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A Portable Orifice Meter for Pump Flow Measurement

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Abstract

Tube well irrigation system serves a significant land area for crop production in Bangladesh. Tube well discharge measurement is very important to schedule irrigation practices, means to decide (a) when to irrigate, and (b) how much of water should be applied into the field. Discharge is measured at the time of tube well commissioning only. Thereafter, no one knows how much of flow size is there in their crop field. This may be due to unknowingness the importance of correct flow size that plays a vital role in crop production. Another severe factor is the unavailability of a suitable equipment for flow size determination which can be manufactured with (a) the locally available materials, (b) the materials cost is cheaper, (c) easy to install and operate, and (d) handy. With this end in view, a portable orifice meter was designed and fabricated in the Agricultural Engineering workshop of Bangladesh Agricultural Institute (BARI). This meter was designed for measuring pump flow size operated for shallow tube wells having 4-inch delivery pipe. Concept of end-cap orifice meter was considered to design this portable orifice meter. Shortening the conventional orifice meter and introducing the slit type (rectangular shaped) at the orifice outlet was found to be a very good, handy, cheaper, simple, and fabricated with locally available materials, and shows a promising agreement while compared the calibrated discharge (Q_c) with predicted discharge (Q_p). Errors from using the regression equation to obtain discharge ranged from 0.09 to 2.17% whereas the errors ranged from 0.24 to 6.57% when considered the laboratory measure discharges.

Keywords

Pump Flow Measurement, Orifice Meter, End-Cap Orifice, Vena Contracta Coefficient

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1. Introduction

Measurement of water is a crucial issue for the appropriate use and management of irrigation water. Optimum yield is backboned by irrigation scheduling which is governed by the correct flow size determination and its application into the crop field for optimum yield. Hence, pump discharge measurement plays the vital role for crop production. Several studies proposed different approaches and designs of discharge measurement devices. Pump irrigation system covers a considerable area of crop land in different countries of the world. In some countries it is even 75 to 90 percent of the total cultivable area is irrigated by pump irrigation system. Applying a correct volume irrigation water ensures potential crop yield [1, 2]. Modern irrigation scheduling system offers an easy method to irrigate the land just by operating the pump for a specific time once the following factors are known: they are (1) flow size, *q*, (2) area to be calculated, *a*, and (3) root zone depth of the crop, *d*. Here, the value of, *a,* is adjustable once the correct value of flow size is determined. Time of pump operation can be selected based

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on the flow size, q. Hence, Determination and applying water into the field for certain time plays the crucial role in best management practices (BMP). Pump discharge is measured at the time of pump commissioning only and there is no any measurement taken thereafter. The pump users do not know about their pump discharge rate. It may be due to unawareness of the importance of pump discharge information or lack of a suitable equipment that may help the pump users to record the discharge data. In most cases, the users do not have technical knowledge about the importance of measuring the flow size.

Some of the parameters considered in improving the discharge measurement devices include the accuracy of the measurement, the cost, and the ease in design and construction of the system [3, 4]. To optimize the system and for continuous improvement in the performance of flow measuring devices, numerous experimental studies [5-7], theoretical mathematical modeling and computer simulations have been developed [3, 8−10] that accounted for different parameters of a flow discharge measurement devices [5, 11]. Muñoz-Díaz et al., [9] used the Finite Volume Method to analyze the effects of different geometric profiles of the components and improve the overall performance of orifice flowmeter. Bidkar et al., [12] reported the results of a comparative analysis of flow meters used for 40 lit/sec discharge measurements. The variables used to rank the devices include cost, ease in design and construction. Ramirez et al., [6] described the design and unique calibration curves for each orifice meters for a flow rate of 500 lit/sec. Rhinehart et al., [13] also presented a detailed study on the calibration of orifice flow measurements and used a power law model and the ISO model for analysis.

