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Computational Study of the Aerodynamic Behavior of Flow Conditioners used in the Oil and Gas Industry

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ABSTRACT

Flow rate measurements are among the most important operations in modern industries dealing with increasingly expensive fluids such as petroleum, natural gas and water. The accuracy of flow meters depend mainly on their position in a pipe network and their operating conditions. Pipe fittings such as valves and bends generate turbulence and swirl and distort the flow distribution in the pipe, leading to a substantial amount of measuring error. For accurate flow rate measurements, the standards ISO 5167 specify either a sufficient straight piping lengths or the inclusion of a flow conditioner between the flow distortion and the flow meter. Flow conditioners serve to reduce the developing length between pipe fittings and flow meters and to create fully developed flow condition within short distances. Hence leading to the reduction of the metering errors. In the present study, numerical modeling of the flow development downstream three flow conditioners (the tube bundle, the Etoile flow conditioners described by the standards and the Laws plate flow conditioner) have been made. Computational Flow Dynamics techniques have been used to predict the flow development downstream the flow conditioners. The efficiency of the three flow conditioners to produce fully developed flow conditions is investigated.

Key Words : *Mathematical Modeling, Computational Fluid Dynamics, Flow Conditioner, International Standards ISO, Flow Rate Measurement.*

ملخص البحث

تعتبر دقة أجهزة قياس تدفق الموائع الصناعية (مثل الماء، الغاز و البترول) من العوامل الأساسية في العديد من الصناعات التي تصنع هذه المواد ذات الأسعار المتزايدة في الأسواق العالمية و المحلية. عند استخدام هذه الأجهزة لقياس التدفق في الأنابيب الصناعية و حسب المواصفات القياسية الدولية الايزو ٥١٦٧ يلزم مراعاة أن يسبق الجهاز طول مستقيم كاف لضمان انتظام السريان أو إدراج جهاز انتظام السريان. عادة ما تحتوي المواسير الصناعية على تجهيزات مثل الأكواع ، المحابس و المضخات من أجل التحكم في سريان المائع. تؤدي هذه التجهيزات إلى اضطرابات حادة و حدوث حركة دوامية في السريان مما يؤثر سلبا على دقة قراءة جهاز التدفق. يعمل جهاز انتظام السريان على إزالة أثر الالتواء في السريان و تطويره إلى سريان منتظم مما يساعد إيجابا في تحسين دقة القياس. في هذه الورقة نقدم نتائج دراسة عددية و محاكاة لتطور السريان بعد هذه الأجهزة.

الكلمات الدالة : المحاكاة، الطرق العددية، ديناميكا الموائع ، المواصفات القياسية الدولية الايزو ٥١٦٧، قياس التدفق.

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 barrels 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, axisymetric, 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 ±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 minimizes installation effects and increase metering 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 Bart02)) 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 to 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 metering 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. The present paper is dedicated to present only the computational part of the work.

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 to predict the flow development downstream flow conditioners. The equations for the numerical model are:

Continuity equation (Mass Conservation) :

$$\frac{\partial(\rho U_i)}{\partial X_i} = 0 \qquad (1)$$

Momentum Equation :

$$\frac{\partial}{\partial X_j}\left(\rho U_i U_j\right) = -\frac{\partial P}{\partial X_i} + \frac{\partial}{\partial X_j}\left(\mu\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right) - \rho\overline{u_i u_j}\right) \qquad (2)$$

Where $-\rho\overline{u_i u_j}$ represents the Reynolds shear stresses which is modeled by the K-ε turbulence model through the equation:

$$-\rho\overline{u_i u_j} = \mu_t\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right) - \frac{2}{3}\delta_{ij}\rho K \qquad (3)$$

