International Standard 7194

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION•МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ•ORGANISATION INTERNATIONALE DE NORMALISATION

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

Mesure de débit des fluides dans les conduites fermées — Mesure de débit dans les conduites circulaires dans le cas d'un écoulement giratoire ou dissymétrique par exploration du champ des vitesses au moyen de moulinets ou de tubes de Pitot doubles

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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.

International Standard ISO 7194 was developed by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*, and was circulated to the member bodies in May 1982.

It has been approved by the member bodies of the following countries :

Australia	India	Romania
Belgium	Italy	South Africa, Rep. of
Czechoslovakia	Netherlands	United Kingdom
Egypt, Arab Rep. of	Norway	USSR
France	Poland	

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0 Introduction

In order to carry out measurements of the flow-rate of single phase fluids in closed pipes by velocity-area methods, using either current-meters or Pitot static tubes, with satisfactory accuracy (of the order of ± 2 % for example), it is usually necessary to choose a measuring plane where the velocity distribution approaches that of fully developed flow (see ISO 3354 and ISO 3966).

There are, however, some cases where it is practically impossible to obtain such a flow distribution, but where as good as possible a measurement of the flow-rate is desirable.

1 Scope and field of application

This International Standard specifies velocity-area methods for measuring flow in swirling or asymmetric flow conditions in circular ducts by means of current-meters or Pitot static tubes.

It specifies the measurements required, the precautions to be taken, the corrections to apply, and describes the additional uncertainties which are introduced when a measurement in asymmetric or swirling flow has to be made.

Although methods of using velocity-area integration techniques to measure flow-rate under conditions where there is swirl and/or asymmetry in the flow are described, every effort should nevertheless be made to choose a measuring section in the pipe where the swirl or asymmetry is as small as possible.

Only flows with a negligible radial component are considered, however. Furthermore, it is not possible to make a measurement in accordance with this International Standard if, at any point in the measuring cross-section, the local velocity makes an angle of greater than 40° with the axis of the duct, or where the index of asymmetry Y (defined in annex F) is greater than 0,15.

It should be noted that this International Standard deals only with instruments for measuring local velocity as defined in ISO 3354 and ISO 3966. If Pitot static tubes are used, this International Standard applies only to flows where the Mach number corresponding to local velocities does not exceed 0,25.

2 References

ISO/TR 3313, *Measurement of pulsating fluid flow in a pipe by means of orifice plates, nozzles or venturi tubes, in particular in the case of sinusoidal or square wave intermittent periodic-type fluctuations.*

ISO 3354, *Measurement of clean water flow in closed conduits — Velocity-area method using current-meters.*

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

ISO 3966, *Measurement of fluid flow in closed conduits — Velocity-area method using Pitot static tubes.*

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.*

3 Symbols (see also ISO 4006)

Symbol	Description	Dimension	SI unit
D	Pipe diameter	L	m
d	Diameter of the head of a Pitot static tube Diameter of holes or tubes of a straightener	L	m
E	Uncertainty, as a relative value	—	—
e	Uncertainty, as an absolute value	*	*
k_{φ}	Directional calibration coefficient	—	—
l	Length of the head of a Pitot static tube	L	m
R	Pipe radius	L	m
r	Measuring circle radius	L	m
U	Mean axial fluid velocity	LT^{-1}	m/s
U_i	Mean velocity along the i^{th} radius	LT^{-1}	m/s
v	Local velocity of the fluid	LT^{-1}	m/s
v_x	Component of the local velocity parallel to the pipe axis	LT^{-1}	m/s
Y	Index of asymmetry of the flow	—	—
y	Distance between the heel of a Pitot static tube and the wall	L	m
y_1	Distance between the nose of a Pitot static tube and the wall	L	m
α	Calibration factor of a Pitot static tube	—	—
Δp	Differential pressure registered by a Pitot static tube	$ML^{-1}T^{-2}$	Pa
ε	Expansibility factor	—	—
θ	Angle of the local velocity with the pipe axis	—	rad**
ϱ	Mass density of the fluid	ML^{-3}	kg/m³
φ	Angle of the local velocity with the metering device axis	—	rad**

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

** Although the radian is the SI unit, for the purpose of this International Standard, angles are expressed in degrees.

4 Principle

This International Standard describes

— methods which minimize the errors in carrying out a traverse in swirling or asymmetric flow;

— corrections which should be applied for certain sources of error;

— methods of determining the increase in uncertainty in the flow-rate measurement when it is not possible to compensate for a particular source of error.

