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LABORATORY STUDY OF A FLAT-BOTTOM TRAPEZOIDAL VENTURI FLUME

R. A. Dodge
Engineering and Research Center
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16. ABSTRACT

One flat-bottom trapezoidal venturi flume was studied in the laboratory as part of the Bureau of Reclamation Water Measurement Program. The flume has side slope angles of 45 deg. The angles of convergence of the inlet transition and divergence of the outlet transition were 5 deg. The inlet transition, throat and outlet transition were 3 ft long. The throat bottom width was 4 in. The measuring station was one-half ft upstream from the start of the convergence. The flume was calibrated for a painted wood surface and a sand-coated surface. The discharge range was 0.5 to 5.0 cfs. The measuring head for the sand roughened flume was 2% higher at 0.5 cfs and 1% higher at 5.0 cfs than for the painted wood flume. Errors in discharge from 2-1/2 to 4-1/2% occur when friction is neglected in computing the discharge for the sand roughened flume using the equation developed for the painted wood flume. Energy losses for the flat-bottom trapezoidal venturi flume are from 30 to 50% of the losses for the 1-ft Parshall flume which has about the same discharge range. Backwater computations can be used to calculate measuring head elevation. However, prior knowledge of friction and eddy loss factors is required. Relative roughness effects should be accounted for in the low discharge range.

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Hydraulics Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
Rogers C. B. Morton, Secretary
Ellis L. Armstrong, Commissioner

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SYMBOLS AND NOMENCLATURE

A = Area
b = width
c = subscript denoting convergence
D = depth of flow
d = subscript denoting divergence
E = energy
e = subscript denoting eddy loss
f = denoting functional relationship, Darcy Weisback Friction Factor and subscript denoting friction loss
g = acceleration of gravity
H = head loss
h = head
k = Nikuradse sand roughness
L = length and subscript denoting loss
M = eddy loss factor
m = subscript denoting measuring station
μ = viscosity
o = subscript denoting dimensionless
P = wetted perimeter
ϕ = convergence and divergence angle
Q = discharge
R = hydraulic radius
r = subscript denoting reach
ρ = density
s = subscript denoting submergence measuring stations
σ = standard deviation
t = subscript denoting throat
θ = side slope angle
V = velocity

PURPOSE

These studies were made to help determine the feasibility of using flat-bottom venturi flumes as water-measuring devices in Bureau of Reclamation projects and to obtain some experience to aid in the development of designing and discharge rating of these flumes.

BACKGROUND

Because of the increasing need for better utilization and conservation of water resources, a continuing water-measurement program was formulated to refine, standardize, and simplify the design of water-measuring devices. Bureau personnel on irrigation projects became aware of studies of flat-bottomed trapezoidal venturi flumes conducted by other Government organizations and universities. The investigators and users of these flumes cite many advantages of this particular water-measuring device. Because of these purported advantages, the Bureau conducted preliminary studies of one flat-bottomed trapezoidal venturi flume as part of the Water Measurement Program. The studies were directed toward providing a more generalized procedure for design and discharge rating of flat-bottom trapezoidal venturi flumes. The results of these preliminary studies are included in this report.

SUMMARY OF LABORATORY STUDIES

Laboratory studies were conducted in one flume with two different boundary roughness forms. The effect of boundary roughness on measuring head of a flume was determined by comparing results of a painted surface with the same surfaces coated with sand.

The dimensionless calibration equation for free flow in the painted wood flume is:

$$Q_o = 0.820 \left(\frac{h_m}{b_t}\right)^{2.240} \qquad (7)$$

The dimensionless calibration equation for free flow in the sanded flume is:

$$Q_o = 0.782 \left(\frac{h_m}{b_t}\right)^{2.260} \qquad (8)$$

The measuring station head is (h_m) and (b_t) is the bottom throat width. The dimensionless discharge (Q_o) in these equations is equal to $\left(Q/\sqrt{gb_t^5}\right)$. Because of the laboratory test range the validity of the equation is limited by:

$$1.2 < Q_o < 17.5$$

Furthermore, the submergence characteristics of the flume, equations (7) and (8), are further limited to:

$$(h_s/h_m) < 0.88$$

where (h_s) is downstream submergence in the canal.

The sensitivity of the flat-bottomed trapezoidal venturi flume and the 1-foot (ft) Parshall flume with respect to the effect of an error of plus or minus 0.01 ft (0.305 centimeters (cm)) in measuring head was determined. The resulting error in discharge for Parshall flume is about plus or minus 4 percent at 0.5 cubic feet per second (cfs) (14.2 liters per second (lps)) and plus or minus 1-1/2 percent at 5.0 cfs (141.6 lps). The resulting error for the trapezoidal flume is about plus or minus 5-1/2 and plus or minus 2 percent at the same discharges.

Boundary roughness has a significant effect on the measuring head. The calibration head for the sand-coated flume was about 2-1/3 percent greater than for the painted wood flume at a discharge of 0.5 cfs (14.2 lps) and about 1-1/4 percent greater at 5.0 cfs (141.6 lps). The percent error caused by applying the discharge equation for the painted wood flume to the sand-coated flume is about 4-1/2 percent at 0.5 cfs (14.2 lps) and 2-1/2 percent at 5.0 cfs (141.6 lps).

Ackers' and Harrison's[2]* method was applied to both flumes. Measuring station heads computed by this method were from 1-1/4 to 4 percent low for the painted wood flume and from 2 to 4-1/2 percent low for the sanded flume.