Where μ_t is the turbulent viscosity which is function of the turbulence energy K and its dissipation rate ε :

$$\mu_t = C_\mu \rho \frac{K^2}{\varepsilon} \qquad (4)$$

K and ε can be described from their respective differential equations:

$$\frac{\partial}{\partial X_j}(\rho U_j K) = \frac{\partial}{\partial X_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial K}{\partial X_j}\right) - \rho\overline{u_i u_j}\frac{\partial U_i}{\partial X_j} - \rho\varepsilon \qquad (5)$$

$$\frac{\partial}{\partial X_j}(\rho U_j \varepsilon) = \frac{\partial}{\partial X_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial X_j}\right) - C_1\frac{\varepsilon}{K}\rho\overline{u_i u_j}\frac{\partial U_i}{\partial X_j} - C_2\rho\frac{\varepsilon^2}{K} \qquad (6)$$

The model constants are those recommended by the Launder and Spalding (1974) :

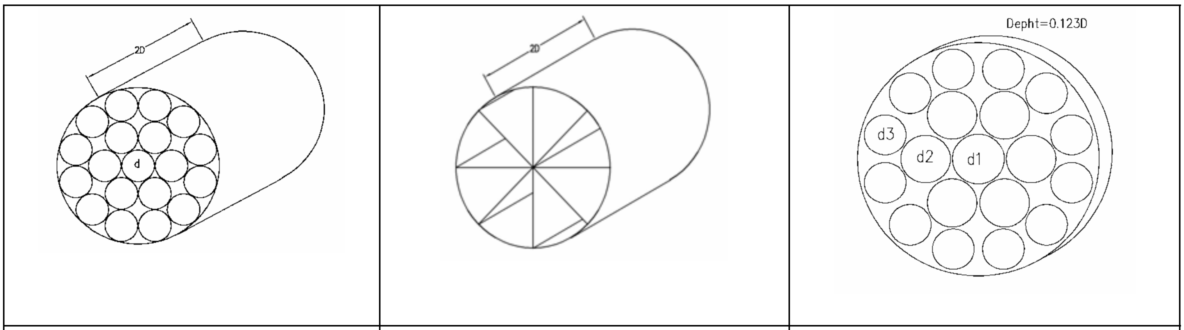
Table 1 - Constants of the Standard K-ε model

Cμ	Cε1	Cε2	σk	σε
0,09	1,44	1,92	1,0	1,3

The differential 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). Further details on the numerical procedure can be found 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 – 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 (figure 1) described by the standards and the Laws plate flow conditioner have been made. The initial conditions were prescribed from the experimental data taken respectively from (Laws and Ouazzane 1994, 1995 and Merzkirch 2001). The conditioners were subjected to severe flow distortions created either by a 90° double bend or a ball valve 50 %, 70 % or 100 % open.



a - The 19 tube bundle flow conditioner (ISO 5167)

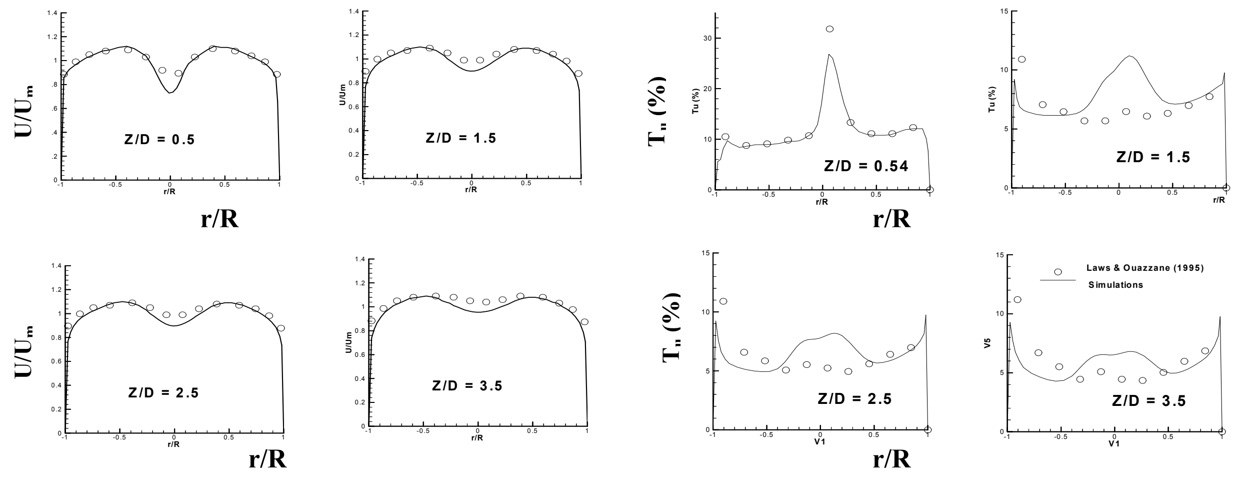
b – The Etoile flow conditioner (ISO 5167)

