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Numerical Analysis of Newtonian Fluid Flow Through Multi-Hole Orifice Meter

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Abstract **-** The influence of multi-hole orifice flow meter geometry parameters on the parameters of Newtonian fluid through multi-hole orifice meters was investigated using computational fluid dynamics as well as the effect of contamination in front of the MHO flow meter. The air flow was steady, three-dimensional, and turbulent. Analysed Newtonian fluid was air and physical properties that were considered were density and dynamic viscosity. The numerical method was finite volume method, and standard k-ε turbulence model was used for turbulence modelling. Multi-hole orifice meter with three different β parameters 0.55, 0.6 and 0.7, was observed and Reynold's number was 10^5. The pressure drop and discharge coefficient were analysed. Numerical simulations were performed using commercial software the STAR-CCM+ 2019.2. It was found that increase in β parameter results with the decrease in pressure drop and increase in discharge coefficient. Also, it was found that that the influence of β parameter is much higher when analyzing pressure drop rather than discharge coefficient values. Numerical simulations were also performed to investigate the effect of contaminations in front of the MHO plate with $\beta = 0.5$, on the discharge coefficients. It was found that as the contamination angle is increased the discharge coefficient tends to increase.

***Keywords*:** multi-hole orifice meter, β parameter, contamination, CFD, turbulence, pressure drop, discharge coefficient

1. Introduction

Orifice meters, which are known for their simplicity, affordability and reliability have been used for many years in many industries to measure the flow of various fluids. Multi-hole orifices (MHO) are also extensively used in a variety of refrigeration technology applications such as electrical expansion valves, integrated evaporator condenser and in implementation of two-stage MHOs in certain refrigeration systems. They work on the principle of measuring differential pressure, i.e., pressure drop, where the pressure drop is linear and directly proportional to the volume or mass flow of fluid. They are characterized by an opening that is perpendicular to the fluid flow, while the pressure gauges are located at certain distances upstream and downstream from the measuring aperture. Single-hole orifices are most commonly used, because there is still no specific standard for multi-hole orifice meters, therefore any research regarding multi-hole orifice flow meter is of great importance.

Extensive experimental and numerical studies of single and multi-hole orifices have been conducted to provide insight into the fluid flow characteristics through them. The authors [1-5] used numerical simulations (CFD) to predict the flow through conventional single-hole orifice meters. Durst and Wang [6] found a good correlation between the calculations obtained using the k-ε turbulent model and the experimental measurements. The authors [7, 8] determined the influence of Reynolds number, β parameter, pipe surface roughness and boundary conditions of upstream and downstream flow on the properties of the orifice meter. Naveenji et al. [9] investigated the variation in the discharge coefficient for the flow of a Newtonian fluid, at different values of the β parameter.

When it comes to numerical analysis of MHOs several research studies were conducted as well. Moosa and Hekmat [10] examined numerically the performance of three different designs of MHOs developed by Singh and Tharakan [11], Shaaban [12] and Huang et al. [13] as well as the standard SHO. They found that the Singh's model has the best performance among them in which the highest discharge coefficient is observed. They also found that the MHO is less sensitive to upstream disturbances compared to the standard SHO. Tomaszewski et al. [14] performed experimental and numerical study on several 6-hole orifices with different equivalent diameter ratios to investigate the relationship between the mass flow and the pressure loss coefficient.

In this research the authors investigated the variation in the discharge coefficient for the flow of a Newtonian fluid for MHO flow meter with 1 central opening and 8 additional smaller opening distributed around the circle for 3 different values of β parameter. Also, numerical simulations were performed to investigate the effect of contaminations in front of the MHO plate with β = 0.55.

2. Mathematical Model and Numerical Method

The mathematical model can be summarized in the following governing and constitutive equations:

Continuity equation

$$\frac{d}{dt}\int_{V} \rho \mathrm{dV} + \int_{S} \rho(\mathbf{v}\text{-}\mathbf{v}_{\mathrm{s}})\cdot \mathrm{ds} = 0 \qquad (1)$$

where $\boldsymbol{\rho}$ is density, $\mathbf{v}$ is velocity vector, and $\mathbf{v}_s$ the velocity of the surface S.

Momentum equation

$$\frac{d}{dt}\int_{V} \rho \mathbf{v} \mathrm{dV} + \int_{S} \rho \mathbf{v}(\mathbf{v}\text{-}\mathbf{v}_{\mathrm{s}})\cdot \mathrm{ds} = \int_{S} \mathbf{T} \mathrm{ds} + \int_{V} \mathbf{f}_b \mathrm{dV} \qquad (2)$$

where $\mathbf{T}$ the Cauchy stress tensor and $\mathbf{f}_b$ is the resultant body force.