A portable pump flow size measuring device was designed and fabricated in the Agricultural Engineering Division workshop of Bangladesh Agricultural Research Institute using the locally available materials, less expensive, and easy to install with the delivery pipe of the pump. The initial flow measuring device was designed and fabricated for using for measuring the shallow tube well (STW) discharge having 4-inch delivery pipe diameter. The developed orifice meter was calibrated in a specially designed set up of calibration bench. The result was found to be very promising while considering the accuracy and acceptability by the users.

2. The Model

Lack of an appropriate portable shallow tube well flow size measuring device has been a critical issue for deciding the required amount of flow or deciding required time of pump operation once the pump flow size is known. This situation ultimately affects the potential yield of crops. Considering the portability of the flow measuring device, the conventional end-cap orifice meter as describe by Layne and Bowler in 1958 [14] was shortened. Keeping in mind to deliver a better, higher accuracy, and easiness in using the equipment to California Pipe method as described by, also considering the Trajectory method that was developed in Purdue University by Green [6]. It was theorized that the equipment should be a portable type, low cost in manufacturing cost and cheaper price, and a very simple coupling system of this meter with the delivery pipe of the pump so that the users become interested and enthusiastic to use it after a field demonstration.

Shallow Tube Well (STW) version - The equipment was designed for 4-inch delivery pipe diameter. The length of the orifice meter was 12-inch pipe of mild steel. Hence, the rectangular orifice opening was at one end and the specially designed coupling device was made at the other end (to attach to the delivery pipe of the STW pump). The orifice was made of two pieces of rectangular glasses (hard plastic could also be used of same dimensions). These two pieces of glasses were placed at the top and one at the bottom at the discharge end to form the rectangular orifice and they were held in place with screwed clams and screws. Selection of the thickness of glass was 3 mm based on the reference to be less than 1/30 th of the delivery pipe diameter as stated by ASME (1959) [15]. From hereafter, space between glass strips will be called *Slit-Orifice opening*.

Pressure measuring tap – Location for inserting the pressure tap was selected one pipe diameter distance upstream from the slit orifice opening. An outlet nipple was welded at that point with a diameter that allowed inserting the plastic transparent tube without leakage of water and the pipe was held tied with a meter scale. This meter scale was vertically held by an iron slot on top of the iron angle that hold the top glass piece of the orifice as shown in Figure 1. This arrangement of measuring the rise of water was made for observing the data of pressure heads in the transparent tube to serve as the manometer, for various discharges through the slit orifice meter. The pressure tap was placed along the plane and parallel to the center of the pipe with an aim to yield the minimum errors in measuring flow sizes that might be caused due to not precisely levelling the meter while in use.