c – The Laws plate flow conditioner

Figure 1 – The investigated flow conditioners

Predictions of the mean flow and turbulent flow structures downstream the flow conditioners were obtained and analyzed. Though the numerical procedure described here has been used and tested in early research works (Laribi and Aichouni 2000), during the present research, grid independent test and predictions validation (figure2) have been carried out. It is clear that this numerical procedure is suitable to carry out the investigation of flow development downstream these devices.

Figures3-a, 3-b and 3-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 figures 4, 5,6 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 standards. Such an observation has been made recently by Merzkirch (2001) in his PIV experimental investigation upon examining 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 – Mean Velocity (U/U_m) Profiles b – Axial Turbulence Intensity Profiles

Figure 2 - Comparison between numerical predictions and experimental results (Laws and Ouazzane 1994) for the case of the Etoile flow conditioner with a valve fully open.

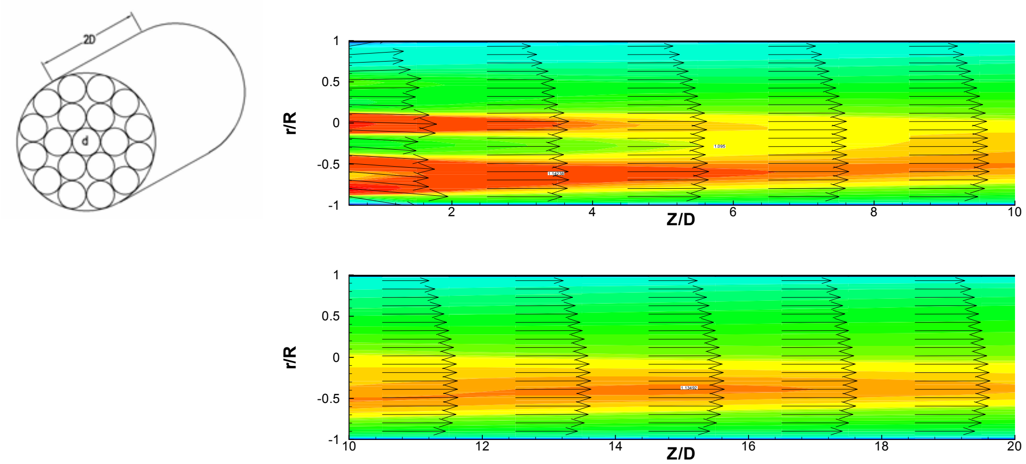
4 – CONCLUSIONS

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 and propose practical solutions. Through this research work, computational fluid dynamics (C.F.D) techniques have been used to investigate the flow development downstream three flow conditioners working under severe flow distortions. Their performance to produce fully developed flow condition was investigated numerically. The tested flow conditioners were the 19 tube bundle and the Etoile flow conditioner, which are described in the standards, and the Laws plate, which is not included in the standards yet.

