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A Review of Multi-Hole Orifice Plate

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Abstract: Orifice metre in simplest form is a hole in plate which is introduce in flow to determine discharge of flow. The orifice metre is the cheapest and simplest method to carryout flow analysis. However, this process has major drawback of energy transmutation phenomenon; which is accompanied by various losses. In order to wrest these drawbacks; instead of single hole Multi-hole orifice is preferred. The paper aims on review of several annals in the field of flow measuring techniques aided by Multi-hole orifice plate. The paper elaborates analysis of various flow parameters associated with Multi-hole orifice plate and their physical existence in the flow; also, how this method is efficient than conventional method. Various analysis method such as CFD, finite elemental methods, numerical methods and experimental methods are elaborated in this paper suggesting efficient functioning of Multi-hole orifice plate. The future prospects in the respective field through exploration of the developments in its applications and research this far are also discussed.
Keywords: Multi-hole orifice plate, CFD analysis, Flow Simulations, Finite Element Modelling, Experimental Modelling, Flow Analysis, Vortex Elimination, Numerical Solutions to Fluid Parameters.

I. INTRODUCTION

The flow measuring technics completely rely on the energy transmutation phenomenon where flow parameters are analysed with regard to energy transmuted. This is done by perceiving change in particular flow factor depending on energy transmutation i.e. velocity, pressure etc. Till date all flow measuring technics are govern by above stated phenomenon. Conventional technics are associated with various losses such as eddy formation, separation, cavitation, friction losses etc. Stated losses can't be entirely eliminated however can be minimised up to certain extent. In such an attempt single holed orifice plate have been modified into Multi hole and the resulted study is highlighted by Shanfang Huang et al. [10].

A Multi-hole orifice plate is a plate with multiple holes, whose number of holes and hole's diameters varies depending on the desired flow rate and pressure drop through the system. Multi-hole orifice has peculiar characteristics which makes it exclusively desired for complex flow analysis where the cost is compromised and the outcomes are expected to be near accurate. The accuracy of the orifice plate depends on the loss occurred in the velocity transaction of the pressure energy of the flow across the notch. This causes the reduction in the area of the flow gradually with the flow axis which results in the formation of the 'Vena-Contracta'. The pressure drop at this point viz. 'Vena-Contracta' is measured and compared with the pressure characteristics with the upstream pressure, this results in determination of the pressure difference head which is used to find the flow velocity. This velocity is then used to determine the discharge, however this velocity determined is associated with a coefficient which differentiates the practical flow velocity with actual. It is called 'Coefficient of Discharge', this constant covers up the cumulative effect of various effects associated with the flow losses. Higher the value of this number, more are the losses present in the flow. Thus it is aimed to keep this number as low as possible. The multi-hole orifice meter dominates the conventional orifice in this regard. There are various theories, numerical analysis and experimental conclusions which prove this eminent factor of the multi-hole orifice.

Various theories are proposed to support the noteworthy characteristics, but the finite element methods are proven to be the most near practical if compared to the experimental methods. The computational simulations defined with most possible practical boundary conditions helped to visualize the effects on the flow. This simulation technique still can't compute the 'Coefficient of Discharge', but helps to visualize the changes in the flow across the orifice which in turn throws light in which direction the analysis has to be carried out, to get most probable results. The plots of various flow parameters indicated change in pressure characteristics with respect to flow axis, where, across the plate the characteristics have quite notable changes useful for further analysis as studied by V.K. Singh and T. John Tharakan [1]. The major drawback which clings the widespread use of orifice plate is the cavitation. The cavitation causes irrecoverable pressure loss which is reflected as the 'Frictional Loss' when tried to balance against 'Bernoulli's equation'. The cavitation is resulted due sudden drop in flow pressure below vapour pressure, thus the flow medium evaporates and results in cavitation. In multi-hole orifice plate, the cavitation is minimized due to divided energy transmutation. The coefficient of discharge is theoretically determined by finite element method where the cumulative effect of cavitation along with other factors considered. The effect of sharpness of orifice edges also has a vital role on the flow parameters as given by G.J. Holt et al. [2].

As the finite element method completely relies on the theoretical assumptions stated, which define the variation in the flow parameters lack the practical touch. Practically various factors such as flow temperature, gravitational effects, pipe losses, inertial forces et cetra cause changes in the actual flow parameters variation. As the principal focus of the experiment is to minimize the 'Coefficient of Discharge', the effect of other factors is considered cumulatively reflected on the coefficient itself. It is fair to assume the effect of these external factors reflected under single constant which in turn delivers the actual output result. However, for practical insight statistical analysis of many readings is required which also indicates an asymptotic result that multi-hole orifice are efficient than single holed.

II. NOMENCLATURE

ρ = Flow Density
t = Time
k = Turbulent Kinetic Energy
ε = Turbulent Kinetic Energy Dissipation Rate
$C_{\delta 1}$, σ_k, $C_{\delta 2}$, σ_e = k-ε Turbulence Modelling Constants
P_k = Turbulence Production Due to Viscous and Buoyance Force
μ_t = Turbulence Viscosity
C_μ = Turbulent Viscosity Constant
u^+ = Near Wall Velocity
u_τ = Friction Velocity
U_t = Velocity Tangent to the Wall at Distance Δy From Wall
y^+ = Dimensionless Distance From Wall
τ_w = Wall Shear Stress
κ = Von Karaman Constant
C = Log Layer Constant Depending on Wall Roughness
s_i = Incipient Cavitation Number
s_c = Critical Cavitation Number
C_d = Discharge Coefficient
K_{LP} = Loss Coefficient Based On Average Pipe Velocity
β = Constriction Ratio = $\sqrt{\frac{Area\ of\ multiple\ Holes}{Area\ of\ Pipe}}$
R_{ed} = Reynolds Number as Function of Diameter
d_h = d = Orifice Diameter
t = Orifice Thickness
D = Pipe Diameter
φ = % Uncertainity
k = Loss Coefficient
k_n= Non Dimensional Loss Coefficient
n_h = n = Number of Holes

