Estimation Optimal Value of Discharge Coefficient in a Venturi Tubes

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Abstract. Development of an accurate and reliable differential pressure flow meters is needed for industry. The relationship between the Reynolds number (Re) and the discharge coefficient (Cd) was investigated using a differential pressure flow meter. Venturi meter is a type of baffle meter, widely used in industry for flow measurement. The ISO standard (ISO-5167-1) provides discharge coefficient values for classic Venturi tubes in turbulent flow with Reynolds number values above 2x10^5. This study shows that various discharge coefficient decrease rapidly and constant discharge coefficient values vary with meter design. The main focus of this study is to compare experimental results with theoretical predictions and estimate the optimal value of the meter discharge coefficient at various flow rates. The experimental results showed that the optimal value of the venturi tube discharge coefficient of about 0.983 was obtained.

I. Introduction
Fluid is one that cannot be separated from our daily lives, wherever and whenever we are, fluid always affects our various activities in the form of liquid or gas. Pipes are a cheap means of fluid transportation, pipes have various sizes and shapes, and those with circular sections are the most widely used. The fluid flow inside the pipe actually decreases the pressure along with the length of the pipe through which the fluid passes because the fluid has a viscosity. This viscosity causes a shear force that is inhibiting. To counteract the shear force, energy is needed so that the energy is lost in the flow of fluid. This lost energy results in a decrease in fluid flow pressure or also called pressure loss. In the industrial world most of the fluids flow in closed pipes and have several main problems, among others, the occurrence of friction along the pipe wall, the occurrence of pressure losses, the formation of turbulence due to relative movement in fluid molecules that are affected by fluid viscosity. Muchsin (2011), analyzes losses in straight pipes with variations in flow rate [1]. The results showed the relationship between Reynolds number and friction factor is inversely proportional, which means that the greater the Reynolds number, the smaller the friction factor, the relationship between the speed and the major loss is directly proportional, which means the greater the loss the greater the loss, and at Re numbers starting at 1.50 x 10^5 - 2 x 10^5 the value of the friction factor tends to be stable. Nurcholis, L. (2008), examines the calculation of fluid flow rates in pipelines, the results of calculations show that there is a relationship between power loss and flow rate. If the flow is large with a high head loss coefficient, then the head loss for each pipe length is greater [2].

Pipes as fluid flows are widely used in piping systems in industry, mining, and distribution of drinking water. The series of pipes are designed in such a way as to be able to meet the need for fluid distribution. Various types and angles of pipe branching in piping systems will produce different flow...
distributions. Previous research stated that there was a difference in pressure losses in the main pipe with a separation pipe caused by differences in the cross-sectional area of the flow passing through each channel. A more complete study was conducted by Basset, et al. Calculating the pressure loss coefficient for branching pipes between branching entry and exit points, which is explained in the form of a relationship curve between the mass flow ratio and the stagnation pressure loss coefficient [3]. From several methods that have been developed for the analysis of pipelines, including the method of head balance. The head balance method is the earliest method used for pipeline network analysis. The head balance method is used for the pipe system that supports the closed loop.

The relationship between the flow and pressure is essentially like a flow measurement system that uses a differential head meter facility [4] where changes in flow from the percentage of valve openings will also be followed by changes in pressure. Every fluid that passes a control valve has a pressure called P1 or in ISA S75.01 referred to as upstream absolute static pressure. Because it gets an obstacle from a valve that is opened with a certain percentage, the pressure discharge from the control valve will decrease. Because the amount of pressure discharge from the control valve is very closely related to the opening valve, a pressure transmitter is put in place to measure the amount of pressure that is available and sent to the controller, so the controller is able to condition the right opening valve according to the desired pressure [4]. Takamoto et al. describe fluid flow measurements using disk type ultrasonic flow meters [5]. Man Gyun Na has described the estimation method to find out the feed water flow rate report [6]. Lijun Xu, et al. describes the wet gas flow rate measured using Venturi meters [7]. While Santhosh and Roy describe the design of adaptive measurement techniques using the Venturi flow meter [8].