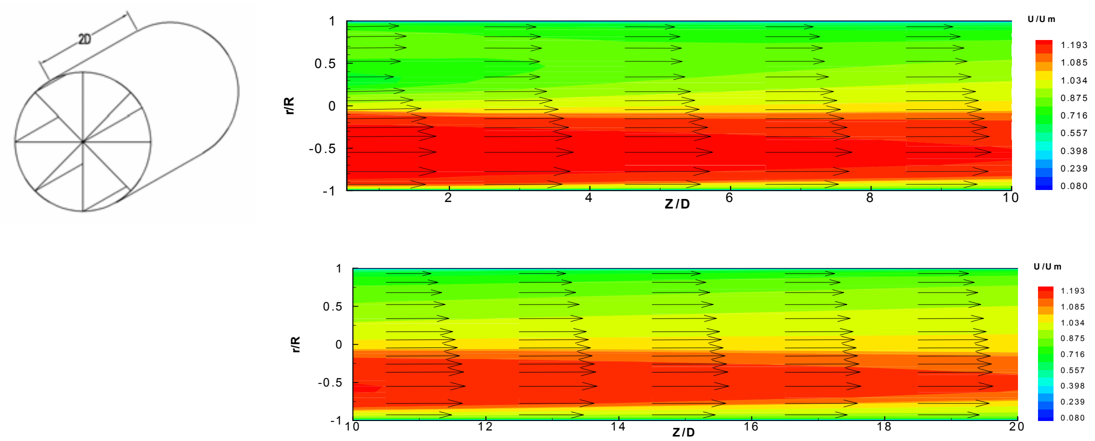
Through an analysis of the predicted velocity profile development downstream the three flow conditioners, it has been shown that the effectiveness of flow conditioners, either those described in the standards or those newly introduced in the technical literature, to produce the fully developed flow condition within reasonable distances (some 20 diameters) remain questionable.

NOMENCLATURE

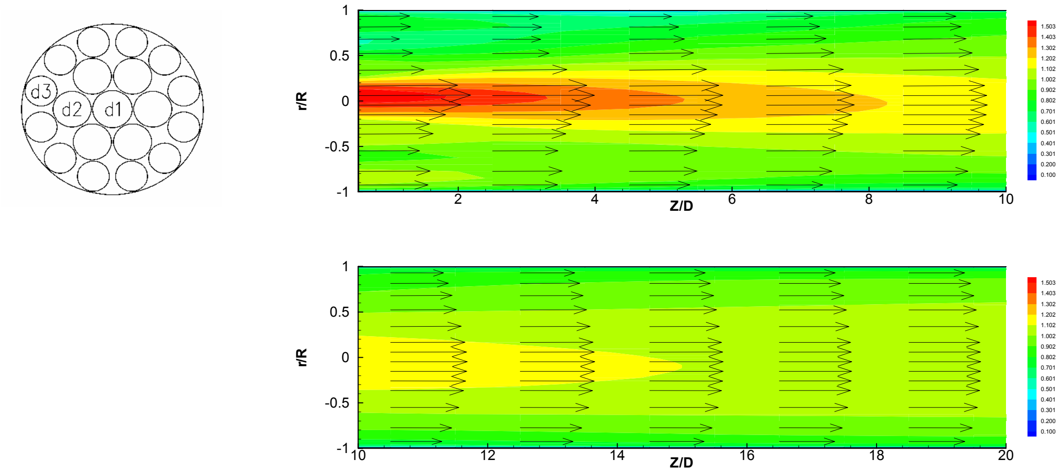
D : pipe diameter
K : turbulent kinetic energy
p : pressure
T_u (%) : axial turbulence intensity
y , Z : radial and axial co-ordinates
U_i : mean velocity components
u_i : fluctuating velocity components
U_m : axial mean velocity
ε : dissipation rate of the kinetic energy
μ : fluid dynamic viscosity
μ_t : turbulent eddy viscosity
ρ : fluid density



