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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~~ flow rate 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~~ values given in parentheses are ~~for information only.~~ mathematical conversions to SI units that are provided for information only and are not considered standard.

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~~ safety, health, and ~~health~~ environmental practices and determine the applicability of regulatory limitations prior to use.

1.4 This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

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

3.1.1 For definitions of terms used in this standard, refer to Terminology D1129.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *boundary layer displacement ~~thickness—thickness, n—~~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—flow, n—~~the energy in* open channel flow ~~in which the energy~~ expressed in terms of depth plus velocity ~~head,~~ head and *is* a minimum for a given ~~flowrate~~ flow rate and channel. The Froude number is unity at critical flow.

3.2.3 *Froude ~~number—number, n—~~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—head, n—~~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—jump, n—~~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—flume, n—~~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—instrument, n—~~the* device (in this case the flume) that creates a hydrodynamic condition that can be sensed by the secondary instrument.

3.2.8 *Reynolds ~~number—number, n—~~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—float, n—~~an* in-stream float for depth sensing, usually mounted on a hinged cantilever.

3.2.10 *secondary ~~instrument—instrument, n—~~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,~~ flow rate, or could totalize ~~flowrate.~~ flow rate.

3.2.11 *stilling ~~well—well, n—~~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—flow, n—~~open* channel flow that is deeper and at lower velocity than critical flow for the same ~~flowrate;~~ flow rate; sometimes called tranquil flow.

3.2.13 *~~submergence—submergence, n—~~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~~ flow rate can no longer be related to a single upstream head.

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

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

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3.2.16 ~~throat—~~*throat, n—*the constricted portion of the flume.

3.2.17 *velocity* ~~head—~~*head, n—*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~~ flow rate 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~~gauge for manual readings to an instrument that continuously senses the head, converts it to a ~~flowrate,~~flow rate, and displays or transmits a readout or record of the instantaneous ~~flowrate~~flow rate or the totalized flow, or both.

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

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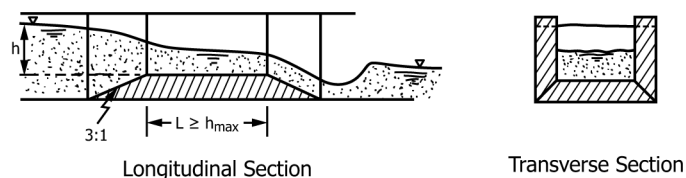
FIG. 1 Generalized Palmer-Bowlus (Long-Throated) Flume in a Rectangular Channel

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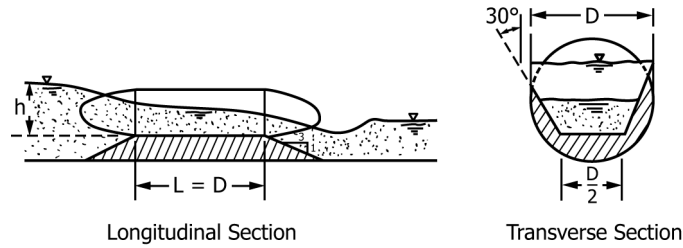
FIG. 2 Palmer-Bowlus Flume (Typical) for Sewer

Longitudinal Section   Transverse Section

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 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,~~ flow rate, Q, through a Palmer-Bowlus flume of bottom throat width, B, operating under a head, h, above the throat floor is:

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

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:

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

Here B_e is an effective throat width given by:

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

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:

$$\delta_* = 0.003\, L \tag{4}$$

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~~/$\underline{B}_e$.H_e is the upstream total effective head, which is (for essentially uniform upstream velocity distribution):

$$H_e = h + V_u{}^2/2g - \delta_* \tag{5}$$

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

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	...	...

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

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

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:

(1) $0.1 \leq h/L \leq 0.5$, with minimum $h = 0.15$ ft (0.05 m),

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

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

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

(5) Throat floor is level,

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

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

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:

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

(2) 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.),

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

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

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

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

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

7.2.3.7 *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:*

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~~ flow rate 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.

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

[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.

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.