Numerical Study on Performance Characteristics of Multihole Orifice Plate

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Abstract: The multi-hole orifice plate is one of the effective devices for measuring flow rate accurately. In this study, an experimental and numerical investigation of the flow characteristics behavior caused by a water flow through a multi-hole orifice configuration is reported. A circular centered single hole orifice and a multi-hole orifices are used for the test. Orifices of interest for present study have an area ratio of 0.36, the equivalent diameter ratio of 0.6 and number holes 9, 16 and 25. Discharge coefficients for flow through multi-hole orifices are evaluated. Parameters investigated were the number of holes, orifice pressure drop and Reynolds number. In the present work, k-\(\varepsilon\) turbulence model has been used to predict velocity fields, pressure loss and discharge coefficient around this device. Advantages gained by using multiple holes in an orifice plate instead of a single hole are discussed. It is shown that number of holes, orifice diameter and aspect ratio influences the discharge coefficients. Tests were conducted under laboratory conditions. The experimental results were compared with numerical modeling and appropriate conclusions are discussed.

Key Words- Multi-hole orifice, Equivalent diameter ratio, Discharge coefficient, Reynold’s Number

1. Introduction

Flow measurement is one of the most complex and demanding tasks in industry. Even today there does not exist a universal measuring instrument for all applications. Orifice plates are mainly used as a device of flow measurement for fluid delivery systems based on the measurement of the pressure difference created when forcing the fluid to flow through a restriction in the pipe. The multi-hole orifice plates or perforated plates are assumed to be composed of a number of individual orifices acting independently and parallel will have flow characteristics different compared to the flow characteristics of a single hole orifice plate having same flow area [1]. This is basically because of the flow restriction due to the small flow area of each hole.

Flow control characteristics investigated by Tianyi Zhao et al.[2] to identify the key factors affecting multi-hole orifices throttle. The discharge coefficient of a perforated orifice with different aspect ratio was presented by Shangfan Huang et al. [3], the dissipation characteristics of multi-hole orifices under cavitation-free conditions are investigated experimentally by Stefano Malavasi et al [4]. On the perforated plate flow conditioner having a a valve 50\% closed and 90° double bend numerical experimentation was conducted by B. Laribi and M. Mehdi [5] the simulation is done with air as fluid in 100 mm pipe diameter with Reynolds numbers 10\textsuperscript{4}, 10\textsuperscript{5} and 10\textsuperscript{6}. D. Maynes G. J. Holt J. Blotter [6] investigated experimentally the cavitation and loss coefficient caused by water flow through perforated plates. Plates with beta ratio = 0.11 to 0.6, and t/d = 0.25 to 0.33 were considered. Akshay Dandwate et al. [7] using CFX solver does simulations on orifice plates with various geometry on the basis of their coefficient of discharge with k-\(\varepsilon\) and SST model.

A great deal of work on the pressure drop characteristics of orifice plates in pipe flows has been reported as per literature review. The performance characteristics of the multi-hole orifice meter are limited in the open literature. whatever little information available shows that for an orifice plate whose axis is coincident with that of duct or for a multi-hole orifice plate with regularly spaced holes, the factors influencing flow characteristics of the multi-hole plates are area ratio of the plate (m), the
number of holes and its distribution on the plate. Past research has also shown that the value of \( C_d \) is primarily considered to be a function of aspect ratio \((t/d)\), equivalent diameter ratio \((\beta = d/D)\) and nature of flow defined using the pipe/hole Reynolds number \((Re)\).

The paper, therefore, addresses the problem of relating flow rate to pressure drop and the discharge coefficient prediction by experiments and numerical simulations through a single orifice over multi-hole orifice geometries and operating conditions. The main objective is to validate the numerical simulations with experimental data to predict pressure loss, velocity fields and discharge coefficient \( C_d \). The present work has been subdivided into three sections. The experimental setup is first presented, numerical models are then detailed, experimental results are compared with numerical simulations in the last section.

2. Experimental arrangement and measurements:

Experiments were conducted to measure the pressure drop across multi-hole orifice plates at known flow rates. Experimental test section consists of 30 D upstream and 50 D downstream side of the orifice. At a location 50mm upstream and 25.4mm downstream from the orifice flange pressure taps, were used to measure pressure differences across the orifice using water –mercury manometer. By means of the collecting tank, the discharges were measured volumetrically. A systematic procedure was used in making the orifice plates and experiments were conducted at room temperature. Twenty square edged orifice plates were used during the study.

