INTERNATIONAL STANDARD ISO 3354

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Measurement of clean water flow in closed conduits – Velocity-area method using current-meters

Mesure du débit d'eau propre dans les conduites fermées – Méthode d'exploration du champ des vitesses au moyen de moulinets

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FOREWORD

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Draft International Standards adopted by the Technical Committees are circulated to the Member Bodies for approval before their acceptance as International Standards by the ISO Council.

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It has been approved by the Member Bodies of the following countries :

Australia	Germany	Switzerland
Austria	India	Thailand
Belgium	Ireland	Turkey
Bulgaria	Netherlands	United Kingdom
Czechoslovakia	Romania	U.S.S.R.
France	Spain	Yugoslavia

The Member Body of the following country expressed disapproval of the document on technical grounds :

U.S.A.

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1 SCOPE AND FIELD OF APPLICATION

This International Standard specifies a method for the determination, in a closed conduit, of the volume rate of a regular flow[1]

– of clean water[2] or water considered as clean,

– running full in this conduit,

– under steady flow conditions,

this measurement being carried out by means of the velocity-area method using propeller-type current-meters. It deals particularly with the technology and calibration of current-meters, the measurement of local velocities and 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 not greater than ± 2 % provided that the correction for blockage effect has been applied. If any of the requirements of this International Standard are not fulfilled, this method may still be applied but the uncertainty on flow rate will be larger.

2 REFERENCE

ISO 3455, *Liquid flow measurement in open channels – Calibration of current-meters in straight open tanks.*[3]

3 DEFINITIONS

The following definitions are given only for terms used with a special meaning or for terms the meaning of which might be usefully recalled :

3.1 current-meter : A 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 flow.

3.2 stationary battery : A set of current-meters mounted on one or several fixed supports which explore the whole measuring section simultaneously.

3.3 peripheral flow rate : The volume of liquid which flows, per unit time, in the region located between the pipe wall and the contour defined by the velocity measuring points which are the closest to the wall.

3.4 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.

3.5 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.

3.6 straight length : A 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 possibly rectangular.

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

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

4 PRINCIPLE

4.1 General

The principle of the method consists in :

a) measuring the dimensions of the gauging section which shall be chosen as normal to the conduit axis; this measurement is intended for defining the area of the cross-section (see 4.2);

1) See 6.1.

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

3) At present at the stage of draft.

b) defining the position of the measuring points in the cross-section;

c) measuring the axial component of the velocity at a sufficient number of points in a flow cross-section to determine the velocity profile adequately (see 4.3);

d) determining the discharge velocity from the preceding measurements;

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

The error made when using the velocity distribution 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 types of method for determining the discharge velocity, namely

— *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 the laws of a turbulent boundary layer.

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 preceding 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; 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, assumption is made in the peripheral zone of a logarithmic law for velocity distribution as a function of the distance from the wall.

4.2 Measurement of the gauging 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 at approximately equal angles to one another in the gauging 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 conduit width and height 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

The flow velocity at a point of the gauging section is determined by measuring the rotational speed of a current-meter placed at that point and 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 within a pre-determined period, or by measuring the time required by the propeller to perform the specified number of rotations. Another method that can be used is the one whereby the velocity is determined by direct measurement of the signal frequency.

Various measuring points in one cross-section may be explored simultaneously or successively (see 4.3.1 and 4.3.2).

4.3.1 *Simultaneous measurements*

When several current-meters are used simultaneously, the second method given above requires more sophisticated counting equipment than the first one, but it is more accurate. The first method actually leads to an error the statistical resultant of which is positive, due to time intervals not being taken into account at the beginning and at the end of the counting time; the greater the number of counted contacts, the smaller the percentage error.

As flow is generally subject to long period 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 flow velocity.

4.3.2 *Non-simultaneous measurements*

In cases when all velocity measurement points are not explored simultaneously, it is essential that the shape of the velocity profile in the gauging cross-section remain stable and be unaffected by possible variations of the flow rate during the measurement.

In such a case the stability of flow may 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 shall be checked by frequently repeating measurements at the reference point.

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 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 to velocity $v_{r,t}$ at this reference point at time t :

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

However, it must be emphasized 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 flow steadiness by means of any pressure-difference device (standardized or non-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.

4.3.3 *Checking of velocity distribution*

Even when discharge 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, to carry out this plotting or at least to check its regularity 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 3.3) to check their consistency with one another and hence 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 that the doubtful measurement is false.

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

4.4.1 *General requirements*

The rules to be followed for locating the measuring points differ according to the methods of determination of the discharge velocity as specified in this International Standard. These rules are given in clauses 8, 9 and 10 respectively.

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

– minimum distance between the current-meter axis and the wall : 0,75 d,

– minimum distance between the axes of two current-meters : d + 0,03 m,

where d is the outside diameter of the current-meter propeller.

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

± 0,001 L, where L is the dimension of the duct parallel to the direction of measurement of the current-meter position,

± 0,02 y, where y is the distance of the current-meter from the nearest wall.

A 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, the number of measuring points can be advantageously increased provided that this is allowed by the above-mentioned requirements and that it does not cause notable blockage effects (see 6.4.3).

When a single meter 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. It is therefore 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.

4.4.2 *Circular cross-sections*

The measuring points shall be located on concentric circles and on at least two mutually perpendicular diameters in the cross-section.

The measurements shall be carried out at at least three points per radius, so that there shall be 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.

NOTE – When the measurements are carried out by means of a stationary battery, reference shall 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 above on the minimum distance between two current-meters forbid the use of a stationary battery within conduits the diameter of which is less than $(7.5\,d + 0{,}18)$ m.

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 wall of the conduit.

NOTE – When the measurements are carried out by means of a stationary battery, reference shall be made to 6.4.4 for the minimum dimensions of conduits in which the method can be applied; but in any case the general requirements above on the minimum distance between two current-meters forbid the use of a stationary battery within conduits the smaller dimension of which is less than $(5{,}5\,d + 0{,}12)$ m.

5 DESCRIPTION OF THE CURRENT-METER

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

5.2 Each current-meter may be fitted with different types of propeller (pitch, diameter, etc.). The propeller is made of two or more blades and may be manufactured out of metal or plastics material.

5.3 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.

5.4 Components shall be interchangeable to allow easy substitution of worn or damaged parts, but interchange shall not increase the uncertainty of the measurement.

5.5 Signals may be transmitted by mechanical contact or 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.

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

6 REQUIREMENTS FOR USE OF CURRENT-METERS

6.1 Selection of the measuring cross-section

6.1.1 The cross-section selected for measurements shall be located in a straight pipe length, perpendicular to the direction of flow and 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 current-meters used (see 6.4.2).

6.1.2 Close to the measuring cross-section, flow shall be substantially parallel to and symmetric about the conduit axis and present 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).

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

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

6.1.3 Although measurements with current-meters in oblique or converging flow shall as far as possible be avoided, they may be carried out provided that

– the current-meters used are designed to measure accurately the true axial component of the velocity, this being checked by an appropriate calibration;

– 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 incidences of 5° with an accuracy of 1 % (relative deviation between the measured velocity and the axial component of the flow velocity). There exist self-component propellers which measure directly the axial component of velocity with an error smaller than 1 % for greater angles of incidence, but attention shall be drawn to the particular sensitivity of such propellers to the influence of the current-meter support and to the flow turbulence.

1) See 3.7.

For guidance, it can 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 5°.

6.1.4 If there is doubt about the flow conditions, it is necessary to make preliminary traverse tests by which 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 6.2.

