METROLOGICAL ASPECTS OF INDUSTRIAL FLOW METERING SYSTEMS

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ABSTRACT

Accuracy and precision of flow meters are the most important metrological parameters in most industries dealing with increasingly expensive fluids such as petroleum, natural gas and water. The accuracy of these devices depends mainly on their position in a pipe network and their operating conditions. Pipe fittings such as valves, bends and other fixtures generate turbulence and swirl and distort the flow distribution in the pipe leading to a substantial amount of measuring error. The paper discusses results of a research project on the metrological performances of industrial flow meters under real operational conditions. Experimental and numerical results on the effects of non-standards operating conditions (swirling flows generated by a double bend out of plane) on the accuracy of orifice flow meters and the efficiency of flow conditioners to eliminate these effects are presented and discussed. The results obtained during the research programme show that the error caused by such non-standards operating conditions can be very important and is well beyond the error limit tolerated by international standards (ISO 5167). The efficiency of flow conditioner to improve the quality of the metering operation is tested and investigated.

Key Words : *Metering error, Accuracy, Metrology, Orifice Flow meters, Pipe flow, International Standards ISO, Computational Fluid Dynamics, Laser Doppler Anemometry.*

1. INTRODUCTION

Orifice plates have been used for flow measurement for many years for process and fiscal purposes. The ability to accurately measure the gas flow rate in a duct is of a major concern and vital importance when large volumes are handled. Gas and Petroleum companies recorded receipts of billions of barils or cubic meters (m^3) of gas and petroleum over a period of one year. The quality of gas measurement, receipt and major delivery points distributed through thousands of km of pipe lines, is very important from an economical and technological stand points. Errors in flow measurement can have large cost and efficiency implications.

The majority of the meters must be calibrated. This is done in fully developed pipe flow, axisymmetric, free from swirl and pulsation. Standards such as ISO 5167 and AGA3/ASME 2530 define a satisfactory flow as one which has a swirl angle less than two degrees and for which the axial mean velocity is within ±5% of the corresponding fully developed profile measured in the same pipe after 100 pipe diameter of development length. Given that most industrial installations include pipe fittings such as bends, valves, expanders and reducers, which are sources of both swirl, asymmetries and turbulence distortions, insuring that fully developed flow in terms of mean flow and turbulence structure approaches the meter is difficult to achieve in practical and industrial situations. While high accuracy about $\pm 0,1\%$ flow rate measurement is required, disturbances in the flow caused by contractions, bends, and other components introduce metering errors of the order of ±5% and greater (Yeh and Matingly 1996).

For best accuracy, a flow meter needs to be presented with an axisymetric, fully developed velocity profile with zero swirl. Either very long lengths of straight pipe work upstream of the meter must be provided (recommended by ISO 5167) and these may need to be of the order of 80 to 100 pipe diameters, which will give a higher installation cost and greater space requirement. Alternatively, upstream disturbances can be attenuated by using flow conditioner to control the quality of the flow approaching the metering device.

A fundamental understanding of the approaching velocity profiles and their effects on the discharge coefficient of a metering device is an essential knowledge for the optimum design of a flow conditioner-meter package that minimises installation effects and increase metrological performances of these devices. Concentrated research work undertaken at international laboratories and research institutes (Reader-Harris and Keegans (1986); Morrow et al. (1991), Gajan and Hebrard (1991), Morrison et al. (1992); Ouazzane and Laws (1994, 1997), Ouazzane and Barigou (1999), Merzkirch (1998, 2001), Aichouni and Laribi (2000, 2001) and more recently Barton (2002)) has been focused to investigate experimentally and computationally installation effects on industrial flow meters. Most of these studies investigated the effect of flow conditioner location with respect the flow meter on its calibration coefficients. The major conclusions show that the distortions in the approaching flow generated by pipe fittings upstream the meter can cause significant shifts in the meter's calibration coefficient, hence leading to considerable errors in flow metering.

In early papers presented by Aichouni et al. (1996, 2002) and Laribi et al. (2001, 2003) experimental and numerical results on installation effects upon Venturi and orifice flow meters were discussed. The present paper discusses further the results of the metrological performances of industrial flow meters under real operational conditions. Experimental and numerical results on the effects of non-standards operating conditions (swirling flows generated by a double bend out of plane) on the accuracy of orifice flow meters and the efficiency of flow conditioners to eliminate these effects are presented and discussed. The efficiency of flow conditioner to remove the flow distortion and produce the fully developed condition is investigated. In the present work flow conditioners to be investigated are : the 19 tube bundle, the Etoile flow straighteners (described in the standard ISO 5167 and AGA 3) and the Laws perforated plates both experimentally and numerically.

