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Mobile Flume for Inverted Semicircular Open Channel.

Hoda Matter Abo elmaaty
Civil Engineering, Master student, is with Faculty of Engineering, Tanta University, Tanta, Egypt

Mossaad Bayoumi Khadr
Associate Professor, is with Irrigation and Hydraulic Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

Ibrahim Mohamed Rashwan
Hydraulic Professor, is with Irrigation and Hydraulic Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

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Mobile flume for inverted semicircular Open channel

القناة المحمولة للمجارى المفتوحة النصف دائرية المقلوبة

Hoda A. Matter, *Mosaad Khadr* and I.M.H. Rashwan

KEYWORDS:

Semicircular; flow measurement; mobile; open channel; partially filled.

الملخص العربى:

ان قياس التصرف خلال المجاري المائية المفتوحة جزء أساسي من إدارة المنظومة المائية ولقياس قيم التصرف خلال المجاري المائية المفتوحة أستخدمت عدة طرق منها ماهو معتمد علي قياس السرعة في عدة نقاط وتتم من خلال معرفة مساحة القطاع المائي حساب التصرف . وتوجد طرق اخرى تعتمد علي تكوين قطاع حرج خلال السريان ومن ثم قياس الطاقة النوعية الحرجة ومنها يتم حساب العمق الحرج والذي منه يتم حساب قيمة التصرف المار. وغالبا مايتم إستنتاج معادلة تربط بين الطاقة النوعية الحرجة والتصرف المار. ويمكن تصنيف المنشآت المستخدمة لتكوين قطاع حرج لقياس التصرف إلي منشآت ثابتة وأخري متنقلة.

ان الهدف من هذا البحث هو إستخدام جهاز نقال لقياس التصرف في المجاري المائية المفتوحة ذات الشكل نصف دائرى ولقد تم أختيار الجهاز بحيث يتم استخدام ماسورة رأسية لخلق إختناق في القطاع لتوليد سريان حرج خلال الماسورة الأفقية التي يمر بها التصرف. ولقياس التصرف بواسطة الجهاز الجديد تم عمل دراسة نظرية وأخري عملية. الدراسة النظرية تم من خلالها دراسة شكل سريان المياه خلال الماسورة الأفقية واظهرت النتائج تولد القطاع الحرج عند الاختناق. وعليه تم إستخدام معادلة الطاقة النوعية والتصرف وكذلك معادلة رقم فرويد مما أدي إلي الوصول لمعادلات مبسطة للربط بين الطاقة النوعية الحرجة وعمق المياه الحرج والتصرف المار في صورة لابعدية. ولقياس التصرف المار تم استخدام هذه العلاقات النظرية التي تربط الطاقة الحرجة والعمق الحرج مع التصرف في صورة لابعدية في جداول وبيانيا ومن ثم استخدام النتائج المعملية فى تصحيح هذه المعادلات النظرية وبالتالي أصبح قياس التصرف من خلال الجهاز يتضمن قياس عمق المياه داخل الماسورة الرأسية على اعتبار انه الطاقة الحرجة وتحويله لصورة لابعدية بقسمته علي قطر الماسورة الأفقية ومن ثم إيجاد العمق الحرج ويلي ذلك إيجاد التصرف المار كما يمكن إيجاد التصرف المار مباشرة وبنسبة خطأ لاتتعدى 8.7%.

***Abstract*— The discharge measurement is significant in wide engineering applications such as water conveyance, sewer system, irrigation, and drainage system. Many devices are designed to measure discharge in partially filled circular and semicircular channels. In this study new semicircular mobile flume depends on the concept of developing a contracted zone to have a control section was examined. The contraction was made by installing a vertical pipe with axial holes at the semicircular open channel to create critical flow. To evaluate the efficiency of this type of devices mathematical and experimental studies were presented. Specific energy, discharge, and Froude number equations were used to deduce the mathematical model. Experimental work was carried out in measuring the discharge values with known specific energy values. The experimental data was used to evaluate the mobile device to measure discharge. New equations for both discharge and discharge coefficient were presented. The verification leaded to have a discharge correction equation to calculate the discharge based on the contraction ratio and the measured water depth in the vertical pipe. Results of the comparison showed that the proposed model provided a reliable prediction of the discharge with high accuracy and maximum error up to 8.7%.**

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Hoda A. Matter, Civil Engineering, Master student, is with Faculty of Engineering, Tanta University, Tanta, Egypt,(e-mail: enghoda_matter87@ yahoo.com).

M. Khadr, Associate Professor, is with Irrigation and Hydraulic Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt, (e-mail: mosaad.khadr@f_eng.edu.eg).

I. M. H. Rashwan, Hydraulic Professor, is with Irrigation and Hydraulic Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt, (e-mail: imh_rashwan@yahoo.com).

I INTRODUCTION

MEASUREMENT of discharge in open channels has been a classical topic of interest to many engineers. When the water available from a particular source is limited and must be used very carefully, it is necessary to measure the discharge at various points in the system and the flow at farmer's intakes. Some benefits of water measurement were listed by the U. S. Department of the Interior Bureau of Reclamation [1]. Simonovic [2], selected 27 methods for flow measurement from the handbook published by the International Organization for Standardization [3, 4].

1.1. Mobile Venturi Flume

There are two types of discharge measurement structure, either the structure is mounted permanently in the channel or the structure is temporarily positioned for discharge evaluation. The device may be mounted and removed quickly, and such device might then be referred to as a mobile device. Its major advantages include low cost, reading precision and rapid installation in running water. A Venturi body allows determining the discharge by a single depth reading. The mobile discharge measurement for rectangular, trapezoidal, triangular, U-shape and circular profiles is introduced.

