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Distortion of Flow Measurement and Cavitation Occurs Due to Orifice Inlet Velocity Profiles

Byung-Soo Shin, Nam-Seok Kim, Sang-Kyu Lee and O-Hyun Keum

***Abstract*—This analysis investigates the distortion of flow measurement and the increase of cavitation along orifice flowmeter. The analysis using the numerical method (CFD) validated the distortion of flow measurement through the inlet velocity profile considering the convergence and grid dependency. Realizable k-e model was selected and y+ was about 50 in this numerical analysis. This analysis also estimated the vulnerability of cavitation effect due to inlet velocity profile. The investigation concludes that inclined inlet velocity profile could vary the pressure which was measured at pressure tab near pipe wall and it led to distort the pressure values ranged from -3.8% to 5.3% near the orifice plate and to make the increase of cavitation. The investigation recommends that the fully developed inlet velocity flow is beneficial to accurate flow measurement in orifice flowmeter.

***Keywords*—**Orifice, k-e model, CFD

I. INTRODUCTION

ONE of widely used flowmeter is an orifice flowmeter installed inside pipe due to easy installation and low cost. However, if flow is not fully developed, the inlet velocity may be distorted and it leads to change local static and total pressure. Another possible problem about orifice flowmeter with distorted inlet velocity profile is early cavitation. Cavitation formed gas bubbles in region where inlet velocity may be distorted. During cavitation, vapor bubbles make iterative growth and lead to affect the local static and total pressure. That is the reason ASME PTC requires maintaining the upstream length of orifice plate for consistent measurement from assuring inlet velocity is developed fully. [2, 3] The distorted velocity profile could depress the local total pressure and it leads to local cavitation early. Therefore, wrong installation affects to integrity of orifice flowmeter. In this study, two kinds of CFD works were performed. First, the pressure at the upstream and downstream of orifice plate was calculated and investigated using commercial CFD code, CFX 13.0. The maximum ratio of flowrate distortion was estimated when using original discharge coefficient. Second, unexpected cavitation was simulated with inclined velocity profile using same code. In this calculation, working fluid was treated as two phase flow with cavitation model. The results show the distortion of anticipated characteristics of orifice plate.

Byung-Soo Shin is with Korea Institute of Nuclear Safety, Guseong, Yuseong, Daejeon, 305-338, Republic of Korea (e-mail: k975sbs@ kins.re.kr)
Nam-Seok Kim is with Korea Institute of Nuclear Safety, Guseong, Yuseong, Daejeon, 305-338, Republic of Korea (e-mail: nskim@ kins.re.kr)
Sang-Kyu Lee is with Korea Institute of Nuclear Safety, Guseong, Yuseong, Daejeon, 305-338, Republic of Korea (e-mail: sklee@ kins.re.kr)
O-Hyun Keum is with Korea Institute of Nuclear Safety, Guseong, Yuseong, Daejeon, 305-338, Republic of Korea (e-mail: k092koh@ kins.re.kr)

II. ORIFICE FLOWMETER

The flowrate is measured by the pressure difference between the upstream and downstream of pressure as shown in figure 1. [1]

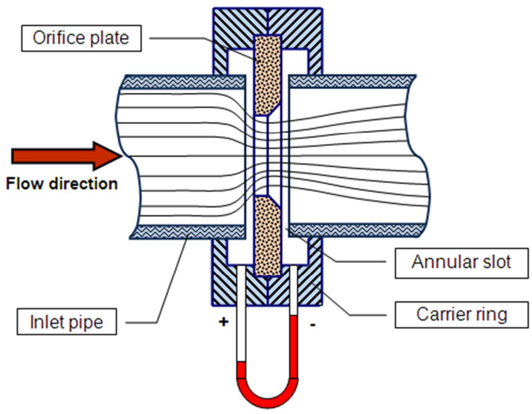


Fig. 1 Schematic diagram of orifice flowmeter

Introducing discharge coefficient, the expression is as follows.

$$Q = C_d A_2 \sqrt{\frac{1}{1-\beta^4}} \sqrt{2(P_1 - P_2)/\rho} \quad (1)$$

That is, the flowrate is determined by pipe diameter, orifice hole-diameter, pressures at upstream and downstream or orifice. The pressure in equation (1) means the local static pressure at the pressure tab and this point is considered at the development of discharge coefficient. That is, the discharge coefficient is applicable to the situation at which valve installation meets the code requirement. If the discharge coefficient is not acceptable by wrong installation (that is, inlet velocity is distorted), the measurement error could be made. Figure 2 shows general 4 step process of cavitation. The distorted velocity profile could depress the local total pressure and it leads to local cavitation early. Therefore, wrong installation affects to integrity of orifice flowmeter.