III. LITERATURE REVIEW

A. Flow SimSulations

V.K. Singh and T. John Tharakan [1] carried out the computational fluid dynamic simulations for single and multi-hole orifice meter over a wide range of Reynolds numbers. They have determined pressure recovery pattern for these orifices and used it for the estimation of discharge coefficient. It has been identified that pressure recovery for multi-hole orifice meters is larger than that of single-hole orifice flow meter with an equivalent flow area. They investigate higher-pressure recovery for multi -hole orifices can be attributed to smaller size of eddies generated immediately downstream of the orifices. The discharge coefficient of multi-hole orifices is larger than that of single-hole orifice over a wide range of Reynolds numbers. The measurement accuracy is also expected to be higher for multi-hole orifice meter as the velocity at the exit of the orifice is more uniform. The governing equations for the orifice can be stated as:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0$$

Momentum equation:

$$\frac{\partial(\rho U)}{\partial t} + \nabla(\rho U x U) = \nabla.(\rho\delta + \mu(\nabla U + (\nabla U)^T))$$

For k-ε turbulence modelling following are the governing equations:

$$\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho U k) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla.(\rho U\varepsilon) = \nabla\left[\left(\mu + \frac{\mu_f}{\sigma_e}\right)\nabla\varepsilon\right] + \frac{\varepsilon}{k}(C_{\delta 1}P_k - C_{\delta 2}\rho\varepsilon) + P_{kb}$$

'P_k' is modelled as:

$$P_k = \mu_t \nabla U.(\nabla U + (\nabla U)^T) - \frac{2}{3}\nabla.U(3\mu_t \nabla.U + \rho k)$$

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$

Water at ambient temperature (300K) was used as working fluid. CFD simulations were carried out for a wide range of Reynolds numbers from 500 to 20000. Static pressure at inlet of the pipe and mass flow rate at outlet of the pipe were used as boundary conditions. The value of pressure at inlet and mass flow rate at outlet specified for the simulation at various Reynolds numbers are given in table. Symmetric boundary condition was applied at both the symmetric planes of the one -eighth of the pipe. No slip boundary condition was applied at the wall of the pipe and regions proximate to the wall were modelled using the log-law of the wall. The log-law of the wall is an extension to the method of Launder and Spalding (1974). In the log-law region, the near wall tangential velocity is related to the wall - shear stress by means of the following logarithmic relation:

$$u^+ = \frac{U_T}{u_\tau} = \frac{1}{\kappa}\ln(y^+) + C$$

Where,

$$y^+ = \frac{(\rho \Delta y \mu_\tau)}{\mu}$$

$$\mu_\tau = \left(\frac{\tau_w}{\rho}\right)^{\frac{1}{2}}$$

TABLE I

Boundary conditions used for CFD simulation at different reynolds number.

Sr. No.	Re	Pressure at inlet (bar)	Mass flow rate at outlet (kg/s)
1	500	10	0.44
2	1500	10	1.33
3	2500	25	2.22
4	3000	25	2.67
5	4000	25	3.56
6	6000	50	5.34
7	8000	100	7.12
8	10000	200	8.90
9	12000	200	10.68
10	14000	200	12.46
11	16000	450	14.24
12	20000	450	17.80

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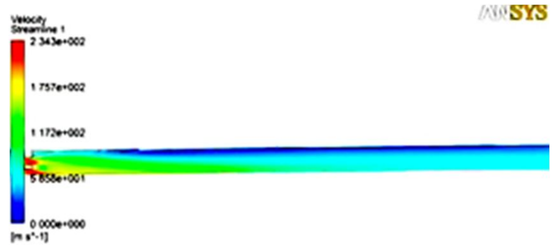