1.2. Mobile Venturi Flume in Rectangular Channel

Balloffet [5] introduced simple elements for mobile discharge measurement in rectangular channels. Diskin [6] described a mobile arrangement for discharge measurement by using Venturi bodies similar to bridge piers instead of circular cylinders. In 1985, Hager [7] used a cylinder made of a high plastic material to make a contracted section to have with the critical flow in contracted rectangle channel. Hager [8] presented a modified Venturi type discharge measurement. Hager [9] declared that Ueberl and Hager (1994) tested the standard Venturi body in a rectangular channel. The Venturi body was provided with holes of about 5 mm diameter arranged along the front of the cylinder, with an inter distance of about 50 mm. If this line of holes is located against the flow direction, the flow depth in the cylinder equals to the stagnation head, i.e. the energy head H of the flow. Peruginelli and Bonacci [10] used mobile pier-shaped prism device to measure the discharge in a rectangular channel. Samani and Magallanez [11] attached a two semi cylinder of polyvinyl chloride (PVC) to the side wall of the rectangular channel. Wu and Molinas [12] developed a new discharge equation, which based on the conservation of energy and experimental data with a wide range of opening ratios. In 2004, three-dimensional turbulent flow field at a vertical semicircular cylinder, attached to the sidewall of a rectangular channel, was taken in the laboratory using an Acoustic Doppler Velocimeter (ADV) [13]. Gole [14] estimated a discharge equation for free and submerged flow condition. Ghare and Badar [15], investigated experimentally and calibrated a simple mobile flume to measure a discharge through small rectangular open channels in agricultural fields.

1.3. Mobile Venturi with Circular Cone

Hager [16] used a circular cone to made contraction section through a rectangular channel.

1.4. Mobile Venturi in Trapezoidal Channel

In 1986, Hager [17] used a cylinder made of a high plastic material to make a contracted section with the critical flow in the contracted trapezoidal channel. In 1993, Samani and Magallanez [18] used flume consisted of pipe installed axially inside a trapezoidal channel with side slope 1:1. In 2012, Badar and Ghare [19] developed a new mathematical model to predict the discharge through a trapezoidal canal by simple cylindrical flume using experimental data available in the literature for trapezoidal canal having 1:1 side slope.

1.5. Mobile Venturi in U-Shape Channel

Hager [9] explained the proposal of Hager and Züllig refers to a mobile flume inserted in a prefabricated U-shaped channel.

1.6. Mobile Venturi Flume in Circular Pipe

Hager [20] used a mobile device as shown in Fig. 1 to measure the discharge in partially field pipe. The device is a cylinder of diameter d < D and the base of the cylinder is rounded to D/2. Using specific energy equation and Froude number led to having the following expressions:

$$Q_{me}/Q_{cal} = 0.985 + 0.205E_* \quad (1)$$

Where Q_{me} is measured discharge, Q_{cal} is calculated discharge and E_* is the dimensionless specific energy (E/D), D is the semicircular diameter.

Samani et al. [21] replaced the graphical approach presented by Hager, which was used to calibrate the water measuring device based on the measured value of upstream energy. The relation between the measured and the calculated discharge was as follows:

$$Q_{me}/Q_{cal} = 1.075 + 0.2266E_* \quad (2)$$

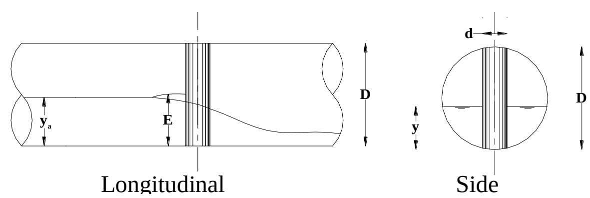


Fig. 1. Schematic plot of mobile device unit.

Kohler and Hager [22] improved the circular mobile flume to measure discharge in partially filled pipes, as the case in sewage and drainage engineering. Enciso [23], assessed the impact of the best management practices (BMPs) on water quality at selected agricultural fields located in the Arroyo Colorado watershed during two irrigation events in 2009 and 2010. He used a PVC mobile circular flume placed at the drainage ditch to measure runoff flow-rate using a data logger and a pressure transducer. Figure (2) shows schematic of the flume that was used to measure irrigation return flows. To assure that the circular flume measured accurately and with less than 10% error, the flow meter was calibrated in the Harlingen Irrigation District.

Fig. 2. Calibration of the circular flow meter in the Harlingen Irrigation District.

Rashwan and Idress [24] evaluated the efficiency of mobile flume as discharge measurement device for the partially filled circular channel. The experimental data was used to evaluate the mobile flume as a device to measure discharge. A general equation was developed for discharge coefficient (C_d) as:

$$C_d = ((7.3839)\delta - 1.9348) + ((4.4912)\delta - 0.2883)E_{*me} \quad (3)$$

Where C_d is discharged coefficient, E_{*me} is the dimensionless specific energy (E_{me}/D) and δ is contraction ratio (*d/D*).

In 2016, Davis and Samani [25] produced manually for simple flow measurement devices in open channels. This manual is divided into two main chapters; the first one outlines the design characteristics of simple flow measurement devices which are typically easier and less expensive to be produced. The second chapter investigates more traditional flow measurement devices and illustrates the strengths and weaknesses of both types. In 2017, Zohrab Samani [26] discussed the design and the calibration of three simple flumes for flow measurements in open channels. The flumes were designed based on principles of critical flow in open channels. The critical flow was created through the contraction of the flow cross section by installing vertical cylindrical columns in an open channel.

In the present study, a semicircular mobile flume is proposed to measure discharge in the small open channel. This mobile device consists of a vertical pipe with diameter *d* fixed on semicircular flume with diameter *D*. The presence of the vertical pipe reduces the cross section of the flow and creates a critical flow condition.

