Effect of Release Coefficient of Orifice Plate on Water Fluid Flow Systems

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Abstract. The orifice plate is used to estimate the flow rate of a mass flowing through a pipe by connecting the measured loss pressure and mass flow rate. In this paper, the relationship between Reynolds number (Re) and Cd is observed based on pressure variations in a pipe. The test results show that the release coefficient rapidly decreases when the Reynolds number approaches 1 for each meter of flow. By knowing the difference of the occurs pressure, the value of the parameter Cd can be calculated from the actual discharge ratio to its theoretical. The calculation results show that the average value of Cd for the orifice plate sensor about 0.599 (with a deviation value of about 0.001 and Re value around 10^5 is obtained.

1. Introduction
Fluid flow control is a very important process in the industry. Flow control can only be done if flow information can be accurately measured. Flow measurement is the determination of the quantity of liquid passing through a pipe or open channel. Flow can be measured by measuring the speed of a fluid above a certain area or object of measurement. Accurate fluid measurements are important to get specific proportions according to process requirements. It is important to maintain a definite flow rate for maximum efficiency and production results. Without accurate measurement proper quality control will be difficult to do.

Previous researchers describe in detail the various types of flow meters that can be used in gluing and usually depend on the application and type of industry [1]. Flow meters can be classified as meter based pressure including: venturi meter, dali tube, pilot tube, optical flow meter, electromagnetic flow meter, ultra sonic flow meter, cast flow meter, laser droplet flow meter, and orifice plate. Other researchers describe several types of flow meters that rely on the Bernoulli principle, either by measuring pressure differences in constriction or by measuring static pressure and stagnation to obtain dynamic pressure [2, 3]. The orifice plate is a thin plate with holes in it that are used to measure the flow rate of the flowing liquid. When the liquid passes through the hole, the pressure increases in the upstream part of the hole and the liquid is forced to pass through a small hole, so that pressure rises upstream. Roul et al. Stated that obstruction results in increased flow velocities and causes decreased pressure [4]. Downstream, the flow reaches a point where the maximum velocity and minimum pressure and this part is known as the vena contracta are formed due to the Venturi effect.

The orifice plate is usually used because of its simplicity and can also be obtained at low cost [5]. However, meter orifice is becoming more popular in developing countries to measure the discharge of...
a fluid in a pipe. Despite having minimum installation problems in pipes, the main disadvantage of this device is having greater energy losses due to friction, contraction, blockage, etc. than venturi tubes or flow nozzles. In principle, meter orifice occurs due to the narrowing of the flow in the pipe and produces a pressure difference between the plate upstream and downstream. The ISO standard specifies the geometry design, installation, and operating conditions of the device when a single phase fluid flow in a circular channel [6]. This ISO standard also sets out general principles and methods of measurement and calculation of mass flow rates and Cd under different conditions. The limits used in differential meters are those specified by the ISO 5167 Standard (ISO, 2003): orifice plates and venturi tubes. The effect of low pressure on the flow rate (orifice plates is more likely to cause blockage of the fluid phase) and for the lowest pressure loss has been evaluated in other studies [7].

The difficulties found in real experiments can be anticipated by conducting simulations such as those conducted by Eiamsa-ard et al. (simulation of compressible flow through orifice plates with three different β ratios) [8]. They compared the results of axial velocity and pressure gradient results for three interpolation schemes and two turbulence models namely the standard k model - and the Reynolds stress model. In a simulation, the orifice plates are analyzed out of the estimation by both formulations where the model k-ω shows a slightly better agreement [9]. The superiority of the viscosity effect in reducing pressure through the nozzle is satisfactory with two turbulence models, which present C_d within the 1% limit of the expected ISO standard value. However, C_d has no unique value; The contrast varies with the beta ratio and Reynold number. For most commercial orifice plates and high Reynold numbers (Re > 30000), C_d values are almost constant, while for lower Reynold numbers the value of C_d are varies. On the other hand, C_d increases with the beta ratio for Re fixed and results in a decrease in the pressure difference on the orifice plate. Too much decrease in difference for extreme beta ratios will usually reduce the accuracy of measurements. For this reason, the beta ratio must be maintained so that the value remains in optimal. Though several studies have been conducted on the relationship between the combined effects of C_d and Re from Re & β in C_d very rarely. The purpose of this study was to obtain the performance of orifice plate release coefficients used in water treatment systems.

