Metrological Comparison of Metering Characteristics of Differential Pressure Meters

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Abstract: It is often difficult to realize calibrated accuracy of a flow metering system over measurement range when it is installed under hostile and perturbed flow conditions. Though widespread studies are reported in literature on individual characteristics of meters, comparative evaluation of the performance of these devices under real life installation situations is relatively inadequate. Present study compares classical venturi, cone, standard orifice and new slotted orifice and four hole orifice meters. Experiments are carried out to investigate the effects of single elbow, double elbow in and out of plane, reducer, and expander on the response characteristics of these devices. Discharge coefficients and pressure loss characteristics are analyzed and compared. Pressure and velocity variations created by the flow element restrictions with adjacent meter tubing are also analyzed with computational fluid dynamic simulations. Minimum upstream straight pipe lengths to suppress the effects for each of these tested flow meters are proposed.

Keywords: Classical venturi meter, Orifice meter, Cone meter, Slotted orifice meter, Four hole orifice meter, Discharge and flow coefficients, CFD

1. Introduction

Flow meters are designed to accurately measure the flow rates in many process, power, chemical and steel industries in order to assess overall plant efficiency, mass balance of material, billing in custody transfer, control, indication, alarm etc. There is always concern about installation effects, especially on meters in non ideal field conditions where mean velocity profile deviates from a 'fully developed' turbulent pipe flow by having deficit at centerline and higher velocities at the outer edges of the pipe. Further, there are always additional uncertainties that may arise if the installation does not conform to ISO standards [1,2] where perturbations in velocity profiles are caused by the fluid interaction with pipe fittings. This paper presents comparative investigations both by experiments and CFD to provide insight into the characteristics of conventional and new metering approaches.

2. Differential Pressure Meters

Method of flow metering consists basically determination of the pressure difference across the element and estimating corresponding volume flow rate. Applying Bernoulli and continuity equations for two sections of the flow system shown in Fig.1, with underlying assumptions of

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steady, one dimensional, uniform, frictionless, incompressible flow, final mass flow rate is given by
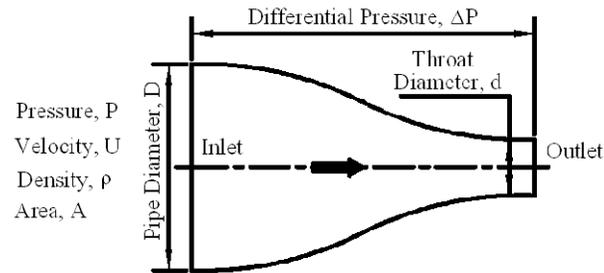

Fig. 1. Differential Pressure Meter Geometry

$$m = C\frac{\pi d^2}{4}\varepsilon\frac{1}{\sqrt{1-\beta^4}}\sqrt{2\rho\Delta P} \qquad\qquad (1)$$

Alternately

$$m = K\frac{\pi d^2}{4}\varepsilon\sqrt{2\rho\Delta P} \qquad\qquad (2)$$

Where $K = C\dfrac{1}{\sqrt{1-\beta^4}}$ $\qquad\qquad$ (3)

ε : Expansion Factor, $\beta = \sqrt{FlowArea/PipeArea}$ C: Discharge Coefficient, K Flow Coefficient

3. Selected Studies on Differential Pressure Devices

Irving [3] studied the effects of pipe fittings on the flow through the orifice meter and observed that standards were inadequate in specifying minimum straight lengths. Reader Harris [4] extensively investigated orifice plate discharge coefficients to develop correlations between fluid and geometrical factors. Morrison et al [5] experimented to find out the effects of swirl on orifice meters on different β ratios and concluded that larger β ratio orifice plates are more susceptible to swirl than smaller β ratio orifice plates. Mattingly et al [6] studied the decay of swirl and its effects on flow measurement accuracy and modeled orifice plates with β ratios from 0.4 to 0.7 and Reynolds Numbers in the range 10^4 to 10^6. Classical venturi meter has restriction with a relatively long passage with smooth entry and exit, minimizing entry losses and recovering pressure energy with less overall pressure loss. It would produce less permanent pressure loss than a similar sized orifice. Stewart et al [7] analyzed cone meters using differential pressures, measured between a tap on the pipe wall and a second tap on the downstream end of the cone and thus calculated the flow rates. This special construction woud provide some "Conditioning" of the flow field by redistributing the kinetic energy and creating a more or less uniform flow field. Ifft et al [8] analyzed the installation effects on a cone meter of flow disturbances with 90^0 long radius elbow with R/D=1.5 and double elbows out of plane and found that cone meter was performing better even for zero upstream piping length. Prabhu et al. [9] investigated the effects of single 90^0 mitre elbows and double 90^0 in and out of plane on the performance of cone meter and orifice meter over Reynolds numbers ranging from $3*10^4$ to $4.94*10^5$ for a constant β ratio of 0.75 with air. Morrison et al. [10] investigated a slotted orifice flow meter to address the problem of upstream flow conditioning and

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comparatively evaluated the performance of a standard and a slotted plate and found that the slotted plate was less sensitive to upstream flow conditioning as the slots themselves conditions the flow breaking the irregularities in upstream flow fields into small jets that were issued through the orifice slots. Four hole orifice meter [11] would differ from standard orifice meter primarily in number of holes bored through the meter and its orientation to fluid flow. It is believed that this also conditions the flow, minimizing the requirements for upstream straight run for most disturbances.

