Designation: D5390 – 93 (Reapproved 2013)

Standard Test Method for
Open-Channel Flow Measurement of Water with Palmer-Bowlus Flumes[1]

This standard is issued under the fixed designation D5390; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers measurement of the volumetric flowrate of water and wastewater in sewers and other open channels with Palmer-Bowlus flumes.

1.2 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1129 Terminology Relating to Water

D1941 Test Method for Open Channel Flow Measurement of Water with the Parshall Flume

D2777 Practice for Determination of Precision and Bias of Applicable Test Methods of Committee D19 on Water

D3858 Test Method for Open-Channel Flow Measurement of Water by Velocity-Area Method

D5242 Test Method for Open-Channel Flow Measurement of Water with Thin-Plate Weirs

2.2 *ISO Standards:*[3]

ISO 4359 Liquid Flow Measurement in Open Channels—Rectangular, Trapezoidal and U-Shaped Flumes

ISO 555 Liquid Flow Measurements in Open Channels—Dilution Methods for Measurement of Steady Flow—Constant Rate Injection Method[3]

2.3 *ASME Standard:*[4]

Fluid Meters— Their Theory and Application

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method refer to Terminology D1129.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *boundary layer displacement thickness*— the boundary layer is a layer of fluid flow adjacent to a solid surface (in this case, the flume throat) in which, owing to viscous friction, the velocity increases from zero at the stationary surface to an essentially frictionless-flow value at the edge of the layer. The displacement thickness is a distance normal to the solid surface that the surface and flow streamlines can be considered to have been displaced by virtue of the boundary-layer formation.

3.2.2 *critical flow*—open channel flow in which the energy expressed in terms of depth plus velocity head, is a minimum for a given flowrate and channel. The Froude number is unity at critical flow.

3.2.3 *Froude number*—a dimensionless number expressing the ratio of inertial to gravity forces in free-surface flow. It is equal to the average velocity divided by the square root of the product of the average depth and the acceleration due to gravity.

3.2.4 *head*—the depth of flow referenced to the floor of the throat measured at an appropriate location upstream of the flume; this depth plus the velocity head is often termed the total head or total energy head.

3.2.5 *hydraulic jump*—an abrupt transition from supercritical flow to subcritical or tranquil flow, accompanied by considerable turbulence or gravity waves, or both.

3.2.6 *long-throated flume*—a flume in which the prismatic throat is long enough relative to the head for essentially critical flow to develop on the crest.

3.2.7 *primary instrument*—the device (in this case the flume) that creates a hydrodynamic condition that can be sensed by the secondary instrument.

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[1] This test method is under the jurisdiction of ASTM Committee D19 on Water and is the direct responsibility of Subcommittee D19.07 on Sediments, Geomorphology, and Open-Channel Flow.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[4] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990, http://www.asme.org.

3.2.8 *Reynolds number*—a dimensionless number expressing the ratio of inertial to viscous forces in a flow. In a flume throat the pertinent Reynolds number is equal to the (critical) throat velocity multiplied by the throat length and divided by the kinematic viscosity of the water.

3.2.9 *scow float*—an in-stream float for depth sensing, usually mounted on a hinged cantilever.

3.2.10 *secondary instrument*—in this case, a device that measures the depth of flow (referenced to the throat elevation) at an appropriate location upstream of the flume. The secondary instrument may also convert this measured head to an indicated flowrate, or could totalize flowrate.

3.2.11 *stilling well*—a small free-surface reservoir connected through a restricted passage to the approach channel upstream of the flume so that a head measurement can be made under quiescent conditions.

3.2.12 *subcritical flow*—open channel flow that is deeper and at lower velocity than critical flow for the same flowrate; sometimes called tranquil flow.

3.2.13 *submergence*—a condition where the depth of flow immediately downstream of the flume is large enough to affect the flow through the flume so that the flowrate can no longer be related to a single upstream head.

3.2.14 *supercritical flow*—open channel flow that is shallower and at higher velocity than critical flow for the same flowrate.

3.2.15 *tailwater*—the water elevation immediately downstream of the flume.

3.2.16 *throat*—the constricted portion of the flume.

3.2.17 *velocity head*—the square of the average velocity divided by twice the acceleration due to gravity.

