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Water Velocity Measurements in Open Channels Using Volumetric Current Meter (VCM)

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ABSTRACT

An innovative Volumetric Current Meter (VCM) was designed in order to allow quick velocity measurements in open channels. At first, the coefficient of velocity (C_v) of the device was determined through calibration under different water velocities in the laboratory. The measurement performance was verified by measurements performed in similar flows in irrigation channels using an ordinary current meter. The obtained results showed that the new device can be used to measure the discharge with an acceptable precision (RMSE and MAD equal to 5.353% and 0.027, respectively compared to a digital flow meter). It was shown that velocity computation by using this device will result in a lower precision in higher water velocities.

Keywords

Volumetric Current Meter (VCM), velocity measurement, open channel, current meter

1. Introduction

Measurement of discharge of water in open channels is critical from the viewpoint of water conservation (Goel, 2006). Accurate measurement of applied water volumes in surface irrigation fields is important towards improving irrigation efficiencies and management of the surface irrigation system (Tod et al. 1991).

Many methods and various devices in the field of water measurement in open channels have been covered in different researches (e.g. Brakensiek et al., 1979, Bos, 1989, Clemmens et al., 1993, and Water Measurement Manual, 2001).

Usually simple and inexpensive devices of velocity measurement have low precision and high precision devices are sophisticated and expensive and are not suitable for field applications (Yousef et al., 1995).

VCM is a new and simple instrument for measurement of point velocity of water in channels, invented by Moosavi (2007) (Moosavi, 2007). Acceptable precision, simple structure and ease of production, no need for high specialization, and low costs are among the advantages of this instrument compared to other velocity measuring tools. This device is appropriate for field applications and is capable to determine water flow in irrigation distribution networks.

In this method, which is based on volumetric concept of flow measurement, only a small portion of flow collects in a vessel. The point velocity of flow in a small section is determined based on the measurement of the elapsed time of filling the vessel with water, cross section area of the vessel inlet nozzle, and depth of inlet nozzle below water surface.

In this paper, first the overall theory and structure of VCM is described and then, calibration and comparison setup for testing this new device will be provided. This is followed

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by an evaluation of the results obtained from experiments performed in irrigation channels.

2. Theory

Consider a duck shaped vessel located at some depth of the flowing water in a channel so that the axis of the inlet nozzle is horizontal and almost parallel to the stream lines (Fig. 1).

Water flows into the vessel and exposes air via MN pipe. Points 1 and 2 were selected on X-X horizontal centerline in the center of the inlet nozzle and in the middle of the jet after the nozzle, respectively.

Bernouli equation between points 1 and 2 is as follows [9]:

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = Z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + h_{l_{1-2}} \quad (1)$$

where Z_1 and Z_2 are elevation heads of points 1 and 2 with respect to X-X axis, respectively, and can be omitted since they are equal.

P_1/γ and P_2/γ are pressure heads at points 1 and 2, respectively, V_1 is the velocity of flowing water at point 1, which is along the X-X, V_2 is the velocity of water at point 2.

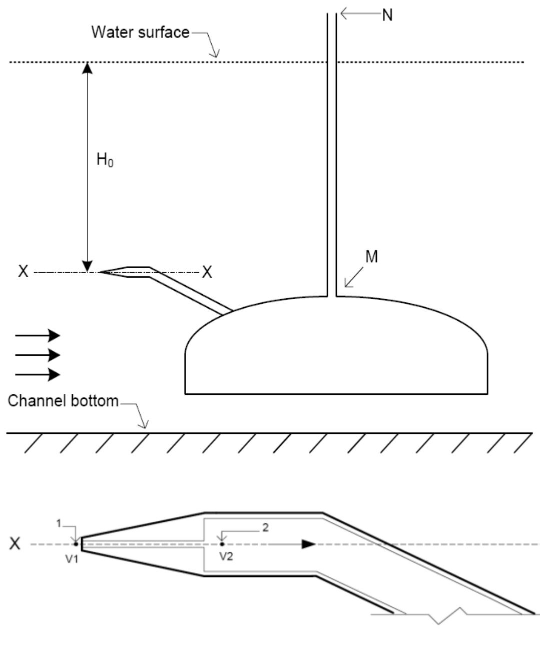


Fig. 1. Schematic view of the vessel and water inlet pipe in the flowing water

P_1/γ is equal to the vertical distance between water surface in the channel and point 1, which is shown as H0 in Fig. 1. P_2/γ is zero, since the water jet surface at point 2 is at atmospheric pressure as the vessel is connected to atmosphere through pipe MN. Therefore, Eq. (1) can be written as:

$$H_0 + \frac{V_1^2}{2g} = \frac{V_2^2}{2g} + h_{l(1-2)} \quad (2)$$

In Eq. (2), if V_2 is substituted by its equivalent value in terms of discharge (Q), time to fill the vessel (t) , and volume of the vessel ($\forall$) using the following equations:

$$Q = \frac{\forall}{t} \quad (3)$$

$$Q = a.V_2 \quad (4)$$

$$V_2 = \frac{Q}{a} = \frac{\forall}{t.a} \quad (5)$$

where a is the cross section area of the vessel inlet nozzle, from Eq. (2) we have:

$$\frac{V_1^2}{2g} = \frac{V_2^2 - 2gH_0 + 2gh_{l(1-2)}}{2g} \quad (6)$$

$$V_1^2 = V_2^2 - 2gH_0 + 2gh_{l(1-2)} \quad (7)$$

$$V_1^2 = \left(\frac{\forall}{t.a}\right)^2 - 2gH_0 + 2gh_{l(1-2)} \quad (8)$$

$$V_1 = \left\{\left(\frac{\forall}{t.a}\right)^2 - 2gH_0 + 2gh_{l(1-2)}\right\}^{1/2} \quad (9)$$

As $h_{l(1-2)}$ is unknown, its effect can be substituted by considering a velocity coefficient (C_v) in Eq. (9) to obtain the final equation to calculate water velocity:

$$V_1 = C_v.V_t = C_v\left(\frac{\forall^2}{t^2.a^2} - 2gH_0\right)^{1/2} \quad (10)$$

Equation (10) indicates that water velocity (V_1) at a given point can be calculated by measurement of t, a, H_0, and $\forall$ parameters. V_t is considered as the theoretical velocity with an ideal fluid.

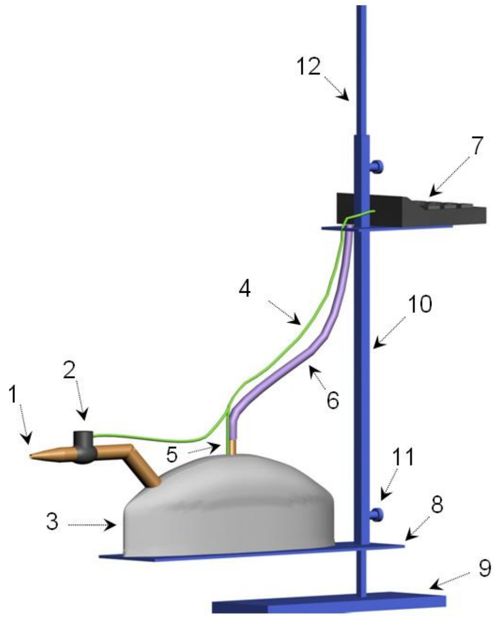
The value of C_v is indirectly related to the energy loss along the inlet nozzle and assumption errors made for simplification of the velocity equation derivation (Eq. (10)). In other words, the resultant of the effect of velocity disturbance and other assumptions proposed in obtaining the velocity formula is reflected in the velocity coefficient. C_v ($0< C_v\leq 1$) can be obtained through calibration process in which velocities obtained from a standard measuring instrument are compared with values obtained from the innovated instrument.

Different parts of the velocity measuring device are shown in Fig. 2. A brief description of each part is given under the figure. All parts of the instrument were placed in a 45×35×15 cm wooden case. The vessel volume of the VCM was 340 cm3 and the inner diameter of its inlet pipe was 3.25 mm.

3. Materials and methods

3.1. Calibration setup

Experiments were performed in hydraulic laboratory of Shiraz University, Shiraz, Iran. The laboratory was equipped with a pumping system that provided water to the inlet reservoir through a pipe (Fig. 3). After reduction of the kinetic energy and turbulences in the downstream part of the reservoir, the conduit led to a rectangular recirculating glass-sided flume of 0.7 m wide, 0.7 m deep and 15 m long. Calibration tests and measurement of velocity coefficient were done in this flume. At the end of the channel, water discharged into an output reservoir to be collected and recirculated in the system. Flow was controlled by a valve on the inlet pipe, and discharge was measured by a calibrated digital flowmeter (Danfoss Magflo Flowmeter MAG 5000) set in the reservoir inlet pipe.