Fig.1 Velocity Streamline Downstream of Multi Hole Orifice

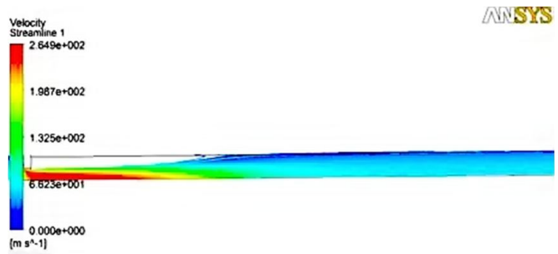


Fig.2 Velocity Streamline Downstream of Single Hole Orifice

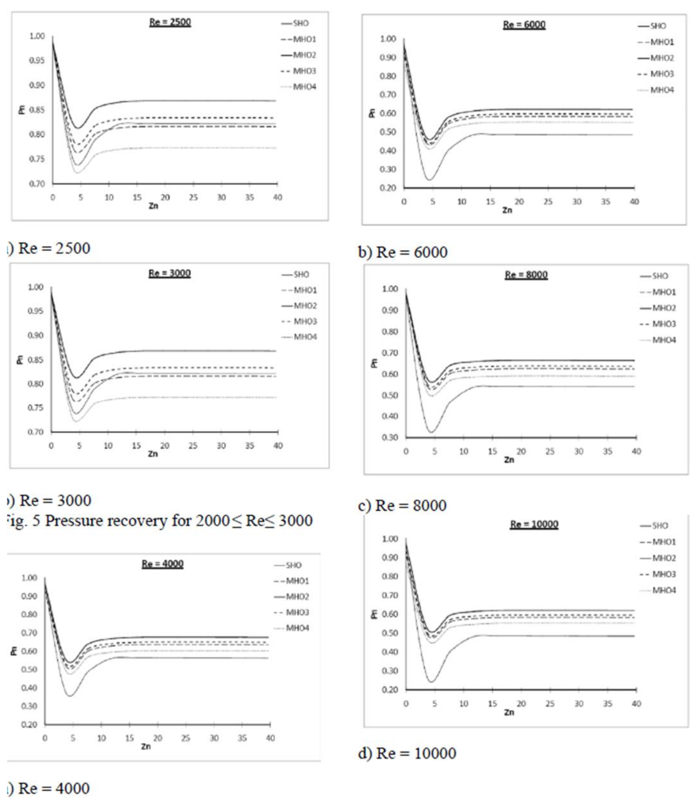


Fig. 3 Comparison of Discharge Coefficients for Single-Hole and Multi-Hole Orifices

B. Cavitation at sharp-edge

G.J. Holt et al. [2] reveal the dependence of multi holed baffle plates on both showed that the thickness to diameter ratio and total through area ratio. A model for predicting the loss coefficient in terms of these variables were also presented by them. They determined, cavitation inception is dependent upon the loss coefficient, thickness to baffle-hole diameter ratio, and through area ratio. They concluded with increased through area ratio the cavitation number at incipient cavitation increases as well as with regards to the thickness to diameter ratio, the cavitation number at incipient cavitation exhibited a local maximum around $0.5 < t/d < 1.0$. Models to allow prediction of the point of cavitation inception and the point where critical cavitation begins were presented.

$S_i = -944C_d^4 + 1375C_d^3 - 663C_d^2 + 136C_d - 5.7$

$S_c = -685C_d^4 + 1026C_d^3 - 449C_d^2 + 102C_d - 4.3$

$C_d = \frac{1}{\sqrt{K+1}}$

$K_{LP} = (2.69 - 3.79F + 1.19F^2)\, K_{LP} \quad F < 0.9$

$\quad\quad (0.876 + 0.069F)\, K_{LP} \quad F \geq 0.9$

$F = (\frac{t}{d})*(A_H / A_P)^{1/5}$

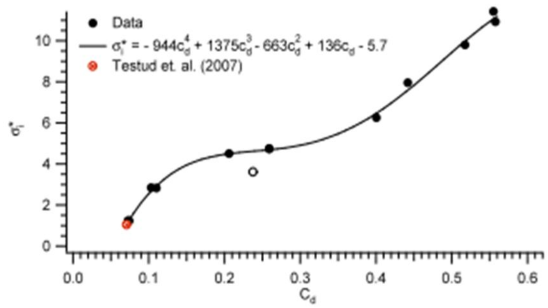


Fig.4 The Critical Cavitation Number with Size Scale Effects against The Discharge Coefficient

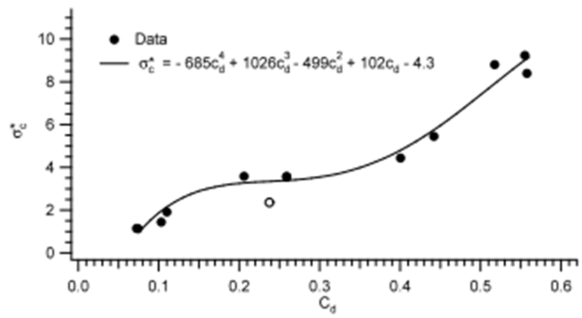


Fig.5 The Incipient Cavitation Number with Size Scale Effects against The Discharge Coefficient

C. Pressure Loss Characteristics

One of the objectives of work was to establish a technique for predicting the pressure loss through orifice plates and perforated plates and other duct fittings. Guohui Gan and Saffa B. Riffat's [3] study has shown that CFD can be used to predict the pressure loss coefficient for these types of plates and that in making this prediction the geometry of holes for a perforated plate can be simplified. The practical applications of CFD include the effect of thickness, free- area ratio and cross- sectional area of an orifice plate on the pressure loss as well as flow and pressure interactions between a plate and components upstream and downstream of the plate.

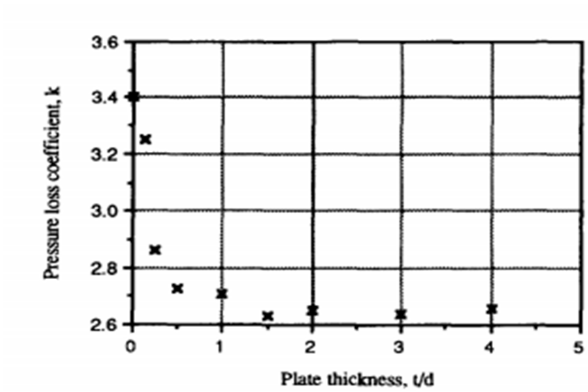


Fig.6 Effects of Reynolds Number on the Measured Pressure Loss Coefficient for The Orifice Plate

D. Design Methodology for Multi-hole Orifice Plate

Tianyi Zhao et al. [4] introduced a MO structural design methodology and implemented it experimentally. First, the MO structures were quantified through the geometric architecture. Then, their experiments were used to simplify and further develop the correlation between MO geometric features and ξ. The final ξ model is highly accurate, indicating that the methodology used here is effective. They found that ξ values of MOs are generally higher for MOs with fewer perforated holes. They worked on orifice arrangement of MOs can be expressed by three key parameters: the total orifice number, n; the equivalent diameter ratio, EDR; and the distribution density, Dd. EDR has a dominant influence on the MO ξ value compared with the other two parameters. The design methodology and test procedure presented in their work allow for the simplification of the structural design of MOs. Zhao and his team also provide a good reference for further studies of MO throttle characteristics in two-phase flow systems.