2 EXPERIMENTAL INVESIGATION OF THE INSTALLATION EFFECTS ON ORIFICE FLOW METERS

2.1 SCOPE OF THE INVESTIGATION

This first part of the research program has been undertaken within a PhD and an MSc theses to be submitted by the end of 2003. The purpose of this experimental programme was to study the decay process of highly swirling flow generated by a typical industrial piping element (a double bend out of plane) in a circular pipe and to evaluate the effect of such a distortion on the accuracy of the orifice meter. The efficiency of three flow conditioners to improve metering accuracy is also investigated.

2.2 EXPERIMENTAL FACILITY

The basic experimental facility is presented in figure 1. It consists of a long Plexiglas pipe with 100 mm inner diameter. The air flow was powered by a motor driving a centrifugal fan. The air enters the pipe through a nozzle then flows through a straight pipe of 11 pipe

planes. The double bend represents the source of the flow disturbance. A reference orifice meter is installed 97 pipe diameter downstream where the flow is fully developed. The tested orifice meter was first installed at 1.5D downstream of the double bend and then moved at different locations downstream. The orifice plates studied were of standard geometry and had pressure tappings one D upstream and D/2 downstream, where D is the inner pipe diameter. The static pressure (upstream and downstream of the meter) was measured by four pressure tappings connected to a multitube manometer. The opening diameters d of the orifices used are 50, 62 and 70 mm, so the respective ratios of the opening diameter to the pipe diameter, d/D, were β=0.5, 0.62 and 0.70. The three flow conditioners investigated in the present study are shown in Fig. 2 (a,b,c). Full details about their geometry and their operating condition an be found in the standards ISO 5167 and the AGA 3 or in Laribi et al (2003).

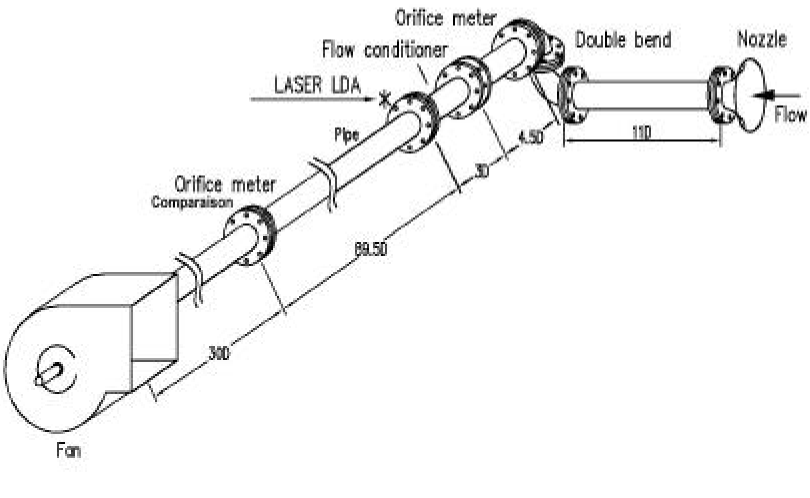


Figure 1. Flow meters and conditioners experimental facility

The mean and the fluctuating components of the velocity downstream the two elbows and the flow conditioners were measured using a two components Laser Doppler Anemometer. Tests have been done at Reynolds number ranging from 3 $x10^4$ to $11x10^4$. Profiles of the mean velocity and the axial turbulence intensity have been measured at different axial stations downstream of the double bend and the flow conditioners. Swirl angle was determined at every station from the measured axial and radial velocity components.

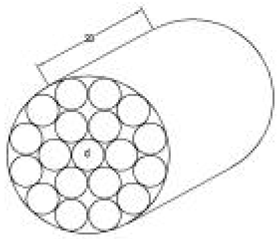
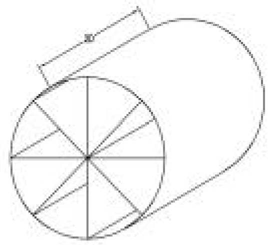
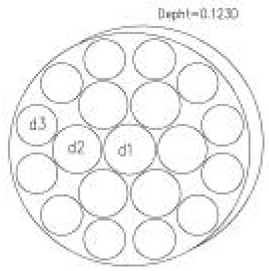
		
a - The 19 tube bundle flow conditioner (ISO 5167)	**b The Etoile flow conditioner (ISO 5167)**	**c The Laws plate flow conditioner**

Figure 2 The investigated flow conditioners

2.3 DISCUSSION OF THE EXPERIMENTAL RESULTS

2.3.1 - Flow development downstream the 90 degrees double bend out of plane

The first part of the research program was dedicated to study the decay process of highly swirling pipe flow. The radial distribution of the axial mean velocity U/U_{max} , the axial turbulence intensity Ix(%) and the swirl angle measured at axial stations z/D=0.8, 6, 9, 14, 22 are presented and compared to their fully developed values in figure 3. The figure shows that the double bend in two perpendicular planes generates a high distortion in terms of mean flow and its turbulent structure. The flow exhibits a pronounced asymmetry. The velocity profiles are higher on one side of the pipe. At the centre line there is a deficit of the velocity associated with relatively high level of turbulence which is due to the shear in the mean flow. The swirl angle measured at the same stations varied from

swirl angle limit fixed at ±

appears that the swirl angle profile needs more than 22 diameters to achieve its reference profile. It is clear that the flow distortion would take long downstream length to decay towards its fully developed condition. At distance of 22 pipe diameters from the disturbance source, the flow is far from fully developed. It is important to note here that the ISO 5167 specifies such a distance between this disturbance and the orifice flow meter. This would suggest that the lengths specified by the standards are not sufficient to guarantee fully developed flow condition. It is obvious that any flow meter operating under this condition would register a measuring error that should be quantified.

