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NUMERICAL INVESTIGATION ON EFFECTS OF DEFORMATION ON ACCURACY OF ORIFICE METERS

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ABSTRACT

Flow measurement errors caused by deformation of orifice plates are analyzed numerically using finite element method. Deformation due to rounding of the sharp edges and plate bending are investigated. The pressure drop and velocity profile of the turbulent pipe flow are simulated by CFD technique. Rounded and bent orifice plates in 2 and 4 inch diameter pipes were tested and results were used to assess measurement error as a function of edge radius, orifice bore diameter and plate deflection angle. The study shows that, buckled plates and rounded edge plates both under-measures the flow. For bent plates with 8 degree bending angle the error is near 3.3% for 2 inch line and 2.5% for 4 inch line. It also shows that, flow rate prediction by Mason, Wilson and Birkhead correlation for buckling works well with lower bending angles. But at higher angles, the deviation is more. For high edge radii the current numerical simulation predicts an error as high as 5%.

Keywords: Orifice Meter, Coefficient Of Discharge, Plate Buckling, Edge Radius, Turbulent Flow, k-ε Model.

1. INTRODUCTION

An orifice meter is one of the most commonly used devices for flow measurement in oil and gas industries. In these industries, accurate and economical measurement of process fluid is necessary. In a conventional orifice meter in good condition, differential pressure measured across orifice plate indicates the flow rate. Although it measures flow rate accurately, its use is restricted by different international standards such as BS1042, ISO 5467, AGA reports etc. Based on AGA report no.3 [1], the primary consideration in the design of a metering station is to sustain accuracy. These standards provide standard dimension and design of orifice meter with respect to various parameters such as beta ratio (β), pipe diameter, plate thickness, working fluid etc.

Extensive and systematic researches have been completed over the years to evaluate the performance of orifice meter. Crockett and Upp [2] worked on effect of edge sharpness on the flow coefficients of standard orifices. Spencer [3] reviewed data on the effect of edge sharpness on orifice discharge coefficients and recommended an empirical correlation. Hobbs and Humphreys [4] calibrated two orifice plates after localized damage to the upstream edge. When a pressure differential is applied across an orifice plate, it deflects due to unbalanced force on both sides. If the bending stress is within the elastic limit, the plate gets back to its original shape after halting the differential pressure. If bending stress exceeds materials elastic limit, the deformation becomes permanent. Jepson and Chipchase [5] developed a theoretical model to predict flow measurement error from plastically deformed plates. Ting [6] calibrated flow in 4-inch and 6-inch buckled orifice plates for different β- ratios. Mason, Wilson and Birkhead [7] worked on flow measurement error caused by elastic deformation of orifice plate. Since, most results obtained from these studies are contradictory; a need has been identified for more data to verify the reported trends.

Computational Fluid Dynamics (CFD) has emerged as an effective tool to predict results for difficult experimental condition. CFD analysis of flow meters in abnormal conditions are quite complex and careful selection of numerical technique is required for accuracy. Among various numerical methods for solving complex engineering problems, finite element method (FEM) has advantage over finite difference method (FDM) and finite volume method (FVM) due to its built in abilities to handle unstructured meshes, a rich family of element choices and natural handling of boundary conditions. Previous investigators also worked on orifices numerically and found agreement with experimental observation. Davis and Mattingly [8] modeled orifices with different β- ratios and checked their performances varying the Reynolds number. Ganiev *et al.* [9] worked on the choice of turbulence models to compute discharge coefficient of orifice meter.

The present study concentrates on analysis of flow pattern and differential pressure across an orifice and finding out relative measurement errors caused by blurring the sharp edge of the orifice plate through solving a numerical turbulence flow model. The study also focuses on orifice plate buckling effects on measurement of flow rate and comparative study with Mason, Wilson and Birkhead model. 3D Geometries were modeled in CAD programs and simulated by selecting non-symmetric pattern multi frontal FEM method and using un-symmetric multifrontal sparse LU factorization package (UMFPACK) in COMSOL MULTIPHYSICS v3.4.