4. Summary of Test Method

4.1 In Palmer-Bowlus flumes, critical free-surface flow is developed in a prismatic throat so that the flowrate is a unique function of a single measured upstream head for a given throat shape and upstream channel geometry. This function can be obtained theoretically for ideal (frictionless) flows and adjustments for non-ideal conditions can be obtained experimentally or estimated from fluid-mechanics considerations.

5. Significance and Use

5.1 Although Palmer-Bowlus flumes can be used in many types of open channels, they are particularly adaptable for permanent or temporary installation in circular sewers. Commercial flumes are available for use in sewers from 4 in. to 6 ft (0.1 to 1.8 m) in diameter.

5.2 A properly designed and operated Palmer-Bowlus is capable of providing accurate flow measurements while introducing a relatively small head loss and exhibiting good sediment and debris-passing characteristics.

6. Interferences

6.1 Flumes are applicable only to open-channel flow and become inoperative under full-pipe flow conditions.

6.2 The flume becomes inoperative if downstream conditions cause submergence (see 7.3.2).

7. Apparatus

7.1 A Palmer-Bowlus flume measuring system consists of the flume itself (the primary), with its immediate upstream and downstream channels, and a depth or head measuring device (the secondary). The secondary device can range from a simple scale or gage for manual readings to an instrument that continuously senses the head, converts it to a flowrate, and displays or transmits a readout or record of the instantaneous flowrate or the totalized flow, or both.

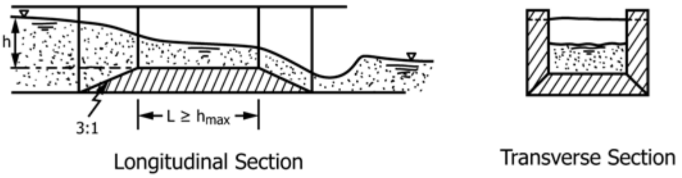

FIG. 1 Generalized Palmer-Bowlus (Long-Throated) Flume in a Rectangular Channel

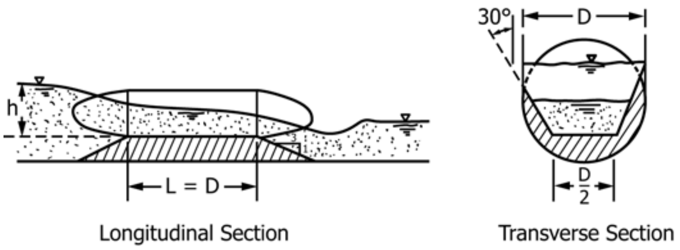

FIG. 2 Palmer-Bowlus Flume (Typical) for Sewer

7.2 *The Palmer-Bowlus Flume:*

7.2.1 *General Configuration:*

7.2.1.1 The Palmer-Bowlus flume is a class of long-throated flume in which critical flow is developed in a throat that is formed by constricted sidewalls or a bottom rise, or both. Sloped ramps form gradual transitions between the throat and the upstream and downstream sections. See Fig. 1. The flume was developed primarily for use in sewers[5] but it is adaptable to other open channels as well. There is no standardized shape for Palmer-Bowlus flumes and, as long-throated flumes, they can be designed to fit specific hydraulic situations using the theory outlined in 7.2.3.

7.2.1.2 *Prefabricated Flumes*—Prefabricated flumes with trapezoidal or rectangular throats and with circular or U-shaped outside forms are commercially available for use in sewers. Although there is no fixed shape for Palmer-Bowlus flumes, many manufacturers of trapezoidal-throated flumes use the proportions shown in Fig. 2. These prefabricated flumes are also available in several configurations depending on how they are to be installed, for example, whether they will be placed in the channel at the base of an existing manhole, inserted into the pipe immediately downstream of the manhole, or incorporated

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[5] Palmer, H. K., and Bowlus, F. D., "Adaptation of Venturi Flumes to Flow Measurements in Conduits," Trans. ASCE, Vol 101, 1936, pp. 1195–1216.

into new construction. The size of these prefabricated flumes is customarily referenced to the diameter of the receiving pipe rather than to the throat width. Refer to manufacturers' literature for flume details.