As the preceding survey of different technologies indicates, there is a deficiency of data for a systematic comparison of these devices and standardization of new meters. In this paper, different metering approaches having constant diameter ratio are compared under diverse real field installation conditions both experimentally and CFD Analysis.

4. Experimental Schemes

In a typical metering layout, swirl is caused by interacting elbows in same or different plane. Flattening of the velocity profile is caused by a conical reducer and expander results in small amount of reverse flow close to the wall owing to the separation of the boundary layer. The fittings selected are single 90° elbow, Double 90° elbow in same plane, Double elbow in and out of plane, reducer of 0.15-0.1m and an expander of 0.075-0.1m. Experiments are conducted at various flow rates with air as the working medium in a set up similar to shown in Fig.2.
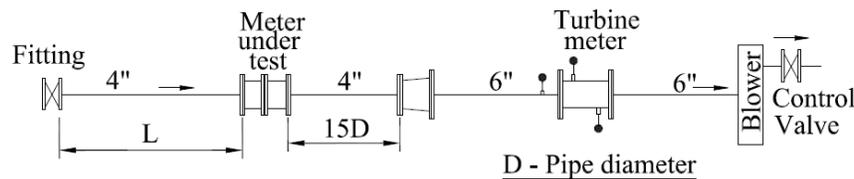

Fig.2. Experimental Schemes for Installation Studies

Initially, each flow device is tested by providing more than the minimum required straight lengths. The discharge coefficients calculated from these experiments are applied for comparative metrological performance. Variation of discharge coefficient with Reynolds number is calculated for flow rates in the range 90-600 m³/h. The effect of upstream distance is measured by changing the straight pipe length L (between the upstream fittings and the flow meter) from 0 to 40 D. Practically, the effect of fittings is largely understood as the resultant effect of the velocity profile, secondary flows on the impact pressure, and the jet contraction. These effects are summarized and quantified in terms of the resultant change in discharge coefficients of the tested element which is expressed in percentage. With this representation, a negative change in the discharge coefficient implies that application of undisturbed discharge coefficient always over estimates the mass flow rate in the pipe and vice versa. Discharge coefficient is given by

$$C = \frac{Actual\,mass\,flow\,rate}{Theoretical\,mass\,flow\,rate} = \frac{m_r}{m_t} \qquad (4)$$

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Theoretical mass flow rate m_t is calculated using Eq. (1) assuming unity for C. Actual mass flow rate m_r is determined using equations relevant to reference metering systems. β is calculated using the following relationships for different devices. $\beta = d/D$ for Venturi and orifice, $\beta = \sqrt{(D-d)/D}$ for Cone meter, $\beta = \sqrt{As/A}$ for Slotted orifice, $\beta = \sqrt{4d^2/D}$ for four hole orifice plate, $K = C/\sqrt{1-\beta^4}$, $\Delta C = (C-Ci)/Ci \times 100$. Ci : Discharge Coefficients at Ideal conditions, A_s : Area of Slots, A : Pipe Area. Table 1 gives the specifications of flow loops used for various tests with standard installation.

Table 1.Specification of Test facilities

| Sl. No.	Facility	Specifications
1	Low Pressure Air	Flow rate : 10000 m³/h,Reference : Sonic Nozzles, Uncertainty : 0.25% Pressure : 100 kPa(a),Temperature : 25± 1ºC, ISO 9300 [12]
2	100 mm Water	Flow rate : 250 m³/h, Reference : Weighing Uncertainty :0.04%, Pressure: 160 kPa (g), ISO 4185 [13].
3	Closed Loop Air	Flow rate : 400 m³/h, Reference : Turbine Meters, Uncertainty : 0.3%, Pressure : 200-2000 kPa, Temperature : 25± 1ºC, ISO 9951 [14]
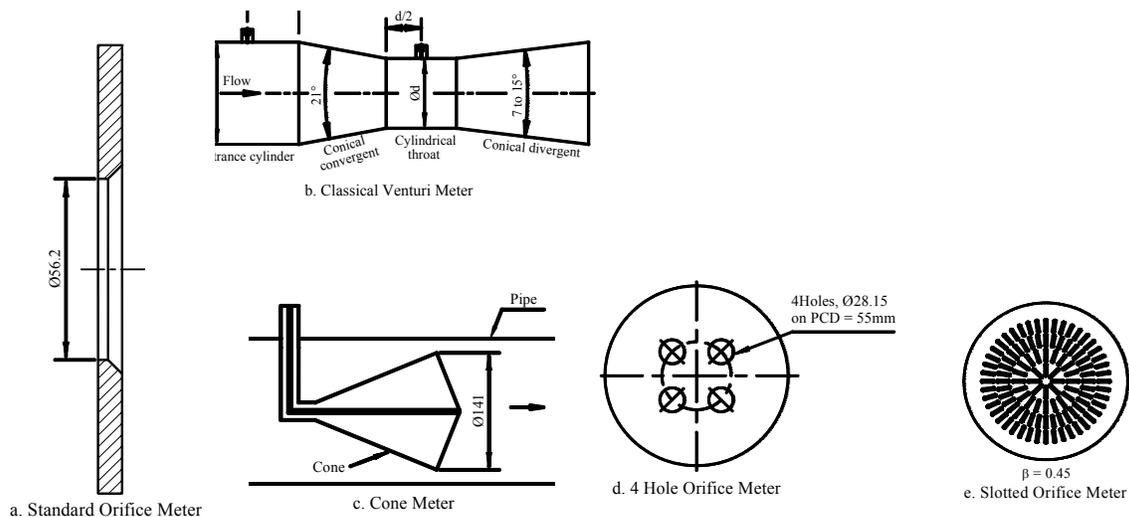
Fig. 3. Geometry of Devices