The origins of the errors giving rise to the uncertainties considered in this International Standard are

a) errors in the determination of local velocities, due to the behaviour of the instruments in a disturbed flow;

b) errors in the calculated mean pipe velocity, due to the number and position of the measuring points and the methods of integration used.

Corrections are possible for some of these errors, but, in general, the limiting uncertainty in the flow-rate measurement has to be increased according to the characteristics of the flow.

5 Choice of measuring plane

When the configuration of the pipe and any fittings installed in it is such that any changes of direction of the flow are all in the same plane (for example, a single bend, a single valve, or two bends in an "S" shape), no significant bulk swirl will be introduced and the disturbance to the flow will result in an essentially asymmetric velocity distribution.

If, however, the pipe configuration is such that the flow changes direction in two or more different planes in rapid succession (for example, two bends at 90° to each other), a bulk swirl will be introduced in addition to the asymmetry which the individual fittings introduce.

Unlike asymmetry, swirl has a big effect on the response of Pitot static tubes and current-meters, and also persists for very much longer distances; whenever possible, therefore, the traverse plane should not be downstream of swirl inducing configurations. Care should also be taken to avoid locating the traverse plane downstream of any adjustable fitting for which the geometry may change (for example, a flow control valve), especially if several different flow-rates have to be measured.

6 Devices for improving flow conditions

6.1 Where asymmetric or swirling flow is to be measured, a device (straightener) for improving flow conditions should be used, if possible. It should be installed as shown in figure 1.

The lengths L_1, L_2, L_3 shall fulfill the conditions : $L_1 > 3D$; $L_2 > 5D$; $L_3 > 2D$.

These distances should be increased whenever possible, and, where a total straight length of more than 10 pipe diameters exists upstream of the traverse plane, it is better to increase the distance between the pipe fitting and the straightener than to increase the distance between the straightener and the traverse plane.

6.2 The choice of straightener is dependent on the nature of the velocity distribution which has to be corrected and on the head loss which can be tolerated. Five types of straightener are described below.

6.2.1 Type A — Zanker straightener (see figure 2)

The purpose of this device is to eliminate both swirl and asymmetry, and has a head loss of approximately five velocity heads. The various plates should be chosen to provide adequate strength, but should not be unnecessarily thick.

6.2.2 Type B — Sprenkle straightener (see figure 3)

The Sprenkle straightener consists of three perforated plates in series, and is particularly effective in eliminating asymmetry. It does however have a high head loss (about 15 velocity heads) but two plates or even one plate (with head losses of about ten and five velocity heads respectively) can be used if such a high head loss is not acceptable. Although they cannot completely eliminate such severe asymmetry as can the three plates, they are often sufficient for disturbances such as a single bend. Perforated plate straighteners have some effect in reducing swirl, but are not designed for this; if, therefore, swirl is the dominant type of irregularity in the velocity distribution, one of the other straighteners should be used.

6.2.3 Type C — Tube bundle straightener (see figure 4)

The basic purpose of the tube bundle straightener is to eliminate swirl, but it also has some effect in reducing asymmetry. There shall be a minimum of 19 tubes, with a length of at least 20 times the diameter of the tubes, and each tube shall have a maximum diameter of one-fifth of the pipe diameter. The head loss of this straightener depends on the size and length of the individual tubes, but is typically about five velocity heads.

6.2.4 Type D — AMCA straightener (see figure 5)

The AMCA straightener is useful only in eliminating swirl; it does not improve asymmetric velocity distributions. Its dimensions are given in figure 5, and it has a very low head loss, normally about 0,25 times the velocity head.

