Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (42) No. (2) April, 2020

INVESTIGATING THE EFFECT OF ORIFICE AREA ON THE DISCHARGE COEFFICIENT FOR DIFFERENT ORIFICE SHAPES

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ملخص البحث:

يعتبر معامل التصرف خلال الفتحات من أهم المؤثرات التى يجب دراستها بعناية كبيرة حيث أنه يعبر عن مدى كفاءة السريان ويلعب دوراً مهما في التصميمات الهيدروليكية. وفي هذا البحث تم عمل دراسة معملية حول تأثير تغير مساحة الفتحات على معامل تصرف المياه خلالها لأشكال هندسية مختلفة ومقارنتها ببعضها.

تم اقتراح واستخدام أربعة أشكال مختلفة للفتحات وهي الشكل الدائري والمربع والمثلث متساوي الأضلاع والمستطيل كما تم اختبار أربعة مساحات مختلفة وهي (78.54 مم^2 و 176.71 مم^2 و 314.16 مم^2 و 490.87 مم^2) وهذه المساحات هي المكافئة لدوائر أقطارها (10 مم و 15 مم و 20 مم و 25 مم) على التوالي.، وجدير بالذكر أنه تم استخدام أربعة قيم مختلفة للضغط الرأسي وهي: (35 سم و 40 سم و 45 سم و50 سم) و قد تم قطع هذه الفتحات على 16 شريحة مصنوعة من الاكريلك الشفاف (أبعاد الشريحة: 7 سم x 7 سم). ولإجراء هذه الاختبارات تم بناء نموذج معملي بمعمل الري والهيدروليكا بجامعة الأزهر.

توصلت الدراسة إلى أنه في حال ثبات ضغط عمود الماء الواقع رأسياًعلى الفتحة فإن زيادة نسبة قطر الفتحة إلى سمكها تزيد قيمة معامل التصرف لوغارتمياً.وفي جميع المقارنات التحليلية التي تمت في هذه الدراسة تم ملاحظة أن الفتحات الدائرية تعطي أعلى قيم لمعامل التصرف مقارنة بجميع الاشكال الأخرى تليها الفتحات المثلثية متساوية الأضلاع ثم الفتحات المربعة وأخيراً لوحظ أن الفتحات المستطيلة تعطي أقل قيم لمعامل التصرف.

ABSTRACT

This paper experimentally examines the effect of orifice area on the discharge coefficient (C_d) for water discharge though different orifice shapes. To fulfill this objective, a laboratory physical model was built and operated in the Hydraulic Laboratory of the Faculty of Engineering, Al-Azhar University. Orifice shapes have been inspected were circle, square, rectangle and equilateral triangle.

To study these parameters of orifice flow, 16 orifice plates (7cm. x 7cm.) each was manufactured and fit in the constructed model. Bernoulli's Equation was utilized as a hypothetical establishment for calculating the discharge coefficient.

The study found that in nearly every case of pressure head, the increase of (d/t) ratio can increase (C_d) in asymptotic manner. Additionally, in the context of comparing the four tested orifice shapes, it was found that circular shape always gives a higher value of the C_d followed by the equilateral triangular shape then the square shape and finally the rectangular shape gives the least value of the discharge coefficient.

1. INTRODUCTION

Geometric characteristics related to orifice discharge are the most important factors affecting the discharge coefficient. The behavior of the discharge coefficient has a substantial importance in several fields, such as piping systems. flow measurement devices, dams, and fuel injection into combustion engines **[1].** The discharge coefficient

(C_d) of an orifice is very significant parameter as it is express the orifice flow efficiency. Correspondingly, Orifice flow has been used widely for flow control and restriction. Previous studies emphasized the existence of relationships between the geometric characteristics and the discharge coefficient. For example, ***Abd, Alomar, and Mohamed*** experimentally investigated the flow characteristics of different diameter sharp-edged orifices. The concluded that beta ratio (the ratio between orifice diameter and pipe diameter) has a positive effects on the C_d whereas it has inversely effects on pressure head losses. **[2].** Also, ***Parshad et al.*** studied how extend the coefficient of discharge can be affected by changing orifice diameter. They concluded that the coefficient of discharge is directly proportional to the orifice diameter and orifice plates whose diameters are less than 0.45 inches may have coefficient of discharge uncertainties as great as 3.0% due to problems of edge sharpness**.[3].** Nevertheless, no studies were showed the effect of orifice area on the discharge coefficient as a comparative study between different orifice shapes. Accordingly, this research was initiated with the objective of comparing the effect of orifice area on the discharge coefficient (C_d) for four different orifice shapes (circle, square, equilateral triangle and rectangle) under four different vertical pressure heads.