2.3.2 - Flow development downstream flow conditioners

The mean velocity profile development downstream the three flow conditioners is shown in figure 4. The velocity profiles were determined at four axial positions downstream of the double bend (z/D=6, 9, 14 and 22). The exit plane of each flow conditioner is positioned at station z/D=4.5. For the purpose of comparison the fully developed profile measured at station 91 D was included in the graphs. The influence of the conditioner on the velocity profile is clearly visible at the first measuring station z/D=6 downstream the double bend, i.e, 1.5 D downstream of the flow conditioner. The profile measured immediately downstream of the Etoile shows a central wake which is due to the solid centre of the conditioner near the pipe centre line. This influence however has mixed out of by z/D=14 to give a fairly flat distribution which is in fact less developed than the reference profile. The results show that the perforated plate appears to be an efficient flow conditioner regarding the redistribution of the flow and the production of an almost fully developed velocity profile within a short downstream distance. At station z/D=9 the axial velocity profile downstream the conditioners show a local minimum at the centre of the pipe. This disturbances decreases relatively quickly with increasing straight pipe length. The tube bundle and the Etoile still exhibit considerable deviation and need more than 22 D to develop towards the fully developed profile.

The swirl angles downstream the three flow conditioners, including the fully developed profile, are presented in figure 5. As it can be seen from figure 3 at the station z/D=0.8

z/D=22, the swirl angle decays to values efficiency of the three flow conditioners to reduce swirl from ± ±

is clearly visible from figure 5. At the far downstream position z/D=22 the swirl is about ± for the three flow conditioners. The best results were obtained by the tube bundle where the swirl angle is reduced from ± ±

conditioner and finally to a value of ±

plate conditioner showed a less good performance to remove swirl than the tube bundle. However, at station z/D=22 they both produce a angle of about ± hich is within the ISO limits of ±

remove tangential velocity component in the flow and suppress the swirl in particular. Figure 5 shows that all the three devices are capable of reducing swirl to manageable levels within and that all three units could meet the ISO swirl angle limit of ±

2.3.3 - Effect of upstream flow conditions on orifice meter Performance

Experiments were conducted to determine the relative change in the orifice meter discharge coefficient when subjected to non-standard approaching flow conditions such as the double bend in perpendicular plane. The test sections were 1.5, 6, 7.5, 12, 13.5 and 17.5 diameters downstream the double bend. The effect of the double bend on the orifice meter with a β=0.70 over a range of Reynolds numbers from 0.79×10^5 to 3.21×10^5 is shown in figure 6. The double bend out of plane produced a discharge coefficient error ΔCd(%) ranging from 1% to 2.74% depending on the Reynolds number for the orifice meter place at 1.5 D downstream. As the orifice meter is moved further downstream the flow distortion source, the discharge coefficient error decreases for all the flow Reynolds numbers. However, it has to be noted here, that even at 17.5 diameters downstream, the error in the discharge coefficient ΔCd still varies from 1.5% to 0.70% which indicate clearly that the flow at this station is far to be considered as fully developed. These errors are still beyond the ±0.5% limits required by the standards. It is well known that a double bend with a spacer of 1D, similar to the one used in the present experiments, produces an intense single eddy swirl that decays slowly in the downstream direction and would take much more length to develop and to reach the fully developed flow condition. This observation which is shown in the present results (figure 3), has been made by Yeh and Mattingly (1996) and Merzkirch and Kalkuhler (1998, 2001).

