Further Analysis of the Aerodynamic Behaviour of Flow Conditioners

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Abstract

The flow development downstream different combinations of flow conditioners, namely the Laws perforated plate, the tube bundle and the Etoile, has been investigated by measuring the axial velocity component and the turbulence intensity with a Laser Doppler Anemometry technique. The development of the velocity profile and the axial turbulent intensity downstream a 90° out of plane double bend with and without a flow conditioner, have been examined. The performance of the three devices in conditioning the disturbed flow and to produce the fully developed flow condition with respect to the standards specifications has been studied. Experiments have been performed with airflow through a circular pipe of 100 mm internal diameter. Discharge coefficient shifts due to the flow distortion were 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 3.21×10^5.

Keywords: Metering error; Orifice Flow Meter; Flow Conditioner; Fully Developed Pipe Flow; Disturbed Pipe Flow; 90 degrees Double Bend out of Plane; Laser Doppler Anemometer (LDA).

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1. Introduction

In the last few years many efforts have been made by scientists all over the world to understand the physics of the behaviour of flow rate and volume-measuring devices in order to study how they can be affected by the flow conditions prevailing in their inlet pipe section.

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 diameters 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 even greater [3].
Given that most industrial installations include bends, valves, expanders and reducers, which are sources of 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 diameters, which will give a higher installation cost and greater space requirement. Alternatively, upstream disturbances can be attenuated by using flow conditioners to control the quality of the flow approaching the metering device.

Recent research work in the USA (Morrison et 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 paper, the authors (Laribi and al [13]) presented an experimental investigation into the effect of disturbed flow condition on the performance of orifice plate flow meters with and without flow conditioning devices. The efficiency of three flow conditioners, namely the Etoile, the tube bundle and the Laws plate, to remove the flow distortion and to increase the flow meter accuracy was investigated. Experiments were conducted to determine the relative change of the discharge coefficient when subject to non-standard approachingflow conditions. The conditioners were exposed to the flow disturbed by a 90° out of plane double bend.

The experiments were performed with air flow through a pipe line of 100 mm internal diameter D. Discharge coefficient shifts due to the flow distortion were determined for three orifice meters with a diameter ratio □=0.5, 0.62 and 0.70 at flow Reynolds number ranging from 0.79 to 3.21×10^5. The major conclusions show that the distortion in the approaching flow generated by the double bend out of plane upstream of the orifice meter causes significant shifts in the meter's calibration coefficient and that the three flow conditioners exhibit different performances with respect to the removal of the distortion in terms of mean flow, turbulence and swirl. In general, for the tested conditioners, the flow needs more than 22 D to develop towards the fully developed pipe flow condition. A certain combination of the flow conditioners would lead to better removal of the flow distortion and the production of the fully developed flow condition within reasonable distances, hence leading to an increased meter accuracy. This paper presents further results on the flow development downstream different combinations of the conditioners (Etoile, tube bundle and the Laws plate) exposed to the 90° out of plane double bend disturbance. The efficiency of the new flow conditioner designs to remove the flow distortion and to produce the fully developed condition and its effect on the performance of the orifice plate flow meter is investigated.

2. Test facility and procedure

2.1. Air Flow Rig

The test facility layout is shown in figure 1. Basically, it consists of a long Plexiglas pipe with 100 mm inner diameter. Airflow is sucked into the pipe through a bell mouth nozzle by means of a centrifugal fan placed at the downstream end. The air enters the pipe through the nozzle, and 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.

A reference orifice meter was installed at 97 pipe diameters downstream where the flow has been checked to be fully developed. The tested orifice plate flow meter were installed at 7.5 diameters downstream the flow disturbance source. They are of standard geometry having pressure tapings at one D upstream and D/2 downstream, where D is the inner pipe diameter. The opening diameters d of the orifice meters are 50, 62 and 70 mm, which correspond to diameter ratios, □=d/D, equal to 0.5, 0.62 and 0.70.

The static pressure (upstream and downstream of the meter) was measured by four pressure tapings connected to a multi-tube manometer. The tested flow conditioners were positioned at 4.5 D downstream of the double bend.