2. OBJECTIVE

This research aims to experimentally inspect the effect of orifice area on the discharge coefficient (C_d) and presenting analytical comparison between four (4) different orifice shapes (circle, square, equilateral triangle and rectangle).

3. COEFFICIENT OF DISCHARGE OF AN ORIFICE

Discharge coefficient is defined as the ratio of the quantity of water discharged through an orifice to the quantity theoretically possible at that flow conditions. Discharge coefficient illustrates what proportion the flow defers from the ideal theoretical flow. A smaller value of discharge coefficient shows that the actual discharge is smaller compare to the theoretical or ideal value and vice versa.

Orifice can be defined as opening which can be exist in the vertical side or the base through which the liquid flows out of a tank. This hole or opening is termed an orifice, with the condition that the liquid level of the upstream side is always above the top of the orifice. The use of an orifice is the flow measurement. Orifices can be utilized in an extensive range of applications, as these plates are existing in a variety of materials and in several designs, such as concentric, eccentric, or segmental. Additional advantage is that the orifice plate can be badly worn or damaged, yet it will still offer a sensibly repeatable output, albeit expressively imprecise. Another very useful feature of the orifice type installation is the capability to service or replace the readout or transmitter without the need to take out the orifice or to interfere the flow process **[4].**

4. THEORITICAL BACKGROUND

Bernoulli's equation was applied between two points ***Figure 1*** where point (1) is being at the free water surface and point 2 is being at the vena contracta. It can be assumed that the velocity and the gauge pressure at point (1) are zeroes as it is subjected to atmospheric pressure. In addition, the gauge pressure at point (2) is also zero because water is discharged into the atmosphere.

$$\frac{P_1}{\gamma} + \frac{{v_1}^2}{2g} = \frac{P_2}{\gamma} + \frac{{v_2}^2}{2g} + h_L \qquad \textbf{\textit{Eq. 1}}$$

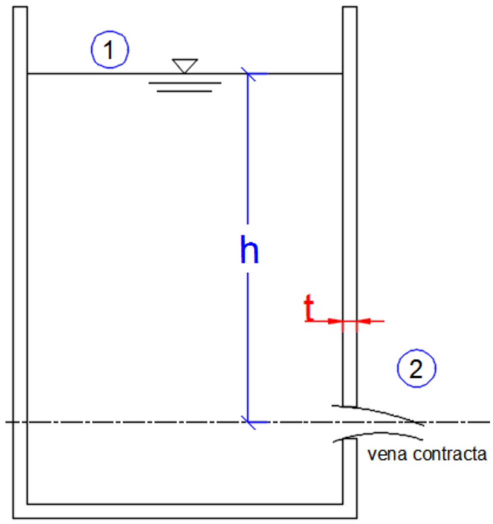


Figure 1: Definition sketch of the two points in Bernoulli's equation

Two separate coefficients are the components of the discharge coefficient, C_c and C_v. C_c is the coefficient of contraction and should be calculated at the vena contracta of the water jet (Water jet is a continuous stream of water that comes out or flows out of an orifice).
Because of the phenomenon of vena contracta, the actual area of flow from an orifice is smaller than the area of the orifice itself. ***Vena contracta can be defined as*** the ratio of the flow area at the vena contracta to the area of the orifice. **[5].**
Although it is not easy to determine precisely the location of the vena contracta, some researchers investigated that for a circular orifice, the vena contracta is located nearly half diameters downstream the orifice plate inner face **[6].**
The coefficient of velocity, C_v represents head loss that can be generated as water moves out of the tank through an orifice. Taking the origin form of the energy equation between two points as shown in ***Figure 1***, point 2 is located at the vena contracta while point 1 is being some point inside the tank at the same level of the orifice.
Coefficient of velocity have been investigated experimentally in one of the previous studies for (2– 6) cm diameter orifices and for heads between (0 – 30) m. The investigation concluded that C_d varies from 0.951 to 0.993 and as the head decreases, the velocity coefficient slightly decreases.**[7].**