II MATHEMATICAL WORK

There are several types of flow measurement devices currently in use across the world. The most common flume designs, in use nowadays, include the Parshall flume, the Cutthroat flume, the Trapezoidal flume, and the Mobile flume. The mobile flume with rectangular, triangular, trapezoidal, U-shape and circular cross-sections was developed earlier. The present study provides a new arrangement mobile with an inverted semicircular section that can be used as a measurement device in a partially filled pipe.

The discharge equation is estimated by using specific energy equation, discharge equation, and Froude number equation. The assumptions to estimate the discharge equation led to having an error in the calculated discharge value. This error has to be corrected; therefore an expression of the correction factor was driven to have the actual value of the discharge.

2.1. Governing Equations

Chow [27] reported that Bakhmeteff (1912) introduced the specific energy term as the energy of water at any section of the channel with respect to the channel bottom as a datum as follows,

$$E = d_w \cos\theta + \frac{\alpha V^2}{2g} \quad (4)$$

Where *E* is the specific energy, d_w is the normal depth of the point below the water surface, θ is the slope angle of the channel bottom, α is the energy coefficient due to variable velocity distribution, *V* is the stream line velocity and *g* is the gravitational acceleration.

For a channel of small slope (mild) or horizontal, the section depth is more or less the same as the water depth $(d_w \cos\theta \approx y)$. The ideal parallel flow has a uniform velocity distribution. This type of flow has unity energy coefficient (α ≈ 1). Therefore, for ideal parallel flow, the energy head can be written with substitute the term of the velocity in Eq. (4) by discharge term (*Q/A*) as follows:

$$E = y + \frac{Q^2}{2gA^2} \quad (5)$$

Where *y* is the water depth, *Q* is the discharge and *A* is an area of the water section.
For a semicircular channel with diameter *D*, divided Eq. (5) by *D* yields to

$$E_* = Y + \frac{Q_*^2}{2A_*^2} \quad (6)$$

Where *Y* is the relative water depth (*y/D*), Q_* is the dimensionless discharge ($\sqrt{Q^2/gD^5}$) and A_* is dimensionless water area (A/D^2).

2.2. Inverted Semicircular Mobile Device

The main contracted section on the semicircular mobile flume is controlled section. This section is shown in Figure (3).

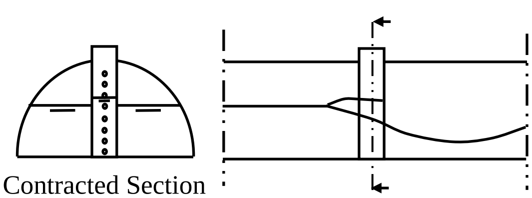


Fig. 3. Contracted sections through semicircular mobile flume

The discharge, through semicircular mobile flume, can be estimated by using specific energy, discharge, and Froude number equations.

The contracted section is contracted by a vertical cylinder with outside diameter (d) which made contraction ratio δ (d/D) as shown in Figure (4).

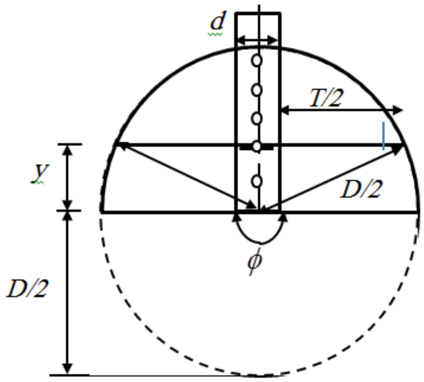


Fig. 4. Geometric properties of contracted section

The geometric properties of the contracted inverted semicircular section can be easily computed as follows

$$A_* = \frac{\phi - \sin\phi - \pi}{8} - \delta(Y) \tag{7}$$

Where ϕ is the central angle and δ is the relative diameter of the vertical cylinder (d/D)

The top width at contracted section can be calculated as, Fig. (4);

$$\frac{T}{2} + \frac{d}{2} = \sqrt{\left(\frac{D}{2}\right)^2 - (y)^2} \tag{8}$$

Where T is top width at the contracted section.
Divided Eq. (8) by D yields to

$$T_* = 2\sqrt{0.25 - (Y)^2} - \delta \tag{9}$$

Where T_* is dimensionless top width at contracted section

According to the water profile through the flume pipe, the critical flow happened at the contraction section. So, at the contraction zone, the relative specific energy can be written as

$$E_{*C} = Y_C + \frac{A_{*C}}{2T_{*C}} \tag{10}$$

Where E_{*C} is the relative critical specific energy, Y_C is the relative critical water depth (y_c/D), A_{*C} is the relative critical water area and T_{*C} is the relative critical water top width.

The above equation used to find relative critical water depth (Y_c), from knowing dimensionless critical specific energy (E_{*C}). By putting Eq. (7) and Eq. (9) in Eq. (10) one obtains:

$$E_* = Y_c + \frac{\phi - \sin\phi - \pi - 8\delta(Y_c)}{16\left(2\sqrt{0.25 - (Y_c)^2} - \delta\right)} \tag{11}$$

The general equation of Froude number is as follows;

$$F_r^{\ 2} = \frac{Q^2 T}{gA^3} = \frac{Q^2 (T/D)}{gD^5 \left(A/D^2\right)^3} = \frac{Q_*^2 T_*}{A_*^{\ 3}} \tag{12}$$

Where F_r^2 is Froude number

Applying equation (12) for critical flow, $F_r^2 = 1.0$ and $y = y_c$ yields the following expression:

$$Q_*^{\ 2} = \frac{A_{*C}^{\ 3}}{T_{*C}} \tag{13}$$

Substituting Eq. (7) and (9) in Eq. (12) gives:

$$Q_* = \left[\frac{\left(\phi - \sin\phi - \pi - 8\delta(Y_c)\right)^3}{512\left(2\sqrt{0.25 - (Y_c)^2} - \delta\right)}\right]^{1/2} \tag{14}$$