Using the backwater method produced measuring station heads that agreed with data to within plus or minus 1.0 percent for $\left(Q/\sqrt{gb_t^5}\right)$ greater than 2.5. Relative roughness should be accounted for when applying backwater computations to determine measuring station heads.

Two combinations of eddy loss (M) and Darcy Weisbach friction factors (f) were found by the standard step backwater computation method that resulted in common water surface profiles. Any number of other combinations are possible because relative roughness effect was not accounted for, causing water profiles to vary linearally with respect to (f) and (M) factors.

*Numbers refer to references at end of text.

Before the backwater computation can be effectively used for calibrating venturi flumes, prior knowledge of friction and eddy loss factors is required.

The ratio of change of measuring station head to change of assumed critical depth location was 0.0032. The backwater computation method was relatively insensitive to assumed locations for critical depth for the flume studied.

The energy losses for the 1-ft (30.5-cm) Parshall flume were compared with the losses in the painted wood flat-bottom trapezoidal venturi flume for approximately the same discharge range. The loss for the trapezoidal flume was about 50 percent of the loss for the Parshall flume at 0.5 cfs (14.2 lps) and about 30 percent at 5.0 cfs (141.6 lps).

APPLICATIONS

Flat-bottom trapezoidal venturi flumes can be used where head must be conserved. Unlike the Parshall flumes, they do not have a floor drop. They will pass a greater range of discharges than Parshall flumes for a given range of head because of their trapezoidal cross section. The trapezoidal flume is more convenient to fit to the usual canal shape.

A. R. Robinson and A. R. Chamberlain[4] have studied small trapezoidal flumes covering the range 0.02 to 2.0 cfs (0.56 to 56.3 lps). Their flumes had side slopes (θ) ranging from 30° to 60°, throat bottom widths varying from 0 to 4 inches (10.2 cm), and convergence angles (ϕ) varying between 8° and 22°. If their recommended dimensions are carefully followed, the flumes should be adequate for use without field calibrations.

The one flume studied by the USBR can be used for the discharge range from 0.5 to 5.0 cfs (14.1 to 14.6 lps), providing the dimensions used in this study are carefully reproduced. Equation (7) can be used for calculating tables if the boundary surface roughness is similar to the painted wood flume studied in the laboratory.

Further studies are required before a more-generalized procedure for design and accurate computed discharge rating of flat-bottom trapezoidal venturi flumes can be made. It is recommended that dimensionless parameters be used for correlating the data. The use of dimensionless parameters permit the full use and advantage of similitude and model scaling rather than obtaining individual calibration for many various flumes. However, the effects of frictional drag should be included in the analyses.

PRELIMINARY INVESTIGATIONS

Review of Literature

Although this laboratory study is restricted to flat-bottom trapezoidal venturi flumes, literature was reviewed on other types of venturi flumes as well as those on this particular type. Many universities and Government organizations have studied venturi flumes. These studies usually consisted primarily of calibrations for flumes of specific geometries for a particular use. Few investigators have made as extensive attempts to unify data such as Davis[1] did for Parshall flumes or to develop comprehensive general design procedures similar to Ackers and Harrison.[2]

Dimensional Analysis

A dimensional analysis was made assuming the relevant variables (list of symbols and Figure 1) are related functionally as:

$$f\,(h_m, L_m, L_c, L_d, h_s, L_s, k, \theta, \phi, \rho, g, Q, \mu, b_t) = 0$$

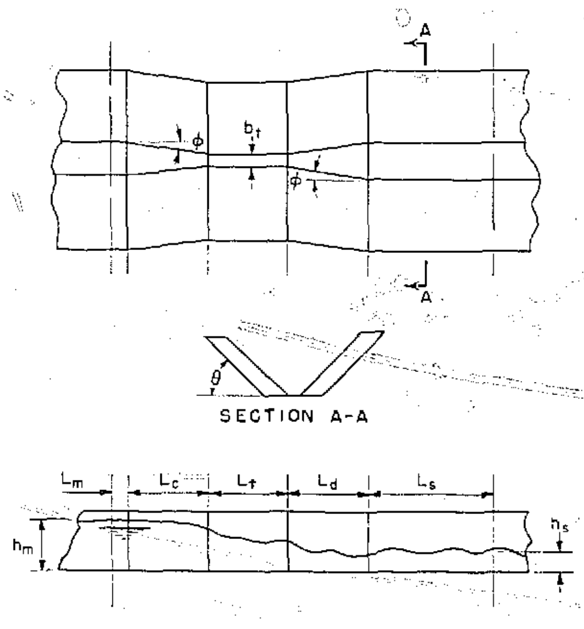

Figure 1. Schematic sketch of laboratory flat-bottomed trapezoidal venturi flume.

