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DESIGN OF A TUBE BUNDLE CONDITIONER FROM AERODYNAMIC CONCEPTS

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Summary

This paper presents an investigation on the behaviour of a tube bundle flow conditioner from experimental and flow modelling analyses. For a given geometry, the method of calculation gives the velocity profiles and the flow development downstream of the conditioner. From these results, two devices were designed and tested both in laboratory and industrial environment. For a fully developed upstream flow or for a swirling flow obtained downstream of two bends in different planes, the comparison between the prediction and the experiments is satisfactory. When the upstream flow is non symmetric like downstream of a U bend, the results show that the flow conditioner does not cancel entirely the flow asymmetry.

Introduction

Since twenty years, many studies have investigated the influence of the flow characteristics on the behaviour of different flowmeters. They have shown the necessity to place important lengths of straight pipe upstream of the metering device in order to ensure accurate flow counting. Nevertheless these lengths, which may reach 100 pipe diameters, can not always be achieved and the use of special devices called flow straightener or flow conditioner seems to be necessary.

As indicate in [1], while a number of such conditioner are included in international Standards ISO 5167 and ASME/ANSI 2530, there are considerable differences between installation lengths recommended in these two Standards. Furthermore, HUMPHREY[2] and SMITH[3] have shown that in many cases, the distance indicated in Standards are not sufficient to ensure the flow metering accuracy expected. Nevertheless, as pointed out by LAWS[1], in most studies, the performance of the flow conditioner was judged, not by the quality of the flow produced, but by the effect on the flow metering.

In order to improve the behaviour of such a device in many industrial configurations, recent works were undertaken to analyse the flow up and downstream of different flow straighteners and classify their performance[1,4,5,6]. In these studies new types of devices are proposed. Nevertheless, despite of the great number of results presented, no information is provided to answer the following questions: How these straighteners are designed? What are the useful geometrical parameters which influence the flow mixing and the flow development? In particular, even if in a recent paper LAWS[1] pointed out the role of the turbulence profile on the flow development, no result provides information about the « best » turbulence profile to be achieved close downstream of the conditioner.

Although, following the conclusion of recent work[1,5,7], it seems that the perforate plate flow conditioner are more efficient in terms of flow quality and pressure loss than tube bundle devices, we present in this paper a study performed between 1984 and 1988 with the financial support of Gaz de France and Gaz du Sud Ouest on the design of a tube bundle flow conditioner/orifice plate package. The tube bundle system is of the same type than SENS and TEULE [8] and HEBRARD and BOSCH[9] conditioners. This means that, contrary to the tube bundle systems proposed in Standards, the length of the different tubes depends on their radial positions. So, the outlet of the different tubes are not in the same plane. The aim of this work is to understand how such a system works? and what are the optimal geometrical parameter (tube length distribution, tube diameter) which ensure a « good flow » with the lower pressure loss?. From this study, two systems were designed and tested in industrial environment on the Gaz de France facilities

1. Experimental analysis of the flow conditioner behaviour.

1.1 Description of the flow conditioner

The geometry of the flow conditioner is presented in figure 1. It is made of concentric rings of small tubes with an internal diameter d_t . The radial position of the i^{th} ring is r_i. These tubes are combined so that one face of the flow conditioner is flat.

1.2 Description of the flow through the conditioner

The flow through the conditioner is schematised in figure 2. It can be divided in four zones. In the first one, upstream of the system, the fluid accelerates due to the diminution of the section. The static pressure decreases to a minimum value corresponding to the contraction of the flow at the inlet of the small tubes. In the second zone, in each individual tubes, the flow characteristics move from the inlet conditions (velocity, pressure) to fully developed ones. From the experimental results of DIESSLER[10], it is possible to calculate for each tube the static pressure variation between the inlet and the outlet [11]. In the third zone, the mixing of the small jets issued from each tube occurs. The static pressure increases due to the flow expansion. This flow region is essential in the behaviour of the flow conditioner and was studied in details. In the fourth zone, downstream of the jet mixing zone, the flow develops to the steady conditions. This flow development is mainly influenced by the flow conditions occurring at the end of the mixing jet region and in particular by the velocity gradients.