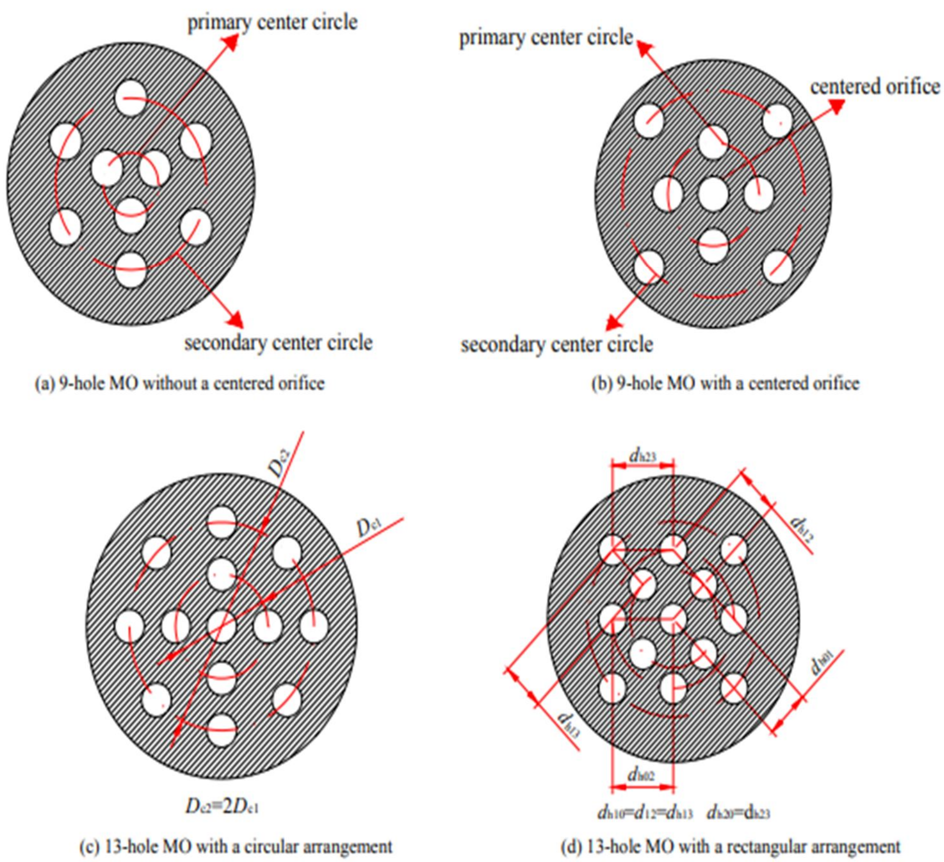


Fig. 7 Description of The Orifice Arrangement

E. Experimental Investigation of Multi-hole orifice-plate

Gajendra Kumar et al. [5] suggested multi-hole orifice-meter is a better candidate from the perspective of the less pumping power requirement compared to single holed orifice-meter. They found out generally, for single holed orifice-meter, *D-D/2* tapings are considered as pressure measurement locations. However, number of the holes and tap locations play significant role on the coefficient of discharge of multi-hole orifice-meter. Hence, the present study explores the sensitivity of downstream pressure tap on the performance of multi-hole orifice-meter under fully developed flow conditions. The multi-hole orifice-meter design is varied by varying the number of holes and their positions. The locations of downstream static pressure at different tap positions (*D/4, D/2, 3D/4, 1D, 5D/4, 3D/2, 7D/4, 2D*) are evaluated in comparison with the conventional single hole orifice-meter. Irrecoverable pressure loss coefficient is also computed based on the pressure loss across the multi-hole orifice. Following are the conclusions that may be drawn from the present study. The coefficient of discharge (C_d) is independent of the flow's Reynolds number in the range studied under fully developed flow. Best downstream tap location is at 2*D* for all the multi-hole orifice-meter configurations covered in this study. Nine holes multiple orifice-meter with upstream chamfering results in high coefficient of discharge of 1.077 and low irrecoverable loss coefficient of 10.823.

Table ii
Configurations of the orifice with a β ratio of 0.52 covered in this study.

Sr. No.	No. of Holes	Chamfering	Diameter of the Holes (mm)	Downstream Tap for an Upstream tap at D	Reynolds Number Range
1	4	No	26.26mm	D/4, D/2, 3D/4, D, 5D/4, 3D/2, 7D/4 and 2D	2.0×10^4 2.8×10^5
2	9	No	16.5 - 8 peripheral holes 24.5mm – Central hole	D/4, D/2, 3D/4, D, 5D/4, 3D/2, 7D/4 and 2D	2.3×10^4 3.6×10^5
3	9	Downstream	16.5 - 8 peripheral holes 24.5mm – Central hole	D/4, D/2, 3D/4, D, 5D/4, 3D/2, 7D/4 and 2D	2.0×10^4 3.11×10^5
4	9	Upstream	16.5 - 8 peripheral holes 24.5mm – Central hole	D/4, D/2, 3D/4, D, 5D/4, 3D/2, 7D/4 and 2D	2.5×10^4 4.04×10^5
5	9	Both sides	16.5 - 8 peripheral holes 24.5mm – Central hole	D/4, D/2, 3D/4, D, 5D/4, 3D/2, 7D/4 and 2D	2.5×10^4 3.5×10^5