6.2.5 Type E — Étoile straightener (see figure 6)

The étoile straightener is again designed only to eliminate swirl, and is of no assistance with asymmetric velocity distributions. The eight radial vanes should be chosen to provide adequate strength, but should not be unnecessarily thick. This straightener should have a length equal to two pipe diameters. It has a very low head loss, similar to that of the AMCA straightener, but has the advantage that it is much easier to manufacture. In addition it allows the static pressure to equalize radially as the flow passes through it, unlike the AMCA, tube bundle or Zanker straighteners which can induce significant variation in static pressure across the pipe downstream of them.

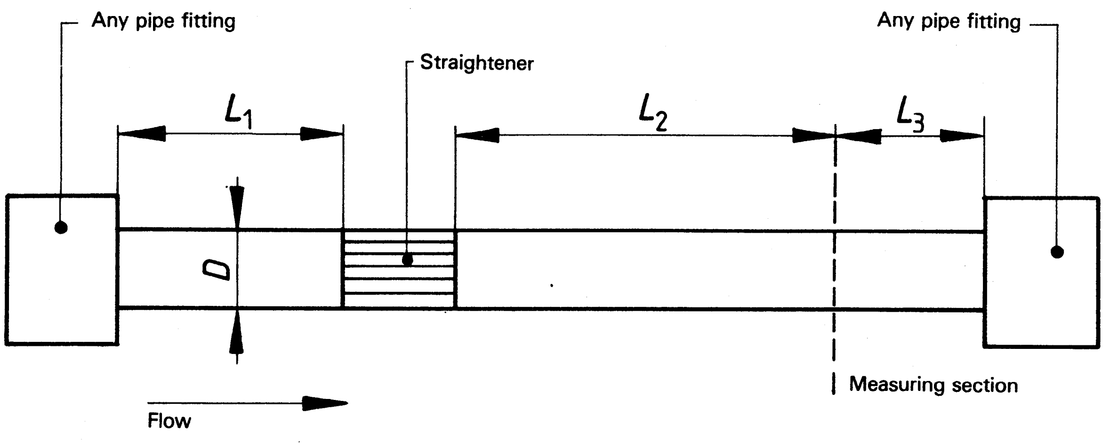

Figure 1 — Installation of straightener

7 Measurement of local velocities

Unless specific indications are given to the contrary elsewhere in this International Standard, the procedures to be followed and the conditions to be fulfilled by the local velocity measuring instruments shall conform to the specifications of ISO 3354 or ISO 3966.

When swirl occurs to any significant extent, the fact that the flow direction is different from the axial direction has an effect on the measuring instrument which has to be taken into account at each measuring position across the pipe in order to determine the local axial velocities. The procedure for doing this depends on whether a Pitot static tube or a current-meter is used.

7.1 Number and position of measuring points

The number and position of measuring points in the measuring section shall conform to the specifications of ISO 3354 or ISO 3966, taking into account the integration technique chosen. However, the minimum number of measurements per radius shall be five (excluding any measurement on the centre line) and, when there is reason to believe that the flow is asymmetric, the minimum number of radii shall be six. Also, at least one measurement of local velocity shall be made in each of the following zones within the pipe on each radius in addition to any measurement which might be made on the centre line :

$$0 < \left(\frac{r}{R}\right)^2 < 0{,}2$$

$$0{,}2 < \left(\frac{r}{R}\right)^2 < 0{,}4$$

$$0{,}4 < \left(\frac{r}{R}\right)^2 < 0{,}6$$

$$0{,}6 < \left(\frac{r}{R}\right)^2 < 0{,}8$$

$$0{,}8 < \left(\frac{r}{R}\right)^2 < 1{,}0$$

This condition is fulfilled automatically when the log-linear or log-Tchebycheff methods of integration are used, but care has to be taken to choose the measuring positions in accordance with this requirement when either the numerical or graphical integration method is used.

Often, especially when there is reason to believe that the flow may be asymmetric, the uncertainty of 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. For example, if 48 current-meters are available for installation in a conduit, it is often slightly better to use six on each of eight radii rather than eight on each of six radii.