Equation of state

$$\rho = \rho(p, T) \qquad (3)$$

where p [Pa] is the pressure of the fluid and T [K] is temperature.

Stoke's law

$$\mathbf{T} = 2\mu\dot{\mathbf{D}} - \frac{2}{3}\mu \mathrm{div}\mathbf{v}\mathbf{I} - p\mathbf{I} \qquad (4)$$

where

$$\dot{\mathbf{D}} = \frac{1}{2}[\mathrm{grad}\mathbf{v} + (\mathrm{grad}\mathbf{v})^{\mathbf{T}}] \qquad (5)$$

is the rate of strain tensor, μ is the dynamic viscosity, p is the pressure and $\boldsymbol{I}$ is the unit tensor.

The working fluid was dry air, while the turbulence model was standard k-ε model [15]. Numerical method employed for modeling the flow of dry air through the multi-hole orifice meter was finite volume method. The methodology follows closely the one presented in [15].

3. Numerical Modelling of Newtonian Fluid Flow Through the Multi-Hole Orifice Meter

The flow of dry air through the multi-hole orifice meter was analyzed. The geometry and the numerical grid of the pipe with the multi-hole orifice meter was given in the Figure 1, while the geometry of the multi-hole orifice meter was given in the Figure 2. Three different values of β parameter were analyzed, 0.55, 0.6 and 0.7. Geometry characteristics for each β parameter are given in Table 1.

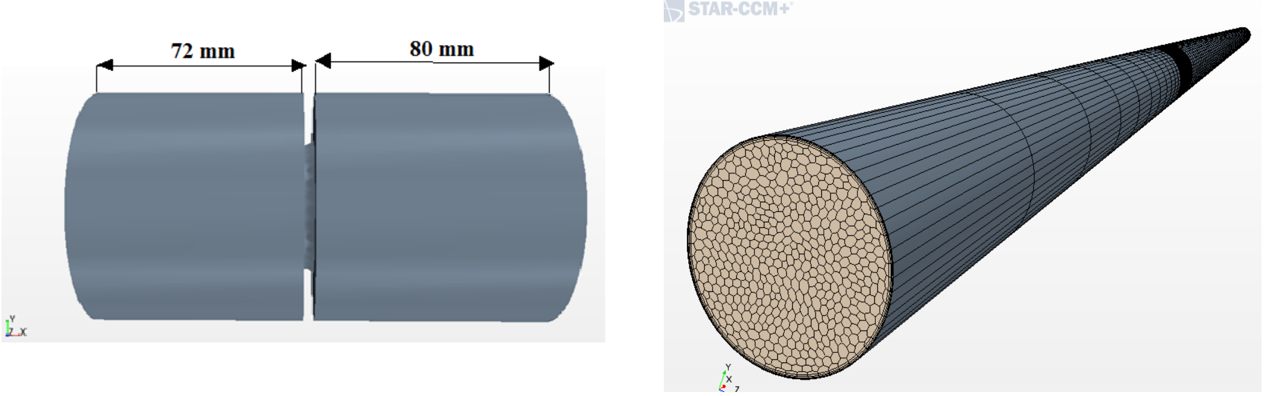

Fig. 1: Geometry (left) and the numerical mesh (right) of the pipe with the multi-hole orifice meter.

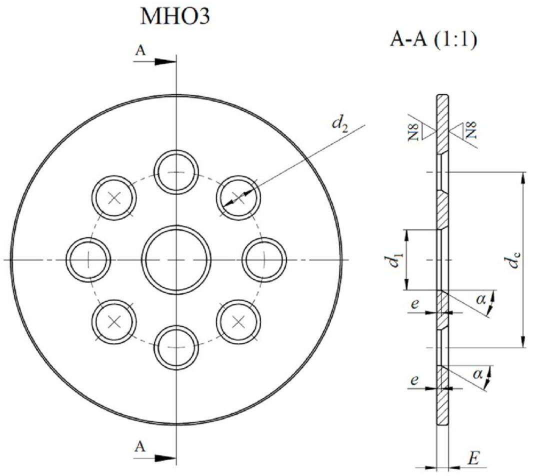

Fig. 2: Geometry of the multi-hole orifice meter.