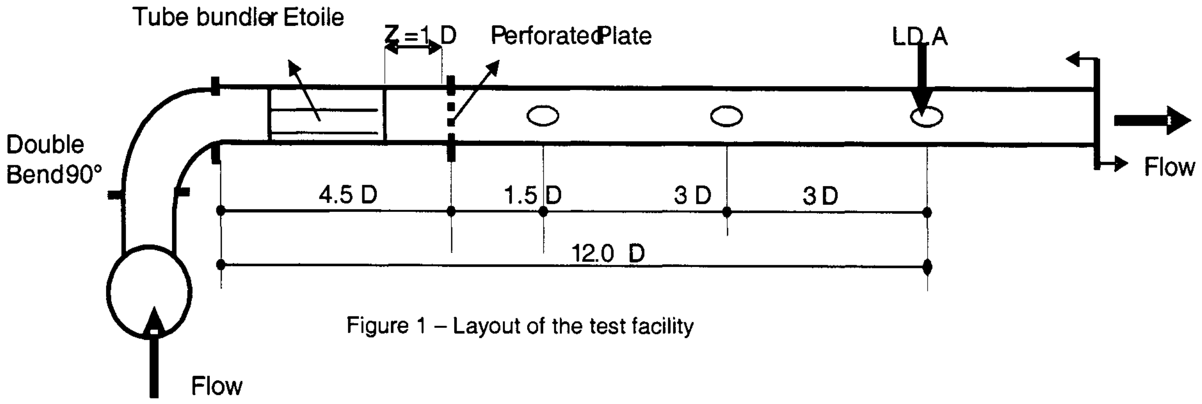
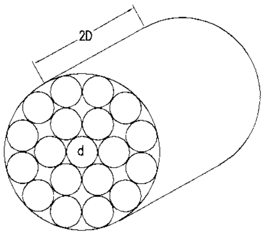


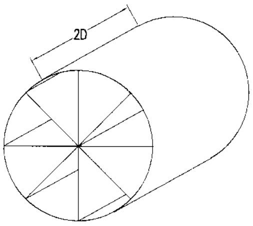
Figure 1 – Layout of the test facility

2.2. Flow conditioners

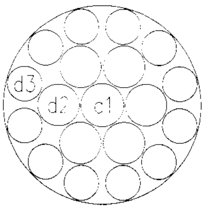
The flow conditioners investigated are the classical tube bundle, the Etoile that have been specified in the norms and the Laws perforated plate. A schematic representation of these conditioners is shown in figures 2, a, b and c.



a - Tube Bundle flow conditioner (ISO 5167)



b - Etoile flow conditioner (ISO 5167)



c - Laws Perforated Plate conditioner

Figure 2 – Tested flow conditioners

The tube bundle flow conditioner, shown in figure (2, a), consists of 19 tubes with 2 diameters of length arranged in a cylindrical pattern. Its pressure loss coefficient is estimated to be equal to 0.75 [1]. The Etoile flow conditioner, figure (2.b), consists of 8 radial vanes at equal angular positions with 2 diameters of length; its pressure loss coefficient is estimated to 0.25 [1]. The Laws conditioner is a perforated plate, with a specific arrangement of the circular holes giving a graded porosity. 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 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 [8].

2.3. Combination of flow conditioners

This part of the experimental work deals with a performance study of different combinations of the three conditioners to remove flow distortion and to produce the fully developed flow condition. The following cases have been investigated:

- **Case 1**: Flow distribution downstream the double bend without any flow-conditioning device.
- **Case 2**: Flow distribution downstream the double bend with the Laws perforated plate.
- **Case 3:** Flow distribution downstream the double bend with combination of the Etoile conditioner and the Laws perforated plate.
- **Case 4**: Flow distribution downstream the double bend with combination of the tube bundle and the Laws perforated plate.

The position of these devices is shown in figure 1.

2.4. Velocity and Turbulence Measurement

The mean and the fluctuating components of the velocity downstream the two elbows and the flow conditioners were measured using two components Laser Doppler Anemometer. For measurement with LDA the airflow was seeded with smoke. Tests have been done at Reynolds number 1.8×10^5. The profiles of the mean velocity and axial turbulence intensity have been measured at different axial stations (z/D= 6, 9, 12 and 91) downstream the exit of the double bend. 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.

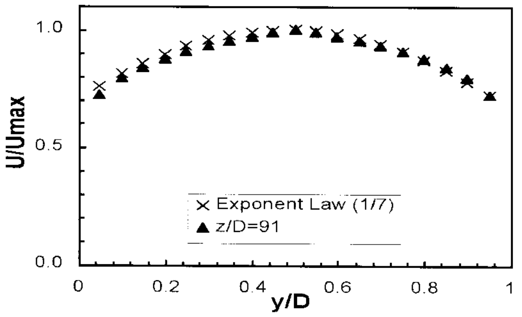


Figure 3 – Comparison of the axial velocity profile measured at the last station with the power law profile.

Hence, the Laser Doppler Anemometry technique is proven to be an effective tool to investigate the flow development downstream piping elements such as double bend out of plane and flow conditioning devices and its effect upon the metrological performance of the orifice flow meter.

2.5. Discharge Coefficient Variation

In order to investigate the flow meter performance under disturbed flow conditions generated by the double bend out of plane the following procedure was followed:
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 axial station z/D =7.5 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:

$$\Delta C_d = 100\left(\frac{C_{d0} - C_d}{C_d}\right) \qquad (1)$$

where C_{d0} represents the discharge coefficient measured under standards conditions (fully developed flow condition) and C_d is the discharge coefficient determined under non-standards operating conditions. Equation (1) can be reduced to equation (2) as follows:

$$\Delta C_d(\%) = \sqrt{\frac{\Delta Po}{\Delta P}} - 1 \qquad (2)$$

where ΔP is the measured differential pressure across the tested flow meter placed downstream the double bend and ΔPo is the differential pressure measured across the reference flow meter.
Tests have been done for three different orifice plates with beta ratios (β=0.5, 0.62 and 0.70) at flow Reynolds number ranging from 0.79 x10^5 to 3.21x10^5 with the three different flow conditioners combination described in section 2.3. The test section was 7.5 D downstream the double bend.

