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Flow measurement structures — Rectangular, trapezoidal and U-shaped flumes

Structures de mesure du débit — Canaux jaugeurs à col rectangulaire, à col trapézoïdal et à col en U

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 4359 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 2, *Flow measurement structures*.

This second edition cancels and replaces the first edition (ISO 4359:1983), which has been technically revised. It also incorporates the Technical Corrigendum ISO 4359:1983/Corr.1:1999.

INTERNATIONAL STANDARD **ISO 4359:2013(E)**

Flow measurement structures — Rectangular, trapezoidal and U-shaped flumes

1 Scope

This International Standard specifies methods for the measurement of flow in rivers and artificial channels under steady or slowly varying flow conditions, using certain types of standing-wave, or critical-depth, flumes.

A wide variety of flumes has been developed, but only those which have received general acceptance after adequate research and field testing, and which therefore do not require *in situ* calibration, are considered.

The flow conditions considered are uniquely dependent on the upstream head, i.e. subcritical flow must exist upstream of the flume, after which the flow accelerates through the contraction and passes through its critical depth (see Figure 1). The water level downstream of the structure is low enough to have no influence upon its performance.

This International Standard is applicable to three commonly used types of flumes, covering a wide range of applications, namely rectangular-throated, trapezoidal-throated and U-throated. Typical field installations are shown in Figure 2. Site conditions are important and Figure 3 shows acceptable velocity profiles in the approach channel.

Detailed illustrations of the three types of flumes covered by this International Standard are given as follows:

a) rectangular-throated (see Figure 4);

b) trapezoidal-throated (see Figure 5);

c) U-throated, i.e. round-bottomed (see Figure 6).

It is not applicable to a form of flume referred to in the literature — sometimes called a “Venturi” flume — in which the flow remains subcritical throughout.

NOTE This form is based on the same principle as a Venturi meter used within a closed conduit system and relies upon gauging the head at two locations and the application of Bernoulli’s energy equation.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Symbols

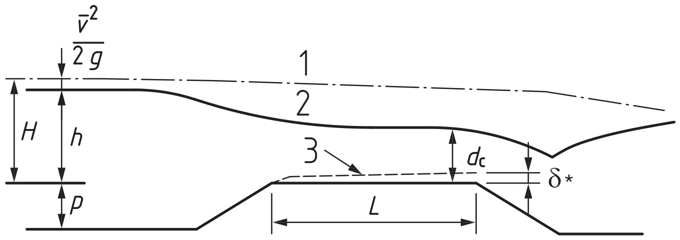
Units of measurement are metres (m) and seconds (s) or derivatives of these.

Symbol	Quantity	Unit of measurement
A	area of cross-section of flow	m^2
B	width of approach channel (width at bed if trapezoidal)	m
b	width of flume throat (width at bed if trapezoidal)	m
C	overall coefficient of discharge (rectangular flumes)	non-dimensional
C_c	coefficient of contraction	non-dimensional
C_D	coefficient of discharge	non-dimensional
C_s	shape coefficient for trapezoidal throated and U-throated flumes	non-dimensional
C_v	coefficient allowing for the effect of approach velocity	non-dimensional
D	diameter of base of U-throated flume	m
d	depth of flow	m
E	specific energy (relative to local invert)	m
Fr	Froude number	non-dimensional
g	gravitational acceleration	m/s^2
H	total head (relative to a specified datum, such as a flume invert)	m
H_*	correction to the total head	m
h	gauged head	m
k_s	equivalent sand roughness of surface, after Nikuradse	mm
L	length of prismatic section of the contraction at a flume	m
L_1	length of bellmouth entrance	m
L_2	length of slope (if present) between throat and downstream stilling basin or channel floor	m
L_3	length of stilling basin (if present)	m
m	side-slope (m horizontal to 1 vertical)	non-dimensional
n	number of measurements in series	non-dimensional
P	wetted perimeter of flow cross-section	m
p	height of flume invert above the invert of the approach channel	m
Q	discharge	m^3/s
R	radius	m
Re	Reynolds number	non-dimensional
r_p	radius of hump	m
R_1	radius of bellmouth entrance	m
S	standard deviation	—
$\bar{S}$	standard error of the mean	—
$\bar{v}$	average velocity through a cross-section, defined by Q/A	m/s
w	water surface width	m