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 3 - Predicted flow development downstream the three flow conditioners

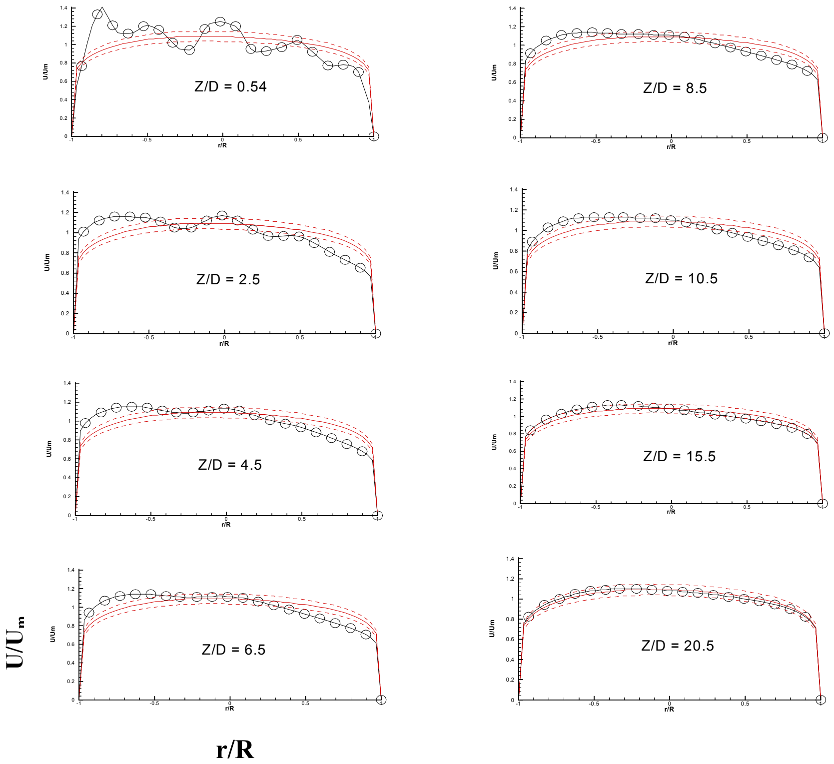


Figure 4 - Velocity profiles simulated at different axial position Z/D compared to the fully developed profile and the ISO limits (±5%) - Case of the 19 Tubes Bundle