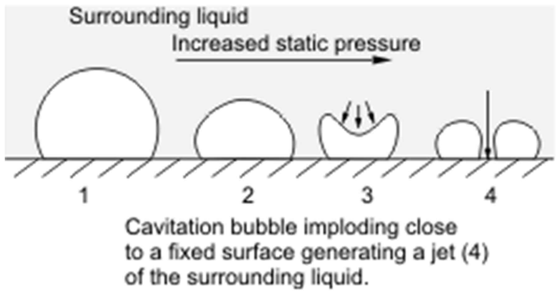


Fig. 2 General 4 step process of cavitation

III. Numerical Approaches

A. For Single Phase Flow

Salim et al. [4] have conducted the estimation of turbulent model and first wall thickness for flow upon the ridge. Because the flow upon the ridge is similar to flow through orifice plate, their works are meaningful to this calculation. Their estimation results were shown as figure 3 and 4.

They concluded that the acceptable turbulent models are realizable k-e model and Reynolds Stress Model and about several tens is appropriate to the size of y+ for calculation on the ridge geometry. Hence, the realizable k-e model was selected in this analysis. The realizable k-e model is expressed like following:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)= \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\upsilon\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \quad (2)$$

The ratio of pipe diameter and orifice size is 0.7464 and the lengths of upstream and downstream of orifice plate are 2D and 10D respectively. The inlet velocity profile has an inclination to simulate the not-fully developed inlet velocity and it is equated with following expression.

$$v=V_{slope}\times\frac{D/2+x}{D}+V_{base} \quad (3)$$

B. For Two Phase Flow

The governing equation is two fluid model suggested by Ishii [5]. The model is composed of mass and momentum equation for each phase. And each equation has interfacial transfer terms. In this study, homogeneous flow option was selected and the thermal effect was not concerned because it is expected that the amount of mass transfer will be small. The turbulent model is realizable k-e model for homogeneous water flow. This model was validated in single phase flow calculation. Here, the level of y+ was also the same as single phase flow calculation. The boundary conditions are inlet velocity and pressure outlet as inlet and outlet boundary respectively. And for 2D simulation, symmetry boundary condition was applied to surfaces along the y-axis. For cavitation model, Rayleigh-Presset model implemented in CFX code was used. Generally, due to rapid process of cavitation, the assumption of typical thermal equilibrium at the interface could not be applied. In the simplest cavitation models, mechanical effects are only considered ignoring thermal effects. [6]

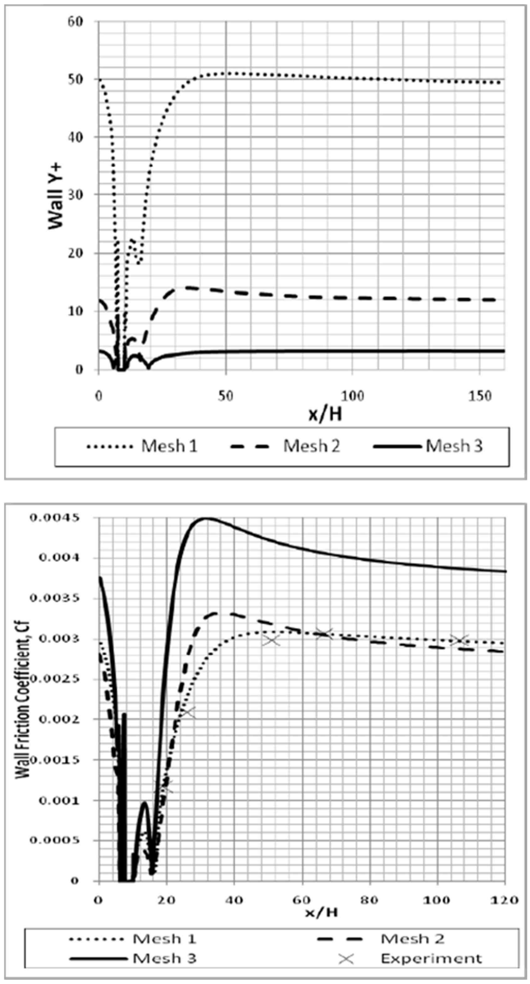


Fig. 3 Effect of grid size [4]

