
British Standard

Measurement of fluid flow in closed conduits

Part 2. Velocity-area methods

Section 2.4 Method of measurement of clean water flow using current meters in full conduits and under regular flow conditions

Mesure de débit des fluides dans les conduites fermées
Partie 2' Méthodes d'exploration du champ des vitesses
Section 2.4 Méthode de mesurage du débit d'eau propre à l'aide
de moulinets dans les conduites en charge et dans des conditions
d'écoulement régulier

Durchflußmessung in geschlossenen Rohrleitungen
Teil 2. Netzmessung in Strömungsquerschnitten
Abschnitt 2.4 Durchflußmessung mittels Meßflügel in von reinem
Wasser voll durchströmten Rohrleitungen bei gleichförmigen Durchflußbedingungen

National foreword

This Section of BS 1042 has been prepared under the direction of the Industrial-process Measurement and Control Standards Policy Committee. It is identical with ISO 3354 : 1988 (Second Edition) 'Measurement of clean water flow in closed conduits — Velocity-area method using current-meters in full conduits and under regular flow conditions' published by the International Organization for Standardization (ISO).

Cross-references

International standard	Corresponding British Standard
ISO 3455 : 1976	BS 3680 : 1980 Part 8C Calibration of rotating-element current meters in straight open tanks (Identical)
ISO 4006 : 1977	BS 5875 : 1980 Glossary of terms and symbols for measurement of fluid flow in closed conduits (Identical)
ISO 5168 : 1982	BS 5844 : 1980 Methods of measurement of fluid flow: estimation of uncertainty of a flow-rate measurement (Identical)
ISO 7194 : 1983	BS 1042 : Section 2.3 : 1984 Methods of flow measurement in swirling or asymmetric flow conditions in circular ducts by means of current-meters or Pitot static tubes (Identical)

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Measurement of clean water flow in closed conduits — Velocity-area method using current-meters in full conduits and under regular flow conditions

1 Scope and field of application

1.1 Scope

This International Standard describes a method for the determination of the volume flow-rate in a closed conduit by means of the velocity-area method using propeller-type current-meters under the following conditions:

- a) the velocity distribution is regular (see 6.1.2);
- b) the fluid is water which is clean or considered to be clean¹⁾;
- c) the conduit is full;
- d) the flow is steady²⁾.

It deals in particular with the technology and calibration of propeller-type current-meters, the measurement of local velocities and the calculation of the flow-rate by velocity integration.

1.2 Field of application

The method of measurement and the requirements defined in this International Standard aim at achieving (at the 95 % confidence level) an uncertainty in flow-rate not greater than ± 2 % provided that the correction for blockage effect (see 6.4.3 and annex B) has been applied.

However, this method is valid only if the flow is not affected by excessive swirl or asymmetry; criteria are given in 6.1.2 so that an estimate can be made of whether or not the flow is regular enough for this International Standard to be applicable and whether the uncertainty lies within the required range. If not, reference should be made to ISO 7194.

In general, if any of the requirements of this International Standard are not fulfilled, this method may still be applied but the uncertainty in the flow-rate measurement will be larger.

Moreover, only circular and rectangular cross-sections are specifically dealt with in this International Standard, to cover the large majority of practical cases. Nevertheless directions on how to proceed for certain other cross-sections of particular shape are given in annex A.

2 References

ISO 3455, *Liquid flow measurement in open channels — Calibration of rotating-element current-meters in straight open tanks*.

ISO 4006, *Measurement of fluid flow in closed conduits — Vocabulary and symbols*.

ISO 5168, *Measurement of fluid flow — Estimation of uncertainty of a flow-rate measurement*.

ISO 7194, *Measurement of fluid flow in closed conduits — Velocity-area methods of flow measurement in swirling or asymmetric flow conditions in circular ducts by means of current-meters or Pitot static tubes*.

3 Definitions and symbols

3.1 Definitions

For the purposes of this International Standard, the definitions given in ISO 4006 apply.

The definitions given here are for terms used with a special meaning or for terms the meaning of which might be usefully recalled.

3.1.1 current-meter: Device provided with a rotor the rotational speed of which is a function of the local velocity of the fluid in which the device is immersed.

This International Standard is concerned only with propeller-type current-meters, i.e. current-meters the rotor of which is a propeller rotating around an axis approximately parallel to the direction of flow.

NOTE — Obviously this definition does not prohibit the use of self-compensating propellers (see 6.1.5), the merit of which is, in particular, that they can be used at a rather high angle relative to the local direction of the flow. However, the use of cup-type current-meters is not allowed for the purposes of this International Standard.

1) This method may be applied to other single-phase fluids but special precautions should be taken in this case.

2) The steady flows observed in conduits are in practice flows in which quantities such as velocity, pressure, density and temperature vary in time about mean values independent of time; these are actually "mean steady flows".

3.1.2 stationary array: Set of current-meters mounted on one or more fixed supports which sample simultaneously the whole measuring cross-section.

3.1.3 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 closest to the wall.