2. Results and discussion

The purpose of the present experimental work is to investigate the efficiency of a new flow-conditioning device made by combining the three flow conditioners, to remove highly swirling flow distortion and to produce the fully developed condition within short distances for metering purposes.

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

Radial distributions of the axial mean velocity U/U_{max} and the axial turbulence intensity Ix (%) were measured at 6, 9 and 12 diameters downstream the double bend for the four cases. The mean velocity profiles are compared to the fully developed profile with a tolerance of ±5%. The choice of such limits was made on the basis of the ISO 5167 requirements which stipulate that an acceptable flow condition for metering purposes can be achieved when the flow is within ±5% of the U/U_{max} level which would be reached after 100 pipe diameters of development in a straight pipe. The measured turbulence intensity profiles are compared with the fully developed profile measured at the last measuring station (91 diameters downstream the double bend).

Figure 4 shows the axial mean velocity profile distribution measured at station z/D=6 downstream the double bend with and without flow conditioners (i.e. 1.5 diameters downstream the flow conditioner). This figure shows that the double bend in perpendicular planes generates a high distortion in terms of mean flow and its turbulent structure. The flow exhibits an asymmetry and the velocity levels are higher near the pipe wall and lower at the centre line where there is a deficit of the velocity. This has been shown to be associated with a high swirl angle [13]. The best velocity profile, which agrees with the ISO specifications, is obtained by the combination of the Etoile and the Laws Plate. For the other combinations the velocity profile cannot be considered to fall within the ISO limits.

The radial distribution of the axial turbulent intensity Ix (%) measured at the same axial station (z/D= 6) is shown in figure 5. Without flow conditioner, the turbulence intensity presents higher values than the fully developed profile over the major part of the pipe cross-section. Here again the best turbulence profile compared to the fully developed profile was obtained with the conditioner combining the Etoile and Laws plate. For the other combinations, the turbulence intensity has not yet reached the known fully developed flow.

The axial mean velocity profile measured at the axial station z/D=9 downstream the double bend with and without flow conditioning device is shown in figure 6. At this station the best velocity profile that is close to the fully developed flow condition according to the ISO specifications was obtained by the Laws perforated plate. Here it can be noted that, for the combination Etoile-Laws perforated, the profile exhibits some deviations in the core region (0.5<y/D<0.70) from the ISO limits profile and loses his profile obtained at the axial station z/D=6. This can be attributed to the unsteady flow in the turbulence structure associated with the flow development downstream of the flow conditioning devices. The three conditioner combinations seem to produce the fully developed flow profile at 9 diameters downstream. Some discrepancies can be noticed for the Etoile/Plate combination. The combination tube bundle with the Laws plate produces the best velocity profile with accordance to the ISO specifications.