2. DESIGN AND SIMULATION

2.1 Model Definition:

Fig.1 shows geometry of the fluid domain in 2D inside the pipe being simulated (standard condition without buckling or, deformed edge). The generated model is an union of 3 subdomains. Subdomains 1 and 3 construct the inlet and outlet section of the pipe and

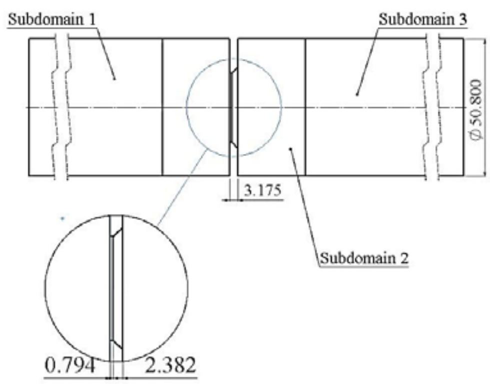

Fig 1. Fluid domain (in 2D view)

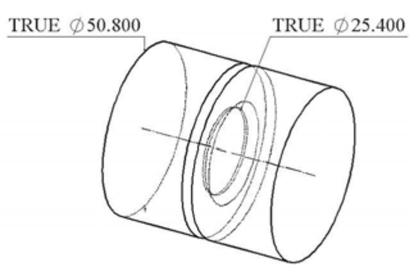

Fig 2. Fluid subdomain 2

subdomain 2 is the fluid domain that contains the orifice plate. The plate thickness is assumed as 3.175 mm and the throat thickness is 0.794 mm. The bevel angle of the plate is 45^0. Fig-2 shows the fluid domain containing the orifice plate. The fluid flow is taken along x-direction and a Reynolds number of 1.5×10^4 is selected for simulation.

2.2 Mathematical Formulation

Governing Equation

Standardized and realizable k-ε models are used in this numerical study of orifice meters. Application of k-ε model assumes Newtonian and incompressible fluid flow. Governing equation for steady and incompressible turbulent flow:

$$\rho \mathbf{u}.\nabla \mathbf{u} = \nabla.[-p\mathbf{I}+(\eta+\eta_T)(\nabla \mathbf{u}+(\nabla \mathbf{u})^T)]+\mathbf{F}$$

$$\nabla.\mathbf{u} = 0$$

The k-ε model introduces two additional transport equations with two new variables; the turbulent kinetic energy, k, and dissipation rate of turbulent energy, ε.

$$\rho \mathbf{u}.\nabla k = \nabla.[(\eta+\eta_T/\sigma_k)\nabla k] + \eta_T P(\mathbf{u}) - \rho\varepsilon$$

$$\rho \mathbf{u}.\nabla \varepsilon = \nabla.[(\eta+\eta_T/\sigma_\varepsilon)\nabla \varepsilon]+C_{\varepsilon1}\varepsilon\eta_T \mathbf{P}(\mathbf{u})/k - C_{\varepsilon2}\rho\varepsilon^2/k$$

Where, $\mathbf{P}(\mathbf{u}) = \nabla \mathbf{u}:(\nabla \mathbf{u}+(\nabla \mathbf{u})^T)$ and $\eta_T = \rho C_\mu \kappa^2/\varepsilon$

Wall Modeling

Turbulence close to a solid wall is very different from free stream turbulence. The proper modeling of a turbulent flow near wall is a vital step in solution. In this study, logarithmic wall function is applied to the finite elements assuming that the computational domain begins at a distance δ_w from the wall and flow is parallel to the wall.

Flow velocity, $U^+ = U/u_\tau = (1/k)\ln(\delta_w / l^*) + C^+$

Where,

u_τ = friction velocity,

k = von-Karman constant ≈ 0.42,

C^+ = universal constant for smooth walls

2.3 Code Validation

The 3D flow simulations were carried out in COMSOL v3.4 and UMFPACK solver was used for faster convergence of the solution. Converging criteria was selected in the order of 10^{-4}.

The CFD code was validated against the numerical results obtained from RK Singh *et al.* [10]. Since they have performed 2D axisymmetric flow simulation for orifice plate β- ratio 0.5, pipe diameter of 40 mm and bevel angle of orifice plate 45^0, similar model was prepared and then analyzed in both 2D and 3D for different Re. Their comparison is shown in table-1.

Table-1: Comparison of the average predicted values of C_d with RK Singh *et al.* [10]

Turbulence model	Coefficient of Discharge, C_d		
	2D axisymmetric analysis		3D analysis
	Singh *et al.*	Current analysis	Current analysis
Standard k-ε model	0.6265	0.65	0.665
Realizable k-ε model	0.616	0.612	0.68

The deviation of values in 3D analysis is due to lack of proper computational facilities to work with large number of mesh elements. In case of axisymmetric analysis realizable values shows less error, but in case of 3D analysis the standard k-ε model gives more reasonable result than realizable model. Since, this study focuses on 3D analysis of orifice plate deformation, the main fluid domains were analyzed with standard k-ε model.

