance " values * and equal to or greater than the "± 0.5 per cent additional tolerance " values,** as given in Table 1, an additional deviation of ± 0.5 per cent should be added to the error in flow measurement, in the following manner:

First computation Compute the tolerance for the flow measurement as if there was no additional tolerance for installation conditions. This computation should be made as shown in section 5 dealing with errors. Assume the result to be $\pm 2\sigma_q$ per cent.

Second computation Then add to this value of the tolerance an additional deviation of ± 0.5 per cent. This should be made *arithmetically*, in such a way that the final result will be $\pm (2\,\sigma_q + 0.5)$ per cent.

If the straight lengths are *shorter* than the "± 0.5 per cent additional tolerance" values ** given in Table 1, this ISO Recommendation gives *no information* by which to predict the value of any further tolerance to be taken into account; this is also the case when the upstream and downstream straight lengths are *simultaneously* shorter than the " zero additional tolerance " values.*

2.4.5 The valves mentioned in Table 1 should be fully open. It is recommended that control be effected by valves located downstream of the primary element. Isolating valves located upstream should be preferably of the " gate " type and should be fully open.

2.4.6 After a single change of direction (bend or tee), it is recommended that the tappings (if single tappings) be in a plane at right angles to the plane containing the change of direction (plane of the bend or tee).

2.4.7 The values given in Table 1 were obtained experimentally with a very long straight length upstream of the particular fitting in question. Usually, such conditions are not available and the following remarks may be used as a guide in usual installation practice.

(*a*) If the primary element is installed in a pipe leading to an upstream open space or large vessel, either directly or through any fitting given in Table 1, the total length of pipe between the open space and the primary element should never be less than 30 *D*.

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* Unbracketed values in Table 1.

** Bracketed values in Table 1.

(*b*) If several fittings other than 90° bends are placed in series upstream from the primary element, the following rule should be applied: between the closest fitting (1) to the primary element and the primary element itself, there should be a minimum straight length such as is indicated for the fitting (1) in question and the actual value β in Table 1. But, in addition, between this fitting (1) and the preceding one (2), there should be a straight length equal to one half of the value given in the Table 1 for fitting (2) applicable to a primary element of diameter ratio $\beta = 0.7$, whatever the actual value of β may be. This requirement does not apply when the fitting (2) is an abrupt symmetrical reduction, which case is covered by paragraph (*a*) above.

2.4.8 The primary element should be calibrated under actual installation conditions in cases which are not covered by the above statements.

3. SYMBOLS AND DEFINITIONS

The symbols used in this ISO Recommendation are given in Table 2, under clause 3.1.
The definitions, in the following clauses, are given only for terms used in some special sense or for terms the meaning of which it seems useful to emphasize.

3.1 Symbols

TABLE 2. — Symbols

Symbol	Represented quantity	Dimensions *
α	Flow coefficient	Pure number
β	Diameter ratio, $\beta = \frac{d}{D}$	Pure number
C	Coefficient of discharge, $C = \frac{\alpha}{E}$	Pure number
E	Velocity of approach factor, $E = (1 - \beta^4)^{-\frac{1}{2}}$	Pure number
ε	Expansibility (expansion) factor	Pure number
κ	Isentropic exponent **	Pure number
m	Area ratio, $m = \beta^2$	Pure number
Re_D	Reynolds number of upstream pipe referred to D	Pure number
x	Differential pressure ratio, $x = \frac{\Delta p}{p_1}$	Pure number
X	Acoustic ratio, $X = \frac{x}{\kappa}$	Pure number
d	Diameter of orifice or throat of primary element at operating conditions	L
D	Upstream pipe diameter at operating conditions	L
k	Absolute roughness (see clause 6.4.1.2)	L
Δp	Differential pressure	$ML^{-1}T^{-2}$
η	Dynamic viscosity of the fluid	$ML^{-1}T^{-1}$
ν	Kinematic viscosity of the fluid	L^2T^{-1}
p	Absolute static pressure of the fluid	$ML^{-1}T^{-2}$
q_m	Mass rate of flow	MT^{-1}
q_v	Volume rate of flow	L^3T^{-1}
ρ	Mass density of the fluid	ML^{-3}
t	Temperature of the fluid	Θ
$\bar{v}$	Mean axial velocity of the fluid in the pipe	LT^{-1}

* M = mass. L = length. T = time.
** For ideal gases, the ratio of the specific heat capacities and the isentropic exponent have the same values.

Subscript 1 applies to conditions (of the fluid, etc.) in the plane of the upstream pressure tap.
Subscript 2 applies to conditions (of the fluid, etc.) in the plane of the downstream pressure tap.

3.2 Pressure measurement: definitions

3.2.1 *Pipe-wall pressure tap.* Hole drilled in the wall of a pipe, the inside edge of which is flush with the inside surface of the pipe.

The hole is usually circular but in certain cases may be an annular slit.

3.2.2 *Static pressure* of a fluid flowing through a straight pipe-line. Pressure which can be measured by connecting a pressure gauge to a pipe-wall pressure tap. Only the value of the absolute static pressure is used in this ISO Recommendation.