1.3 Experimental study of the mixing zone

The aim of this study is to understand the role of the decay of the outlet of the small individual tubes on the mixing of the small jets and so on the flow conditions obtained at the end of this region. For this, a simplified flow conditioner was built with only a central tube and two rings (six tubes on the first and twelve on the second). These tubes have the same length and the same diameter d_t. At the inlet of each individual tube, a same small perforated plate is placed in order to ensure a same flowrate in each of them. The internal diameter d_t of the tubes is 11 mm and their length is 300 mm. The set-up used permits to place the outlet of each individual tubes at a given longitudinal position and so to impose a given decay between two rings. This device is placed in a 100 mm pipe. The velocity and turbulence profiles are measured with a constant temperature anemometer (CTA).

Detailed results may be found in [11]. Nevertheless the main conclusions of this work are:

- The shape of the velocity profile obtained at the end of the mixing zone is greatly dependant on the decay between the outlet of the small tubes. In particular, the maximum in the velocity profiles is achieved at the radial location corresponding to the most shifted tubes(figure 3).
- The pipe wall influences the mixing process.
- In a given pipe section, the static pressure is approximately constant
- The static pressure can be described by an analytical expression given by TYLER and WILLIAMSON[12].
- The length of this zone depends on the tube diameter and on the radial distance between two rings.

1.4 Experimental study of the flow development downstream of the mixing zone

The length of this zone i.e. the distance between the end of the mixing zone and the section where the flow is fully developed mostly depends on the flow characteristics obtained at the end of the mixing zone[1]. In order to analyse the influence of these flow characteristics on the flow development, many tests were performed with different flow conditions (velocity profile, turbulence profile). In figures 4 to 7, the flow development obtained for different initial conditions are plotted. These results show that the rate of development of the flow towards steady conditions depends on the intensity and the location of the velocity gradients. The existence of steep velocity gradients induces an important production of energy of turbulence and therefore an increase in the turbulence levels. Furthermore, the existence of high levels of turbulence produces a radial diffusion of momentum. Consequently, it seems preferable to obtained at the end of the mixing zone, not a smooth velocity profile but flow conditions with steep radial gradients which ensure a rapid development of the flow.

2 Optimisation of the flow conditioner

In the study presented in the previous paragraph, the different parameters which may modify the performance of the flow conditioner were pointed out. Nevertheless, in order to perform a quite exhaustive analysis of these parameters, it is necessary to develop numerical methods.

The method used is divided in two parts. In the first part, the velocity profile obtained at the end of the mixing zone is calculated from an integral method. The choice of the first method was done in consideration of the complex 3D phenomena occurring in the jet mixing zone. In this method an balance equation for momentum is solved for each ring. The interaction of two different jets is modelled from the experimental results. In the second part, the flow development further downstream is predicted with a classic k-ε method in axisymmetric form. The correlation between the inlet U-profile and the inlet conditions for turbulent quantities (energy k and rate of dissipation ε) has been fixed from experimental results.

Details about these methods of flow modelling may be obtained in [11, 13].

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[1] The development is also influenced by the pipe roughness but this factor has not be taken into account in this study

These different tools were then used in the following steps. At first, the k-ε method was applied to define the optimal U-profile needed at the end of the mixing region. Then the integral method was used to fix the geometry of the conditioner (shape, tube diameter). This choice imposes the pressure loss induced by the flow conditioner. Two straighteners were defined with two tube diameters (CERT 1: d_t = 5 mm and CERT 2: d_t = 10 mm respectively). The internal pipe diameter D is equal to 100 mm.(figure 8). In both cases, the length of the smaller tubes was fixed to 40 mm. These two flow straighteners were tested in laboratory environment with different upstream flow conditions (fully developed profile, uniform profile, swirling flows, non-symmetric profile). Figure 9 shows a comparison between the flow development obtained experimentally downstream of the first flow conditioner (d_t =5 mm) with an upstream uniform profile, and the prediction given by our numerical method. At 6.5 pipe diameter D, the flow characteristics have been judged to be sufficiently closed to the fully developed conditions to ensure good accuracy with an orifice plate flow conditioner[2]. For this reason the overall length of the package has been fixed to 6.5 pipe diameters. The pressure loss coefficient K ($= \Delta P/(1/2\rho U_0^2)$) for the first device varies from 3.9 to 3.7 for Reynolds numbers between 30,000 and 80,000.

