Computational study of the performance of the Etoile flow conditioner

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ABSTRACT

Flow conditioners serve to reduce the developing length between pipe fittings and flow meters and to create the fully developed standard flow condition within short developing distances. This has been used in industrial settings as means for metering errors reduction and elimination. The authors undertook a research project to predict the flow development downstream different flow conditioners to optimize their performance in reducing flow distortion and the attainment of the standard fully developed condition within shorter distances. The tested flow conditioners were the Etoile and the tube bundle, described by the standards ISO 5167, and other plate-type flow conditioners. The present paper will discuss only the results obtained for the Etoile flow conditioner, with its standard geometry and other proposed design settings. Powerful Computational Flow Dynamics techniques have been used to predict the flow development downstream the flow conditioners.

1. Background and literature review

Flow rate measurements have always been an important industrial operation for process control and fiscal purposes. The ability to accurately measure the flow rate in a duct is of a major concern and vital importance when large volumes of fluids are handled. Gas and Petroleum companies recorded receipts of billions of barrels or cubic meters of gas and petroleum over a period of a year. The quality of gas measurement, receipt and major delivery points distributed through thousands of kilometers of pipe lines, is very important from an economical and technological stand points. Errors in flow measurement can have large cost and efficiency implications.

For accurate flow measurements, industrial flow meters must be calibrated. This is done in fully developed pipe flow, axisymmetric, free from swirl and pulsation. Standards such as ISO 5167:2003 and ANSI/API 2530 AGA 3 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 (Aichouni et al., 1996; Merzkirch, 2001; Sawchuk, 2016).

For acceptable accuracy, a flow meter needs to be presented with an axisymmetric, fully developed velocity profile with zero swirls. 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 conditioners or flow straighteners 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 increases metering performances of these devices. Since early 1980`s concentrated research work has been undertaken at international laboratories and research institutes (Morrow et al., 1991; Gajan and Hebrard, 1991; Morrison et al., 1992; Laws and Ouazzane, 1994; Merzkirch, 2001; Aichouni and Laribi, 2000; Laribi et al., 2003; Gersten, 2008; Laribi et al., 2012; Manshoor and Amir, 2012; Brown and Griffith, 2013) Sawchuck, 2016). It has been focused to investigate experimentally and computationally installation effects on industrial flow meters and the efficiency of flow conditioners to minimize the installation effects on flow meters accuracy. Most of these studies investigated the effect of flow conditioner location with respect to the flow meter on its calibration coefficients. The major conclusions showed 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, 2000) and Laribi et al. (2003, 2012), experimental and numerical results on installation effects upon differential pressure flow meters were discussed, and the performance of flow conditioners to produce the fully developed flow condition and to reduce metering errors were presented. Frattolillo and Massarotti (2002) compared numerically the performance of different flow conditioners, independently from their effects on particular flowmeters. The main fundings of their work were that the etoile presents good characteristics in term of swirl, but the flatness and asymmetry relative efficiencies are not very high and the tube bundle shows very good performance in terms of symmetry, but it also shows a large disturbance of the axial velocity profile.

Though extensive research has been carried out worldwide, there is still a need for fundamental understanding of the flow behavior within this industrial metering setting. The present research project falls within this perspective and the international scientific efforts towards the understanding of the flow development and the efficiency of flow conditioners to remove flow distortions and to produce the standard fully developed condition. In the present paper, we will discuss the numerical predictions of the Etoile flow straightener described in the international standards ISO 5167(R:2014) and ANSI/API 2530 AGA 3. A particular focus will be made on the effect of the length of the Etoile straightener on the flow development towards the fully developed flow condition.

2. Geometry, mathematical model and numerical method

Fig. 1 shows the geometry studied and the grid used. The flow conditioners studied is positioned immediately downstream from the second elbow.

The Reynolds number Re, is defined as follows (Eq. 1):

$$Re = \rho U_i D_h / \mu \tag{1}$$

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 to set a closed system of partial differential equations to predict the flow development downstream flow conditioners.