3.1.4 mean axial fluid velocity: Ratio of the volume flow-rate (the integral over a cross-section of the conduit of the axial components of the local fluid velocity) to the area of the measuring cross-section.

3.1.5 relative velocity: Ratio of the flow velocity at the considered point to a reference velocity measured at the same time, which is either the velocity at a particular point (for example, at the centre of a circular conduit) or the mean axial fluid velocity in the measuring section.

3.1.6 straight length: Portion of a conduit whose axis is straight, and in which the cross-sectional area and cross-sectional shape are constant; the cross-sectional shape is usually circular or rectangular, but could be annular or any other regular shape.

3.1.7 irregularity: Any pipe fitting or configuration of a conduit which renders the conduit different from a straight length or which produces a considerable difference in wall roughness.

In the case of the method of measurement described in this International Standard, those irregularities which create the most serious disturbances are generally bends, valves, gates and sudden widening of the cross-section.

3.1.8 hydraulic diameter: Diameter equal to four times the hydraulic radius, i.e. four times the ratio of the wetted cross-sectional area to the wetted perimeter. (In a conduit of circular cross-section running full, the hydraulic diameter is thus equal to the geometric diameter.)

3.1.9 index of asymmetry (for circular ducts): Ratio of the standard deviation of the mean velocities calculated along each radius (i.e. along each radial line from the pipe centre to the wall along which velocity measuring positions are located) to the mean axial fluid velocity calculated for the pipe, i.e.

$$Y = \frac{\sigma_{U_i}}{U} = \frac{1}{U} \left[\frac{\sum_{i=1}^n (U_i - U)^2}{n-1} \right]^{1/2}$$

where

U_i is the mean velocity, calculated, in accordance with the integration method agreed, from the individual point velocity measurements on the i th radius (see 8.2 and 9.2);

U is the mean axial fluid velocity calculated from all the individual point velocity measurements throughout the cross-section;

n is the number of radii along which measurements are made.

3.1.10 regular velocity distribution: Distribution of velocities which sufficiently approaches a fully developed velocity distribution to permit an accurate measurement of the flow-rate to be made.

3.2 Symbols

Symbol	Quantity	Dimensions	SI unit
A	Area of the measuring cross-section	L^2	m^2
a, a'	Distance along a measuring line in a rectangular cross-section from the extreme measuring point to the nearest wall	L	m
D	Pipe diameter	L	m
d	Propeller diameter	L	m
e	Uncertainty (absolute value)	$1)$	$1)$
e_r	Random uncertainty	$1)$	$1)$
e_s	Systematic uncertainty	$1)$	$1)$
E	Relative uncertainty	—	—
E_r	Relative random uncertainty	—	—
E_s	Relative systematic uncertainty	—	—
H	Length of the smaller side of the cross-section of a rectangular conduit	L	m
h	Distance from a given measuring point to the reference wall, in the direction parallel with the smaller side of the cross-section	L	m
k	Equivalent uniform roughness	L	m
L	Length of the larger side of the cross-section of a rectangular conduit	L	m
l	Distance from a given measuring point to the reference wall, in the direction parallel with the larger side of the cross-section	L	m
m	Boundary layer coefficient	—	—
n	Frequency of rotation of a propeller	T^{-1}	rev/s
p	Number of measuring points along a radius (circular cross-section) or a straight line (rectangular cross-section)	—	—
q_v	Volume flow-rate	$L^3 T^{-1}$	m^3/s
R	Pipe radius	L	m
r	Measuring circle radius	L	m
r^*	Measuring circle relative radius	—	—
	$r^* = \frac{r}{R}$		
Re	Reynolds number	—	—
U	Mean axial fluid velocity	LT^{-1}	m/s
u	Mean velocity along a measurement circumference or line	LT^{-1}	m/s
v	Local velocity of the fluid	LT^{-1}	m/s
v_0	Local velocity of the fluid at the centre-line of the pipe	LT^{-1}	m/s
Y	Index of asymmetry of the flow	—	—

Symbol	Quantity	Dimensions	SI unit
y	Distance from a measuring point to the nearest wall	L	m
y^*	Relative interval between two measuring points $y^* = \frac{l_i - l_{i-1}}{L}$	—	—
α	Polar angle of a measuring point (in a circular cross-section)	—	rad
λ	Universal coefficient for pipe head loss	—	—

1) The dimensions and units are those of the quantity to which the symbol refers.

4 Principle

4.1 General

The principle of the method consists of

- measuring the dimensions of the measuring section, which shall be chosen to be normal to the conduit axis; this measurement is for defining the area of the cross-section (see 4.2);
- defining the position of the measuring points in this cross-section, where the number of measuring points shall be sufficient to permit adequate determination of the velocity distribution (see 4.3);
- measuring the axial component of the velocity at these measuring points;
- determining the mean axial fluid velocity from the preceding measurements;
- calculating the volume flow-rate, which is equal to the product of the cross-sectional area and the mean axial fluid velocity.

However, for certain cross-sections of particular shape, the treatment of the measurement leads directly to the flow-rate determination without a preliminary calculation of the cross-sectional area and mean axial fluid velocity (see annex A).