3 Tests of the CERT flow conditioners

These two flow conditioners were tested both in laboratory and industrial environment for different upstream flow conditions. These tests included velocity and turbulence measurements and metering error with an orifice plate placed 6.5 pipe diameter downstream of the flow conditioner. The upstream flow perturbations were created either by flow generators (swirling flows, non symmetric flows) or by bend arrangement (two bends in different planes or a U bend), In this last case the flow conditioner is placed just at the outlet of the second bend.

3.1 Flow measurements

In figure 10, the U-profile obtained in gas downstream of the first flow conditioner with an upstream flow condition fully developed is plotted. It is compared with the flow measured downstream of 300 D of straight pipes. It can be noted that the CERT flow conditioner do not modify the fully developed conditions near the wall. On the centreline, a slight deficit can be noticed.

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[2] These reasonable flow conditions were obtained from an analysis of different works on orifice plate measurements [11, 14].This analysis try to link metering errors obtained downstream of various devices with flow conditions measured at different locations downstream of this devices.

In figure 14, the turbulence levels u/U_o are presented. They are compared with the results of LAWS [1] (50% porosity Laws plate preceded by vanes positioned 0.5 D upstream) It can be seen than the first CERT conditioner gives better results than the second. When compared to LAUFER's results (Re = 50,000), the LAWS conditioner seems to be more efficient than the two CERT devices.

The flow conditions obtained when the conditioner is placed downstream of two bends in different planes are plotted in figure 12. It can be seen than, as for in fully developed flows, the velocity near the wall is well described. Nevertheless, in the centre of the pipe the velocity is too weak. In this case, the LAWS conditioner gives better results.

The behaviour of the flow conditioners with an upstream non symmetric flow is investigated in figure 13. The characteristics of the flow at the outlet of the U bend are not available. If the CERT conditioner attenuate the upstream flow perturbation, it is evident that they does not remove it entirely. Nevertheless the comparison between the profiles obtained for different conditions shows that the «signature» of the flow conditioner is always noticeable (figure 14). Although the results obtained by LAWS show that the asymmetry, still appears 5.5 D downstream its plate, its device is obviously more efficient.

3.2 Metering error

These tests were performed with an orifice plate flowmeter placed 6.5 diameters from the downstream face of the conditioner. For non symmetric flows, the β ratio is fixed to 0.57. For swirling flows, a 0.4 β ratio is considered. These results are plotted in figure 15. It can be seen that for a non symmetric flow, the metering error is about 1% for the two flow conditioner. This results confirmed the poor efficiency of these devices concerning such flows. For swirling flows, the errors obtained is near 0.5 %. This is due to the shape of the velocity profile and in particular the low velocities near the pipe axis. This is confirmed by a recent study on orifice plate flow meters in which the metering error has been linked to the velocity deficit on the pipe axis[15]. In this work the C_D deviation is compared to the variation of the dynamic pressure ($1/2\ \rho\ U^2$) on the pipe axis due to the flow acceleration. between an section located upstream of the orifice plate and the vena contracta. When the upstream flow is flatter than a fully developed flow, this variation rises. This increase of the dynamic pressure variation corresponds to an increase of the pressure difference measured between the two faces of the plate and so, a decrease of the discharge coefficient. In this study, a good correlation is obtained between the discharge coefficient variation measured from ΔP measurements and the discharge coefficient variation computed from the flow acceleration on the pipe axis. For an orifice plate of β ratio equal to 0.4 the discharge coefficient variation obtained for a flat profile is about 0.5%. These recent studies permit to quantify the influence of an upstream velocity profile distortion on the flow counting by an orifice plate. Such information were not available in 1988. This may explain the poor efficiency of this package.

Conclusions

This paper presents an attempt to design a flow conditioner from aerodynamic concepts. It shows how, from a detailed analysis of the flow through the straigthener, it is possible to determine the shape which corresponds to the best compromise between its efficiency, its pressure loss and its cost. This definition needs flow modelling methods to analyse the influence of all the geometric parameters. The results show a good correlation between the flow condition predicted and the experiments. For symmetric flows, the tests in industrial conditions have confirmed these conclusions. Nevertheless it seems that these devices do not permit to eliminate the non symmetric flow perturbation. The use of three dimensional flow computation may be consider in order to improve the efficiency of the flow conditioner.

