# Preliminary Validation of Turbulent Flow Through an Orifice Meter

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ABSTRACT

*An orifice meter is a device to measure the rate of fluid flow in a pipe by recording the pressure difference upstream and downstream of the meter. Due to the sensitive nature of orifice meter on the upstream flow conditions, measuring the pressure drop and determining the discharge coefficient pose a challenge and may possibly yield a large deviation. The present work intends to establish a numerical procedure verified with experiment results from ISO 5167-2 standard to evaluate the pressure drop and thus the discharge coefficient of orifice plates. An open source CFD simulation software is employed to simulate the steady-state turbulent flows with a fully developed velocity profile imposed at the pipe inlet. The numerical analysis revealed discharge coefficient errors of less than 4% when compared with experiment data. Following this analysis, three new concepts of orifice meter are introduced, with the goal to minimize the sensitivity to the upstream flow conditions and thus improve measurement accuracy.*

**Keywords:** *Orifice Meter; Discharge Coefficient; Pressure Loss; Flow Conditioner; CFD*

## Introduction

An orifice meter is used to determine the flow rate of a fluid in a pipe system by limiting the water's flow through the pipe. Because of the constriction in the pipe, there will be a difference in pressure between the steady flow and the flow that passes through the constriction area [1]-[2]. However, orifice meters

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produce the relatively biggest pressure loss when compared to other meters like venturi meters because of the way they are built, which causes the flow in the pipe to suddenly contract at the orifice meter's intake and suddenly expand at the orifice meter's outlet. The orifice meter has been accepted as a measurement standard because of its straightforward design and ease of fabrication [3].

The shapes of the orifice plate have its effects on the turbulent flow in pipe. It was reported that the slotted orifice flowmeter maintains calibration better than the standard orifice flowmeter under a variety of intake flow circumstances [1]. In their study, an upstream swirl inducer was placed to create an axisymmetric swirl of flow in the pipe. The authors also reported that the ideal range for beta ratio is in between 0.3 and 0.7, which resulted in the best performance. Furthermore, comparing a slotted orifice plate to a normal orifice plate with the same beta ratio, the slotted orifice plate is significantly less susceptible to upstream flow conditioning. It is also reported that comparing fractal orifices to circular orifices of the same area, they produce additional smaller velocity scales, which might be the primary factor resulting in a smaller pressure drop when using a fractal orifice [2]. This finding is further corroborated by a more recent research [3], which has reported that multi-hole orifice has then tendency to accelerate pressure recovery, reduce pressure drop and increase discharge coefficient. Furthermore, compared to orifices with lower $\beta$ parameters, those with higher $\beta$ parameters (ratio of orifice diameter to pipe diameter) exhibited reduced power consumption and relative power loss [4].

In another study, Likitha et al. [5] have numerically investigated three shapes of concentric orifice plate. The first orifice plate consists of short-square edged hole with back bevel angle, the second orifice plate consists of long-square edged hole and the third orifice plate consists of knife edged hole with back bevel angle. All orifice plates tested in the simulation has equal pipe diameter to orifice beta ratio (ratio of orifice dieter to pipe diameter), which are 0.3 and 0.5, and subjected to a water flow with Reynolds number ranges between 10,000 and 1,000,000. It was reported that at a given Reynolds number, a higher beta ratio produced a lower discharge coefficient than a lower beta ratio for long square edged orifices and short square edged back bevel angle orifices. The discharge coefficient for a knife edged back bevel angle orifice decreases as the beta ratio increases. However, this only happens for Reynolds numbers higher than 10,000. The results also indicated the discharge coefficient increases from 0.66 to 0.68 when the beta ratio used in the simulation is increased from 0.3 to 0.5.