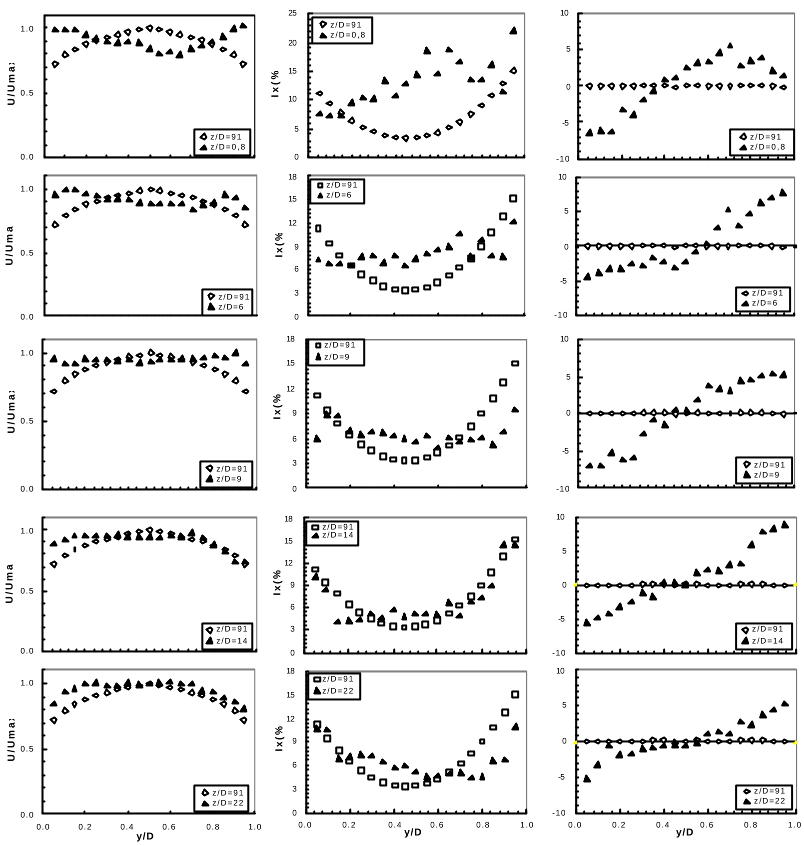


Figure 3 - Velocity profile, turbulent intensity and swirl downstream double bend without flow conditioner