7.2.1.3 Because the dimensions of prefabricated flumes may differ depending upon the manufacturer or the configuration, or both, it is important that users check interior dimensions carefully before installation and insure that these dimensions are not affected by the installation process.

7.2.1.4 A Palmer-Bowlus flume can be fabricated in a pipe by raising the invert (see Fig. X3.1). Floor slabs that can be grouted into existing sewers are commercially available, as are prefabricated slab-pipe combinations for insertion into larger pipes. Details may be obtained from the manufacturers' literature. Discharge equations for this throat shape are given in Appendix X1.

7.2.2 *Head Measurement Location*—The head, h, on the flume is measured at a distance upstream of the throat-approach ramp that is preferably equal to three times the maximum head. When the maximum head is restricted to one-half the throat length, as is recommended in this test method, an upstream distance equal to the maximum head will usually be adequate to avoid the drawdown curvature of the flow profile.

7.2.3 *Discharge Relations:*

7.2.3.1 The volumetric flowrate, *Q*, through a Palmer-Bowlus flume of bottom throat width, *B* , operating under a head, h, above the throat floor is:

$$Q = (2/3)(2g/3)1/2 C_D C_S C_V B h^{\frac{3}{2}} \quad (1)$$

where g is the acceleration due to gravity and $C_D C_S$ and C_V are, respectively, the discharge coefficient, throat shape coefficient, and velocity-of-approach coefficient as defined in the following sections. The derivation of Eq 1 is outlined in Appendix X2.

7.2.3.2 *Discharge Coefficient, C_D*—This coefficient approximates the effect of viscous friction on the theoretical discharge by allowing for the development of a boundary layer of displacement thickness δ_* along the bottom and sides of the throat:

$$C_D = (B_e/B)(1 - \delta_*/h)^{\frac{3}{2}} \quad (2)$$

Here B_e is an effective throat width given by:

$$B_e = B - 2\delta_*\left[(m^2+1)^{\frac{1}{2}} - m\right] \quad (3)$$

where m is the horizontal-to-vertical slope of the sides of the throat (zero for rectangular throats). The displacement thickness, δ_*, is a function of the throat Reynolds number and surface roughness. However, a reasonable approximation that is adequate for many applications is:

$$\delta_* = 0.003\,L \quad (4)$$

where L is the length of the throat. (Better estimates of δ_* can be obtained from boundary-layer theory, as in ISO 4359.)

7.2.3.3 *Shape Coefficient, C_S (See Also Appendix X2)*—C_S is given in Table 1 as a function of mH_e/B_e. H_e is the upstream total effective head, which is (for essentially uniform upstream velocity distribution):

$$H_e = h + V_u^{\,2}/2g - \delta_* \quad (5)$$

where V_u is the average velocity at the position of head measurement. For a rectangular throat, $m + 0$ and C_S is unity.

7.2.3.4 *Velocity-of-Approach Coefficient, C_V*—This coefficient allows the flowrate to be expressed conveniently in terms of the measured head, *h*, rather than the total head, *H*:

$$C_V = [(H - \delta_*)/(h - \delta_*)]^{\frac{3}{2}} = (H_e/h_e)^{\frac{3}{2}} \quad (6)$$

C_V is given in Table 2 as a function of $C_S B_e h_e / A_u$, where A_u is the cross-sectional area of the flow at the head measurement station. See also Appendix X3.

7.2.3.5 *Limiting Conditions*—The foregoing discharge equation and coefficients are valid for the following conditions:

(a) $0.1 \leq h/L \leq 0.5$, with minimum $h = 0.15$ ft (0.05 m),

(b) $B \leq 0.33$ ft (0.1 m),

(c) $h < 6$ ft (2 m),

(d) The throat ramp slopes do not exceed one or three,

(e) Throat floor is level,

(f) Trapezoidal throat section is high enough to contain the maximum flow, and

(g) Roughness of throat surfaces does not exceed that of smooth concrete.

