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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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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This third edition cancels and replaces the second edition (ISO 4359:2013), which has been technically revised. It also incorporates the Amendment ISO 4359:2013/Amd.1:2017.

The main changes are as follows:

- 6.1.2 a) and 6.2.3.2 b) have been revised with respect to the flume approach conditions.
- Errors that were introduced in Amendment ISO 4359:2013/Amd.1:2017 have been corrected.
- An acknowledgement has been added that some of the specified tolerances can be difficult to achieve in some installations.
- The spreadsheets have been revised to provide further advice if parameters are outside the applicability range of the curve-fitting formulae for the relative boundary layer thickness (δ^*/L).
- The first edition of this document (ISO 4359:1983) had an additional limitation requiring that the gauged head, h, be not more than 2 m. However, there is no technical justification for this restriction, so it does not appear in the second and third editions of this document.
- In 11.4.7 and 12.4.7, although the relationship of C_s with mH_e/b_e varies very slightly with flume geometry and the value of the boundary layer displacement thickness, this variation was disregarded when applying the coefficient method in the first edition of this document, as a single graphical relationship was provided for trapezoidal flumes. This approximation has been remedied in the second and third editions of this document.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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

1 Scope

This document specifies methods for the measurement of flow in rivers and artificial channels under steady or slowly varying flow conditions, using certain types of critical-depth flumes (also known as "standing-wave flumes"). A wide variety of flumes has been developed, but only those critical-depth flumes which have received general acceptance after adequate research and field testing, and which therefore do not require *in situ* calibration, are considered herein.

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 document is applicable to three commonly used types of flumes, covering a wide range of applications, namely rectangular-throated, trapezoidal-throated and U-throated. The hydraulic theory behind this document was presented in Reference [7].

This document 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 The Venturi form of flume 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 formula.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. 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.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at https://www.electropedia.org/

4 Symbols

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

Symbol	Quantity	Unit of measurement
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	instrument range in uncertainties evaluation	non-dimensional
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	—
$u(E)$	relative datum uncertainty in uncertainties evaluation	m
$u^*(Q)_{68}$	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
$\bar{V}$	average velocity through a cross-section, defined by Q/A	m/s
w	water surface width	m
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

Symbol	Quantity	Unit of measurement
θ	semi-angle subtended at the centre of curvature of the invert of a U-throated flume between the water surface and the vertical	radians
σ	semi-angle subtended at the centre of curvature of the invert of a U-throated flume between the water surface and the horizontal	radians
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

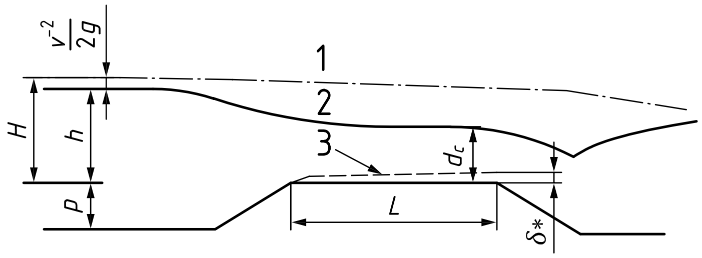
5.1 The flumes covered by this document are often known as “long-throated” or “critical-depth” flumes and rely fundamentally on the occurrence of critical flow in the flume throat. When this occurs, there is a unique relationship, for a given flume geometry, between the upstream head and the discharge, 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. Typical field installations of the three types of flumes covered by this document are shown in Figure 2. The three types are:

a) rectangular-throated;

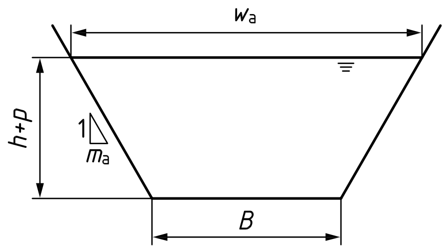
b) trapezoidal-throated;

c) U-throated, i.e. round-bottomed.

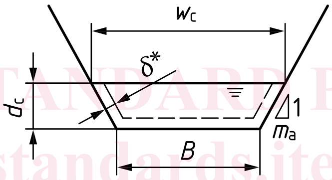
Site conditions are important and Figure 3 shows acceptable velocity profiles in the approach channel.



a) Longitudinal section



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.

NOTE Adapted from Figure 8.1 in Reference [6].