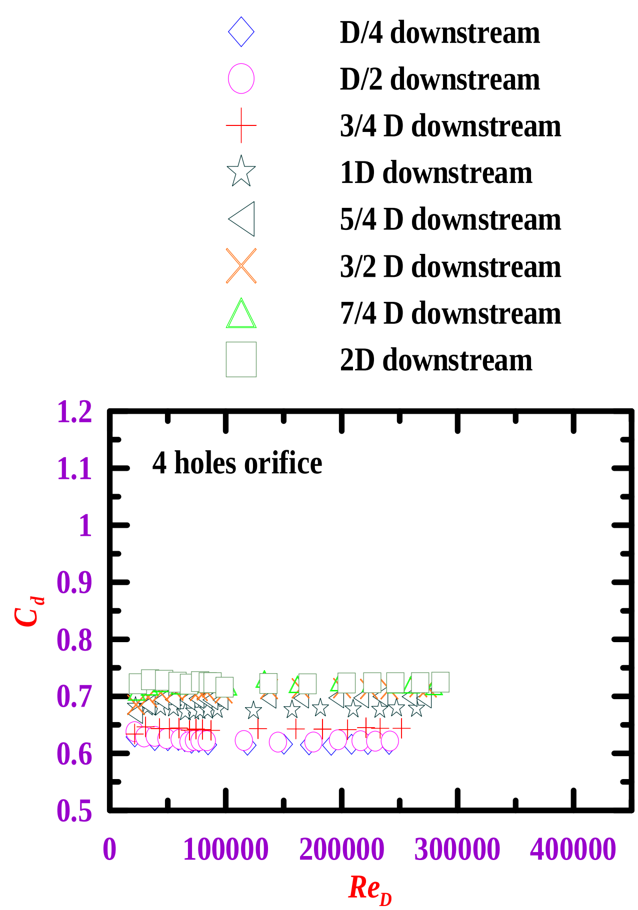


Fig. 8 Variation of Coefficient of Discharge with Reynolds Number for Four Holes Orifice without Chamfering

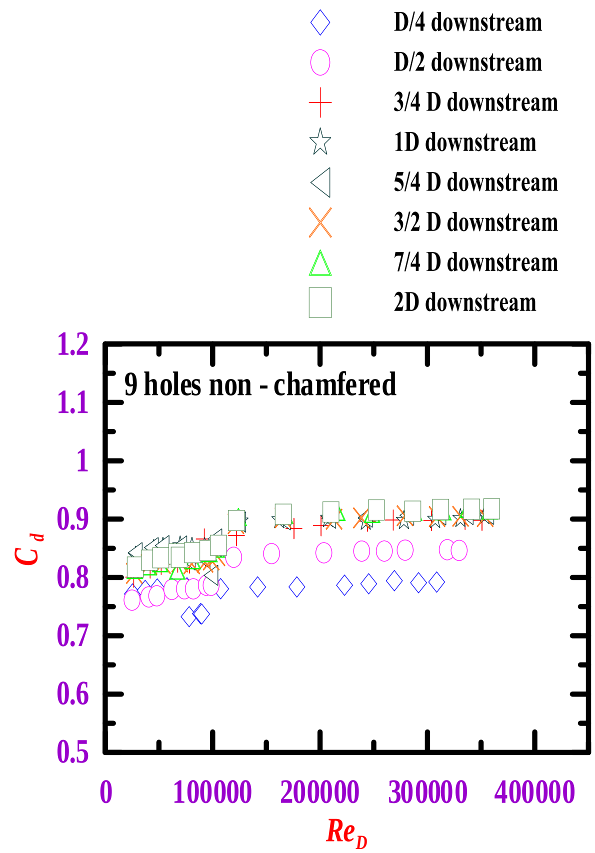


Fig. 9 Variation of Coefficient of Discharge with Reynolds Number for Nine Holes Orifice without Chamfering

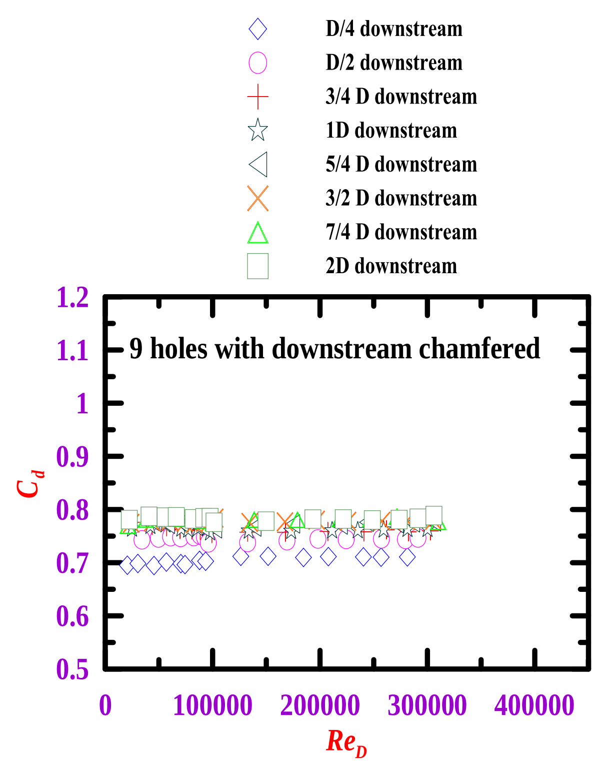


Fig. 10 Variation of Coefficient of Discharge with Reynolds Number for Nine Holes Orifice with Downstream Chamfering