Flow meters are widely used in industry to measure fluid volumetric flow rates. This flow meter is usually a differential pressure type, which measures the flow rate by entering a narrowing into the flow. The pressure difference caused by constriction is used to calculate the flow rate using the Bernoulli theorem. If there is a narrowing of the pipe carrying liquid, there will be an increase in speed and hence kinetic energy increases at the point of narrowing. From the energy balance equation given by the Bernoulli theorem, there must be a corresponding reduction in static pressure. So knowing the pressure reduction, fluid density, the area available for flow in the constriction and the discharge coefficient, the release rate from the constriction can be calculated. $Cd$ discharge coefficient is the actual flow ratio with theoretical flow. Venturi is a tool used to measure the flow rate along a pipe. The liquid that moves past it accelerates towards a tapered contraction with an increase in speed in the neck. This is accompanied by a decrease in pressure, the amount depends on the flow rate. Therefore, the flow rate can be inferred from the difference in pressure as measured by a piezometer placed in the upstream part of the neck. The effect that a meter has on changes in pressure is called the Venturi effect. Venturi meters are usually used in single flow and multiphase. The conditions encountered in thick liquid metering can be beyond the scope of application of industry standards (ISO 5167-1). ISO standards are limited to turbulent flow for Reynolds numbers (based on pipe diameter upstream) above 2x10^5.

The performance of the venturi meter in terms of the discharge coefficient value and pressure loss has been investigated by several researchers [9-17]. Gordon Stobie et al. make a performance study of the effects of erosion on Venturi with Laminar and turbulent flow and measurement of discharge coefficient at Reynolds numbers [9]. Naveenji Arun et al. Conducted a CFD analysis to predict Venturi coefficients as a function of Reynolds numbers with different beta ratios for single-phase non-Newtonian currents. Hollingshead et al. conducted an experimental study of venturi discharge coefficient and validated them using numerical analysis [10]. Nithin et al. examine the effect of divergence angles on total and differential pressure [11]. The discharge coefficient is the actual flow ratio with the theoretical flow and makes allowances for flow contractions and friction effects. The discharge coefficient is a function of the Reynolds number while the Reynolds number is a function of the flow rate calculated using the discharge coefficient value. The purpose of this study is to introduce the effect of the discharge coefficient ($Cd$) on fluid flow measurements using a venturi tube.
2. Theory and Method

Venturi meters are more often used to measure flow in closed channels. Venturi meters are usually used in single flow and multiphase. The conditions encountered in thick liquid metering can be beyond the scope of application of industry standards (ISO 5167-1). The ISO standards are limited to turbulent flow for Reynolds numbers (based on upstream pipe diameters) above 2\times10^5. Boyes explained that the venturi was designed to consist of three types; namely the classic Venturi type, short Venturi, eccentric Venturi [18]. Each Venturi tube is made of stainless steel and is suitable for use at pressures up to 70 bar with ANSI Class 600 flanges. The Venturi is designed not only to meet ISO 5167-1 requirements, but to follow recommendations. The classic Venturi is always produced with the castiron body and bronze or stainless steel neck section shown in Figure 1. At the midpoint of the neck, six to eight tap taps connect the neck to the annular space so that neck pressure is averaged. The cross-sectional area of the space is 1.5 times the cross-sectional area of the tap. This flow meter is limited to clean and non-corrosive liquids, because it is not possible to clean the pressure tap if it is clogged with dirt. The flow coefficient for classic venturi is 0.984, with an uncertainty tolerance of ± 0.75%. While the short Venturi form can be made of cast iron or welded from various materials according to the application given. The short flow coefficient for Venturi is 0.985 with a tolerance of uncertainty of ± 1.5%.

The venturi meters have convergent cone inlets, cylindrical necks and divergent recovery cones. It has no projection to the liquid, there is no sharp angle and no sudden changes in the contour. The following (Figure 1) shows venturi meters with uniform cylindrical parts before converging, neck canal and divergent.

![Figure 1. Venturi klasik dengan ruang tekanan annular [18].](image)

The inlet part converges to reduce the fluid flow area, which causes the speed to increase and the pressure to decrease. Low pressure is measured in the middle of the cylinder neck because the pressure will be at the lowest value, where the pressure or speed will not change. Thus the pressure difference between the inlet and neck is developed. This pressure difference correlates with the fluid flow rate using the Bernoulli equation. As the theorem states that with an ideal and stable fluid flow, the total energy at each point of the fluid is constant, the total energy consists of pressure energy, kinetic energy and potential energy.

\[
\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + z_2
\]

(1)

Due to the smooth passage of contraction and venturi expansion, irreversible pressure loss is low. However, to get a significant pressure drop, the downstream pressure tap is located on the neck of the Venturi meter. Equation (1) is based on the assumption that the flow is stable, unstable, and the flow and uniform velocity profiles occur at the pressure site. However, to account for real fluid effects such as viscosity and compressibility to the empirical coefficients \(C_d\) and \(\varepsilon\) are introduced in the equation.
The fluid flow rate, \( Q_m \), is proportional to the square root of the pressure drop. This relationship is the basis of flow measurement using Venturi classic with the equation:

\[
Q_m \propto \sqrt{\Delta P}
\]  