Figure 1 — Trapezoidal-throated flume showing key geometrical parameters, water surface profile and development of boundary layer displacement thickness

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

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

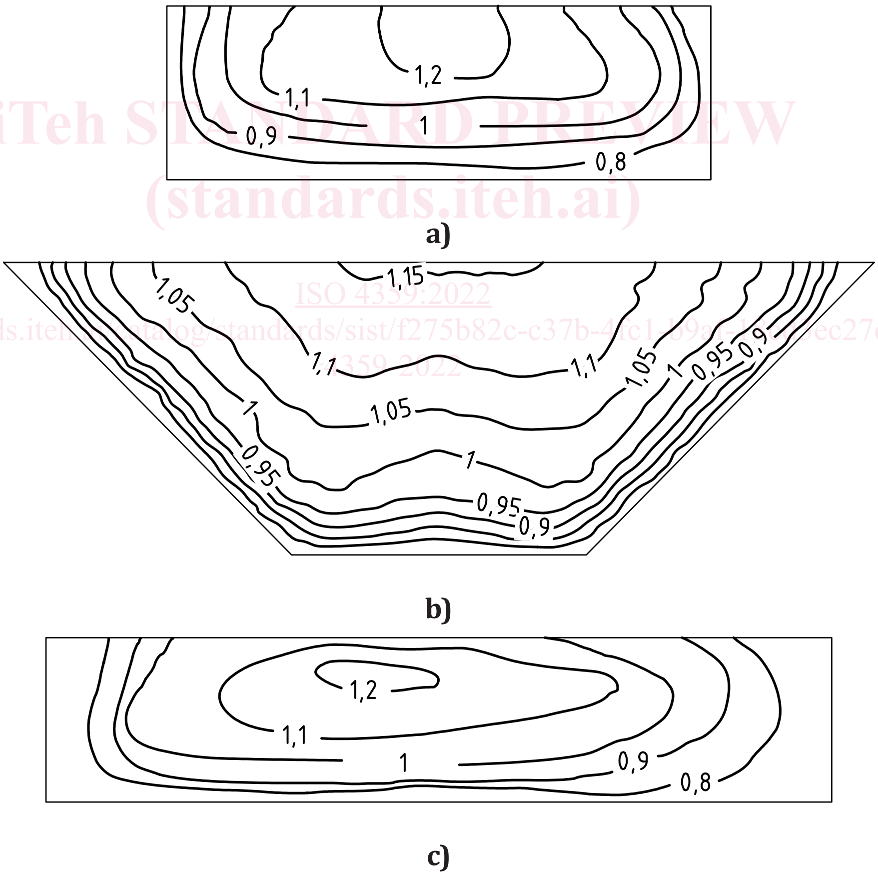


Figure 3 — Examples of typical dimensionless velocity distributions in approach channels

5.2 Because the flume design is based on critical flow, this document 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. It can be observed that, in comparison with weirs, flumes provide a lesser obstruction to the passage of sediment, so are less likely to cause significant accretion of sediment (which can affect the approach channel geometry at the flow gauging location). The graphs in Annex A provide 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.

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 can 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 formula for a critical-depth flume can be derived from the general energy formula, as shown by Formula (1):

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

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 in Formula (1) with respect to depth, it can be shown by Formula (2) that, for critical flow:

$$Q=\sqrt{\frac{gA_{\mathrm{c}}^{3}}{w_{\mathrm{c}}}} \qquad (2)$$

where w is the water surface width and the 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, Formula (3) is obtained:

$$H=d_{\mathrm{c}}+\frac{A_{\mathrm{c}}}{2w_{\mathrm{c}}} \qquad (3)$$

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 9.2.2), they can be combined to produce the explicit relationship, as given by Formula (4):

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

5.9 This is readily recognizable as the same formula that applies (for an ideal fluid) for the flow over a round-nosed horizontal-crested weir. In order to extend the use of this formula, three additional coefficients may be introduced, resulting in a generalized formula for long-throated critical-depth flumes, as given by Formula (5):

$$Q=\frac{2}{3}\sqrt{\frac{2g}{3}}\,C_{\mathrm{D}}C_{\mathrm{s}}C_{v}\,b\,h^{1,5} \qquad (5)$$

where

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 Formulae 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 sufficient straight length of approach channel.

b) The acceptable degree of uniformity of the existing velocity distribution (see Figure 3).

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 can 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 dye observations 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.

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 effect on the aquatic ecology where this can be an issue.

NOTE National or supranational legislation or regulations, such as the European Parliament EU Water Framework Directive (Directive 2000/60/EC), can apply to the gauging structure.

Where it is possible that the movement of aquatic life can 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 Appropriate legislation should be identified 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 can 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, providing that no tolerance with respect to alignment or dimension is required to be less than 0,001 m:

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;