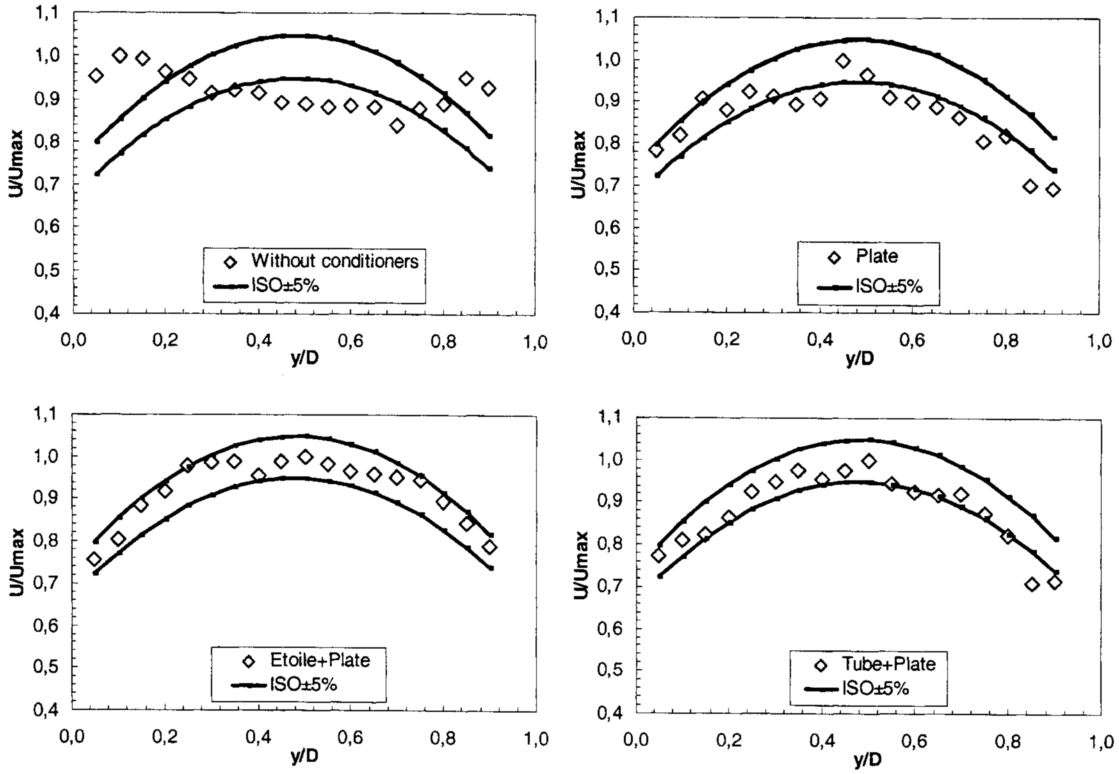


Figure 4- Mean velocity profile measured at the axial station z/D=6 for the four cases.

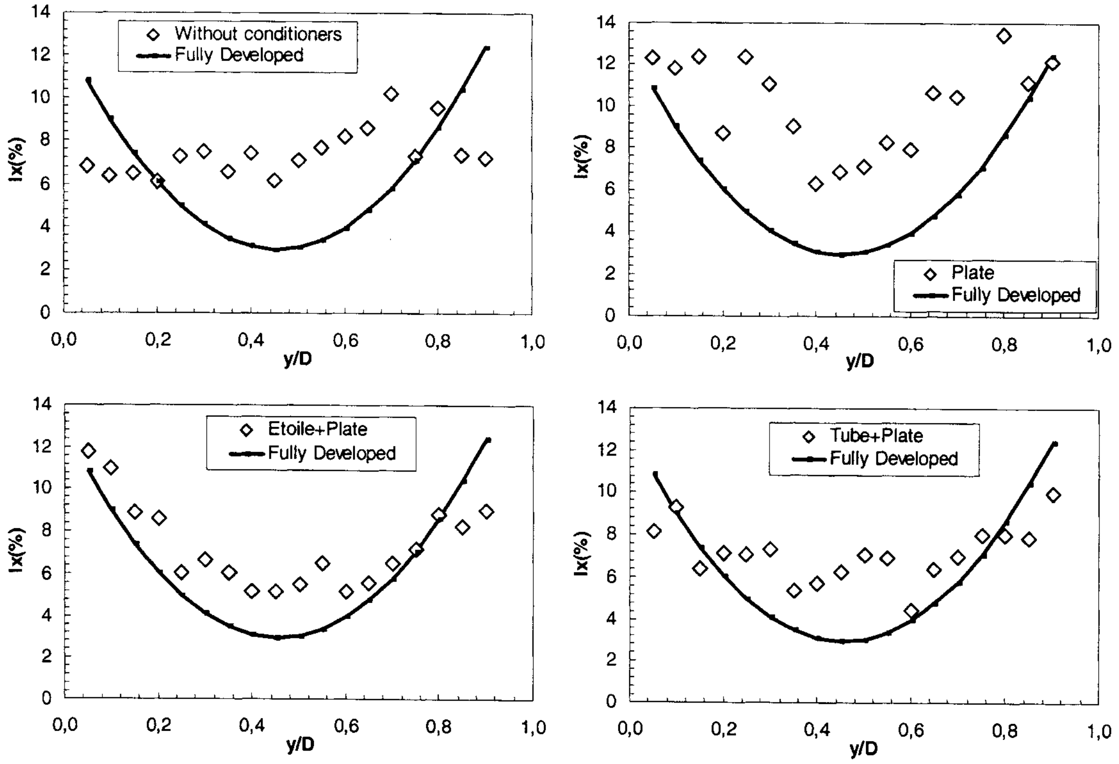


Figure 5 - Turbulent intensity profile measured at the axial station z/D=6 for the four cases.