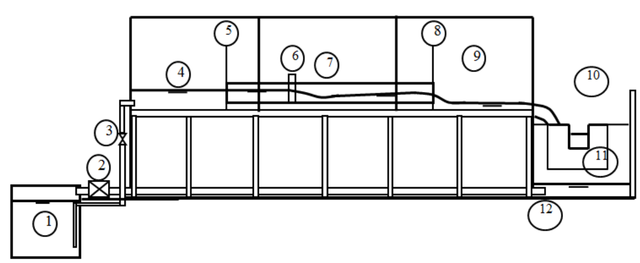
2.2. *Proposed Model*

The main problem of the study is the determination of the discharge value, and this can be done using the proposed model with the following steps:

1. Measure the water depth through the contraction device which can be regarded as critical specific energy (E_{me});
2. Divide the critical specific energy by the diameter (D) to get the relative critical specific energy (E_{*c});
3. Estimate the value of relative critical water depth (Y_c) by knowing the value of the relative critical specific energy and δ from Eq. (11). The solution of this equation can be done by trial and error, or by using tables, or from the graph.
4. Using the relative critical water depth, the required discharge can be calculated from Eq. (14).

III EXPERIMENTAL WORK

Diagrammatic sketch for the experimental flume is shown in Fig (5).



1- Ground water tank
2- 10 H.P pump
3- Control valve
4- Inlet channel
5- Upstream sluice gate
6- Vertical cylinder
7- Plastic semicircular pipe
8- Downstream gate
9- End channel part
10- Inner collected tank
11- Rectangular notch
12- Return pipe

Fig. 5. Diagrammatic sketch for the Flume.

A storage tank of 12.00 m^3 was made to feed the flume by water requirement. The flow of water through supplier pipe and flume can be obtained by 10 H.P pump. A valve at the downstream side of the pump was used to control discharge value. Precaution from turbulence at the inlet of flume was used in the first part of the flume to have uniform flow. The flume dimensions are 14.25 m long, 1.00 m wide and 1.00 m height. It was divided into three sections. The first one was used to remove eddies and to give a uniform flow condition. The second part of flume has a Plexiglas plate as a side to have a clear view during the experimental work. The development of models based on the design of simple flume for flow measurement in the open channel was proposed. The semicircular contraction flume was constructed by placing a vertical circular cylinder inside the semicircular pipe portion of the hydraulic flume. In the present experiment, semicircular pipe with three different diameters and three different contractions were prepared, (Table 1).

TABLE 1
CONTRACTED RATIOS AND PIPE DIAMETERS

Pipe Diameter D (cm)		**Contraction Ratios**		
		32.4 %	**41.3 %**	**47.5 %**
internal	**external**	**Vertical Pipe Diameter d**		
15.00	16.00	4.86	5.90	7.84
18.40	20.00	6.20	7.60	16.70
24.20	26.20	7.13	8.70	11.50

TABLE 2
EXPERIMENTAL RESULTS

Run No.	Q_{me} **(cm3/s)**	$\delta = 0.324$		$\delta = 0.413$		$\delta = 0.475$	
		E_{me} **(cm)**	E_{*me}	E_{me} **(cm)**	E_{*me}	E_{me} **(cm)**	E_{*me}
1	685	2.5	0.1033	2.6	0.1074	2.7	0.1116
2	921	2.9	0.1198	3.0	0.1240	3.2	0.1322
3	1501	3.6	0.1488	3.7	0.1529	4.1	0.1694
4	1611	3.8	0.1570	4.0	0.1653	4.2	0.1736
5	1932	4.2	0.1736	4.3	0.1777	4.5	0.1860
6	2281	4.5	0.1860	4.6	0.1901	4.8	0.1983
7	2440	4.6	0.1901	4.8	0.1983	5.0	0.2066
8	2531	4.8	0.1983	4.9	0.2025	5.1	0.2107
9	2730	4.9	0.2025	5.0	0.2066	5.2	0.2149
10	2813	5.0	0.2066	5.2	0.2149	5.4	0.2231
11	2933	5.1	0.2107	5.3	0.2190	5.5	0.2273
12	3054	5.2	0.2149	5.4	0.2231	5.6	0.2314
13	3326	5.3	0.2190	5.6	0.2314	5.8	0.2397
14	3452	5.4	0.2231	5.7	0.2355	5.9	0.2438
15	3529	5.4	0.2231	5.7	0.2355	6.2	0.2562
16	3606	5.4	0.2231	5.8	0.2397	6.3	0.2603
17	3813	5.6	0.2314	5.8	0.2397	6.0	0.2479
18	4023	5.7	0.2355	6.2	0.2562	6.4	0.2645
19	4103	5.9	0.2438	6.1	0.2521	6.3	0.2603
20	4278	5.9	0.2438	6.5	0.2686	6.7	0.2769
21	4482	6.1	0.2521	6.3	0.2603	6.5	0.2686
22	4675	6.5	0.2686	6.7	0.2769	6.9	0.2851
23	4885	6.3	0.2603	6.7	0.2769	7.2	0.2975
24	5370	6.6	0.2727	7.0	0.2893	7.5	0.3099
25	5721	7.0	0.2893	7.2	0.2975	7.4	0.3058
26	6094	7.2	0.2975	7.4	0.3058	7.6	0.3140
27	6214	7.3	0.3017	7.7	0.3182	7.9	0.3264
28	7173	8.0	0.3306	8.3	0.3430	8.5	0.3512
29	7652	8.1	0.3347	8.4	0.3471	8.6	0.3554
30	8042	8.2	0.3388	8.5	0.3512	8.7	0.3595

The water depth in the semicircular pipe can be read using piezometer. Discharge through the experimental flume was determined using a rectangular notch at the flume sump. Once the cylinder was fixed in the circular channel, discharge was varied from Q min = 0.685 L/s to max =8.042 L/s. For each discharge, the approaching depth of flow in the semicircular pipe channel was observed and the energy head was evaluated. Then this quantity was equal to critical energy head, the sought relation Q_{me} / E_{me} can be established (Table 2).