Orifice and venturi meters conform to the respective ISO standards. Cone meters, slotted and four hole orifice are custom built proprietary devices as they are yet to be standardized. A beta ratio of 0.55 is selected except for the slotted orifice which is having a beta ratio of 0.45. The reason being that the slot orientations and pitch diameters exceeds the pipe internal diameter. Fig.3 defines the geometry and Table 2 lists the actual dimensions of the devices. For venturi meter, the differential pressure is sensed between pressure taps located at 0.5 D upstream of the inlet and at middle of the throat. Irrespective of the type of orifice, flange taps are used for pressure measurements.

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Table 2 Dimensions of Differential Pressure Devices

Sl. No.	Meter	Orifice/hole diameter and diameter ratio (ß)
1	Classical venturi	Throat diameter,d=0.0565m for ß=0.55
2	Standard orifice	Orifice bore :d=0.0565m for ß=0.55 Orifice bore : d=0.0460m for ß=0.45
3	Cone	Cone Diameter : d=0.0854m
4	Four hole orifice	Hole diameter : 0.2802 for ß 0.55 Hole diameter : 0.0230 for ß= 0.45
5	Slotted orifice	Total slots : 110 ,Slot length : 0.0563 for ß = 0.55, Slot Length : 0.04604 for ß= 0.45

5. Discharge and flow coefficients

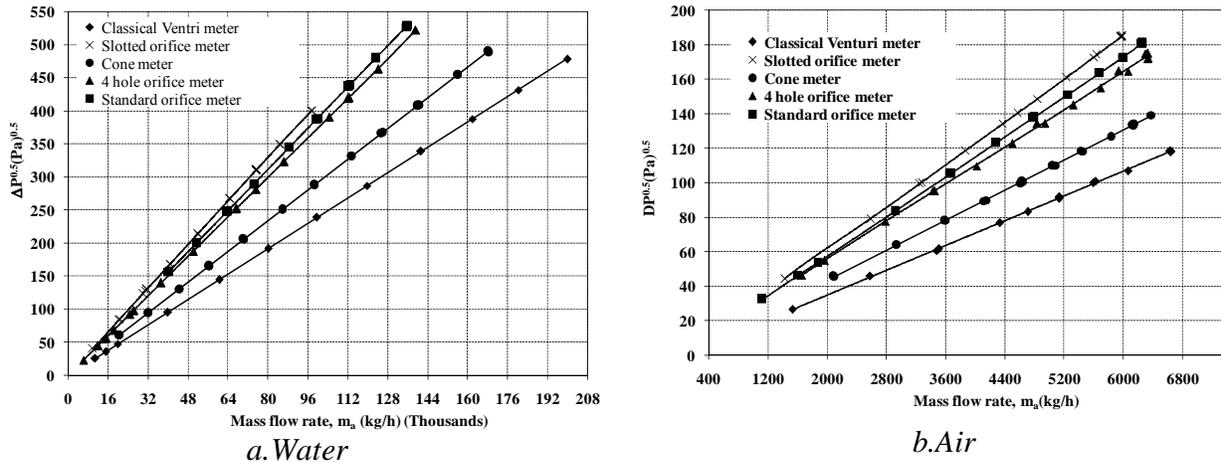As seen in Fig.4, m and $\sqrt{\Delta P}$ has approximately linear relationship for all devices with different slopes.