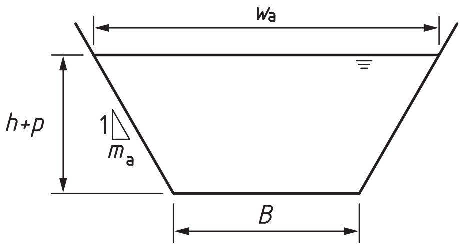
Symbol	Quantity	Unit of measurement
$u^*(Q)_{68}$	overall percentage uncertainty in the determination of discharge expressed as a percentage standard deviation at 68 % confidence limits	non-dimensional
$u^*(b)$	percentage uncertainty in b (or D)	non-dimensional
$u^*(C)$	percentage uncertainty in the combined coefficient value	non-dimensional
$u^*(h)$	percentage uncertainty in h	non-dimensional
$u^*(m)$	percentage uncertainty in m	non-dimensional
α	kinetic energy correction coefficient (taking into account non-uniformity of velocity distribution)	non-dimensional
β	coefficient dependent on mean curvature of stream lines	non-dimensional
γ, φ, ψ	coefficients in the uncertainty computation	—
δ^*	boundary layer displacement thickness	m
η	a numerical coefficient related to the sideslope angle in trapezoidal flumes	non-dimensional
ν	kinematic viscosity of the fluid	m^2/s
θ	semi-angle subtended at the centre of curvature of the invert of a U-throated flume between the water surface and the vertical	non-dimensional
σ	semi-angle subtended at the centre of curvature of the invert of a U-throated flume between the water surface and the horizontal	non-dimensional
Subscripts		
a	values in approach channel	
c	values at critical flow	
d	values downstream of the flume	
e	effective values after making allowance for boundary layer effects	
1	values assuming an ideal frictionless fluid	
M	maximum value	

5 Flume types and principles of operation

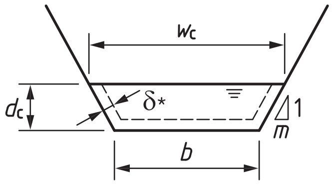
5.1 The flumes covered by this International Standard are often known as “long-throated” or “critical-depth” flumes and rely fundamentally on the occurrence of critical flow in the flume throat. When this occurs, there is a unique relationship, for a given flume geometry, between the upstream head and the discharge, that is independent of the conditions downstream of the flume throat. Figure 1 shows a simplified sketch of where the critical depth typically occurs in a critical depth flume and the consequent water surface profile through a long-throated trapezoidal flume, together with key hydraulic and geometrical parameters.



a)



b) Section in approach channel upstream from throat



c) Section at downstream end of throat

Key

1 total energy line

2 typical flow profile

3 edge of boundary layer displacement thickness

δ^* has been exaggerated.

Figure 1 — Trapezoidal-throated flume showing key geometrical parameters, water surface profile and development of boundary layer displacement thickness (after Figure 8.1, Ref.[9])

5.2 Because the flume design is based on critical flow, this International Standard is largely based on fundamental hydraulic theory, without the need for the large-scale volumetric testing that has been used to derive the coefficients for other forms of flow measurement structure. In order to obtain critical flow within the throat of the flume, the following conditions shall be satisfied.

a) The throat of the flume shall be long enough for the flow to be virtually parallel with the flume invert, so that hydrostatic pressure conditions occur at the *control section*.

b) The entrance to the flume throat shall be shaped so that there are virtually no energy losses between the point where the head is gauged and the point where critical flow occurs.

c) The flume throat shall constrict the channel severely enough to raise the energy level in the throat sufficiently high above the energy level downstream to ensure that the flume is “modular”.