2.4 Grid Independent Test

Grid independency test is a must to ensure accurate result from the simulation. Several grid independent tests were performed on computational fluid domains containing both standard orifice plate and deformed plates and it was found that 12325 mesh elements (Tetrahedral and prism mesh elements) were sufficient to provide accurate results for most of the cases. For higher bending angles, about 15000 mesh elements were necessary.

2.5 Simulation

Flow predictions were carried out for concentric orifice meter having pipe diameter, D = 2 inch and orifice bore diameter, d = 1 inch. Different models were simulated varying the inlet edge sharpness of the plate (up to edge radius 0.02 inch) and taking into account the plate buckling angle (up to 8 degree). The

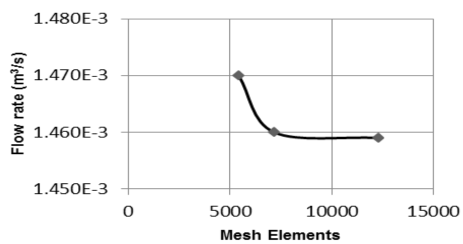

Fig-3. Grid independent test for standard orifice Plate

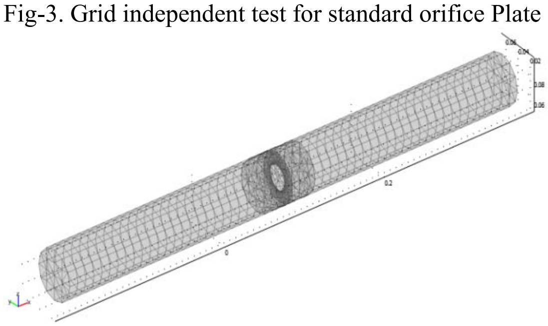

Fig-4. Meshed fluid domain

orifice plate had a 45^0 bevel angle and edge thickness of 1/32 inch (0.794 mm), where, the plate thickness was 1/8 inch (3.175 mm).

Fully developed turbulent flow is assumed for convenience. At the inlet, the velocity in x- direction is used as the boundary condition. At the outlet, zero pressure is assumed to configure the differential pressure in the system.

Both Turbulent kinetic energy k, and dissipation rate of turbulent energy, ε were assumed a value of 0.005 in the inlet. Remaining faces of the fluid domain, including pipe wall and orifice plate surfaces was boundary conditioned with wall function of COMSOL Multiphysics which are so called "lift off wall functions," that is, the computational domain is displaced a small distance, δ_w = h/2 from the surface, where, h = mesh element diameter.

Working fluid used in this simulation is water at a temperature of 20^0C. Dynamic viscosity of water is taken as 1.002×10^{-3} Pa-s. The flow simulations were carried out for β- ratio 0.5 and Reynolds number ranging from 0.75×10^4 to 2×10^4. Different fillet radius was introduced in the sharp edge of the orifice plate inlet. Again, to evaluate performance of plastically deformed or, buckled plate, bending angles of 2, 4, 6 and 8 degree were used. According to D.L. George [11] practical buckling phenomena may result three types of shapes of orifice plate. Conic plates with flat surfaces are found up to a bending angle of 4^0. Plates having higher bending angle shows a parabolic profile with the radius of curvature facing upstream. For this study 2 types of profile- conic and parabolic (facing upstream) were considered.

Since, the flow varies significantly less in subdomain 1 and 3, considered further upstream and downstream of orifice region; swept meshes were introduced in subdomain 1 and 3. In subdomain 2, where the orifice region is located and flow variation is noteworthy, unstructured fine meshes were considered with longest mesh refinement method.

3. RESULT AND DISCUSSION

Various parameters obtained from simulating different geometries deforming the orifice plate are given in table-3 and table-4. Parameters include pressure drop across orifice plate, maximum velocity at the vena contracta and obtained for Reynolds number of 1.5×10^4. Flow rate was calculated assuming the flow incompressible and C_d value was calculated using ISO (1998) correlation.

$$Q = \frac{C_d}{\sqrt{(1-C_c\times\beta^4)}} \times \frac{\pi}{4} \times d^2 \times \sqrt{(2\rho\Delta P)};$$

Table-2: C_c values (for different bending angles)

Bending angle, θ	C_c
0	0.6440
2	0.6473
4	0.6508
6	0.6544
8	0.6672

The coefficient of contraction, C_c values for different bending angles of orifice plate was calculated using von Mises (1917) correlation,

$C_c = M_0 + M_1\theta + M_2\theta^2 + M_3\theta^3$;

Where, θ = Bending angle

Values shown in table-2 are used for calculating flow rate for different bending of orifice plates.