a.Water   *b.Air*

Fig.4. Variation of m and $\sqrt{\Delta P}$

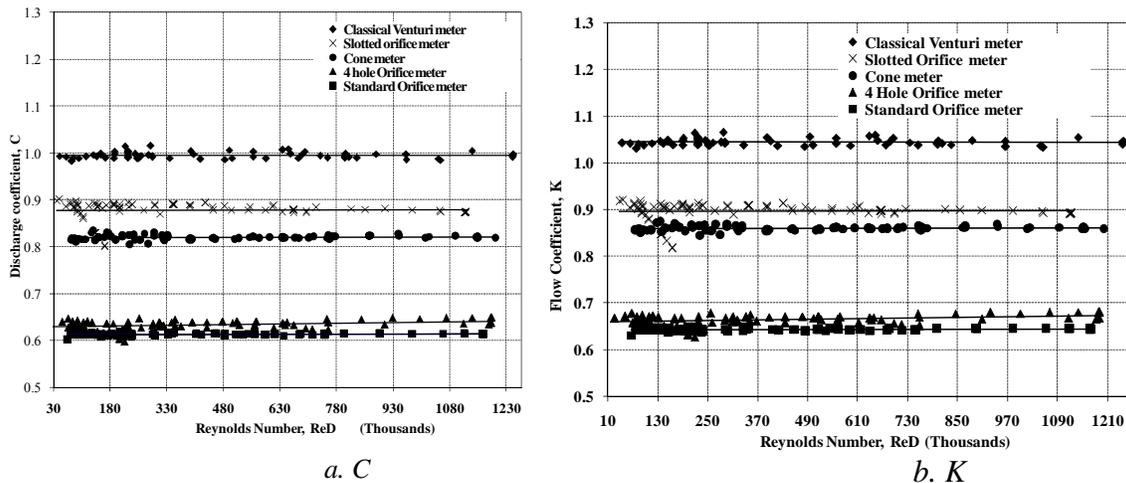*a. C*   *b. K*

Fig. 5. Variation of K and C with Reynolds numbers

In order of increasing differential pressure, the devices are grouped as classical venturi, cone, four hole orifice, standard orifice and slotted orifice meters. Flow and discharge coefficients exhibit gradual increasing trend with Reynolds number as shown in Fig.5. Test results show mean C of 0.995, 0.613, 0.82, 0.633, 0.896 and K of 1.044, 0.6430, 0.860, 0.664 and 0.896 respectively for venturi, standard orifice, cone, four hole orifice and slotted orifice meters. When compared to standard orifice, venturi meter has about 65%, cone meter about 34%, four hole orifice about 1-5% higher flow coefficients.

6. Effects of Pipe Fittings

Pipe fitting configurations tested are given in Fig.6. From a practical viewpoint, it is very important to find the required minimum value of pipe length L,L $_{min}$, for each pipe fitting needed to suppress its effect to a certain level. ISO standard for orifice meters specifies two kinds of L_{min} corresponding to suppressing levels of 0.5% and 0%. The standard fixes Lmin (0.5%) at 0.25-0.5 of L_{min} (0%). However, this relation is being thought to be unreal. For good results, the resulting flow pattern have to be stationary i.e. fixed flow pattern at a fixed position enabling assignment of error shifts with flow patterns. Effects of various fittings on different flow meters are depicted in Figs.7-11. In each case, the percentage change in discharge coefficient, ΔC% is plotted against the distance L/D. Fig.7a presents the effects of single elbow swirl with decreasing trend and variation up to -2%, when compared to the reference value. The highest deviation is nearest to 0 D and lowest near 40 D. In real situation the meter is over reading with high average pressure drop. Single elbow has relatively less effect on venturi meter, four hole orifice and cone meter when compared to standard and slotted orifice meters. With double elbows, closely coupled without any spacing between them present in same plane, the profile distortions are complex and are experiencing high differential pressure resulting in higher flow rates. Effect of swirl extends up to 40 D in case of standard and slotted orifice meters. For four hole and venturi meter, the effects extend up to 15 D and cone meter is least influenced (Fig.8). The discharge coefficients are reduced with   deviations up to about -1.8%. It is well known that double elbows out of plane configuration generate swirl flows which hardly decay even fairly far downstream whose direction depends on the orientation of the elbows. With this configuration, effects of swirl are relatively high when it is compared with in plane configuration (Fig.9), producing higher deviation   up to 2.5%. Uniform reducer is accelerating the fluid flow creating a velocity profile flattening. Consequently the shift is less when compared to above configurations with maximum deviation up to -2%. Effect persists till 40 D for slotted orifice and 14 D for four hole orifice (Fig.10). With orifice, venturi and cone meter, the effect persists for relatively shorter distances i.e. 4-15D. Expander presents symmetric gradual increasing passage resulting in separation of fluid from the boundary wall resulting in eddies. The percentage deviation is up to -1.8 (Fig.11). A straight length of 20 D is required for the slotted and orifice meters to achieve desired accuracy. Cone meter has relatively better response causing a shift in the range of - 0.84-1.5% for all combination of fittings. Similarly the venturi meter shifts in the range -1.12-0.92%. Four hole orifice meter has shift of -1.27-1.59%. Above devices inherently conditions the flow, owing to their design. A shift of up to 2% in the discharge coefficient is reported for cone meter [9] which is comparable to the present studies. Based on the current study, Table 3 proposes minimum straight lengths for two uncertainties. Standard and slotted orifice requires more than 40 D for most of the fittings which is contrary to the existing norms. ISO [1] stipulates maximum of 10 D. Table 4 gives the current specifications