Once these devices are in place a check shall be carried out for compliance with the flow requirements of this International Standard. In the contrary case 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.

6.2 Devices for improving flow conditions

6.2.1 If swirl can be observed in the flow, this can be tentatively suppressed by means of an anti-swirl device constituted either by piled up pipes parallel to the flow direction or by 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.

— the length l shall be greater than 10 a.

6.2.2 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 effective only at the price of a rather high head loss.

6.2.3 The devices described in 6.2.1 and 6.2.2 shall be located at the greatest possible distance upstream from 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-sectional shape). Furthermore, they shall not be located immediately downstream of a disturbance.

6.2.4 If the velocity distribution is too irregular or if the flow is not sufficiently parallel, but if it is known that no swirl exists in the flow, it is sometimes possible to remedy those irregularities by means of a guiding installation. The latter will consist of a slightly converging entrance connected, without creating any separation, to a straight pipe length, the length of which will be, if possible, at least equal to twice the larger dimension of the conduit.

6.3 Calibration of the current-meter

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

$$v = An + B$$

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.

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 The calibration report shall include :

— a graph on which each calibration point is plotted and the mean straight lines are set out (with n in abscissa and $\Delta v = v - A_0 n$ in ordinate, A_0 being a value close to the actual values of A);

— the equations $v = An + B$ of calibration straight lines with the limits of the velocity ranges where each equation is applicable.

The shapes and dimensions of the current-meter support, the lubricant used for current-meter lubrication and the temperature of the calibrating channel water shall be indicated as well.

6.3.5 In principle, each current-meter shall be calibrated before and after each series of measurements. However, if the calibration shows a hydraulic similitude of the propellers and if the propellers are dimensionally consistent and interchangeable, statistical calibration may be carried out 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 formula 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 suspended materials in the conduit water.

6.4.2 *Range of velocities*

Current-meters shall be used only in their normal range of use, i.e. the range of velocities for which they have been calibrated; extrapolation towards higher velocities may nevertheless be tolerated in the case when calibration cannot be achieved at those higher velocities. However, the calibration curve shall never be extrapolated in the area of lower velocities where the accuracy and above all the reliability 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 reliability may lead to important errors (the threshold is a function of the current-meter type).

6.4.3 *Blockage effect*

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

It will be clear that the magnitude of this error is dependent upon the types of current-meter being used, their number, and the profile of the support rods. 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 main support cross to the 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 A); 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 to the dimensional requirements as specified in 4.4.1 on the other hand, lead to the proscription of gauging by means of current-meters in conduits, the dimensions of which are too small compared with those of the current-meters used.

In general, it can be accepted that a fixed current-meter battery may be used if the diameter of a circular cross-section conduit is greater than 9 times the propeller diameter or if the smaller side of a rectangular cross-section is greater than 8 times the propeller diameter, provided that the relative blockage as defined in 6.4.3 is less than 6 %.

Thus, for example, for those types of current-meter and support cross that are commonly used for industrial measurements and have propellers with diameters in the range 0,10 to 0,125 m (4 to 5 in), 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 battery mounted on cross-bars may be used only in circular conduits of diameters greater than 1,4 m (56 in). In a rectangular cross-section, it is also agreed that the smaller dimension of the conduit (the support rods being parallel to that direction) shall be at least equal to 1 m (40 in), and furthermore that the other dimension shall be sufficient to limit the blockage effect (see 6.4.3).

In conduits with smaller dimensions, a device which enables non-simultaneous measurements to be made should preferably 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 current-meter gauging by hauling in stagnant water and use of current-meters in turbulent flow. Longitudinal fluctuations lead to a positive error on the velocity measured by means of the current-meter whereas transverse fluctuations generally lead to a negative error. While keeping generally in mind that many factors influence the current-meter response, it may be observed that the error will increase as :

- fluctuation amplitude and frequency increase,
- the mean velocity decreases,
- 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.

Friction inspection in bearings may be carried out by observing how the propeller slows down after having been started at a certain speed. In no case shall stopping be abrupt.

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, then re-lubricated using the same lubricant as that used for calibration.

7 SETTING OF CURRENT-METERS INTO THE CONDUIT

7.1 Setting of current-meters

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

Mounting rods themselves shall 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. To this effect it is especially recommended that polygonal profile rods such as that described in annex B be used.

7.2 Mounting in a circular cross-section

7.2.1 *Stationary battery*

Current-meters are generally used as stationary batteries. Mounting rods shall therefore be arranged along the conduit radius so as to constitute 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.

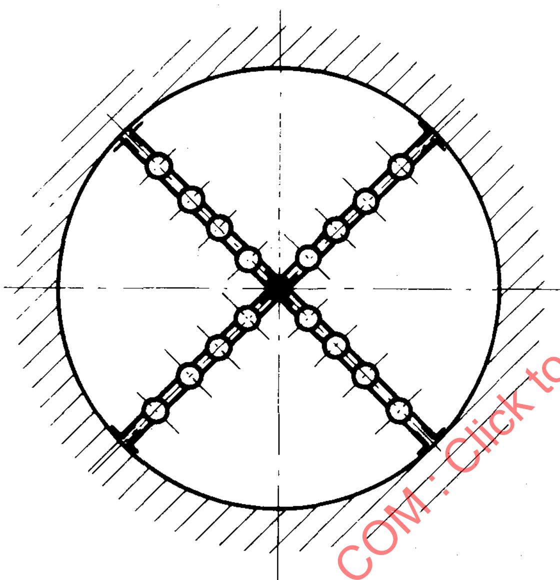


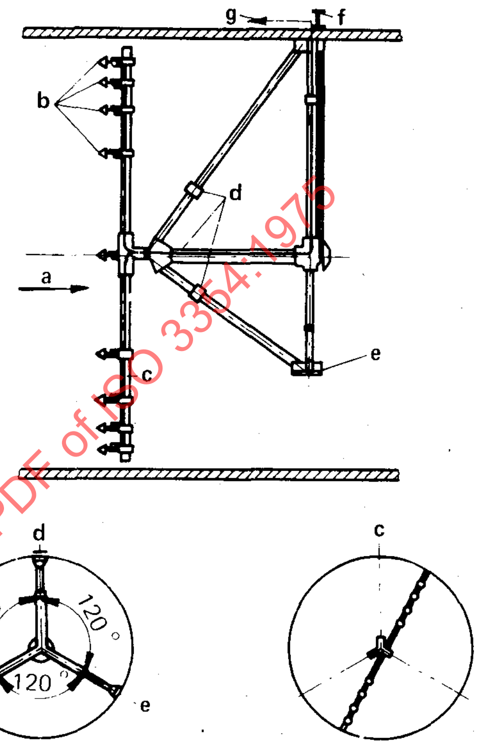
FIGURE 1 — **Stationary battery of current-meters mounted on cross-bars in a circular conduit**

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 shall be controlled from the outside and vibration risks shall be avoided) allows the exploration of a far greater number of measuring points.

It may, if required, allow direct measurement of the mean velocity per circle, 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 gradient of the apparent velocity with respect to the current-meter, due 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 rotating the rotating arm in the reverse direction or by making a gauging by positioning the arm at a number of fixed locations.



a) Direction of flow
b) Current-meters
c) Rotating arm
d) Tripod support
e) Attachment at wall
f) Driving gear of rotating arm
g) To the recorder

FIGURE 2 — **Diametrical arm device rotating in a circular conduit**

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 arrangements (lock-vanes) which enable the current-meter support rod to be guided along the explored diameter and to be transferred from one measuring diameter to the next one, while maintaining the water-tightness. In other respects, account shall be taken of 4.3.2.

