SUBMERGED VENTURI FLUME

Tom Gill[1]
Robert Einhellig[2]

ABSTRACT

Improvement in canal operating efficiency begins with establishing the ability to measure flow at key points in the delivery system. The lack of available head has been a constraint limiting the ability to measure flow using traditional critical-flow measurement structures at many locations. Engineers at Reclamation's Water Resources Research Laboratory (WRRL) have been investigating the viability of measuring flow where limited head is available using a submerged venturi flume.

The term "venturi flume" is used in flow measurement literature to describe a broad range of measurement structures. The geometry being referred to as a venturi flume in this paper is a flat bottomed-structure with prismatic upstream and downstream sections, a gradual contraction leading to a prismatic throat of narrowed width, followed by a gradual expansion to the downstream section. Sidewalls may be either sloped or vertical. Flumes of this geometry with sloped sides have commonly been called trapezoidal flumes. Venturi flumes have been used for many years as a critical-flow measurement device that will perform with greater tolerance for submergence than Parshall flumes. When functioning as a critical flow device, discharge through a venturi flume is a function of only the upstream water level. For submerged-flow measurement, water levels both upstream and at the throat section must be known.

Laboratory tests were performed using a long-throated flume installed in series with, but downstream from a venturi flume. The long-throated flume both created submergence on the venturi flume and provided a means of comparative flow measurement. In initial laboratory testing, agreement between flows measured with the long-throated flume and the submerged venturi flume was within 4% over a discharge range from 0.5 ft^3/s to 5.0 ft^3/s.

Key to practical field use of the submerged venturi is identification of an affordable means of obtaining accurate measurement of small head differential in an efficient manner. WRRL engineers are working to develop an affordable,

[1] Hydraulic Engineer, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007; Phone 303 445 2201; e-mail tgill@do.usbr.gov
[2] Hydraulic Engineer, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007; Phone 303 445 2201; e-mail reinhellig@do.usbr.gov

robust differential-head sensing system to field test with the submerged venturi flume during the 2005 irrigation season.

INTRODUCTION

The degree to which utilization of modernized control technology such as Supervisory Control and Data Acquisition (SCADA) systems can provide improved delivery system efficiency is directly related to the ability to measure flow rates at points throughout the delivery system. Until recently, flow measurement in an open channel has almost exclusively been performed by passing flow through a critical-flow measurement structure. If critical flow is developed, then there will be a unique relationship between an upstream flow depth and the discharge. Where sufficient head is available, critical flow devices remain an excellent choice for flow measurement accuracy and, in most cases, for flow measurement affordability.

When limited water-surface drops can be tolerated in a system, critical-flow measurement structures often experience conditions of downstream submergence. Submergence of a critical-flow measurement structure occurs whenever the downstream water-surface elevation exceeds the control elevation of the structure (e.g., the crest of a weir). The amount of submergence on a flow-measurement structure is commonly defined as the ratio of the height of the downstream water surface to the height of the upstream water surface, where each is measured relative to the control elevation.

Many flumes can tolerate varying degrees of submergence while maintaining the critical-flow conditions necessary for accurate measurement. This is a distinct advantage over weirs which require more head drop and are unable to maintain critical-flow conditions if any submergence is present. The Parshall flume—long the open channel measurement standard—will continue to provide accurate flow measurement with submergence levels of up to 70 percent (U.S. Bureau of Reclamation, 1997).

With the widespread availability of personal computers, rating and calibration procedures have been incorporated into software for designing and calibrating long-throated flumes (Wahl et al, 2000). These structures continue to provide accurate flow measurement with downstream flow depths above the flume crest approaching 90 percent of the upstream flow depth. When it is recognized that these flumes often feature a raised crest, the minimum differential (or head loss) between the upstream and downstream water surfaces at which accurate measurements can be made with a long-throated flume is considerably smaller that the minimum elevation differential required for accurate measurements with the Parshall flume.

Despite the improved performance characteristics offered by the long-throated flume, many districts have the need to measure flows at sites where the limited head available is insufficient for even a long-throated flume. Recently developed acoustic doppler profiling instruments are often able to measure open-channel flow under such conditions with essentially no resulting head loss. With the cost of these instruments varying from a few thousand up to about twenty thousand dollars and the lower-end units providing varying degrees of accuracy and performance consistency, these devices are not yet widely deployed for irrigation turnout applications. This paper examines a structural alternative (the venturi flume) for measuring flows under any degree of submergence.

VENTURI FLUMES

The term venturi flume can be found in literature referring to a class of structures in which the flow cross-sectional area is gradually reduced to accelerate flow velocity. Under this broad definition, Parshall, cutthroat and broad crested flumes would all be subsets of the venturi flume class. A narrower, more concise use of the term venturi flume is a flat-bottomed structure with prismatic approach, throat and discharge sections. A gradual contraction section joins the approach and throat, while the throat and discharge sections are joined by a gradual expansion section. A popular geometry for these flumes uses trapezoidal cross sections at all locations, however vertical-walled structures would also meet the criteria for venturi geometry.