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for orifice meter. Slotted orifice meter, when compared to the standard orifice of equivalent diameter ratio, has higher shifts for all combination of fittings present at upstream. Double elbow out of plane configuration has the highest shift of up to about -2.58%. Otherwise the maximum shift is about -0.72% for standard orifice.
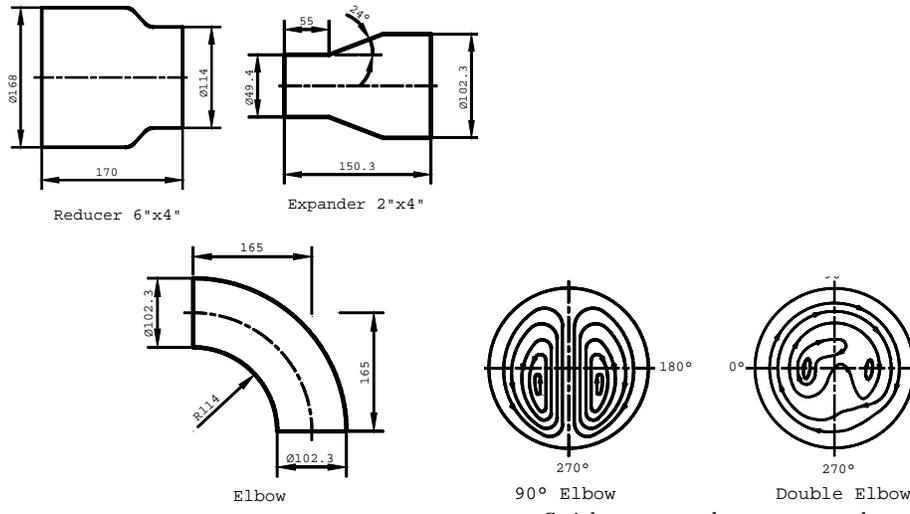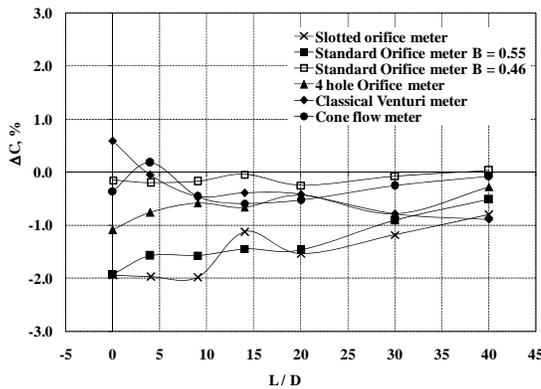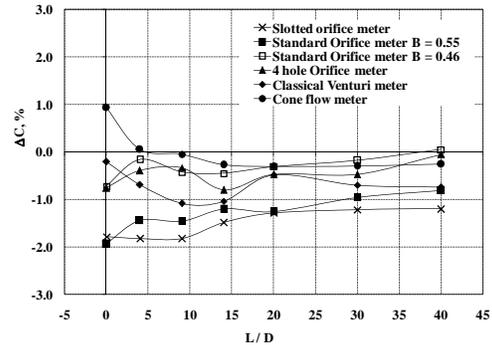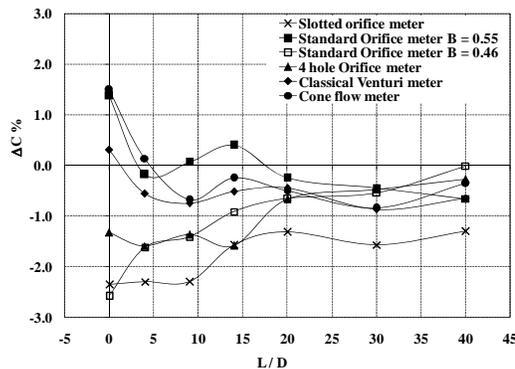

Swirl pattern at downstream end

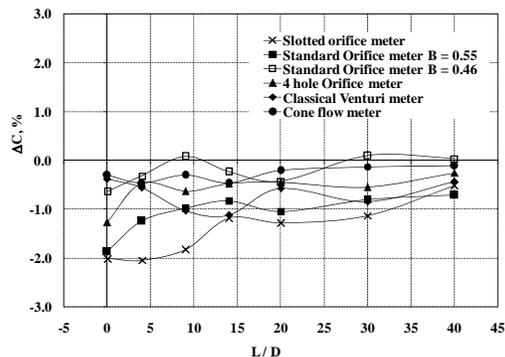*Fig.6 Pipe Fitting Configurations*

7. Installation Effects Single Elbow

8. Installation Effects Double Elbow in Plane

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9. Installation Effects of Double Elbow out of Plane

10. Installation Effects of Reducer

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Table 3. Proposed Straight Lengths

1	Single 90 elbow		Two 90° elbows in plane		Two 90° elbows out of plane		Expander		Reducer	
	2		3		4		5		6	
	A	B	A	B	A	B	A	B	A	B
Standad Orifice	40	30	40	30	40	30	40	20	40	20
Venturi Meter	9	0	9	0	9	0	20	0	20	0
4 Hole Oifice	9	0	14	0	20	9	9	0	9	0
Slotted orifice	40	40	40	40	40	40	30	20	30	20
Cone meter	0	0	4	0	9	0	0	0	0	0
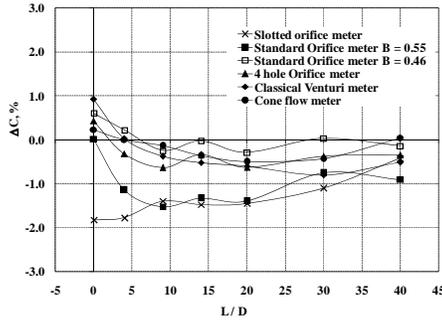
A : Lengths corresponding to zero additional Uncertainty
B Lengths corresponding to 0.5 % additional Uncertainty

11. Installation Effects of Expander

Table 4 Straight length between Orifice Meter and Fittings

Diameter ratio	Single 90 elbow		Two or more 90° elbows		Expander 0.67D to D		Reducer 3D to D	
	A	B	A	B	A	B	A	B
0.40	8	3	8	3	4	-	2.5	-
0.50	9	3	10	3	5	4	5.5	-
0.60	10	3	10	3	6	4	8.5	2.5

7. Measurement Uncertainty in Discharge Coefficient

Measurement uncertainty in C is estimated as per [15]. Following major component uncertainties are considered for evaluating the propagation of experimental errors and their contribution. Pressure: 1.05 mbar (Reference), 0.58 mbar (Test), Differential Pressure: 6 Pa, Temperature: 0.07^oC, Pulse: 1, K Factor for turbine meter: 0.5%. Combined overall uncertainty in C is 0.53 %.