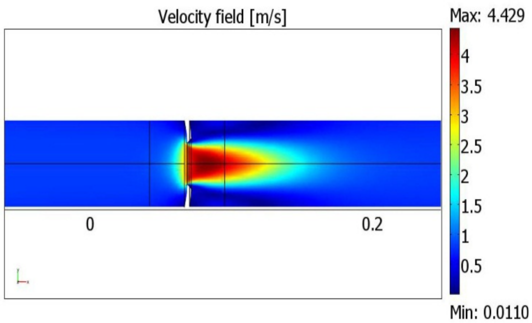

Fig-5. 2D view of the velocity profile for orifice plate assembly (For plate bending angle 8^0)

Table-3: Pressure and velocity data from numerical analysis for pipe diameter = 2 inch

Condition of orifice plate		Differential pressure (Pa) × 10^3	Maximum velocity at vena contracta (m/s)
Standard orifice plate		10.6	4.557
Edge radius/ bore diameter	0.005	10.3	4.527
	0.010	10.15	4.432
	0.015	10.0	4.430
	0.0175	9.80	4.410
	0.020	9.65	4.391
Plate bending angle (degree)	2	10.60	4.514
	4	10.45	4.503
	6	10.30	4.466
	8	10.00	4.436

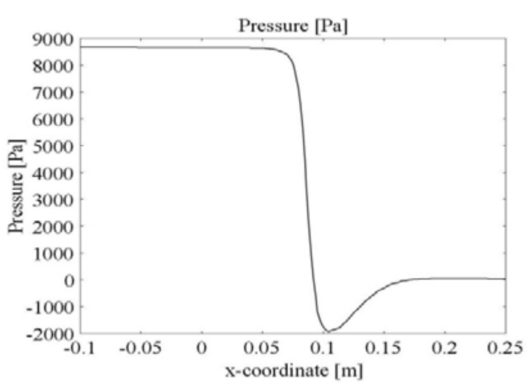

Fig-6. Pressure plot across standard orifice plate

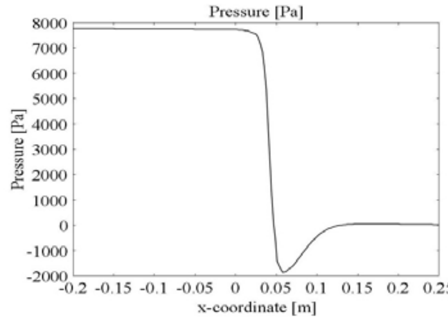

Fig-7. Pressure plot across orifice plate (for edge radius/ bore diameter = 0.02)

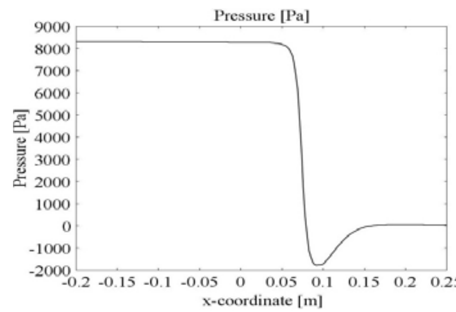

Fig-8. Pressure plot across orifice plate (for bending angle, θ = 8^0)

Table-4: Pressure and velocity data from numerical analysis for pipe diameter = 4 inch

Condition of orifice plate		Differential pressure (Pa) × 10^3	Maximum velocity at vena contracta (m/s)
Standard orifice plate		11	4.682
Plate bending angle (degree)	2	10.90	4.670
	4	10.75	4.683
	6	10.70	4.653
	8	10.50	4.611

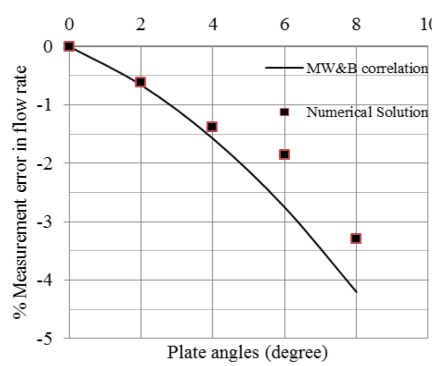

Fig-9. Variation in flow measurement error with plate bending angle and comparison with Mason, Wilson and Birkhead model.(For 2 inch line)