Using Q, μ, b_t as repeating variables the resulting compact equation is:

$$f_1\left(\frac{h_m}{b_t}, \frac{Q^2}{gb_t^5}, \frac{\rho Q}{\mu b_t}, \frac{h_s}{b_t}, \theta, \phi, \frac{k}{b_t}, \frac{L_m}{b_t}, \frac{L_c}{b_t}, \frac{L_d}{b_t}, \frac{L_s}{b_t}\right) = 0$$

It is recognized that $(\rho Q/\mu b_t)$ and (Q^2/gb_t^5) are peculiar forms of Reynolds and Froude numbers. However, a more familiar form of Reynolds number can be obtained by using continuity of flow, introducing hydraulic radius (R_m) of the measuring station denoted by the subscript (m) and writing:

$$\frac{\rho Q}{\mu b_t} = \frac{\rho V_m A_m}{\mu b_t} \cdot \frac{R_m}{R_m}$$

where (V_m) and (A_m) are the velocity and area of the measuring stations. Since $\left(R_m = A_m/P_m\right)$ where (P_m) is the wetted perimeter at the measuring station and by regrouping

$$\frac{\rho Q}{\mu b_t} = \frac{\rho V_m A_m}{\mu b_t} \cdot \frac{R_m P_m}{A_m} = \frac{\rho V_m R_m}{\mu} \cdot \frac{P_m}{b_t}$$

by geometry

$$\frac{P_m}{b_t} = \frac{b_t + 2\,L_c \operatorname{Tan}(\phi) + 2\,h_m \operatorname{Cosc}(\theta)}{b_t} =$$

$$1 + 2\left(\frac{L_c}{b_t}\right)\tan(\phi) + 2\left(\frac{h_m}{b_t}\right)\operatorname{Cosc}(\phi)$$

Therefore

$$\frac{\rho Q}{\mu b_t} = f\left(\frac{\rho V_m R_m}{\mu}, \frac{L_c}{b_t}, \phi, \theta, \frac{h_m}{b_t}\right)$$

Multiplying by four, then

$$\frac{\rho Q}{\mu b_t} = f\left(4 \cdot \frac{\rho V_m R_m}{\mu}, \frac{L_c}{b_t}, \phi, \theta, \frac{h_m}{b_t}\right)$$

Therefore $\left(\frac{\rho Q}{\mu b_t}\right)$ can be replaced by $\left(\frac{\rho V_m 4 R_m}{\mu}\right)$.

By algebraic manipulation of (k/b_t) and known flume geometry (k/b_t) can be replaced by $(k/4R_m)$

Therefore $\left(\frac{\rho V_m 4 R_m}{\mu}\right)$ and $\left(\frac{K}{4R_m}\right)$ can be simply replaced by the Darcy-Weisbach friction factor (f) determined from a conventional pipe friction factor curve.

The square root of the Froude number (Q^2/gb_t^5) was taken to obtain Davis' discharge parameter. However, it was not further manipulated to avoid having measuring head and discharge within one dimensionless term.

Downstream submergence is usually expressed with respect to measuring head. Therefore (h_s/b_t) was divided (h_m/b_t) and replaced by the quotient.

The compact equation after these transformations is

$$f\left(\frac{h_m}{b_t}, Q/\sqrt{gb_t^5}, \frac{h_s}{h_m}, f, \phi, \theta, \frac{L_m}{b_t}, \frac{L_c}{b_t}, \frac{L_d}{b_t}, \frac{L_s}{b_t}\right) = 0 \quad (1)$$

where

$$f = f_1\left(\frac{\rho V_m 4 R_m}{\mu}, \frac{K}{4R}\right) \quad (2)$$

However, the effects of friction losses are often neglected by investigators. For convenience of design and calibration the (L/b_t) terms could be held constant throughout a set of flumes. Since only one flume geometry was studied, the parameters entirely dependent upon geometry were not varied. However, the remaining parameters are convenient for expressing and plotting results.

Computed Calibration by Ackers' and Harrison's Method

Ackers and Harrison[2] outline a method for computing the discharge-head relationship for critical depth flumes. The method accounts for frictional drag by assuming all friction loss occurs in the throat. The data from the present study were used to compare computed and measured discharge-head relationship.

Standard Step Method for Computing Measuring Station Head

Water surface profiles can be computed through venturi flumes. Thus the measuring station head could be determined. However, an adequate accounting of losses and a known water surface elevation at a known station are required. Water surface profile computations are based on application of Bernoullis energy equation to successive reaches such as shown in Figure 2.

The bottom slope is usually assumed small and in our case is actually zero. Therefore

$$\frac{V_1^2}{2g} + D_1 = \frac{V_2^2}{2g} + D_2 + E_L \qquad (3)$$

Where (E_L) is the sum of energy losses through the reach. The friction loss slope through the reach is assumed to be the average of the normal flow friction slopes (S_f) for the geometry and hydraulics at the ends of the reach expressed such as

$$S_f = f \cdot \frac{1}{4R} \cdot \frac{V^2}{2g} \qquad (4)$$

where (f) is the Darcy-Weisbach friction factor, (R) is the hydraulic radius and (V) is the velocity at a station. The friction loss through the reach is taken as:

$$H_f = L_r \left(\frac{S_{f_1} + S_{f_2}}{2} \right) \qquad (5)$$

where (L_r) is the length of reach.

Eddy losses (H_e) are commonly expressed as

$$H_e = M \left(\frac{V_2^2}{2g} - \frac{V_1^2}{2g} \right) \qquad (6)$$

where (M) is an eddy loss factor commonly taken as 0.1 for converging flow and 0.5 for diverging flow.[3]

An unknown depth at the end of a reach is found by successive approximation until both sides of equation (3) balance to within sufficient precision.

Critical depth would be a logical place to start a water surface profiles computation. However, determining the location of critical depth may be as difficult as calibrating measuring heads. Also the proper selection of (f) and the value of eddy loss factors could be a problem. Despite these expected difficulties water surface profiles were computed and compared with measured data.