1. Entrance of the water inlet pipe, 2. Inflow electrical control valve. 3. Water collection vessel, 4. Wires of the electrical control valve, 5. Electric sensor alarm wires, 6. Pipe for air connection, 7. Controller kit of the inflow electrical valve and time monitor, 8. Plate for holding water vessel, 9. Base plate of the whole system, 10. Sliding 2×2 cm square profile for displacement of the vessel along the vertical rod, 11. Tightening screw for fixing the vessel elevation, and 12. Vertical rod.

Fig. 2. Schematic view of the assembly and structure of the VCM instrument

An ADV current meter (Micro-ADV, SonTek) was applied as a criterion to determine actual velocity in calibration experiments. ADV can measure velocity with an accuracy of ±0.1 mm/s in full scale, if water salinity and temperature are correctly determined.

To reduce the errors, water salinity and temperature were measured during the experiment. Velocity was measured in three directions with a sampling rate of 50 Hz, but streamwise velocity was used. The accuracy of velocity data collected by ADV was checked by WinADV software developed by USBR (Wahl, 2000).

The device was evaluated in a velocity range of 0.3 m/s to 0.99 m/s available in the laboratory. To reach the desirable velocity, discharge and slope ranges in the channel were adjusted to 0.06 m3/s to 0.33 m3/s and 0.0001 to 0.001, respectively (Table 1).

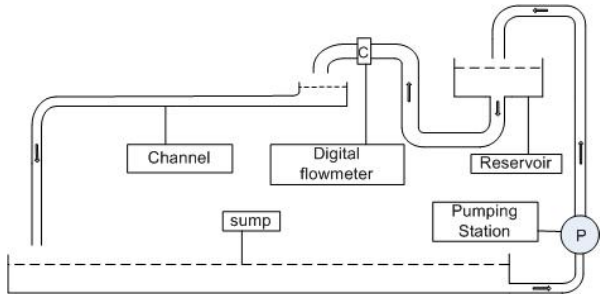


Fig. 3. The calibration hydraulic system

Fig. 4. Calibration setup for VCM device in the flume

For each test, upon starting pumps when the system reached the steady state, ADV and VCM instruments were synchronously placed (aligned) in the channel centerline with 1 meter spacing (Fig. 4). Probe alignments were checked before performing the measurements, with recorded velocities for a downstream still-water carriage flight checked to see that the average lateral velocity tended to zero. Probe vertical alignment was checked with a spirit level.

Table 1. Characteristics of the calibration experiment

Test Index	$Q(m^3/s)$	$Y_n(m)$	U(m/s)
1A	0.14	0.31	0.65
2A	0.20	0.39	0.73
3A	0.27	0.49	0.80
4A	0.06	0.30	0.30
5A	0.20	0.48	0.60
6A	0.17	0.49	0.49
7A	0.22	0.46	0.68
8A	0.14	0.36	0.56
9A	0.22	0.60	0.52
10A	0.25	0.36	0.99
11A	0.22	0.40	0.80
12A	0.25	0.43	0.82
13A	0.30	0.50	0.86
14A	0.33	0.54	0.87
15A	0.30	0.47	0.91
16A	0.30	0.45	0.95
17A	0.27	0.39	0.98

Experiments were carried out under uniform flow conditions with Reynolds number, Re=Uh/ν, in the range of about 90000 to 469800, where U=Q/(hW) is mean velocity, Q is flow discharge, h is flow depth, W is channel width, and $\nu=1.23\times10^{-6}$ m^2/s is kinematic viscosity of water at $13^{\circ C}$. Froude number was in the range of 0.17 to 0.53, corresponding to subcritical flows. Experimental conditions are summarized in Table 1.

3.2. Experimental setup for the comparative study

As the most important application of this instrument is discharge measurement in irrigation channels and rivers, VCM was compared with a regular propeller current meter in the second part of the study. Valeport “Braystoke” BFM001 (Valeport Limited, 1999) current flow meter (CM) calibrated in Water Research Institute, Tehran, Iran, was applied in the six-tenths-depth method in the irrigation channels of water engineering department of Shiraz University. The channels included a collection of rectangular channels in various dimensions. The inlet water was measured by digital contour pumps to a reser-voir and distributed in the channels. Leading the total discharge into a certain channel, the ideal conditions for the experiments were provided.