The European standard EN ISO 5167-2:2012 provides the definition for the contraction coefficient β as the square root of the ratio of the sum of the cross-sectional areas of the orifice holes A to the cross-sectional area of the pipe A_1. The formula for β

$$\beta = \sqrt{\frac{A}{A_1}}\,, [-] \tag{6}$$

Table 1: Geometry characteristics of multi-hole orifice meter for different values of β parameter

β	***D*** **[mm]**	***d_1*** **[mm]**	***d_2*** **[mm]**	***d_c*** **[mm]**	***A_1*** **[mm^2]**	***A_2*** **[mm^2]**	***E*** **[mm]**	***e*** **[mm]**
0.55	70.3	21	11.5	52	346.36	103.87	3.5	1.5
0.6	70.3	23	12.5	54	415.48	122.72	3.5	1.5
0.7	70.3	28	14.3	53	615.75	160.61	3.5	1.5

Figure 3 illustrates the geometrical parameters of the MHO with contamination. The contaminant angle θ can be defined as the inverse tangent of the ratio of the contamination thickness h to the radial distance between the edge of the hole and the contamination r, and can be expressed mathematically as follows:

$$\theta = tan^{-1}\frac{h}{r} \tag{7}$$

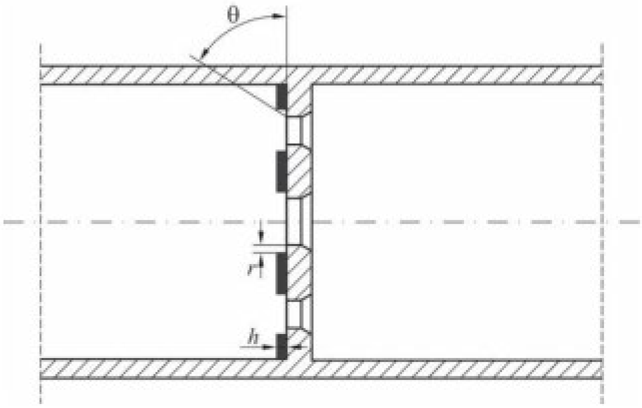

Fig. 3: Geometrical factors for the multi-hole orifice featuring impurities situated ahead of the orifice plate.

To obtain the pressure drop (Δp), we calculate the static pressure on two perpendicular planes placed at specific locations relative to the multi-hole orifice (MHO). The first plane is located at a distance of D upstream of the MHO, while the second plane is positioned at a distance of D/2 downstream of the MHO. We then calculate the difference between the averaged static pressure values on these two planes. The value of D corresponds to the diameter of the main pipe.

The discharge flow coefficient C_D can be determined using the expression given in [16], which is

$$C_D = \frac{1}{\epsilon}\sqrt{\frac{1-\beta^4}{\xi}}, [-] \tag{8}$$

Here, ϵ represents the expansion coefficient of the MHO orifice, and since no experimental study has obtained it for the multi-hole orifice yet, we assume its value to be 1 in this study. ξ represents the singular pressure loss coefficient, which can be expressed as

$$\xi = \frac{\Delta p}{1/2\rho v^2}, [-] \tag{9}$$

Here, Δp represents the pressure drop, ρ is the density, and υ is the average velocity through the orifice holes, which can be obtained from the total mass flow rate $\dot{m}$ entering the pipe using the following equation:

$$v = \frac{\dot{m}}{\rho A}, \left[\frac{m}{s}\right] \tag{10}$$

The flow was steady state, three dimensional and turbulent with the $Re=10^5$. The initialized pressure was p=25 bar, while the temperature of dry air was T=298.15 K. Since grid sensitivity study was performed in previous research by authors [16,17,18] here the validation with experimental results obtained from literature [19] was done and presented in Table 2. Validation was done for simulation of flow through MHO without contamination, for $\beta = 0.7$ and $\mathrm{Re} = 10^6$ and as it can be seen from Figure 4, a good agreement was observed.

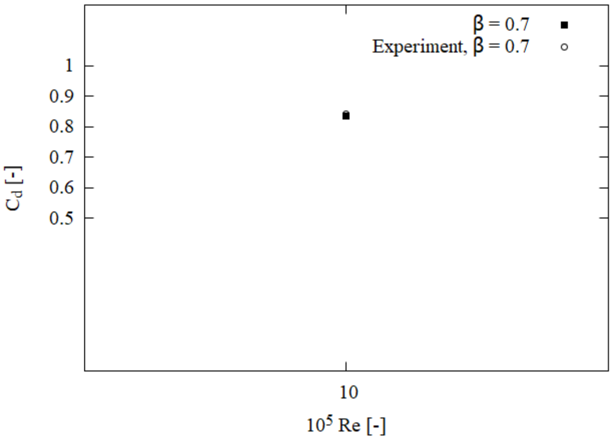

Fig. 4: Validation with experimental results obtained from literature [16].