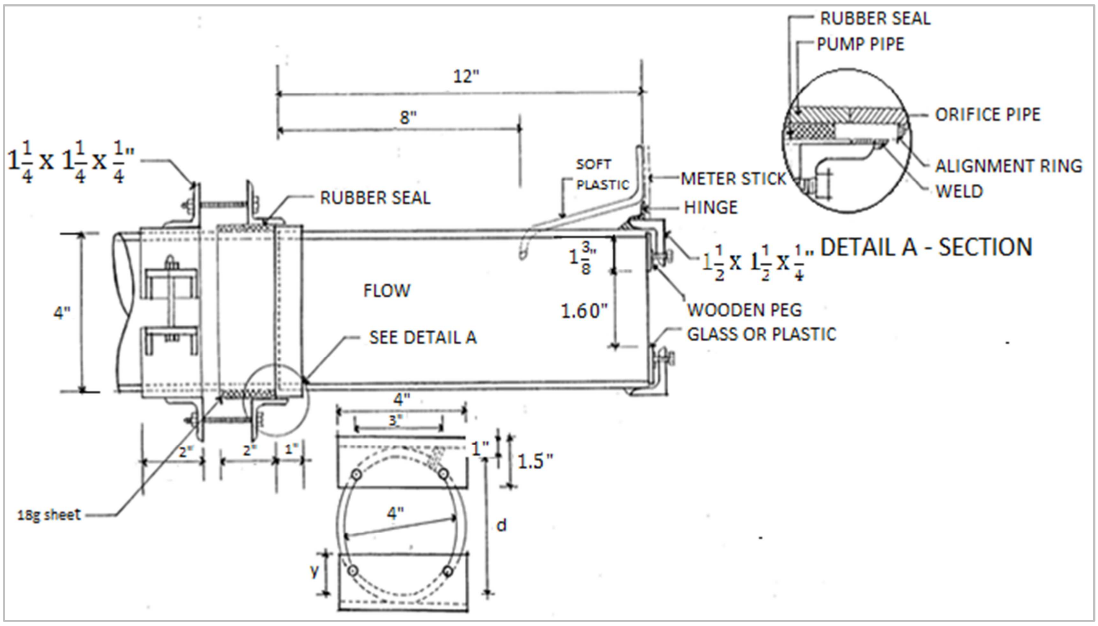

Figure 1. Diagram of a 4-inch slit-orifice meter with coupling.

Meter-to-pump-pipe connector – The coupling which is called meter-to-pump-pipe connector was devised by a same size (4-ich diameter) of pipe, cut longitudinally, spread out, filled with an extra strip, and welded at the outer circumference of the other pipe end (Figure 1). A 18 gage steel sheet served as a guide while a rubber pad was used to serve as a sealant. Two pieces of half circled (looks like C clamp) devices were made of 2-inch long that can be attached at the end of 4-inch delivery pipe of the pump. Two pairs of $1\,{}^{1}/_{4}" \times 1\,{}^{1}/_{4}" \times {}^{1}/_{4}"$ angle bar were diametrically welded on each side of the C clamp. One pair was attached to the discharge pipe and another pair was attached at the free end of the slit orifice meter. Two pairs of nuts and bolts were used to hold together firmly the slit orifice meter and the delivery pipe of the pump.

Head- discharge relations – The theoretical head-discharge relations was assumed to be the same as in an end-cap nozzle as described in ASME (1959). But with an exception of the area of vena contracta was used in lieu of the cross sectional area of the contracted throat. Basic equation of orifice flow is defined by

$$Q = CA_o\sqrt{2gH} \tag{1}$$

Considering for velocity of approach in a pipe,

$$H = h + k\frac{v^2}{2g} \tag{2}$$

Where,

Q = Discharge (cfs)

C = Vena contracta coefficient

k = Velocity distribution coefficient

A_o= Area of cross section of orifice (ft^2)

v = velocity in pipe (ft/s)

g = Acceleration due to gravity (ft/s^2)

h = Pressure head (ft)

Thus, substituting the value of H in equation (1)

$$Q = CA_o\sqrt{2g\left(h + k\frac{v^2}{2g}\right)} = CA_o\sqrt{\left(2gh + 2gk\frac{v^2}{2g}\right)} \tag{3}$$

Squaring both sides of equation (3)

$$Q^2 = C^2{A_o}^2\left\{2gh + 2gk\frac{v^2}{2g}\right\} = C^2{A_o}^2 \times 2gh + C^2{A_o}^2 \times kv^2 \tag{4}$$

As $Q = A_o \times v$; therefore, $v = \frac{Q}{A_o}$ and substitute this value in equation (4)

$$Q^2 = C^2{A_o}^2 \times 2gh + C^2{A_o}^2 \times k\frac{Q^2}{{A_o}^2} \tag{5}$$

$$\text{Or } Q^2 - Q^2C^2k = C^2{A_o}^2 \times 2gh \tag{6}$$

$$\text{Or } Q^2(1 - C^2k) = C^2{A_o}^2 \times 2gh \tag{7}$$

Therefore,

$$Q = \frac{1}{k^{0.5}\left\{1-\left(A_o/A_p\right)^2\right\}^{0.5}} \tag{8}$$

It should be mentioned here that the general equation of the end-cap nozzle is the same as a venturi meter.