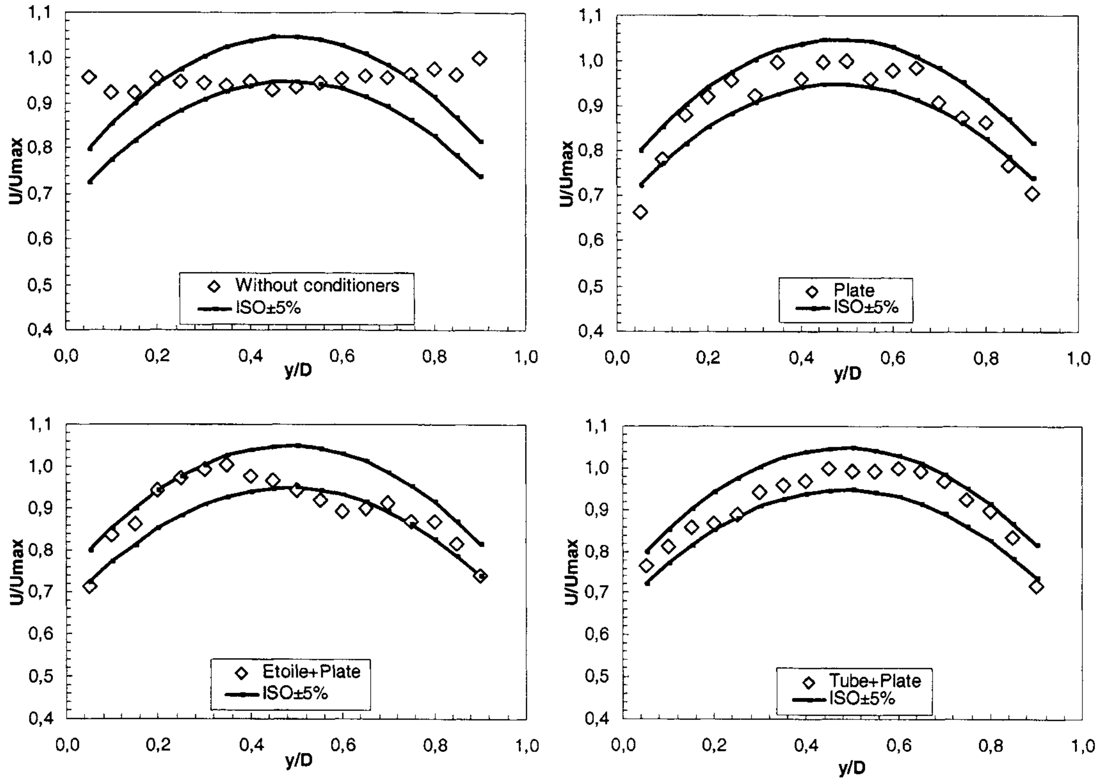


Figure 6 - Velocity profile measured at the axial station z/D=9 downstream the double bend with and without flow conditioning devices

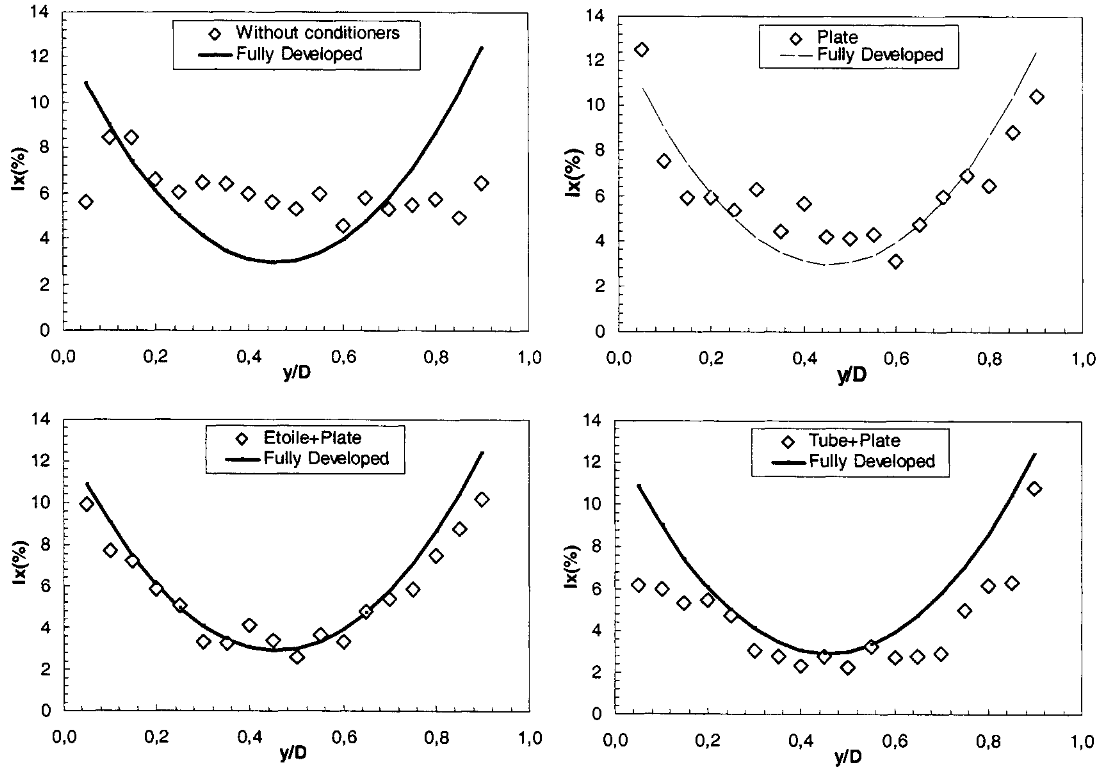


Figure 7 - Turbulent intensity profile measured at the axial station z/D=9 downstream the double bend with and without flow conditioner