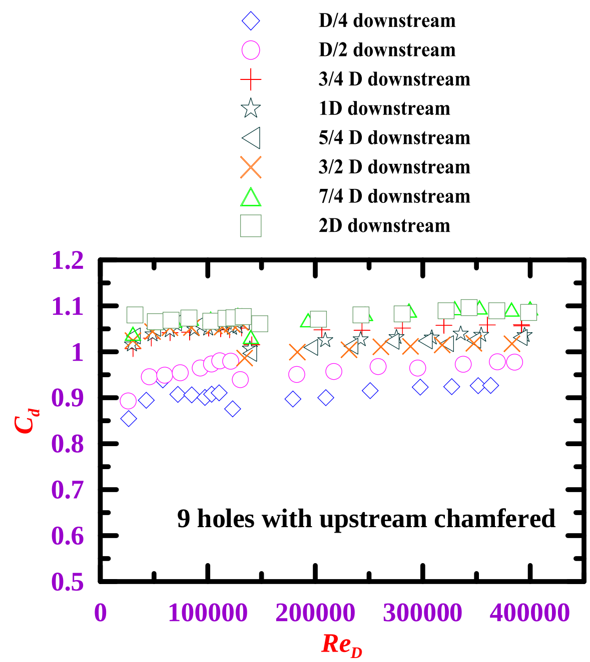


Fig. 11 Variation of Coefficient of Discharge with Reynolds Number for Nine Holes Orifice with Upstream Chamfering

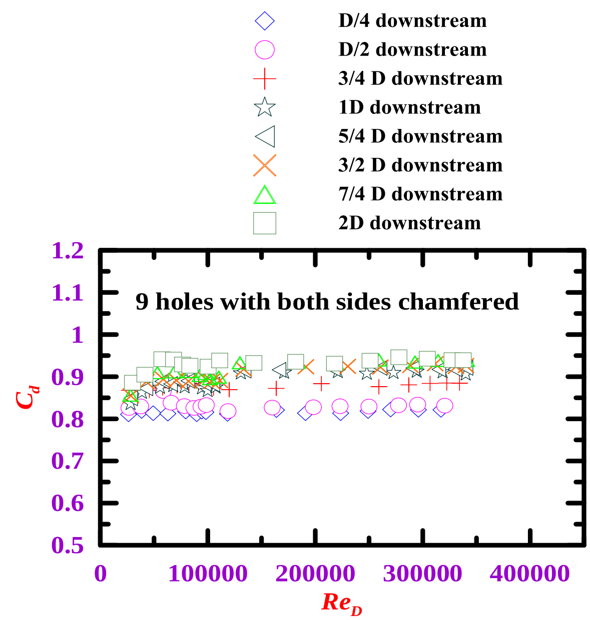


Fig. 12 Variation of Coefficient of Discharge with Reynolds Number for Nine Holes Orifice with Both side Chamfering

F. Head Loss Characteristics

L. J. Webber et al. [6] elaborated the application of Idelchik's thin-screen head loss correlation in conjunction with Miller's t/d correction was found to be the best estimator for head loss coefficient. The comparison between the head loss coefficients predicted by this method and the values determined experimentally for perforated plates and flat bar screens is illustrated in table below. The regression is questionable because of two major reasons:

1) The trend of the curves theoretically and practically obtained differs because of variation of coefficient of contraction getting progressively smaller for large holed number plates.

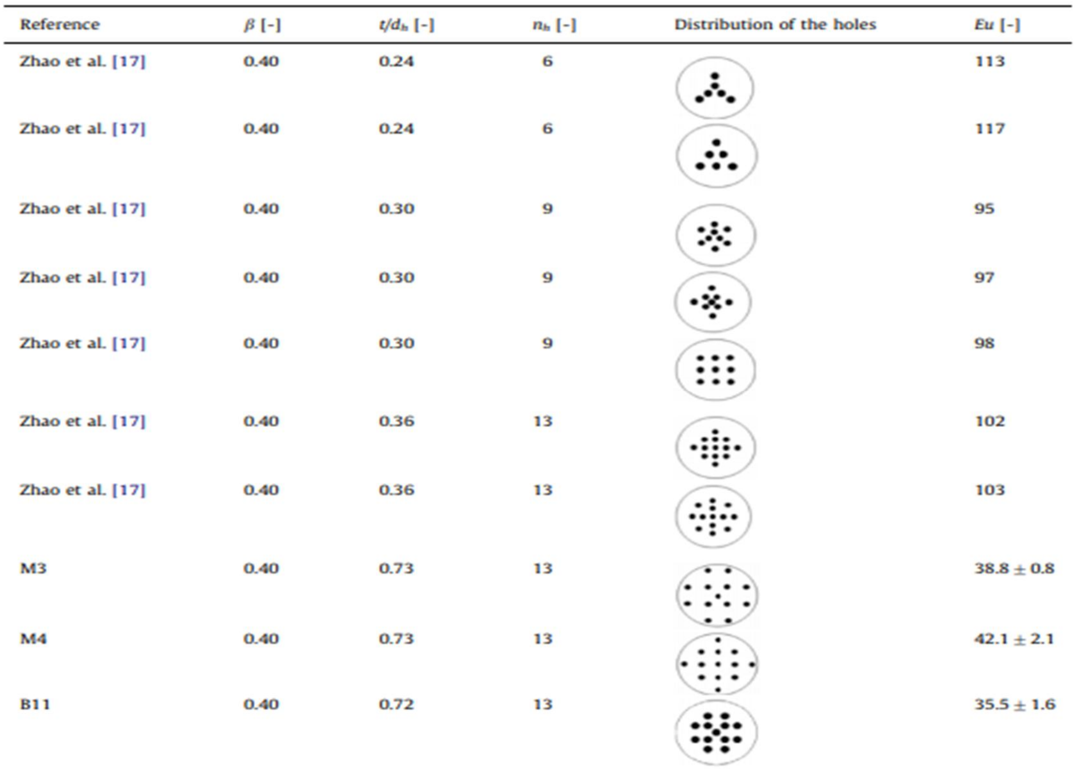
2) The variation existing in the interpolation of further curves due to the lack cumulative effect of coefficients.