3.2.3 *Differential pressure.* Difference between the static pressure measured by pipe-wall taps, one of which is on the upstream side and the other on the downstream side of a primary element inserted in a straight pipe through which flow occurs, when there is no variation in gravitational energy between the upstream and downstream taps.

The term " differential pressure " is used only if the pressure taps are in the positions specified by the ISO Recommendation for each standard primary element.

3.2.4 *Differential pressure ratio.* The differential pressure divided by the absolute static pressure existing at the level of the centre of the cross-section of the pipe in the plane containing the centre-line of the upstream pressure tapping.

3.2.5 *Pressure loss.* Difference in static pressure between the pressure measured on the upstream side of the primary element, at a point free from the influence of approach impact pressure, and that measured on the downstream side of the element, at a point where static pressure recovery by expansion of the jet is completed.

3.3 Primary elements: Definitions

3.3.1 *Orifice or throat.* Opening of minimum cross-sectional area in a primary element.

Standard primary element orifices are always circular and coaxial with the pipe-line.

3.3.2 *Orifice plate.* Thin plate in which a circular aperture has been machined.

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 is sharp and square.

3.3.3 *Nozzle.* Device which consists of a convergent inlet to a cylindrical portion generally called the " throat ".

3.3.4 *Diameter ratio* of a primary element in a given pipe. The diameter of the orifice of the primary element divided by the diameter of the measuring pipe upstream of the primary element.

3.4 Flow

3.4.1 *Rate of flow* of fluid passing through a primary element. Quantity of fluid passing through this orifice in unit time.

This quantity can be characterized by its mass or its volume and the rate of flow can be expressed in units of mass or volume per unit time.

In all cases, it is necessary to state explicitly whether the type of flow rate referred to is expressed by mass or by volume per unit time.

3.4.2 *Pipe Reynolds number.* The pipe Reynolds number used in this ISO Recommendation is referred to the upstream condition of the fluid and to the upstream diameter of the pipe, i.e.

$$Re_D = \frac{\bar{v}_1 D}{\nu_1}$$

3.4.3 *Isentropic exponent.* The isentropic exponent κ appears in the different formulae for expansibility (expansion) factor ε either directly or in the ratio X. There are many gases and vapours for which no values for κ have been published so far. For gases, however, the behaviour of which fairly equals that of ideal gases, the isentropic exponent may be replaced by the ratio of the specific heat capacities. The isentropic exponent, as well as the ratio of the specific heat capacities, vary in general whenever the gas temperature and/or pressure vary.

3.4.4 *Acoustic ratio.* The differential pressure ratio divided by the isentropic exponent (compressible fluid).

3.4.5 *Velocity of approach factor.* It is equal to:

$$E = (1 - \beta^4)^{-\frac{1}{2}} = D^2 / \sqrt{D^4 - d^4} = (1 - m^2)^{-\frac{1}{2}}$$

3.4.6 *Flow coefficient.* Calibration of standard primary elements by means of incompressible fluids (liquids) shows that the quantity α defined by the following relation is dependent only on the Reynolds number for a given primary element in a given installation.

$$\alpha = \frac{q_m}{\frac{\pi}{4} d^2 \sqrt{2 \Delta p \, \rho_1}}$$

The quantity α, a pure number, is called the “ flow coefficient ”.

The numerical value of α is the same for different installations, whenever such installations are geometrically similar and the flows are characterized by the identical Reynolds number.

The ratio $C = \frac{\alpha}{E}$ is called the “ coefficient of discharge ”.

The numerical values of α and of C given in this ISO Recommendation were determined experimentally.

3.4.7 *Expansibility (expansion) factor.* Calibration of a given primary element by means of a compressible fluid (gas), shows that the ratio

$$\frac{q_m}{\frac{\pi}{4} d^2 \sqrt{2 \Delta p \, \rho_1}}$$

is dependent both on the value of the Reynolds number and on those of the relative differential pressure and the isentropic exponent of the gas.

The method adopted for representing these variations consists in multiplying the flow coefficient α of the considered primary element, as determined by direct calibration effected by means of liquids for the same value of Reynolds number, by the “ expansibility ”, a so-called (expansion) factor defined by the relation

$$\varepsilon = \frac{q_m}{\frac{\pi}{4} \alpha \, d^2 \sqrt{2 \Delta p \, \rho_1}}$$

ε differs from and is less than unity, when the fluid is compressible.

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

The numerical values of ε given in this ISO Recommendation have been determined experimentally.

4. COMPUTATION — FORMULAE

4.1 Basic formula

4.1.1 For calculating the mass rate of flow, q_m, the flow coefficient α and expansibility (expansion) factor ε, as specified in this ISO Recommendation, should be used in the following formula:

$$q_m = \alpha \, \varepsilon \, \frac{\pi}{4} \, d^2 \sqrt{2 \, \Delta p \, \rho_1}$$

ε is equal to unity when the fluid is incompressible.