8. CFD Analysis and Comparison of Data

Velocity and pressure variation through the devices are analyzed numerically using CFD. Due to turbulent nature of fluid flow, characterized by the high Reynolds Numbers, two equations turbulence model each for transfer of kinetic energy of turbulence and specific rate of kinetic energy dissipation is applied using k-ε model for numerical computation.

8.1. Velocity Distribution and Velocity Vectors

In general, axial fluid velocity continuously increases along the convergent section and reaches maximum at the throat due to the transformation of pressure into kinetic energy and drops gradually in the divergent section due to reconversion of kinetic energy into pressure energy. Because of increasing flow area and reduction in density, velocity at exit remains higher than that is present at inlet. Axial velocity contours for 16 bar, 180 m^3/h are presented in Fig.12. Fig.12a. shows clear and gradual development of velocity through the meter. Close to the wall, velocities are minimum, approaching zero and towards the centre, the velocity reaches maximum. Fig.12b shows symmetric distribution with central zone having maximum velocity.

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Stagnant zones are visible at both upstream and downstream of the orifice device. Fig.12c exhibits velocity distribution which is characteristic for intrusive type of meters. At downstream of the cone, stagnant zones are formed into vortices and eddies. At backside of the cone, velocity vector circulates and vortices are formed. Along downstream convergent edge, the flow is stagnant with stagnant zones present behind the cone. Velocity profiles are severely disturbed at outlets of cone and slotted orifice meter contour with high permanent pressure drop than different types of orifices. Velocity pattern of four hole meter is similar to that of standard orifice. Velocity defects are observed and static pressure recovery reaches steady state value within short distance due to better mixing of multiple fluid streams. With hemispherical distribution at entrance, a smooth conical contour at downstream and far downstream, the contour merges forming a single envelope. At downstream of slotted orifice (Fig.12e), velocity rises with subsequent reduction which is typical to a diffusing jet which may be due to filling of the pipe by expanding jets, tending to mix and attain the mean velocity. At outlet vicinity, the pressure remains constant for a small distance and subsequently exhibits a gradual recovery trend. Four hole orifice plate is having highest permanent pressure loss. Fig.13 shows the velocity vectors through the elements at 16 bar and 180 m^3/h. Velocity vector corroborates the flow patterns and discussions on velocity contours.

8.2. Pressure Contours

Fig.14 shows pressure distribution contours for the five devices at maximum test conditions of 16 bar & 180 m^3/h. Static pressure difference between inlet and outlet represent permanent pressure drop across the meter due to expansion and eddy loses in the flow path. With smooth variation of pressure from inlet to outlet, venturi meter exhibits minimum pressure drop (Fig.14a). Standard orifice meter shows quick pressure recovery at downstream (Fig.14b). Cone meter exhibits minimum pressure at downstream of cone and subsequent recovery as in Fig.14c. Four hole orifice behaves similar to standard orifice with stagnant zones present at the blind zone in between holes (Fig.14d). Slotted orifice requires longer recovery length when compared to other meters as can be inferred from Fig.14e. Table 5 compares experimental and computed differential pressures. The difference between the experimental and computed differential pressures is found to be about -14% to -16% for four hole orifice, ±10% for cone and standard orifice, 3% to 6% for venturi and a lowest of -3% to 0.3% for slotted orifice. The errors depend on complexity of the geometry. However in flow rates, it is within 4%.