In the present work, the « good » flow condition to be produce by the flow conditioner has been defined from an bibliographical analysis of the different studies on flow metering and fluid mechanics available at this time. This extrapolation done from the different results taken into account was not sufficiently accurate to ensure a precise flow counting with an orifice plate flow meter. Nowadays, more recent works on orifice plate can be used to precise the actual flow condition needed downstream of a flow conditioner.

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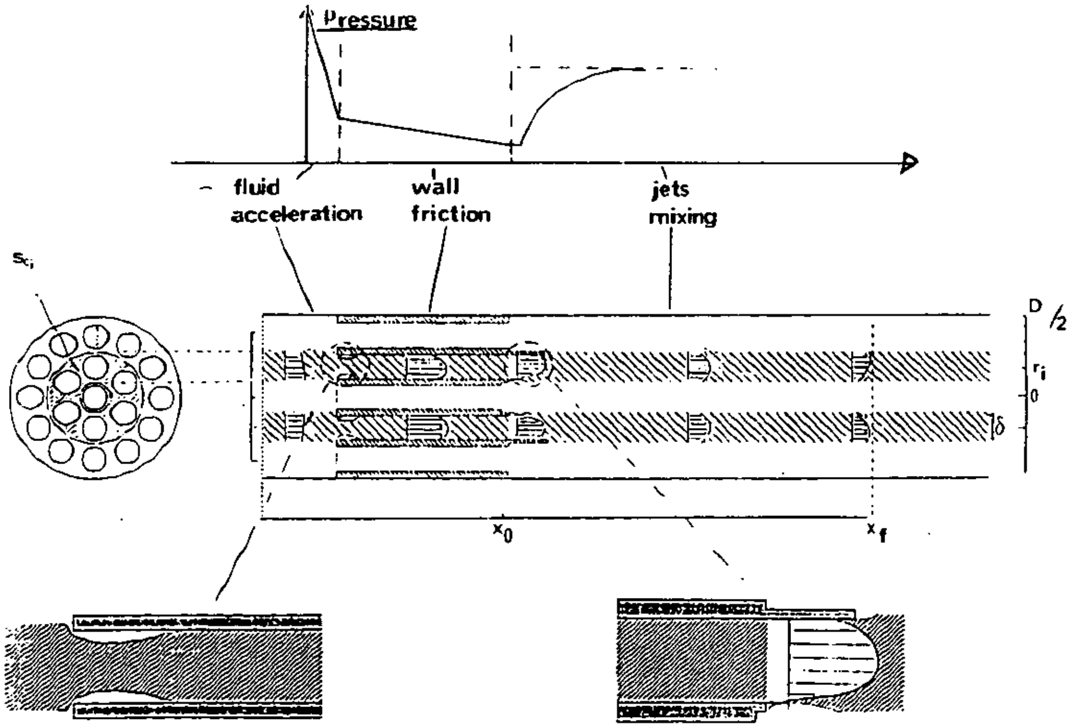
Figure 1: Sketch of the flow conditioner