5. DISCHARGE CALCULATION

Discharge can be defined the product of the velocity and area of flow at the vena contracta and can be written as:

$$Q = Av_2 \qquad \textbf{\textit{Eq. 2}}$$

By taking into consideration the coefficient of contraction and the coefficient of velocity, the following equation can be written:

$$Q = C_c C_v A_o \sqrt{2gh} \qquad \textbf{\textit{Eq. 3}}$$

This Equation is called Torricelli's theorem [8] and the velocity is called the theoretical velocity.
By combining the two coefficients C_c and C_v into one coefficient C_d, standard equation

for estimating a flow through small orifice discharging the water into the atmosphere under constant head can be written as:

$$Q = C_d A_o \sqrt{2gh} \qquad \textbf{\textit{Eq. 4}}$$

(Small orifice means that we can disregard the pressure distribution across the orifice, i.e., diameter of the orifice is low compared to the head).

6. DIMENSIONL ANALYSIS

For investigating model studies and correlating the results of the experimental work, it is crucial to create dimensionless groups. Dimensional analysis is also defined as the procedure used to find the groups for experimental design. There are two methods: the step-by-step method and the exponent method. **[5].**

In this study, the discharge coefficient (C_d) is the dependent variable. It can be stated as a function of all other independent variables as follows:

$$C_d = f(\rho, v, d, \mu, t, h, g, k) \qquad \textbf{\textit{Eq. 5}}$$

Where, ρ is the density of fluid, g is the gravity acceleration, μ is the dynamic viscosity, v is the velocity, d is the orifice diameter, ***t*** is the orifice thickness, ***h*** is the pressure head and ***k*** is a factor reflecting the orifice shape.

- No of variables (n) = 8 variables.
- No. of fundamental dimensions (m) = 3 dimensions (L, M, and T).
- No. of π - terms = n – m = 8 – 3 = 5.
- No. of repeating variables = 3.
- Selected repeating variables: g, d, and ρ.

According to Buckingham Pi-theorem, we get the following equation:

$$C_d = \mathrm{f}\left(\frac{h}{d}, \frac{t}{d}, \frac{v}{\sqrt{gh}}, \frac{\mu}{\rho h\sqrt{gh}}\right) \qquad \textbf{\textit{Eq. 6}}$$

By taking into confederation ***<u>π1</u>*** and ***<u>π2</u>*** (geometric factors), we get following equation:

$$C_d = \mathrm{f}\left(\frac{h}{d}, \frac{t}{d}, k\right) \qquad \textbf{\textit{Eq. 7}}$$

Where, **(h/d)** is the head to diameter ratio, **(t/d)** is the thickness to diameter ratio and ***k*** factor reflecting the orifice shape.