Data for each orifice plate were collected by a strict set of test procedures to ensure the collection of repeatable and accurate data. Air was removed from the system by the help of knob providing for the purpose whenever the orifice plate was changed. Once the air was removed the system was run for approximately 15 minutes in the maintenance configuration. About seven to eight data points were taken for each orifice plate, corresponding to a pressure drop across the orifice meter using mercury manometer. To check the consistency of the data five to six runs were made independently on the same plate to get a good sample of the data. The coefficient of discharge \( C_d \) was obtained for all the orifice plates.

The physical data and other dimensions for all the orifices used for the computations and experiments are summarized in Table 1.

### Table 1: The relevant parameters in these experiments/Computations

| Number of holes | Diameter of the hole mm | Aspect Ratio t/d | Equivalent Diameter Ratio d/D |
|-----------------|-------------------------|-----------------|------------------------------|
|                 | 1.5 mm thickness of the Orifice plate |                 |                             |
| 1               | 30                      | 0.05            | 0.6                          |
| 9               | 10                      | 0.15            | 0.6                          |
| 16              | 7.5                     | 0.2             | 0.6                          |
| 25              | 6                       | 0.25            | 0.6                          |

*Overall Range: 0.05 < t/d < 0.25 and d/D = 0.6*

3. Numerical approach:

3.1 Computational model:

Analysis is done as per the domain shown in fig.1. The pressure loss minimization and the discharge coefficient maximization of the multi-hole orifice plate are the main objectives of the analysis. Inlet diameter of the pipe is 50mm. to ensure a fully developed flow at inlet during the simulation distance of 5D is set at upstream of the plate. The present numerical analysis is done using fluent. Finite volume technique is used for discretization. The applied discretization schemes are second order scheme for pressure, the SIMPLE scheme for pressure - velocity coupling and second order upwind scheme for momentum, kinetic energy \((k)\) and turbulence dissipation rate \((\varepsilon)\). To achieve the convergence criteria the residuals of mass, momentum and turbulence are considered to be less than \(1\times10^{-6}\).
3.2 Governing equations:

In the modeling, mass, momentum, energy conservation equations (if necessary) must be satisfied. The governing equations for present study are:

Continuity: \( \nabla \cdot (\rho \mathbf{V}) = 0 \).

Momentum:
\[
\nabla \cdot (\rho \mathbf{u} \mathbf{V}) = -(\partial p/\partial x) + (\partial \tau_{xx}/\partial x) + (\partial \tau_{xy}/\partial y) + (\partial \tau_{xz}/\partial z) + \rho g \\
\nabla \cdot (\rho \mathbf{v} \mathbf{V}) = -(\partial p/\partial y) + (\partial \tau_{xy}/\partial x) + (\partial \tau_{yy}/\partial y) + (\partial \tau_{yz}/\partial z) + \rho g \\
\n\nabla \cdot (\rho \mathbf{w} \mathbf{V}) = -(\partial p/\partial z) + (\partial \tau_{xz}/\partial x) + (\partial \tau_{yz}/\partial y) + (\partial \tau_{zz}/\partial z) + \rho g
\]

3.3 Boundary conditions:

The present three-dimensional flow field is solved by considering water as the incompressible fluid. There are three boundaries: inlet, outlet and the wall. The boundary conditions are summarized in Table 2.

| Sl.No | Quantities     | Condition/value |
|-------|----------------|-----------------|
| 1     | Working fluid  | Water           |
| 2     | Inlet velocity | 0.5 to 1.5 m/sec|
| 3     | outlet          | Zero Pascals    |
| 4     | Wall            | No slip         |

3.4 Grid independence study:

A hexahedral block structured mesh is employed for the entire computational domain using mesh application from ANSYS Workbench. In order to test the adequacy of the discretization, the number of elements is varied in the range \(4.5 \times 10^5\) to \(1.6 \times 10^6\).

The computational meshes employed for simulation with full domain and section plane detail of discretized fluid domain for nine orifice holes model with 3D hexahedral mesh is presented in Fig.2 and Fig.3. The mesh principal parameters are presented in Table 3.

| Element size (mm) | Number of Elements | Number of nodes | Skewness | Aspect ratio | Orthogonal quality |
|-------------------|--------------------|-----------------|----------|--------------|-------------------|
| 1                 | 1.6x10^6           | 166526          | 0.098    | 1.182        | 0.989             |
| 1.2               | 9.2x10^4           | 964627          | 0.108    | 1.207        | 0.989             |
| 1.3               | 7.5x10^4           | 792270          | 0.112    | 1.220        | 0.988             |
| 1.4               | 5.7x10^4           | 608990          | 0.117    | 1.215        | 0.987             |
| 1.5               | 4.5x10^5           | 484219          | 0.136    | 1.237        | 0.984             |
3.5. Validation:

The validation of the CFD analysis has been done by comparing the CFD results with the results obtained by experiments for a single hole orifice plate with mass flow rate of \(2.091 \times 10^{-3}\) m\(^3\)/sec in terms of discharge coefficient and pressure drop. The validation results are presented in table 4.

| Element size (mm) | Number of Elements | Pressure drop \(\Delta P\) (Pa) | Coefficient of discharge \(C_d\) | Relative error % |
|-------------------|--------------------|-------------------------------|---------------------------------|-----------------|
|                   | Exp                | Num                          | Exp                            | Num             | \(\Delta P\) | \(C_d\) | |
| 1                 | 1.6x10^6           | 8528.81                      | 9002.2                         | 0.6682          | 0.6504      | 5.25   | 2.66 |
| 1.2               | 9.2x10^5           | 8862.85                      | 8602.7                         | 0.6556          | 0.6655      | 3.76   | 1.88 |
| 1.3               | 7.5x10^5           | 8620.7                       | 8620.7                         | 0.6556          | 0.858       | 0.85     | 0.40 |
| 1.4               | 5.7x10^5           | 8829.35                      | 9181.2                         | 0.6569          | 0.6441      | 7.12   | 3.61 |
| 1.5               | 4.5x10^4           | 9181.2                       | 9181.2                         | 0.6441          | 0.6441      | 7.12   | 3.61 |

It is observed that for all the meshes studied the agreement between computed and experimental values \(C_d\) and \(\Delta P\) is reasonably good. On the basis of this study a mesh size of \(7.5 \times 10^5\) and element size of 1.3mm with finer mesh is adequate for ensuring accurate computation.
4. Results and discussion:

**Fig a:** Pressure drop with volume flow rate with $R_e$

**Fig b:** Variation of coefficient of discharge

**Figure 4.** Comparison between numerical and experimental results of (Fig. a) pressure drop with volume flow rate and (Fig. b) coefficient of discharge with Reymold’s number for single and multi-hole orifice plate.

**Fig c:** Pressure recovery (For $Q=2.091e^{-3}$ m$^3$/s)

**Fig d:** Variation of Velocity Profiles

**Figure 5.** Comparison of variation of pressure (Fig. c) and velocity (Fig. d) with number of holes for orifice with $t=1.5$mm, $\beta=0.6$.

At various flow rates pressure drops were calculated experimentally and by simulation for single and multi-hole orifice meter. Figure 4 (a) shows the graph of volumetric flow rate vs. pressure drop. The increase in pressure drop is observed with increase in flow rate, also as the number of holes increases pressure drop decreases. Figure 4 (b) shows coefficient discharge vs. Renold’s number. Over a wide range of Reynold’s number the higher coefficient of discharge is obtained for multi-hole orifice plate. The $C_d$ found out from the simulation is found to be greater than that from experimentation, since in simulation losses are not considered. Simulations results are 1% - 4% greater than experimental results.
Static pressure recovery and axial velocity profiles are given in figure 5 (c) and (d) respectively. Figure 5(c) shows that, as the water flows through the orifice meter the pressure decreases, reaching the minimum at vena-contracta and starts recovering, recovery is quicker for multiple hole orifice. This leads to a better turbulent mixing resulting in a faster recovery of flow for the multi-hole orifice as compared to the single-hole orifice. As seen in figure 4(d) as the flow approaches the throat of orifice meter there is an increase in the axial velocity is observed and reaches its maxima at 276.5 mm, beyond this point, the velocity decreases. Therefore we can conclude that it is possible to improve discharge coefficient of a single-hole orifice meter by distributing the flow area into multiple number of holes.

5. Conclusions:

Pressure drop and discharge coefficient has been studied experimentally and numerically for multi-hole orifices and compared with a generally used single hole orifice plate to measure flow. As the results of this study the following points are obtained. Performance characteristics of multi-hole orifice plates were observed to be better than a single hole orifice plate both in simulation and experimentation. The highest value of the coefficient of discharge i.e. 0.83 was obtained for 16 and 25 holes orifice plate and about 25 % greater compared with single hole orifice plate at an actual discharge of 2.09x10^{-3} m^3/s. Simulation results are greater than that found from experimentation because in the physical model the losses occurring due to friction inside the pipe, leakage, etc. which are not considered during simulation.

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