Plate (1) Second part of Flume

IV ANALYSIS AND DISCUSSIONS

The main objective of the present study is to get the discharge using the mobile flume in the semicircular open channel for values of contraction ratio δ. With E_{*c} and Yc that is presented in Eq. (11). The corresponding dimensionless discharge Q_* can be computed from Eq. (12). Table 3 shows the values of E_{*c} and Q_* corresponding to values of Yc for contraction ratios δ = 0.324, 0.413 and 0.475.

TABLE 3
VALUES OF CRITICAL SPECIFIC ENERGY E_{*C} AND Q_* CORRESPONDING TO VALUES OF YC FOR CONTRACTION RATIOS Δ = 0.324, 0.413 AND 0.475

Y_c	$\delta = 0.324$		$\delta = 0.413$		$\delta = 0.475$	
	Q_*	E_{*C}	Q_*	E_{*C}	Q_*	E_{*C}
0.000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
0.020	0.00188	0.02989	0.00163	0.02987	0.00145	0.02986
0.040	0.00536	0.05995	0.00465	0.05994	0.00415	0.05993
0.060	0.00988	0.09010	0.00857	0.09011	0.00766	0.09013
0.080	0.01523	0.12040	0.01322	0.12046	0.01181	0.12052
0.100	0.02131	0.15091	0.01849	0.15105	0.01653	0.15118
0.120	0.02803	0.18169	0.02433	0.18196	0.02176	0.18221
0.140	0.03535	0.21282	0.03069	0.21328	0.02745	0.21370
0.160	0.04323	0.24440	0.03754	0.24513	0.03358	0.24580
0.180	0.05165	0.27652	0.04487	0.27764	0.04015	0.27867
0.200	0.06059	0.30934	0.05266	0.31099	0.04714	0.31254
0.220	0.07006	0.34303	0.06093	0.34542	0.05459	0.34769
0.240	0.08008	0.37783	0.06971	0.38125	0.06252	0.38453
0.260	0.09068	0.41406	0.07905	0.41892	0.07099	0.42364
0.280	0.10193	0.45216	0.08904	0.45905	0.08014	0.46590
0.300	0.11395	0.49277	0.09982	0.50261	0.09014	0.51264
0.320	0.12692	0.53685	0.11166	0.55109	0.10131	0.56611
0.340	0.14115	0.58592	0.12497	0.60702	0.11425	0.63032
0.360	0.15716	0.64254	0.14052	0.67503	0.13004	0.71326
0.380	0.17589	0.71142	0.15980	0.76455	0.15110	0.83350
0.400	0.19919	0.80229	0.18620	0.89857	0.18385	1.04666
0.420	0.23137	0.93930	0.22942	1.15174	0.25455	1.63035
0.440	0.28526	1.20418	0.33684	1.98567	------	------
0.460	0.43146	2.17502	------	------	------	------

Figure (6) shows the plot for the critical depth Yc with critical specific energy E_{*c} for contraction ratios δ = 0.324, 0.413 and 0.475.

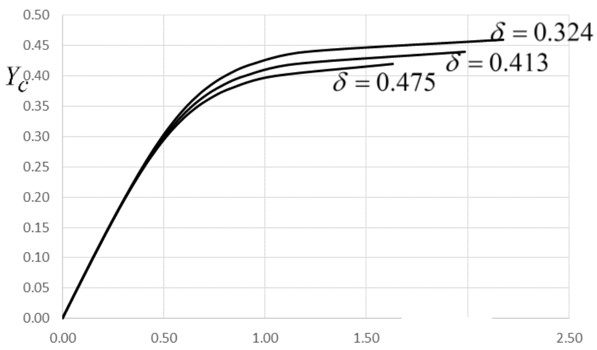


Fig. 6. Critical depth *Yc* with critical specific energy E_{*c} for contraction ratios δ = 0.324, 0.413 and 0.475.

A relative critical water depth plot as ordinate against the dimensionless measured specific energy as abscissa will appear approximately as a straight line for specific energy less than 0.5 regardless of the device diameter. The final result corresponds to explicit equations for critical water depth once the specific energy height in the vertical pipe at contraction section is recorded.

Also, Figure (7) shows the plot for the Discharge Q_* with critical specific energy E_{*c} for the same contraction ratios.

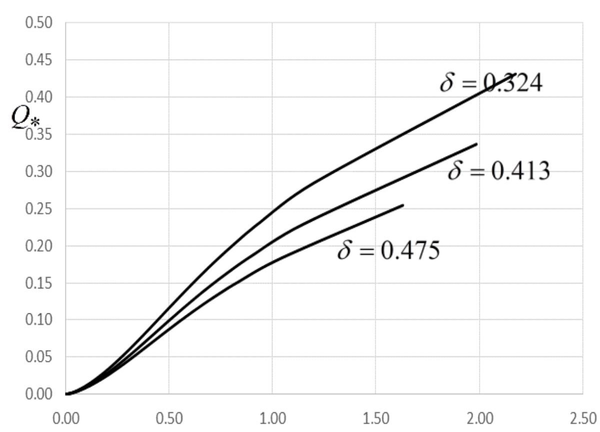


Fig. 7. Discharge Q_* versus critical specific energy E_{*c} for contraction ratios δ = 0.324, 0.413 and 0.475.

According to experimental work (Table (1)), the relationship between measured discharge and measured specific energy can be easily plotted. Figure (8) shows the dimensionless measured discharge Q_{*me} with dimensionless measured critical specific energy E_{*me} for contraction ratios δ = 0.324, 0.413 and 0.475.