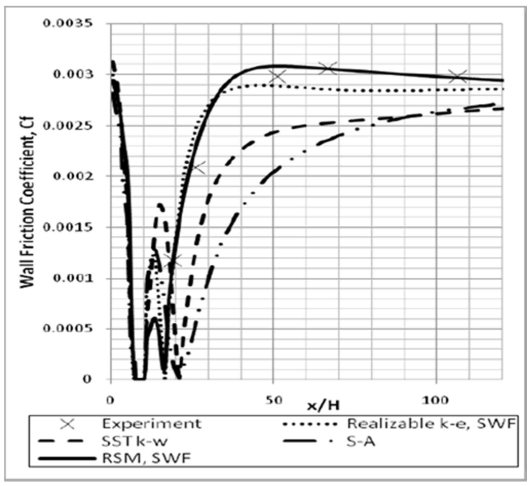


Fig. 4 Effect of turbulent model [4]

C. For Two Phase Flow

The governing equation is two fluid model suggested by Ishii [5]. The model is composed of mass and momentum equation for each phase. And each equation has interfacial transfer terms. In this study, homogeneous flow option was selected and the thermal effect was not concerned because it is expected that the amount of mass transfer will be small. The turbulent model is realizable k-e model for homogeneous water flow. This model was validated in single phase flow calculation. Here, the level of y+ was also the same as single phase flow calculation. The boundary conditions are inlet velocity and pressure outlet as inlet and outlet boundary respectively. And for 2D simulation, symmetry boundary condition was applied to surfaces along the y-axis. For cavitation model, Rayleigh-Presset model implemented in CFX code was used. Generally, due to rapid process of cavitation, the assumption of typical thermal equilibrium at the interface could not be applied. In the simplest cavitation models, mechanical effects are only considered ignoring thermal effects. [6]

The Rayleigh-Presset equation is given by:

$$R_B \frac{d^2 R_B}{dt^2} + \frac{3}{2}\left(\frac{dR_B}{dt}\right)^2 + \frac{2\sigma}{\rho_f R_B} = \frac{p_v - p}{\rho_f} \tag{4}$$

Neglecting the seconds order terms and surface tension, this equation reduces to:

$$\left(\frac{dR_B}{dt}\right) = \sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{5}$$

If there are N_B bubbles per unit volume, the total interphase mass transfer rate per unit volume is:

$$\dot{m}_{fg} = \frac{3 r_g \rho_g}{R_B}\sqrt{\frac{2}{3}\frac{p_v - p}{\rho_f}} \tag{6}$$

It can be generalized to include condensation as follows:

$$\dot{m}_{fg} = F\frac{3 r_g \rho_g}{R_B}\sqrt{\frac{2}{3}\frac{|p_v - p|}{\rho_f}}\,\mathrm{sgn}(p_v - p) \tag{7}$$

Here, introducing the concept of nucleation sites, the equation is:

$$\dot{m}_{fg} = F\frac{3 r_{nuc}(1-r_g)\rho_g}{R_B}\sqrt{\frac{2}{3}\frac{|p_v - p|}{\rho_f}}\,\mathrm{sgn}(p_v - p) \tag{8}$$

IV. VALIDATION

To assure analysis results, the grid size and convergence criteria should be determined with the selection of turbulent model and y+. For convergence criteria, following four relations were investigated under reference conditions.

1) Iterative Number vs. Residual Norm
2) Iterative Number vs. Mass conservation
3) Iterative Number vs. Target Variable
4) Residual norm Target Variable

On the basis of these relations, convergence was investigated as figure 5. Here, turbulent model and y+ was consistent with Salim's suggestions and discretization scheme was upwind scheme. High resolution was applied to turbulent terms. Then, physical timescale was controlled for improvement of convergence. Conclusively, convergence was good below 10-5 for residual norm.

The prototypes of grid generation are shown as figure 6. The pressure difference between inlet and outlet of orifice plate was compared for grid prototypes. The results are summarized in Table I. For accuracy and efficiency of calculation, gird #2 was selected for main calculations.