Here,

${A_o}/{A_p}$= ratio of area of orifice to area of pipe

Table 1. Values of vena contracta coefficient C and $\left(A_o/A_p\right)^2$.

R=100000			*K* =1.02
$(A_o/A_p)^{0.5}$	(A_o/A_p)	$(Ao/A_p)^2$	C
0.2	0.04	0.0016	0.5955
0.3	0.09	0.0081	0.5989
0.4	0.16	0.0256	0.6072
0.5	0.25	0.0625	0.6241
0.6	0.36	0.1296	0.6545
0.7	0.49	0.2401	0.7063
0.8	0.64	0.4096	0.8000

Values of vena contracta coefficient C can be obtained in relation with $\left(A_o/A_p\right)^2$ using the tabulated values from the reference of ASME, 1959 shown above and it is as follows:

$$C = 0.6 + 0.454 \times \left(A_o/A_p\right)^2 \tag{9}$$

Table 2. Predicted equation of discharge through the orifice meter for different slit-openings. The calculation was done based on the information from ASME, 1959.

Slit Opening (inch)	Dam Closure (y/d)	Single Dam (A/d^2)	Double Dam (2A/d^2)	Relative Orifice Area	Vena Contracta Coefficient (C)	Area of Orifice (inch^2)	Predicted Discharge (cfs)
1.2	0.3500	0.2450	0.4900	0.2954	0.6641	0.0030	0.0090 $(h)^{0.5}$
1.5	0.3125	0.2097	0.4194	0.3660	0.6999	0.0038	0.0123 $(h)^{0.5}$
1.6	0.3000	0.1982	0.3964	0.3890	0.7107	0.0040	0.0133 $(h)^{0.5}$
1.7	0.2875	0.1868	0.3736	0.4118	0.7250	0.0043	0.0148 $(h)^{0.5}$

Table 2 has been developed to calculate the predicted discharge for different slit openings. Equation (1) was assumed to be valid when the value for velocity distribution coefficient was considered to be 1.02 and the best slit opening was 1.60 inch (as obtained after calibration). The discharge prediction equation for 1.60 inch slit opening was,

$$Q_p = 0.0133(h)^{0.5} \tag{10}$$

Where,

Q_p = predicted discharge in ft^3/s, and

h = pressure head in ft.

3. Calibration of Slit-Orifice Meter

A special bench for calibration of the slit-orifice meter was developed in the Agricultural Engineering workshop of Bangladesh Agricultural Research Institute (BARI) in Joydebpur, Gazipur, Bangladesh. This set up is shown in Figure 2. It consisted of three empty barrels interconnected with each other in series form. Each barrel was 55-gallon capacity was taken and they were joined through pipe welded at the bottom of each barrel in series way. These three barrels were placed on a 2000-pound capacity platform type of scale. A flexible 4-inch diameter hose pipe was attached at the bottom of the central barrel to use it for draining away water from the barrels after each calibration run. A baffle box was used on top of the middle barrel so that the water jet does not get splashed away without getting into the middle barrel. A portable pump was connected with a suction pipe of 4-inch flexible hose type was immersed under a sump of water while the delivery pipe of 3.5 inch was connected with a 6 ft long (including the length of the slit-orifice meter) and 4-inch diameter. These two portions of delivery pipes (one is 3.5-inch diameter hose pipe and another is 4-inch) were connected with a guide vane. The downstream of discharging pipe was raised to a certain height and hold with a bracing frame to adjust the height of discharge falls into the baffle box. The pump was operated for different discharges and their corresponding manometer readings were recorded from the transparent tube set along with a scale vertically held at the top of the $1\,^1/_4" \times 1\,^1/_4" \times ^1/_4"$ angle and shown in Figure 2. At pre-determined weights of water were allowed to fall in the baffle box and ultimately into the barrels. Times to fill those pre-determined weights of water were also recorded. Data for the weights of water and their time to deliver that waters flows through the slit-orifice were transformed into their flow rates equivalents. Calibration tests were done for several slit-openings and the trial with 1.6-inch slit opening with the ration of $^{A_o}/_{A_p}$ (ratio of area of orifice to area of pipe) equals 0.4953 gave the best fitting between the theoretical and calibrated results of flow sizes. Results of calibration of the best slit-opening of 1.6-inch are shown in Table 3.