4. Results and Discussion

The numerical results for pressure drop and singular pressure loss coefficient for β=0.55, 0.6 and 0.7 for Newtonian fluid flowing through multi-hole orifice meter are given in Table 2. It can be seen from the results that pressure drop decreases, while discharge coefficient increases with the increase of β parameter . Also, it is noticable that although decrease in the pressure drop between $\beta = 0.6$ and $\beta = 0.7$ is over 50%, when analyzing discharge coefficient which is directly related to the measured flow values we see that increase in discharge coefficient is just over 6%. Pressure fields just after the orifice flow meter for smallest and largest values of β parameter are given on Figure 5, where the smallest value of pressure is 249.989 Pa (blue color) while the highest pressure obtained in this cross-section is 250.001 Pa (red color).

Table 2: Pressure drop and discharge coefficient values for $\boldsymbol{\beta}$=0.55, 0.6 and 0.7 for multi-hole orifice meter

β [-]	Re	Δp [Pa]	C_d [-]
0.55	10^5	180.88	0.815
0.6	10^5	122.35	0.817
0.7	10^5	49.59	0.882

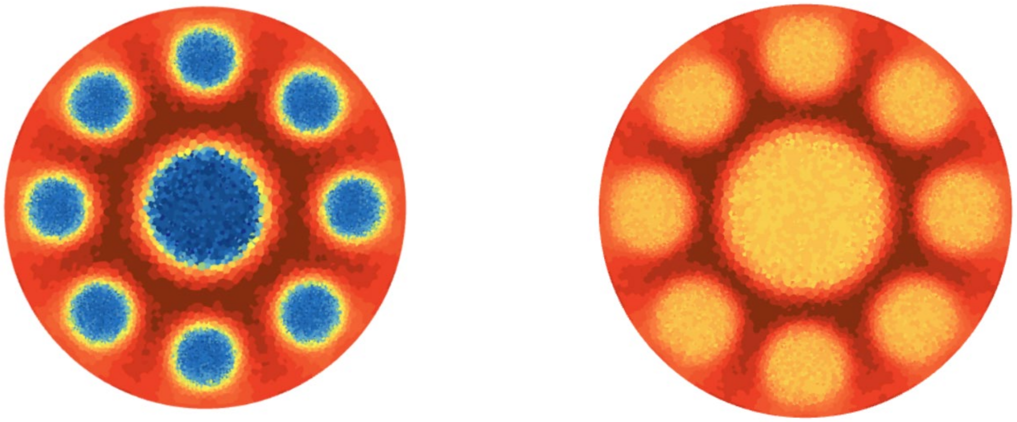

Fig. 5: Pressure field in the cross-section after the orifice flow meter (*left:* β=0.55, *right:* β=0.7).

It can be seen from Figure 5 that for β=0.55 which correspond to smaller opening diameters pressure difference between highest and smallest obtained pressure is bigger than for β=0.7 whose opening diameters are higher. Also, when analyzing pressure drop for different β parameters one can conclude that for higher β parameter, the smaller pressure drop is obtained, which can also be concluded from Figure 5 where more uniform pressure field is obtained for higher value of β parameter.

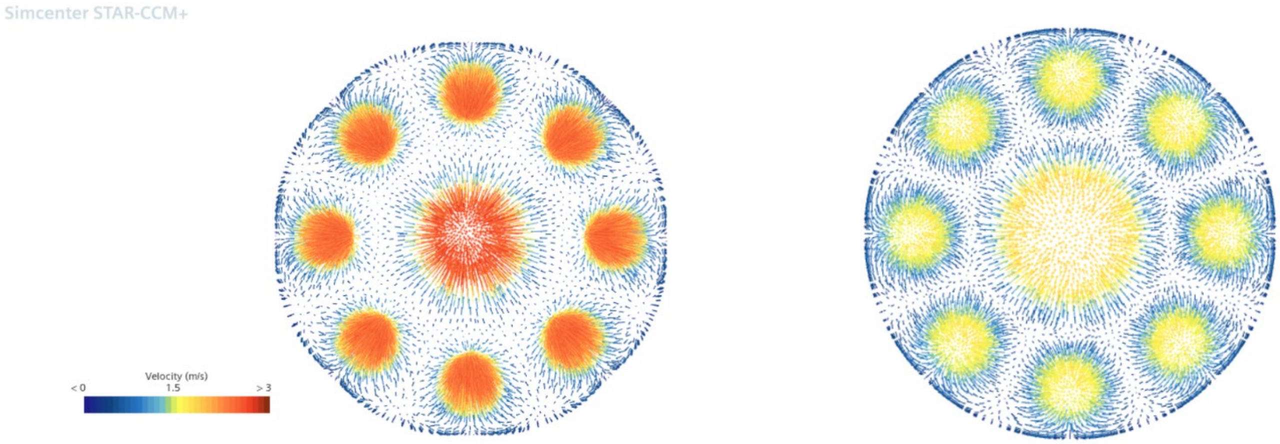

Fig. 6: Velocity field in the cross-section after the orifice flow meter (*left:* β=0.55, *right:* β=0.7).