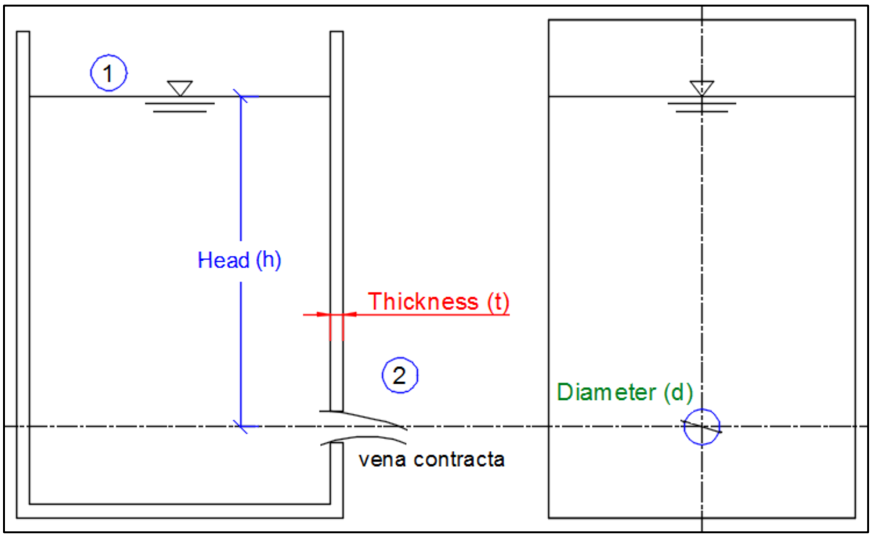


Figure 2 : Geometric parameters taken into consideration in dimensional analysis

7. PHYSICAL MODELING

To achieve the purpose of this investigational work, a laboratory physical model was built ***Figure 3.*** The model mainly consists of two tanks, lower and upper. Both tanks are formed of transparent acrylic plastic to be easy in laser cutting and to allow visual observation of the water flow. The lower tank (collecting tank) was designed to collect water passing through the orifices and recycle it into the upper tank. To do that, a centrifugal pump was installed to raise water from the lower to the upper tank. The upper tank was designed to keep constant water head above the orifice.