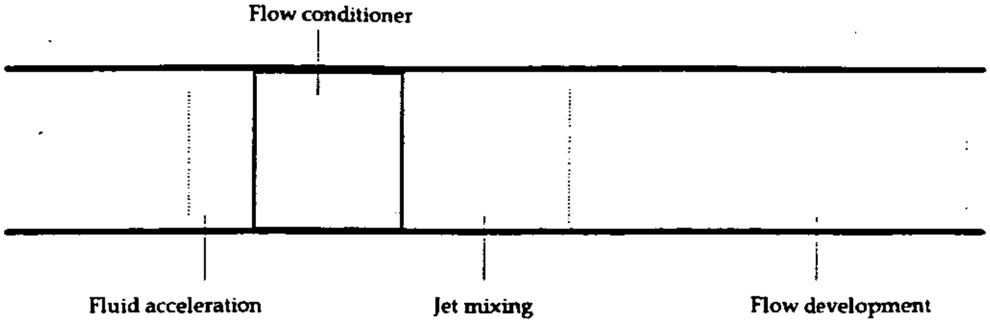


Figure 2: Sketch of the flow patterns through the flow conditioner

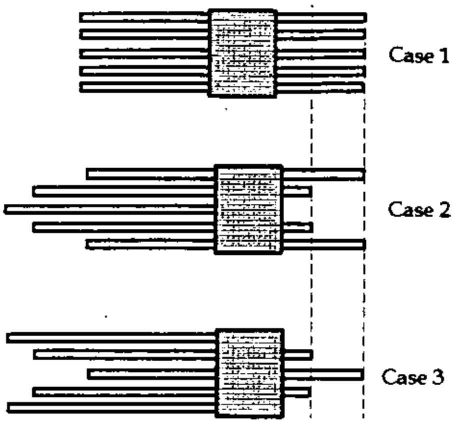


Figure 3: Study of the jets mixing

U profile at the end of the mixing region ($x/d_i = 18.5$)

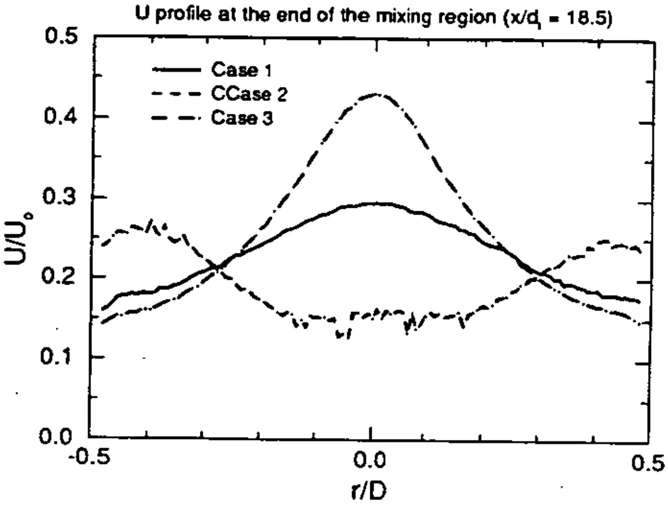


Figure 4: Flow development downstream of the mixing zone

First condition - U profile

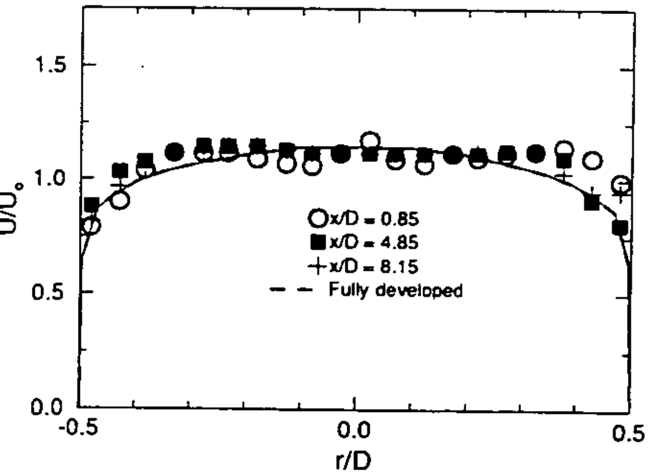
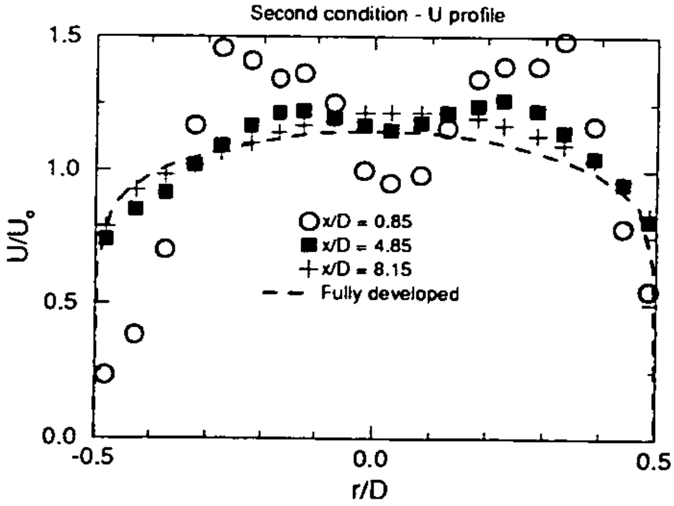
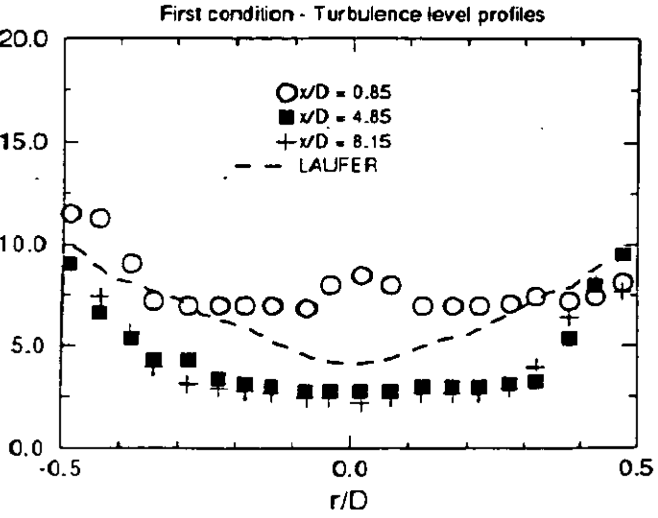


