ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 4, April 2017

Discharge Coefficient Prediction for Multi hole Orifice Plate in a Turbulent Flow through Pipe: Experimental and Numerical Investigation

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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 tested. Orifices of interest for present study have an area ratio of 0.36, equivalent diameter ratio of 0.6 and number holes between 4 to 25. Discharge coefficients for flow through multi hole orifices are evaluated. Parameters investigated were hole numbers, orifice pressure drop, Reynolds number and effect of plate design. Computational fluid dynamics calculations (CFD) using the k-ε turbulence model to predict velocity fields, pressure loss and discharge coefficient around this device. Advantages gained by using multiple holes in an orifice plate instead of single hole are discussed. It is shown that number of holes, hole 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.**

Keywords: Multi hole orifice, Equivalent diameter ratio, Discharge coefficient, Reynold's Number

INTRODUCTION

Flow measurement is one of the most complex and demanding task 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 is 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 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 small flow area of each hole.

Tianyi Zhao et al.[2] investigated the key factors affecting multi-hole orifices throttle or flow control characteristics. Nine test plates were selected with various combinations of diameter ratio and different Orifice distribution density. Shanfang Huang et al. [3] presented the discharge coefficient of a perforated orifice, Twelve square-edged perforated orifices with n = 6 to 25, t = 3 and t/D is 0.1, 0.21, 0.31. Stefano Malavasi et al [4] has conducted two experimental campaigns to investigate the dissipation characteristics of multi-hole orifices under cavitation-free conditions. B. Laribi and M. Mehdi [5] presents a numerical experimentation on the perforated plate flow conditioner with a 90° double bend and a valve 50% closed. The simulation is done with air as fluid in 100 mm pipe diameter with Reynolds numbers 104, 105 and 106. D. Maynes G. J. Holt J. Blotter [6] experimentally investigated the loss coefficient and cavitation caused by water flow through perforated plates. Plates with n = 4 to 1800, beta ratio = 0.11 to 0.6, and t/d = 0.25 t0 0.33 were considered.

A literature review shows that a great deal of work has been done on the pressure drop characteristics of orifice plates in pipe flows. The performance characteristics of the multi hole orifice meter are not available in open literature. CFD has not been used by the earlier investigators to predict the performance of multi-hole orifice flow meter, but 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 Cd is primarily considered to be a function of aspect ratio (t/d), Equivalent diameter ratio (β = d/D) and Nature of flow defined using the pipe/hole Reynolds number (R_e).
The paper therefore addresses the problem of relating flow rate to pressure drop and the discharge coefficient prediction by experiments and numerical simulations through 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.

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The present paper is subdivided into three sections. The experimental setup is first presented. Numerical models are then detailed. The experimental data are presented and compared with numerical simulations in the last section

II. EXPERMENTAL ARRANGEMENT AND MEASUREMENTS:

The experiments were conducted to measure pressure drop across multi hole orifice plates at known flow rates. Water, the only fluid used was obtained from a collecting tank available in the laboratory. The multi hole orifice plates were flanged between two sections of 50 mm inner diameter GI pipe. The test section had a length of 30D upstream and 50D downstream of the orifice. Flange pressure taps used here were located 50 mm upstream and 25.4 mm downstream from the orifice plate. The pressure differences were measured by water- mercury manometers which could read accuracy of 0.05 cm. The discharges were measured volumetrically by means of the collecting tank. The experiments were conducted at room temperature. A systematic method was used in making the orifice plates so that a practical range of variables might be tested. Twenty square edged orifice plates were studied during this work. All holes were drilled on a vertical drill press with plates backed by wooden blocks to prevent excess burring. After drilling, the plates were drawn across No. 0 emery paper on a flat surface to knock off the burrs.

A strict set of test procedures was established to ensure the collection of repeatable and accurate data for each orifice plate. Whenever the orifice plate was changed, it was necessary ensure that air was removed from the system. This was accomplished by the help of knob providing for the purpose. Once the air was removed by this method, the system was run for approximately 15 minutes in the maintenance configuration. For each orifice plate, about seven to eight data points were taken corresponding to a pressure head across the orifice meter using mercury manometer. To get a good sample of the data, five to six runs were made independently on the same plate to check the consistency of the data. For all the orifice plates, the coefficient of discharge Cd was obtained and is given by the relation $Q = \frac{C_d A_o \sqrt{2gH}}{\sqrt{1-\beta^4}}$

Where Q is the Volume flow rate, m^3/s, C_d the Discharge coefficient, d the Orifice diameter in meter, D the Diameter of pipe, is the Equivalent diameter ratio $\sqrt{N\frac{A_o}{A_p}}$, H is the Pressure differential across the metering tap in meters of water.