Work funded by the US Department of Agriculture (USDA) was performed at Colorado State University to assess the suitability of venturi flumes as critical flow structures. In this effort, Robinson and Chamberlain (1960) developed laboratory-calibrated rating curves for two trapezoidal venturi flume sizes based on empirically-developed data. Their studies showed that as a critical-flow measurement device, venturi flumes continue to provide accurate flow measurements up to a submergence level of eighty percent. This represents approximately a ten percent increase in submergence tolerance over the Parshall flume.

SUBMERGED VENTURI FLUMES

It has long been recognized that if water levels (and hence cross-sectional flow areas) can be accurately determined at both the prismatic approach section and the prismatic throat section, flow can be calculated analytically by combining and solving the energy and continuity equations. This methodology could be utilized both when critical flow is present or under highly submerged conditions. Unfortunately, the degree of accuracy in depth measurement needed—particularly at low flow conditions—requires a significantly greater resolution than the 0.01 ft. least reading of common staff gages used to measure depth in critical-flow devices.

A series of tests was performed at Reclamation's Water Resources Research Laboratory (WRRL) in 2003 with a submerged venturi flume to evaluate the viability of measuring approach section and throat depths with sufficient accuracy to provide acceptable measurement accuracy. The test model featured a trapezoidal channel with a 0.860-ft bottom width and 1:1 side slopes. The throat section has a 0.333-ft bottom width with 1:1 side slopes and a length in the direction of flow of 3 ft. Gradual contraction and expansion sections in either direction from the throat are each 3 ft long in the direction of flow and maintain a 1:1 side slope. A long-throated flume was constructed at the downstream end of the channel, both for obtaining a control flow measurement and to create submerged conditions on the venturi flume. The invert of the test flume was horizontal throughout.

Taps were placed in the channel wall just above the channel invert at four locations. The first tap was located in the approach section 1.5 ft upstream of the upper end of the converging section. The second tap was placed at mid-reach of the venturi throat. A third tap was placed 1.5 ft downstream of the lower end of the expansion section. The fourth tap was placed upstream of the long-throated flume at the design location called for by the WinFlume software. Valves were placed in all tap lines, beyond which all taps were connected into a manifold plumbed to a common stilling well equipped with a hook-type point gage with a reading increment of 0.001 ft.

Figures 1 & 2 show the laboratory venturi flume model. Figure 1 is a view looking in the direction of flow. Submergence of the venturi flume (seen in the foreground) is caused by presence of the long-throated flume at the downstream end of the channel (upper middle of photo). Discharges measured with the long-throated flume served as the control measurements for the study. The stilling well equipment is seen at the right of the venturi flume in Figure 2 which is shown which a discharge in excess of 5 ft^3/s.

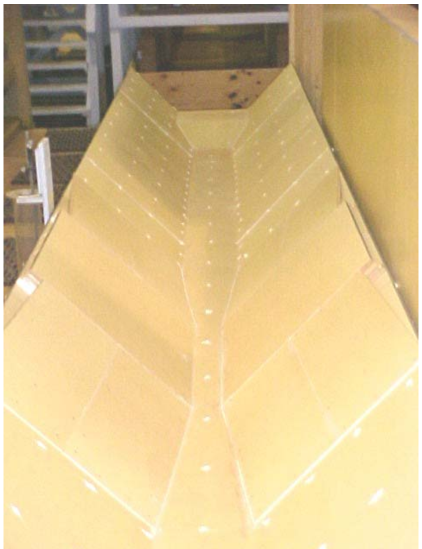

Figure 1.

Figure 2.

LABORATORY TEST RESULTS

In the 2003 tests, eight flows over a targeted discharge range of 0.5 to 5 ft^3/s were delivered to the model. Flow depths at each of the three venturi tap locations were measured as was the flow depth over the long-throated flume. Each time the tap connection to the stilling well was changed, the stilling well was given 5 minutes to stabilize before a reading was taken. After another 5 minutes, a second reading was taken to confirm the level in the stilling well had reach equilibrium. If a differential in readings was observed, a reading would be taken after a third five minute interval. For all measurements taken, consecutive equivalent level readings were obtained in 15 minutes or less using this methodology. As previously mentioned, discharge through a submerged venturi flume may be determined analytically by combining the Energy and Continuity equations. The formula derived from this combination is:

$$Q = C_d * \frac{A_1 * A_T}{(A_1^2 - A_T^2)^{0.5}} * \left(\frac{2g}{\alpha} * (H_1 - H_T)\right)^{0.5} \qquad \text{Equation 1}$$

