Comparative Study of Aerodynamic Behaviour of Three Flow Conditioners

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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. The accuracy of these devices depends not only on their construction and method of operation but also of their position in the pipe network. Pipe fittings such valve, bends and other fixtures generate turbulence and swirl and distort the flow distribution in the pipe. The present paper is concerned with an experimental study of the decay process of highly swirling flow in a circular pipe and its effect on orifice flow meter reading. The efficiency of three flow conditioners (The Etoile and the Tube bundle straighteners described in the Standards ISO 5167 and the Laws perforated plate) to remove swirl and to reduce metering errors has been investigated using a two components Laser Doppler Anemometer. Highly swirling flow distortion was generated by a 90° out of planes double bend upstream the flow meter. Discharge coefficient shifts due to the flow distortion was determined for three orifice meters with a diameter ratio β=0.5, 0.62 and 0.70 at flow Reynolds number ranging from 0.79 to $3.21 x 10^5$. The results show that the disturbance causes important deviations in the meter's calibration coefficient. The effectiveness of the flow conditioning devices to remove the flow distortion and to reduce the resulting metering error was not evident for all the working conditions studied here.

Keywords : Metering error; Orifice flow Meter; Flow Conditioner; Flow Measurement; Disturbed Pipe Flow; Double Bend out of Plane; Laser Doppler Anemometer (LDA).

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 major concern and vital importance when large volumes are handled.

The Algerian petroleum company recorded receipts of 56×10^9 m^3 of gas over one year. The quality of gas measurement, receipt and major delivery points distributed through 13000 km of pipe line, is very important. 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[1] and ASME 2530 [2] define a satisfactory flow as one which has a swirl angle less than two degrees and for which the ratio of the axial velocity to the maximum axial velocity is within ±5% of the corresponding ratio in fully developed flow measured in the same pipe after 100 pipe diameter of development length. While high accuracy about ±0,3% mass flow measurement is required, disturbances in the flow caused by contractions, bends, and other components introduce metering errors of the order of ±3% and greater [3].

Given that most industrial installations include 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 situations.

For best accuracy, a flow meter needs to be presented with an axisymmetric, 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 [1]) and these may need to be of the order of 80 to 100 pipe diameter, which will give a higher installation cost and greater space requirement. Alternatively, upstream disturbances can be attenuated by using flow straightener and/or 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 minimizes installation effects.

Recent research work in the USA(Morrison and al [4]; Morrow and Park [5]), in the U.K (Reader-Harris and Keegans [6]; Ouazzane [7]; Ouazzane and Laws[8,9]), in France (Gajan and Hebrard [10]), in Algeria (Aichouni and Laribi [11,12]) has reported a number of experimental and computational studies of installation effects on orifice meter performance. Most of these studies investigated the effect of flow conditioner location with respect the orifice meter on the discharge coefficient. In a recent study, Ouazzane and Barigou [13] conducted an experimental investigation into the effects of two different flow conditioners on the performance of orifice plate flow-meter. The first flow conditioner was the Vaned-plate flow conditioner, the second the NEL-plate flow conditioner. Experiments were conducted to determine the relative change discharge coefficient when subject to non standard approaching flow conditions. Three different velocity profiles were generated by various valve settings based on flow area upstream of the orifice meter (fully open, 50% closed, 70% closed). Three orifice plates were examined on the orifice-pipe diameter ratio β = 0.5, 0.6 and 0.7 over a range of Reynolds number from 0.33×10^5 to 2.5×10^5. The major conclusions show that the distortions in the approaching flow generated by pipe fittings upstream of the orifice meter can cause significant shifts in the meter's calibration coefficient, hence leading to considerable errors in flow metering.

In this paper, the effect of entrance flow velocity profile, generated by a 90° out of plane double-bend is examined. In many investigations on installation effects, the double bend is taken as a standard disturbance which is known to produce an asymmetry of the velocity profile and significant swirl (Fielder [14], Merzkirch [15]).

The efficiency of flow conditioner to remove the flow distortion and produce the fully developed condition was investigated. In the present study three flow conditioners were compared : the 19 tube bundle flow, the Etoile flow straighteners (described in the standard ISO 5167 and AGA 3) and the Laws perforated plate.

2. Experimental facility and procedure

2.1. Air Flow Rig

The basic experimental facility is presented in figure 1. It consists of a long Plexiglass 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 diameters length which is followed by the 90° double-bend out of plane. The double bend represents the source of the flow disturbance.

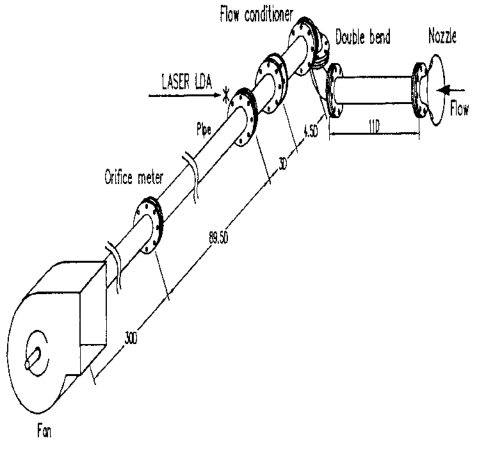


Fig. 1 Experimental test facility

A reference orifice meter was installed at 97 pipe diameter downstream where the flow is fully developed. The tested orifice meter was first installed at 1.5 D downstream the double bend and then removed at different locations downstream. The orifice plates were of standard geometry and had pressure tapings 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 tapings connected to a multi tube 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 tested flow conditioners were positioned at 4.5 D downstream of the double bend.