2. Materials and Methods

The basic concept of the orifice plate is a circular plate with a hole in the middle attached to the pipe to measure the flow rate by making pressure down on it. The orifice plate is basically a cylindrical tube in the form of a thin hole in the middle. Thin holes basically force fluid to flow faster through a hole to maintain the flow rate. The maximum convergence point usually occurs a little downstream from the actual physical hole, this is the reason meter orifice is less accurate than the venturi meter. This happens because the location and diameter of the maximum convergence point cannot be used in calculations. The variable position of the vena contracta is related to the orifice plate and is shown by the flange tap flow pattern as shown in Figure 1.
Miller explained that a large number of studies related to flow meter release coefficients had been carried out, but very few were handled with very small Reynolds numbers \[10\]. The Reynolds number depends on the viscosity of the liquid, where the definition of small and large Reynolds numbers can vary. For water, small Reynolds numbers can be defined as \(\text{Re} < 10,000\). When the fluid approaches the orifice hole, the pressure increases slightly and then suddenly drops. This continues until the vena contracta drops and then gradually increases from the hole downstream. The decrease in pressure when the liquid passes through the hole is due to an increase in the speed of the liquid that passes through the orifice reduction area. When speed decreases while fluid leaves the vena contracta in contracts resulting in increased of the pressure and tends to reach the actual level. All pressure losses occur due to friction and turbulence of flow during pressure changes (due to increased flow rates in the orifice). The pressure difference is proportional to the square of the speed. The application of the same equation in the upstream and downstream of the orifice plate can be found by measuring debit theoretically \((Q_{th})\).

The maximum convergence point actually occurs in the downstream part of the physical hole which is precisely at the constrained vein point. By measuring the difference in fluid pressure between the pipe sections in the constrained vein, the volumetric and mass flow rates can be obtained from the Bernoulli equation \[11\]. In the 1700s, Daniel Bernoulli investigated the forces present in a moving fluid. The Bernoulli equation has appeared in many physics, fluid mechanics, and airplane textbooks.

\[
\frac{1}{2} v_1^2 + g z_1 + \frac{P_1}{\rho} = \frac{1}{2} v_2^2 + g z_2 + \frac{P_2}{\rho} \quad (1)
\]

with continuity equations:

\[
Q = A_1 v_1 = A_2 v_2 \quad (2)
\]

By substituting the equations (1) into (2), pressure difference are obtained

\[
P_1 - P_2 = \frac{1}{2} \rho \left( \frac{Q}{A_1} \right)^2 - \frac{1}{2} \rho \left( \frac{Q}{A_2} \right)^2 \quad (3)
\]

So the value of \(Q\) in equation (3) becomes,

\[
Q = A_1 \sqrt{\frac{1}{1 - (d/D)^2}} \sqrt{2(P_1 - P_2/\rho)} \quad (4)
\]

The above expression for \(Q\) gives a theoretical volume flow rate. By involving the beta factor \(\beta = d/D\) and the release coefficient that is owned, then equation (4) can be written as.

\[
Q = C_d A_2 \sqrt{1 \beta^{-\frac{1}{2}} \sqrt{2(P_1 - P_2/\rho)}} \quad (5)
\]

By defining the meter coefficient \((C)\) as

\[
C = \frac{C_d}{\sqrt{1 - \beta^\frac{1}{2}}} \quad (6)
\]

Then the final equation of fluid volumetric flow through the hole is,

\[
Q = CA_2 \sqrt{2(P_1 - P_2/\rho)} \quad (7)
\]
Equation (8) can be obtained by multiplying the density of the liquid with the mass flow rate in each part of the pipe

$$m = \rho Q = CA_2 \sqrt{2(P_1 - P_2 / \rho)}$$  \hspace{1cm} (8)

to produce a pressure difference equation, equation (5) is made into

$$\Delta P = P_1 - P_2 = \frac{Q^2 \rho(1 - \beta^4)}{2C^2 A^2} = \frac{Q^2 \rho(1 - \beta^4)}{2C^2 A^2 \beta^4}$$  \hspace{1cm} (9)

while the density equation can be obtained from equation (5) as

$$\rho = \sqrt{\frac{2(P_1 - P_2)C_{12}A_{12}(1/1 - \beta^4)}{Q}}$$  \hspace{1cm} (10)