TABLE 1 Shape Coefficient, C_S

mH_e/B_e	C_S	mH_e/B_e	mC_S	mH_e/B_e	C_S	mH_e/B_e	C_S
0.010	1.007	0.40	1.276	1.80	2.288	3.80	3.766
0.015	1.010	0.45	1.311	1.90	2.360	3.90	3.840
0.020	1.013	0.50	1.346	2.00	2.433	4.00	3.914
0.025	1.017	0.55	1.381	2.10	2.507	4.10	3.988
0.030	1.020	0.60	1.417	2.20	2.582	4.20	4.062
0.040	1.028	0.65	1.453	2.30	2.657	4.30	4.136
0.050	1.035	0.70	1.490	2.40	2.731	4.40	4.210
0.060	1.041	0.75	1.527	2.50	2.805	4.50	4.284
0.070	1.048	0.80	1.564	2.60	2.879	4.60	4.358
0.080	1.054	0.85	1.600	2.70	2.953	4.70	4.432
0.090	1.060	0.90	1.636	2.80	3.027	4.80	4.505
0.10	1.066	0.95	1.670	2.90	3.101	4.90	4.579
0.12	1.080	1.00	1.705	3.00	3.175	5.00	4.653
0.14	1.093	1.10	1.779	3.10	3.249	5.50	5.03
0.16	1.106	1.20	1.852	3.20	3.323	6.00	5.40
0.18	1.119	1.30	1.925	3.30	3.397	7.00	6.15
0.20	1.133	1.40	1.997	3.40	3.471	8.00	6.89
0.25	1.169	1.50	2.069	3.50	3.545	9.00	7.63
0.30	1.204	1.60	2.142	3.60	3.618	10.0	8.37
0.35	1.240	1.70	2.215	3.70	3.692	...	...

TABLE 2 Velocity-of-Approach Coefficient, C_V

$C_S C_e h_e/A_u$	C_V
0.1	1.002
0.2	1.009
0.3	1.021
0.4	1.039
0.5	1.064
0.6	1.098
0.7	1.146
0.8	1.218
0.9	1.340

7.2.3.6 *Calculating the Discharge for a Given Head*—Obtaining the theoretical discharge for a given or measured head using Eq 1 is necessarily an iterative procedure; one possible approach is outlined in the following:

(a) Calculate the estimated C_D from Eq 2. (This coefficient remains the same during subsequent iterations.),

(b) For first trial: assume $H = h$, compute mH_e/B_e and obtain C_S from Table 1. (In most cases, use of mH/B would be adequate.),

(c) Compute Q from Eq 1. (C_V is 1.0 for first trial.),

(d) Determine the approach velocity, V_u, for this Q and h,

(e) For second trial: use $H = h + V_u^2/2g$ and corresponding second-trial values of C_V and C_S, and

(f) Compute the second-trial Q and repeat the last three steps until convergence.

7.2.3.7 *Discharge Curves for Commercial Flumes*—When head versus discharge data are provided with a commercial prefabricated flume, the manufacturer must specify the method by which the information was obtained, that is, from laboratory experiments, from theory as described in this section or a modification thereof. An accuracy estimate should be included.

7.3 *Installation Conditions:*

7.3.1 *Approach Conditions:*

7.3.1.1 The flow approaching the flume should be tranquil and uniformly distributed across the channel in order to conform to the conditions assumed in the derivation of Eq 1. For this purpose, uniform velocity distribution can be defined as that associated with fully developed flow in a long, straight, moderately smooth channel. Unfortunately there are no universally accepted quantitative guidelines for implementing this recommendation, so the adequacy of the approach flow must be demonstrated on a case-by-case basis using measurements, experience with similar situations, or analytical approximations. In the case of sewers, it is suggested that there be no bends, junctions or other major disturbances within 25 diameters upstream of the flume.

7.3.1.2 If the flow in the channel or sewer is supercritical, the flume should be installed so that a hydraulic jump is caused to form at least 25 channel widths or 30 pipe diameters upstream.

7.3.1.3 To avoid surface disturbances at the head measurement location it is recommended that the Froude number, F, of the approach flow not exceed 0.5 for about 20 channel widths or pipe diameters upstream, that is:

$$F = V_u/\left(g\,\bar{d}_u\right)^{\frac{1}{2}} \leq 0.5$$

where $\bar{d}_u$ is the average approach depth (area divided by water surfaced width).