5.3 Figure 2 shows examples of flow in rectangular-throated, trapezoidal-throated and U-throated flumes. The choice of flume type from these three depends upon several factors, such as the range of discharge to be measured, the accuracy required, the head available and whether or not the flow carries sediment that is liable to accrete. The graphs in Annex A give the user of this International Standard a means of quickly comparing the idealized performance of a range of flume designs, to aid a preliminary choice of the size and form of flume needed to deliver the required discharge capacity and stage–discharge relationship.

a) Rectangular-throated flume **b) Trapezoidal-throated flume** **c) U-throated flume**

Figure 2 — Examples of rectangular-throated, trapezoidal-throated and U-throated flumes

5.4 The rectangular-throated flume is the simplest to construct. It generally proves necessary to raise the invert of the flume throat above the bed of the channel upstream, in order to generate a constriction that is sufficiently severe to allow low flows to be gauged. However, this may result in a regime of cyclic sediment accretion and erosion upstream, which would affect the accuracy and consistency of gauging.

5.5 The trapezoidal-throated flume is more appropriate where a wide range of discharge is to be measured with consistent accuracy. This shape of throat is also more likely to be suitable where it is desirable to produce a particular stage-discharge relationship. In some cases, it is not necessary to raise the invert of the throat above the approach channel invert when using a trapezoidal-throated flume, so reducing the risk of upstream sediment accretion.

5.6 The U-throated flume is useful for installation in a U-shaped channel or where the flow is from a circular-section conduit. It has found particular application in sewers and at sewage works.

5.7 The detailed theory for the critical-depth flume is given in Clauses 9 to 12, but is introduced here in simplified form, based on the assumption of a uniform velocity across the flow section and disregarding boundary layer effects. The basic discharge equation for a critical-depth flume can be derived from the general energy equation:

$$H = d + \frac{\bar{v}^2}{2g} = d + \frac{Q^2}{2gA^2} \tag{1}$$

where

H is the total head above the flume invert;

d is the depth of flow;

$\bar{v}$ is the average velocity through the section (= Q/A);

Q is the discharge;

A is the area of the flow cross-section;

g is the gravitational acceleration.

By differentiating the energy Formula (1) with respect to depth, it can be shown that, for critical flow:

$$Q = \sqrt{\frac{gA_c^3}{w_c}} \tag{2}$$

where subscript c refers to conditions at the critical-flow section.

Substituting Formula (2) into Formula (1) and disregarding any energy losses between the gauging section and the critical-flow section, the following is obtained:

$$H = d_c + \frac{A_c}{2w_c} \tag{3}$$

5.8 In general, Formulae (2) and (3) are solved alongside each other for successive values of depth d_c (with the corresponding values of area and surface width) to obtain the relationship between H and Q, but for the special case of a flume with a rectangular throat (see Figure 4), they can be combined to produce the explicit relationship:

$$Q = \frac{2}{3}\sqrt{\frac{2g}{3}}\, bH^{1,5} \tag{4}$$

5.9 This is readily recognizable as the same equation that applies (for an ideal fluid) for the flow over a round-nosed horizontal-crested weir. In order to extend the use of this equation, three additional coefficients may be introduced, resulting in the following generalized equation for long-throated critical-depth flumes:

$$Q = \frac{2}{3}\sqrt{\frac{2g}{3}}\, C_D C_s C_v\, b\, h^{1,5} \tag{5}$$

where the coefficients are as follows:

C_D is a discharge coefficient that takes account of the non-ideal fluid properties, in particular the effect of the boundary layer in the throat;

C_s is a shape coefficient, to allow for the effect of a non-rectangular flow section in the throat;

C_v is a velocity coefficient, to allow the upstream gauged head, h, to be used in place of the total head or specific energy, H.

5.10 Equations for these coefficients are given in Clauses 9 to 12 and generally require an iterative approach to be adopted.

6 Installation

6.1 Selection of site

6.1.1 The flume shall be located in a straight section of channel, avoiding local obstructions, roughness or unevenness of the bed.