7.2 Effect of pressure fluctuations

In any conduit subject to flow covered by ISO 3966 or this International Standard, there will be pressure fluctuations directly linked to the turbulent components of the local velocities superimposed on the mean flow. The traversing Pitot static tube will transmit these to the manometer or pressure transducer as components of the instantaneous differential pressure. Sufficient damping in the manometer circuit will help the operator to estimate the average differential pressure, but such damping shall be symmetrical and linear, in order to avoid an additional error which cannot be assessed. The error in the mean velocity estimated from the time mean differential pressure reading in the presence of turbulence is considered separately in clause 8.

There shall be sufficient symmetrical and linear damping in the manometer circuit to ensure that fluctuations of the manometer reading at each point of measurement do not exceed ± 3 % of the average reading at that point.

Recommendations on ensuring that damping is symmetrical and linear are given in annex B.

Pressure fluctuations of acoustic origin, quite unrelated to the local flow velocities, may be present in some conduits, particularly those subject to gas flows. Such pressure fluctuations are usually much greater than those arising from turbulence and the smallest departure from linearity in damping of the manometer circuit inevitably leads to a considerable error in the local velocities estimated from the average manometer reading. Therefore, before measurements can be carried out in accordance with this International Standard, the user shall check that no significant regular pressure fluctuations are present in the conduit and, if there are, shall eliminate them. Advice on detection and removal is given in annex A.

7.3 Axial velocity measurement using a Pitot static tube

Guidance on the use of Pitot static tubes is given in annex D. The Pitot static tube used shall be one of those specified in ISO 3966, and measurement may be made by one of the two following methods.

In method A (see 7.3.1), the probe shall be aligned with the axis of the pipe at each measuring position, and use made of a knowledge of the response of the particular Pitot static tube at various angles of inclination to the local flow direction. This method may be used only for swirl angles up to 20°.

In method B (see 7.3.2), the Pitot static tube shall be aligned with the local flow direction at each measuring position; from a knowledge of the measured velocity and the angle the local velocity makes with the pipe axis, the axial velocity can be calculated. This method applies over the whole range covered by this International Standard (that is, up to swirl angles of 40°).

NOTE — Fewer data are available at present to assess the uncertainty for method B than for method A.

In both cases, a preliminary traverse using a yaw probe is necessary to determine the angle of swirl at each of the measuring positions.

Two types of yaw probe are illustrated in figures 7 and 8; in both cases, the method of use is to rotate them about the axis of their stem until the pressures from the two pressure taps are equal : the probe is at that stage aligned with the local direction of flow. Before use, a test should be made with appropriate facilities (for example, in a wind tunnel) to determine the connection between this direction and a reference plane of the yaw probe itself.

7.3.1 Method A

This method may be used only when the angle which the local velocity makes with the axis of the pipe is less than 20° at all the measuring positions across the traverse plane.[1)]

The effect of swirl on the Pitot static tubes specified for use in this International Standard is given in figure 9 for typical probes, but the directional response of the particular probe used for the measurement shall be determined from previous calibration in an appropriate facility (for example, in a wind tunnel) since individual probes have different characteristics. The result of the calibration shall be expressed in terms of

$$k_\varphi = \cos \varphi \sqrt{\frac{\Delta p_o}{\Delta p_\varphi}}$$

versus the swirl angle φ, where Δp_o and Δp_φ are, for a given velocity, the values of differential pressure when the angle between the probe and the flow is, respectively, zero and φ.

After determining the angle of swirl with a yaw probe at each of the measuring positions, the head of the Pitot static tube shall be aligned parallel to the axis of the duct at each position at which a measurement of local velocity is required, and the differential pressure noted. From measurements of individual differential pressures Δp_φ and of individual angles of swirl, the individual point axial velocities v_x shall be calculated from the equation

$$v_x = k_\varphi \alpha (1 - \varepsilon) \sqrt{\frac{2\,\Delta p_\varphi}{\varrho}}$$

7.3.2 Method B

This method may be used only when the angle which the local velocity makes with the axis of the pipe is less than 40° at all of the measuring positions across the traverse plane.