7.3.2 *Downstream Conditions—Submergence :*

TABLE 3 Critical Depth in Throat

mH_e/B_e	d_e/H_e	mH_e/B_e	d_e/H_e
0.00	0.667	2.00	0.762
0.05	0.674	2.50	0.768
0.10	0.680	3.00	0.773
0.20	0.692	3.50	0.776
0.30	0.701	4.00	0.778
0.40	0.709	4.50	0.780
0.50	0.717	5.00	0.782
0.60	0.723	5.50	0.784
0.70	0.728	6.00	0.785
0.80	0.733	8.00	0.788
0.90	0.737	10.00	0.791
1.00	0.740	12.00	0.792
1.50	0.754	20.00	0.795

7.3.2.1 Palmer-Bowlus flumes must be installed so as to avoid submergence by the tailwater. There is insufficient data on flow through submerged flumes to permit flowrate adjustments for this condition to be made reliably.

7.3.2.2 Submergence will be avoided if the tailwater depth (relative to the throat floor) does not exceed the critical depth in the throat. Values of the critical depth are given in Table 3. This is a conservative criterion and adherence to it may in some cases require a steeper downstream slope or a built-in drop in the channel immediately downstream of the flume.

7.3.2.3 Less stringent criteria than that of 7.3.2.2 have been proposed, taking into account the energy recovery provided by the gradually sloped downstream ramps. In sewer applications, for example, a limiting downstream depth-to-upstream depth ratio (flow depth referred to pipe invert) as high as 0.85 has been suggested.[6]

7.3.2.4 In all cases, but particularly when the criterion of 7.3.2.3 is used, the existence of free or unsubmerged flow should be confirmed by observing the presence of a hydraulic jump downstream of the throat.

7.3.3 *Level*—The flume must be installed so that the floor of the throat is level, preferably within a slope of 0.001 longitudinally and transversely.

7.3.4 Flumes must be installed so that there is no leakage between the flume body and the channel.

7.4 *Secondary Instrumentation:*

7.4.1 *Stilling Wells*— Although stilling wells are desirable for accurate head measurements, they typically cannot be accommodated in sewer installations except where they are built into new construction or where a flume smaller than the pipe is temporarily installed to measure low initial flows (see 11.4.2). Users requiring information on stilling wells should refer to Test Method D1941 on Parshall flumes or Test Method D5242 on thin-plate weirs.

7.4.2 A minimal secondary system for continuous monitoring would contain a depth (head) sensing device and an indicator or recorder from which the user could determine

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[6] Wells, E. A., and Gotaas, H. B., "Design of Venturi Flumes in Circular Conduits," Trans. Amer. Soc. Civil Eng., Vol 123, 1958, pp. 749–771.

flowrates from the head-discharge relations. Optionally, the secondary system could convert the measured head to an indicated or recorded flowrate, or both, and totalized flow, or further could transmit the information electrically or pneumatically to a central location.

7.4.3 Continuous head measurements can be made with several types of sensors including, but not restricted to, the following:

7.4.3.1 Scow-type floats,

7.4.3.2 Cylindrical floats (can be used only with stilling wells),

7.4.3.3 Pressure sensors, for example, bubble tubes, and diaphragm gages,

7.4.3.4 Acoustic sensors, and

7.4.3.5 Electrical sensors, for example, resistance, capacitance, admittance, and oscillating probes.

8. Sampling

8.1 Sampling as defined in Terminology D1129 is not applicable in this test method.

9. Calibration

9.1 An in-place calibration of the flume system is recommended for highest accuracy and is required if the design and installation conditions of Section 7 are not met. However, if those conditions are satisfied, calibration of the secondary system alone will suffice provided further that the error associated with a standard flume installation (see Section 11) is acceptable for the purpose of the measurement.

9.2 *Calibrating the Secondary System :*

9.2.1 To check the secondary instrument it is necessary to make independent reference head measurements with a scale or preferably a point gage. Carefully reference the zero of the scale or point gage to the elevation of the throat floor. If the installation has a stilling well, make the reference measurement there for greatest accuracy.