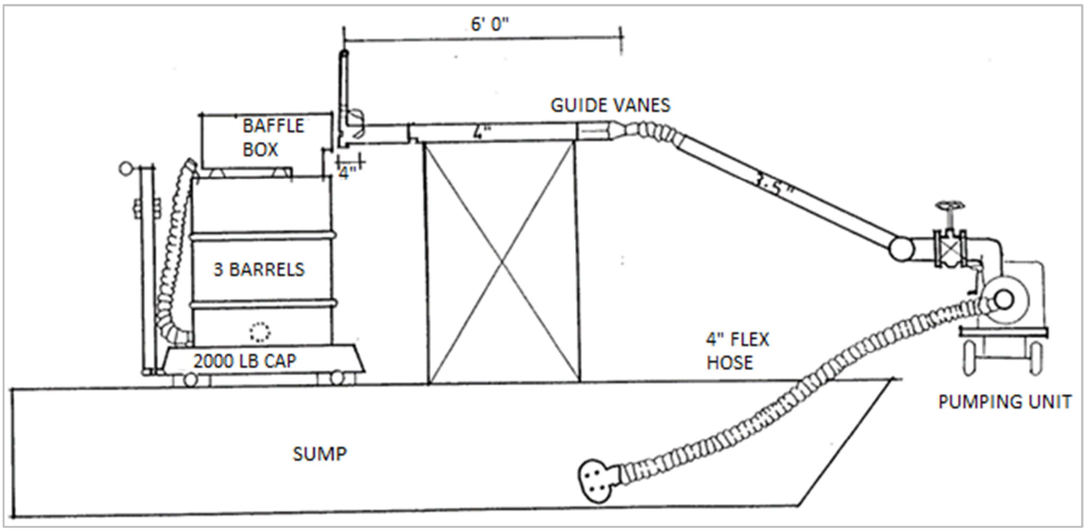

Figure 2. Calibration set up for 4-inch slit-orifice meter.

Specific volume of water has been taken from the standard value of 0.016083 ft^3/lb against water temperature at the time of calibration of 84°F. For example, equivalent volume of water of 500 lb at 84°F is 0.016083 ft^3/lb × 500 lb = 0.189 ft^3. Figure 3 has been drawn with the predicted discharge, Q_p and calibrated values of discharge, Q_c in ft^3/s against head in ft. Calibration data were regressed between the calibrated discharge in cfs and the pressure head in ft. The regression equation was derived to be

$$Q_r = 0.267(h)^{0.46} \quad (11)$$

Where,

Q_r = regressed discharge in ft^3/s, and

h = pressure head in ft.

4. Results and Discussions

The slit-orifice meter for discharge measurement of shallow tube wells was designed and fabricated in the Agricultural Engineering workshop of Bangladesh Agricultural Research Institute, Joydebpur, Gazipur, Bangladesh. The design was based on several aspects to provide a means of understanding the importance of measuring the discharge and using a portable discharge measuring fabricated with the materials that are cheaper in price and readily available in the local market. The delivery pipes of shallow tube wells are 4-inch in diameter. Hence the slit-orifice meter was also designed to be coupled and stays firmly and can be used to measure the discharge on site basis.

Utilizing the basic concept of an end-cap orifice meter and introducing the idea of slit type opening for the orifice flow was found to be very promising and suitable in actual field use purposes. Figure 3 has been drawn with the results of calibration of the slit-orifice meter. In the Figure, it is clearly observed that the logarithmic values of theoretical and calibrated discharges were in very good agreement when drawn against the pressure heads. Errors from using the regression equation (11) to obtain discharges ranged from 0.09 to 2.17% when compared with calibrated discharge, the errors ranged from 0.24 to 6.57% for theoretically derived relationship Table 2.