Laboratory Study Program

Because of alternative approaches that could be applied to generalizing the design of flat-bottomed trapezoidal venturi flumes, one laboratory flume was built to aid in determining the approach of possible further research. Any future research would of course seek to generalize procedures for the design and calculations of discharge rating for flat-bottomed trapezoidal venturi flumes. To more fully evaluate the effect of roughness, the same flume was artificially roughened by gluing sand on the flow surfaces of the flume.

LABORATORY FLUME AND MEASURING TECHNIQUES

Fabrication of Painted Wood Laboratory Venturi Flume

The plane surfaces of the venturi flume and canal sections were made out of painted marine plywood and were supported by wood framing. The venturi flume and canal sections were fabricated in an existing sheet metal lined rectangular laboratory channel that was 25 ft (7.64 meters (m)) long, 20 inches (in.) (50.8 cm) deep, and 44 in. (112 cm) wide. An 8-ft (2.4-m) wide by 6-ft (1.8-m) deep box with a bellmouth exit calmed the inflow and provided a uniform flow in the canal section approaching the trapezoidal flume.

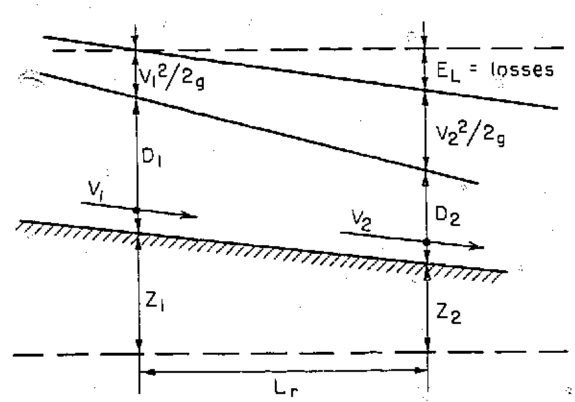

Figure 2. Definition sketch for standard step reach.

Geometry of Laboratory Venturi Flume

The flat-bottomed trapezoidal venturi flume had side slope angles (θ) of 45° and convergence-divergence angles (ϕ) of 5°, Figure 1. The convergence, divergence, and throat lengths were each 3 ft (91.4 cm). The throat bottom width (b_t) was 4 in. (10.20 cm). The canal, represented both upstream and downstream of the venturi flume, had side slope angles (θ) of 45° and a bottom width of 0.86 ft (26.21 cm). The measuring station was 0.5 ft (15.24 cm) upstream of the start of convergence.

Sand-coated Flume

When tests of the flume with painted wood finish were completed, the flat surfaces of the venturi flume and a part of the upstream channel were coated with a layer of sand, Figure 3.

A closeup view comparing the sand-coated surface with the painted surface is shown in Figure 4. A resinous paint used in the hydraulic laboratory models bonded the sand to the flume surfaces. The sand had a mean diameter of 1.7 millimeters (mm) with 73 percent by weight having a diameter equal to or less than 2.00 mm and 9 percent having a diameter equal to or less than 1.2 mm.

To determine the effective boundary elevation of the sand-coated flume, a mechanical device was used to make random measurements of the physical roughness, Figure 5, and was placed on the sanded surface. Without moving the sampling ring, point gage vernier readings were obtained on the test surface by randomly placing the spaced bars on the ring and randomly placing the point gage on the bars for each reading. Enough point gage readings were obtained on the rough surface to determine a statistically meaningful average point gage reading of the test surface irregularities. The point gage rested on sand particles for 78 percent of the readings and on painted wood for 22 percent of the readings. The mean of the painted wood readings was subtracted from the mean of all the readings, giving a difference of 0.003 ft (0.092 mm)

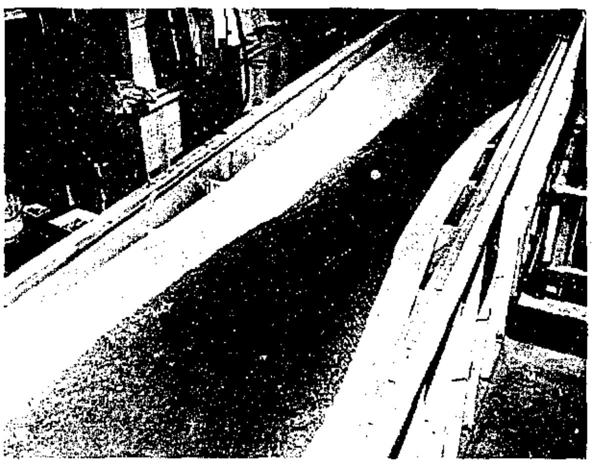

Figure 3. Sand-coated flat-bottomed trapezoidal venturi flume. Photo PX-D-71000

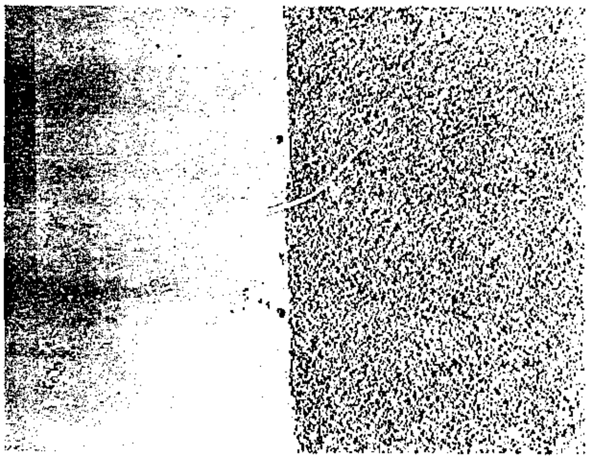

Figure 4. Comparison of painted wood and sand-coated flume surfaces. Photo PX-D-45809