2.2. Flow conditioners

The geometry and dimensions of the three flow conditioners investigated in the present study are shown in figure 2.

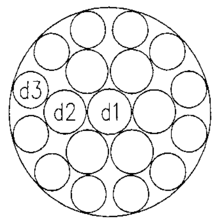


Fig. 2.1. Laws Perforated Plate

The Laws plate shown in figure 2.1 is a perforated plate, with a specific arrangement of the circular holes. The holes are arranged so that a central hole of diameter d_1=0.224 D is surrounded by an inner ring of six holes having equal diameter d_2=0.213 D, and an outer ring of twelve holes of equal diameter d_3=0.177 D. The values for the ratio of open area to total cross-section area is 0.70 and the pressure loss coefficient is estimated to be equal to 0.90 [13].

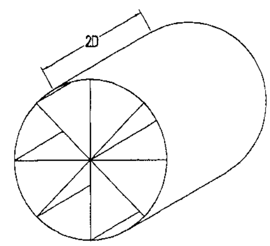


Fig. 2.2. Etoile Straightener

The Etoile flow straightener, figure 2.2, consists of eight radial vanes at equal angular position with tow diameters of length and his pressure loss coefficient is estimated to 0.25 [1].

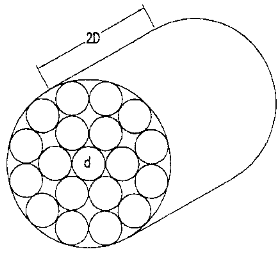


Fig. 2.3. Tube Bundle Straightener

The 19 tube bundle straightener consists of 19 tubes with 2 diameters of length and is arranged in a cylindrical pattern as shown in figure 2.3. The pressure loss coefficient is estimated at 0.75 [1].

2.3. Velocity and Turbulence Measurement

The mean and the fluctuating components of the velocity downstream the two elbows and the flow conditioner were measured using a two components Laser Doppler Anemometer. For measurement with LDA the air flow was seeded with smoke. Tests have been done at Reynolds number 1.9×10^5. The profiles of the mean velocity and axial turbulence intensity have been measured at different axial stations (z/D=0.8, 6, 9, 14, 22 and 91) downstream the piping elements (either the double bend or the flow conditioner). These measurements were done without any flow meter on line. At the last measuring station the flow is assumed to be fully developed. This is checked by comparing the axial mean velocity profile measured at that station and the $(1/7)^{th}$ power law profile at the same Reynolds number. Figure 3 shows the comparison where the agreement between the two profiles is clearly seen. Hence it was concluded that the flow has achieved its fully developed conditions at 91 diameters downstream of the disturbance source and this station can be used as a base line or reference for the installation effect study.

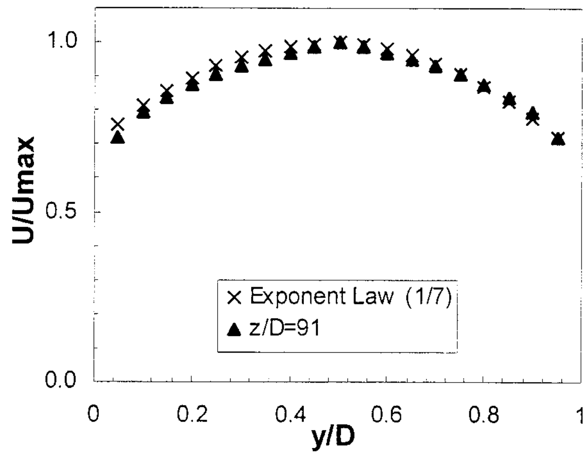


Fig 3. Velocity profile in a horizontal plane

This procedure is judged to be effective to investigate the flow development downstream a double bend out of plane and its effects upon the metrological performance of the orifice flow meter.

2.4. Swirl Measurement

The swirl angle was obtained by using the two components u and v of the mean velocity obtained by the LDA with equation (1).

$$A = arctg\left(\frac{v}{u}\right) \quad (1)$$

2.5. Discharge Coefficient Variation

The metering error under the disturbed flow condition(double bend out of plane) was determined as follows:
The true flow rate was measured from the reference meter placed at the fully developed flow condition position (97 diameters downstream the flow disturbance). Then the tested flow meter was placed at different axial stations from the double bend and the corresponding flow rate was measured. The flow rate error and the discharge coefficient shift were determined to see the effect of the installation conditions on the meter reading. The discharge coefficient was determined as the ratio of the local measured flow rate to the true flow rate. The percentage shift in the discharge coefficient was determined from the relationship :

$$\Delta C_d = 100\left(\frac{C_{d0} - C_d}{C_d}\right) \quad (2)$$

where C_{d0} represents the discharge coefficient measured under standards conditions (fully developed flow condition) and C_d the discharge coefficient determined under non-standards operating conditions.