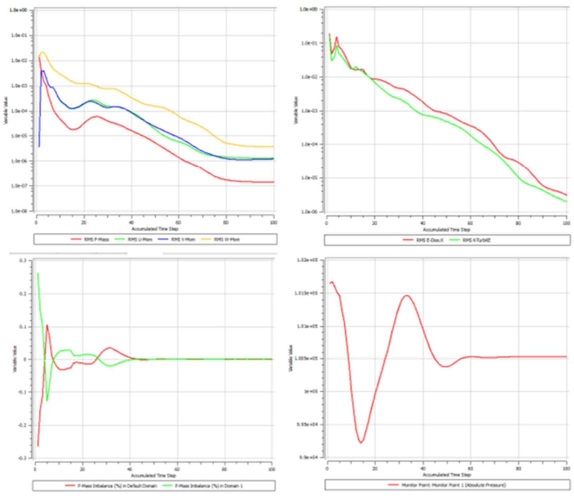


Fig. 5 Convergence transients

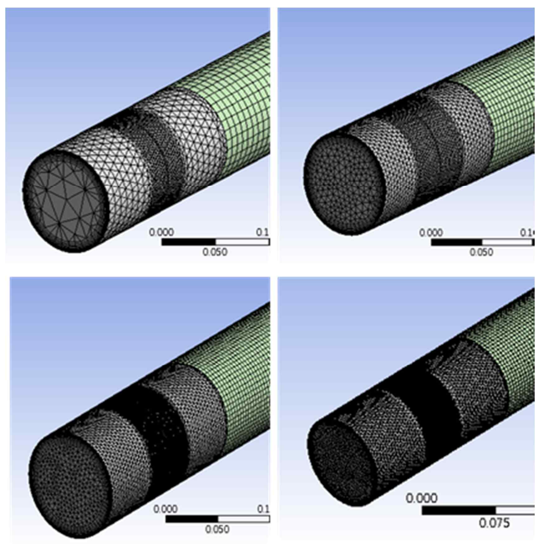


Fig. 6 Prototypes of grid generation

TABLE I
COMPARISON OF PRESSURE DIFFERENCE

	Grid #1	Grid #2	Grid #3	Grid #4
No. of Mesh	153,974	260,066	745,683	1,213,951
Norm. P	0.981	0.995	0.998	1 (ref.)

To assure reliability and accuracy of numerical calculation, mesh size and convergence criteria was investigated. Figure 7 shows grid generations which have 3 different sizes for optimization. All meshes are hexagonal mesh with constant size except region of orifice which has denser meshes and inflation meshes were inserted at the wall.

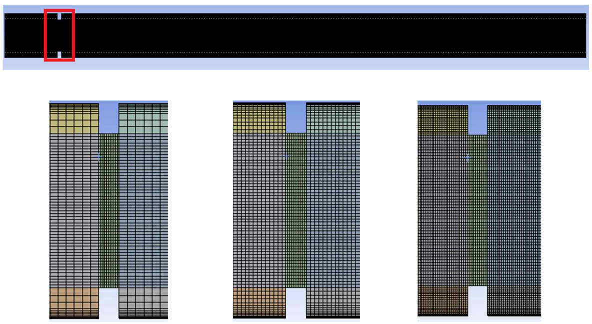


Fig. 7 Prototypes of grid generation for 2D and two phase calculation

According to guidelines for analysis of cavitation, for good convergence, it should be calculated after preliminary calculation under the condition without cavitation was performed in advance. From figure 8 we can know that, as iteration number increases, local static pressure, mass residual and momentum residual have enough convergences especially below 10^{-7} of residual value. The comparison between some physical variables was present in this context. As shown in Table II, the variables go to a certain constant value with the increase of mesh size. To consider the efficiency and accuracy of calculation at the same time, case 2 was selected as a reference mesh.