4.1.2 Similarly, the value of the volume rate of flow, at the upstream conditions of the fluid, may be calculated by the following relation:

$$q_{v_1} = q_m \, / \, \rho_1$$

4.1.3 The formulae of clauses 4.1.1 and 4.1.2 apply for any consistent system of units.

4.2 Method of determination of a standard primary element

The principle of the method consists essentially in selecting *a priori*

— the type of standard primary element to be used,

— a rate of flow and the corresponding value of the differential pressure.

The related values of q_m and Δp should be inserted in the basic formula rewritten in the form below:

$$\alpha \, \beta^2 = \frac{4 q_m}{\varepsilon \, \pi \, D^2 \, \sqrt{2 \, \Delta p \, \rho_1}}$$

and the diameter ratio of the selected primary element is determined by successive approximations.

4.3 Computation of rate of flow

Computation of the rate of flow is effected by replacing the different terms on the right-hand side of the basic formula

$$q_m = \alpha \, \varepsilon \, \frac{\pi}{4} \, d^2 \, \sqrt{2 \, \Delta p \, \rho_1}$$

by their numerical values, obtained in the course of the measurement, and by calculating their product. The computation itself involves no difficulty other than of an arithmetical nature and merely calls for the following comments:

(1) α may be dependent on Re_D, which is itself dependent on q_m. Therefore, the final value of q_m may be obtained by successive approximations, after first calculating q_m from a value of Re_D (or of α) chosen *a priori*. For instance, $\alpha = \alpha_0$ can be taken as a first value.

(2) Δp represents the differential pressure, as defined under clause 3.2.3.

5. ERRORS

5.1 Definition of the tolerance

5.1.1 For the purpose of this ISO Recommendation, tolerance is defined as a value equal to *twice* the standard deviation; this deviation should be calculated and given under this name whenever a measurement is claimed to be in conformity with this ISO Recommendation.

5.1.2 When the partial deviations, the combination of which gives the standard deviation, are independent of one another, are small and numerous, and have a distribution conforming to the so-called Laplace-Gauss normal law, there is a 95 per cent probability that the absolute value of the true error does not exceed *twice* the standard deviation.

5.1.3 When the standard deviation σ_q of the flow measurement q has been calculated, the absolute tolerance e_a is therefore defined as

$$e_a = 2\,\sigma_q$$

The relative tolerance e_r is

$$e_r = \frac{e_a}{q} = 2\,\frac{\sigma_q}{q}$$

The result of the flow measurement q should be then given in any one of the following forms:

rate of flow $= q \pm e_a$
or rate of flow $= q\,(1 \pm e_r)$
or rate of flow $= q$, within $(100\,e_r)$ per cent

5.2 Definition of the standard deviation

5.2.1 If the different *independent* quantities which are used to compute the flow rate are called $X_1, X_2, \ldots, X_i$, then the flow rate can be expressed as a certain function of these quantities:

$$q = \text{function}\,(X_1, X_2, \ldots\ldots, X_i)$$

and if the standard deviations of the quantities $X_1, X_2, \ldots, X_i$ are designated σ_{X_1}, $\sigma_{X_2}, \ldots, \sigma_{X_i}$, the standard deviation of the rate of flow q is defined as

$$\sigma_q = \left[\left(\frac{\partial q}{\partial X_1}\,\sigma_{X_1}\right)^2 + \left(\frac{\partial q}{\partial X_2}\,\sigma_{X_2}\right)^2 + \ldots + \left(\frac{\partial q}{\partial X_i}\,\sigma_{X_i}\right)^2\right]^{\frac{1}{2}}$$

where the partial derivatives $\frac{\partial q}{\partial X_i}$ depend on the manner in which q is a function of the quantities X_i.

5.2.2 If a certain quantity X_i has been measured several times, each measurement being independent of the others,

the standard deviation of an *individual* measurement of X_i is

$$\sigma_{X_i} = \left[\frac{\sum\limits_{j=1}^{j=n} (X_i - X_j)^2}{n-1}\right]^{\frac{1}{2}}$$

where X_i is the most probable value of the quantity;
X_j are the values obtained of each individual measurement;
n is the total number of measurements.

5.2.3 If repeated measurements of a quantity X_i are not available or are so few that direct computation of the standard deviation σ_{X_i} is likely to be unreliable, it is assumed that one is able to, at least, estimate the maximum deviation of the measurements, above *and* below the adopted value of X_i.

It is then permissible to take the standard deviation as ¼ of this estimated total deviation (that is to say as one half of the mean maximum deviation above *or* below the adopted value of X_i).

5.2.4 The ruling in clause 5.2.2 is valid only if the deviations such as are given by clause 5.2.2 or 5.2.3 are independent, or is only applicable to those deviations which can be considered as such.

5.3 Practical computation of the standard deviation

5.3.1 *The basic formula of computation* of the mass rate of flow q_m is

$$q_m = \alpha\,\varepsilon\,\frac{\pi}{4}\,d^2\sqrt{2\,\Delta p\,\rho_1}$$

As a matter of fact, the various quantities which appear on the right-hand side of this formula are not independent, so that it is not correct to compute the standard deviation of q_m directly from the standard deviations of these quantities.

For example α is a function of d, D, k, $\bar{v}_1$, ν_1
ε is a function of d, D, Δp, ρ_1, κ