7.3 Mounting in a rectangular cross-section

7.3.1 *Stationary battery*

Current-meters may be used as a stationary battery mounted on a number of parallel rods. This method may present the disadvantage of having the cross-section significantly obstructed by the supports.

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

Another method consists in 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 all vertical lines). This device requires external control with watertight sealing of certain parts. In other respects, account shall be taken of 4.3.2.

This process may allow direct measurement of the mean velocity along one vertical line (or one horizontal line), 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.

In order to ensure that the measurement is not falsified by an excessive gradient of the apparent velocity with respect to the current-meter, due 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 a gauging by positioning the slide at a number of fixed locations.

However, in the case of a flow where the maximum water-level is only slightly above the upper boundary of the conduit, the application of this procedure is simplified : the slide device can be moved in wells or grooves (for example bulkhead grooves) opening to atmosphere and its control device can be located above the maximum water-level.

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

The general principle of this method is specified in 4.1.

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.

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

An example of measuring point distribution for a circular section for which no indication on the velocity distribution is available will be found in annex C.

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

8.1 Circular cross-sections

If v is the flow velocity at a point of polar co-ordinates r and α, and if R is the mean radius of the measuring section, the discharge velocity U is given by the formula :

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

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

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

where

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

r_n is the radius of the circle relative to 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 a circle of radius r_c) as the value of u;[1)]

b) plotting the variation curve of u_c with $(r_c/R)^2$ between $r = 0$ and $r = r_n$;[2)]

c) determining graphically the value of the included area below this curve between $r = 0$ and $r = r_n$ (see figure 3);

d) adding to this value the following term[3)] corresponding to the peripheral zone :

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

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);

m is a coefficient depending on the wall roughness and on the flow conditions, the value of which can be determined in accordance with the indications given in annex D and is generally between 4 (rough wall) and 10 (smooth wall).

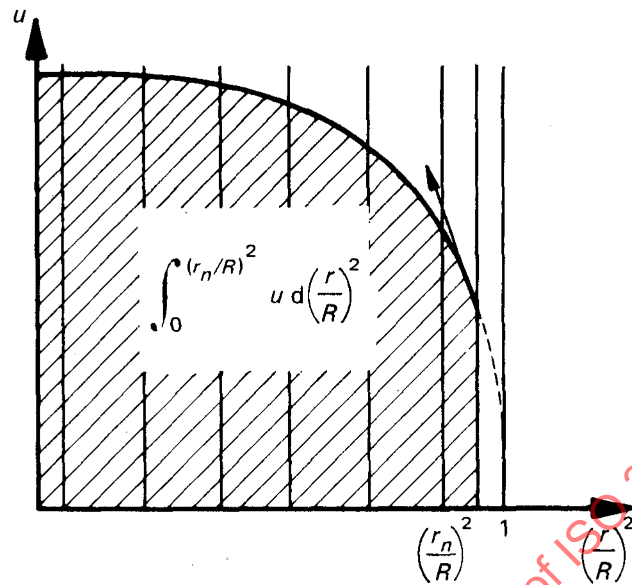


FIGURE 3 — **Computation of the discharge velocity in a circular conduit — Graphical integration in the area explored by the current-meters**

1) Methods exist which allow direct measurement of the mean velocity along a circumference (see 7.2.2).

2) To help 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 :

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

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 :

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

3) 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 represents only about

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

times the flow in the peripheral zone.

8.2 Rectangular cross-sections

The computation of the discharge velocity requires a double integration across both dimensions of the conduit. Measurement shall be started either on the vertical lines[1)] or on the horizontal lines.[1)] The matter is developed here starting with horizontal line measurements.

The formula for the discharge velocity is :

$$U = \int_0^1 \int_0^1 v \frac{dh}{H} \frac{dl}{L}$$

where

L is the conduit width in the measuring cross-section (arithmetical mean of the widths measured on at least each horizontal measuring line;

H is the conduit height in the measuring cross-section (arithmetical mean of the heights measured on at least each vertical measuring line);

l is the distance from the considered point to the side-wall chosen as origin;

h is the height of the considered point above the bottom.

The method used consists in :

a) plotting the variation curve of the velocity on each horizontal line between the extreme measuring points, as a function of the relative distance l/L (see figure 4);[2)]

b) determining graphically the value of the included area below this curve between the extreme measuring points (see figure 4);

c) adding to this value two terms corresponding to peripheral zones and respectively equal to

$$\frac{m}{m+1} \frac{a}{L} v_a$$

where

v_a is the velocity at the considered extreme measuring point (at a distance a from the nearest wall);

m is a coefficient depending on the wall roughness and on the flow conditions, the value of which can be determined in accordance with the indications given in annex D and is generally between 4 (rough wall) and 10 (smooth wall).

(the sum so obtained is the mean velocity u_i on the horizontal measuring line concerned[3)]);

d) plotting the variation curve of u_i between the extreme horizontal measuring lines as a function of the relative height h_i/H of the corresponding horizontal line (see figure 4)[4)];

e) determining graphically the value of the included area below this curve (see figure 4) between the extreme horizontal measuring lines;

f) adding to this latter value two terms corresponding to the peripheral zones in order to obtain the discharge velocity. Both terms are respectively equal to :

$$\frac{m}{m+1} \frac{a'}{H} u_{a'}$$

where u_a' is the mean velocity on the horizontal measuring line closest to the wall (at a distance a' from the wall).

1) Throughout this sub-clause, a "vertical line" will mean a line parallel to the conduit height and a "horizontal line" will mean a line parallel to the conduit width.

2) To facilitate plotting in the vicinity of these extreme measuring points, the tangent line to the curve for each of them will be drawn with a slope the absolute value of which is equal to

$$\frac{v_a L}{ma}$$

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

$$v_x = v_a \left(\frac{x}{a}\right)^{1/m}$$

3) Methods exist which allow direct measurement of the mean velocity along a horizontal (or vertical) line (see 7.3.2).

4) To facilitate plotting in the vicinity of the peripheral zones, the same procedure shall be followed as for the determination of the mean velocity along each horizontal line (see 8.2a)).