The upstream flow conditions have also been identified as one of the factors that has a significant effect on the flow measurement accuracy. Prabu et al. [6] studied how upstream pipe fittings affected the performance of orifice and conical flowmeters. They looked into the upstream deviation of various mitre bend kinds while keeping the beta ratio constant for both types of orifices. A beta ratio of 0.75 was selected for both types of orifices because of the sensitivity of the orifice plate to the swirl. In the experiment, the changes in discharge coefficient were observed when there was no upstream disturbance in the pipe. Conical flowmeters have a positive deviation from the ideal coefficient of discharge, while orifice meters experience a negative deviation. In the end, they discovered that the conical flowmeter's shape tends to cause the velocity profile to be flattened and more uniformly distributed, which resulted in the conical flowmeter to be less sensitive to swirl than an orifice flowmeter. They also discovered that the discharge coefficient is influenced by the length of the upstream pipe.

It was recommended that a sufficient upstream length of the pipe (i.e., the length of pipe before the fluid enters the orifice plate) be maintained in order to achieve an accurate measurement of the orifice meter. This will allow a fully developed turbulent flow to be generated. However, this necessary upstream length sometimes cannot be achieved due to the size of the design constraint of the piping system. In this case, a flow conditioner might be used in order to improve the profile of a fluid flow, i.e. removes swirl (tube bundles type of flow conditioner), removes flow asymmetry and causes the flow to be fully developed.

Out of numerous related investigations, most of the orifice-type flowmeter has shown to be sensitive to the upstream flow conditions, unless flow conditioners are installed in the pipe system. However, this will lead to additional pumping power requirement due to pressure loss. The present preliminary study seeks to device a novel flow meter combined with flow conditioner that is expected to minimize swirls and uniformly distribute the flow. Of the many parameters of the flow conditioner, porosity (also quantified as equivalent diameter ratio, EDR) has been shown to significantly affect the pressure loss, where the number of holes has a negligible linear decreasing trend with pressure loss coefficient and the pressure fluctuations on the downstream were reduced with an increase in the number of holes [7]. First, the solver used was validated against data from the ISO 5167-2 Standard, which was then followed by a preliminary concept generation and analysis of the flow meter.

## Methodology

In the present study, CFD approach was employed to solve the flow passes through an orifice flow meter. Previous numerical investigations suggested that the experiments needed to estimate the discharge coefficient and other flow features (such as recirculation, reattachment and shear layer regions downstream the orifice) can be replaced by the CFD technique as an alternative and more affordable tool [8]–[10].

OpenFOAM, an open source CFD code was used to solve the momentum and continuity equations, and k-epsilon turbulence model was employed due to its usage in numerous flowmeter researches [11]. The time-dependent variable was dropped from both equations since the flow was thought to be steady state and incompressible. At the pipe inlet, a fully developed velocity profile is imposed, while a zero-reference static pressure is imposed at the pipe outlet (see Figure 1). All solutions were deemed fully converged when the sum of residuals was less than $10^{-5}$. The turbulent kinetic energy, $k$ and turbulence dissipation rate, $\varepsilon$ were calculated based on the turbulent intensity which is dependent on the flow Reynolds number and turbulence length scale. For $Re$ = 5000 and turbulent model constant, $C_\mu = 0.09$ (following [12]), $k = 1.75 \times 10^{-5}$ and $\varepsilon = 2.39 \times 10^{-6}$. The turbulent model constant, $C_\mu$, used for this case is similar to the value presented in the previous paper by [19] , which is 0.09.

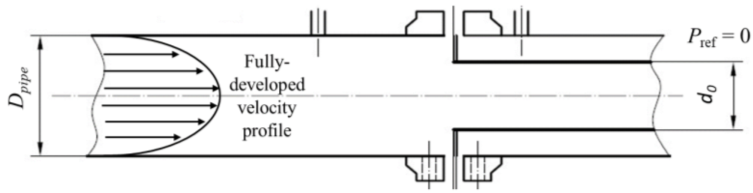



Figure 1: Schematic diagram of numerical domain

To strengthen the stability of the computation and reduce variable changes from one iteration to the next, relaxation factor of 0.2 was applied for pressure filed and 0.6 for velocity, $k$ and $\varepsilon$. The computation is stable when the relaxation factor is equal to 1, and that it is also large enough to advance the iterative process swiftly. However, if the relaxation factor is too low, the time taken for iterative processes to complete will be too slow, and the computational time for simulations to complete will increase [13].