The error resulting from the use of the velocity-area method is dependent, among other factors, on the shape of the velocity profile and on the number and position of the measuring points.

This International Standard presents three methods for determining the mean axial fluid velocity as follows.

4.1.1 Graphical integration of the velocity area (see clause 8)

This method consists of 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 term representing the peripheral flow-rate (see 3.1.3) which is calculated 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 9)

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

4.1.3 Arithmetical methods (see clause 10)

The arithmetical methods assume that the velocity distribution follows a particular law; 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.

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 arithmetical mean of measurements carried out on at least four diameters which are at approximately equal angles to one another in the measuring section. If the difference between the lengths of two consecutive diameters is greater than 0,5 %, the number of measured diameters shall be doubled.

4.2.2 Rectangular cross-sections

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

4.3 Measurement of local velocities

4.3.1 General

The flow velocity at a point of the measuring section is determined by measuring the rotational speed of a current-meter placed at that point and by entering this value in the calibration equation of the current-meter.

The current-meter rotational speed may be obtained

- either by counting the number of propeller rotations which occur within a pre-determined period,
- or by measuring the time required by the propeller to perform a specified number of rotations.

Another method that may be used is that whereby the velocity is determined by direct measurement of the signal frequency.

For both methods, various measuring points in the cross-section may be explored simultaneously or successively (see 4.3.2 and 4.3.3).

4.3.2 Simultaneous measurements

When several current-meters are used simultaneously, the method by measuring the time requires more sophisticated counting equipment than the method by counting the number of revolutions, but it is more accurate. The latter method may actually lead to an error since if a time interval is chosen, it may not correspond to a whole number of rotations.

As local velocities are generally subject to long-term fluctuations, it is necessary to provide a sufficient period of measurement for determining the mean velocity correctly. This period of time may be determined by measuring the same flow-rate during gradually increasing intervals of time. The time of measurement t to be adopted shall be such that the values of the mean velocity in the cross-section, obtained for measuring times equal to t and $t + \Delta t$, shall not vary by more than x %. For example, Δt could be about 30 s and x could be chosen equal to 0,1 %. Time t may vary according to the mean fluid velocity.

4.3.3 Non-simultaneous measurements

In cases where all velocity measurement points are not sampled simultaneously, it is essential that the shape of the velocity profile in the measuring cross-section remain stable and be unaffected by possible variations in the flow-rate during the measuring period. The steadiness of flow-rate shall then be checked and point velocities possibly corrected by means of a continuous measurement, during the whole duration of gauging, of the velocity at a reference point.

If only one measuring device is available, the steadiness of the flow-rate shall be checked by frequently repeating measurements at the reference point.

However, it must be emphasized that velocity profile fluctuations do not necessarily create flow-rate fluctuations. In such a case the use of a reference point velocity may lead to errors and it is preferable to check that the flow-rate is steady by means of any pressure-difference device (e.g. standardized or non-standardized pressure-difference flow-meter, a piezometric control on a convergence, a device on a bend, a spiral casing, a device for indicating a peculiar pressure loss, etc.) even if it is not calibrated provided that its reliability and adequate sensitivity have been ascertained.

When the curve of the reference velocity v_r has been plotted against time, this curve is used to relate all velocity measurements to the same reference flow-rate q_0 (preferably that which corresponds to the mean of the reference velocity measurements). For comparatively small changes in the reference velocity, the velocity $v_{i,t}$ measured at any point at time t can be corrected by multiplying by the ratio of the reference velocity $v_{r,0}$ corresponding to the flow-rate q_0 to reference velocity $v_{r,t}$ at time t :

$$v_{i,0} = v_{i,t} \times \frac{v_{r,0}}{v_{r,t}}$$

where $v_{i,0}$ is the velocity at point i to be used for the integration.

4.3.4 Checking the velocity distribution

Even when the mean axial fluid velocity is calculated by a method which does not require plotting of the velocity profile, it is recommended, in order to be confident that the velocity distribution is regular, that this plotting be carried out, or at least that its regularity be checked by some other means.

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 3.1.5)] to check their consistency with one another 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 rejected and the velocity profile drawn on the basis of the remaining data, provided that there are independent reasons for believing that the doubtful measurement is false.

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

4.4.1 General

The location of the measuring points depends on the method chosen to calculate the flow-rate. The rules relating to the methods specified in this International Standard are given in clauses 8, 9 and 10.

Whatever the method, the following dimensional rules shall be complied with:

- the minimum distance between the current-meter axis and the wall shall be $0,75d$;
- the minimum distance between the axes of two current-meters shall be $(d_1 + d_2)/2 + 0,03$ m, where d_1 and d_2 are the outside diameters of the propellers of the current-meters.

NOTE — d_1 and d_2 are usually equal, but it may be useful to set current-meters having propellers smaller in diameter than those used at other locations in the cross-section in the vicinity of the wall to explore best the flow pattern in this area (see clause 8).