Where:

Q = discharge in ft^3/s

C_d = discharge coefficient (dimensionless) to account for losses between the upstream and mid-throat flow cross sections. (This value is empirically determined – typically near 0.95)

A_1 = upstream flow cross section area in ft^2 (at location of upper tap)

A_T = throat flow cross section area in ft^2
α = velocity correction term (dimensionless) to account for the fact that flow velocity near the taps will be less than the mean cross section velocity. (α is commonly assigned a value of 1.02)
H_1 = depth of flow (ft) at the upstream tap
H_T = depth of flow (ft) in the flume throat

A_1 & A_T of Equation 1 are calculated from measured values for H_1 & H_T and from known geometry of respective channel cross sections. Table 1 shows the respective flow level readings obtained at the taps for each of the flow rates observed. As shown in the lower right of the table, discharges measured in the submerged venturi flume varied by less than four percent from flows measured in the long-throated flume for all observed flow rates.

Table 1.

Submerged Venturi Meter

Run #	Depth of Flow up stream ft	throat ft	down stream ft	Calculated Discharge ft^3/s	Flume Submergence %
1	0.632	0.623	0.628	0.549	99.4
2	0.731	0.710	0.725	1.049	99.2
3	0.821	0.788	0.812	1.575	98.9
4	0.902	0.854	0.891	2.177	98.8
5	0.937	0.881	0.923	2.474	98.5
6	1.021	0.945	1.002	3.249	98.1
7	1.148	1.033	1.123	4.568	97.8
8	1.214	1.052	1.184	5.428	97.5

Long-Throated Flume

Run #	Depth of Flow Above Invert ft	Above Flume Crest ft	Calculated Discharge ft^3/s	Deviation in Calculated Discharge %
1	0.628	0.203	0.53	3.95
2	0.725	0.300	1.01	3.99
3	0.812	0.387	1.57	0.24
4	0.891	0.466	2.19	0.55
5	0.923	0.498	2.47	0.23
6	1.002	0.577	3.23	0.60
7	1.123	0.698	4.59	0.55
8	1.184	0.759	5.37	1.05

Flow for the long-throated flume was calculated from flow levels at tap 4 using the following rating equation (developed using the WinFlume software):

$$Q = 0.05684 * (H/12 + 0.6134)^2$$

Equation 2

Where: Q = discharge in ft3/s
H = depth of upstream flow above flume crest (ft)

Discharge rates calculated for both flumes are plotted in Figure 3. In this plot, discharges from both flumes are plotted against the discharge for the long-throated flume which served as the control for this study. This graphic representation of the discharge data from Table 1 shows the high degree of agreement in discharge measurements obtained from the two structures during the laboratory tests.

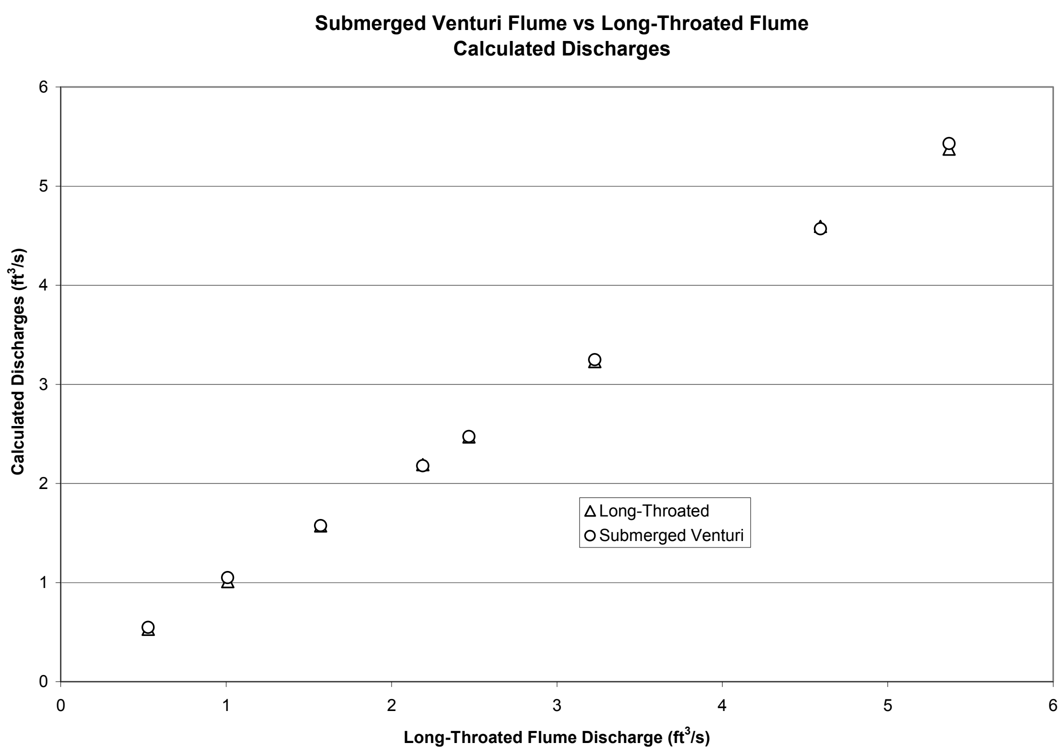

Figure 3.