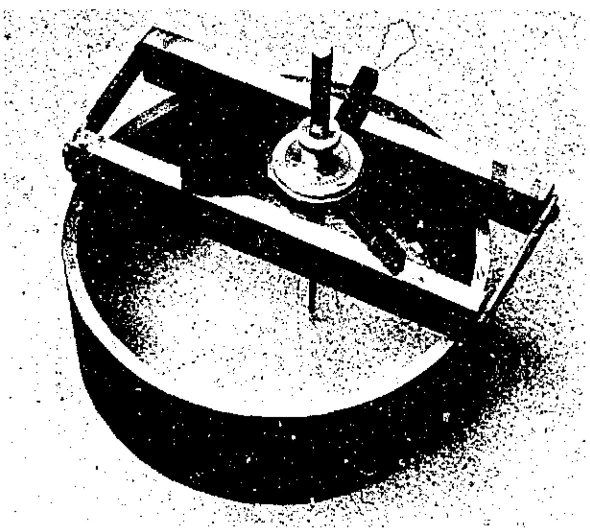

Figure 5. Device used for random mechanical measurement of physical surface roughness—(a) sampling ring—(b) spaced bars—(c) point gage. Photo PX-D-51179

difference. This was assumed to be the offset of the hydraulic boundary of the sanded venturi flume from the flume's original painted surface.

Discharge Measurements

Flow through the trapezoidal venturi flume was measured by means of volumeterically calibrated Venturi meters. The Venturi meters are an integral part of the permanent hydraulic laboratory installation and can measure discharge with an accuracy of plus or minus 1 percent.

Centerline Water Surface Profiles

Water surface elevations were measured by a point gage mounted on a support resting on the railings of the channel containing the flume. The point gage was zeroed at each measuring station by reading the vernier when the point was resting on the bottom of the flume. The repeatability of reading the water surface elevation was found to be within plus or minus 0.002 ft (plus or minus 0.061 cm).

Transverse Water Surface Profiles for Free Flow

Transverse water surface profiles were measured for selected discharges and at selected cross sections along the length of the venturi flume. These transverse profiles indicated that point gage readings at the centerline of the discharge measuring station of the flume would determine the average depth with the same plus or minus 0.002 ft (plus or minus 0.061 cm) accuracy of the point gage reading technique. However, in the throat section of the venturi flume, standing waves affected the water surface depending on the relative location of the station. These standing waves caused centerline water surface deviations of plus or minus 0.01 ft (plus or minus 0.305 cm) from the average depth. Because these deviations are not at the measuring station, they are of no consequence in making head-discharge measurements, but they would interfere in determining the location of critical depth in the flume.

Measurement of Submergence Head

To define submergence, some location downstream of the measuring station must be selected for measuring the submergence head. For design, a location where the flow depth is controlled by the downstream canal rather than in some internal downstream part of the venturi flume itself would be convenient for designers. The submergence head was measured 5 ft (1.5 m) downstream from the downstream end of the flume. However, standing waves interfered with this measurement. To alleviate this difficulty, one inverted knife-edged static pressure measuring disk was immersed at a wave crest and another was immersed at a succeeding wave trough nearest to the submergence measuring station. The two static disks were connected to a common hook gage well. The positioning of the static disks with respect to the wave and the common well measured the average water surface elevation midway between the static disks.

RESULTS OF LABORATORY STUDY AND ANALYSES

Dimensionless Discharge Calibrations

The head at the measuring station was determined for 30 laboratory Venturi meter discharges in the painted wood flume. Measuring head was determined for 32 Venturi meter discharge settings in the sand-coated flume. These calibration data, transformed into terms of dimensionless discharge (Q_o) which is equal to $\left(Q/\sqrt{gb_t^{\,5}}\right)$, and dimensionless measuring head (h_m/b_t) where (b_t) is the throat bottom width, were fitted by the method least squares to power function form. The resulting equation for the painted wood flume is

$$Q_o = 0.820 \left(\frac{h_m}{b_t}\right)^{2.240} \qquad (7)$$

For the sand-coated flume the resulting equation is

$$Q_o = 0.782 \left(\frac{h_m}{b_t}\right)^{2.260} \qquad (8)$$

Percent difference of equation values for (Q_o) from those computed from measured data were determined. The frequency distributions of these deviations for both the painted wood flume and the sand-coated flume are shown in Figure 6. The standard deviation from the percent deviation (σ) for the painted wood flume is 1.4 percent and the sand-coated flume the standard deviation is 1.3 percent.

Computations using equation (7) show the sensitivity of discharge measurement to errors of head reading. In the laboratory, the head measurements repeated to within plus or minus 0.002 ft (plus or minus 0.061 cm). The error of discharge for this deviation of head is