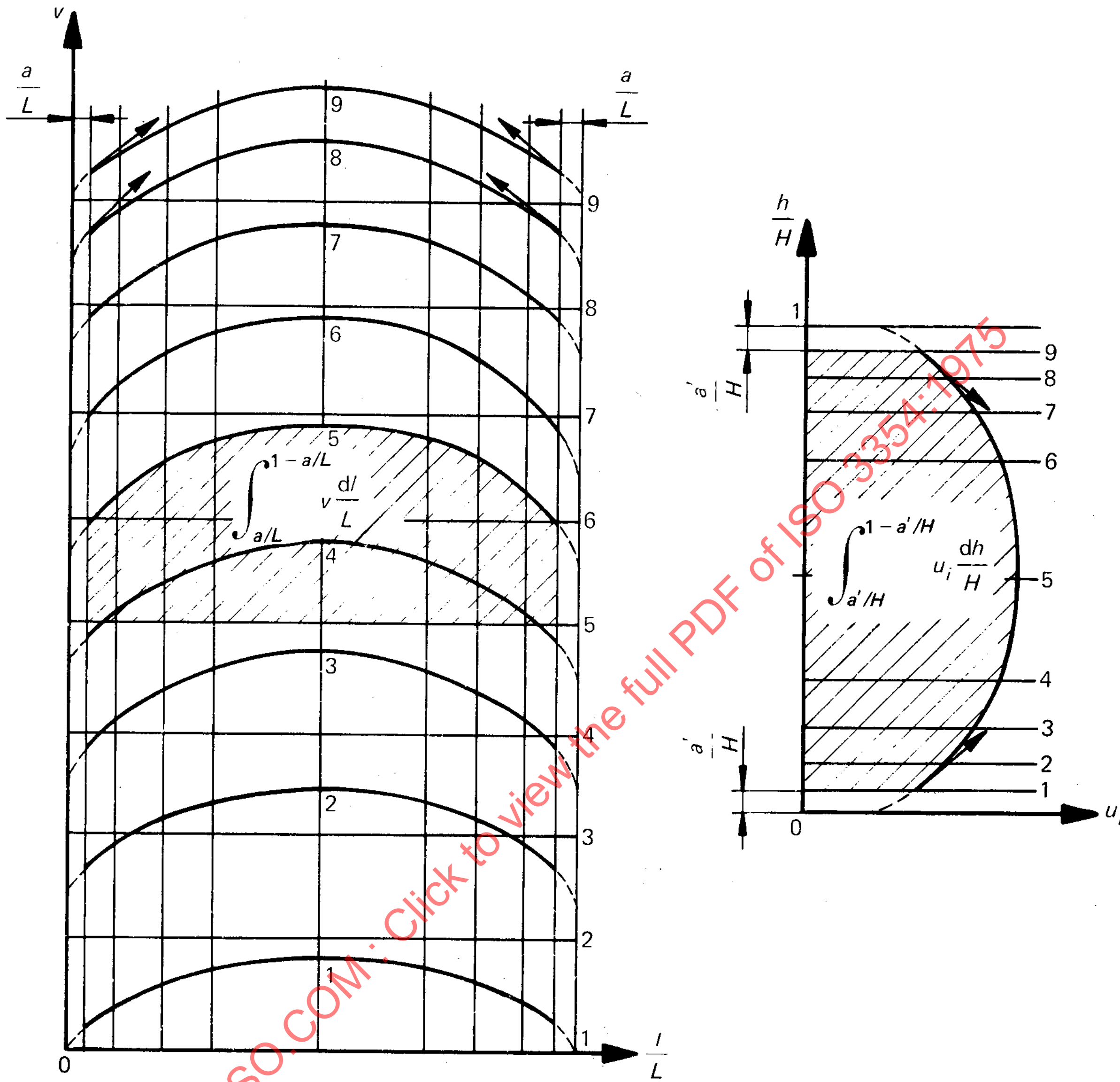


FIGURE 4 – **Computation of the discharge velocity in a rectangular conduit – Graphical integration in the area explored by current-meters**

9 DETERMINATION OF THE DISCHARGE VELOCITY BY NUMERICAL INTEGRATION OF THE VELOCITY AREA

The general principle of this method is laid down in 4.1.

The formulae proposed below are derived from interpolations between successive pairs of measuring points along third degree curves in $(r/R)^2$ for circular cross-section conduits, or in l/L or h/H for rectangular cross-section conduits. The different individual arcs combine to form a continuous curve with a continuous derivative.

In the peripheral zone the same law as indicated in the preceding clause is applied.

For the number and position of measuring points, reference shall be made to the indications of clause 8.

9.1 Circular cross-sections

If v_0 is the velocity at the conduit centre, $u_1, u_2, ..., u_n$ are the mean velocities (calculated as indicated in 8.1a)) along the circumferences with increasing relative radii $r_1^*, r_2^*, ..., r_n^*$ (with $r_1^* = r_i/R$, where R is the radius of the cross-section), the discharge velocity U in the cross-section is given by the formula

$$U = v_0 \left[-\frac{1}{12} r_2^{*2} + \frac{5}{12} r_1^{*2} + \frac{r_1^{*3}}{12\, r_2^*} \right]$$

$$+ u_1 \left[\frac{1}{6} r_1^{*2} + \frac{2}{3} r_2^{*2} - \frac{1}{12} r_3^{*2} \right]$$

$$- u_2 \left[\frac{r_1^{*3}}{12\, r_2^*} \right]$$

$$+ \sum_{i=2}^{i=n-2} u_i \left[-\frac{1}{12} r_{(i+2)}^{*2} + \frac{2}{3} r_{(i+1)}^{*2} - \frac{2}{3} r_{(i-1)}^{*2} + \frac{1}{12} r_{(i-2)}^{*2} \right]$$

$$+ u_{(n-1)} \left[\frac{1}{2} r_n^{*2} + \frac{1}{12} r_{(n-1)}^{*2} - \frac{2}{3} r_{(n-2)}^{*2} + \frac{1}{12} r_{(n-3)}^{*2} \right]$$

$$+ u_n \left[\frac{m}{m+1} (1 - r_n^{*2}) + \frac{(r_n^{*2} - r_{(n-1)}^{*2})^2}{12\, m\, (1 - r_n^{*2})} + \frac{7}{12} r_n^{*2} - \frac{2}{3} r_{(n-1)}^{*2} + \frac{1}{12} r_{(n-2)}^{*2} \right]$$

NOTE — When $n = 3$, the term on the fourth line of the equation above disappears and the formula is simplified as follows :

$$U = v_0 \left[-\frac{1}{12} r_2^{*2} + \frac{5}{12} r_1^{*2} + \frac{1}{12} \frac{r_1^{*3}}{12\, r_2^*} \right]$$

$$+ u_1 \left[\frac{1}{6} r_1^{*2} + \frac{2}{3} r_2^{*2} - \frac{1}{12} r_3^{*2} \right]$$

$$+ u_2 \left[-\frac{1}{12} \frac{r_1^{*3}}{r_2^*} - \frac{2}{3} r_1^{*2} + \frac{1}{12} r_2^{*2} + \frac{1}{2} r_3^{*2} \right]$$

$$+ u_3 \left[\frac{m}{m+1} (1 - r_3^{*2}) + \frac{(r_3^{*2} - r_2^{*2})^2}{12 m\, (1 - r_3^{*2})} + \frac{7}{12} r_3^{*2} - \frac{2}{3} r_2^{*2} + \frac{1}{12} r_1^{*2} \right]$$

When $n = 4$, the term on the fourth line of the equation is reduced to a term in u_2.

Table 2 in annex C gives the values of weighting coefficients for u_i in the particular case of the measuring points distribution as defined in clause C.1.