Equation (2) can be reduced to equation (3) as follows :

$$\Delta C_d(\%) = \sqrt{\frac{\Delta Po}{\Delta P}} - 1 \quad (3)$$

where Δp is the measured differential pressure across the tested meter placed downstream the double bend and Δpo is the differential pressure measured across the reference flow meter.
The distance between the two orifice meters was in all the cases greater than 77 diameters.

Tests have been done for three orifice plates with beta ratios (β=0.5, 0.62 and 0.70) at flow Reynolds number ranging from 0.79 to 3.21×10^5 with the three different flow conditioners described in section 2.2. The test sections were 1.5 D , 6 D, 7.5 D ,12 D, 13.5 D and 17.5 D downstream the double bend.

3. Results and discussion

The purpose of the 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 two flow straighteners and one flow conditioner to improve metering accuracy is also investigated.

3.1. Flow development downstream the 90 degrees double bend out of plane

The first part of 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 at z/D=91 in figure 4. 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 center 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 –7° to 10°. It is to be noted here that the ISO swirl angle limits is ±2°.

At station z/D=22 the swirl angle varied from –5° to +5°, it 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 [1] 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 will be quantified.

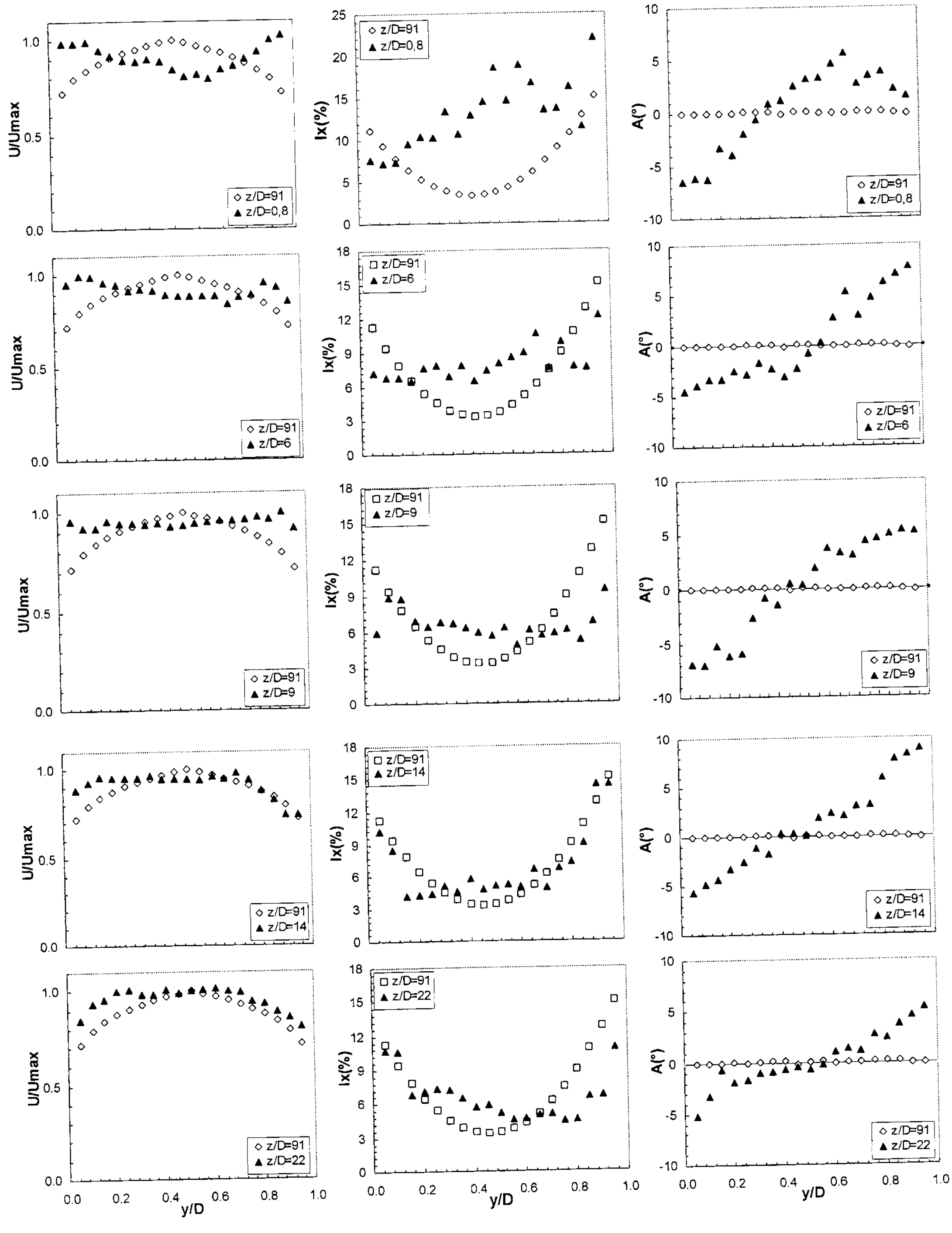
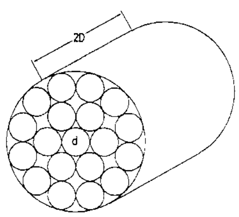


Fig. 4. Velocity profile, turbulent intensity and swirl downstream double bend without conditioner

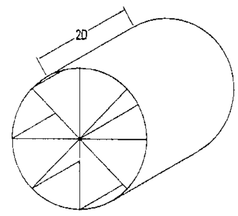
3.2. Flow development downstream flow conditioners

The mean velocity profile development downstream the three flow conditioners is shown in figure 5. 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.