Figure 5: Flow development downstream of the mixing

Second condition - U profile



gure 6: Flow development downstream of the mixing zone



gure 7: Flow development downstream of the mixing zone

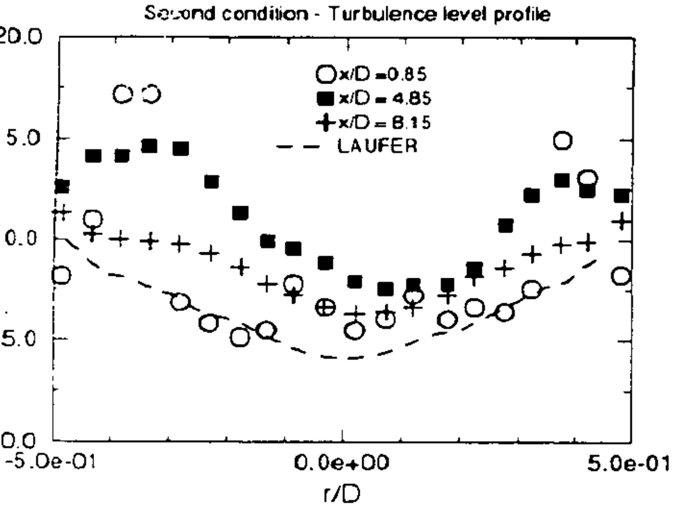


Figure 8: First CERT flow conditioner

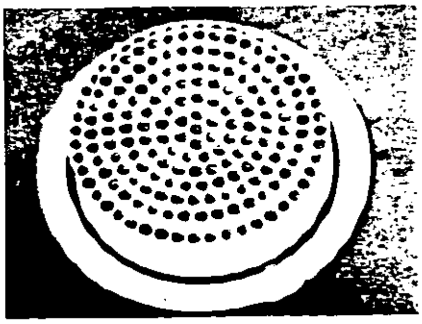