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

Table I: 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			

III. NUMERICAL APPROACH

A. Computational model

Numerical investigation using the CFD code “Fluent” was implemented in the present work for multi hole orifice plate. The main objective is to minimize the pressure loss and maximize the discharge coefficient of the multi hole orifice plate. The computational domain was extended 15 D upstream and 20D downstream of the plate.Thedistance15D upstream the plate was used to ensure a fully developed flow at inlet during the simulation. Numerical simulation was performed by solving the standard k-ε model with enhanced wall treatment was used to model turbulence and simulate the near wall flow. Discretization was performed using the finite volume technique. The applied discretization schemes are second order scheme for pressure, SIMPLE scheme for pressure–velocity coupling and second order upwind scheme for momentum, kinetic energy (k) and turbulence dissipation rate (ε). Convergence was considered to be achieved when the residuals of mass, momentum and turbulence are less than 1x10-6.

B. Governing equations

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

Continuity : $\nabla.(\rho V) = 0$.

momentum:

$$\nabla.(\rho u\mathbf{V}) = -(\partial p/\partial x) + (\partial \tau_{xx}/\partial x) + (\partial \tau_{yx}/\partial y) + (\partial \tau_{zx}/\partial z) + \rho g$$

$$\rho v\mathbf{V}) = -(\partial p/\partial y) + (\partial \tau_{xy}/\partial x) + (\partial \tau_{zy}/\partial y) + (\partial \tau_{zx}/\partial z) + \rho g$$

$$\nabla.(\rho w\mathbf{V}) = -(\partial p/\partial z) + (\partial \tau_{xz}/\partial x) + (\partial \tau_{yz}/\partial y) + (\partial \tau_{zz}/\partial z) + \rho g$$

C. Boundary conditions

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

Table II: Boundary conditions

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

D. Grid independence study

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

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.1 and Fig.2. The mesh principal parameters are presented in Table III.

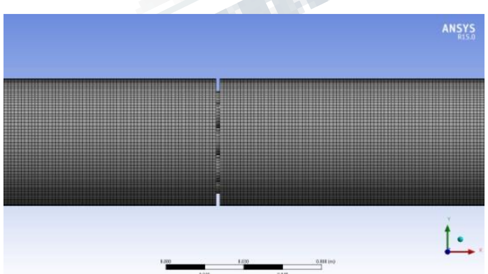

Fig.1 Discretized fluid domain for nine orifice holes model with 3D hexahedral mesh

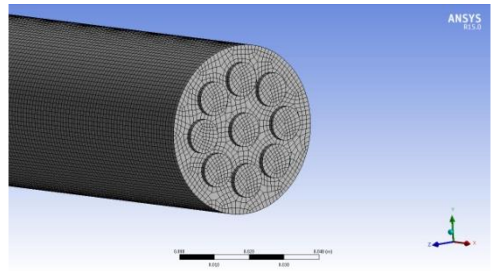

Fig.2. section plane detail of discretized fluid domain for Nine orifice holes model with 3D hexahedral mesh

Convergence study with k- ε model

Table III: The mesh principal parameters

Element size (mm)	Number of Elements	Number of nodes	Skewness	Aspect ratio	Orthogonal quality
1	1.6×10^6	166526	0.098	1.182	0.989
1.2	9.2×10^5	964627	0.108	1.207	0.989
1.3	7.5×10^5	792270	0.112	1.220	0.988
1.4	5.7×10^5	608990	0.117	1.215	0.987
1.5	4.5×10^5	484219	0.136	1.237	0.984

E. Validation

The validation of the CFD analysis has been done by comparing the CFD results with the results

Obtained by experiments for single hole orifice plate with mass flow rate of 2.091x10-3 m3/sec in terms of discharge coefficient and pressure drop. The validation results are presented in table IV.

Table IV: Validation results

Element size (mm)	Number of Elements	Pressure drop ΔP (Pa)		Coefficient of discharge C_d		Relative error %	
		Exp	Num	Exp	Num	ΔP	C_d
1	1.6×10^6	8528.81	9002.2	0.6682	0.6504	5.25	2.66
1.2	9.2×10^5		8862.85		0.6556	3.76	1.88
1.3	7.5×10^5		8602.7		0.6655	0.858	0.40
1.4	5.7×10^5		8829.35		0.6569	3.4	1.69
1.5	4.5×10^5		9181.2		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 ΔP is reasonably good. On the basis of this study a mesh size of 7.5×10^5 and element size of 1.3mm with finer mesh around the orifice plate is adequate for ensuring accurate computation.