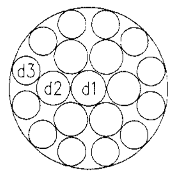
The influence of the conditioner on the velocity profile is clearly visible at the first measuring station z/D=6 downstream the double bend, i.e, 1.5 D downstream of the flow conditioner. The profile measured immediately downstream of the Etoile shows a central wake which is believed to be due to the solid centre of the straightener near the pipe centre line.



Tube Bundle



Etoile



Laws Perforated Plate

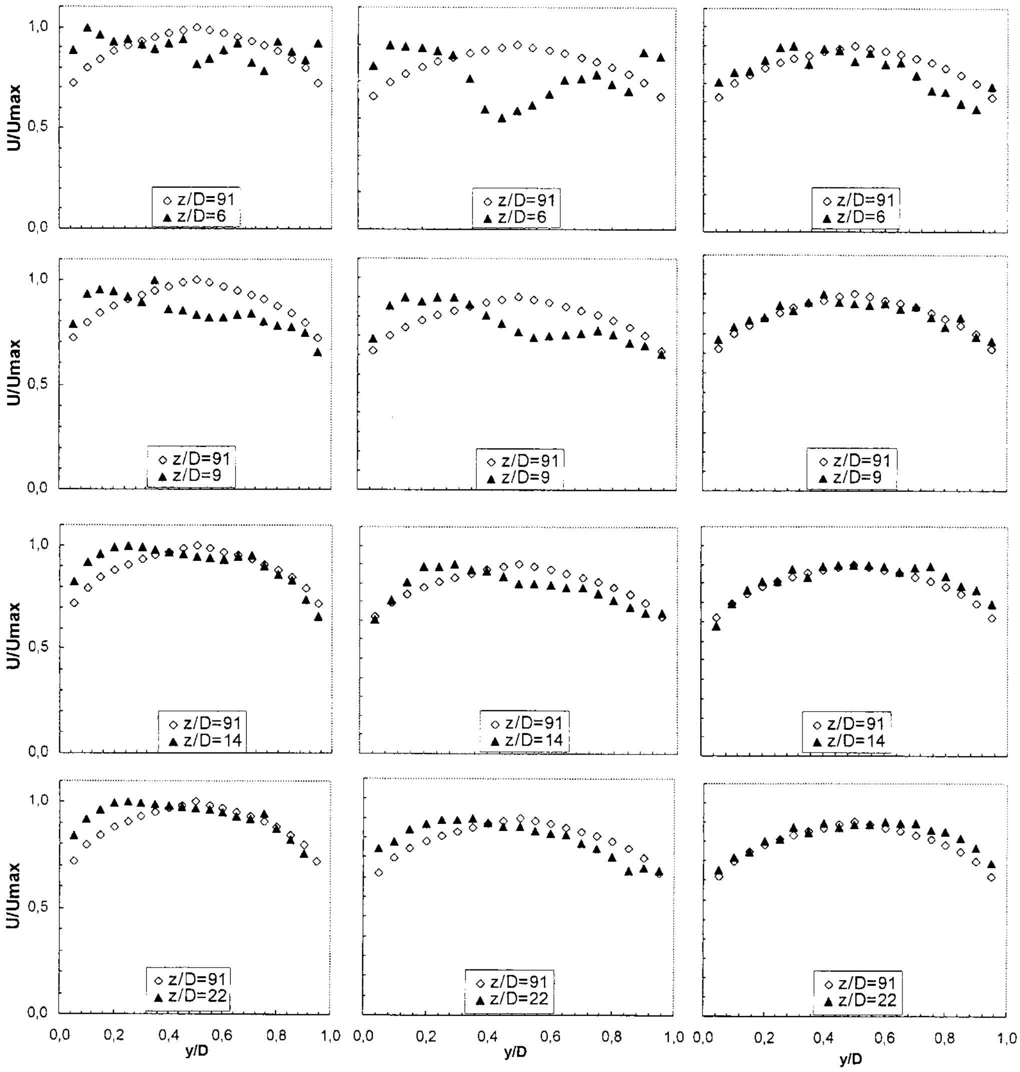


Fig 5. Velocity profiles downstream conditioners

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.