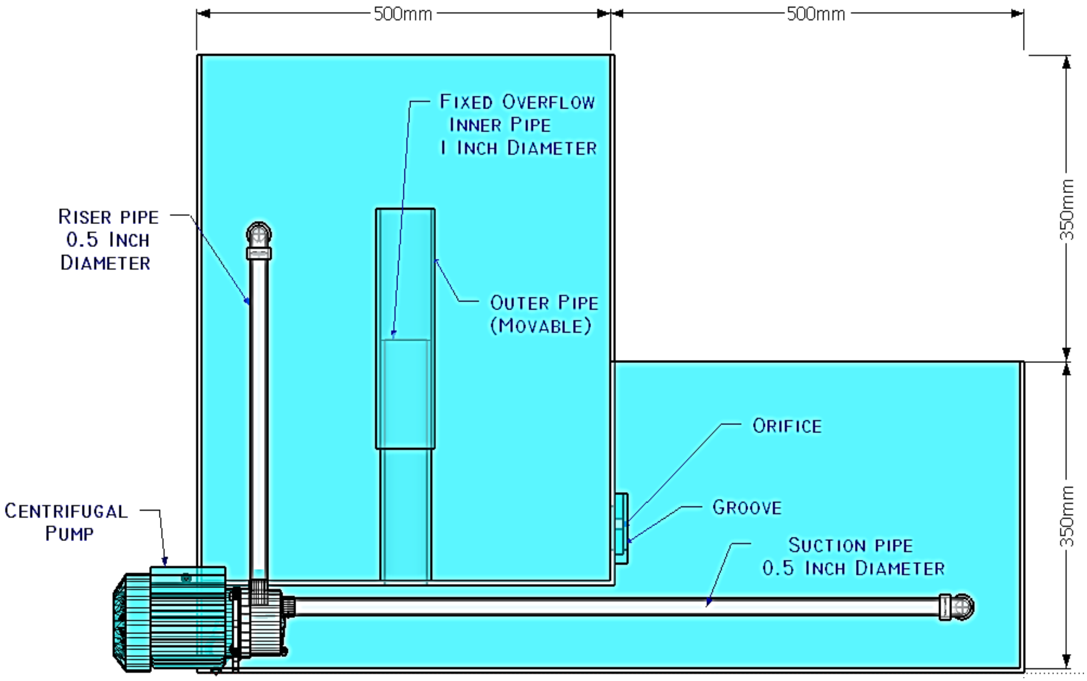


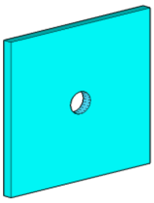
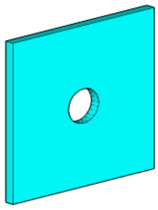
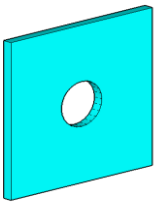
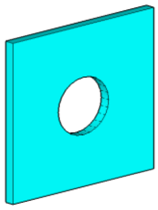
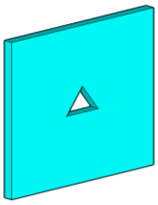
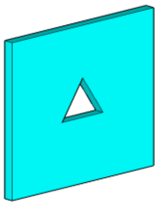
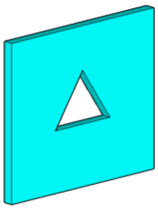
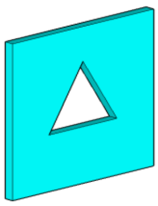
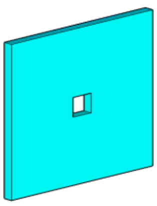
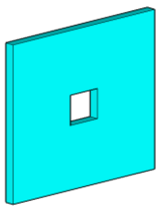
Figure 3: Model elevation View definition sketch

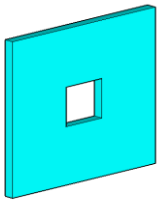
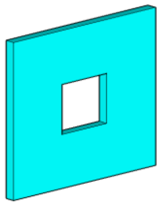
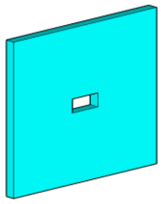
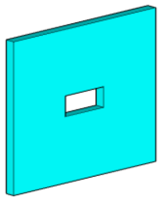
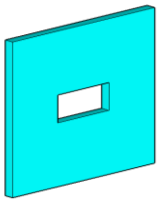
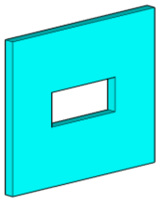
To control water head, two concentric pipes were installed in the middle of the upper tank in order to return water back to the lower tank. The inner pipe was designed to be

fixed on the bottom of the tank and the outer pipe was installed to be moveable in order to control water head above the orifice.
In order to study the effect of orifice thickness on the discharge coefficient, 24 orifice plates (7cm. x 7cm.) ***Table 1*** each was manufactured from transparent acrylic plastic. Orifices were cut using laser technology. The shown groove was designed to be fixed into the tank wall to facilitate changing the orifice plates.
To supply the system with the needed flow rate, a 0.25 HP centrifugal pump was installed to withdraw water from the lower to the upper tank. The function of the pump is to substitute the water discharged from the orifice to keep constant head pressure above the orifice.

The discharge passing through the orifices was calibrated using a graduated container and stopwatch. The graduated container was used to collect passing water in a certain time.

Table 1: properties of the orifices used in the experiments.

No.	Orifice Properties		No.	Orifice Properties	
1	Orifice Diameter = 10 mm. Orifice Area = 78.54 mm^2. Orifice Thickness = 4 mm.		2	Orifice Diameter = 15 mm. Orifice Area = 176.71 mm^2 Orifice Thickness = 4 mm.	
3	Orifice Diameter = 20 mm. Orifice Area = 314.16 mm^2. Orifice Thickness = 4 mm.		4	Orifice Diameter = 25 mm. Orifice Area = 490.87 mm^2. Orifice Thickness = 4 mm.	
5	Side Length = 13.47 mm. Orifice Area = 78.54 mm^2. Orifice Thickness = 4 mm.		6	Side Length = 20.20 mm. Orifice Area = 176.71 mm^2 Orifice Thickness = 4 mm.	
7	Side Length = 26.94 mm. Orifice Area = 314.16 mm^2. Orifice Thickness = 4 mm.		8	Side Length = 33.67 mm. Orifice Area = 490.87 mm^2. Orifice Thickness = 4 mm.	
9	Side Length = 8.86 mm. Orifice Area = 78.54 mm^2. Orifice Thickness = 4 mm.		10	Side Length = 13.29 mm. Orifice Area = 176.71 mm^2 Orifice Thickness = 4 mm.	

11	Side Length = 17.72 mm. Orifice Area = 314.16 mm^2. Orifice Thickness = 4 mm.		12	Side Length = 22.16 mm. Orifice Area = 490.87 mm^2. Orifice Thickness = 4 mm.	
13	12.53 mm. X 6.27 mm. Orifice Area = 78.54 mm^2. Orifice Thickness = 4 mm.		14	18.80 mm. X 9.40 mm. Orifice Area = 176.71 mm^2 Orifice Thickness = 4 mm.	
15	25.07 mm. X 12.53 mm. Orifice Area = 314.16 mm^2. Orifice Thickness = 4 mm.		16	31.33 mm. X 15.67 mm. Orifice Area = 490.87 mm^2. Orifice Thickness = 4 mm.	