Table 3. Calibration results of slit-orifice meter with 1.6-inch slit-opening at 84°F water temperature..

Run No.	Weight of water trapped (Lb)	Time to Fill (Sec)	Equivalent Volume of water (ft^3)	Calibrated Discharge Q_c (cfs)	Theoretical Discharge Q_t (cfs)	Head (cm)	Head (ft)
1	500	42.55	0.684	0.189	0.176	13.85	0.454
2	500	44.05	0.708	0.183	0.171	13.10	0.430
3	600	52.08	0.838	0.185	0.173	13.35	0.438
4	500	44.01	0.708	0.183	0.174	13.55	0.445
5	500	23.37	0.376	0.344	0.344	52.85	1.734
6	500	23.09	0.371	0.348	0.344	52.85	1.734
7	500	23.26	0.374	0.346	0.342	52.35	1.718
8	500	24.99	0.402	0.322	0.326	47.55	1.560

Run No.	Weight of water trapped (Lb)	Time to Fill (Sec)	Equivalent Volume of water (ft^3)	Calibrated Discharge Q_c (cfs)	Theoretical Discharge Q_t (cfs)	Head	
						(cm)	(ft)
9	500	24.43	0.393	0.329	0.325	47.35	1.553
10	500	24.30	0.391	0.331	0.325	47.35	1.553
11	700	37.44	0.602	0.301	0.295	38.85	1.275
12	700	37.75	0.607	0.298	0.295	38.85	1.275
13	700	40.43	0.650	0.278	0.273	33.25	1.091
14	700	40.61	0.653	0.277	0.271	32.95	1.081
15	700	45.01	0.724	0.250	0.244	26.70	0.876
16	700	45.58	0.733	0.247	0.243	26.35	0.865
17	700	49.66	0.799	0.227	0.217	21.10	0.692
18	700	50.28	0.809	0.224	0.218	21.25	0.697
19	500	40.45	0.651	0.199	0.189	16.03	0.526
20	500	40.68	0.654	0.198	0.190	16.10	0.528