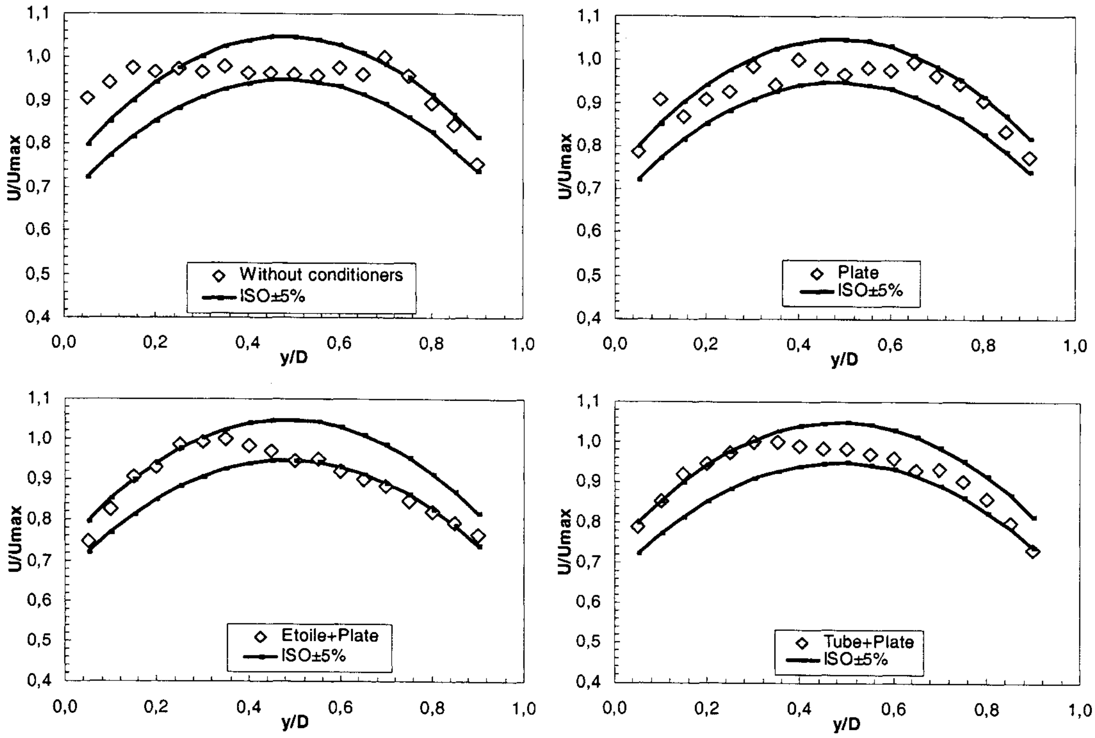


Figure 8 - Velocity Profile measured at the axial station z/D=12 downstream the double bend with and without flow conditioner

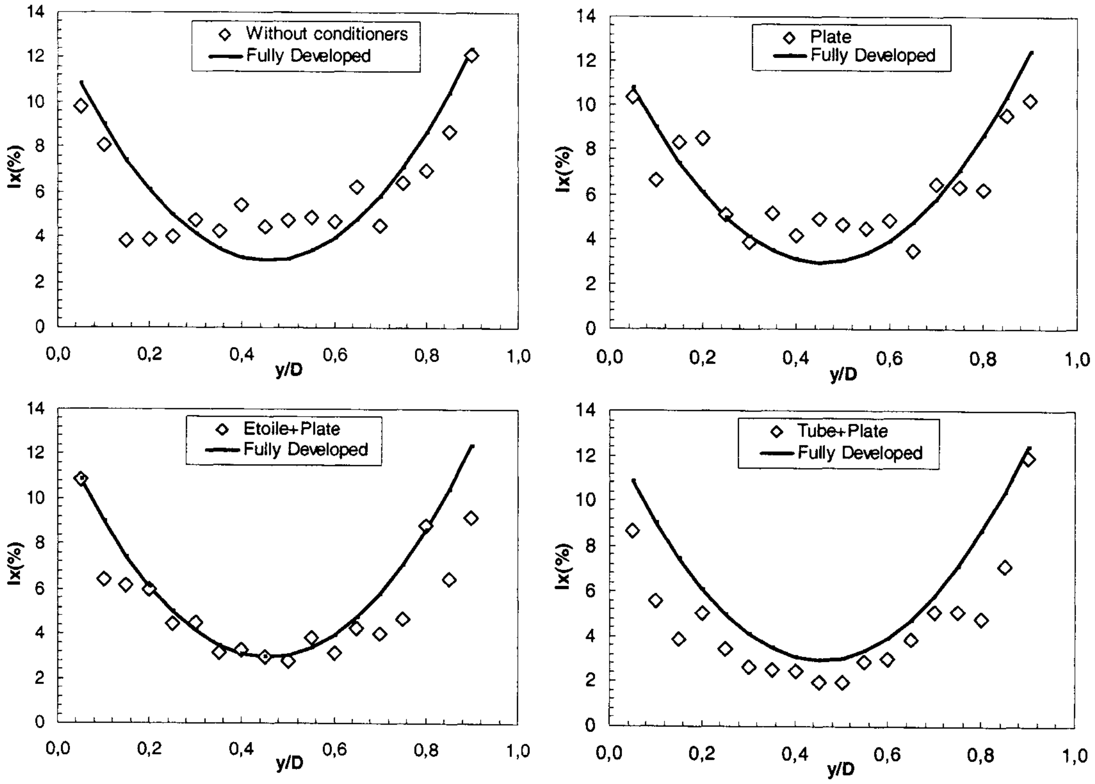


Figure 9 - Turbulent intensity Profile measured at the axial station z/D=12 downstream the double bend with and without flow conditioner