Figure 9: First CERT flow conditioner

Comparison between predictions and experiments

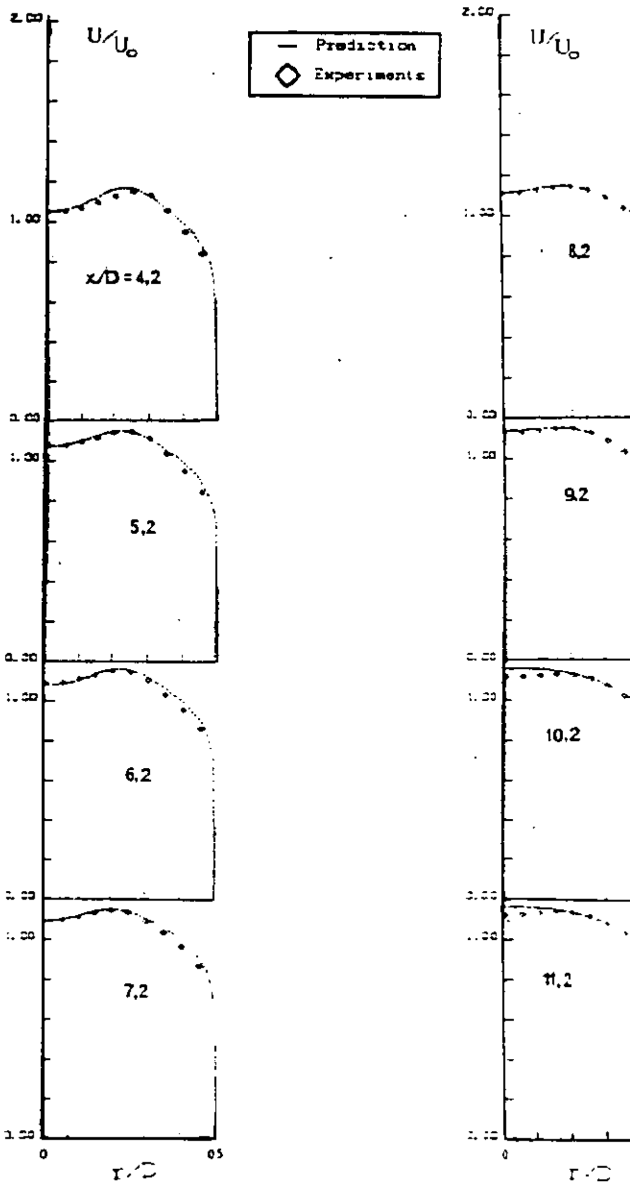


Figure 10: CERT 1 flow conditioner

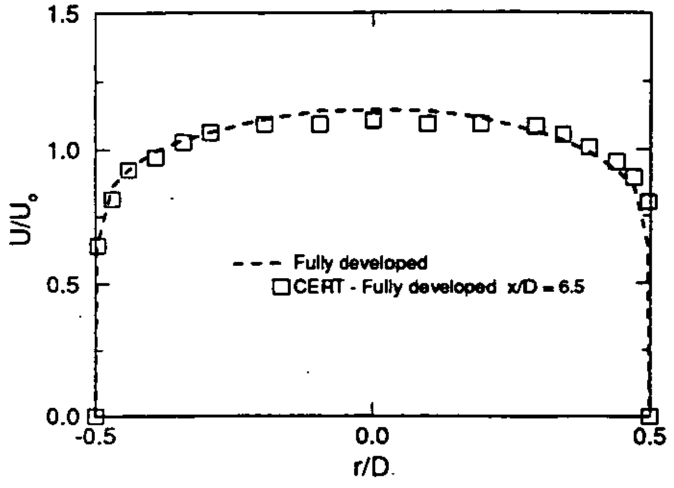

U profile

Figure 11: Turbulence quantities

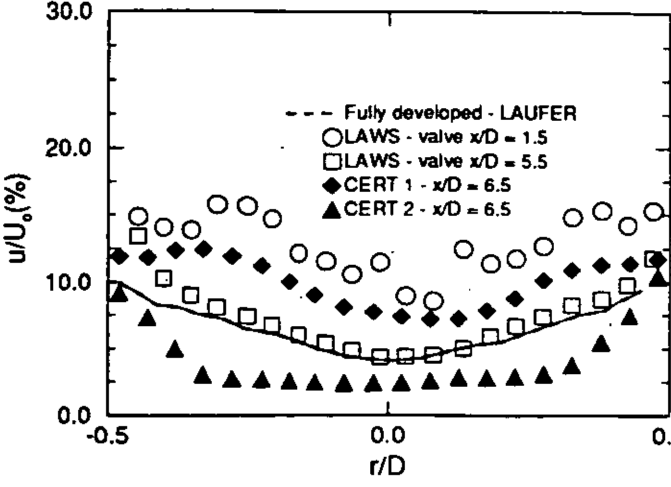

u profile

Figure 12 : Swirling flows : Two bends