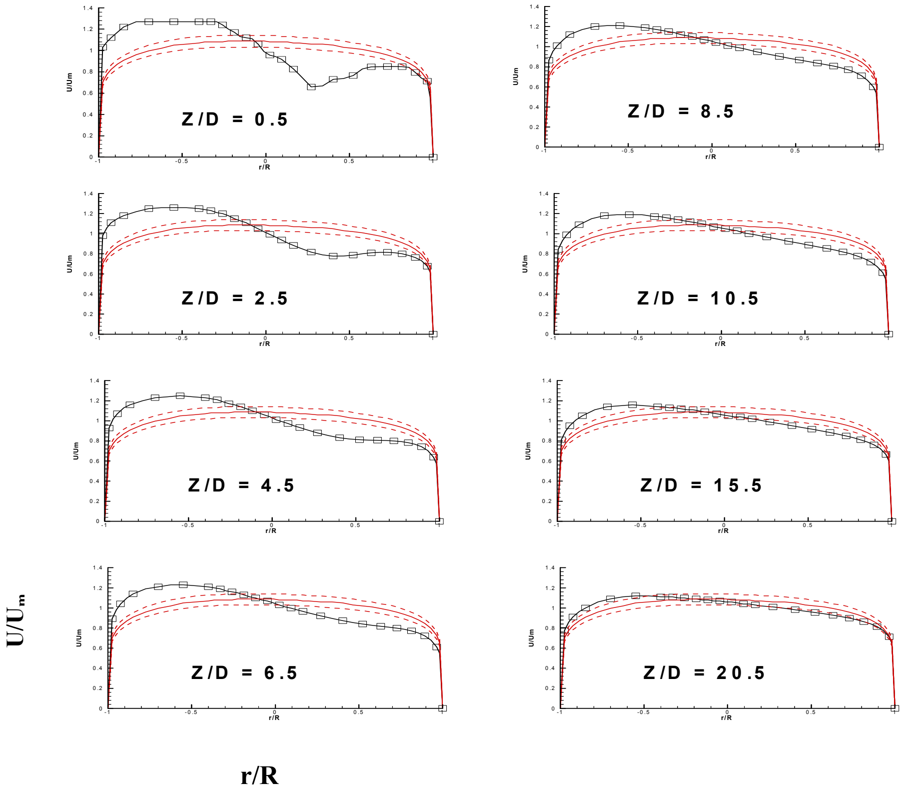


Figure 5 - Velocity Profiles Predicted at different axial position Z/D compared to the fully developed profile and the ISO limits (±5%) - Case of the Etoile Flow Conditioner

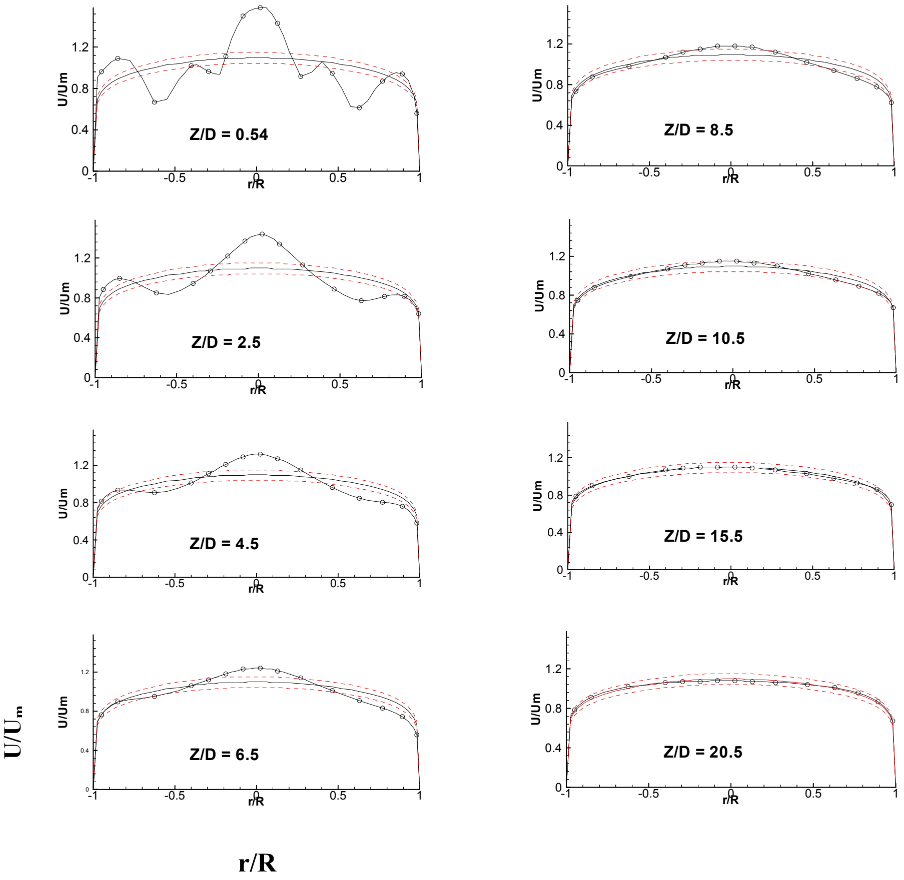


Figure 6 - Velocity profiles simulated at different axial position Z/D compared to the fully developed profile and the ISO limits (±5%) - Case of the Laws Plate Flow Conditioner

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