6.1.2 A preliminary study shall be made of the physical and hydraulic features of the proposed site, to check that it conforms (or can be constructed or modified so as to conform) to the requirements necessary for measurement of discharge by a flume. Particular attention should be paid to the following features in selecting the site.

a) The availability of a straight length of approach channel of at least 10 times the maximum head anticipated.

b) The existing velocity distribution.

c) The avoidance of a steep channel, the characteristics of which would induce supercritical flow.

d) The effects of any raised upstream water levels due to the measuring structure.

e) Conditions downstream, including such influences as tides, confluences with other streams, sluice gates, mill dams and other controlling features which might cause submerged flow.

f) The impermeability of the ground on which the structure is to be founded and the necessity for piling, grouting or other means of controlling seepage.

g) The necessity for floodbanks, to confine the maximum discharge to the channel.

h) The stability of the banks, and the necessity for trimming and/or revetment in natural channels.

i) The clearance of rocks or boulders from the bed of the approach channel.

j) Wind, which can have a considerable effect on the flow in a river, weir or flume, especially when these are wide and the head is small and when the prevailing wind is in a transverse direction (which would introduce a bias whose direction would depend on whether the gauge were at the windward or leeward side of the approach channel).

6.1.3 If the site does not possess the characteristics necessary for satisfactory measurement, the site shall be rejected unless suitable improvements are practicable.

6.1.4 If an inspection of the stream shows that the existing velocity distribution is reasonably uniform, then it may be assumed that the velocity distribution will remain satisfactory after the construction of the flume.

6.1.5 If the existing velocity distribution is markedly non-uniform and no other site for the flume is feasible, due consideration shall be given to checking the distribution after installation of the flume and to improving it if necessary.

6.1.6 Several methods are available for obtaining a more precise indication of irregular velocity distribution: velocity rods, floats or concentrations of dye can be used in small channels, the latter being useful in checking conditions at the bottom of the channel. A complete and quantitative assessment of velocity distribution may be made by means of a current-meter and other point velocity measurements.

NOTE Information about the use of current-meters is given in ISO 748. Further information on measuring river velocities and using acoustic Doppler profilers can be found in ISO/TS 24154.

The user should confirm that the dye material used is acceptable for flow measurement purposes within a natural channel in the country of operation.

6.1.7 Figure 3 gives typical examples of velocity distributions in channels of varying shape that can be taken as acceptable for flow measurement purposes.

6.1.8 Flumes can act as obstacles to the movement of fish and other aquatic species. Care should therefore be taken to ensure that the installation of gauging structures such as flumes does not have a detrimental affect on the aquatic ecology where this might be an issue. In addition, the gauging structure may be subject to compliance with national or supranational legislation or regulations, such as the

European Parliament EU Water Framework Directive (Directive 2000/60/EC). Where the movement of aquatic life could be compromised by the installation of a flow measurement structure this should be reflected in the design. Alternatively, a fishpass in accordance with ISO 26906 should be installed.

6.1.9 Reference to appropriate legislation should be made before a site for a measuring weir is chosen.

6.2 Installation conditions

6.2.1 General requirements

6.2.1.1 The complete measuring installation consists of an approach channel, a measuring structure and a downstream channel. The conditions of each of these three components affect the overall accuracy of the measurements.

6.2.1.2 Installation requirements include features such as the surface finish of the flume, the cross-sectional shape of channel, the channel roughness and the influence of control devices upstream or downstream of the gauging structure.

6.2.1.3 The distribution and direction of velocity have an important influence on the performance of the flume, these factors being determined by the features mentioned above.

6.2.1.4 Once a gauging flume has been installed, the user shall prevent any change that could affect the discharge characteristics.

6.2.2 Flume structure

6.2.2.1 The structure shall be rigid and watertight and capable of withstanding flood flow conditions without distortion or fracture, from outflanking or from downstream erosion. The axis shall be in line with the direction of flow of the upstream channel, and the geometry shall conform to the dimensions given in Clauses 10, 11 and 12.