For this process, water pump was started and upon reaching a uniform and steady state flow, VCM and current meter instruments were located in a specific depth to measure the velocity. Discharge was measured using a calibrated digital flowmeter (Danfoss Magflo Flowmeter MAG 5000). The experiment was repeated three times for velocity and discharge ranges of 0.5 m/s to 0.96 m/s and 0.08 m^3/s to 0.25 m^3/s, respectively. Reynolds number was in the range of 150000 to 499200 and Froude number was in the range 0.27 to 0.45 indicating a subcritical flow. Table 2 summarizes the experimental conditions.

4. Results and discussion

According to the calibration results and the velocity equation of the device, with a high R^2 (0.97), the coefficient of velocity (C_v) for VCM can be considered about 0.97 which is the gradient of the calibration equation, as shown in Eq. (10) and Fig. 5.

Table 2. Characteristics of the comparative experiment

Test	Q(m3/s)	Yn(m)	U(m/s)
1B	0.08	0.33	0.61
2B	0.10	0.39	0.64
3B	0.13	0.49	0.66
4B	0.20	0.53	0.75
5B	0.20	0.43	0.78
6B	0.25	0.52	0.80
7B	0.09	0.30	0.50
8B	0.15	0.45	0.56
9B	0.15	0.41	0.91
10B	0.20	0.52	0.96

Comparing with CM instrument, the regression curve of V_{vcm} versus $V_{Digital\ flowmeter}$ is supported by a higher coefficient of linear correlation, R^2, of the experimental data and also its gradient is closer to unity. It indicates that the experimental results obtained by the new instrument are more satisfying and accurate for the tested velocities. Figs. 6 and 7 show results of the calibration tests. The bias and trends of the obtained data were examined by plotting actual velocity measurements (digital flowmeter) using VCM and CM instruments versus their means according to Bland-Altman plot (Bland et al., 1986) in Fig. 8.

Results showed that in case of CM instrument, more points were out of the limits of agreement in comparison to VCM. The difference between VCM and digital flowmeter measurements reached to 12% for a velocity of 0.96 m/s. In other words, Fig. 7 indicates a bit more differences for higher velocities. It can be ignored, because the limits of agreement (-0.08 to 0.05 m/s) are small enough to satisfy the use of VCM with a high confidence for the desired purposes.

To clarify the errors of the both devices, the root mean square error (RMSE) and mean absolute error (MAE) for the recorded measurements were calculated by using the following equations:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2\right]^{0.5}\left(\frac{100}{M}\right) \qquad (11)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|S_i - M_i\right| \qquad (12)$$

where S_i is water velocity (m/s) measured by VCM and CM by applying C_v= 0.97, M_i is water velocity (m/s) measured by digital flowmeter, and M is average water velocity measured by the digital flowmeter (m/s).

Velocities were divided into 5 different ranges. RMSE and MAD of the velocities measured with VCM and CM were compared with the obtained values using digital flowmeter (Table 3).

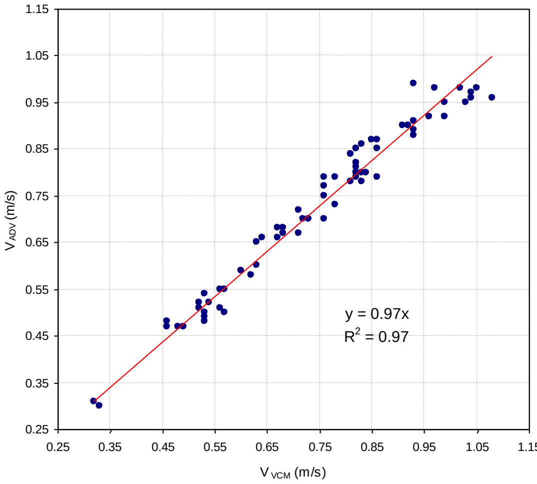


Fig. 5. Calibration graph of VCM (VCM)