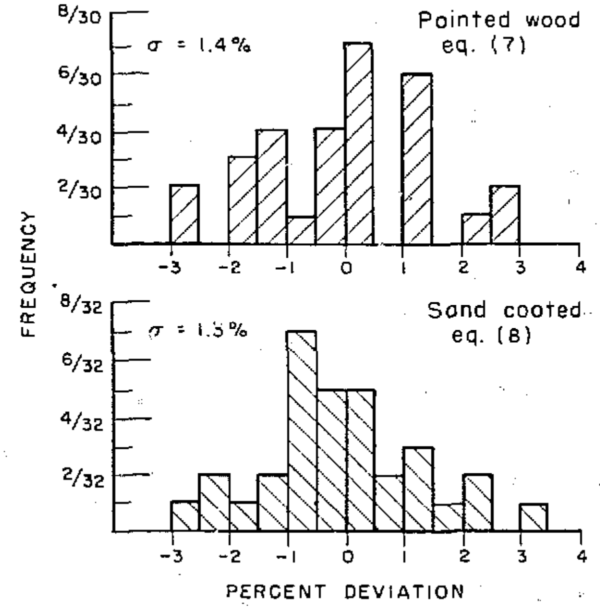

Figure 6. Frequency distributions of percent deviations of equation from measured values of dimensionless discharge.

plus or minus 1 percent at 0.5 cfs (14.2 lps) and plus or minus one-half percent at 5.0 cfs (141.6 lps). Using a staff gage in a field installation, heads can be measured to within plus or minus 0.01 ft (plus or minus 0.305 cm). The error of discharge for this deviation of head reading is about 5-1/2 percent at 0.5 cfs and about plus or minus 2 percent at 5.0 cfs. Similarly for a 1-ft Parshall flume the error of discharge is plus or minus 4 percent and plus or minus 1-1/2 percent at the same discharges.

To assess discharge error due to neglecting frictional drag, percent errors due to using heads measured in the sanded flume, and the calibration for the painted wood flume were calculated with equations (7) and (8). The error in discharge was about plus 4-1/2 percent at 0.5 cfs (14.2 lps) and plus 2-1/2 percent at 5.0 cfs (141.6 lps). Experience has determined that the painted plywood used in the fabrication of the Bureau of Reclamation hydraulic models has a (K) of 0.001 ft (0.030 cm). Standard deviations based on physical measurements of a painted surface and a sanded surface were calculated. The standard deviation for the sanded surface was 3.6 times greater than for the painted wood surface. Therefore it was assumed that (K) for the sand-coated flume is 0.0036 ft (0.11 cm) and the errors of discharge are the result of about a 3.6-fold change in (K).

Dimensionless Submergence Functions

Submergence data were obtained for the painted wood flume discharges covering the range from 0.5 to 5.0 cfs (14.2 to 141.6 lps). The measuring head versus submergence head were measured for eight increments of submergence head for each of the five discharges. No submergence depths were measured for the sand-coated flume.

The data for the painted wood flume indicated that the free flow equation (7) can be applied with no significant error for submergences up to 88 percent of the measuring station head. Above 88 percent submergence the discharge decreases as the submergence increases, Figure 7.

Although no submergence data were obtained for the sand-coated flume, it is expected that transition to free flow would occur nearly at 88 percent submergence as it does for the painted wood flume. Also, the use of equation (8) and the percentage discharge correction factor from Figure 7 would be adequate for determining actual discharge through the sand-coated flume during submerged conditions.

Ackers' and Harrison's Method Compared with Flume Data

A calibration of the venturi flume was performed by the computational method of Ackers and Harrison[2]

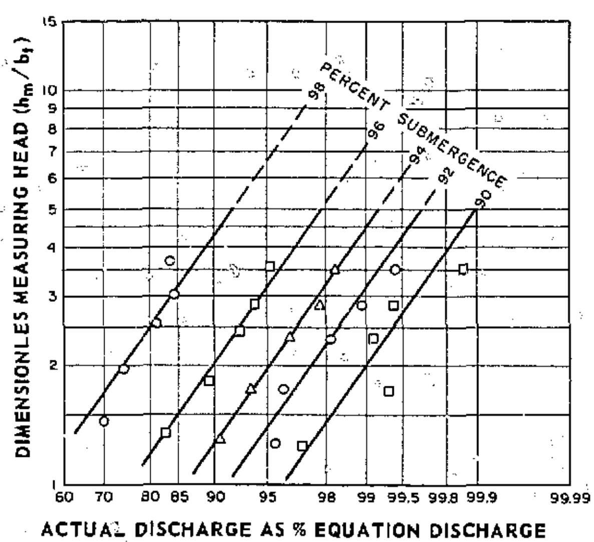

Figure 7. Submergence correction factor curves for the painted wood flume.

that includes a simplified method for accounting for frictional drag that assumes all friction loss occurs in the throat. The Ackers discharge values for a given head were less than those obtained by laboratory measurement. The percent differences varied from about 4-1/2 to 2 percent for the sanded flume and about 4 to 1-1/4 percent for the painted wood flume.

Water Surface Profiles

At least eleven water surface elevations along the centerline of the painted wood flume were measured for each of seven discharges ranging from 0.5 to 5.0 cfs (14.2 to 141.6 lps). Nine water surface elevations along the centerline of the sand-coated flume were determined for each of four discharges in the same discharge range. Dimensionless plots of the water surface profiles for both flumes are shown in Figure 8. As would be expected, these profiles also show the effects of boundary surface roughness in that the water surface profiles for the sand-coated flume are slightly higher than for the painted wood flume.

Values of critical depth were computed for the discharges of the profiles in Figure 8 and the geometry of the throat section. The dimensionless location in the throat at which these critical depths occurred on the painted wood flume profiles are shown in the plot in Figure 9.