9.2 Rectangular cross-sections

In the following formula, U represents :

— either the mean velocity along a measuring line;

in this case $v_1, v_2, ..., v_n$ are the velocities measured at points located at distances $l_1, l_2, ..., l_n$ from the origin end; L is the distance between the two walls on the considered line :

$$d_1 = \frac{l_1}{L},\; d_2 = \frac{l_2 - l_1}{L},\; ...,\; d_n = \frac{l_n - l_{(n-1)}}{L},\; d_{(n+1)} = \frac{L - l_n}{L}$$

— or the discharge velocity in the measuring cross-section;

in this case $v_1, v_2, ..., v_n$ represent the mean velocities $u_1, u_2, ..., u_n$ along the measuring lines located at distances $h_1, h_2, ..., h_n$ from the origin wall; H is the height of the measuring cross-section :

$$d_1 = \frac{h_1}{H},\; d_2 = \frac{h_2 - h_1}{H},\; ...,\; d_n = \frac{h_n - h_{(n-1)}}{H}$$

$$d_{(n+1)} = \frac{H - h_n}{H}$$

$$U = v_1 \left[\frac{m}{m+1} d_1 + \frac{1}{12m} \frac{d_2^{\,2}}{d_1} + \frac{7}{12} d_2 - \frac{1}{12} d_3 \right]$$

$$+ v_2 \left[\frac{1}{2} d_2 + \frac{7}{12} d_3 - \frac{1}{12} d_4 \right]$$

$$+ \sum_{i=3}^{i=n-2} v_i \left[\frac{7}{12} (d_{(i+1)} + d_i) - \frac{1}{12} (d_{(i+2)} + d_{(i-1)}) \right]$$

$$+ v_{(n-1)} \left[\frac{1}{2} d_n + \frac{7}{12} d_{(n-1)} - \frac{1}{12} d_{(n-2)} \right]$$

$$+ v_n \left[\frac{m}{m+1} d_{(n+1)} + \frac{1}{12m} \frac{d_n^{\,2}}{d_{(n+1)}} + \frac{7}{12} d_n - \frac{1}{12} d_{(n-1)} \right]$$

NOTE — When $n = 5$, the third line of the equation above is reduced to a term in v_3.

The general principle of these methods is laid down in clause 4.1.

10 DETERMINATION OF THE DISCHARGE VELOCITY BY ARITHMETICAL METHODS

For each method the measuring cross-section is divided into a small number of section elements. The measuring locations are pre-determined for each section element from :

a) an assumption concerning the mathematical form of the velocity distribution law in the section element concerned;

b) a choice of the weighting coefficients.

The various curves corresponding to each section element do not need to constitute a continuous curve with a continuous derivative in these methods.

In the arithmetical methods described hereafter, the weighting coefficients are taken as equal in the case of circular cross-sections and the section elements have areas proportional to the number of measuring points in the element concerned; furthermore, in the peripheral zone, a logarithmic law is assumed for velocity distribution with respect to the wall distance.

10.1 "Log-linear" method

By hypothesis, the mathematical form of the velocity distribution law for each element is

$$u = A \log y + By + C$$

where

y is the distance to the wall;

A, B, C are any three constants (except for the external ring element where B is zero).

10.1.1 *Circular cross-sections*

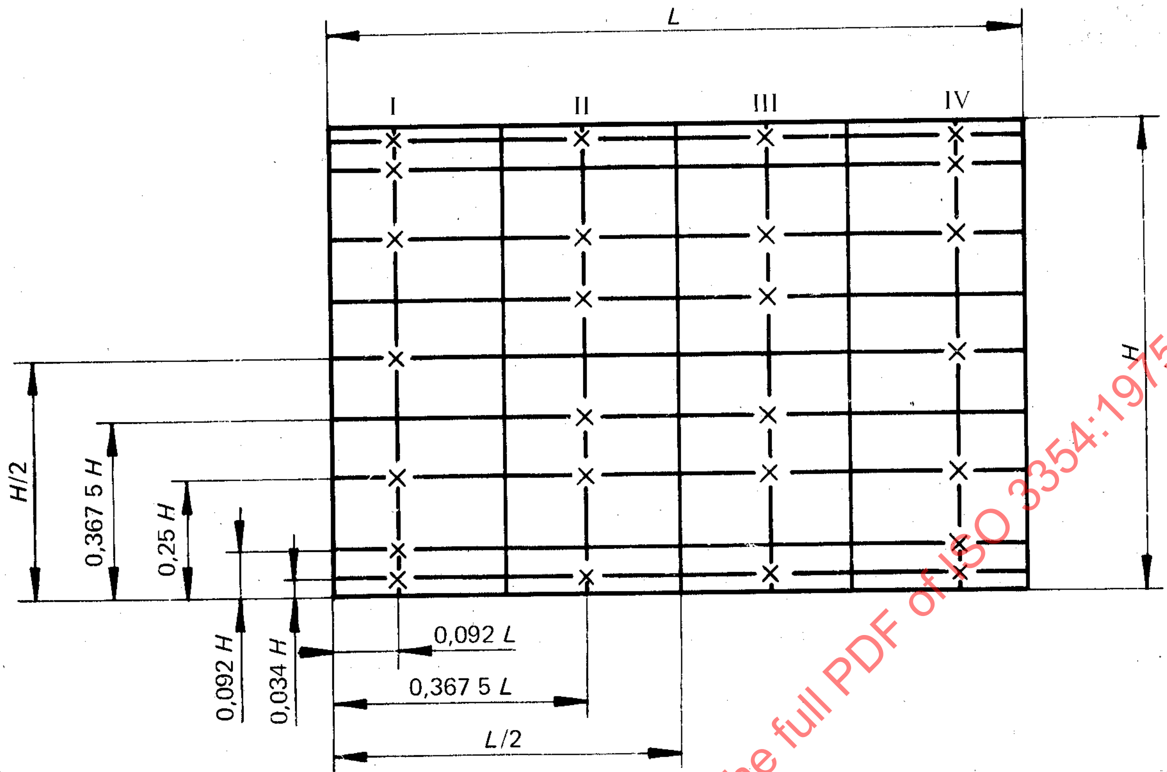
The location of the measuring points corresponds to the following values of the relative radius r/R or of the relative distance to the wall y/D :

Number of measuring points per radius	r/R	y/D
3	0,358 6 ± 0,010 0 0,730 2 ± 0,010 0 0,935 8 ± 0,003 2	0,320 7 ± 0,005 0 0,134 9 ± 0,005 0 0,032 1 ± 0,001 6
5	0,277 6 ± 0,010 0 0,565 8 ± 0,010 0 0,695 0 ± 0,010 0 0,847 0 ± 0,007 6 0,962 2 ± 0,001 8	0,361 2 ± 0,005 0 0,217 1 ± 0,005 0 0,152 5 ± 0,005 0 0,076 5 ± 0,003 8 0,018 9 ± 0,000 9

The mean velocity on each radius is taken as equal to the arithmetical mean of the velocities determined at the measuring points located on the radius concerned, and the discharge velocity is equal to the arithmetical mean of the mean velocities on each radius. The discharge velocity is therefore given by the arithmetical mean of the local velocities.

10.1.2 *Rectangular cross-sections*

Different layouts may be developed to apply the log-linear method in a rectangular cross-section, using a variety of numbers of measuring points. This International Standard is limited to the method using 26 points, for which the location of the measuring points is given in the table below and in figure 5. In addition to the location of the measuring points given by x/L and y/H, the table in figure 5 gives the weighing coefficients k for each measured velocity.



	I	II	III	IV
y/H \ x/L	0,092	0,367 5	0,632 5	0,908
0,034	2	3	3	2
0,092	2	–	–	2
0,250	5	3	3	5
0,367 5	–	6	6	–
0,500	6	–	–	6
0,632 5	–	6	6	–
0,750	5	3	3	5
0,908	2	–	–	2
0,966	2	3	3	2

FIGURE 5 – **Location of measuring points in a rectangular cross-section conduit in the case of the "log-linear" method using 26 points**

In all cases the discharge velocity is equal to the weighted mean of the measured local velocities :

$$U = \frac{\Sigma k_i v_i}{\Sigma k_i}$$

For the method using 26 points $\Sigma k_i = 96$.

10.2 "Log-Tchebycheff" method

By hypothesis the mathematical form of the velocity distribution law as a function of the distance from the wall is logarithmic in the elements on the circumference of the section and polynomial in the other elements.

10.2.1 *Circular cross-sections*

The position of the measuring points corresponds to the following values of the relative radius or of the relative distance to the wall y/D.