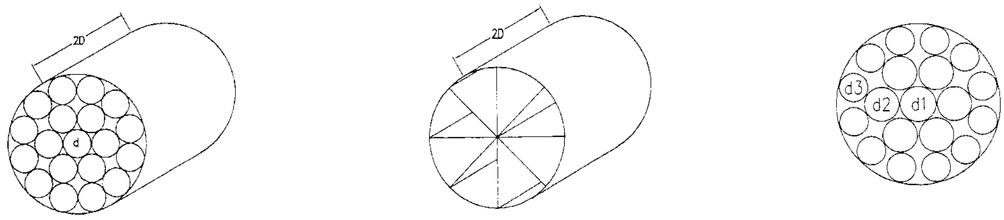
The results show that the perforated plate appears to be an efficient flow conditioner regarding the redistribution of the flow and the production of an almost fully developed velocity profile within a short downstream distance. At station z/D=9 the axial velocity profile downstream the conditioners 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 turbulence intensity profiles measured downstream the three flow conditioners are presented in figure 6.

Again here, in order to study the development process of the turbulent structure downstream the flow conditioning devices the fully developed profile measured at 91 D downstream is included. The results show that the axial turbulent intensity profiles measured immediately downstream the three flow conditioners (z/D=6) exhibit different trends.

The constant radial distribution porosity of the tube bundle generates the highest turbulence levels (about 15%) compared to the Etoile (12%) and the Laws plate (9%).



Tube Bundle Etoile Laws Perforated Plate

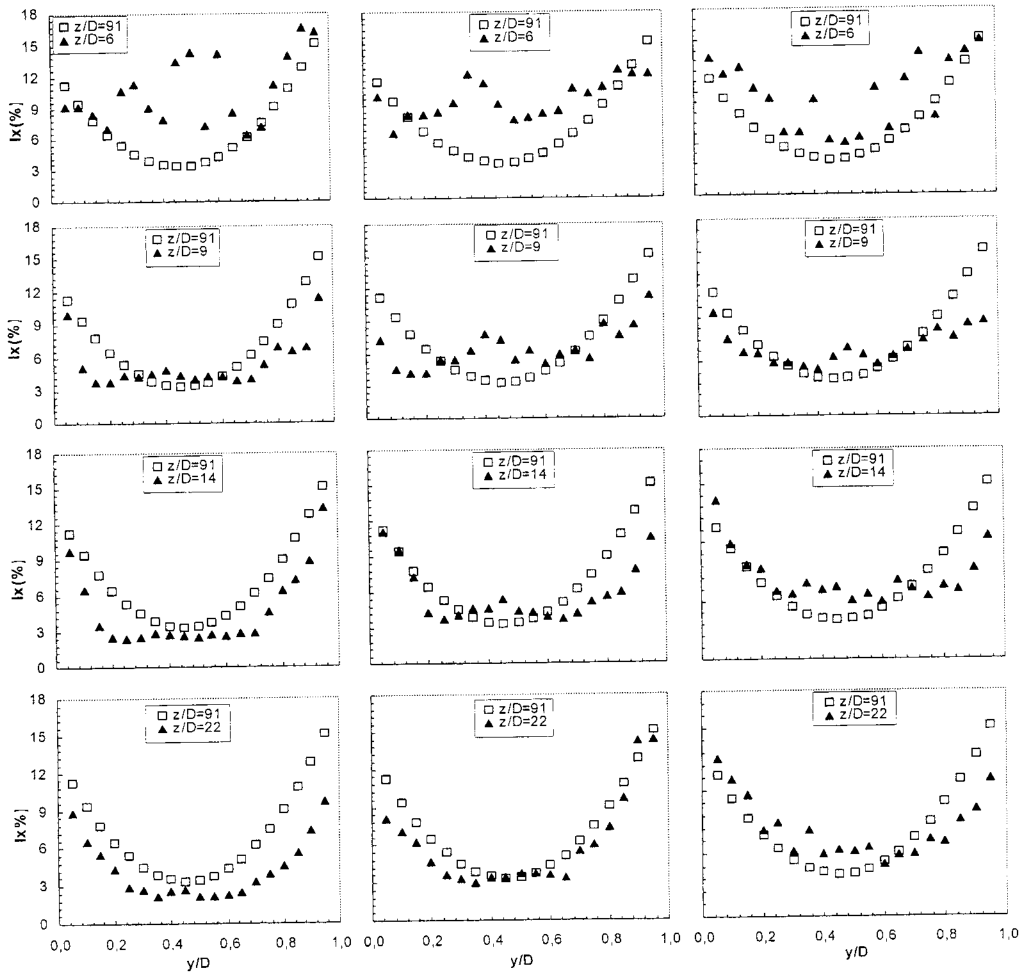
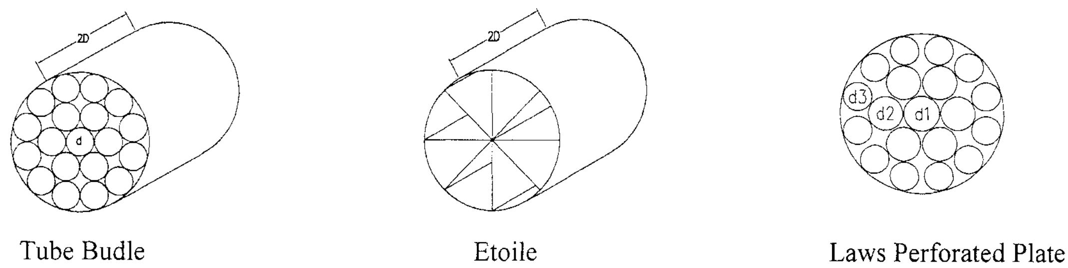