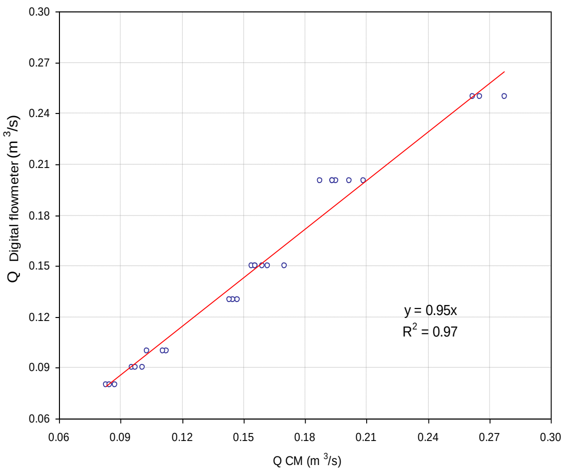


Fig. 6. Comparison of the actual velocities with CM results

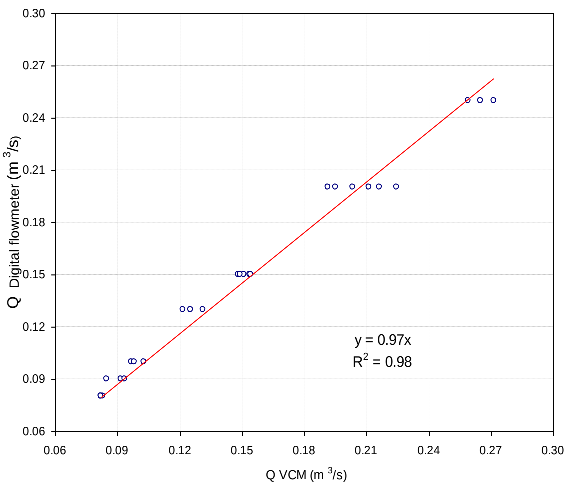


Fig. 7. Comparison of the actual velocities with VCM results

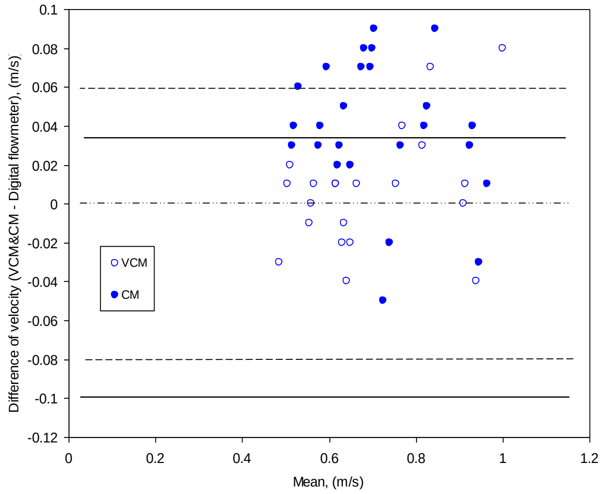


Fig. 8. Comparison of VCM and CM velocity measurements with digital flowmeter; ‘agreement limits’ ($\bar{V} \pm 2sd$) indicated by exterior hatched lines (VCM) and solid lines (CM)

Table 3. Error analysis

Velocity range (m/s)	RMSE (VCM)	RMSE (CM)	MAE (VCM)	MAE (CM)
V1 (0.5-0.6)	3.081	8.950	0.013	0.045
V2 (0.6-0.7)	3.141	9.781	0.018	0.057
V3 (0.7-0.8)	3.528	4.745	0.023	0.033
V4 (0.8-0.9)	6.575	7.971	0.050	0.060
V5 (0.9-1.0)	6.679	3.382	0.047	0.030

Experimental results indicated a less error in VCM in comparison to CM measurements so that the total RMSE and MAD values for VCM were 5.353% and 0.027, respectively and for CM, 7.192% and 0.046, respectively confirming the accuracy of the device. In higher velocities, RMSE and MAD values of VCM increased to 6.679% and 0.047, respectively. The lower precision in this range of velocity is attributed to the higher sensitivity of the device to elapsed time of vessel filling in the velocity equation of VCM (Eq. 10).

5. Conclusions

In this study, a new device was introduced for measuring water discharge in open channels. High accuracy of the device makes it as a reliable instrument. Moreover, availability, quick set-up, no need for a technician, fast performance and low production, maintenance and operation costs are among the advantages of this instrument. However, sensitivity of the measurements to the position and inner diameter of water entering pipe as well as difficulty in device application in points near the stream bed are problematic. In addition, as channel systems often carry a significant amount of sediments, coarse sediments (>2 mm) can make the flow measurement inaccurate or the device inoperative, especially in wastewaters and high-sediment flows. Furthermore, results showed that in open channels, the measurement error of VCM increased with the velocity.

The velocity coefficient, C_v= 0.97, obtained in this study can vary depending on the size and shape of the vessel and the inlet pipe. Therefore, it is suggested that the effects of VCM device geometry on its velocity coefficient would be studied in future works.

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