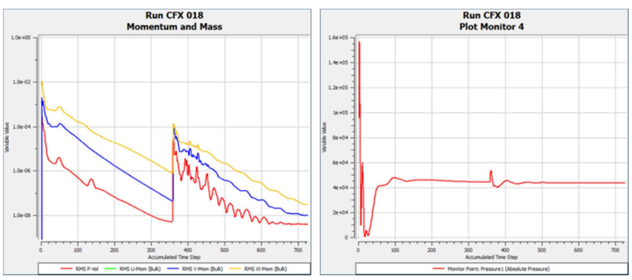


Fig. 8 Convergence plot

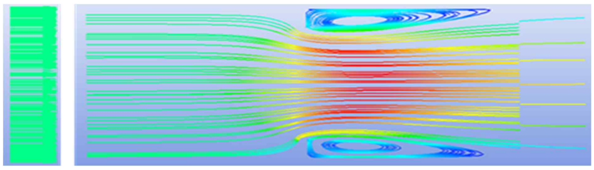
TABLE II
CALCULATION RESULTS ABOUT DIFFERENT 2D GRIDS

	Mesh Number [-]	Local Velocity [m/s]	Local Pressure [kPa]	Pressure Drop [kPa]
Case 1	18,950	1.739	45.40	30.07
Case 2	55,560	1.746	43.35	28.13
Case 3	153,375	1.749	42.61	27.07

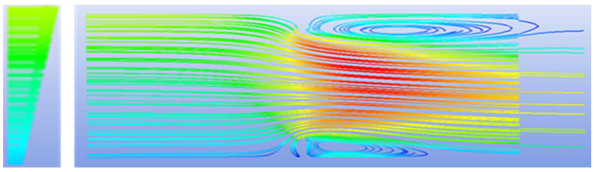
V. RESULTS

A. Measurement Distortion

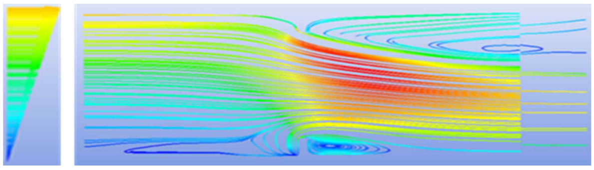
If the velocity profile according to equation (1) applies to inlet boundary condition of orifice plate, the velocity streamline at the downstream of orifice plate was biased and one of secondary flow enlarged as shown in figure 9. As the velocity inclination increase, asymmetric velocity profile was strengthened. Generally, orifice tab is located at the secondary flow region. Asymmetry of secondary flow is resultant cause of measurement distortion.



(a) Uniform inlet flow



(b) Velocity inclination = 4.8 m/s



(c) Velocity inclination = 8.8 m/s

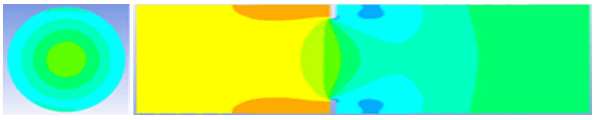
Fig. 9 Effect of velocity inclination to streamline

The velocity inclination leads to the change of local pressure distribution naturally as shown in figure 10. In this figure, assuming the 2 bend exist at the upstream of orifice plate, the velocity inclination along the rotational direction was also considered. The figure informs that the tab location along the rotational direction should also be considered when the orifice flowmeter intend to be installed right.

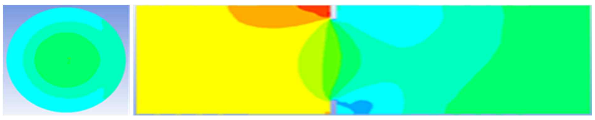
To estimate the effect of pressure distortion on flow measurement quantitatively, the predicted flow measurement with inclined velocity was compared with that with uniform velocity. In figure 11, the distortion rate of flow measurement is ranged from -3.8% to 5.3% near the orifice plate. However, if the tab distance increases, the rate is ranged from -3% to 9%. That is, it means that the way of orifice tab location could affect the distortion rate.

B. Cavitation

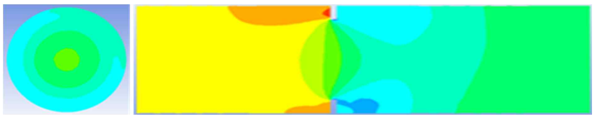
Generally, possibility of cavitation is higher at low cavitation number. Therefore, when local velocity is fast and local pressure is low, cavitation tends to occur well. Figure 12 shows the occurrence of cavitation with increasing of average velocity. As the velocity increases, the gas vapor is increased near the wall of orifice and the vapor is extended along the velocity direction and cavitation occurs inside the region of secondary flow.