Fig. 6. Turbulence intensity downstream conditioners

The initial higher turbulence levels exhibit a rapid decay downstream the three devices nine diameters downstream the double bend and gradually develop towards the fully developed distribution.
The most remarkable change was that the turbulence in the core region 0.2<y/D<0.8 which decreases by approximately 10% between z/d=6 and 9. This is believed to be due to strong 'mixing' of flow immediately downstream the devices and to the difference in the holes arrangements of the conditioning devices. At the far downstream position z/D=22, the turbulence intensity has not yet reached the distribution known for fully developed flow. However, the capability of the Etoile straightener to produce the fully developed pipe flow in this distance is noticed.
The swirl angles downstream the three flow conditioners, including the fully developed profile (z/D=91), are presented in figure 7. The efficiency of the three flow conditioners to reduce swirl from ± 5° (figure 4) to ± 1° (figure 7) at station z/D=6 downstream the double bend is clearly visible. At the far downstream position z/D=22 the swirl is about ±0.4° for the three flow conditioners.



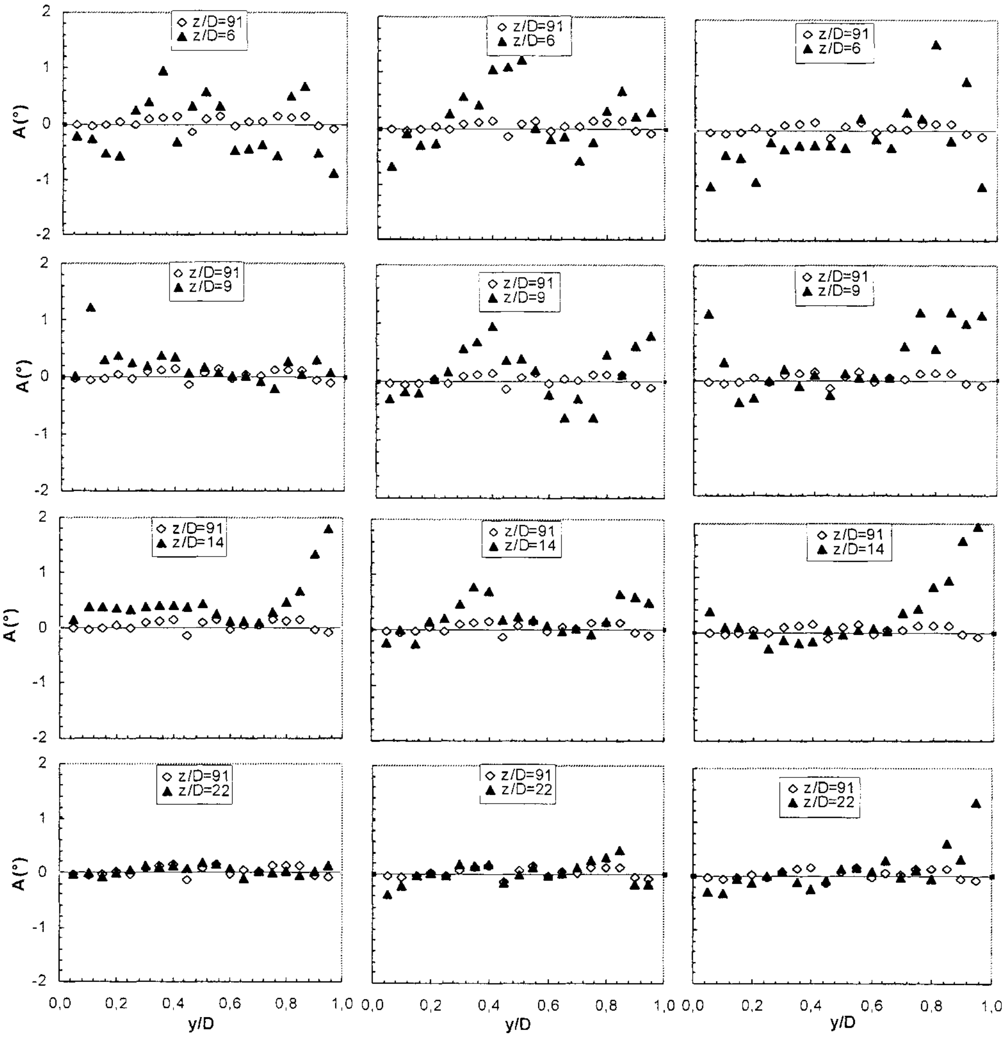


Fig 7. Swirl development downstream the three flow conditioners

The best results were obtained by the tube bundle where the swirl angle is reduced from ±5° at station z/D=22 (figure 4) to ±1° at station z/D=6 downstream the conditioner and finally to a value of ±0.2° at station z/D=22 (figure 7). The Etoile straightener and the Laws 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 ±0.4° which is well within the ISO limits of ±2°.