Number of measuring points per radius	r/R	y/D
3	0,375 4 ± 0,010 0 0,725 2 ± 0,010 0 0,935 8 ± 0,003 2	0,312 3 ± 0,005 0 0,137 4 ± 0,005 0 0,032 1 ± 0,001 6
4	0,331 4 ± 0,010 0 0,612 4 ± 0,010 0 0,800 0 ± 0,010 0 0,952 4 ± 0,002 4	0,334 3 ± 0,005 0 0,193 8 ± 0,005 0 0,100 0 ± 0,005 0 0,023 8 ± 0,001 2
5	0,286 6 ± 0,010 0 0,570 0 ± 0,010 0 0,689 2 ± 0,010 0 0,847 2 ± 0,007 6 0,962 2 ± 0,001 8	0,356 7 ± 0,005 0 0,215 0 ± 0,005 0 0,155 4 ± 0,005 0 0,076 4 ± 0,003 8 0,018 9 ± 0,000 9

As the weighting coefficients have been chosen to be equal, the discharge velocity is equal to the arithmetical mean of the measured local velocities.

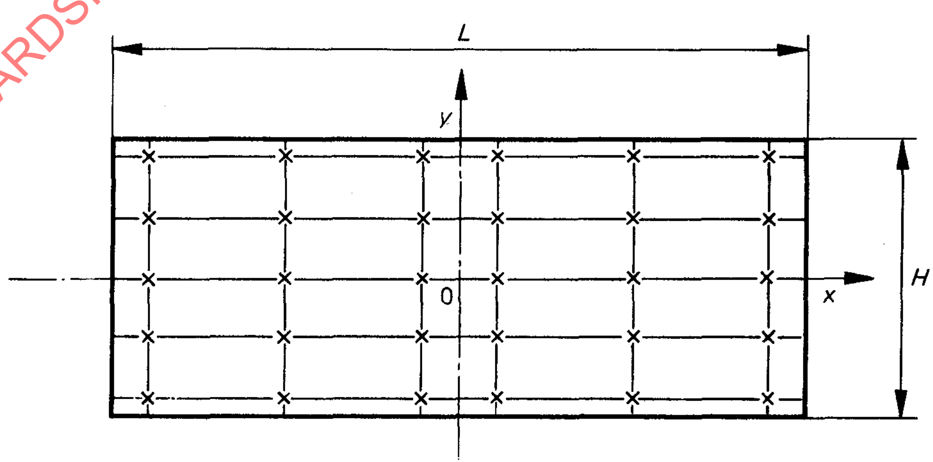
10.2.2 *Rectangular cross-sections*

A number (e) of traverse straight lines, at least equal to 5, are selected parallel to the smaller side of the rectangle; on each of them a number (f) of measuring points, at least equal to 5, are located (see figure 6).

The positions of ($e\ f$) measuring points (abscissa X_i – ordinate Y_j) are defined from the table below.

e or f	Values of $\frac{X_i}{L}$ or $\frac{Y_j}{H}$			
5	0	± 0,212	± 0,426	
6	± 0,063	± 0,265	± 0,439	
7	0	± 0,134	± 0,297	± 0,447

As the weighting coefficients have been chosen to be equal, the discharge velocity is equal to the arithmetical mean of the measured local velocities at the various measuring points.



NOTE — For the example chosen, $f = 5$ and $e = 6$.

FIGURE 6 — **Location of measuring points in a rectangular cross-section conduit in the case of the "log-Tchebycheff" method**

11 ERRORS

This clause defines some of the basic statistical terms used in this International Standard and outlines the method for assessing the accuracy of a volume flow rate measurement.

In annex E some typical values of the error introduced by several of the sources of error are given. It is emphasized that there are other sources of error for which it is not possible to give typical values, and that the magnitudes of the errors given may vary appreciably; each individual case shall therefore be the subject of careful study.

11.1 Definition of the error

The error in the estimate of a quantity is the difference between that estimate and the true value of the quantity.

No measurement of a physical quantity is free from uncertainties arising either from systematic errors or from the random dispersion of measurement results. Systematic errors cannot be reduced by repeating measurements since they arise from the characteristics of the measuring apparatus, the installation, and the flow characteristics. However, a reduction in the random error may be achieved by repetition of measurements, since the random error of the mean of n independent measurements is $\sqrt{n}$ times smaller than the random error of an individual measurement.

11.2 Errors in the estimation of local velocity

11.2.1 *Random errors*

11.2.1.1 Error due to measurement of rotation speed

The measurement of the rotation speed of a current-meter is inevitably altered by a random error δ_n due to counting pulses and to measuring time duration. This error is reduced as the duration of measurement is increased.

11.2.1.2 Error due to slow fluctuations in the flow velocity

A random error δ_f will be made if the time of measurement is not long enough to allow correct integration of slow fluctuations in the flow velocity. The error is reduced as the number and duration of measurements at a given point are increased.

11.2.2 *Systematic errors*

11.2.2.1 Error due to current-meter calibration

Any error in the calibration of a current-meter will have a systematic effect on the measured velocity, introducing an error e_c.

11.2.2.2 Error due to turbulence and velocity fluctuations

The finite response time of current-meters to changes in velocity results in an erroneous reading when high frequency velocity fluctuations or turbulence is present. The resulting error e_t in the measured velocity will be the same for all measurements at the same point and velocity, although the errors will change with both flow rate and position of measurement.

11.2.2.3 Error due to current-meter inclination

If a current-meter is installed with its axis at an angle to the flow direction a systematic error e_φ will result since the calibration results for that meter will no longer hold exactly.

11.2.2.4 Error due to conduit blockage

This effect is described in detail in 6.4.3 and annex A where corrections are given to allow for the effect. However, the corrections themselves have an associated uncertainty, so that a systematic error of random nature e_b will result when they are applied.

11.3 Errors in the estimation of flow rate

11.3.1 *Random errors*

11.3.1.1 Error due to local velocity measurements

The errors in the local velocity measurements will not be truly random, as they will in part depend on the position of the measurement across the duct. However, the error on each measurement will be different, and the major contributions to each error will be random in nature, so that the overall error δ_v contributed to the estimation of flow rate may be regarded as random.

11.3.1.2 Error due to graph in graphical integration technique

When the graphical integration technique is used, an error δ_i will be introduced in drawing the velocity profile and evaluating the area under the central portion of the graph; this is random in nature, and the magnitude will depend both on the operator and on the shape of the velocity distribution.

11.3.1.3 Error due to evaluation of power law index *m*

If the power law index m is calculated by the graphical method given in annex F then the error δ_m from this source will be random in nature.

11.3.1.4 ERROR DUE TO POSITIONING OF CURRENT-METERS

If the errors associated with the positioning of the current-meters are independent of one another (i.e. no large common systematic error is present, see 4.4.1), then the overall effect will be to introduce a random error δ_l in the flow rate estimation. However, provided the conditions of 4.4.1 are met, this error is negligible.

11.3.2 *Systematic errors*

11.3.2.1 ERROR DUE TO MEASUREMENT OF DUCT DIMENSIONS

Although the area A of the plane of flow rate measurement is evaluated from the mean of several measurements of the duct dimensions (see 4.2), a systematic error e_A still remains in the calculated flow rate.

11.3.2.2 ERROR DUE TO NUMERICAL OR ARITHMETICAL INTEGRATION TECHNIQUES

The techniques given in clauses 9 and 10 involve either an approximation to the velocity distribution or the assumption of a velocity distribution. For a given velocity distribution, there is therefore a systematic error e_i introduced in the calculated flow rate.