Figure 7 presents the radial distribution of the axial turbulence intensity Ix (%) measured at z/D=9 downstream the double bend out of planes. Without a flow conditioner, the turbulence profile is relatively flat and higher than the fully developed profile over most of the pipe section. This is due to the shear in the mean flow and the swirl generated by the double bend. In the first part of the experimental results, it has been shown that this distortion persists well beyond 22 diameters downstream the source distortion. The conditioner setting combining the Etoile and the Laws perforated plate produces the best turbulence profile with respect to the fully developed distribution.

The examination of the velocity profiles measured at the axial station z/D=12, for the four cases considered, shown in figure 8, indicates that at this developing length the three conditioner combinations seem to produce a satisfactory velocity profile in accordance with the standards specifications. However, the best profile was produced by the Laws plate flow conditioner whereas some deviations were noticed with the other combinations (Etoile-Laws Plate and the tube bundle-Laws Plate).

The associated turbulent profiles measured at z/D=12 downstream the double bend are presented in figure 9 for the four cases considered. The figure clearly shows substantial deviations from the fully developed profile for the conditioners except the combination Etoile-Laws plate which produced a relatively accepted turbulent profile at z/D=12.

The analysis of the above experimental results indicates that substantial deviations from the known fully developed flow profile, in terms of mean flow and its turbulent structure, are still evident at the last measuring station (z/D=12) downstream the double bend (i.e. 9 diameters downstream the flow conditioner). This would suggest that the distortion caused by the double bend out of planes would need developing distances greater than 12 pipe diameters even with the use of a flow-conditioning device. These results are in very good agreement with the previous results reported in [13] and with the PIV measurements reported by Merzkirch and Kalkuhler [15, 17].

3.3. Performance of the three conditioners combinations

A performance study of the conditioners combination on orifice meter readings has been carried out. The results are presented in figures 10, 11 and 12 which show the discharge coefficient shifts of the orifice plate meter with diameter ratio β= 0.50, 0.62, 0.70 respectively. The performance test was run at different Reynolds number. The tested flow meter was placed at 7.5 pipe diameters downstream the double bend (3D downstream the flow conditioner combination).

The results show that the double bend out of plane, without any conditioner, generates a highly swirling flow, which causes positive and negative deviations in the discharge coefficient ΔC_d.

The observations show that the discharge coefficient shifts are positive for diameters ratios $\beta<0.7$ and negative for $\beta\geq0.7$. These results are in good agreement with the findings of Zimmermann [16].

Results for the orifice meter with a diameter ratio β= 0.50 are shown in figure 10. The best agreement with the ISO limits is obtained by the combination of the Etoile and the Laws perforated plate where the errors are within the standards limits of ±0.5%. For the other combinations, the errors increase as the Reynolds number increases.

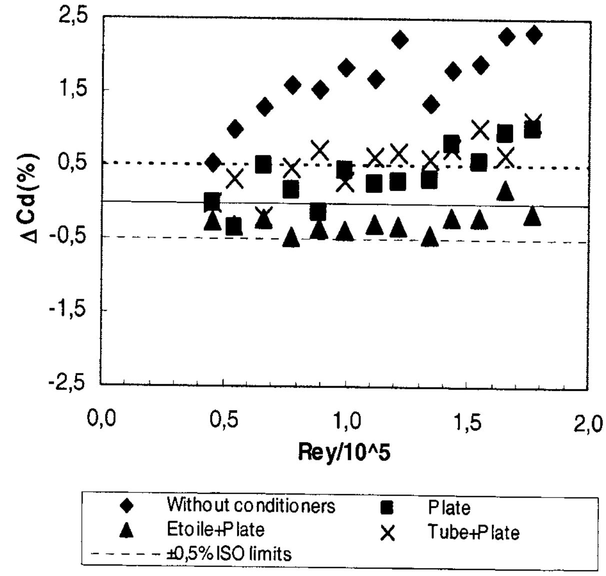
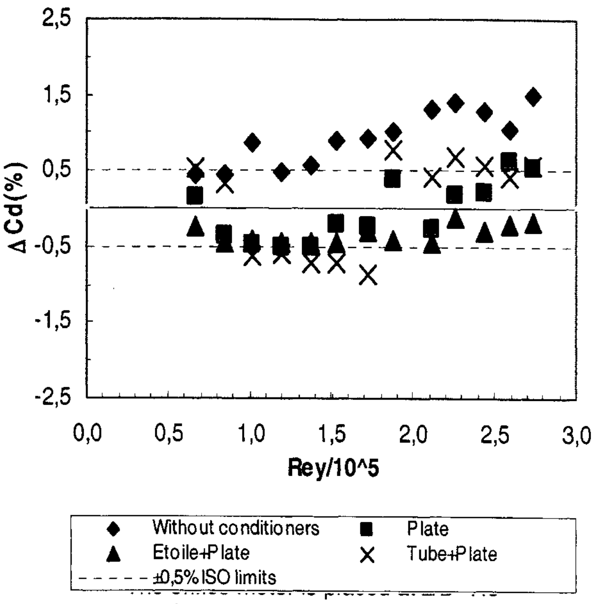