CONCLUSIONS FROM INITIAL LABORATORY TESTING

The laboratory test results presented above indicate discharge rates measured using a submerged venturi flume can approach the flow measurement accuracy of a long-throated flume. This suggests field use of submerged venturi flumes could be viable for measuring discharge under conditions of limited head availability in the field. The methodology used to measure flow depths in the laboratory study (requiring up to 30 minutes per discharge reading) would not be practical for many canal applications.

The issue of time require per discharge reading could be greatly diminished if two level measurements could be obtained with suitable measurement accuracy without using a single stilling well. One option would be installation of two independent water-level sensors—one measuring level at the upstream cross section and the other measuring level at the throat. This would introduce uncertainties into the measurement process both from the accuracy of calibration of each sensor and in terms of the measurement resolution limits of the sensors.

For an example, consider only the resolution limits of a candidate submersible pressure transducer sensor. A selected product has been identified that can operate over a 3.3 ft depth range and provide a 0.2% of full scale accuracy. Based on this information, each sensor would have a resolution limit of 0.007 ft. Utilizing the combined information from two such sensors to calculate flow in the submerged venturi the resolution limits alone would result in an uncertainty of twice the resolution limit or 0.014 ft. This value exceeds the 0.009 elevation differential shown in Table 1 by which a discharge of approximately 0.55 ft^3/s was calculated. When uncertainties related to sensor calibration plus drift away from calibration that is commonly observed over time with various sensor technologies are added to resolution limit uncertainties, use of two independent water-level sensors to determine flow rates in a submerged venturi flume would not appear to provide promising prospects for attaining an acceptable level of measurement accuracy.

A second approach considered is the use of two sensors that do not function independently. One sensor could be used to measure upstream level, while the second sensor would measure level differential. With this configuration, accounting for resolution limitation and calibration uncertainties would present a diminished impact compared with using two independent sensors. Two candidate technologies for measuring level differential that were considered are 1) a differential pressure transducer plumbed between two stilling wells and 2) a "balance beam" system that measures differential buoyant forces on non-buoyant plummets partially submerged in two stilling wells. Either of these differential level sensors could be coupled with any of the range of available level sensors which could be used to measure upstream level.

A third approach for obtaining water levels at the two submerged venturi flume cross sections would be to utilize a single level sensor that remotely senses pressure at a given point, such as a bubbler sensor. A configuration using a bubbler sensor and a two-way solenoid valve installed in the bubbler line could alternately sense flow depth in each of two stilling wells. Signal from the sensor would be coupled with feedback indicating valve position by a controller that would process the information to determine both flow depths, and from flow depth values, calculate discharge. This approach would appear to introduce the least degree of uncertainty into the discharge calculation with a submerged venturi flume, and would represent a more simplistic installation over the other level measurement alternatives identified above.

PLANNED CONTINUATION OF RESEARCH

A proposal has been submitted for fiscal year 2006 funding through Reclamation's Science and Technology Program to investigate water-level measuring methods that will provide the required degree of measurement accuracy for both upstream and throat water levels in a submerged Venturi flume, and that will be practical from a required time duration standpoint. One of the measurement methods outlined in the research proposal includes using a single bubbler sensor to measure both the upstream and throat section levels. A second method proposed would feature use of plummets in two stilling wells suspended from a balance beam to measure differential head. Proposed work with the balance beam would include development of both manual and electronic methods for making differential level measurements.

SUMMARY AND CONCLUSIONS

The initial phase of this study focused on determining whether discharge rates could be determined in a submerged venturi flume with a useful degree of accuracy. Results of the WRRL's 2003 tests indicate that a level of measurement accuracy can be achieved suitable for open-channel measurement applications. From that point, the focus of the study has turned to identifying technologies for both manual and electronic measurement methods that would make the use of submerged venturi flumes practical for measuring flow in agricultural water-delivery systems.

Looking forward, as practical water-level sensing and measurement calculating capabilities are identified for submerged venturi flumes, field demonstrations of the technology will be the next stage of the study. Based on what has been shown in the tests concluded to date, submerged venturi flumes offer promise as an affordable means of measuring open-channel discharge at sites where limited head availability makes use of critical-flow devices unfeasible. This expanded flow measurement capability could play a pivotal role in enhancing the level of sophistication of SCADA operations which a water delivery system is able to develop and adopt.

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