The present results show clearly the effectiveness of these conditioning devices to remove tangential velocity component in the flow and suppress the swirl in particular. Figure 7 shows that all the three devices are capable of reducing swirl to manageable levels and that all three units could meet the ISO swirl angle limits 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 as the double bend in perpendicular plane. The test sections were 1.5 D, 6D, 7.5D, 12D, 13.5D and 17.5D 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 8. 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 bouble bend with a pacer 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 conditions. This observation which is shown in the present results (figure 4), has been made by Yeh and Mattingly [3] and by Merzkirch and Kalkuhler [15].

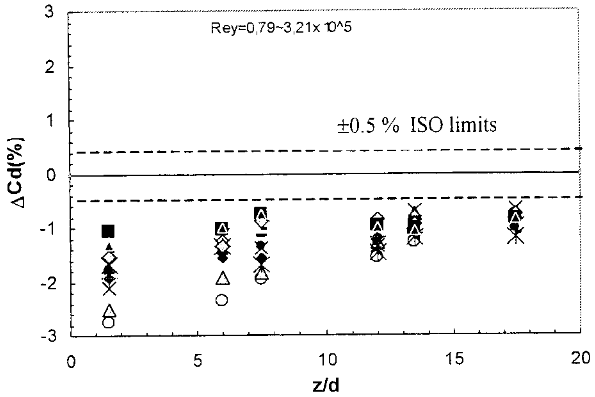


Fig. 8. Discharge coefficient error for the orifice plate mete(β=0.70) placed at different locations (z/D) downstream the double bend without flow conditioners

3.4. Performance of the three flow conditioners

The performance of the three flow conditioning devices is studied in this section. Figures 9, 10 and 11 show the discharge coefficient errors for different Reynolds number respectively for the orifice plate with beta ratio β= 0.50, 0.62 and 0.70 placed at 7.5 diameters downstream of 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 depending on the diameter ratio β. In general, deviations are positive for β<0.7 and negative for $\beta\geq$0.7. These observations have also been made by Zimmermann [16] who noticed the same trend.

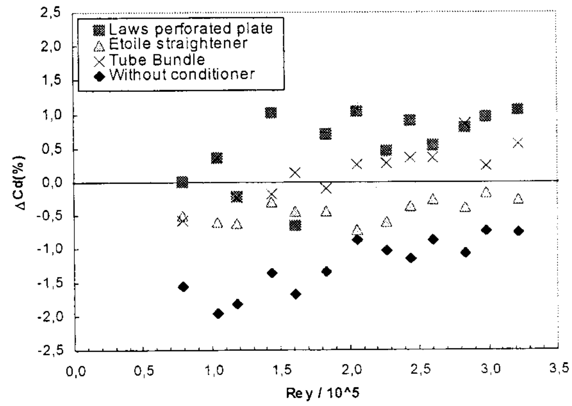


Fig. 9. Discharge coefficient error for β=0.7. The orifice meter is placed at axial station z/D=7.5 downstream the double bend.

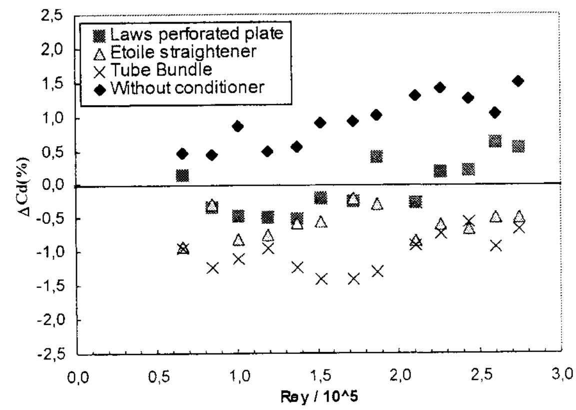


Fig. 10. Discharge coefficient error for β=0.62. The orifice meter is placed at axial station z/D=7.5 downstream the double bend

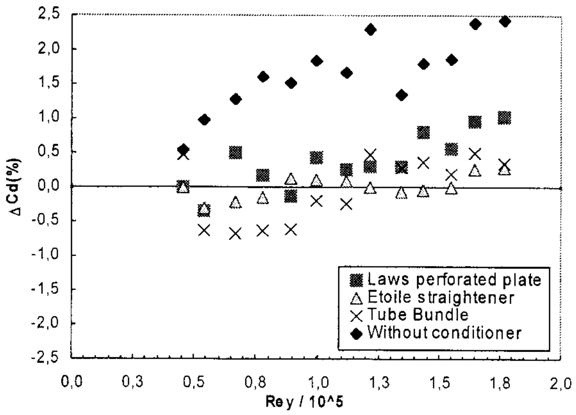


Fig. 11. Discharge coefficient error for β=0.50. The orifice meter is placed at axial station z/D=7.5 downstream the double bend

Table 1 summaries the results shown in figures 9,10 and 11. 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% .