9.2.2 Compare the head indicated by the secondary instrument with the reference head (see 9.2.1); if the secondary readout is in terms of flowrate, compare the indicated flowrate with the flowrate computed using the reference head and the method of Section 7 or with the flowrate from the head-discharge information furnished with a commercial flume (see 7.2.3.7). Repetition of this process over a range of heads will indicate whether zero or span adjustment is required. Repetition of individual points will provide information on the precision of the system.

9.3 *Calibrating the Complete System :*

9.3.1 Methods for in-place calibration include: velocity, area traverse (see Test Method D3858), tracer dilution,[6] tracer velocity (see ASME standard, Fluid Meters—Their Theory and Application), volumetric, and comparison with reference flowrate meter.

9.3.2 There is no single calibration method that is applicable to all field situations, and in many sewer applications it is likely that only the first three methods of 9.3.1 could be considered. Whatever method is used, conduct the calibration tests at enough flowrates with enough repetitions to establish the head-discharge relation. Use a scale or point gage to measure heads during these tests. Calibrate the secondary system separately from the primary so that future performance checks need involve only the secondary, provided that conditions related to the primary remain unchanged.

10. Procedure

10.1 After initial calibration according to 9.2 or 9.3, compare the secondary measurement daily with a reference measurement until a suitable frequency of monitoring can be established from the accumulated data.

10.2 Make routine equipment checks frequently at first; in some cases, daily; until a more suitable frequency can be derived from the performance history. These checks include, but are not limited to, solids accumulation in the approach channel, flume surface condition, secondary-sensor condition, flume level, etc. In addition, perform maintenance on secondary instrumentation as recommended in manufacturers' instructions.

11. Precision and Bias

11.1 Determination of precision and bias for this test method is not possible, both at the multiple and single operator level, due to the high degree of variability of open-channel flow. Both temporal and spatial variability of the boundary and flow conditions do not allow for a consent standard to be used for representative sampling. A minimum bias, measured under ideal conditions, is directly related to the bias of the equipment used and is listed in the following sections. A maximum precision and bias cannot be estimated due to the variability of the sources of potential errors listed in Section 11 and the temporal and spatial variability of open-channel flow. Any estimate of these errors could be very misleading to the user.

11.2 In accordance with 1.6 of Practice D2777, an exemption to the precision and bias statement required by Practice D2777 was recommended by the Results Advisor and concurred with the Technical Operations Section of the Executive Subcommittee on June 24, 1992.

11.3 The error of a flowrate measurement results from a combination of individual errors, including errors in the coefficients of the head-discharge relation for the flume (see Eq 1), errors in the head measurement and errors from other sources, some of which are cited in the following.

11.4 *Accuracy of the Head-Discharge Relation, Eq 1 and Eqs 2:*

11.4.1 The estimated uncertainty of the combined coefficients $C_V C_D C_S$ for flumes that satisfy the requirements of Section 7 is ±3 % for $0.3 < h/L < 0.5$. This estimated uncertainty increases to± 4 % for $0.1 < h/L < 0.3$.

11.4.2 For $0.05 < h/L < 0.10$ or $0.5 < h/L < 0.6$ (values somewhat beyond the limits of 7.2.3.5) the uncertainty should be increased to ±5 %.

11.4.3 For flumes with throat widths, B, less than 0.33 ft (10 cm) it is recommended that the uncertainty of the coefficients be increased by ±1 %.

11.4.4 Because errors in C_D increase significantly at very low values of h/L, users may wish to consider temporary installation of a prefabricated flume smaller than the sewer diameter in cases where very low initial flows are anticipated. Gradual convergence from the sewer diameter to the flume diameter must be provided to ensure good approach flow.

11.5 *Errors Due to Installation Conditions:*

11.5.1 *Approach Conditions*—Errors introduced by severely distorted upstream velocity profiles (see 7.3.1.1) generally cannot be quantified and measuring stations exhibiting these characteristics must be calibrated in place to assure accuracy. In the case of high-velocity approach flow (see 7.3.1.3), some sources have suggested an additional uncertainty of ±2 % for Froude numbers between 0.5 and 0.6 (see ISO 4359).

11.5.2 *Downstream Conditions*—Errors due to submergence cannot be quantified and this condition must be avoided.