Where the cross section area of orifice is

$$A_1 = Q \rho \sqrt{2(P_1 - P_2)C_{12}(1/1 - \beta^4)} / Q$$  \hspace{1cm} (11)

The value of $Cd$ depends on the ratio of the orifice to the pipe diameter which is expressed as the beta ratio ($\beta$) and Reynold ($Re$) number or known as the release coefficient, namely the ratio of the actual flow rate to the theoretical flow rate. By, $Q$ is the volumetric flow rate (in each cross section), $m$ is the mass flow rate (for each cross section), $C$ is the orifice flow coefficient, $A_1$ is the pipe cross-sectional area, $A_2$ is the cross-sectional area of the hole, $d_1$ is pipe diameter, $d_2$ is orifice hole diameter, $\beta$ is orifice hole diameter ratio of pipe diameter, $v_1$ is upstream fluid velocity, $v_2$ is fluid velocity through orifice hole, $P_1$ is fluid upstream pressure, $P_2$ is down fluid pressure, $\rho$ is fluid density. The standard Orifice has a perfectly round hole in the middle of a circular and sharp edged steel plate, the plate stamped with the diameter of the orifice is shown in Figure 2.

The orifice plate hole can be configured to handle various flow measurement applications. Flow conditions must be checked to determine the appropriate hole configuration for each application. Thin plates, concentric holes are the most commonly used orifice plates. In the design and use of orifice plates, several basic factors must be followed to ensure accurate and reliable measurements. The upstream edge of the hole must be sharp and square.

In addition, the minimum plate thickness is standardized based on pipe IDs, hole holes, etc. Plates should not be separated from flatness along a diameter of more than 0.25 mm per mm or 0.01 inch per inch height of the dam (Dd) / 2. To ensure compliance with recommended practices, the beta ratio may not exceed the recommended limit. The Reynolds number equation is widely used and is the ratio of
the inertial strength to the thick force with \( \nu \) is the kinematic viscosity of the water in 30 °C (0,8 x10\(^{-6}\) m\(^2\)/s).

\[
R_v = \frac{V \cdot D}{\nu}
\]

(12)

with, \( V \) is the average velocity through the pipe, \( D \) is the pipe diameter, and \( \nu \) is kinematic viscosity.

The release coefficient \( C_d \) is defined as the ratio of the actual flow rate from the hole to the theoretical flow rate of the hole (\( Q_{act} / Q_{th} \)). Flow coefficients usually range from 0.6 to 0.9 for most holes, and the value depends on the diameter of the orifice and the pipe and Reynolds number. The relationship of the Reynolds number to the \( C_d \) release coefficient is shown in Figure 3. Some standard values of the relationship of determining the release coefficient on the orifice diameter, pipe and Reynolds number are shown in Table 1.

![Figure 3. Relation of the Reynolds Number with discharge coefficient for orifice plates [12].](image)

| Diameter Ratio (d/D) | Release Coefficient (C<sub>d</sub>) | Reynolds Number | 10<sup>4</sup> | 10<sup>5</sup> | 10<sup>6</sup> | 10<sup>7</sup> |
|----------------------|-----------------------------------|----------------|----------------|----------------|----------------|----------------|
| 0,2                  | 0,6                               | 0,595          | 0,594          | 0,594          |                |
| 0,4                  | 0,61                              | 0,603          | 0,598          | 0,598          |                |
| 0,5                  | 0,62                              | 0,608          | 0,603          | 0,603          |                |
| 0,6                  | 0,63                              | 0,61           | 0,608          | 0,608          |                |
| 0,7                  | 0,64                              | 0,614          | 0,609          | 0,609          |                |

3. Eksperiment and Results
The pattern of fluid flow when passing through the orifice is the velocity of fluid flow will rise, otherwise the static pressure will decrease, so that in one area not far from the orifice in the direction of the downstream maximum fluid velocity with minimum static pressure is called the caontractive vein. After the vein the contracta static pressure or fluid velocity will return to its original state, but because there is a pressure difference between before and after, the static pressure of the fluid after the
orifice will not reach its original pressure. The amount of fluid flowing through it will be directly proportional to the root two of the difference in pressure that occurs.