Table 5 Comparison of Experimental and Computed Differential Pressures

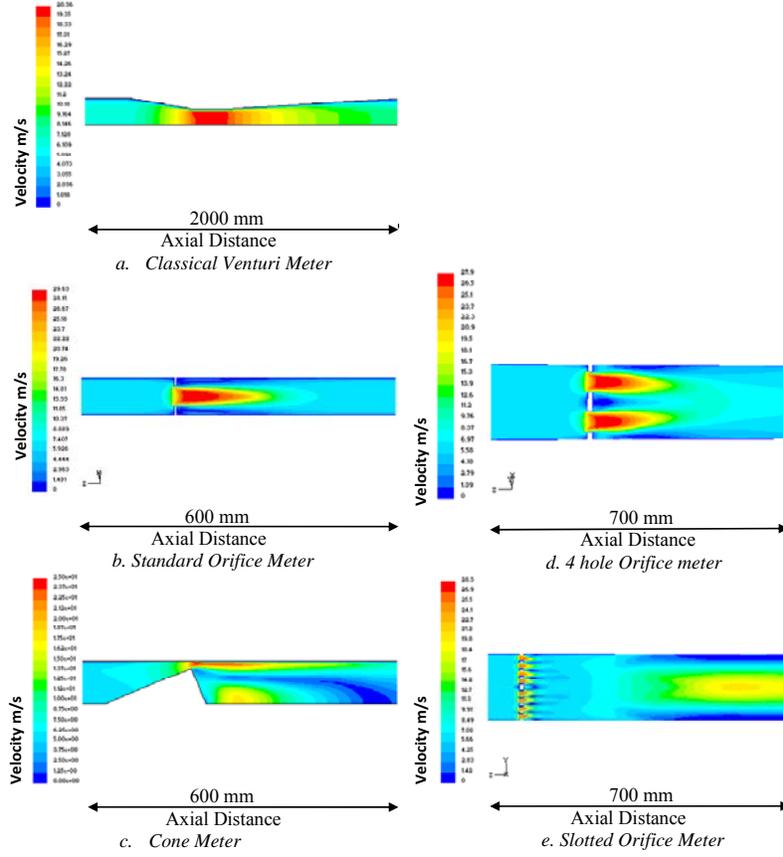| Meter	0.6 MPa			1.1 MPa			1.6 MPa		
	ΔP_{exp} ,Pa	ΔP_{cfd} ,Pa	% Difference	ΔP_{exp} ,Pa	ΔP_{cfd} ,Pa	% Difference	ΔP_{exp} ,Pa	ΔP_{cfd} ,Pa	% Difference
Venturi	1261	1296	2.8	2231	2365	6	3288	3437	4.5
Cone	1855	2045	10.2	3410	3715	9	4898	5400	10.3
Four hole	3182	2673	-16	5740	4910	-14.5	8310	7169	-13.7
Orifice	3330	2980	-10.5	6153	5466	-11.2	8865	7965	-10.2
Slotted Orifice	3863	3749	-3	6836	6855	0.3	10002	10034	0.3

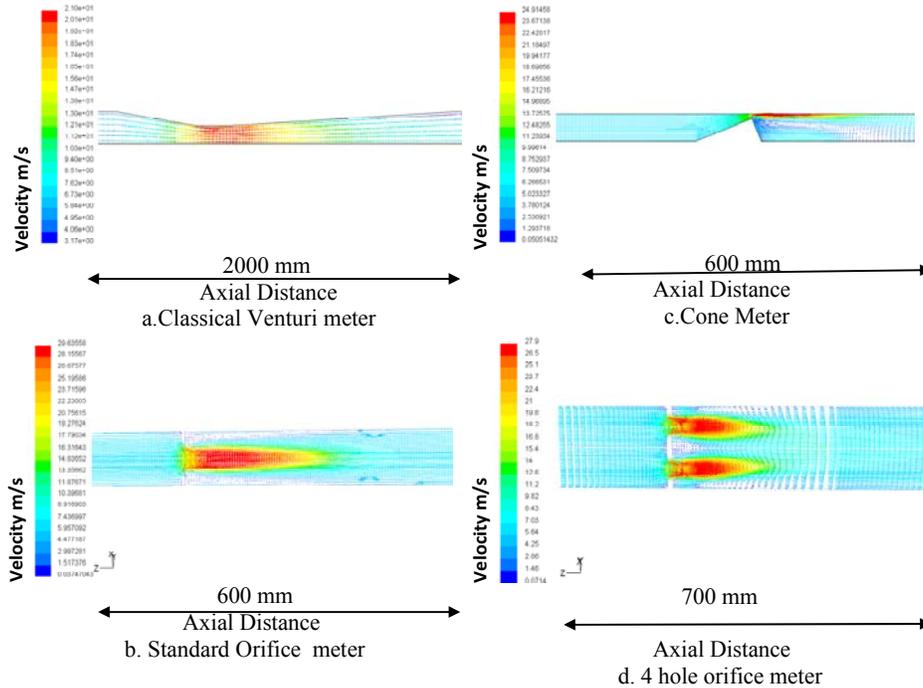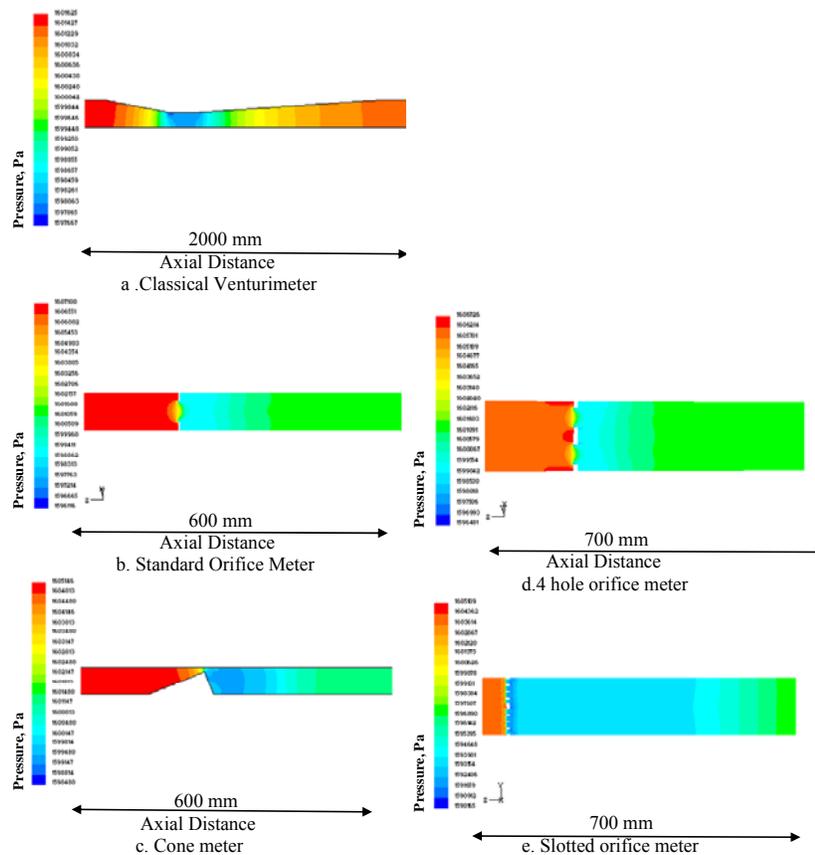*Fig. 12. Velocity Contours (16 bar, 180 m³/h)*