Table III
Comparison of predictions with measurements.

Screen Type	φ	t/D	Measured k	k	k_n=k/k'	Predicted k	% Error
Perforated Plate	10.1	0.64	98	241	0.58	140	43
	15.9	0.64	43.5	87.7	0.66	57.9	33
	22.7	0.48	18.9	37.7	0.77	29.1	54
	32.6	0.32	10.2	14.8	0.84	12.44	22
	51	0.32	3.01	3.73	0.91	3.39	13
	50	0.5	2.2	4.00	0.85	3.4	55
	6.1	2.72	217	709	*	*	*
	7.3	2.34	169	485	*	*	*
	12.2	1.27	50.1	159	*	*	*
	18.4	0.78	24	62.5	0.62	38.8	61
1" Flat Bar Screen	23.9	0.59	14.7	33.2	0.72	23.9	63
	32.2	0.39	8.91	15.3	0.81	12.4	39
	40.6	0.27	5.83	7.87	0.87	6.85	17
	48.6	0.19	3.75	4.32	0.94	4.06	8
	58.1	0.12	2.25	2.28	0.97	2.21	-2
	73.9	0.06	0.821	0.71	0.99	0.7	-15
	6.1	0.94	234	709	0.53	376	61
	15.3	0.34	61.0	95.8	0.78	74.7	23
	24.5	0.19	22.6	31.2	0.91	28.4	26
3" Flat Bar Screen	33.7	0.12	12.3	13.5	0.93	12.56	2
	42.8	0.08	6.41	6.69	0.96	6.42	0
	52	0.06	3.68	3.48	0.98	3.41	-7
	61.2	0.04	2.06	1.83	0.99	1.81	-12
	70.4	0.02	1.15	0.93	1.00	0.93	-19

G. Pressure losses through perforated plates

The pressure loss coefficient is independent of the Reynolds number as long as this parameter stays in the self-similarity range. For lower values of the Reynolds number, the pressure loss coefficient can either increase or decrease with the Reynolds number. The lower limit of the self-similarity range depends on the geometry of the plate but not on the testing pressure, unlike the upper one. A reduction of the equivalent diameter ratio – this being, as well known, the dominant parameter affecting the pressure losses – causes the pressure loss coefficient to increase, and the effect of the other parameters to get more relevant. However, the general behaviour of all collected data seems quite homogeneous; in particular, the shape of the pipe section (circular/ rectangular) does not have significant influence on the value of pressure loss. The relative thickness has noticeable effect on the pressure loss coefficient. The modification of the behaviour of the jets causes the pressure loss coefficient to globally decrease as the relative thickness increases, if all other significant parameters are kept constant. The dependence of the pressure loss coefficient upon the relative thickness is often non-monotonic, probably due to flow instabilities. Number and disposition of the holes influence the pressure losses. The analysis of comparable data revealed that in most cases the pressure loss coefficient decreases if the number of holes increases, due to a reduction of the size of the recirculation zones between the holes. Such behaviour is however dependent upon the disposition of the holes. The effect of the distribution of the holes, the number of holes being the same, seems to be instead minor. The gross dependence of the pressure loss coefficient upon the equivalent diameter ratio is well caught by all the considered formulas as studied by Stefano Malavasi et al. [7]. However, he suggested at a more detailed scale, they appear to be inadequate to describe all the characteristics of the phenomenon. Only the overall trend of the pressure loss coefficient as a function of the relative thickness is generally quite well represented by the equations proposed by Idelcick, Miller, ESDU, and Holt et al., which takes into account only the effect of equivalent diameter ratio and relative thickness. It is worth mentioning as all these equations appear to partially fail their prediction skill, especially at low b and relative thickness values, if the number and the disposition of the holes became more significant. The pressure losses of perforated plates appear to be lower than those of a standard single-hole ISO 5167-2 orifice with the same equivalent diameter ratio. Therefore, an upper limit to the pressure loss coefficient of multi-hole orifices with a certain equivalent diameter ratio may be estimated.



Reference	β [-]	t/d_h [-]	n_h [-]	Distribution of the holes	Eu [-]
Zhao et al. [17]	0.40	0.24	6		113
Zhao et al. [17]	0.40	0.24	6		117
Zhao et al. [17]	0.40	0.30	9		95
Zhao et al. [17]	0.40	0.30	9		97
Zhao et al. [17]	0.40	0.30	9		98
Zhao et al. [17]	0.40	0.36	13		102
Zhao et al. [17]	0.40	0.36	13		103
M3	0.40	0.73	13		38.8 ± 0.8
M4	0.40	0.73	13		42.1 ± 2.1
B11	0.40	0.72	13		35.5 ± 1.6

Fig. 13 Effects of the distribution of the holes upon the pressure loss coefficient.