The location of any current-meter shall be measured to the smaller of the following two uncertainties:

- $\pm 0,001 L$, where L is the dimension of the conduit parallel to the direction of measurement of the current-meter position;
- $\pm 0,02 y$, where y is the distance of the current-meter from the nearest wall.

The minimum number of measuring points, applying in particular to small-dimension conduits, is prescribed in 4.4.2 and 4.4.3. As it is necessary that the velocity profile be known as accurately as possible, it may be advantageous to increase the

number of measuring points provided that this is allowed by the requirements given above and that it does not cause notable blockage effects (see 6.4.3).

When a single current-meter is traversed across a conduit, it is first necessary to determine the distance between a reference point (from which each position is measured) and the wall of the duct. This may introduce a relatively large systematic error in all position measurements. In such circumstances it is recommended, in the case of a circular cross-section conduit, 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. However, blockage and vibration problems may be more severe when a complete diameter is traversed.

4.4.2 Circular cross-sections

The measuring points on circular cross-sections shall be located at every point of intersection between a given number of circles concentric with the pipe axis and a given number of diameters at equal angular spacing.

The minimum numbers recommended in the scope of this International Standard are three circles and two mutually perpendicular diameters (see note 2) so that the minimum number of measuring points in the cross-section is 12. An additional measuring point at the centre of the conduit is desirable to check the shape of the velocity profile.

However, this minimum number is acceptable only if one of the following conditions is fulfilled:

- if it is known that the velocity distribution is very nearly axisymmetrical, which is checked either by examining the layout of the pipe or by measurements previously carried out in the same cross-section, or
- if the use of a higher number of diameters results in a prohibitive blockage of the measuring section (see 6.4.3).

If neither of these conditions is fulfilled, the velocity distribution shall be scanned more closely, for instance by increasing to three the number of diameters. It should be noted indeed that in general the uncertainty in flow measurement is reduced more by increasing the number of radii along which measurements are made than by increasing the number of points per radius; nevertheless, there is little advantage in exceeding four diameters.

NOTES

1 When the measurements are carried out by means of a stationary array, reference should be made to 6.4.4 for the minimum diameter of conduits in which this method can be applied; but in any case the general requirements given in 4.4.1 on the minimum distance between two current-meters prohibit the use of a stationary array in conduits the diameter of which is less than $7,5 d + 0,18 \text{ m}$.

2 If a high accuracy is not required, measurements may be made along a single diameter provided that there is a straight length of at least $60 D$ upstream of the measurement section and provided that the Reynolds number is in excess of the values given in table 1 for the corresponding values of the universal coefficient for pipe head loss λ . (For the estimation of λ , see annex E.)

Table 1 — The minimum Reynolds number as a function of the universal coefficient for pipe head loss, λ

λ	Re_D
$> 0,03$	10^4
$0,025$	3×10^4
$0,02$	10^5
$0,01$	10^6

4.4.3 Rectangular cross-sections

The minimum number of measuring points shall be 25. Unless a special layout of measuring points is adopted 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 of the boundaries of the cross-section.

NOTE — When the measurements are carried out by means of a stationary array, reference should be made to 6.4.4 for the minimum dimensions of conduits in which this method can be applied; but in any case the general requirements given in 4.4.1 on the minimum distance between two current-meters prohibit the use of a stationary array in conduits the smaller dimension of which is less than $5,5 d + 0,12 \text{ m}$.

5 Description of the current-meter

A propeller-type current-meter consists of a propeller, an axis of rotation, bearings and the current-meter body with the counting device.

Each current-meter may be fitted with different types of propeller (i.e. of different pitch, diameter, etc.). Propellers may have two or more blades and may be manufactured out of metal or plastic material.

Current-meters for site measurements shall be manufactured out of non-corrosive material only or shall be effectively protected against corrosion. They shall be of sufficiently sturdy construction for their calibration to remain valid under normal field operating conditions.

Components shall be interchangeable to allow easy replacement of worn or damaged parts, but this replacement shall not increase the uncertainty in the measurement.

Output signals may be generated by mechanical contact or by any magnetic, electrical or optical device. They are totalized or recorded on an appropriate receiver or indicated by an acoustic or optical device.

Counting shall be accurate and reliable for any given velocity within the operational range specified by the manufacturer. The number of signals delivered per propeller revolution shall be consistent with the velocities to be measured, the design of the receiver and an acceptable measuring period. In some cases it will therefore be necessary to be able to choose the number of signals per propeller revolution.

Provision shall be made for fixing the current-meter on a support in a well-defined position.

6 Requirements for the use of current-meters

6.1 Selection of the measuring cross-section

6.1.1 The cross-section selected for the measurements shall be located in a straight length; it shall be perpendicular to the direction of flow and of simple shape, for example either circular or rectangular. The measuring cross-section shall be located in an area where the individual local velocities fall within the normal working range of the current-meters used (see 6.4.2).

6.1.2 Close to the measuring cross-section, the flow shall be such that it may be considered to be "regular", i.e. it shall be substantially parallel to and symmetric about the conduit axis and shall present neither excessive turbulence nor swirl. (For further information, see ISO 7194.)