Fig. 13. Velocity Vectors (16 bar, 180 m³/h)

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14. Pressure Contours (16 bar, 180 m^3/h)

9. Conclusions

Metrological performances of classical venturi meter, standard orifice meter, new designs of cone meter, slotted orifice meter and four hole orifice meter are studied. Experimental discharge coefficient behaviors and pressure loss characteristics of the devices are analyzed. Mass flow rate, m and $\sqrt{\Delta P}$ has linear relationship for the devices but with different slopes. Test results show mean C of 0.995, 0.613, 0.82, 0.633, 0.896 and K of 1.044, 0.6430, 0.860, 0.664 and 0.896 respectively for venturi, standard orifice, cone, four hole orifice and slotted orifice meters. Considering the value of C of the standard orifice as reference, venturi meter has about 65% , cone meter about 34% ,four hole orifice about 1-5% higher flow coefficients. Cone meter has a shift in the range of - 0.84-1.5% for all combination of fittings. Similarly the venturi meter shifts in the range -1.12-0.92. Four hole orifice meter has shift of -1.27-1.59%. These devices inherently condition the flow owing to their design. In general, it may be concluded that the cone meter and four hole orifice are less sensitive to swirl than the orifice meter. Based on the present study, minimum straight lengths with and without additional uncertainty are proposed. It is interesting that orifice meters require more straight lengths than the current specifications. CFD simulation is done for pressure and velocity distribution by modeling the meters together with inlet and outlet domain. Classical venturi meter, cone meter, slotted orifice meter, four hole orifice meter and standard orifice meter have increasing order of pressure drops. The difference between the experimental and computed differential pressures is found to be about -14% to -16% for four hole orifice, ±10% for cone and

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standard orifice, 3% to 6% for venturi and a lowest of -3% to 0.3% for slotted orifice. Flow rates are comparables within 4%. The results are within the accuracy anticipated for numerical simulations, depending on the complexity of the geometry.

Acknowledgements

References

[1] Measurement of fluid flow by means of pressure differential devices inserted in circular-cross section conduits running full Part 2: Orifice plates. ISO 5167-2; 2003.

[2] Measurement of fluid flow by means of pressure differential devices inserted in circular-cross section conduits running full Part 4: Venturi Tubes. ISO 5167-4; 2003.

[3] Irving, S.J. The effect of disturbed flow conditions on the discharge coefficient of orifice plates. Int J Heat Fluid Flow 1979; 1:5-11.

[4] Reader Harris MJ, Sattary JA.The orifice plate discharge coefficient equation. Flow Meas and Instrum 1998; 1: 103-9.

[5] Morrison GL, Deottee RE, Moren M, Hall KR, Holste J C.Beta ratio, swirl and Reynolds number dependence of wall pressure in orifice flow meters, Flow Meas Instrum 1990; 1; 269-277.

[6] Mattingley GE, Yeh TT. Effects   of pipe elbows and tube, bundles on selected types of flow meters. Flow Meas Instrum 1991; 2; 4-13.

[7] Stewart D, Hodges D, Steven R, Peters RJW. Wet Gas Metering with V-Cone Meters. Proceedings of the 20th International North Sea Flow Measurement Workshop; October 22–25, 2002.

[8] Ifft S, Mikkelsen ED.Pipe elbow effects on V-cone flow meter.FED.Fluid Meas Instrum. ASME 1993; 161.

[9] Prabu SV, Mascomani R, Balakrishnan K, Konnur MS.Effects of upstream pipe fittings on the performance of orifice and conical flow meters. Flow Mesa Instrum 1196; 7; 49-54.

[10]   Morrison GL, Dwayne Terracina, Carl Brewer, Hall KR. Response of a slotted orifice flow meter to an air/water mixture. Flow Meas Instrum 2001;12 ;175-180

[11]   Emerson Process Management. Rosemount Conditioning Orifice Plate in Wet Gas.

[12]   Measurements of gas flow by means of   critical flow venturi nozzles. ISO 9300;2005

[13]   Measurements of Liquid flow in closed conduits using weighing method. ISO 4185 ;1980

[14]   Measurement of gas flow in closed conduits - Turbine meters". ISO 9951 : 2005 (E) "

[15]   Calculation of the uncertainty of measurement of flow rate. ISO 5168