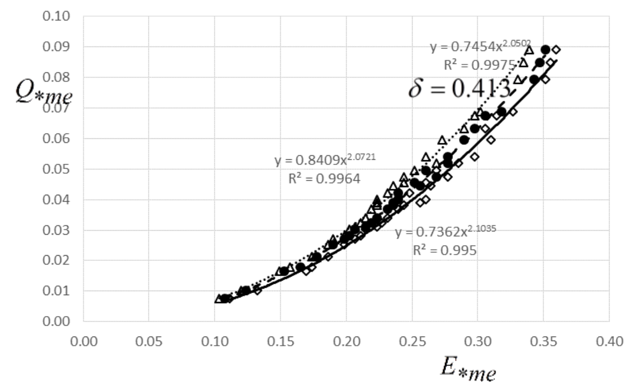


Fig. 8. Discharge Q_{*me} versus measured critical specific energy E_{*me} for contraction ratios δ = 0.324, 0.413 and 0.475.

Using the least-squares techniques, the relationship between the dimensionless measured discharge, Q_{*me} and the dimensionless measured specific energy E_{*me} can be written as follows:

$$Q_* = 0.8409 E_{*me}^{2.0721} \qquad \delta = 0.324 \qquad R^2 = 0.9964 \qquad (15)$$

$$Q_* = 0.7454 E_{*me}^{2.0502} \qquad \delta = 0.413 \qquad R^2 = 0.9975 \qquad (16)$$

$$Q_* = 0.7362 E_{*me}^{2.1035} \qquad \delta = 0.475 \qquad R^2 = 0.995 \qquad (17)$$

The percentage error for the calculated discharge is:

$$\text{Error} = \frac{Q_{me} - Q_{cal}}{Q_{me}} \times 100 \qquad (18)$$

The error percentages in calculating the dimensionless discharge value for various contraction ratios are tabulated in Table (4).

However, the estimated discharge according to Eqs. (15), (16) and (17) deviates from the measured one. The calculated flow rates were compared with the measured rates. The comparison is presented in Table 3. Table 3 shows that the calculated discharge deviates the measured discharge by 6.7%, 6.2% and 8.6% for contraction ratios δ = 0.324, 0.413 and 0.475 respectively.

The error percentages in the calculated dimensionless discharge values for various contraction ratios are tabulated in Table (5).

TABLE 4
COMPARISON OF MEASURED AND CALCULATED DISCHARGE FOR VARIOUS CONTRACTION RATIO (Δ)

Run No.	Q_{me} (cm3/s)	$\delta = 0.324$		$\delta = 0.413$		$\delta = 0.475$	
		Q_{cal} (cm3/s) Eq. (15)	Error %	Q_{cal} (cm3/s) Eq. (16)	Error %	Q_{cal} (cm3/s) Eq. (17)	Error %
1	685	688	-0.4	694	-1.3	659	3.8
2	921	935	-1.5	931	-1.0	942	-2.2
3	1501	1464	2.5	1431	4.7	1587	-5.7
4	1611	1637	-1.6	1679	-4.2	1669	-3.6
5	1932	2014	-4.3	1947	-0.8	1930	0.1
6	2281	2324	-1.9	2236	2.0	2211	3.1
7	2440	2432	0.3	2440	0.0	2409	1.3
8	2531	2657	-4.9	2545	-0.5	2511	0.8
9	2730	2772	-1.6	2653	2.8	2616	4.2
10	2813	2891	-2.8	2875	-2.2	2832	-0.7
11	2933	3012	-2.7	2989	-1.9	2944	-0.4
12	3054	3136	-2.7	3106	-1.7	3057	-0.1
13	3326	3262	1.9	3347	-0.6	3291	1.1
14	3452	3391	1.8	3470	-0.5	3412	1.2
15	3529	3391	3.9	3470	1.7	3787	-7.3
16	3606	3391	6.0	3596	0.3	3917	-8.6
17	3813	3656	4.1	3596	5.7	3535	7.3
18	4023	3793	5.7	4123	-2.5	4049	-0.6
19	4103	4074	0.7	3988	2.8	3917	4.5
20	4278	4074	4.8	4543	-6.2	4458	-4.2
21	4482	4365	2.6	4261	4.9	4183	6.7
22	4675	4979	-6.5	4834	-3.4	4743	-1.4
23	4885	4667	4.5	4834	1.0	5187	-6.2
24	5370	5139	4.3	5288	1.5	5652	-5.2
25	5721	5806	-1.5	5602	2.1	5495	4.0
26	6094	6154	-1.0	5926	2.8	5812	4.6
27	6214	6333	-1.9	6429	-3.5	6305	-1.5
28	7173	7656	-6.7	7498	-4.5	7354	-2.5
29	7652	7856	-2.7	7685	-0.4	7538	1.5
30	8042	8058	-0.2	7873	2.1	7723	4.0

However, the calculated discharge according to Eq. (14) deviates from the measured one. The calculated flow rates were compared with those measured. The comparison is presented in Table 4. Table 4 shows that the calculated discharge deviates the measured one by 59.4%, 47.6% and 56.1% for contraction ratios δ = 0.324, 0.413 and 0.475 respectively. Therefore, the estimated equation must be corrected by the discharge coefficient.