The flow may be assumed to be sufficiently regular to permit the use of this International Standard if the two following conditions are fulfilled:

- a) at any point of the cross-section, the swirl angle shall be less than or equal to 5°;
- b) the index of asymmetry Y (as defined in 3.1.9) shall be less than or equal to 0,05.

As a guide, it can be assumed that a bulk swirl of the flow has no appreciable effect on the confidence limits given in this International Standard for the flow-rate measurement so long as it results in a deviation in the local velocity with respect to the pipe axis of less than 5°. An index of asymmetry $Y = 0,05$ corresponds approximately to a component uncertainty in the flow-rate arising from the asymmetry of the velocity distribution of about 0,35 %, provided that the measuring cross-section is traversed along at least six radii.

6.1.3 For these requirements to be met, the measuring cross-section shall be chosen to be far enough away from any disturbances that could create asymmetry, swirl or turbulence. The length of straight pipe that may be required will vary with the flow velocity, upstream disturbances, wall roughness, the level of turbulence and the degree of swirl, if any.

As a guide, it has often been assumed that there should be a straight length of conduit between the measuring cross-section and any important irregularity upstream (see 3.1.7) of at least 20 times the hydraulic diameter of the conduit (see 3.1.8). Similarly, there should be a straight length of at least five times the hydraulic diameter of the conduit between the measuring cross-section and any important downstream irregularity. These values have been generally acceptable in the past since conduits had comparatively rough walls. However, with the use of very smooth modern linings, having lower hydraulic roughness, and the use of conduits larger and larger in diameter, particular care needs to be taken when estimating the necessary straight lengths.

Furthermore, special consideration is necessary when the upstream irregularity (bends in different planes, for example) is such that it can give rise to a swirl of the flow, which is always very slow to disappear.

6.1.4 If there is any doubt about the flow conditions, it is necessary to make preliminary traverse tests to ascertain the regularity of flow.

If these traverses show that the flow is not satisfactory, i.e. that it does not fulfill the conditions defined in 6.1.2, reference shall be made to ISO 7194 for carrying out the flow measurement. It must be noted, however, that the asymmetry of the velocity distribution is taken into account in some measure by the very principle of the velocity-area method and that it increases only slightly (normally less than $\pm 1\%$ if Y is not greater than 0,25) the inaccuracy of the measurements provided that the number of measuring points is adequate, whereas swirl affects every measurement of local velocity.

6.1.5 Although measurements with current-meters in oblique or converging flow shall as far as possible be avoided, they may be carried out if one of the following conditions is fulfilled:

- a) the current-meters used are designed to measure accurately the true axial component of the velocity, this being checked by an appropriate calibration up to the expected maximum velocity;
- b) the maximum flow deviation with respect to the current-meter axis does not exceed 5°.

NOTE — Commonly used propellers may give correct indications up to angles of incidence of 5° with an accuracy of 1 % (relative deviation between the measured velocity and the axial component of the flow velocity). There exist self-compensating propellers which measure directly the axial component of velocity with an error smaller than 1 % for greater angles of incidence, but it is necessary to consider the particular sensitivity of such propellers to the influence of the current-meter support (especially the angle of the plane containing the velocity vector and the current-meter axis to the plane containing the current-meter support and axis) and to the flow turbulence.

6.2 Devices for improving flow conditions

If the velocity distribution is too irregular or the flow is not sufficiently parallel, but it is known that no swirl exists in the flow, it is sometimes possible to remedy these irregularities by means of a guiding installation. This consists of a slightly converging entrance connected, without creating any separation, to a straight pipe length, the length of which is, if possible, at least equal to twice the larger dimension of the conduit. It shall be ensured by calculation that the current-meters closest to the wall are within the boundary layer, the thickness of which is given by $\delta = 0,37 \times \left(\frac{Ux}{\nu} \right)^{-0,2}$, and that the procedures for evaluating the peripheral flow apply. If this is not the case, the velocity shall be assumed not to vary between the current-meter closest to the wall and the boundary layer, and the peripheral flow shall be calculated in the boundary layer only. If arithmetical integration is used, it shall be checked, for at least one flow measurement, that no abnormal deviation exists with respect to graphical or numerical integration. It should, however, be noted that the installation of such a device may modify the flow-rate value.

6.3 Calibration of the current-meter

6.3.1 The calibration of a current-meter requires the empirical determination of the relationship between the water velocity and the propeller velocity. This relationship is generally represented by one or several straight lines given by the equation

$$v = an + b$$

where

v is the velocity of the water, in metres per second;

n is the rotational speed of the propeller, in revolutions per second;

a and b are constants to be determined by calibration.

6.3.2 Calibration shall be carried out in an installation specially designed for this purpose in conformity with the prescriptions of ISO 3455.