After determining the angle of swirl with a yaw probe at each of the measuring positions, one of the Pitot static tubes specified in ISO 3966 shall be installed at each measuring position in turn. It shall be installed in such a way that the axis of the head is parallel to the local flow direction in each case. The differential pressures are then noted.

With this method, the radial positions of the nose of the Pitot static tube will be different from those of the yaw probe whenever swirl is present. They will not be located along a diameter of the duct, but will follow a curved path. This is illustrated in figure 15 which shows typical positions of the Pitot static tube when axi-symmetrical swirl occurs.

When prescribed locations of the Pitot static tube have to be used (as with the log-linear or log-Tchebycheff integration techniques), it is necessary to calculate the positions at which the Pitot static tube heel has to be located in order that the nose is at these radial positions. Conversely, if the numerical or graphical integration technique is used, it is necessary to calculate the radial positions at which the Pitot static tube nose will be located in terms of the radial positions chosen for the heel. The equation for these computations is given in annex C.

When method B is used, the maximum value of the local swirl angle limits the maximum usable diameter of the Pitot static tube head. Figure 10 shows the relationship between the maximum permissible value of the ratio d/D and the maximum local swirl angle, where d is the diameter of the Pitot static tube head and D the diameter of the duct.

The axial velocities shall be computed for each position from :

$$v_x = v \cos\theta$$

where

v_x is the axial velocity;

v is the magnitude of the vector velocity measured by probe calculated as described in ISO 3966;

θ is the angle that the flow makes with the axis of the duct.

7.4 Axial velocity measurement using a current-meter

The effect of swirl on the response of a current-meter is not well known and basically depends (among other things) on the type of propeller. It is, however, possible to relate the response of a given propeller to the angle it makes with the direction of local velocity; such a calibration may be obtained by towing the current-meter in a calibration tank as specified (see ISO 3455), but aligning it successively at different angles with respect to the axis of the channel. Figure 11 shows, as an example, the response obtained in this way for certain specific propellers.

When it is believed that swirl is present at the measuring section, it is generally advisable to use a special "self-compensating" design of propeller, which has been designed to measure directly the axial component, $v\cos\theta$, of the local velocity for velocities which make an angle of up to 30° with the propeller axis. In cases where the swirl angle never exceeds 30°, no correction is therefore required for this type of propeller. It should, however, be noted that such propellers have the disadvantage of being particularly sensitive to the influence of the current-meter support and to turbulence in the flow.

1) The AMCA probe may only be used for swirl of up to 15° with Method A, since information is not available on its response to greater yaw angles.

If, for these reasons, the use of a conventional type of propeller is preferred, it is necessary to determine in advance the angle of swirl, for example by traversing the measuring section with a yaw probe as described in 7.3. If θ is less than 5°, it can be assumed that a conventional propeller, aligned with the axis of the duct, will give a satisfactorily accurate measurement of the local axial velocity (the error will be less than ± 1 %). If θ is between 5° and 40°, then the reading of a given propeller shall be corrected according to a previous calibration of that propeller which has established the response of the instrument to inclinations at different angles to the flow. Above 40°, it is not possible to make accurate measurements. Further guidance on the use of current-meters is given in annex E.

8 Determination of mean flow velocity

The mean flow velocity shall be calculated by any of the integration techniques described in ISO 3354 or ISO 3966.

When a Pitot static tube is used, the turbulence of the flow produces an overestimate of the flow-rate (see annex C of ISO 3966) which, taking into account the particular conditions of the flows dealt with in this International Standard, lies generally between 1 and 2 %. This overestimate depends not only on the turbulence level, but also on the shape of the Pitot tube nose and it decreases when the Reynolds number increases. The value of the mean flow velocity previously obtained shall therefore be reduced by an amount between 1 and 2 %, that the user of this International Standard shall estimate to his best, taking into account the particular conditions of the measurement (see annex D).

When current-meters are used, no correction shall be applied to the measured value since, with these instruments, turbulence can introduce either positive or negative errors (see annex E).