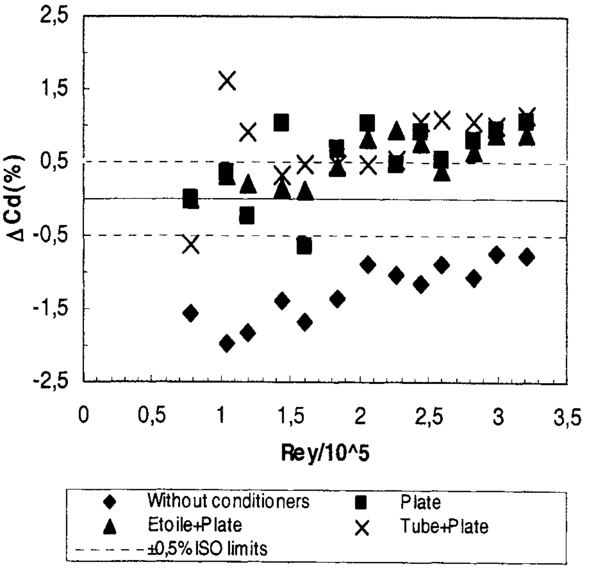
Figure 10 - Discharge coefficient error for β=0.5. The orifice meter is placed at z/D=7.5 downstream the double bend

Figure 11 shows the discharge coefficient error ΔC_d variations for the orifice flow meter with a diameter ratio β= 0.62. The best results, which agree with the ISO specifications, were obtained by the Laws plate alone and the combination Etoile-Plate, where the errors are less than ±0.5%. For the combination plate and the tube bundle the errors were out of the ISO limits independently of Reynolds numbers.

Results for the orifice plate flow meter with diameter ratio β= 0.70 are presented in figure 12. This figure shows that the best agreement with the ISO limits was obtained by the combination Etoile-Laws plate for Reynolds numbers $Re\leq1.9\times10^5$. For Reynolds numbers $Re>1.9\times10^5$ the discharge coefficient shifts were out of the ±0.5% ISO limits and tend to increase when the Reynolds numbers increases.



downstream the double bend



The orifice meter is placed at z/D=7.5 downstream the double bend

4. Conclusions

This experimental work is dedicated to examine the effect of upstream conditions generated by different settings of flow conditioners on orifice flow meter readings. Three combinations of flow conditioners (tube bundle, Etoile and the Laws orifice plate) were used and exposed to the flow disturbed by a 90° double bend in perpendicular planes. The two components Laser Doppler Anemometer was used to investigate the flow behaviour downstream the double bend and the new flow conditioners devices.

The discharge coefficients were measured with three different orifice meters at different Reynolds numbers and the results show that the diameter ratio β has a noticeable effect on the flow meter readings.
This effect has been shown to be dependent on the conditioning device setting used in conjunction with the flow meter.

It has been noted that even with the use of the conditioner combinations, in perspective to improve the flow meter performance, the flow would need more than 12 pipe diameters of straight piping length to be considered at its fully developed condition according to the standards specifications. In fact, the present results suggest that the velocity profile generated by one of the tested combinations (for example the Etoile-Laws plate combination) is close to the fully developed profile at the early stage of flow development (Z/D=6). Then, due to the instabilities of the turbulent structure and the tangential motion (swirl) generated by the double bend, this good profile changes towards a non acceptable flow profile at another station further downstream of the conditioning device. In view of the present results, it is not clear whether such a combination of vortex action and jet mixing conditioners would be of any benefit in conditioning the flow structure and producing the fully developed flow condition within short distances. Based on PIV measurements downstream different flow conditioners, Merzkirch [17] concluded that even at 20 diameters downstream the flow conditioner the flow structure was not at its fully developed condition.

The results show that at the station z/D=7.5 and for a β less than 0.62, the combination Etoile + Plat gives very satisfactory results for the variation of the discharge coefficient ΔC_d. These results are in good agreement with the recommendations of the ISO 5167. But it would be necessary to analyze this combination for other cases of disturbances such as a valve partially closed, a producer of strong swirl such as a propeller. We also think that it would be beneficial to modify the current geometry of the Etoile, especially in the core region.

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