11.3.2.3 ERROR DUE TO NUMBER OF MEASURING POINTS

If the velocity distribution curve is not perfectly smooth, the number of measuring points may not be sufficient to define it adequately, and a systematic error e_p will result.

11.4 Definition of the standard deviation[1]

11.4.1 If a variable X is measured several times, each measurement being independent of the others, then the standard deviation σ_x of the distribution of n measurements X_i is :

$$\sigma_x = \left(\frac{\sum_{i=1}^{i=n} (\overline{X} - X_i)^2}{n-1} \right)^{1/2}$$

where

$\overline{X}$ is the arithmetical mean of the n measurements of the variable X;

X_i is the value obtained by the ith measurement of the variable X;

n is the total number of measurements of X.

For brevity, σ_x is normally referred to as the standard deviation of X.

11.4.2 If repeated measurements of a variable X are not available or are so few that direct computation of the standard deviation on a statistical basis is likely to be unreliable, and if the maximum range of the measurements may be estimated, the standard deviation may be taken as 1/4 of this maximum range (i.e. as 1/2 of the estimated uncertainty above or below the adopted value of X).

11.4.3 If the various independent variables the knowledge of which allows computation of the flow rate are X_1, X_2, ..., X_k, then the flow rate q may be expressed as a certain function of these variables :

$$q = f(X_1, X_2, \ldots, X_k)$$

If the standard deviations of the variables X_1, X_2, ..., X_k are respectively σ_1, σ_2, ..., σ_k, then the standard deviation σ_q of the flow rate is defined as follows :

$$\sigma_q = \left[\left(\frac{\partial q}{\partial X_1} \sigma_1 \right)^2 + \left(\frac{\partial q}{\partial X_2} \sigma_2 \right)^2 + \ldots + \left(\frac{\partial q}{\partial X_k} \sigma_k \right)^2 \right]^{1/2}$$

where $\frac{\partial q}{\partial X_1}, \frac{\partial q}{\partial X_2}, \ldots, \frac{\partial q}{\partial X_k}$ are partial derivatives.

11.5 Definition of the uncertainty

11.5.1 For the purpose of this International Standard the uncertainty on the measurement of a variable is defined as twice the standard deviation of the variable. The uncertainty shall be calculated and quoted under this name whenever a measurement is claimed to be in conformity with this International Standard.

11.5.2 When partial errors the combination of which gives the uncertainty are independent of one another, are small and numerous, and have a Gaussian distribution, there is a probability of 0,95 that the true error is less than the uncertainty.

11.5.3 Having estimated the standard deviation σ_q of the flow rate measurement, q, the uncertainty δ_q is given by

$$\delta_q = \pm 2\, \sigma_q$$

The relative uncertainty, δ'_q, is defined by

$$\delta'_q = \frac{\delta_q}{q} = \pm 2 \frac{\sigma_q}{q}$$

The result of a flow measurement shall always be given in one of the following forms :

a) flow rate $= q \pm \delta_q$ (at the 95 % confidence level);

b) flow rate $= q(1 \pm \delta'_q)$ (at the 95 % confidence level);

c) flow rate $= q$ within $\pm 100\, \delta'_q$ % (at the 95 % confidence level).

1) The standard deviation as defined here is more accurately referred to by statisticians as the "standard deviation estimation".

11.6 Calculation of the standard deviation

11.6.1 *Standard deviation on local velocity measurement*

The standard deviation associated with a measurement of local velocity v is obtained by combining the standard deviations of errors arising from the sources described in 11.2. Although a distinction exists between "systematic" and "random" errors, the probability distribution of the possible values of each systematic component is essentially Gaussian. The combination of the random and systematic errors may therefore be treated as though all were truly random, and the standard deviation for the systematic components can be obtained by calculating a value for their standard deviations in the manner described in 11.4.2. Thus, the standard deviation of a particular systematic component is half of the plus or minus maximum uncertainty on that component.

The relative standard deviation on the local velocity measurement is then the square root of the sum of the squares of the relative standard deviations arising from the sources listed in 11.2. Thus, the result of the local velocity measurement is :

$$v\left[1 \pm 2\sqrt{\left(\frac{\sigma_n}{n}\right)^2 + \left(\frac{\sigma_f}{v}\right)^2 + \left(\frac{\sigma_c}{v}\right)^2 + \left(\frac{\sigma_t}{v}\right)^2 + \left(\frac{\sigma_\varphi}{v}\right)^2 + \left(\frac{\sigma_b}{v}\right)^2}\right]$$

$$= v\left(1 \pm 2\frac{\sigma_v}{v}\right)$$

at the 95 % confidence level

where

σ_n is the standard deviation arising from the rotation speed of the current-meter;

σ_f is the standard deviation arising from slow velocity fluctuations;

σ_c is the standard deviation arising from the current-meter calibration;

σ_t is the standard deviation arising from high frequency velocity fluctuations and turbulence;

σ_φ is the standard deviation arising from the inclination of the current-meter to the flow direction;

σ_b is the standard deviation arising from the uncertainty in the correction for blockage.

11.6.2 *Standard deviation on flow rate measurement*

Once again the possible values of the systematic errors which are listed in 11.3.2 have a probability distribution which is essentially Gaussian, so that all errors may be treated as random for the purpose of estimating the standard deviation on the flow rate; the standard deviations on the systematic components are obtained in the same way as in 11.6.1.

The relative standard deviation on the flow rate measurement is then the square root of the sum of the squares of the relative standard deviations arising from the sources in 11.3. Thus the result of the flow rate measurement is :

$$q\left[1 \pm 2\sqrt{\left(\frac{\sigma_v}{v}\right)^2 + \left(\frac{\sigma_i}{q}\right)^2 + \left(\frac{\sigma_m}{q}\right)^2 + \left(\frac{\sigma_l}{q}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_p}{q}\right)^2}\right]$$

$$= q\left(1 \pm 2\frac{\sigma_q}{q}\right)$$

at the 95 % confidence level

where

σ_v is the standard deviation on local velocity measurements, calculated as described in 11.6.1;

σ_i is the standard deviation arising from the use of the integration technique;

σ_m *is the standard deviation associated with the* estimation of the value of *m*;

σ_l is the standard deviation arising from current-meter positioning;

σ_A is the standard deviation on the evaluation of the area of the measuring cross-section[1];

σ_p is the standard deviation arising from the number of velocity measuring points.

Annex F gives an example of the calculation of the tolerance on the flow rate measured by means of current-meters.

1) It should be noted that the relative standard deviation in the evaluation of the area of the measuring cross-section is twice the relative standard deviation on the length measurements from which it is calculated.

ANNEX A

CORRECTIONS FOR BLOCKAGE EFFECT

It has been pointed out in 6.4.3 that when a battery of current-meters is installed in a conduit the velocity distribution is disturbed. The presence of the meters and their support causes a reduction in the cross-sectional area for flow and hence the velocity distribution and the local velocities are altered in the plane of the propellers. When the meters are calibrated in a towing tank the walls are far enough away and there is a free surface, so that a similar phenomenon does not occur. As a result, therefore, when the flow rate is calculated for the conduit on the basis of the meter calibration equations, the flow rate is overestimated.