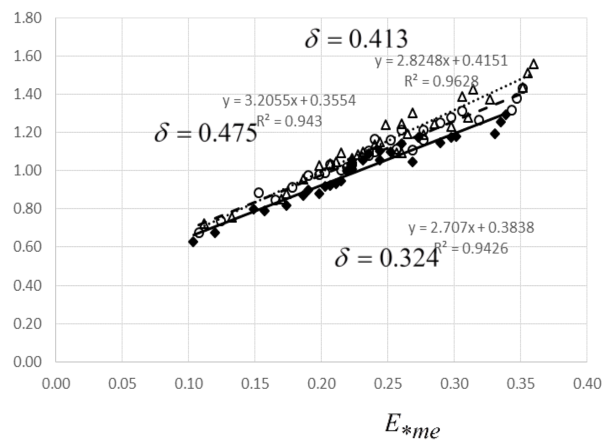
4.1 Discharge Coefficient Equation

The relationship between the discharge coefficients $\left(C_d = Q_{*me}/Q_{*ca}\right)$ versus dimensionless measured specific energy for various contraction ratios are shown in Fig (9).
Equations were developed for the discharge coefficient (Cd) based on the data in Fig. (9), using the least-squares techniques as follows:

$$Q_{me}/Q_{ca} = 2.9946 E_{*me} + 0.3276 \quad \delta = 0.324 \quad R^2 = 0.9435 \tag{19}$$

$$Q_{me}/Q_{ca} = 2.8248 E_{*me} + 0.4151 \quad \delta = 0.413 \quad R^2 = 0.9628 \tag{20}$$

$$Q_{me}/Q_{ca} = 3.2055 E_{*me} + 0.3554 \quad \delta = 0.475 \quad R^2 = 0.943 \tag{21}$$



Applying discharge coefficient equation led to decrease the percentage of error between the corrected calculated dimensionless discharges and measured one for contraction ratios, Table (4).

TABLE 5
COMPARISON OF MEASURED AND CALCULATED DISCHARGE USING EQ. (11) AND EQ. (14) FOR VARIOUS CONTRACTION RATIO (Δ).

Run No.	Q_{me} cm3/s	$\delta = 0.324$			$\delta = 0.413$			$\delta = 0.475$		
		C_d	Q_{cal} cm3/s	Error %	C_d	Q_{cal} cm3/s	Error %	C_d	Q_{cal} cm3/s	Error %
1	685	0.627	1092	-59.4	0.678	1011	-47.6	0.723	947	-27.7
2	921	0.676	1363	-47.9	0.740	1245	-35.1	0.756	1218	-24.4
3	1501	0.800	1877	-25.0	0.885	1696	-13.0	0.853	1760	-14.7
4	1611	0.790	2039	-26.6	0.846	1904	-18.2	0.879	1832	-12.1
5	1932	0.817	2364	-22.4	0.911	2121	-9.8	0.956	2021	-4.4
6	2281	0.872	2617	-14.7	0.976	2337	-2.4	1.028	2220	2.8
7	2440	0.901	2707	-11.0	0.980	2490	-2.1	1.036	2355	3.6
8	2531	0.879	2878	-13.7	0.988	2563	-1.2	1.044	2424	4.4
9	2730	0.920	2969	-8.7	1.033	2644	3.2	1.096	2490	9.6
10	2813	0.922	3050	-8.4	1.006	2797	0.6	1.066	2638	6.6
11	2933	0.934	3140	-7.1	1.019	2878	1.9	1.083	2707	8.3
12	3054	0.945	3230	-5.8	1.032	2960	3.1	1.099	2779	9.9
13	3326	0.999	3330	-0.1	1.065	3122	6.1	1.138	2924	13.8
14	3452	1.010	3420	0.9	1.080	3198	7.4	1.152	2996	15.2
15	3529	1.032	3420	3.1	1.103	3198	9.4	1.095	3221	9.5
16	3606	1.054	3420	5.1	1.101	3276	9.2	1.095	3294	9.5
17	3813	1.056	3609	5.3	1.164	3276	14.1	1.243	3068	24.3
18	4023	1.088	3700	8.0	1.112	3618	10.1	1.195	3366	19.5
19	4103	1.058	3880	5.4	1.160	3537	13.8	1.246	3294	24.6
20	4278	1.103	3880	9.3	1.108	3862	9.7	1.191	3591	19.1
21	4482	1.099	4079	9.0	1.212	3700	17.5	1.303	3441	30.3
22	4675	1.047	4467	4.5	1.159	4033	13.7	1.248	3746	24.8
23	4885	1.142	4277	12.4	1.211	4033	17.4	1.230	3970	23.0
24	5370	1.176	4566	15.0	1.253	4286	20.2	1.277	4205	27.7
25	5721	1.149	4981	12.9	1.281	4466	21.9	1.387	4125	38.7
26	6094	1.177	5179	15.0	1.311	4647	23.7	1.425	4277	42.5
27	6214	1.177	5279	15.1	1.266	4909	21.0	1.375	4518	37.5
28	7173	1.195	6001	16.3	1.318	5441	24.1	1.436	4995	43.6
29	7652	1.254	6100	20.3	1.381	5540	27.6	1.511	5065	51.1
30	8042	1.295	6208	22.8	1.430	5622	30.1	1.561	5152	56.1

From Table (4) it can be clearly seen that Eq. (14) has an error percentage of 0.3 up to 7.0%, 0.1 up to 6.2% and 0 up to 8.7% for contraction ratios 32.4, 41.3 and 47.5% respectively. Also, it can be noticed that the best contraction ratio used in the semicircular mobile flume is 0.413, which gives the discharge coefficient less than other contractions.

TABLE 6
COMPARISON OF CORRECTED CALCULATED AND MEASURED DISCHARGE.