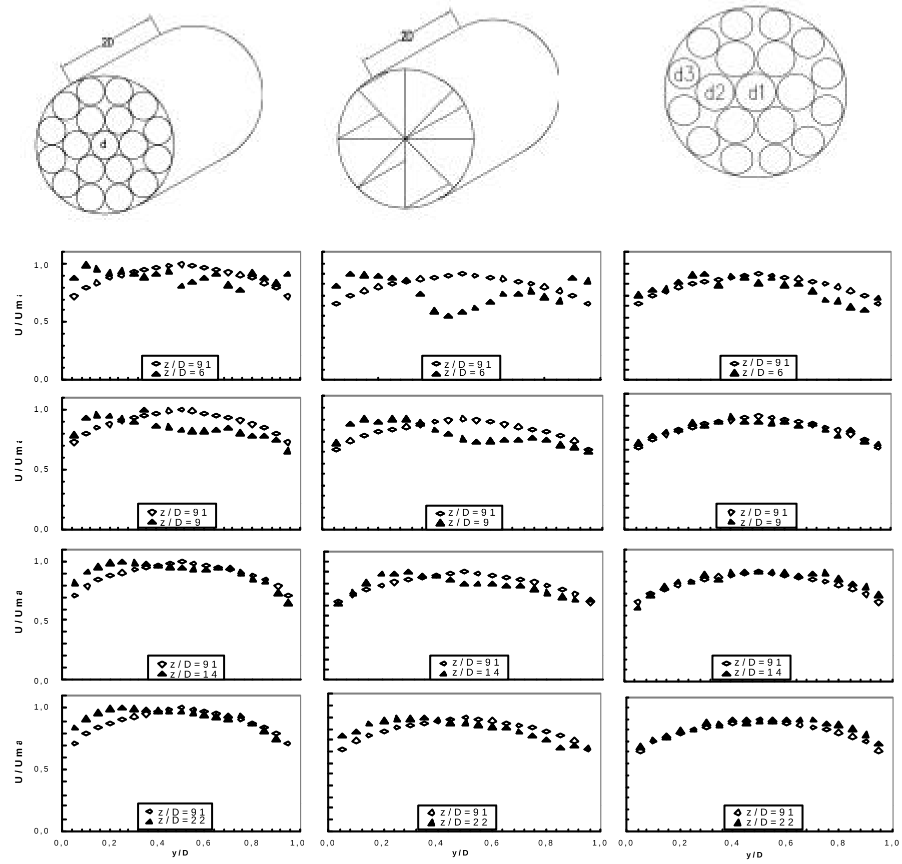


Figure 4 - Velocity profiles measured downstream the flow conditioners

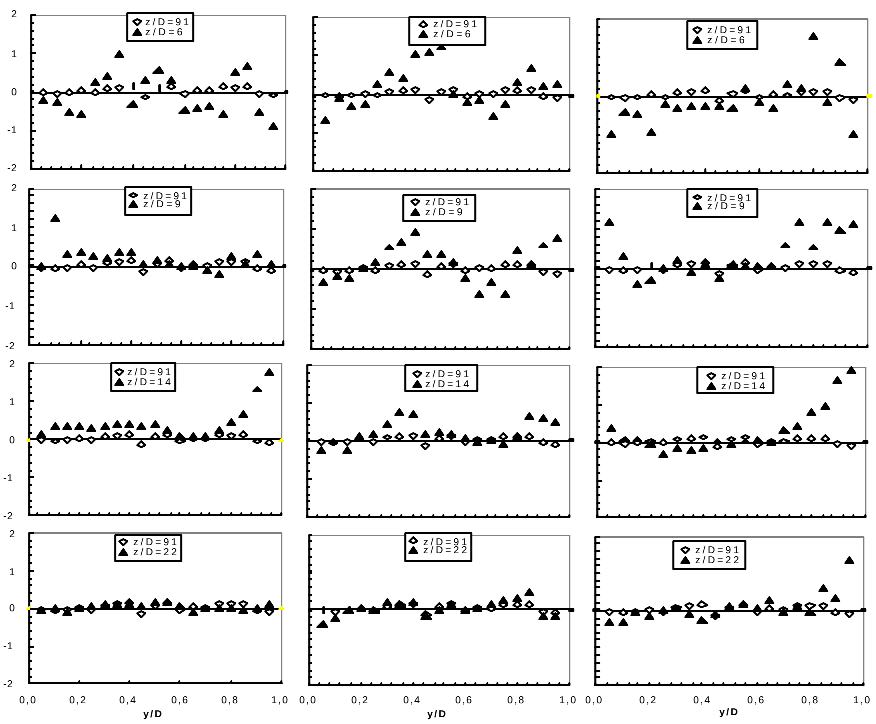


Figure 5 - Swirl development downstream the flow conditioners

2.3.4.- Performance of the three flow conditioners

The performance of the three flow conditioning devices is studied in this section. Figure 7 a, b and c show the discharge coefficient errors for different Reynolds number respectively for the orifice plate with beta ratio β= 0.70, 0.62 and 0.50 placed at 7.5 diameters downstream the double bends and 3 diameters downstream the flow conditioner. The present results show that the double bend out of plane (without a flow conditioner) generates a flow distortion that causes positive and negative deviations in the discharge coefficient ΔCd for the three β ratios. In general, deviations are positive for β<0.7 and negative for β≥0.7. These observations have also been made by Zimmermann (1999) who noticed the same trend. The tube bundle has been shown to be efficient to reduce the discharge coefficient errors ΔCd from 1.96% to 0.58% for β=0.70; The Laws perforated plate has a good results with β=0.62 and the errors were reduced from 1.49% to 0.63%; The best error reduction obtained by the Etoile was noticed for β=0.50 where the discharge coefficient error ΔCd were reduced from 2.44% to 0.30% . These results show clearly that, among the three devices studied in the present work, there is no a single flow conditioning device capable to reduce metering errors to ISO specified limits within 7.5 diameters downstream a double bend. Their performance has been shown to depend on the beta ratio of the orifice flow meter.

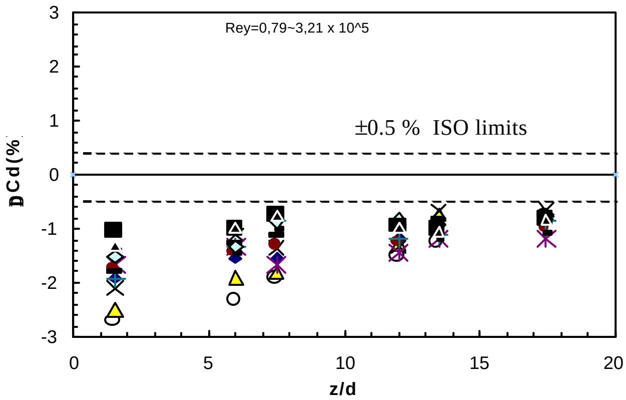
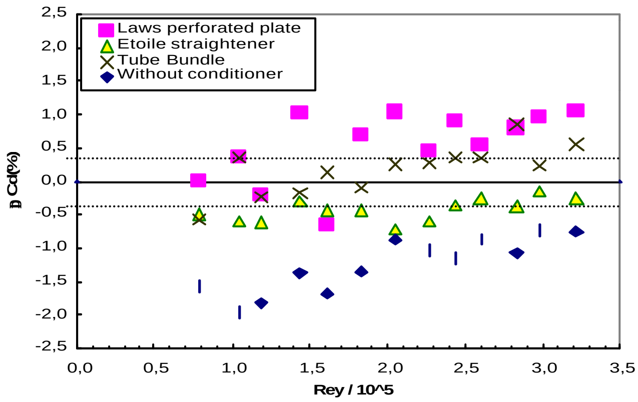
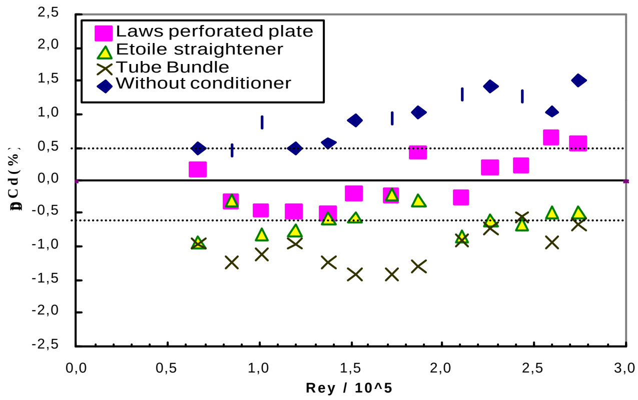