IV. RESULTS AND DISCUSSION

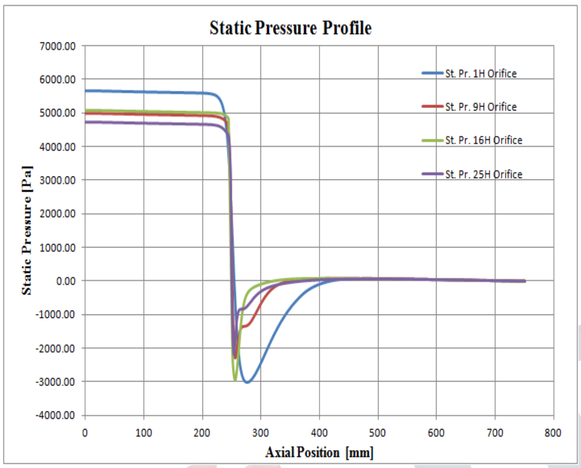

Fig. 3 Pressure plot (For Q =2.091e-3 m3/s)

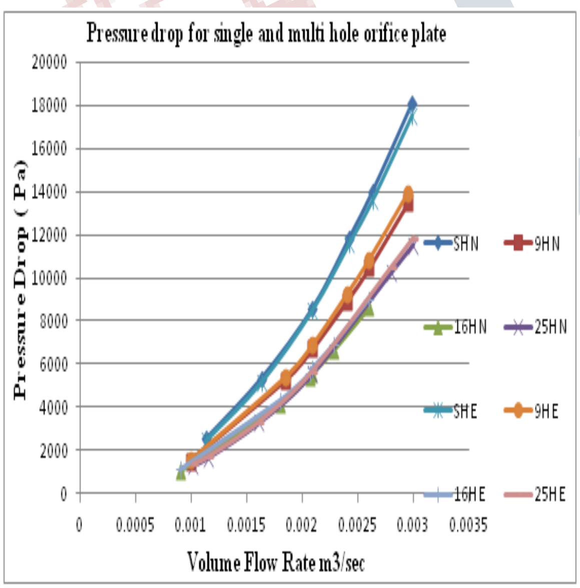

Fig.4 Variation of pressure drop with volume flow rate for single and multi hole orifice plate

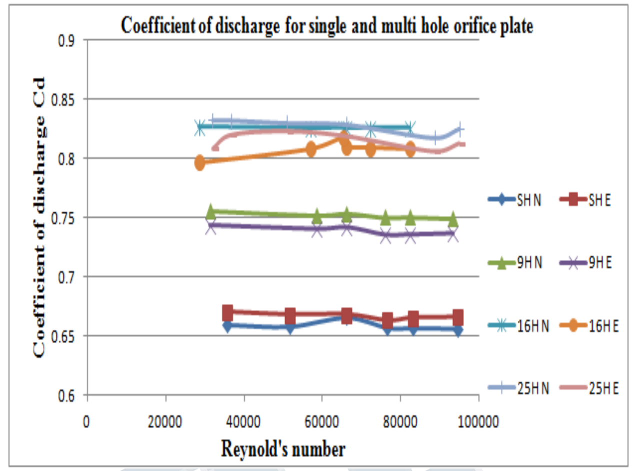

Fig.5 Variation of coefficient of discharge with Reynold's number for single and multi hole orifice plate

Pressure drops in single and multi hole orifice meter at various flow rate were calculated by experiments and simulation. Figure 4 shows graph of volumetric flow rate vs. pressure drop and Figure 5 shows graph of coefficient discharge vs. Renold's number. It can be seen that the pressure drop increases with increase in flow rate also as the number of hole increases pressure drop decreases. As observed from figure 5 that higher coefficient of discharge obtained for multi hole orifice plate. It can be seen that the Cd found out from simulation is greater than that found from experimentation. This is because losses are not considered in CFD. The Cd obtained through simulations is 1% - 4% greater than experimental Cd.

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V. CONCLUSIONS

In this analysis, multi hole orifices have been experimentally and numerically studied in terms of discharge coefficient and pressure drop and compared with a single hole orifice plate which is generally used in orifice meters to measure flow. The following points are obtained as the results of this study. Multi hole orifice plate has better performance characteristics than a single hole orifice plate. Through simulation and experimentation, the 25 holes orifice plate is found to be having the highest value of coefficient of discharge i.e. 0.82 with an actual discharge of 2.09x10-3 m3/s. Compared with single hole orifice plate, the coefficient of discharge of 25 holes orifice plate is 24.2% greater. The Cd found out from CFD is greater than that found from experimentation because of the losses occurring in the physical model due to friction inside the pipe, leakage, impurities present in the fluid, etc. which are not considered in CFD.

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