Backwater profiles were computed through the flume starting at the critical depths and locations shown in Figure 9 using reach lengths from 0.3 to 0.6 of the throat bottom width. The eddy loss factor (M) was assumed to be 0.1. The Darcy Weisbach (f) factor of 0.023 was found by trial and error to give the best agreement with respect to matching measured profiles and measuring station heads. Using a Nikuradse sand roughness of 0.001 ft (0.03 cm) and the average hydraulic radius for critical depth location to the measuring station, a (f) factor of 0.020 was calculated. Using this (f), a (M) factor of 0.105 was found by trial and error that resulted in the best agreement with measured data. These two combinations of (M) and (f) resulted in measuring station heads and intermediate station water elevations that were within plus or minus 0.001 ft (0.03 cm) of each other. A relatively good correlation between the measured and computed profiles was observed throughout the entire flume. The computed backwater profiles are plotted for (f) of 0.023 and (M) of 0.1 in Figure 8 for comparrison with measured profiles. The computed water surfaces near where the convergence of the flume ends show a benching effect. This effect does not actually occur as shown by the measured profiles. The benching is caused because the computation method responds immediately to abrupt changes of geometry whereas actually flowing water would tend to average out in adjusting to the change of geometry.

The percent deviations of computed backwater-curve-measuring head from those computed with equation (7) that was fitted to measured valves are shown in Figure 10. The backwater head valves were within plus or minus 1 percent for (Q_o) equal and greater than 2.5. For (Q_o) of 2.5 the deviation is about minus 1 percent and becomes increasingly negative as (Q_o) decreases. This illustrates that relative roughness effect should have been accounted for during the backwater computations when (Q_n) was 3.0 or less.

The variation of backwater measuring station head was linear with respect to (M) and (f). For (Q_o) of 5.52 and for either a (f) of 0.020 or 0.023 the change of head was 0.002 ft (0.06 cm) for a 0.010 change of (M). For (Q_o) of 5.52 and (M) of 0.105, the change of head was 0.003 ft (0.09 cm) for a 0.010 change of (f). The linearity of head with respect to change of (M) or (f) is due to friction and loss assumptions of the backwater computation method which did not consider relative roughness variation of (f).

The sensitivity of the backwater computation method to assumed location of critical depth was checked by holding (M) at 0.1, (f) at 0.023, (Q_o) at 5.52 and assuming various critical depth locations throughout the entire length of throat and including its end points. The variation of computed measuring head with respect to critical depth location was linear and had a slope, change of measuring station head to change of location, of 0.0032. The insensitivity of the computed measuring station head to location of critical depth is due to the steepness of the slope of the water surface profiles at the start of the throat.

Despite the relative success in applying backwater computations to determine measuring station head in this study, prior knowledge of friction and eddy loss factors is required.

Energy Losses of Flume

Since conservation of energy is considered one of the advantages of using a flat-bottomed venturi flume, computations were made of the energy losses of the laboratory flume. To permit comparison with other devices of similar discharge capacities, the energy loss was determined between the inlet and in the