(2)

This relationship is called the Bernoulli formula. Zhi-yao et al. and Tao et al. using a Bernoulli formula, the flow rate of a single phase fluid mass is proportional to the square root of the differential pressure in Venturi according to the equation (mass flow rate in meters venturi \( Q_m \)) follows [19, 20]:

\[
Q_m = \frac{C_d}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi d^2}{4} \sqrt{2\left(p_1 - p_2 / \rho_1 \right)}
\]  

(3)

where, \( Q_m \) is the mass flow rate, \( C_d \) is the meter venturi discharge coefficient, \( \beta \) is the beta meter venturi ratio, \( d / D \varepsilon \) is expansion factor (\( \varepsilon = 1 \), for flows that cannot be compressed), \( d \) is the neck diameter of the venturi meter, \( D \) is the upstream pipe he converges Venturi, \( P_1 \) is Static pressure on the upstream pressure tap, \( P_2 \) is Static pressure on the Venturi neck tap, \( \rho \) is the density of the liquid on the upstream tap location. In a single phase flow, the discharge coefficient depends mainly on the Reynolds number and the beta factor. Dependence on Reynolds numbers is very weak (except low Reynolds numbers), so the performance of differential flow meters is rather insensitive to liquid viscosity. The discharge coefficient is very close to one unit for the venturi flow and nozzle flow, which indicates that the dissipation effect can almost be ignored.

The discharge coefficient of the Orifice plate (\( C_d \)) is the ratio of the actual flow to theoretical flow and is applied to theoretical flow equations to obtain actual flow. The discharge coefficient, otherwise known as the Venturi meter coefficient, usually has a value between 0.92 and 0.99. Therefore, almost 60% more flow can be obtained through these elements for the same differential pressure. The true value depends on the given Venturi meter, and may even change with the flow rate. For the value of the venturi meter discharge coefficient is the ratio of the actual flow rate to the theoretical flow rate. This is often expressed as a function of the Reynold (Re) number, which is defined as:

\[
Re = \frac{4Q_m}{\pi d \mu}
\]  

(4)

where \( Re \) is Reynolds number and \( \mu \) is viscosity.

The performance of the meters in relation to the discharge coefficient value and pressure loss has been investigated by several researchers. Gordon Stobie et al. reported in a performance study of the effects of erosion on Venturi meters with laminar and turbulent flow and measurement of discharge coefficient at Reynolds numbers [9]. Nithin et al. examined the effect of divergence angles on total pressure and on pressure for various values of divergence angles and inflow velocities for different venturi profiles [11]. The assumptions and flows are ideal and apply the Bernoulli equation before and after contraction, using equation (1), then the equation for velocity is obtained as follows,

\[
v_2 = \frac{1}{\sqrt{1-\beta^4}} \sqrt{\frac{2\Delta p}{\rho}}
\]  

(5)

From the continuity equation obtained,

\[
Q_{teori} = A_2v_2 = \frac{1}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{\frac{2\Delta p}{\rho}}
\]  

(6)
The above equation is based on the assumption that the flow is stable, cannot be compressed, inviscid, and irrotational, there is no loss and velocity $v_1$ and $v_2$ are constant along the cross section.

$$Q_{actual} = \frac{C_{d\text{(std)}}}{\sqrt{1 - \beta^4}} \frac{\pi d^2}{4} \sqrt{\frac{2\Delta p}{\rho}}$$ \hspace{1cm} (7)$$

The discharge coefficient handles real liquid effects, namely the correction factor of kinetic energy, thick effect and loss due to sharp edges. In accordance with ISO-5167-1, for classic venturi meters, flow with Reynolds number $RD > 2 \times 10^5$ the value of the discharge coefficient is equal to 0.995, therefore the loss is only 0.5%. However, if laminar flow occurs, the losses are higher and mainly due to the loss of thickness. When fluid flows through a pipe, the velocity of the liquid layer adjacent to the pipe wall is zero. The velocity of the liquid keeps increasing from the wall and thus the velocity gradient and hence the overall pressure friction produced due to viscosity.