It can be seen from Figure 6 that values of velocity through orifice openings decreases with the increase of β parameter which was expected since opening diameters are lower for higher values of β parameter. Also, it is noticeable that for small difference in diameter openings between β=0.55 and β=0.7 maximum values of velocity doubles. For future research it would be interesting to see whether that ratio stays the same for higher values of Reynolds number.

The discharge coefficients obtained from the numerical simulations for same contamination angles but for different h and r values are presented in Fig. 7. It is clear to see from the figure that regardless of values of h and r values, only the contamination angle has the effect on the discharge coefficient. Also, it can be noted that as the contamination angle is increased, the discharge coefficient tends to increase.

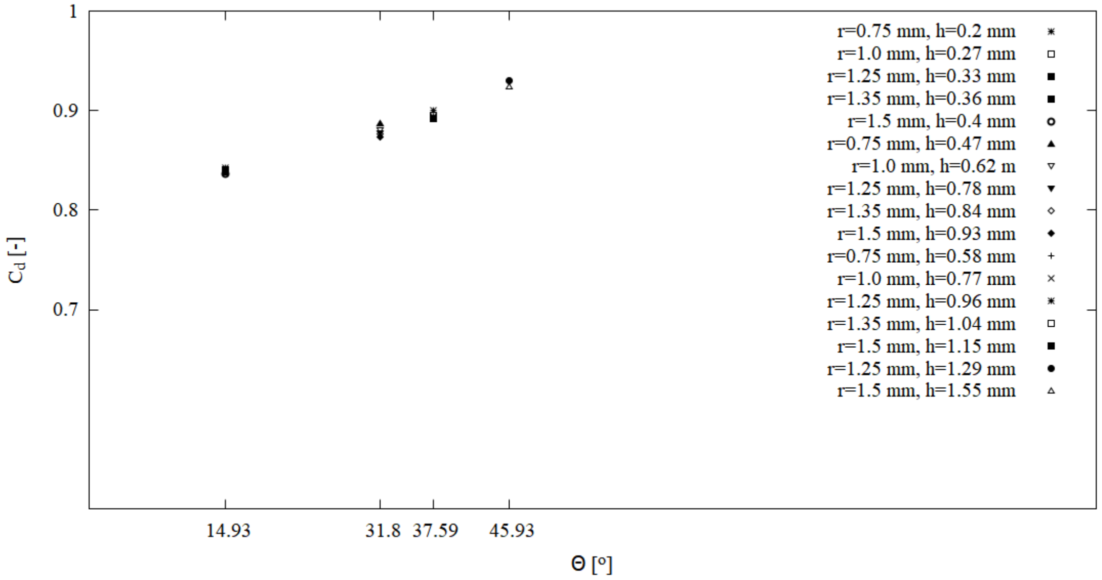

Fig. 7: Discharge coefficient values for various combinations of h and r parameters for same values of contamination angle for β=0.55 and at a Reynolds number of 10^5

5. Conclusion

This paper presents the numerical analysis of the flow of Newtonian fluid through MHO flow meter. The influence of β parameter on pressure drop and discharge coefficient was analysed. Numerical analysis is done for orifice meter without contamination and for Reynolds number corresponding to turbulence flow regime for flow through the pipe. Results were validated with experimental results obtained from the literature and good agrement was observed. The pressure drop, the singular pressure loss coefficient and the discharge coefficient are analysed for Re=10^5 and for β = 0.55, 0.6 and 0.7. It was found that increase in β parameter results with the decrease in pressure drop and increase in discharge coefficient. Also, it was found that that the influence of β parameter is much higher when analyzing pressure drop rather than discharge coefficient values. It can be concluded from the results of MHO incorporating with contaminations that as the contamination angle is increased the dischage coefficient tends to increase. Also, it was found that the contamination angle plays a cruical role on the effect of the discharge coefficient not the geometrical paramters of the contamination (h and r). For future research the influence of contamination on discharge coefficient for different β parameters and higher Reynolds values can be of great interest.

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