A grid independence study was conducted to ensure the mesh were sufficiently refined to resolve expected high gradients variables near the orifice. Four different mesh sizes used are summarized in Table 1. Result of grid independence study shows that the discharge coefficient ($C_D$) increases as the number of cells is increased. Discharge coefficients is defined as:

$$C_D = \frac{u_o\sqrt{1-\beta^4}}{\sqrt{2\Delta p/\rho}} \tag{1}$$

where $u_0$ is average flow velocity at orifice, $\beta$ is ratio of orifice diameter to pipe diameter, $\Delta p$ is pressure drop across the orifice and $\rho$ is fluid density. Relative error in discharge coefficients is defined as:

$$\text{Error} = \left|\frac{C_D - C_{D\,MAX}}{C_{D\,MAX}}\right| \times 100\% \tag{2}$$

to quantify the relative error between each mesh. The results indicated that using medium mesh is sufficient to estimate the discharge coefficient within 2% accuracy. The medium mesh is also sufficient to capture flow acceleration passes through the orifice, as indicated in Figure 2.

Table 1: Summary of grid independence study

| Mesh Properties | Coarse | Medium | Fine | Finer |
|---|---|---|---|---|
| Number of cells | 105,080 | 827,040 | 1,640,480 | 13,123,840 |
| Max Mesh Non-Orthogonality | 31.2947 | 37.8994 | 37.8994 | 41.4761 |
| Average Mesh Non-Orthogonality | 4.10608 | 4.41482 | 4.38751 | 4.55979 |
| Max Skewness | 0.462836 | 0.499522 | 0.499522 | 0.517973 |
| Discharge Coefficient, $C_D$ | 1.299 | 1.331 | 1.337 | 1.352 |
| Relative error (%) | 3.96 | 1.54 | 1.12 | - |