(a) Uniform inlet



(b) 1-bend assumption



(c) 2-bend assumption

Fig. 10 Local pressure distribution

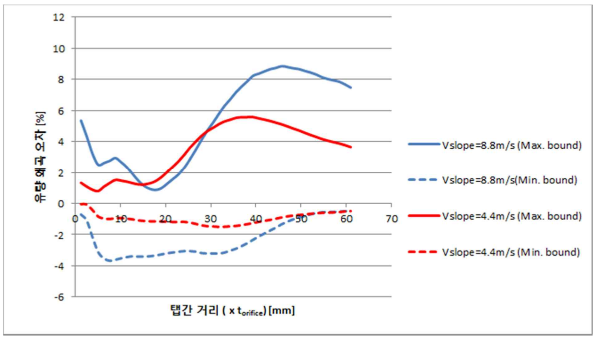
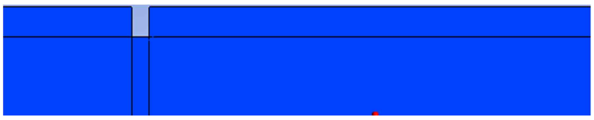


Fig. 11 Variation of distortion rate with tab distance



(a) Low velocity

(b) Medium velocity

(c) High velocity

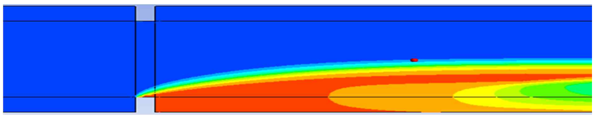
Fig. 12 Contours of void fraction with increasing of average velocity

If inlet velocity has inclination, the region of cavitation is mostly distributed at the one side of pipe wall and void fraction also is intense due to the biased mass flow rate as shown in Figure 13.

In figure 14, the contours of local pressure and velocity were also matched with void fraction. It shows that if the orifice is installed at wrong position, possibility of the occurrence of cavitation is enlarged.

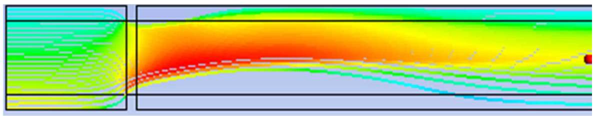
(a) Zero velocity inclination

(b) Medium velocity inclination

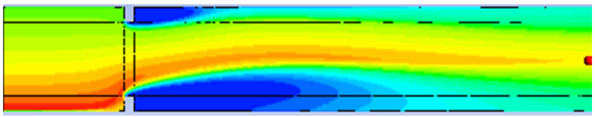


(b) High velocity inclination

Fig. 13 Contours of void fraction with increasing of velocity inclination



(a) Streamline



(b) Total pressure

(c) Vapor void fraction

Fig. 14 Velocity, total pressure and void fraction of upstream and downstream of orifice plate

VI. Conclusions

When inlet velocity has distorted profiles, measurement distortion and unexpected cavitation was investigated using commercial CFD code. This investigation concludes that firstly pressure tab location along the rotational direction should be carefully considered when the orifice flowmeter intend to be installed. Secondly, the distortion rate of flow measurement is ranged from -3.8% to 5.3% near the orifice plate. However, if the tab distance increases, the rate is ranged from -3% to 9%. Thirdly, as the velocity increases, the gas vapor is increased near the wall of orifice and the vapor is extended along the velocity direction and cavitation occurs inside the region of secondary flow. Lastly, if the inlet velocity has inclination, the region of cavitation is mostly distributed at the one side of pipe wall and void fraction also is intense due to the biased mass flow rate. Therefore, if the orifice is installed at wrong position, flow measurement could be distorted and possibility of cavitation will be enlarged.

REFERENCES

[1] *http://en.wikipedia.org/wiki/Orifice_plate, Wikipedia*, 2011.
[2] *General Requirements for Fluid Metering: Installation.* USA: ASME PTC 19.5-72, 1972, pp. 179-181.
[3] *Flow Conditioning and Meter Installation Requirements.* USA: ASME PTC 19.5-2004, 2004, pp. 64-66.
[4] Salim et al., *"Wall y+ Stratagy for Dealing with Wall-bounded Turbulent Flows"*, IMECS 2009, Vol II, Hong Kong, 2009
[5] M. Ishii, K. Mishima, *Two-fluid model and hydraulic constitutive relations*, Nucl. Eng. Des., Vol. 82, 1984, pp. 107.
[6] *CFX Manual*, Theory, 2009