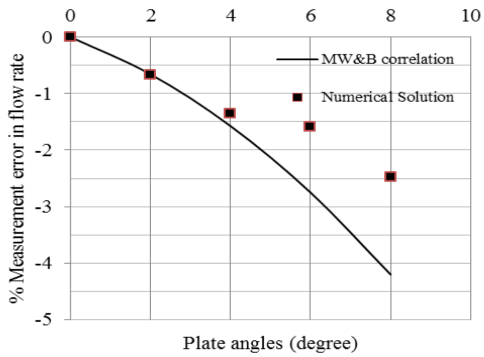

Fig-10. Variation in flow measurement error with plate bending angle and comparison with Mason, Wilson and Birkhead model. (For 4 inch line)

Effect of Edge Sharpness

Edge sharpness of orifice plate is significant for fine measurement of flow. The presence of fillet or, deformation in sharpness increases flow area through the orifice and under-measures the flow by several percent. The numerical study on 2 inch line orifice system supports this finding. The pressure drop across such a plate is given in fig-7 which is less than the value predicted for standard orifice plate shown in fig-6. The flow rate measurement error is plotted as a function of fillet radius and bore diameter ratio. The resulting plot is shown in fig-11.

The trend line drawn from the points achieved after simulation, shows that the measurement error follows almost a linear path.

Effect of Plate Buckling

According to the simulation result, it is found that orifice plates having buckling problem, under-measure the flow rate. The change in differential pressure due to increase in effective diameter of orifice is the main and ultimate cause of this error. Differential pressure across a 8^0 bent plate is also shown in fig-8 which is relatively less than the value obtained for standard orifice plate shown in fig-6. The velocity profile is also presented in fig-5 in 2D format.

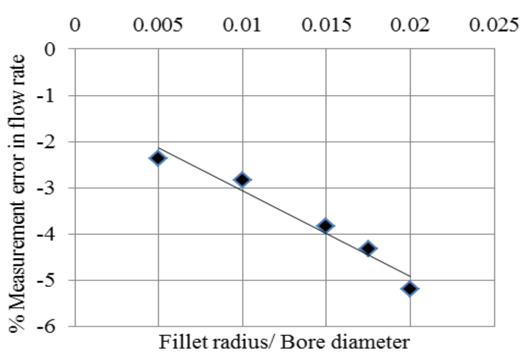

Fig-11 Variation in flow measurement error with change in fillet radius in upstream edge

The error in flow measurement may be as high as near 3.5%. It is also observed that, the error increases significantly for first 2 degrees of buckling, and then the rate slows down for next couple of degrees and again increases for higher values of buckling angles. Comparing simulation results for 2 inch and 4 inch line size, it is also found that, the error in measurement decreases with increasing line size for similar β-ratio. The resulting graph is plotted against Mason, Wilson and Birkhead correlation data and shown in fig- 9 and fig-10. It can be concluded that, the Mason, Wilson and Birkhead formula works fine with lower angle of bending but, the deviation of the exact amount of error increases with intensification of orifice plate bending angle.

4. CONCLUSION

Numerical simulations on 2 inch and 4 inch line size orifice plates with standard k-ε turbulence model were carried out considering two types of deformations, namely plate bending and rounding of sharp edge. Measurement errors have been evaluated for various edge radius and plate buckling angle. Under-measure of the flow rate have been predicted and compared with other correlations. For lower values of deformation, predictions are generally in good agreement with correlations by others. For higher values of deformations existing correlations fail to predict the measurement error.

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6. NOMENCLATURES

Symbol	**Meaning and Unit**
D	Pipe diameter, m
d	Orifice bore diameter, m
β	Beta (β) ratio = d/D
Re	Reynolds number
P	Density, kg/m^3
C_d	Discharge coefficient
C_c	Coefficient of contraction
ΔP	Differential pressure across orifice plate, Pa

Symbol	**Meaning and Unit**
U	Time averaged mean velocity,
Q	Mass flow rate, kg/s
k	Turbulent kinetic energy, m^2/s^2
ε	Dissipation rate of turbulent energy, m^2/s^3
θ	Angle of bending of orifice plate, degree
$C_{\varepsilon 1}, C_{\varepsilon 2}, C_\mu$	Empirical constants for turbulence model
u_τ	Frictional velocity
C^+	Universal constant for smooth walls
k	von Karman constant
T	Stress tensor
F	Volume force, N/m^3
U^+	Flow velocity
σ_k, σ_ε	Turbulent Prandtl number based on k and ε

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