	Discharge coefficient error DCd (%)		
	β=0.70	β=0.62	β=0.5
	ΔCd	ΔCd	ΔCd
Without flow conditioners	1.96	1.49	2.44
Laws Plat	1.06	0.63	1.02
Etoile	0.71	0.92	0.30
Tube Bundle	0.58	1.22	0.67

Table 1. Discharge coefficient errors obtained with the meter placed at 7.5 diameters from the double bend and 3 D downstream a flow conditioners

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.

4. Conclusions

The present experimental study examines the effect of upstream flow condition generated by a 90° double bend out of planes on orifice meter readings. The performance of three flow conditioning devices (namely the tube bundle, the Etoile and the Laws perforated plate) to attenuate the effect of this distortion and to reduce metering errors was also investigated.
The two components Laser Doppler Anemometer technique was used to investigate the flow development downstream the double bend and the flow conditioners and the achievement of the fully developed pipe flow condition.
The discharge coefficients were measured with three different orifice meters (β=0.5, 0.62 and 0.7) at different Reynolds numbers. The results show that the flow distortion generated by the double bend upstream the orifice meter can cause significant shift in the meter's calibration coefficient Cd; Hence leading to a metering error which is well beyond the standards specified limits of ±0.5%.
It has been noted that for the three flow conditioners used separately, the flow needs longer distance to achieve its fully developed state. Some errors on the discharge coefficient were inevitable even after a developing distance of 22 diameters. Indeed, each flow conditioner used separately can only act on one parameter of the flow. The best results were obtained by the Laws perforated plate for the velocity profile. For the swirl angle, the best results were obtained by the tube bundle, whereas the Etoile acts on the turbulence intensity profile. It is the author's belief that a combination of two different flow conditioners can influence not only one parameter but all the parameters of the flow. This subject will constitute the subject of the second part of the paper.

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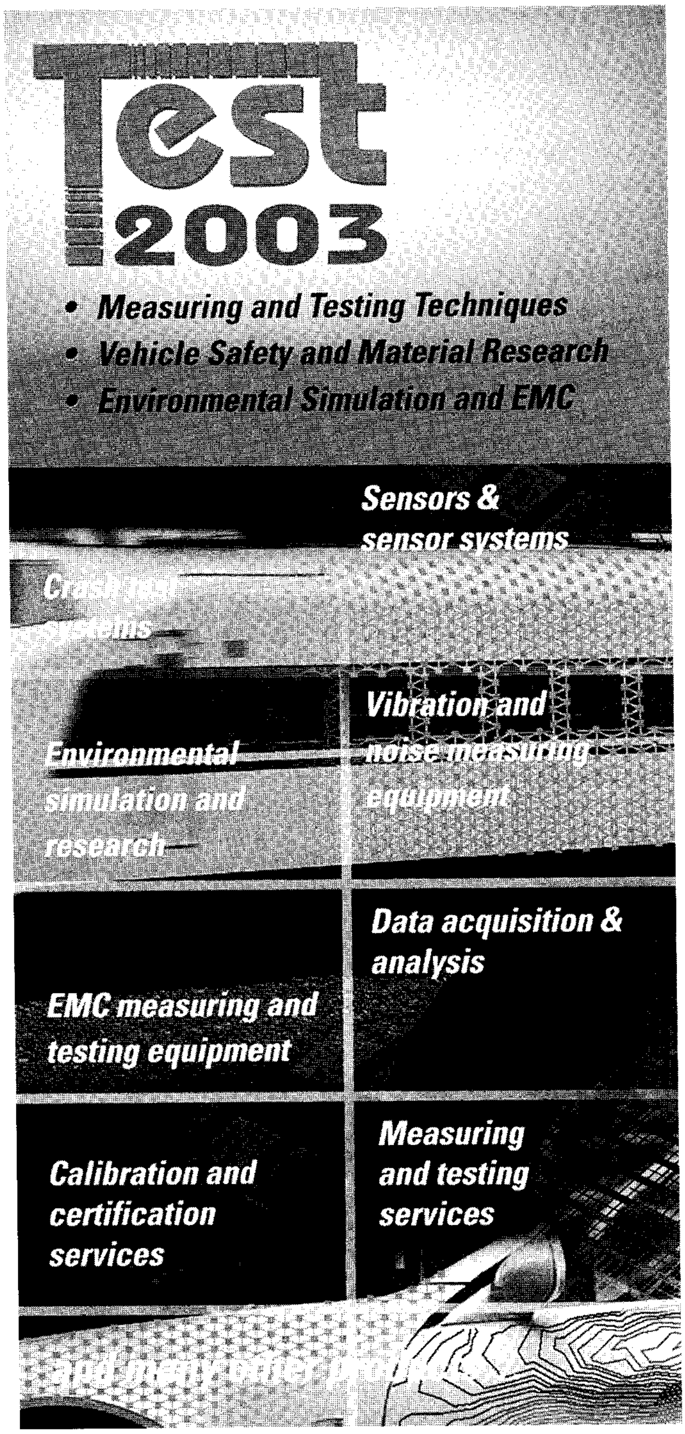

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