8. DISCHARGE MEASUREMENT

The discharge was calculated by measuring the water volume discharged out of an orifice in a known time. This volume was determined by collecting water in a graduated container and the discharge was calculated by dividing the collected volume by the time. Each run was carried out three (3) times and the average discharge was taken.

9. ANALYSIS AND DISCUSSIONS

This study was done to scrutinize what effect, if any, there would be on the discharge coefficient (C_d) when the orifice area (A) was changed. To achieve this work, the relationship between orifice diameter thickness ratio (d/t) and the (C_d) was plotted in which the ***X-axis*** represents the ratio (d/t) and the ***Y-axis*** represents the discharge coefficient C_d. These experiments were tested at four (4) different head values. The orifice thickness was constant for all experiments (4 mm). the output results were plotted in four figures with (16) measured C_d for each figure.

The obvious phenomenon from the data representation was the increase of the discharge coefficient (C_d) as the ratio (d/t) increases. The observed details were the following:

This relationship was represented by dividing the equivalent orifice diameter (d) by the orifice thickness (t = 4 mm.) which was constant in each plot. Data representations ***Figure 5*** to ***Figure 7*** show that the discharge coefficient increases with increasing the ratio (d/t).

- ***Figure 5*** to ***Figure 7*** signposted that the C_d increases about (0.51% to 3.11%) when the ratio (d/t) increased from 3.75 to 5.
- The maximum increase in the C_d was between (d/t) = 2.5 and (d/t) = 3.75 in which the C_d increased about (0.7% to 5.61%).
- Also, the C_d increases about (0.51% to 3.11%) when the ratio (d/t) increased from 5 to 6.25.

Table 2: Ratio "d/t" vs. "C_d" (at t = 4 mm and h = 35 cm).

Effect of Orifice Area on the Discharge Coefficient Orifice Thickness = 4 mm. Head = 35 cm.						
Diameter of Equivalent Circle (mm)	Orifice Area mm^2	d/t	C_d			
			Circular Orifice	Equilateral Triangular Orifice	Square Orifice	Rectangular Orifice
10	78.54	2.5	0.573	0.561	0.549	0.541
15	176.71	3.75	0.577	0.573	0.562	0.548
20	314.16	5	0.589	0.587	0.572	0.564
25	490.87	6.25	0.600	0.593	0.584	0.576

Table 3: Ratio "d/t" vs. "C_d" (at t = 4 mm and h = 40 cm).

Effect of Orifice Area on the Discharge Coefficient Orifice Thickness = 4 mm. Head = 40 cm.						
Diameter of Equivalent Circle (mm)	Orifice Area mm^2	d/t	C_d			
			Circular Orifice	Equilateral Triangular Orifice	Square Orifice	Rectangular Orifice
10	78.54	2.5	0.558	0.550	0.541	0.533
15	176.71	3.75	0.573	0.566	0.553	0.538
20	314.16	5	0.586	0.586	0.570	0.562
25	490.87	6.25	0.599	0.589	0.582	0.574

Table 4: Ratio "h/d" vs. "C_d" (at A = 314.16 mm^2).

Effect of Orifice Area on the Discharge Coefficient Orifice Thickness = 4 mm. Head = 45 cm.						
Diameter of Equivalent Circle (mm)	Orifice Area mm^2	d/t	C_d			
			Circular Orifice	Equilateral Triangular Orifice	Square Orifice	Rectangular Orifice
10	78.54	2.5	0.549	0.542	0.533	0.522
15	176.71	3.75	0.566	0.558	0.547	0.534
20	314.16	5	0.584	0.581	0.568	0.560
25	490.87	6.25	0.599	0.587	0.581	0.572

Table 5: Ratio "d/t" vs. "C_d" (at t = 4 mm and h = 50 cm).