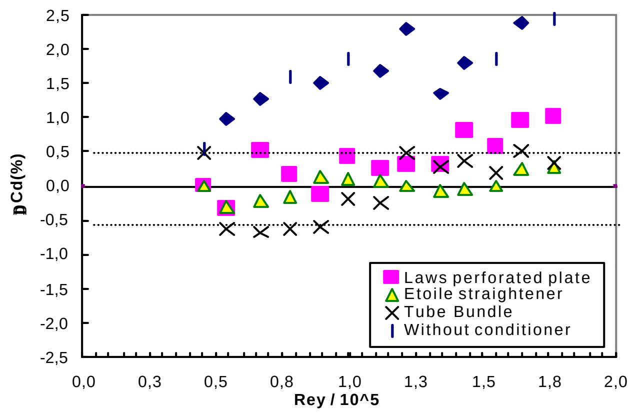
Figure 6. Discharge coefficient error for orifice meter (β=0.70) placed at different axial station z/D downstream the double bend without any flow conditioner.



a) Orifice meter with β =0.7.



b) Orifice meter with β =0.62.



c) Orifice meter with β =0.50.

Figure 7. Discharge coefficient error for orifice meter placed at station z/D=7.5 downstream the double bend and 3 D downstream the flow conditioner.

3 NUMERICAL INVESTIGATION OF FLOW CONDITIONING DEVICES

3.1 SCOPE OF THE INVESIGATION

In parallel to the experimental investigation discussed in the previous sections, a computational study was undertaken to predict the flow development downstream flow conditioners in order to assess their capabilities to produce the fully developed flow condition within reasonable developing distances. The approach is based on Computational Fluid Dynamics (CFD) techniques to investigate the aerodynamic behavior of the Laws plate, the tube bundle and the Etoile flow conditioners. This method which has been described in early work by Aichouni and Laribi (2000) is based on the solution of the Navier-Stokes equations governing the flow in a pipe, associated with the two equation K-ε turbulence model. Different test cases have been studied numerically and the predictions are compared to experimental results for different flow conditions.

3.2 NUMERICAL METHOD

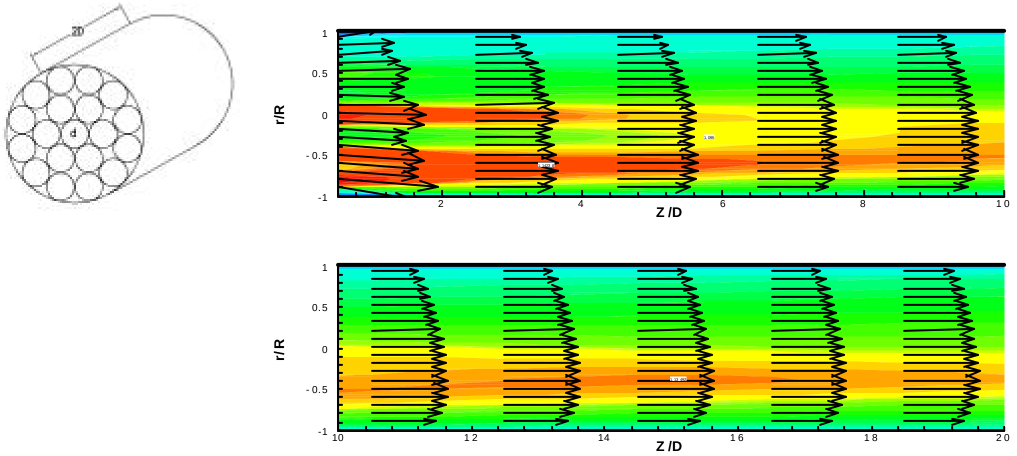
The flow in the pipe is supposed to be steady and the fluid is incompressible; The time mean averaged equations for conservation of mass and momentum have been used together with the standard K-ε turbulence model (Launder and Spalding 1974) to set a closed system of partial differential equations. The equations are discretized using the conservative control volume approach. The procedure for calculation of the flow field is based on the SIMPLE algorithm of Patankar (1980). Full details on the numerical procedure can be fond in Aichouni and Laribi (2000).

In the present study no attempt was made to compute the flow through the flow conditioner. The solution was started by taking as the duct inlet condition the measured profiles at the first axial station 0.5 D downstream of the flow conditioner. Measured profiles of the axial velocity and the turbulence intensity components were used to prescribe the initial conditions required for the solution.