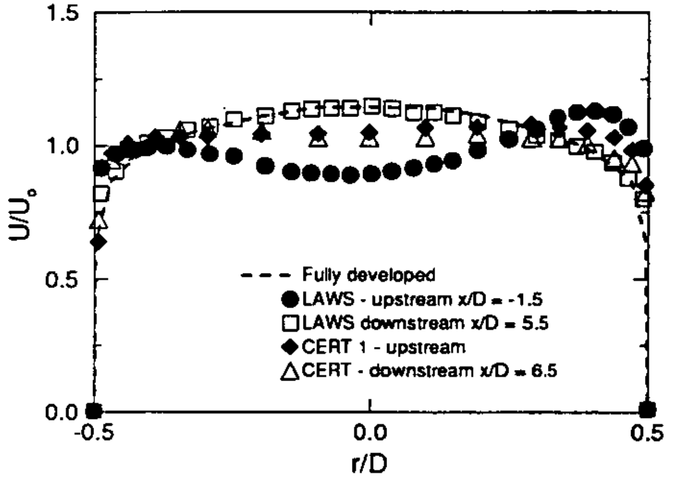

U profile

Figure 13: Non symmetric flows

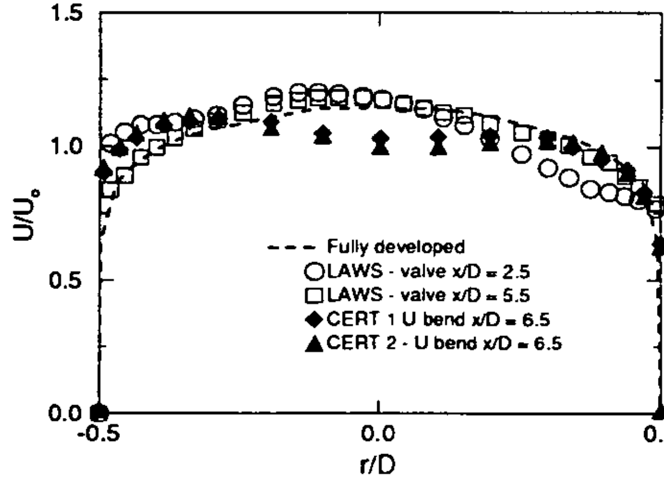

U profile

Figure 14: Influence of upstream conditions

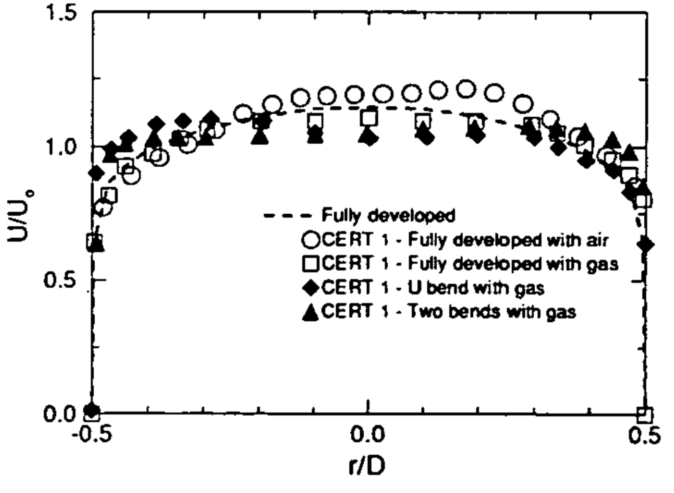
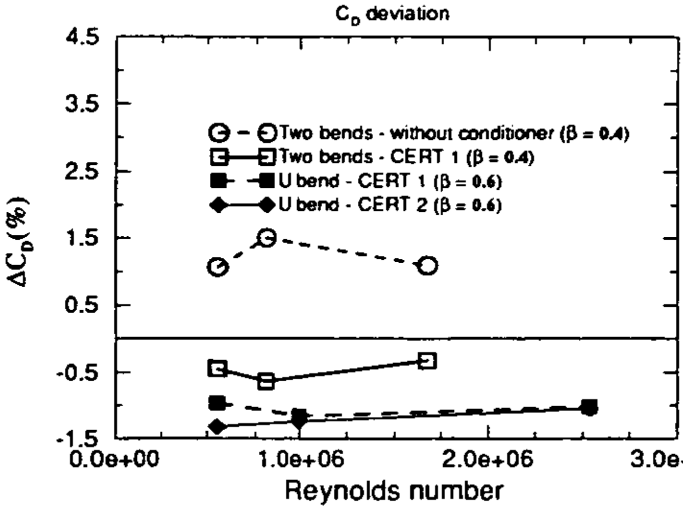

U profile

Figure 15: Orifice plate flow meter


C_D deviation