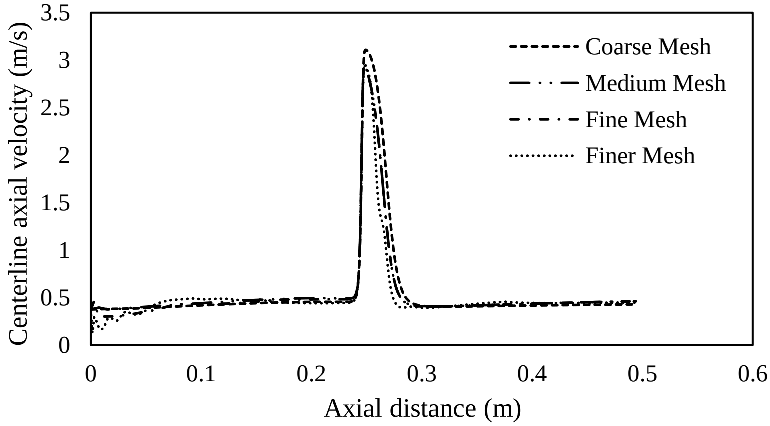



Figure 2: Centreline axial velocity profile along the pipe

The geometry of the orifice was based on the ISO 5167-2 Standard [14], with β = 0.4, pipe diameter $D_{pipe}$ = 0.072 m, orifice diameter $d_0$ = 0.0288 m and pressure drop measurements using *D* and *D*/2 tapping. The orifice is a long-squared hole orifice with no bevel angle. According to the standard, for a long-squared orifice, the orifice thickness, *E*, should be equal to the thickness, *e*, which equal to 0.02*D*. Thus, the calculated orifice thickness obtained is 0.00144 m. The fluid used is water and for Reynolds Number = 5000, the flow mean velocity, *u* is 0.0619236 m/s. Since no flow conditioner is used in the present investigation, the upstream length is in accordance with the distance as specified in Table 3 of the ISO 5167-2. Assuming there is a gate valve before upstream of pipe and the gate valve is fully open, the upstream length is equal to 12D and downstream length is equal to 6D for beta ratio of 0.4. However, for research and calibration work in particular, the upstream length is increased by a factor of 2 to minimize the measurement uncertainty. These conditions lead to an upstream length of 1.728 m and a downstream length of 0.432 m.

## Results and Discussion

Flows through a standard orifice at five different Reynolds number were simulated using an open-source software OpenFOAM. The main objective is to validate the solver and the turbulence model used in the study. Figure 3a and Figure 3b shows, respectively the axial velocity and pressure distributions along the pipe centerline for *Re* = 5000, while Figure 4 shows the contour plots of the corresponding distributions.

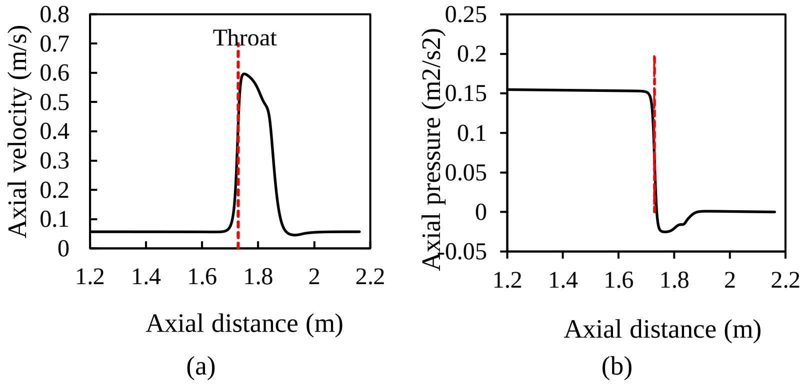



Figure 3: (a) Centreline velocity, and (b) pressure profiles along the pipe

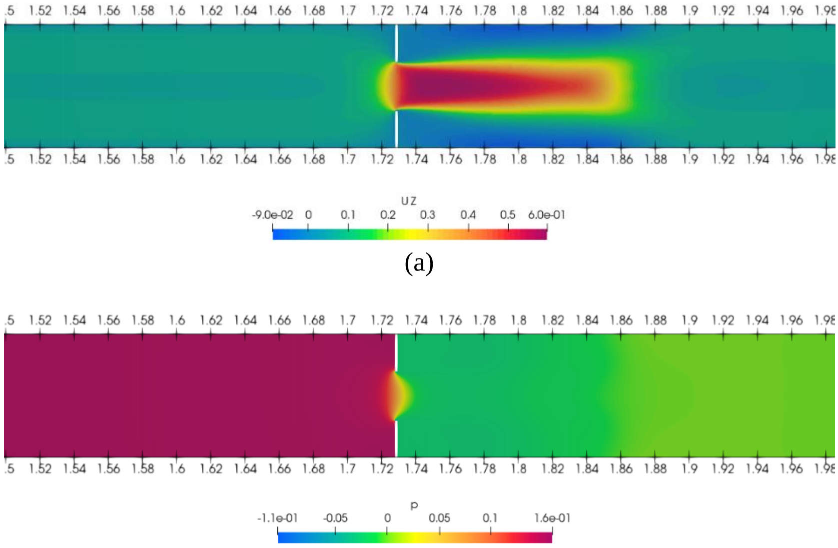



Figure 4: (a) Axial velocity, and (b) pressure distributions along the pipe

It can be seen in Figure 3a that the highest velocity achieved is 0.58 m/s at approximately 0.6 diameter downstream, which is known as vena-contracta. The fluid is then decreased abruptly downstream of the vena-contracta and the pressure started to recover until the end of the pipe. It is also noticed that the velocity remains almost constant once reaching a fully-develop state and the pressure is recovered, which indicate the length of the downstream pipe used in the simulation is sufficient. Table 2 summarizes the discharge coefficient of the standard orifice from CFD simulations and data obtained from ISO 5167 standard [14].