11.5.3 *Level*—If the installed flume has a very small streamwise slope (see 7.3.3) the resulting error can be minimized by referencing the head measurement to the elevation of the downstream end of the throat. Errors due to a small transverse slope can be minimized by referencing the head measurement to the throat floor elevation at the longitudinal centerline.

11.6 *Secondary System Errors:*

11.6.1 Some potential error sources are associated with specific types of secondary instruments. These sources include, but are not limited to, effects of dense foam layers or heavy grease coatings on electrical sensors, dynamic effects on intrusive pressure sensors, and float lag. Such errors, with the exception of float-lag effects, generally cannot be quantified and each situation must be individually evaluated using experience, manufacturers' information and the technical literature.

11.6.2 Regardless of the type of secondary device used, any error in referencing its zero to the elevation of the throat floor will introduce an error in head that is constant in magnitude and therefore relatively more important at low flows.

11.6.3 Humidity effects on recorder chart paper can introduce errors of about 1 %.

11.7 *Estimating the Total Measurement Error:*

11.7.1 One method of estimating the total percentage error of a flow measurement uses the square root of the sum of the squares of the individual error contributions. For example, applying this method to the standard flumes of Eq 1 gives:

$$e_t = [(e_1)^2 + (e_2)^2 + (1.5)^2(e_3)^2]^{\frac{1}{2}} \tag{7}$$

where:

e_t = the estimated total percentage error of a flowrate measurement,

e_1 = the estimated percentage error of the combined coefficients,

e_2 = the estimated percentage error in the measurement of B (this contribution is likely to be significantly smaller than the others), and

e_3 = the estimated percentage error in the head, obtained by combining (square root of the sum of the squares) estimates of all individual contributions to the head measurement error. This error term is multiplied by 1.5, the exponent of the head in the discharge equation.

11.7.2 Equations similar to Eq 7 can be developed to include head-discharge relations obtained from in-place calibrations or to accommodate other error sources. Additional details on estimating total error can be found in ISO 4359.

12. Keywords

12.1 flume; open channel flow; streamflow; water discharge

APPENDIXES

(Nonmandatory Information)

X1. SLAB-IN-PIPE FLUMES

X1.1 By methods similar to those of Appendix X2 it can be shown that the head-discharge relation for slab-in-pipe flumes is (see Fig. X1.1):

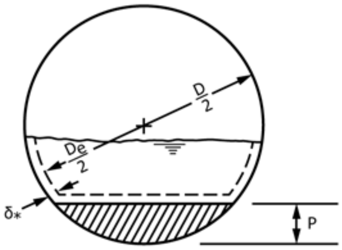

FIG. X1.1 Slab Flume in a Circular Channel

$$Q = (2g/3)^{\frac{1}{2}}(2/3)^{\frac{1}{2}}C_S C_D C_V D h^{\frac{3}{2}} \tag{X1.1}$$

where:

D = the pipe diameter

and:

$$C_D = (1 - 2\delta_*/D)(1 - \delta_*/h)^{\frac{3}{2}}$$

$$C_V = [(H - \delta_*)/(h - \delta_*)]^{\frac{3}{2}}$$

X1.2 The shape factor, C_S, is shown in Fig. X1.2 as a function of H_e/D_e and the slab height-to-effective diameter ratio, P/D_e. Users are cautioned that very low slab heights may be unable to develop critical flow.[5] The sufficiency of the slab height can be determined from theory.