Effect of Orifice Area on the Discharge Coefficient Orifice Thickness = 4 mm. Head = 50 cm.						
Diameter of Equivalent Circle (mm)	Orifice Area mm^2	d/t	C_d			
			Circular Orifice	Equilateral Triangular Orifice	Square Orifice	Rectangular Orifice
10	78.54	2.5	0.535	0.533	0.520	0.510
15	176.71	3.75	0.565	0.552	0.541	0.533
20	314.16	5	0.578	0.574	0.565	0.556
25	490.87	6.25	0.596	0.585	0.580	0.571

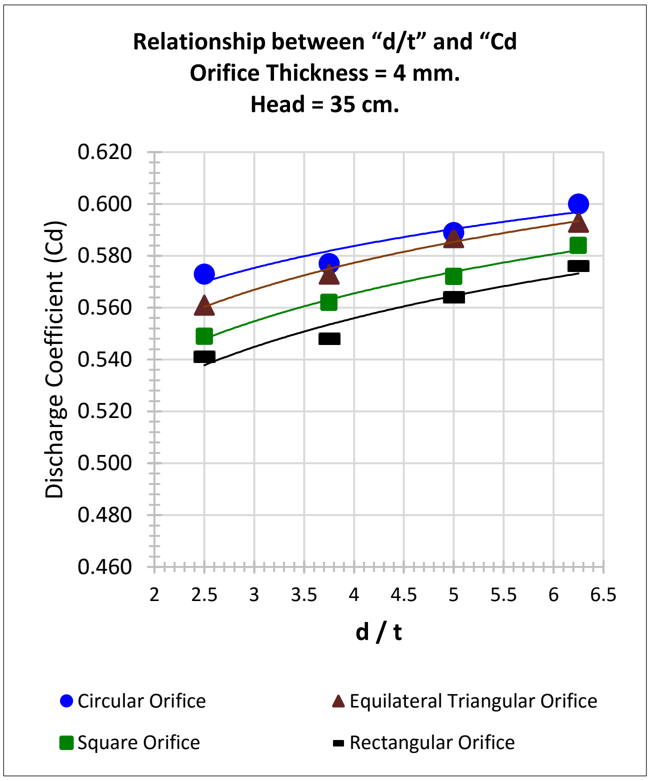


Figure 4: Relationship between "d/t" and "C_d" (at t = 4 mm and h =35 cm).

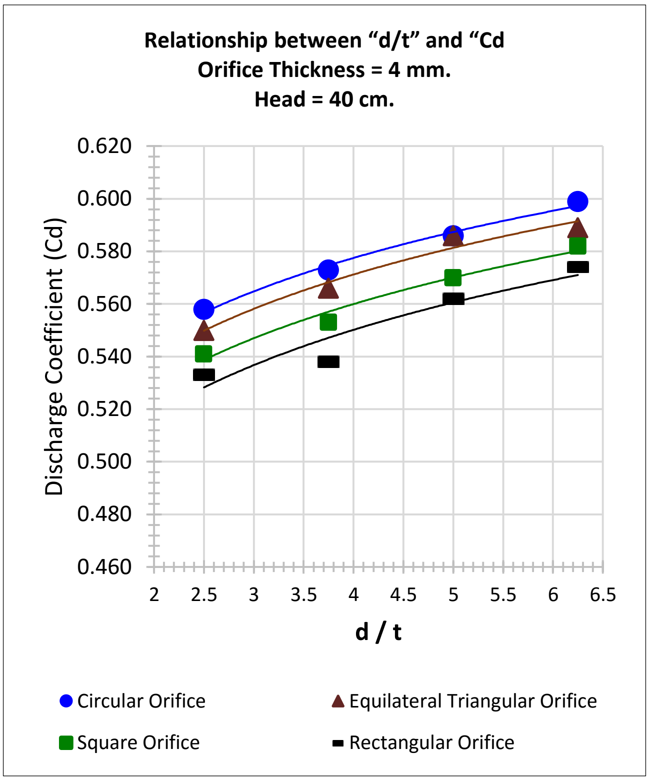


Figure 5: Relationship between "d/t" and "C_d" (at t = 4 mm and h = 40 cm).