The fluid flow measurement system is illustrated in Figure 4 which also shows the configuration of the equipment used in the measurement. The ingredients of the orifice plate experiment are shown in Figure 5. The supporting components of the measurements in the experiment are pump plates, control valve, rotameter, orifice, Flow Transmitter, controller, and 24 V DC voltage source and 200V AC voltage, process tanks are shown in Figure 5. The water fluid is pumped via rotameter by regulating the control valve by the controller, so that the position of fluid flowing through the orifice plate can be determined and detected by the Flow Transmitter which is the input for the controller.

Figure 4. The Experiment Scheme.

Figure 5. The Structure of the orifice plate experiments.

In this experiment, the measurement of flow rate with the principle of pressure difference is limited by data orifice being carried out. The operational dimensions and related data to their characteristics such as pipe diameter (D) of 25.4 mm, orifice diameter (d) of 10.16 mm and beta ratio ($\beta = \frac{d}{D}$) of 0.4, and also the value of the Reynolds number $Re$ is 105. Considering the liquid as water, it is obtained that the density value $\rho$ is 998.2 kg/m$^3$ and the dynamic viscosity $\mu$ is 0.003 Pa. It is assumed that the measurement flow rate with $Q_{mak}$ is 15.0 l/min. The main components in the experiment are orifice plates, rotameters, capacitors, 24 V DC voltage sources, digital multimeters, and experimental data tanks and Qactual (l/minute) calculations of $D/P$, $Q_{teori}$ and $Cd$ from the orifice as in Table 2. So that by calculating $Q_{actual} / Q_{theory}$, then the average value of $Cd$ release coefficient of 0.603 is obtained.
Table 2. The results of the $Q_{\text{actual}}$ calculation (l / min) for $D/P$, $Q_{\text{theory}}$ and $C_d$ from the orifice.

| NO | $Q_{\text{actual}}$ (l/min) | $D/P$ Average (kPa) | $Q_{\text{theory}}$ (l/min) | $C_d$ | $Cd^2$ |
|----|-----------------|-----------------|-----------------|------|------|
| 1  | 1               | 0,20            | 1,952           | 0,512| 0,262|
| 2  | 2               | 0,63            | 3,379           | 0,592| 0,350|
| 3  | 3               | 1,31            | 4,992           | 0,601| 0,361|
| 4  | 4               | 2,32            | 6,644           | 0,602| 0,362|
| 5  | 5               | 3,63            | 8,31            | 0,602| 0,362|
| 6  | 6               | 5,20            | 9,946           | 0,603| 0,364|
| 7  | 7               | 7,10            | 11,622          | 0,602| 0,362|
| 8  | 8               | 9,24            | 13,258          | 0,603| 0,364|
| 9  | 9               | 11,72           | 14,932          | 0,603| 0,364|
| 10 | 10              | 14,45           | 16,580          | 0,603| 0,364|
| 11 | 11              | 17,44           | 18,215          | 0,604| 0,365|
| 12 | 12              | 20,76           | 19,876          | 0,604| 0,365|
| 13 | 13              | 24,27           | 21,488          | 0,605| 0,366|
| 14 | 14              | 28,12           | 23,129          | 0,605| 0,366|
| 15 | 15              | 32,32           | 24,797          | 0,605| 0,366|

The experimental results are determined in the best way by providing a comparison of the release coefficient with the Reynolds number in the graph as shown in Figure 6. Each data point in the graph is calculated separately based on the performance of a predetermined Reynolds number. The speed required to obtain different Re values is the main variable entered into the numerical model when calculating the release coefficient of each meter. The graph of the relationship between $Q_{\text{actual}}$ (l / min) to $D/P$ mean (kPa) for the orifice plate is shown in Figure 6 with a linear mean $D/P$ value indicating a pattern that moves away from the linear function. While the graph of the relationship between $Q_{\text{theory}}$ to the $D/P$ average orifice is shown in Figure 7, where the mean $D/P$ value narrows closer to the linear function. While Figure 9 shows a combination of graphs of the relationship between $Q_{\text{actual}} / Q_{\text{theory}}$ of the average $D/P$ for orifice plates.