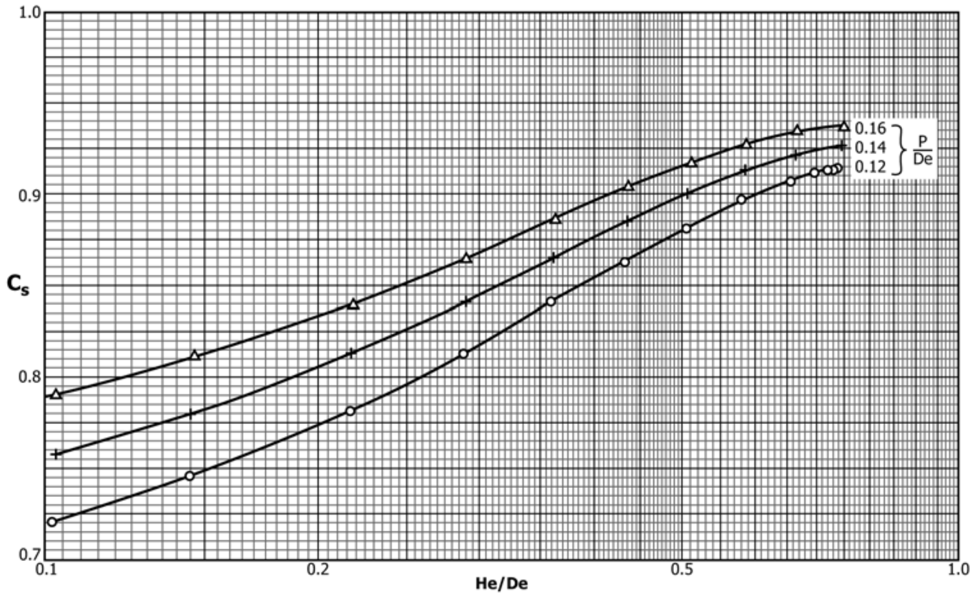

FIG. X1.2 Shape Factor for Slab-Type Flumes

X2. DERIVATION OF THE DISCHARGE RELATION

X2.1 Considering the cross-sectional area of the flow in the throat to be reduced by the boundary-layer displacement thickness, δ_*, and expressing the flowrate, Q, as the product of the velocity and area (see Fig. X2.1):

$$Q = (2g)^{\frac{1}{2}} (H_e - d_e)^{\frac{1}{2}} (B_e d_e + m d_e{}^2) \quad \text{(X2.1)}$$

Maximizing Q for a fixed H_e by differentiating with respect to d_e and setting the result equal to zero gives the critical depth in the throat as:

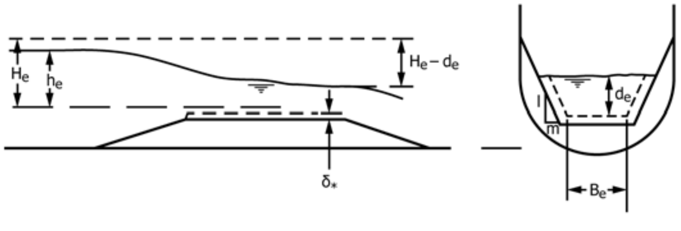

FIG. X2.1 Slab in Pipe Flume

$$d_{ec}/H_e = (2/3)(1+2M)/(1+5M/3) \quad \text{(X2.2)}$$

where:

$M = md_{ec} / B_e$.

X2.1.1 Substituting Eq X2.2 in Eq X2.1, rearranging, and for convenience dropping the critical-flow subscript "c," gives:

$$Q = (2g/3)^{\frac{1}{2}}(2/3)B_e H_e^{\frac{3}{2}}\left[(1+2M)\,(1+M)^{\frac{3}{2}} / \cdot (1+5M/3)^{\frac{3}{2}}\right] \quad \text{(X2.3)}$$

The bracketed term is a shape factor, C_S, which is more conveniently given as a function of mH_e / B_e in Table 1.

Then:

$$Q = (2g/3)^{\frac{1}{2}} (2/3) C_S C_V C_D B h^{\frac{3}{2}} \quad \text{(X2.4)}$$

where C_D and C_V are given in Eqs 2 and Eq 6.

X3. VELOCITY-OF-APPROACH COEFFICIENT, C_V

X3.1 Eq X2.4 or Eq 1 can be written:

$$Q = (2g/3)^{\frac{1}{2}}(2/3)C_S C_V B_e h_e^{\frac{3}{2}} \tag{X3.1}$$

with:

$$C_V = (H_e/h_e)^{\frac{3}{2}} \tag{X3.2}$$

The ratio is, for uniform velocity distribution:

$$H_e/h_e = 1 + Q^2/2gA_u^2 h_e \tag{X3.3}$$

where:

A_u = the cross-sectional upstream area.

X3.1.1 Combining these three equations gives:

$$(3)^{\frac{3}{2}}\left(C_V^{\frac{2}{3}} - 1\right)^{\frac{1}{2}} = 2(C_S B_e h_e/A_u)C_V \tag{X3.4}$$

which can be solved by trial with the results given in Table 2.

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