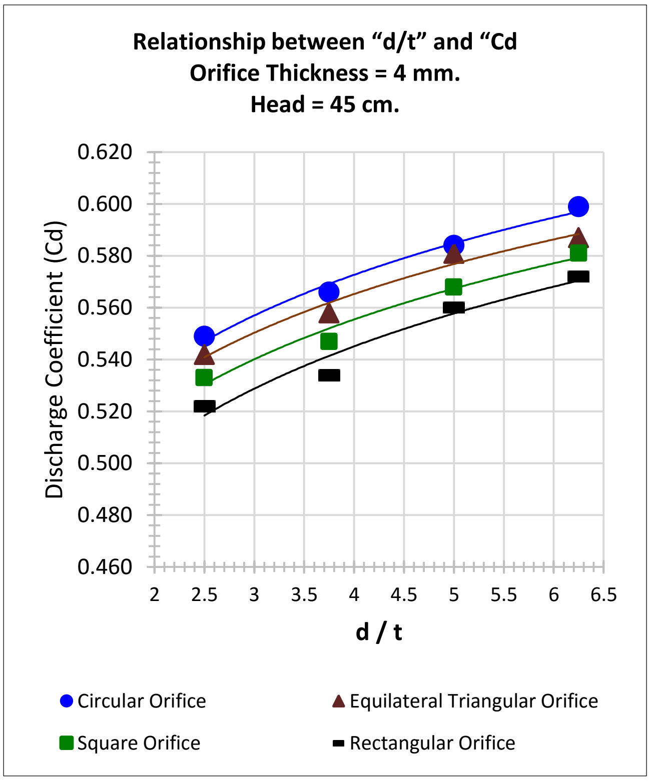


Figure 7: Relationship between "d/t" and "C_d" (at t = 4 mm and h = 45 cm).

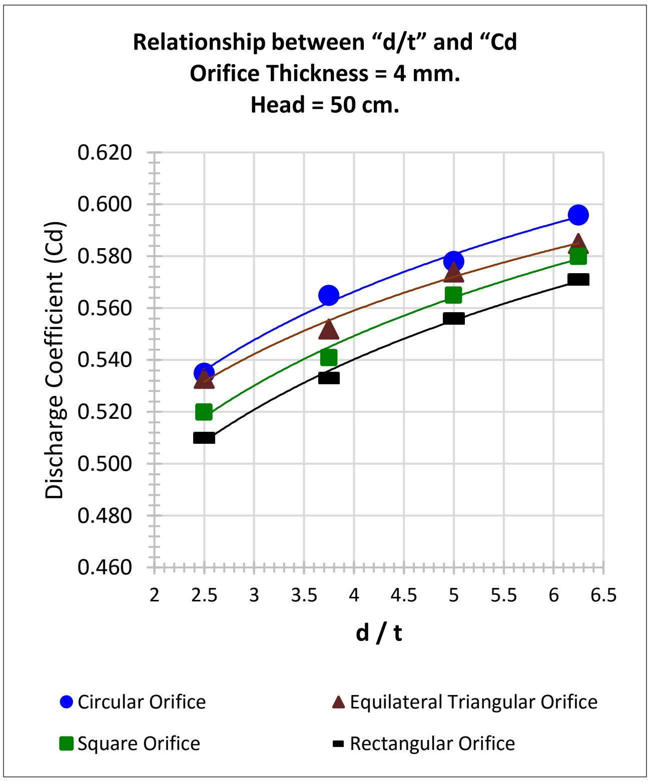


Figure 6: Relationship between "d/t" and "C_d" (at t = 4 mm and h = 50 cm).

10.CONCLUSIONS

- The study found that in nearly every case of pressure head, the increase of (d/t) ratio is capable of increasing (C_d) in logarithmic manner.
- The circular orifice shape was found to give the higher values of the discharge coefficient (c_d) as compared to all tested shapes. On the other hand, the rectangular orifice shape was found to give the lowest values of the discharge coefficient (c_d).

11.RECOMMENDATIONS

Additional investigations on the effect of pressure head above the orifice centerline on the discharge coefficients (C_d) are recommended to be carried out to extend the presented results.

Also, Future studies are recommended to use non-conventional orifice shapes with the same parameters tested here to determine if the discharge coefficients (C_d) vary in the same pattern or not.

12.REFERENCES

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