Table 2: Discharge coefficients and errors of CFD prediction relative to ISO data for Reynolds Number varying from 5,000 to 50,000

| Re | 5,000 | 10,000 | 20,000 | 30,000 | 50,000 |
|---|---|---|---|---|---|
| Δp | 0.1804 | 0.1845 | 0.1864 | 0.1860 | 0.1866 |
| $C_D$ (CFD) | 0.6360 | 0.6288 | 0.6257 | 0.6263 | 0.6254 |
| $C_D$ (ISO 5167) | 0.6153 | 0.6095 | 0.6059 | 0.6044 | 0.6031 |
| Error (%) | 3.36 | 3.17 | 3.27 | 3.63 | 3.70 |

It was found that the CFD simulations can accurately predict the discharge coefficients when compared with the data provided in ISO 5167. The highest error of discharge coefficient was 3.70%, which occurred at the highest Reynolds number of 50,000. It is also interesting to note that the trend of discharge coefficient with the variation of Reynolds number is remarkably similar (as seen in Figure 5, which follows logarithmic law).

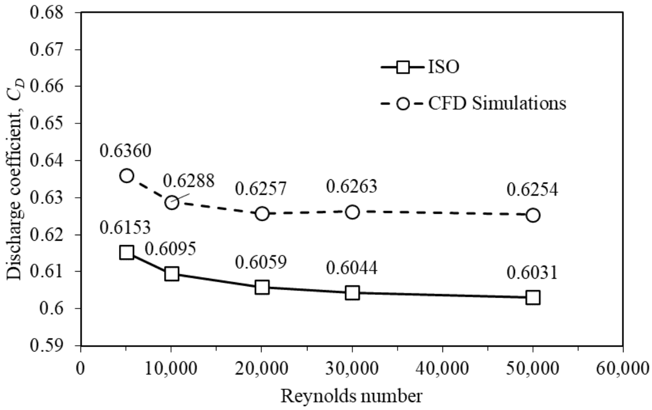
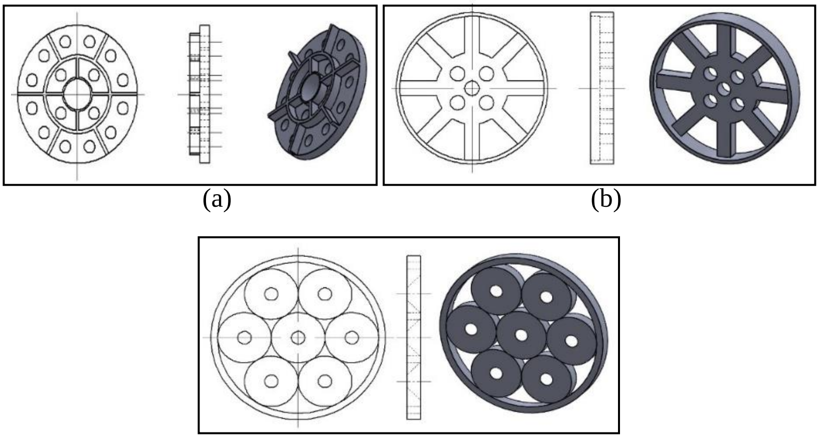



Figure 5: Discharge coefficient plotted against Reynolds number

## Conceptual design for orifice plate

This section discusses the development of new orifice meter concepts. The development was motivated by the needs to eliminate disturbances such as swirling and non-asymmetry flow in upstream pipes. The use of vane in pipe helps in reducing the swirling flow produced by the turbulent flow and pipe fittings and the use of perforated plate helps in distributing the flow into fully developed flow in a short distance [15]. It was reported that the porosity of the plate has a greater influence on the pressure loss of the flow than the type of flow conditioner, where higher porosity leads to a lower pressure difference [16]. This is due to the longer circulation zone and the mean velocity gradient between the rings, particularly for fractal flow conditioner [17]. These findings were corroborated by the optimization study using central composite design, where it was reported that the number of holes is dominant only for low porosity multi-holed orifice plates [18].