9 Accuracy of flow-rate estimation

The uncertainty in the measurement of flow-rate shall be calculated in accordance with ISO 5168. Thus if the independant variables which have to be measured in order to compute the flow-rate are $X_1, X_2, \ldots X_k$, the absolute uncertainty e_q in the flow-rate is given by :

$$e_q^2 = \left[\frac{\partial q}{\partial X_1} e_1\right]^2 + \left[\frac{\partial q}{\partial X_2} e_2\right]^2 + \ldots + \left[\frac{\partial q}{\partial X_k} e_k\right]^2$$

where $e_1, e_2, \ldots e_k$, are the absolute uncertainties of $X_1, X_2, \ldots X_k$, respectively.

Since flow conditions can vary greatly, it is not possible to state that the flow-rate estimation will always have an uncertainty below some limiting value. It is however possible to give an indication of the order of magnitude of the errors which may arise in most cases.

9.1 Uncertainty arising from asymmetry

The percentage uncertainty E_Y which might arise from this source is given by equations in annex F depending on the number of radii along which traverses are made.

9.2 Uncertainty arising from swirl

The uncertainty which the existence of swirl might contribute to the flow-rate estimation will depend on the method and instrument used. There is little information on the effect of swirling flow in Pitot static tubes and current-meters.

For Pitot static tubes used with method A (7.3.1), there will be one error due to the determination of directional response of the probe and another error due to the fact that using a Pitot static tube in swirling flow is not exactly equivalent to inclining a Pitot tube in parallel flow : this was the case in the facility used to determine this response.

For Pitot static tubes used with method B (7.3.2), the main source of error due to the swirl is the not insignificant size of the probe and thus the effect of transverse velocity gradient.

For current-meters, the same sources of error as for Pitot tubes arise, increased by the fact that the conditions under which current-meters are calibrated depart still further from the operating conditions, the directional calibration being made generally by towing in still water.

In all cases, the percentage uncertainty E_s arising from swirl shall be assumed to increase with swirl angles. For the purpose of this International Standard, and for lack of more precise data, the value of E_s shall be taken as ± 5 % of the maximum value (expressed in degrees) of swirl angle observed in the measuring section. For swirl angles above 20°, the assessment of the uncertainty is less reliable.

9.3 Uncertainty arising from turbulence

In swirling or asymmetric flow conditions, the level of turbulence is often higher than it usually is for more regular flows, as considered in ISO 3354 or ISO 3966; the uncertainty from this source of error is thereby increased.

For Pitot static tubes, after reducing the observed flow-rate as indicated in clause 8, the value of the percentage uncertainty E_T arising from turbulence shall be taken as equal to the applied correction (that is, within ± 1 to ± 2 % according to the measuring conditions).

For current-meters, the axial and tangential components of the turbulence have opposite effects on the propellers normally used; these effects may partly compensate one another (see annex E). It is possible, therefore, that turbulence will introduce a smaller error to current-meter results than to Pitot tube results. Nevertheless, as a precaution, the percentage uncertainty E_T shall again be taken as being within ± 1 to ± 2 % according to the measuring conditions.

9.4 Overall uncertainties

The methods for calculating the overall uncertainty of a flow-rate measurement by the velocity-area method, using current-meters or Pitot static tubes, is described, respectively, in ISO 3354, subclause 11.6, and ISO 3966, subclause 12.6.

Furthermore, in asymmetric or swirling flow conditions, the uncertainties listed in 9.1 to 9.3 above shall be taken into account as follows.

— The uncertainty arising from turbulence has already been allowed for in the equation for calculating the uncertainty in the local velocities (see ISO 3354, subclause 11.6.1, or ISO 3966, subclause 12.6.1), but the value to be included in this equation shall be chosen in accordance with 9.3.

— The uncertainties arising from asymmetry and/or from swirl shall be combined by the root-sum-square method with the other component uncertainties already listed in the equation for calculating the overall uncertainty in the flow-rate measurement (see ISO 3354, subclause 11.6.2 or ISO 3966, subclause 12.6.2). According to the flow conditions, one or both of these sources of error shall be taken into account.

As noted earlier, it is not possible to specify precise values for the various uncertainties involved. Nevertheless, as a guide, the overall uncertainty in a flow-rate measurement in asymmetric or swirling flow conditions carried out in accordance with this International Standard will normally be between ± 2 and ± 4 %.