Run No.	Q_{me} cm3/s	$\delta = 0.324$			$\delta = 0.413$			$\delta = 0.475$		
		C_d	Q_{cal} cm3/s	Error %	C_d	Q_{cal} cm3/s	Error %	C_d	Q_{cal} cm3/s	Error %
1	685	0.637	724	-5.8	0.719	726	-6.0	0.713	676	1.4
2	921	0.686	965	-4.8	0.765	953	-3.4	0.779	949	-3.0
3	1501	0.773	1476	1.7	0.847	1437	4.3	0.898	1581	-5.3
4	1611	0.798	1650	-2.4	0.882	1679	-4.2	0.912	1670	-3.7
5	1932	0.847	2018	-4.5	0.917	1945	-0.6	0.951	1923	0.5
6	2281	0.884	2322	-1.8	0.952	2225	2.5	0.991	2200	3.6
7	2440	0.897	2432	0.3	0.975	2429	0.4	1.018	2397	1.8
8	2531	0.922	2650	-4.7	0.987	2530	0.1	1.031	2499	1.3
9	2730	0.934	2767	-1.4	0.999	2641	3.3	1.044	2601	4.7
10	2813	0.946	2876	-2.3	1.022	2859	-1.6	1.071	2825	-0.4
11	2933	0.959	2997	-2.2	1.034	2976	-1.5	1.084	2934	0.0
12	3054	0.971	3119	-2.1	1.045	3094	-1.3	1.097	3049	0.2
13	3326	0.983	3252	2.2	1.069	3337	-0.3	1.124	3285	1.2
14	3452	0.996	3378	2.1	1.080	3455	-0.1	1.137	3406	1.3
15	3529	0.996	3378	4.3	1.080	3455	2.1	1.177	3790	-7.4
16	3606	0.996	3378	6.3	1.092	3577	0.8	1.190	3919	-8.7
17	3813	1.021	3646	4.4	1.092	3577	6.2	1.150	3529	7.5
18	4023	1.033	3779	6.1	1.139	4121	-2.4	1.203	4049	-0.6
19	4103	1.058	4050	1.3	1.127	3987	2.8	1.190	3919	4.5
20	4278	1.058	4050	5.3	1.174	4533	-6.0	1.243	4464	-4.3
21	4482	1.082	4348	3.0	1.150	4256	5.0	1.216	4185	6.6
22	4675	1.132	4962	-6.1	1.197	4829	-3.3	1.269	4755	-1.7
23	4885	1.107	4656	4.7	1.197	4829	1.2	1.309	5198	-6.4
24	5370	1.144	5123	4.6	1.232	5281	1.7	1.349	5672	-5.6
25	5721	1.194	5812	-1.6	1.256	5607	2.0	1.336	5509	3.7
26	6094	1.219	6159	-1.1	1.279	5943	2.5	1.362	5826	4.4
27	6214	1.231	6336	-2.0	1.314	6450	-3.8	1.402	6334	-1.9
28	7173	1.318	7673	-7.0	1.384	7530	-5.0	1.481	7400	-3.2
29	7652	1.330	7868	-2.8	1.396	7732	-1.0	1.495	7570	1.1
30	8042	1.342	8077	-0.4	1.407	7911	1.6	1.508	7769	3.4

V CONCLUSIONS

A simple water discharge device was presented. Theoretical results were compared with measured laboratory data. A model has been proposed to estimate the dimensionless discharge value. The following conclusions have been drawn from the present study.

1- Simple semicircular mobile flume can be used as a mobile discharge measurement device in semicircular open channels. The discharge can be estimated directly using the proposed model, which incorporates the semicircular pipe, the diameter of the vertical cylinder and the column head reading. The proposed model incorporates all the influencing parameters governing the flow. The actual measured flow rates were compared with the calculated flow rates and the proposed model {Equations (15) through (17)}. Results of the comparison showed that the proposed model can predict accurate discharge with a maximum error of up to 8.6%.

2- Also, the discharge can be estimated directly using the proposed mathematical model {Equations (11) and (14)}, which incorporates the semicircular pipe, diameter of the vertical cylinder and the column head reading. Proposed model incorporates all the influencing parameters governing the flow. The actual measured flow rates were compared with the calculated flow rates and corrected by Equations (19) through (21). Results of the comparison showed that the proposed mathematical model {Equation (14)} predicted approximately the same accurate discharge with a maximum error up to 8.7% as compared to the measured discharge.

3- A relative critical water depth plot as ordinate against the dimensionless specific energy as abscissa Fig. (6) appeared approximately as a straight line for specific energy less than 0.5 regardless of the device diameter. The final result corresponds to an explicit equation for critical water depth once the specific energy height in the vertical pipe at contraction section is recorded.

4- Contraction ratio 0.413 is the best contraction value gave a near value for measured dimensionless discharge with least error.

5- Semicircular mobile flume can be used for discharge measurement in open channels with the best accuracy of ± 8.7% equations developed.

List of Notation

A is the area of the water section;
A_* is dimensionless water section area $\left(A/D^2\right)$;
A_{*c} is dimensionless critical water section area $\left(A_c/D^2\right)$;
C_d is the discharge coefficient;
d is vertical pipe diameter;
d_w is the normal depth of the point below the water surface;
D is semicircular open channel pipe;
E is specific energy;
E_* is dimensionless specific energy (E/D);
E_{*c} is dimensionless critical specific energy (E_c/D);
E_{*me} is dimensionless measured specific energy (E_{me}/D);
Fr is Froude Number
g is the gravitational acceleration.
Q is discharge;
Q_{cal} is calculated discharge;
Q_{me} is measured discharge;
Q_* is dimensionless discharge $\left(Q^2/gD^5\right)^{1/2}$;
Q_{*cal} is dimensionless calculated discharge $\left(Q_{cal}^2/gD^5\right)^{1/2}$;
Q_{*me} is dimensionless measured discharge $\left(Q_{me}^2/gD^5\right)^{1/2}$;
R is factor;
T is top width;
T_c is dimensionless critical top width;
V is the stream line velocity and
y is water depth;
Y is dimensionless water depth (*y/D*);
Y_c is dimensionless critical water depth;
θ is the slope angle of the channel bottom,
α is the energy coefficient due to variable velocity distribution,
δ is contraction ratio (d/D)

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