6.3.3 For calibration, the current-meter shall be fitted with the same support as that used for measurements.

6.3.4 Each current-meter shall be recalibrated at regular intervals depending on the conditions of use. As a guide, these intervals are usually of a few hundred hours of operation in water of normal quality. However, after a series of measurements, it is essential to check the calibration of a current-meter, the propeller or the bearings of which appear to have been damaged (due to shocks, corrosion, abrasion, etc.). A recalibration is also necessary if any component of the current-meter is changed.

6.3.5 In principle, each current-meter shall be calibrated individually. However, if the propellers of a series of current-meters are dimensionally consistent and interchangeable and if a first calibration has proved the hydraulic similitude of the propellers, statistical calibration equations may be derived from a sufficient number of individual calibrations under well-defined conditions. In this case, the calibrating organization shall indicate the maximum probable deviations from the mean calibration equation proposed.

6.4 Limits of use

6.4.1 Nature of the liquid

Current-meters shall not be used when their performance may be disturbed by dissolved or suspended matters in the water in the conduit.

6.4.2 Range of velocities

Current-meters shall only be used within their normal range of use, i.e. the range of velocities for which they have been calibrated; extrapolation towards higher velocities may never-

theless be permitted up to 1,25 times the maximum calibration velocity in the case when calibration cannot be achieved at those higher velocities.

However, the calibration curve shall never be extrapolated into the area of lower velocities where the accuracy and above all the repeatability of current-meters decrease considerably. As a general rule no current-meter shall be used at velocities less than a certain threshold below which the lack of repeatability may lead to important errors (the threshold is a function of the current-meter type; it is less than 0,5 rev/s for well-maintained current-meters).

6.4.3 Blockage effect

The velocity distribution in the conduit is disturbed by the current-meters and their support(s) and this leads to a positive error being made in the flow-rate measurement.

Theoretical and experimental studies have shown that the magnitude of this error is dependent on

- the number, the profile and the frontal area of the support struts (and where applicable of the central junction piece),
- the distance between the active part of the propeller and the support strut,
- the type, the number and the size of the current-meters used (e.g. the size of the propeller, hub, body etc.).

In general, however, it has been found that the relative blockage of the main support cross with respect to the measuring section, i.e. the ratio of the frontal area of the support cross to the total cross-sectional area of the conduit, is the most important geometrical parameter. If this relative blockage is between 2 % and 6 %, a correction shall be made (see annex B); if it is greater than 6 %, the measurement cannot be made in accordance with this International Standard.

6.4.4 Dimensional restrictions

The above-mentioned remarks relating to the blockage effect on the one hand, and the dimensional requirements specified in 4.4.1 on the other hand, prohibit measurements by means of current-meters in conduits the dimensions of which are too small compared with those of the current-meters used. Thus current-meters and support struts shall be chosen such that their dimensions are suitable for those of the conduit in which the measurement is to be made.

In general, it is accepted that a fixed current-meter array may be used if the diameter of a circular cross-section conduit is greater than nine times the propeller diameter or if the smaller side of a rectangular cross-section is greater than eight times the propeller diameter, provided that the relative blockage as defined in 6.4.3 is less than 6 %. (See also 4.4.2 and 4.4.3.)

Thus, for example, for those types of current-meter and support cross that are commonly used for industrial measurements and which have propellers with diameters in the range 0,10 to 0,125 m, it is generally accepted in practice [taking account of

the general requirements on the minimum distance between two current-meters on the one hand (see 4.4.2) and of the blockage due to the support on the other hand] that a stationary array mounted on cross-bars may be used only in circular conduits of diameters greater than 1,4 m. In a rectangular cross-section, it is also agreed that the smaller dimension of the conduit (to which the support struts are parallel) shall be at least equal to 1 m, and furthermore that the larger dimension shall be sufficient to limit the blockage effect (see 6.4.3).

When the flow-rate has to be calculated using an arithmetical integration method (see clause 10), the locations prescribed for the current-meters and in particular for those which are closest to the wall result in noticeably higher minimum values of D/d or H/d (e.g. $D/d > 23$ for a measurement method with three points per radius in a circular cross-section).

In conduits with smaller dimensions, current-meters fitted with smaller propellers (e.g. ranging from about 0,03 to 0,05 m in diameter) or even micro-current-meters mounted on a frame as light as possible may be used. Alternatively a device, often complex in design, which enables non-simultaneous measurements to be made may also be used (see 7.2.2, 7.2.3 or 7.3.2).

6.4.5 Influence of turbulence and velocity fluctuations

Although the influence of longitudinal and transverse components of flow turbulence on current-meter behaviour is still incompletely defined, attention is drawn to the fundamental difference between the behaviour of current-meters being calibrated by hauling in stagnant water and current-meters being used in turbulent flow conditions. Longitudinal fluctuations lead to a positive error in the velocity measured by means of the current-meter whereas transverse fluctuations generally lead to a negative error. While bearing in mind that many factors influence a current-meter response, it may be observed that the error will increase as

- the fluctuation amplitude and frequency increase,
- the mean velocity decreases, and
- the moment of inertia of the propeller increases.