In the present study, a few conceptual designs were generated through a morphological chart (not shown for brevity, but the main idea was combining the orifice meter with flow conditioner). The concepts are shown in Figure 6.



(a) (b) (c)

Figure 6: (a) Concept 1: multi-hole orifice with vane, (b) Concept 2: Etoile multi-hole orifice and, (c) Concept 3: tube-bundle style multi-hole (back bevel angle) orifice

Figure 6a shows a combination of multiple holes and vane into a concentric orifice plate. A vane is usually used as a flow conditioner to reduce the flow disturbances (swirl flow) that enter an orifice plate while perforated plate-vane flow conditioner is used to shorten the upstream distance through swirls reduction and redistribution of the flow [19]. The etoile-shaped orifice with multiple holes has shown to successfully eliminate the swirl in flow [20] but can produce a flat flow profile as opposed to a fully-developed profile) under asymmetric upstream flow condition [15]. Figure 6c shows multiple orifice plates that are bundled together, where each hole is designed to have a bevel angle of 45 degrees, which follows the regulation stated in ISO 5167. It was reported that the back-bevel angle orifice plate produces a lower discharge coefficient than the long-squared orifice plate at the same Reynolds number and beta ratio [5]. Thus, it is anticipated that Concept 3 will produce the lowest discharge coefficient compared to other concepts. However, it has been shown that Concept 3 produces a non-symmetric velocity profile when the Reynolds number is higher than 3900 [21].

For the purpose of preliminary analysis, Concept 1 flow conditioner has been numerically evaluated for flow with $Re$ = 5,000. The flow conditioner is placed 3 pipe diameters upstream of the orifice. The flow conditioner has a thickness of 20% of the pipe diameter, with a porosity ratio of 21%. Figure 7 depicts the streamlines of flow along the pipe in the presence of flow conditioner. It was found that the pressure drop across the orifice plate (using $D$ and $D/2$ tapping) has increased by 2.31% in the presence of flow conditioner, while the discharge coefficient dropped by 1.14%.

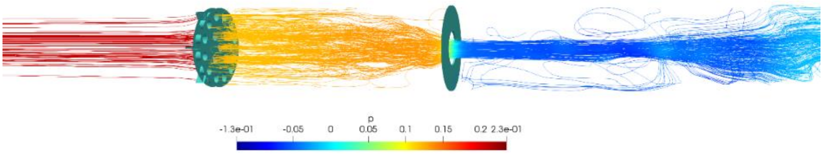



Figure 7: Streamlines of flow across the flow conditioner and orifice plate for Re = 5,000. The streamlines are coloured by the ratio between the local pressure and fluid density. The flow is from left to right

## Conclusion

Flows through a standard orifice plate flow meter have been numerically simulated using OpenFOAM simulation software. Preceding to the flow simulation, a grid independence study was conducted to ensure sufficient cell density to capture flow gradients in the longitudinal and lateral directions. The discharge coefficients of the standard orifice plate flow have been accurately predicted by the solver for various Reynolds number, with maximum error of less than 4%. Subsequent to the analysis, three concepts of orifice plate flow meter were proposed and Concept 1, which is multi-hole orifice with vane flow conditioner was evaluated. It was found that the incorporation of the flow conditioner has resulted in insignificant change in the pressure drop across the orifice plate and flow discharge coefficient.

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