The general approach to friction loss characterization is to use the Fanning friction factor ($f$) which is defined as friction force per unit surface area divided by kinetic energy per unit. The laminar flow friction can be solved by using the Navier-Stokes equation analytically to obtain the friction factor, with, $f$ is the friction factor which is a function of the Reynolds number and for laminar flow $f$ is given as $f = \frac{64}{Re}$, $Re = \frac{Dv\rho}{\mu}$ is the Reynolds number ($\rho$ and $\mu$ is the density and viscosity of the liquid).

For turbulent flow, friction losses are given by empirical relationships, such as the Colebrook equation or the Moody diagram. This relationship involves new parameters that correspond to the roughness of the pipe. Roughness depends on several factors, including the material from which the pipe is made and the level of corrosion. The friction losses due to the fittings are explained using the loss factor $K_f$ given the equation:

$$W_{\text{loss}} = K_f \left[ \frac{v}{2} \right]$$ \hspace{1cm} (8)$$

Fluid viscosity causes loss of energy which is usually known as friction fraction. Thus the liquid experiences several obstacles because some fluid energy is lost, this pressure loss is caused by friction and is given by Darcy’s law,

$$H_L = \frac{(\Delta p)_{\text{viscous}}}{\rho g} = f \frac{v_2}{2} \frac{L}{D}$$ \hspace{1cm} (9)$$

By applying the Bernoulli equation the difference between two pressure is obtained,

$$\frac{(p_1 - p_2)}{\rho} = \frac{(v_2^2 - v_1^2)}{2} + f \frac{1}{2} \frac{v_2^2 L}{D}$$ \hspace{1cm} (10)$$

By assuming $v_1 = v_2$ and $f = 64 / Re_c$, the equation of laminar equation is obtained as

$$\frac{(\Delta p)}{\rho} = \frac{v_2^2}{2} \left[ (1 - \beta^4) + f \left( \frac{L_c}{d} \right)_{\text{actual}} \right]$$ \hspace{1cm} (11)$$

$$Q_{actual} = \frac{C_{d\text{(std)}}}{\sqrt{(1 - \beta^4)}} \frac{\sqrt{1 - \beta^4}}{\sqrt{[1 - \beta^4 + 2,8f]}} \frac{\pi d^2}{4} \sqrt{\frac{2\Delta p}{\rho}}$$ \hspace{1cm} (12)$$

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By comparing (7) and (12) then
\[
C_{La,\text{in,ar}} = C_{d,(nd)} \frac{\sqrt{[1 - \beta^2]}}{\sqrt{[1 - \beta^4] + 2.8f}}
\]  
(13)

If \( \beta \) is 0.5 then,
\[
C_{La,\text{in,ar}} = 0.995 \frac{\sqrt{1}}{\sqrt{1 + 3f}}
\]  
(14)

Equation (14) gives a discharge coefficient for laminar flow with a Reynolds number less than 2000 and beta ratio equal to 0.5. The above equation does not take into account the angle of loss and the correction factor for kinetic energy. Some of the standard values of the relationship between the determination of discharge coefficient on the diameter of the Venturi tube, the pipe and the Reynolds number are shown in Table 1.

### Table 1

| Diameter Ratio (d/D) | 10^4 | 10^5 | 10^6 | 10^7 |
|----------------------|------|------|------|------|
| 0.2                  | 0.968| 0.988| 0.994| 0.995|
| 0.4                  | 0.957| 0.984| 0.993| 0.995|
| 0.6                  | 0.95 | 0.981| 0.992| 0.995|
| 0.7                  | 0.94 | 0.978| 0.991| 0.995|

3. Results and Discussions

Venturi tubes can be installed in any position to fit the application and piping requirements. Upstream piping must be as long as necessary to provide the right speed profile (Installation image). However, for most installations, shorter upstream piping is needed, because the hydraulic venturi shape itself provides some flow conditioning. Often, the combined venturi length and upstream piping is less than the total amount of piping needed for holes or nozzles. In liquid meters, ASME recommends the use of tubular straightener vanes at the venturi upstream to reduce the length of the inlet pipe. The propeller installation must have at least 2 upstream diameters and 2 downstream diameters before entering the venturi. There is no limit to the piping configuration in the lower part of the Venturi tube except that the valve should not be closer than two diameters. Valves on other devices that protrude into the flow should not be installed upstream of the Venturi tube, if possible.

The experiment was carried out on the Venturi tube to directly measure the static pressure difference distribution along the Venturi tube, compare the results of experiments with theoretical predictions and calculate the effective meter discharge coefficient at various flow rates. To conduct an experiment, the flow rate through the venturi meter is measured in the upstream cross section and in the neck. Pressure distribution along the length of the meter is also measured. The procedure is
repeated with a reduced flow rate and takes a similar reading at any time. Table 2 shows the results of the $Q_{\text{actual}}$ trial against $d/p$ and the calculation of the $Q_{\text{actual}} / Q_{\text{theory}}$ called $Cd$ from the Venturi tube.