6.5 Inspection and maintenance of current-meters

6.5.1 Inspection

The condition of the current-meter shall be checked before and after each measurement, in particular for the following:

- free rotation in bearings;
- absence of propeller deformation;
- correct functioning of the rotational speed detection device.

The inspection for friction in the bearings may be carried out by observing how the propeller slows down after having been spun at a certain speed. In no case shall the propeller stop abruptly.

The propeller shape may be checked by means of a plaster mould or by means of a metal profile template.

6.5.2 Maintenance

After each series of measurements the current-meter shall be dismantled, carefully cleaned, and then re-lubricated using the same lubricant as was used for calibration.

7 Setting of current-meters into the conduit

7.1 Setting of current-meters

Current-meters shall be fixed rigidly on the mounting strut in such a way that the propeller axis is perpendicular to the measuring section plane to within 2° .

The mounting struts of a stationary array shall themselves be rigidly connected to the conduit walls. They shall be designed to offer sufficient mechanical strength (in particular to avoid any prejudicial vibration), minimum and stable drag, and minimum interference with the current-meter operation.

Guidelines on the shape of the mounting struts are given in annex C.

7.2 Mounting in a circular cross-section

7.2.1 Stationary array

Current-meters are generally used as stationary arrays. Mounting struts shall therefore be arranged along the conduit radii so as to form at least two diameters (see 4.4.2); an example of this arrangement is given in figure 1. As far as possible, no measuring arm shall be located in the vertical plane of the pipe axis to avoid possible effects of air pockets or sediment load. Blockage on the centre-line can be reduced by cantilevering the radial supporting arms from the conduit wall; if this is done, only a single diameter passing actually through the centre of the conduit is needed.

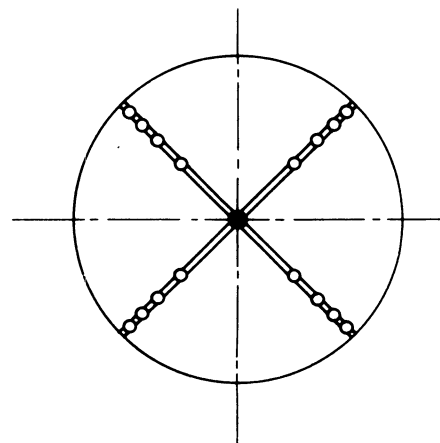


Figure 1 — Stationary array of current-meters mounted on cross-bars in a circular conduit

7.2.2 Rotating arm

Current-meters may be fixed along a diameter rotating around the cross-section axis. (An example of this arrangement is given in figure 2.) This sophisticated device (rotation is controlled from the outside and vibration risks are to be avoided) allows the scanning of a far greater number of measuring points.

It may, if required, allow direct measurement of the mean velocity per circumference, the integration along each circle being obtained by making the diameter rotate at a constant speed. The maximum tangential speed of the rotating diameter shall not exceed 5 % of the mean flow velocity.

In order to ensure that the measurement is not falsified by an excessive angle of the apparent velocity with respect to the current-meter, owing to the combination of the current-meter movement and a pre-existing obliqueness or swirl of the flow, it is recommended that the measurements made by continuous integration be checked either by rotating the rotating arm in the reverse direction or by making measurements with the arm positioned at a number of fixed locations.

7.2.3 Exploration by means of a single current-meter

A current-meter may be used in isolation by placing it successively at each measuring point. This method requires special equipment (lock-vanes) which enables the current-meter

mounting strut to be guided along the scanned diameter and to be transferred from one measuring diameter to the next, while maintaining the water-tightness. In addition, account shall be taken of the requirements given in 4.3.2.

7.3 Mounting in a rectangular cross-section

7.3.1 Stationary array

Current-meters may be used as a stationary array mounted on a number of parallel struts. This method may result in a significant obstruction of the cross-section by the supports.

7.3.2 Exploration of a section by means of a row of current-meters

Another method consists of using a sliding rest bearing one (or two) row(s) of current-meters, travelling in such a way that the current-meters are successively placed on all horizontal measuring lines (or alternatively on all vertical lines). This device requires external control with water-tight sealing of certain parts. In addition, account shall be taken of the requirements given in 4.3.2.

This process may allow direct measurement of the mean velocity along one vertical (or one horizontal), the integration along each vertical (or horizontal) line being obtained by constant-speed displacement of the slide rest. This speed shall not exceed 5 % of the mean flow velocity.