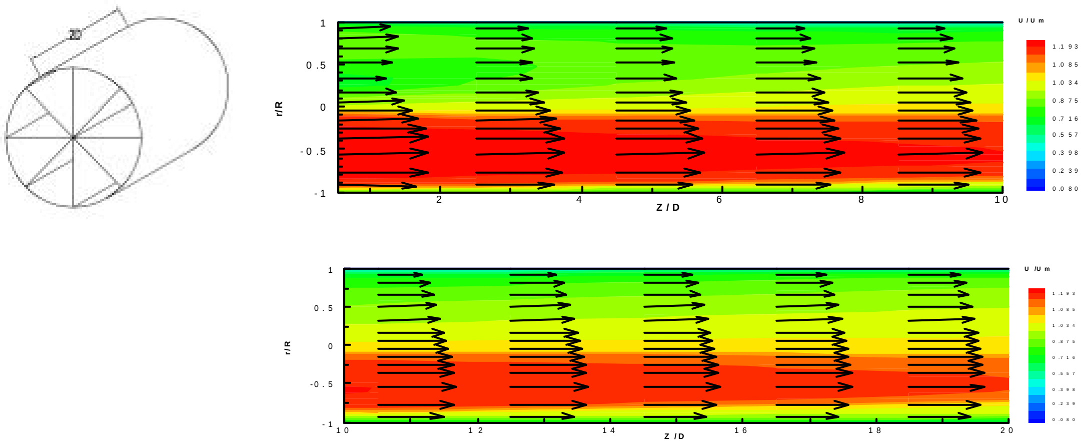
3.3 NUMERICAL PREDICTIONS OF THE FLOW DEVELOPMENT DOWNSTREAM FLOW CONDITIONERS

Flow conditioners serve for reducing the developing length between pipe fittings and flow meters and to create the fully developed flow condition within short distance. Hence leading to reduction of the metering errors. In the present study, numerical predictions of the flow development downstream the tube bundle, the Etoile conditioners described by the standards and the Laws plate flow conditioner have been made. The initial condiion were prescribed from the experimental data taken respectively from (Laws and Ouazzane 1994, 1995 and Merzkirch 2001) The conditioners were subject to severe flow distortions crate ether by a

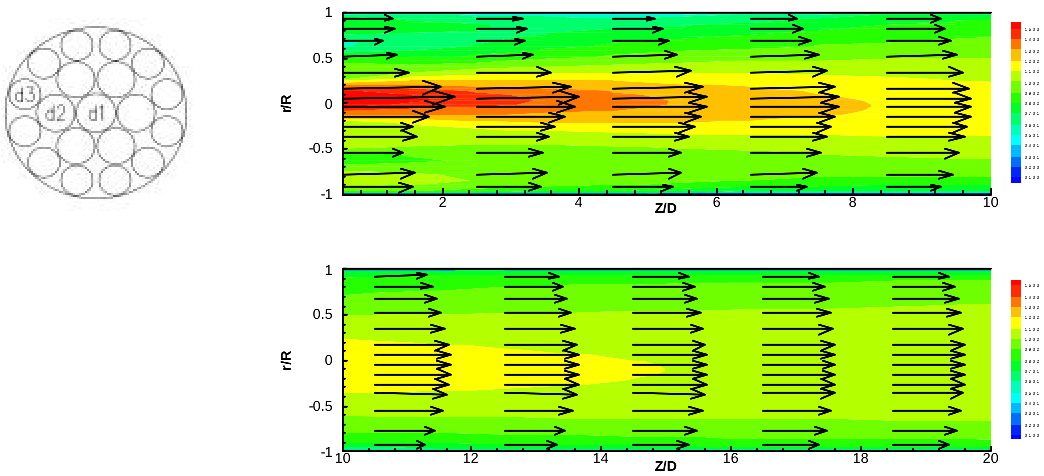
and c show the mean velocity contours and velocity vectors downstream the three conditioners. It is clearly shown from these figures that the flow at downstream distances of 20 diameters is not yet fully developed and the effect of the flow distortion still exists at that distance. The performance of the three flow conditioners to produce the fully developed flow conditions is examined in figure 9 where the predicted velocity profiles at different axial positions (Z/D) are compared to the fully developed profile predicted at 100 diameters downstream and the ±5% ISO limits. The results show a net superiority of the Laws plate conditioner over the conditioners described in the norms. Such an observation has been made recently by Merzkirch (2001) in his PIV experimental investigation upon the performance of the tube bundle, the Laws and the Mutsibushi plates. However, the uniform velocity generated by the Laws plate, though it falls within the ISO limits, would take further distance to achieve its fully developed flow condition in term of both mean and turbulence structure.



a - Flow development downstream the tube bundle conditioner.