**Table 2.** The Different Pressure Results of Venturi Tubes and the Discharge Coefficient.

| No | $Q_{\text{actual}}$ (l/min) | $Q_{\text{theory}}$ (l/min) | Different Pressure Results of Venturi Tubes (kPa) | $Cd$  |
|----|-----------------|----------------|---------------------------------|-------|
| 5  | 5,090           | 1,30           | 1,33, 1,31, 1,31               | 0.982 |
| 6  | 6,113           | 1,79           | 1,83, 1,80, 1,81              | 0.982 |
| 7  | 7,129           | 2,55           | 2,59, 2,58, 2,57             | 0.982 |
| 8  | 8,139           | 3,32           | 3,38, 3,34, 3,35             | 0.983 |
| 9  | 9,156           | 4,21           | 4,26, 4,24, 4,24             | 0.983 |
| 10 | 10,160          | 5,19           | 5,26, 5,20, 5,22             | 0.984 |
| 11 | 11,179          | 6,27           | 6,36, 6,34, 6,32             | 0.984 |
| 12 | 12,186          | 7,48           | 7,54, 7,50, 7,51             | 0.985 |
| 13 | 13,199          | 8,79           | 8,83, 8,80, 8,81             | 0.985 |
| 14 | 14,209          | 10,18          | 10,24, 10,20, 10,21          | 0.985 |
| 15 | 15,223          | 11,69          | 11,75, 11,71, 11,72          | 0.985 |

The experimental results can be determined in the best way to provide a comparison of the discharge coefficient with the Reynolds number on the graph. Each data point in the graph is calculated separately based on the performance of the predetermined Reynolds number. The speed required to obtain different Re values is the main variable entered into the numerical model when calculating the discharge coefficient of each meter. The graph of the relationship between actual $Q$ (l/min) to average $d/p$ (kPa) for the orifice plate is shown in Figure 2 by mean linearly close to the $d/p$ value. The graph of the relationship of the $Q_{\text{actual}} / Q_{\text{theory}}$ value with the discharge coefficient $Cd$ are shown in Figures 2 and 3 which shows the $Cd$ coefficient value in the range of 0.981 to 0.984 for the Reynolds number $10^5$ and diameter ratio $d/D$ between 0.4 to 0.6.

![Figure 2](image-url) **Figure 2.** Graph the relationship between $Q_{\text{actual}} / Q_{\text{theory}}$ with the average of the Venturi tubes.
It should be noted that (in contrast to the hole) the decrease in Reynolds number results in a decrease in flow according to the differential pressure applied. Other correction factors, such as temperature expansion coefficients, gas expansion factors, etc., are similar to orifice and flow nozzles. Calculations are carried out in accordance with BS EN ISO 5167-1: 2014, unless otherwise requested. Other available calculation standards include ASME, API, R W Miller, L W Spink. Pressure losses are usually between 40 and 95% of the differential pressure produced, depending on the neck ratio (d / D). The following results were obtained from experiments conducted using the Venturi meter carried out in the laboratory. The results from the Venturi meter are used to compare that from the Venturi meter made. This proves or demonstrates the efficacy of a fabricated tool. The discharge coefficient \( (C_d) \) increases very irregularly when the \( Q_{\text{actual}} \) value is at a low value that is at a value below 5 l / minute, but after passing the value => 5 l / minute. The value of \( C_d \) is stable.

**5. Conclusions**

It can be concluded that the resulting discharge coefficient value of \( C_d \) shows a range of 0.981 to 0.984 for the range of diameter ratio \((\beta)\) 0.4 to 0.6 with Reynolds number \(10^5\). So by interpolating the relationship of the discharge coefficient value to the diameter ratio, the discharge coefficient tube is obtained Venturi for \((\beta)\) 0.5 is 0.983. The main limitation of the Venturi tube is the cost, both tubes themselves and often the piping layout needed for the length needed in larger sizes. However, the
savings in energy costs caused by the recovery of high pressure Venturi tubes and reduced pressure drops usually justify their use in larger pipes. Another limitation is the relatively high minimum Reynolds number needed to maintain accuracy. The main advantages of this Venturi tube include relatively high accuracy, good range, and high pressure recovery that saves energy. For this reason, in higher speed flows and larger pipelines, Venturi tubes are still favored by many users even though they are expensive.

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