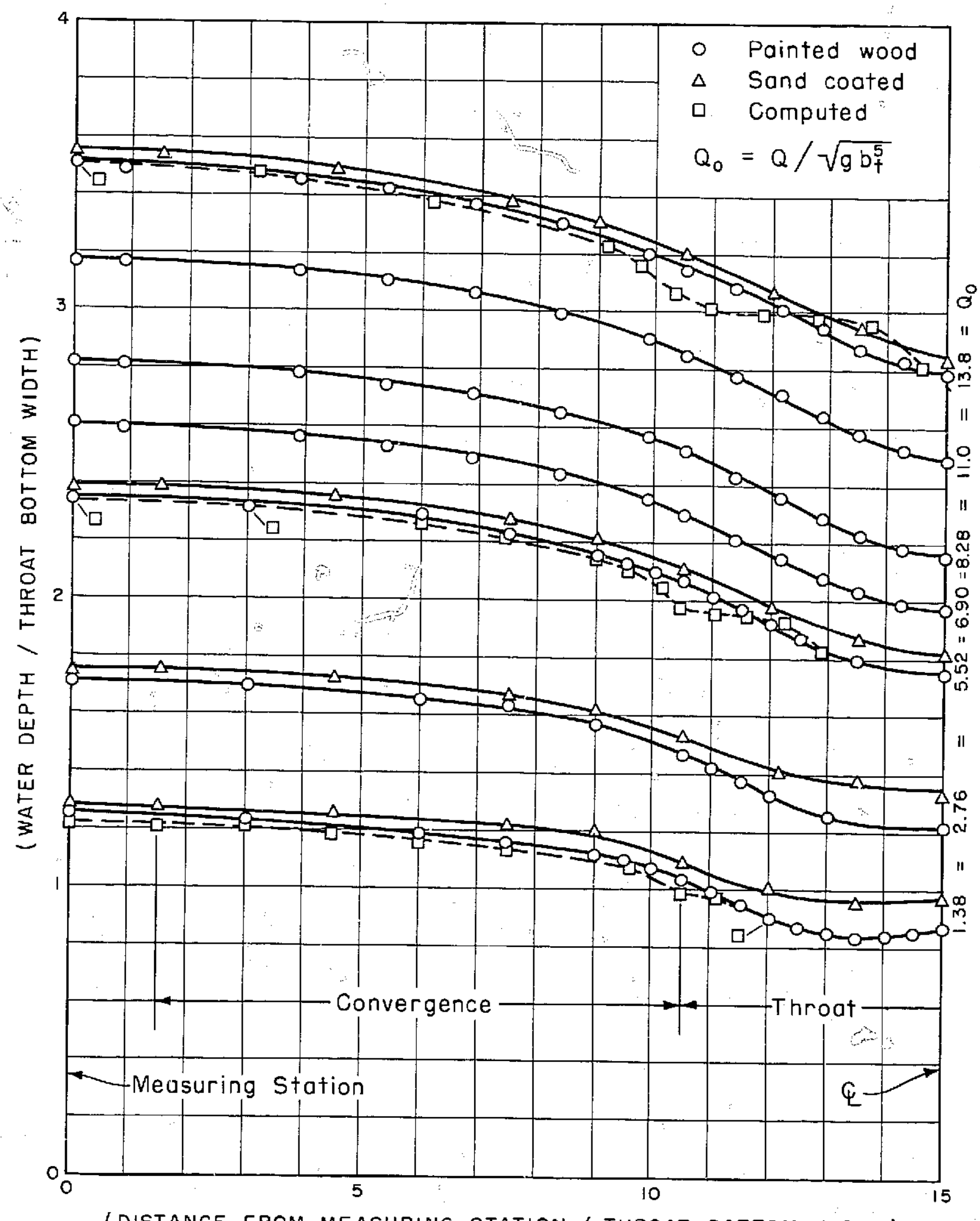

Figure 8. Dimensionless water surface profiles.

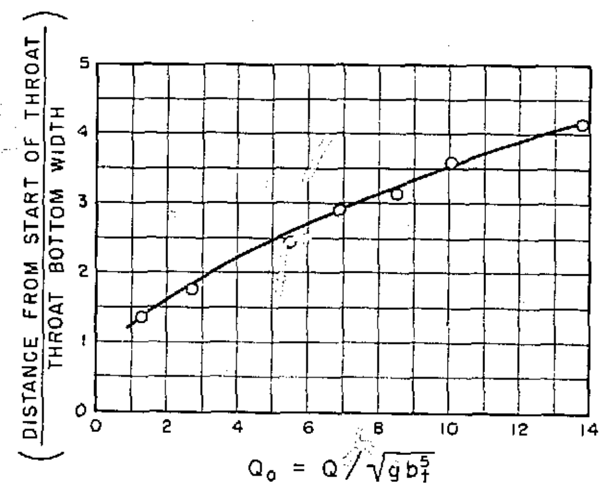

Figure 9. Location of critical depth with respect to discharge–Painted wood flume.

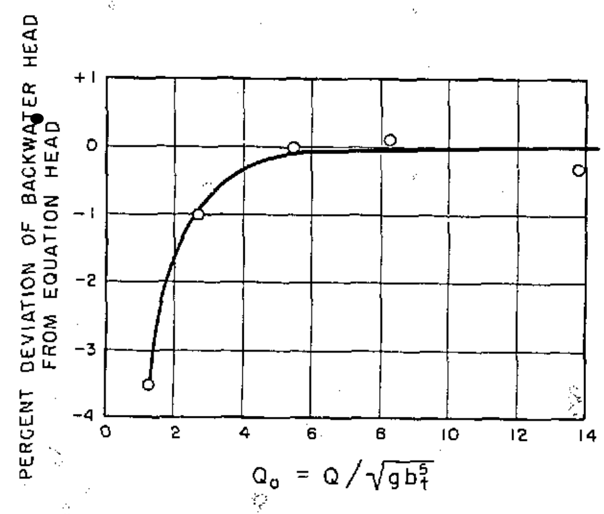

Figure 10. Deviation of backwater computation measuring station heads from equation heads–Painted wood flume.

downstream canal of the laboratory flume over the discharge range from 0.5 to 5.0 cfs (14.2 to 141.6 lps). The 1-ft (30.48-cm) modified Parshall flume which is used for about the same discharge range was selected for comparison. The energy loss for the flat-bottomed trapezoidal venturi flume was about 50 percent of that for the 1-ft Parshall flume at 0.5 cfs and about 30 percent at 5.0 cfs.

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7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482×10^5	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 842-300

ABSTRACT

One flat-bottom trapezoidal venturi flume was studied in the laboratory as part of the Bureau of Reclamation Water Measurement Program. The flume has side slope angles of 45 deg. The angles of convergence of the inlet transition and divergence of the outlet transition were 5 deg. The inlet transition, throat and outlet transition were 3 ft long. The throat bottom width was 4 in. The measuring station was one-half ft upstream from the start of the convergence. The flume was calibrated for a painted wood surface and a sand-coated surface. The discharge range was 0.5 to 5.0 cfs. The measuring head for the sand roughened flume was 2% higher at 0.5 cfs and 1% higher at 5.0 cfs than for the painted wood flume. Errors in discharge from 2-1/2 to 4-1/2% occur when friction is neglected in computing the discharge for the sand roughened flume using the equation developed for the painted wood flume. Energy losses for the flat-bottom trapezoidal venturi flume are from 30 to 50% of the losses for the 1-ft Parshall flume which has about the same discharge range. Backwater computations can be used to calculate measuring head elevation. However, prior knowledge of friction and eddy loss factors is required. Relative roughness effects should be accounted for in the low discharge range.

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REC-ERC-72-14
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LABORATORY STUDY OF A FLAT-BOTTOM TRAPEZOIDAL VENTURI FLUME
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DESCRIPTORS—/ hydraulics/ *discharge measurement/ water measurement/ calibrations/ *venturi flumes/ *trapezoidal flumes/ head losses/ energy losses/ laboratory tests/ test results/ boundaries (surfaces)/ roughness (hydraulic)/ model tests

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