It is very difficult to measure or calculate theoretically the magnitude of this error. In the past fifteen years a number of major investigations into the problem have been made and from these certain conclusions have been drawn. They are not precise since each combination of a number of current-meters and their support cross is likely to result in a different re-distribution of the velocity profile. It appears adequate in the present state of knowledge to regard the error as directly proportional to the velocity over the range of velocities normally experienced. Thus, a direct percentage error correction can be used.

As stated in 6.4.3, the investigations have shown that the main parameter influencing the magnitude of the error is the ratio of the frontal area of the support cross to the cross-sectional area of the conduit. The number of current-meters being used, their type, and the size of their propellers and hubs also have an effect but this is likely not to exceed 0,3 % with the types of meter normally in use and in conformity with this International Standard.

A more important factor is the distance between the plane of the propellers and the plane of the support cross. As this is increased the influence of the blockage caused by the cross on the current-meter readings is reduced. Suggestions for the selection of the current-meter and support cross types and fixing means are given in annex B.

On the basis of present knowledge :

a) if the percentage blockage s is less than 2 %, no correction shall be made to the flow rate measurement;

b) if the percentage blockage s is between 2 and 6 %, then the measured flow rate must be reduced by k %, where $k = 0{,}125\,s$. The additional uncertainty in the flow rate measurement is then $\pm \frac{2k}{3}$ %;

c) if the percentage blockage s exceeds 6 %, the measurement cannot be made in accordance with this International Standard.

ANNEX B

RECOMMENDATIONS FOR THE SELECTION OF THE TYPE OF CURRENT-METER AND MOUNTING ROD

Without prohibiting the use of those types of current-meter and mounting rod currently used up to the present time, the recommendations[1] stated below are intended to orientate the choice of the user to :

- a type of current-meter having the lowest possible sensitivity to the effect of flow turbulence, and especially to its longitudinal component;
- a type of mounting rod ensuring both minimum vibration risks and stable flow separation points, and hence minimum interference with the current-meter response.

B.1 RECOMMENDATIONS RELATING TO THE CURRENT-METER

B.1.1 The "aspect ratio" $\left[\frac{(r_{\text{propeller}} - r_{\text{hub}})^2}{\text{blade area}}\right]$ shall be maximum (short propeller).

B.1.2 The propeller pitch shall be sufficiently large (but not too large, to prevent drag assuming too much importance with respect to lift).

B.1.3 The blade thickness shall be rather small (which limits the propeller diameter).

B.1.4 The material of the propeller shall have low density (light metal or plastics).

B.1.5 The meter body shall be compact with the connecting terminal set in the body.

B.1.6 The measuring plane (or "active part" of the propeller) shall be sufficiently far from the rod.

B.2 RECOMMENDATIONS RELATING TO THE ROD (Figure 6)

B.2.1 The rod profile shall be octagonal with a relative thickness of about 0,3.

B.2.2 The thickness of the leading edge shall be half the total thickness and the smaller edges shall be inclined at an angle of about 12,5°.

B.2.3 Connection wires shall pass along side grooves which may or may not be covered.

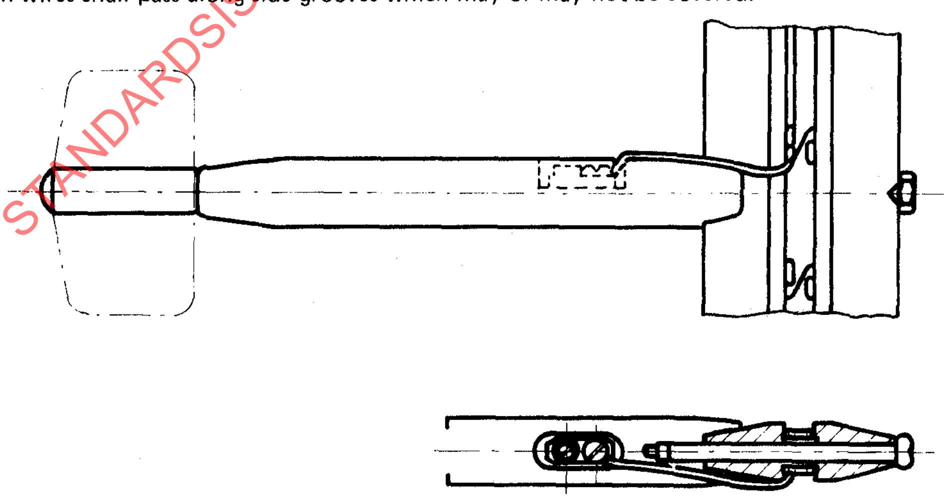


FIGURE 7 – **Example of mounting rod**

1) These recommendations are in conformity with the conclusions of the most recent research work carried out within the International Current-Meter Group; these researches have led to the choice of an octagonal rod circumscribed to an ellipse of 100 mm × 30 mm and to a mounting with a distance of 265 mm between the trailing edge of the propeller and the leading edge of the rod.

ANNEX C

EXAMPLE OF MEASURING POINT DISTRIBUTION ALONG A RADIUS FOR VELOCITY MEASUREMENT IN A CONDUIT OF CIRCULAR CROSS-SECTION IN THE CASE OF THE GRAPHICAL AND NUMERICAL METHODS

C.1 LOCATION OF THE MEASURING POINTS

When no indication of the velocity distribution is given, various layouts of the measuring points along a radius may be used in relation to the number of points. The locations indicated as examples on figure 7 and in table 1 would roughly correspond to equal flow rate rings in the case of uniform velocity distribution (in the hope of minimizing the influence of accidental errors in the determination of the local velocities by giving approximately the same weight to all current-meters).

NOTES

1 The given distribution shall sometimes be amended so as to meet mandatory requirements concerning the minimum distance between two current-meters (see 4.4.1).

2 A current-meter shall be placed on the pipe axis.

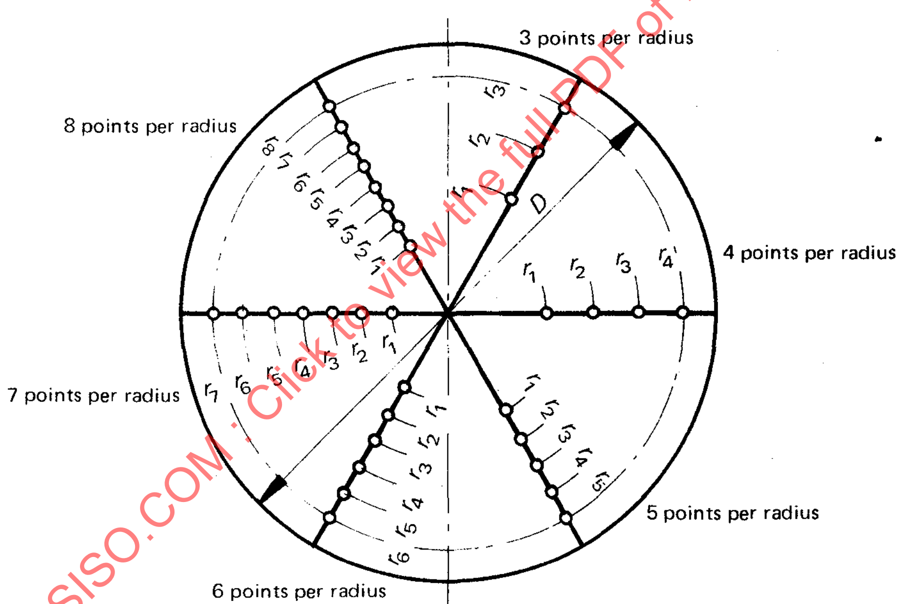


FIGURE 8 — **Example of measuring point distribution on a conduit of circular cross-section**