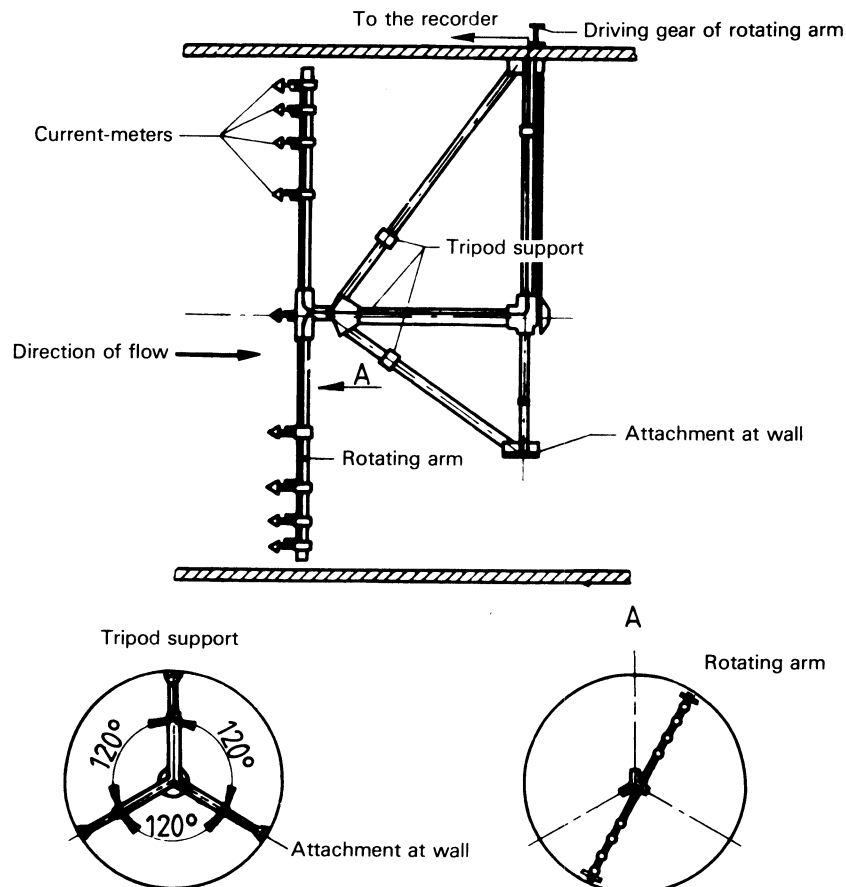


Figure 2 — Diametral arm device rotating in a circular conduit

In order to ensure that the measurement is not falsified by an excessive angle of the apparent velocity with respect to the current-meter, owing to the superposition of the current-meter movement and a pre-existing obliqueness or swirl of the flow, it is recommended that the measurements made by continuous integration be checked either by moving the slide in the reverse direction or by making measurements with the slide positioned at a number of fixed locations.

However, in the case of flow for which the piezometric line is only slightly above the top of the conduit, the application of this procedure is simplified: the slide device can be moved in wells or grooves (e.g. bulkhead grooves) opening to the atmosphere and its control device can be located above the maximum water-level.

8 Determination of the mean axial fluid velocity by graphical integration of the velocity area

8.1 General

The general principle of this method is specified in 4.1.

The measuring points shall be located along straight lines. The measuring points at the ends of each of these lines (the extreme measuring points) shall be located as close as possible to the wall and the adjacent measuring points shall be located sufficiently close to the extreme measuring points to ensure an accurate determination, in the manner prescribed in clause E.1, of the boundary layer coefficient m appearing in the law used for describing the flow in the peripheral zone.

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

An example of the measuring point distribution for a circular cross-section for which no indication on the velocity distribution is available is given in annex D.

In general, reference shall be made to 4.4 to determine the number and location of measuring points.

8.2 Circular cross-sections

The mean axial fluid velocity U is given by the formula

$$\begin{aligned} U &= \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R v(r, \alpha) r dr d\alpha \\ &= \int_0^1 u d\left(\frac{r}{R}\right)^2 \\ &= \int_0^{(r_p/R)^2} u d\left(\frac{r}{R}\right)^2 + \int_{(r_p/R)^2}^1 u d\left(\frac{r}{R}\right)^2 \end{aligned}$$

where

v is the flow velocity at a point having the polar coordinates r and α ;

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

R is the mean radius of the measuring section (see 4.2.1);

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

The determination of the mean axial fluid velocity U is carried out as follows.

- Take u_c (the arithmetical mean of the velocities at the measuring points located on a circle of radius r_c) as the value of u ¹⁾.
- Plot the curve of the variation in u_c against $(r_c/R)^2$ between $r = 0$ and $r = r_p$ ²⁾ (see figure 3).
- Determine graphically the value of the area below this curve between $r = 0$ and $r = r_p$.
- Add to this value a calculated term³⁾ corresponding to the peripheral zone and equal to

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

1) Some experimental devices allow direct measurement of the mean velocity along a circumference (see 7.2.2).

2) To facilitate plotting of the curve in the vicinity of the measuring point closest to the wall, draw the tangent to the curve for $r = r_p$ with a slope equal to

$$\left(\frac{du_c}{dx}\right)_{r=r_p} = \frac{-u_p}{2m \frac{r_p}{R} \left(1 - \frac{r_p}{R}\right)}$$

denoting $(r/R)^2$ as x . The slope of the curve is derived from Karman's conventional law for the variation in the fluid velocities in the peripheral zone:

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

3) This simplified expression omits the other term

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

in the result of the integration (within the peripheral zone) derived from Karman's conventional law: this latter term represents only about $\frac{1 - (r_p/R)}{(4m+2)}$ times the flow in the peripheral zone.