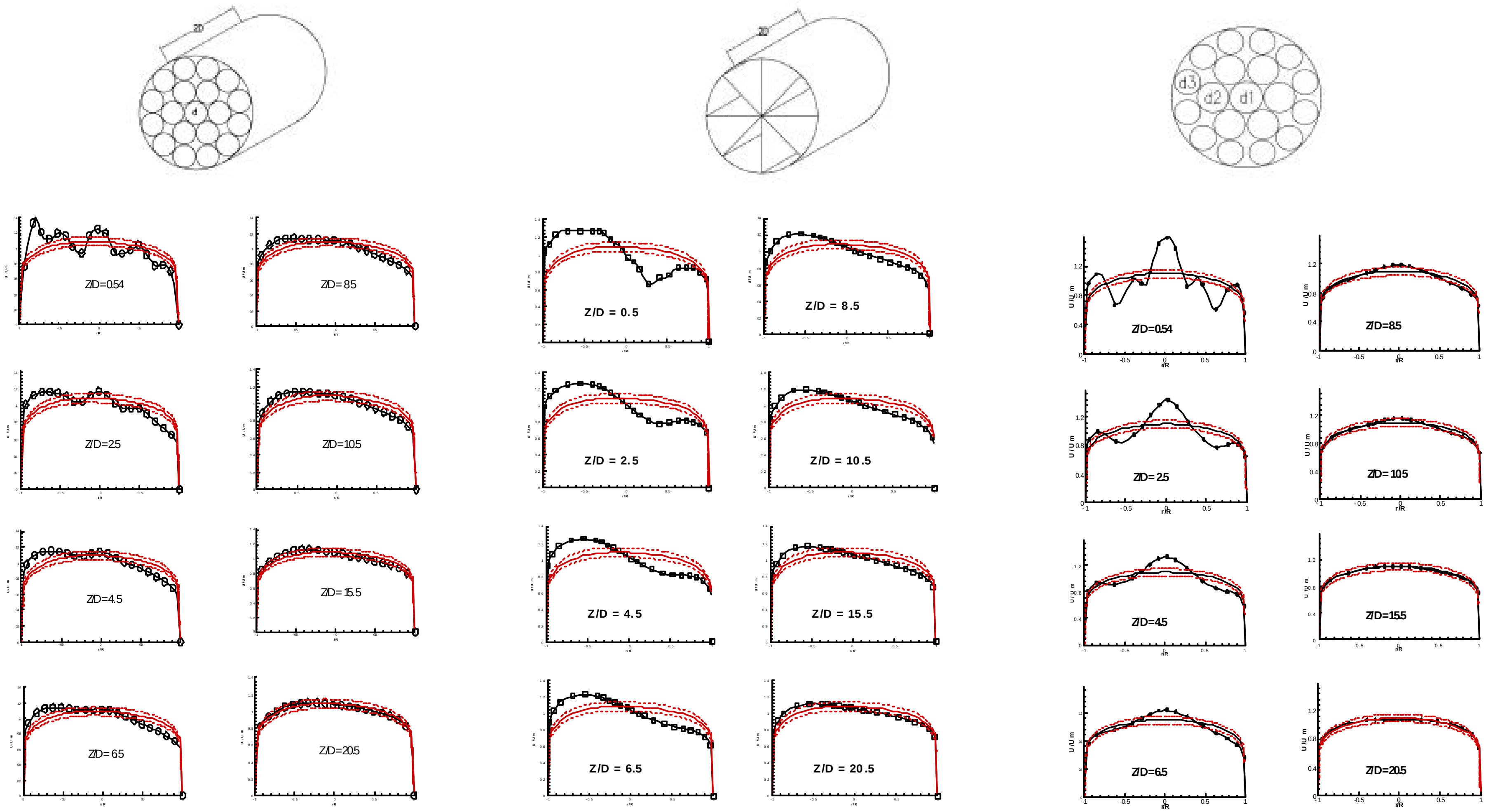


b - Flow development downstream the Etoile conditioner case of valve 70 % open



c - Flow development downstream the Laws plate conditioner case of valve 70 % open

Figure 8 - Predicted flow development downstream the three flow conditioners



a - Tube bundle

b - Etoile

c The Laws Plate

Figure 9 - Velocity profiles simulated at different axial position Z/D compared to the fully developed profile and the ISO limits (±5%)

4 CONCLUSIONS

Measurement of volumetric flow rate in non developing flow conditions remains a problem of highly practical interest from both its technological and economical aspects. A great deal of experimental and numerical studies have been made in an effort to understand the fundamental of the fluid flow involved with the problem an propose practical solutions. Through this research work, experimental (Laser Doppler Anemometry) and computational fluid dynamics (CFD) techniques have been used to investigate the effect of non standards flow conditions on the metrological performances (accuracy) of orifice flow meters and the efficiency of flow conditioners to reduce this effect. The present results confirm early conclusions made by the authors and many other researchers in the fact that pipe fittings such as double bends out of plane generate metering errors which are well beyond the tolerated ISO limits. The effectiveness of flow conditioners, ether those described in the norms or those newly introduced in the technical literature, to produce the fully developed flow condition within reasonable distances (some 20 diameters) remain questionable.

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