Figure 6. Graph to indicate the relationship between $Q_{\text{theory}}$ (l / minute) to $D/P$ average (kPa) Venturi tube.
The linear curve variation can be explained in terms of actual dominance and theoretical release measured by pressure difference $\Delta h$. This shows that the increase in $Q_{th}$ value exceeds the $Q_{act}$ value until the minimum value is reached. Pressure difference consists of two components, temporary pressure loss because it changes the potential of kinetic energy in the hole and irreversible losses which are not responsible for the actual flow rate at all. This finding is in accordance with the results of Daugherty and Franzine [13], the results of which indicate that the value of drop $Cd$ with $Re$ reaches a constant number. The graph of the relationship of the $Q_{actual} / Q_{theory}$ value to the $Cd$ release coefficient is shown in Figures 8 and 9 which shows the $Cd$ coefficient value between the ranges of 0.601 to 0.605 for the Reynolds number of $10^5$.
4. Discussions

Flow meters that have a high degree of accuracy and relatively low costs are some of the most important parameters when determining the purchase of flow meters. Most meters of pressure differential flow meet these two requirements. Many of the most common flow meters have a certain range where the discharge coefficient of $C_d$ can be considered constant and the minimum amount of Re recommended for use by the specified meter. This study will discuss the release coefficient which is focused on the orifice plate flow meter with beta ratio. Standard orifice plates are modeled using beta ratios compared to release coefficient data. This study concludes that $C_d$ vs $\beta$ for flow meters responds to the constant release coefficient.

Although the release coefficient of $C_d$ is not constant, there is a large amount of research on orifice plates carried out to determine the characteristics of the $C_d$ release coefficient for Reynolds Re numbers greater than $10^5$. Britton and Stark stated in their studies that the Reynolds number is less than $10^5$, the release coefficient tends to increase to a number Reynolds Re is approximately 300 times and then reduced, which is associated with the orifice plate effect on the velocity profile [14]. Because the highest velocity in the pipe is usually located in the middle, the small Reynolds Re number has a larger $C_d$ release coefficient because most of the velocity associated with the flow passes through the flow meter without being affected by the orifice plate at the larger Reynolds Re number.

Britton and Stark conducted a physical study of how the release coefficient $C_d$ of sharp-edged orifice plates varied with Reynolds Re numbers [14]. One of the holes they studied has a beta value of 0.5322 where the value is almost the same as the beta value obtained in the current study which is 0.50. Miller explained that data had also been published to distinguish beta values including 0.50 as shown in Figure 11 [10]. As shown in Figure 11, all data sets show the same trend for variations in the value of Reynolds number. The maximum difference between different data sets is only above 4%. The Britton and Starks research focuses on Re between 1,000 and 20,000, while the other two studies have a much wider range. Unlike one of the other flow meters in this study, orifice plates do not have release coefficient $C_d$ constants in the large Re range.

The orifice plate flow has the greatest pressure difference across the meter while Venturi has the smallest pressure difference. Greater pressure variations are easier to determine the more precise differences with less errors than very small pressure differences. Bandyopadhyay and Das explain the steep decrease in static pressure for orifice plate flow similar to the pressure distribution pattern presented in the Bandyopadhyay study [15]. The results for the lower $Q_{actual}$ values show that the $C_d$ value is farther away from the one specified, seen in the $Q_{actual}$ value below 2 liters / minute as explained by Colter L. Hollingshead in relation to Reynolds number vs. release coefficient $C_d$ for orifice plates [11].
5. Conclusion
To find out the effect of the influence of the dissolution coefficient in a fluid flow rate, experiments have been carried out with orifice plate testing. From the test results show that the average release coefficient $C_d$ is 0.604 with a range of $C_d$ coefficient values between 0.601 to 0.605 for the Reynolds $10^5$ number obtained. Low $Q_{actual}$ values can result in uncontrolled release coefficients and $C_d$ values depending on the beta ratio and Reynolds's number. The factors that influence the installation of orifice will affect the overall error in measuring the release coefficient $C_d$. There are several errors in flow measurement. This error is caused by uncertainties in the physical properties of liquids and uncertainties in the shape and size of flow meters.

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