Higher uncertainties may result if the condition that there be no significant radial flow (see clause 1) is not fulfilled.

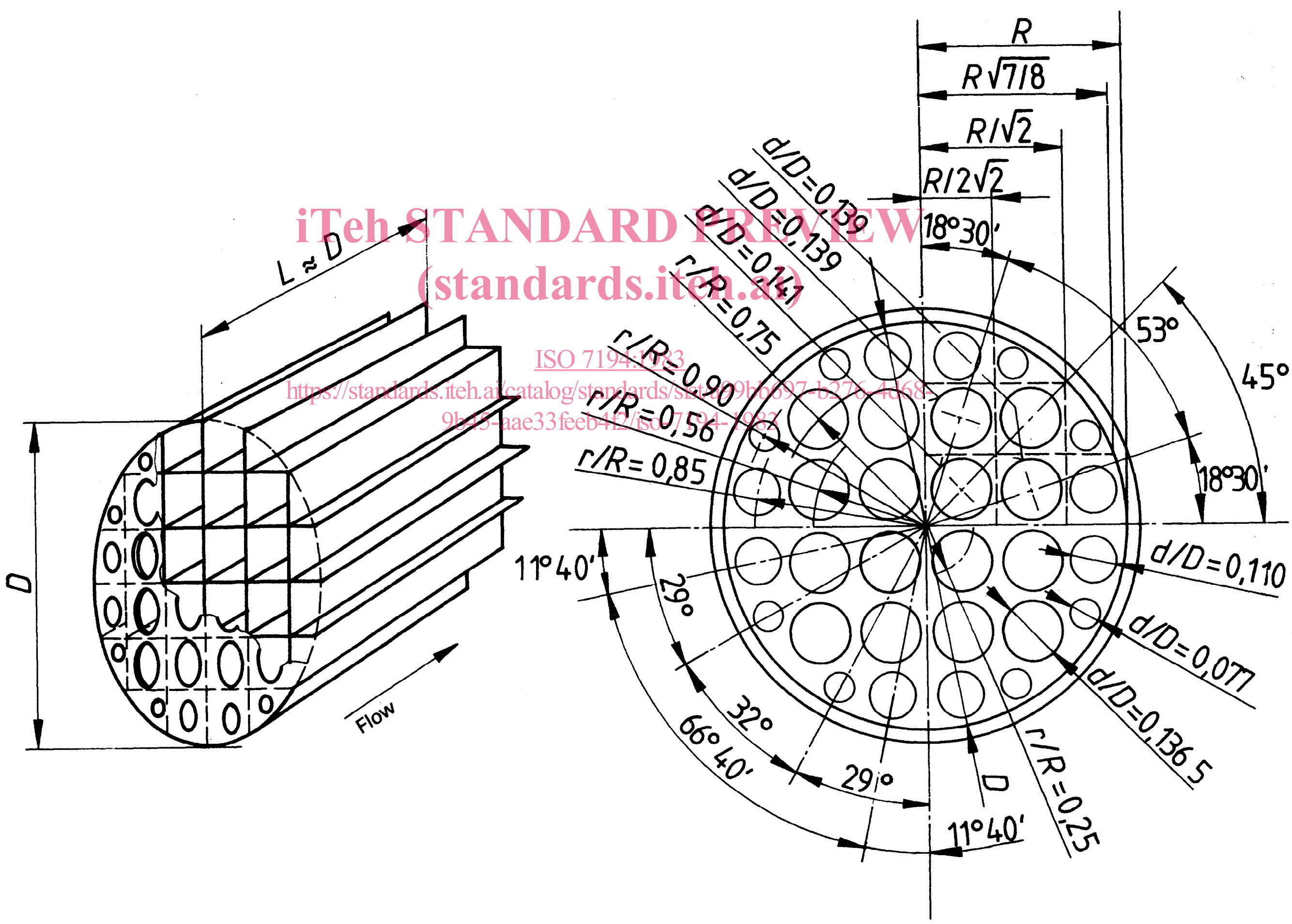

Figure 2 — Type A — Zanker straightener