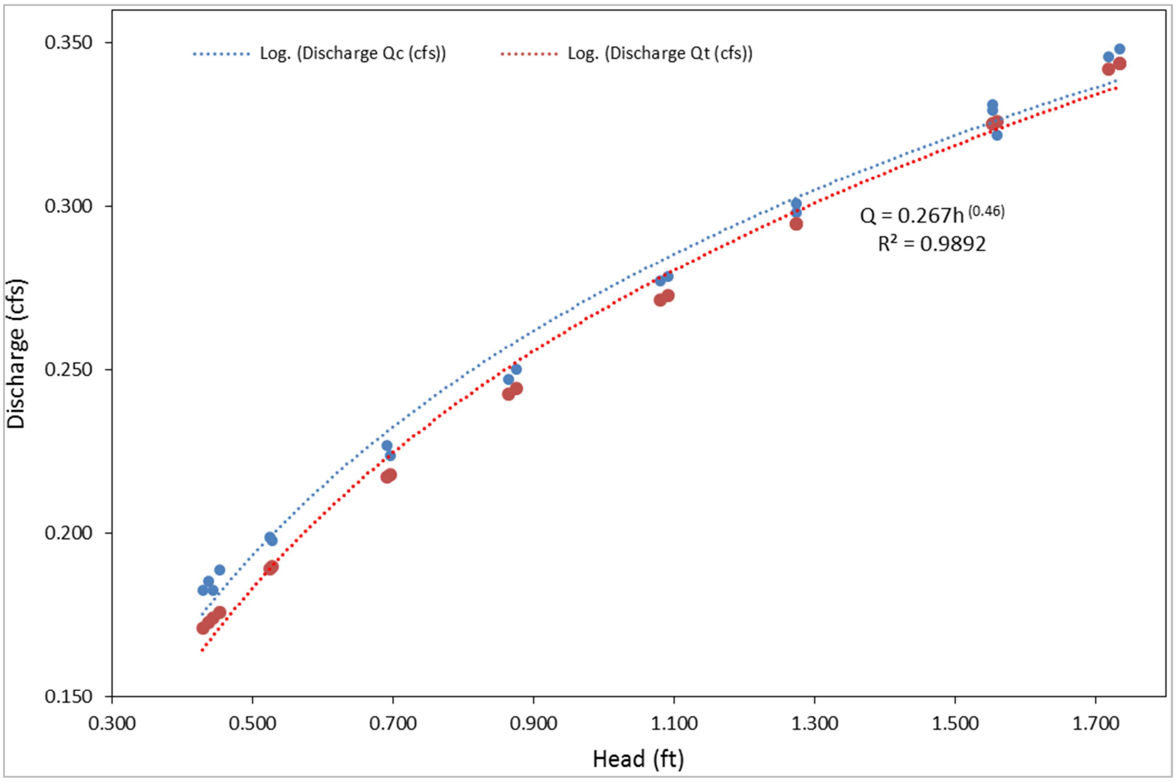

Figure 3. Curves showing the logarithmic values of predicted (Q_p) and calibrated (Q_c) discharges in cfs against pressure head in ft.

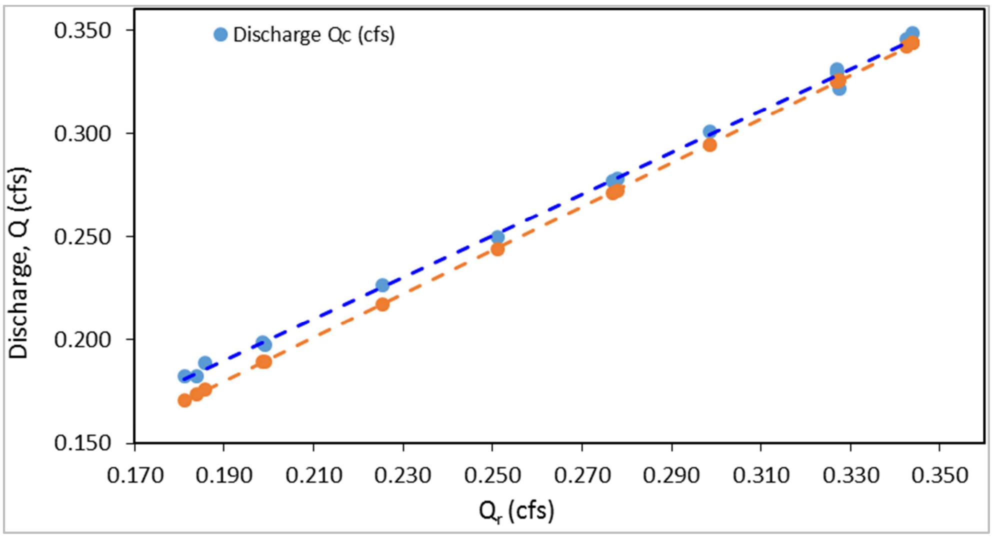

Figure 4. Relationship between the predicted (Q_p) and calculated discharges (Q_c) with respect to regression discharge (Q_r).

5. Conclusion

Need of a portable discharge measuring device has been in an acute stage. Measurement of water discharge out of pump is a very important information needed to determine the irrigation water quantity. A portable water discharge measuring device was designed and fabricated successfully using locally available materials with cheaper price. Calibration shows a very promising result while compared with the predicted discharges. Errors using the regression equation to obtain discharges ranged from 0.09 to 2.17% when compared with calibrated discharge, the errors ranged from 0.24 to 6.57% for theoretically derived relationship. These errors are very nominal when they are measured in the fields. This study shows the gateway for developing such a reliable and transportable device. Based on this information another device to measure the deep tube well flow size will be studied. The usual diameter of the deep tube well discharge pipe is 6-inch.

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