H. Effects Of Cavitation And Plate Thickness On Small Diameter Ratio Orifice Meters

Orifice plates with small diameter ratios were tested to determine the effect of plate thickness and cavitation on orifice meter discharge coefficient experimented by B.-C. Kim et al. [8]. The inception of cavitation as measured by the following three methods was in agreement: 1. an increase in the spectrum from a hydrophone downstream of the orifice meter 2. An increase in noise from a sound level meter external to the orifice meter 3. A cavitation number between 1.0 and 1.2. Cavitation affected the Cd results of only one meter with a b = 0.10 and a plate thickness of 7.0 mm. In that case, the Cd dramatically increased at Re = 14 000. The same meter was unaffected by cavitation for thinner plates with a thickness of 4.0 and 5.5 mm. Otherwise, the effect of plate thickness on meter discharge coefficient was not conclusive. For the b = 0.33 plate, the plate was thicker than allowed by A. G. A. 3 but was within ISO 5167 thickness specifications, and it did not have a downstream bevel as required by the standards. However, the Cd results were in agreement with the ISO 5167 equation and its uncertainty. In the case of the b = 0.15 plate, the results for plate of 2 different thickness were in agreement but were higher than the ISO 5167 equation by 3.3%. Results did differ systematically for 3 plates of different thickness for b = 0.10; however, the results for the thickest plate were between the other two with the Cd being largest for the intermediate plate (5.5 mm). According to A. G. A. Report No. 3, the uncertainty in Cd for small bore plates can be as high as 3%. Most of the uncertainty is attributed to edge sharpness. In the future, several plates (at least three) should be tested with the same bore size and plate thickness to determine the accuracy and reproducibility of the machining on the results. Those results should then be compared to plates of different thickness. In any case, these experiments do demonstrate that Cd is unaffected by cavitation for plates with a b = 0.10, 0.15, and 0.33 and plate thickness of 0.55 $ t/d and over the Reynolds number range reported here.

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IV. CONCLUSION

The presented review article summarises the application of different aspects of multi-hole orifice & flow measuring techniques adopted in the analysis of flow parameters. The article also elaborates about the optimised orifice parameters for different flow types and parameters. It also covers the comparisons between the results obtained from the different techniques for same flow input parameters. From this review, it is evidently indicated that use of multi-hole orifice results in achieving the substantial improvement in the coefficient of discharge and eventually results in a reduction in total losses in flow measuring parameters by selecting an optimal set of design and the operating parameters for the multi-hole orifice operation. The flow measurement techniques used the range of various flow parameters for the objective of study, therefore by selecting specific configuration and methodology corresponding optimum results can be obtained. From this article, it is observed that in comparison of the single holed orifice to the multi-hole orifice, the latter yields efficient results if incorporated in the flow measuring.

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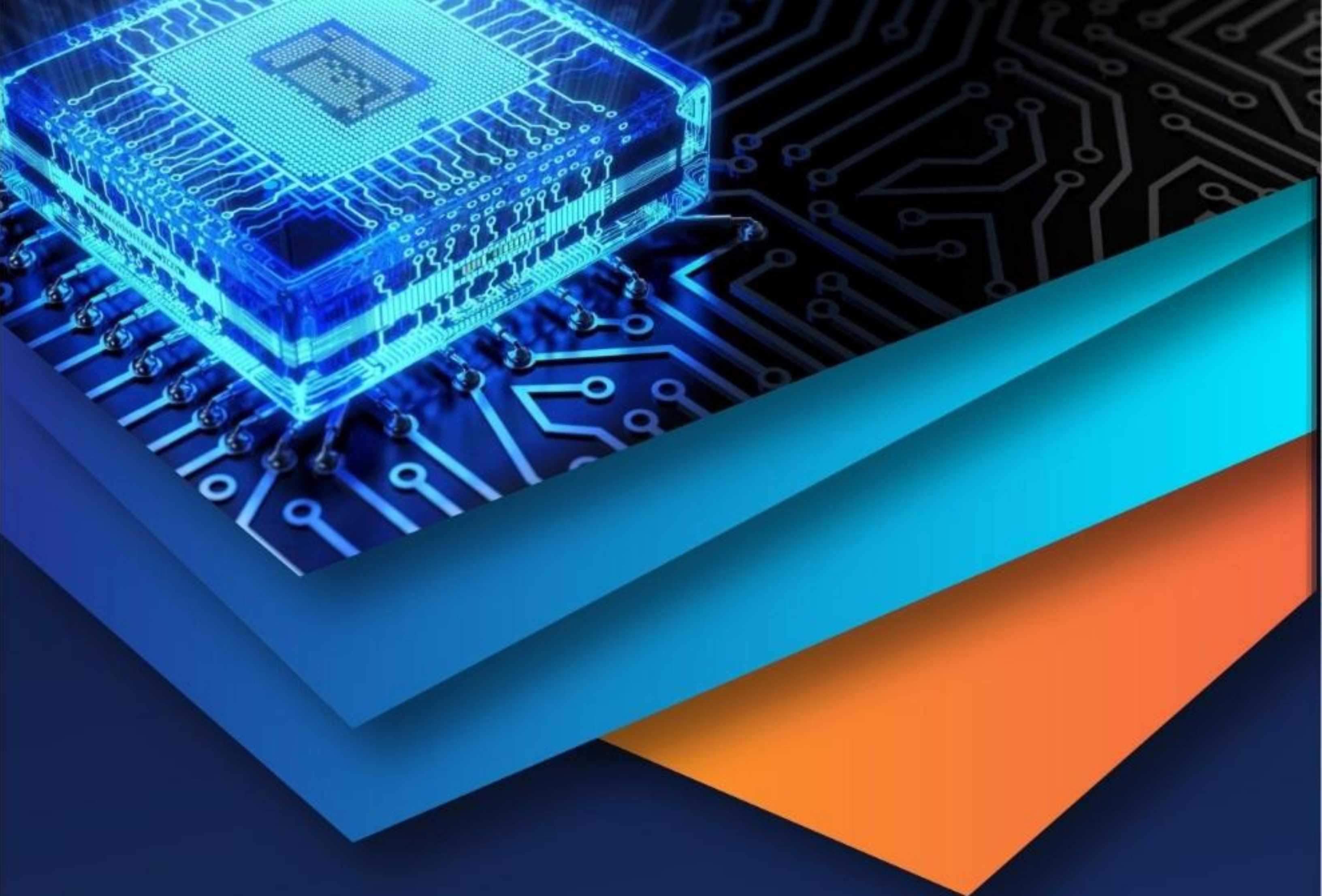

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