6.2.2.2 The surfaces of the flume throat and the immediate approach channel shall be smooth. They shall be constructed in concrete with a smooth cement finish or surfaced with a smooth non-corrodible material. In laboratory installations, the finish shall be equivalent to rigid plastic, rolled sheet metal or planed, sanded and painted timber. The surface finish is of particular importance within the prismatic part of the throat but can be relaxed a distance along the profile $0,5H_{max}$ upstream and downstream of the throat proper.

The user should confirm that the building materials used in the construction of natural channels are acceptable in the country of operation.

6.2.2.3 In order to minimize the uncertainty in the discharge, the following tolerances are acceptable:

a) on the bottom width of the throat, 0,2 % of this width with an absolute maximum of 0,01 m;

b) on deviation from a plane of the plane surfaces in the throat, 0,1 % of L;

c) on the width between vertical surfaces in the throat, 0,2 % of this width with a maximum of 0,01 m;

d) on the average longitudinal and transverse slopes of the base of the throat, 0,1 %;

e) on a slope of inclined surfaces in the throat, 0,1 %;

f) on a length of the throat, 1 % of L;

g) on deviation from a cylindrical or a conical surface in the entrance transition to the throat, 0,1 % of L;

h) on deviation from a plane of the plane surfaces in the entrance transition to the throat, 0,1 % of *L*;

i) on deviation from a plan of the plane surface in the exit transition from the throat, 0,3 % of *L*;

j) on other vertical or inclined surfaces, deviation from a plane or curve, 1 %;

k) on deviation from a plane of the bed of the lined approach channel, 0,1 % of *L*.

6.2.2.4 The structure shall be measured on completion, and average values of relevant dimensions and their standard deviations at 68 % confidence limits computed. The former shall be used for computation of discharge and the latter shall be used to obtain the overall uncertainty in the determination of discharge.

6.2.3 Approach channel

6.2.3.1 On all installations the flow in the approach channel shall be free from disturbance and shall have a velocity distribution as uniform as reasonably practicable over the cross-sectional area. Figure 3 shows typical dimensionless velocity distributions in rectangular and trapezoidal channels, which are relevant in site selection. For a given shape of channel, the velocity distribution should be reasonably similar to one of those presented in Figure 3. This can usually be verified by inspection or measurement. In the case of natural streams or rivers this can only be attained by having a long straight approach channel free from projections into the flow.

6.2.3.2 The following are general recommendations and requirements related to the approach channel.

a) Any alteration in the flow conditions owing to the construction of the flume should be considered. For example, there might be a build-up of shoals or debris upstream of the structure, which in time might affect the flow conditions. Any likely consequential changes in the water level therefore need to be taken into account in the design of gauging stations.

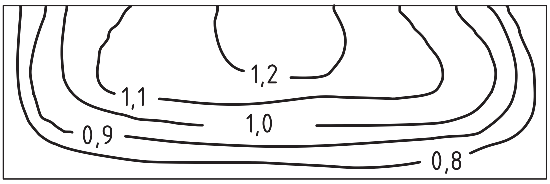
b) In an artificial channel the cross-section shall be uniform and the channel shall be straight for a length equal to at least 10 times its water-surface width.

c) In a natural stream or river the cross-section shall be reasonably uniform and the channel shall be straight for a sufficient length to ensure a reasonably uniform velocity distribution.

d) If the entry to the approach channel is through a bend, or if the flow is discharged into the channel through a conduit or a channel of smaller cross-section, or at an angle, then a longer length of straight approach channel may be required to achieve a reasonably uniform velocity distribution.

e) Vanes to straighten the flow shall not be installed closer to the points of measurement than a distance 10 times the maximum head to be measured.

f) Under certain conditions, a standing wave may occur upstream of the gauging flume, for example if the approach channel is steep. Provided that this wave is at a distance of not less than 30 times the maximum head upstream, flow measurement is feasible, subject to confirmation that a reasonably uniform velocity distribution exists at the gauging station and that the Froude number in this section is no more than 0,6. Ideally, high Froude numbers should be avoided in the approach channel for accurate flow measurement. If a standing wave occurs within this distance the approach conditions and/or the flume shall be modified.



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