The steady three-dimensional differential equations governing the phenomenon can be written as follows:

Continuity equation (Eq. 2):

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

Momentum equation (Eq. 3):

$$\frac{\partial \rho u_i u_j}{\partial x_i} = \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \delta_{ij}\frac{2}{3}\frac{\partial u_k}{\partial x_k} - \frac{\partial(\delta_{ij}P)}{\partial x_j}\right] \tag{3}$$

Turbulent kinetic energy equation (Eq. 4):

$$\frac{\partial \rho u_j K}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{Pr_K}\right)\frac{\partial K}{\partial x_j}\right] + \mu_t \frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\varepsilon \tag{4}$$

Dissipation rate of turbulent kinetic energy (Eq. 5):

$$\frac{\partial(\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{Pr_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{C_1 \varepsilon \mu_t}{K}\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{C_2 \rho \varepsilon^2}{K} \tag{5}$$

The turbulent viscosity is defined as (Eq. 6):

$$\mu_t = \frac{C_\mu \rho \varepsilon^2}{K} \tag{6}$$

with:

$C_\mu = 0.09, C_1 = 1.47, C_\mu = 1.92, Pr_K = 1, Pr_\varepsilon = 1.3$ (Launder (1972))

Boundary conditions:

- $u = 0, v = 0, w = 0$, at all tube walls
- $w = U_i, K = K_i, \varepsilon = \varepsilon_i$, at the inlet;
- $\frac{\partial}{\partial n}(u_i, T, K, \varepsilon) = 0$ at the outlet.

The governing equations for the turbulent pipe flow configurations were solved using the COMSOL Muti-physics CFD code; further details about the numerical procedure can be found in Elashmawy and Kolsi (2016).

Numerical predictions were tested at different mesh sizes and grid -independent solutions were obtained with the grids presented in Table 1.

Table 1: Number of meshing elements

Configuration	Meshing Elements
1D	915919
0.5D	803954
0.25D	755123
0.125D	713785

3. Results and discussions

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 Etoile flow conditioner will be presented and discussed.

The initial flow conditions were set to be severely distorted by a 90° double bend which precedes the flow conditioner. The flow was allowed to develop further in a straight pipe up to 100 pipe diameters. The simulated flow configuration is shown in Fig. 1.
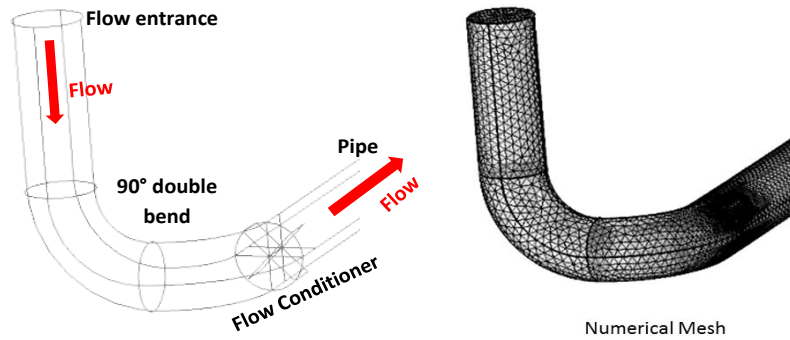
Fig. 1: Flow configuration and computational mesh

Predictions of the mean flow and turbulent structures downstream the flow conditioner was obtained and analyzed.

Fig. 2 shows the axial mean velocity contours downstream the Etoile flow conditioner with three geometrical configurations (i.e. the standard 2 diameters long flow conditioner (L=2D) and L=D and L=D/4). The Fig. shows that the double bend generates a highly distorted flow with a pronounced asymmetry and highly sheared flow, which is associated with high swirl (up to ±8 degrees) and high turbulence levels. A pronounced wake can be noticed at the central region of the pipe which is generated by the solid part of the flow conditioner at the center. The wake associated with the initial flow distortion seems to take several pipe diameters to be attenuated. I is to be noted here that the ISO international standards recommends swirl angle limits for accurate flow metering to be ±2 degrees.
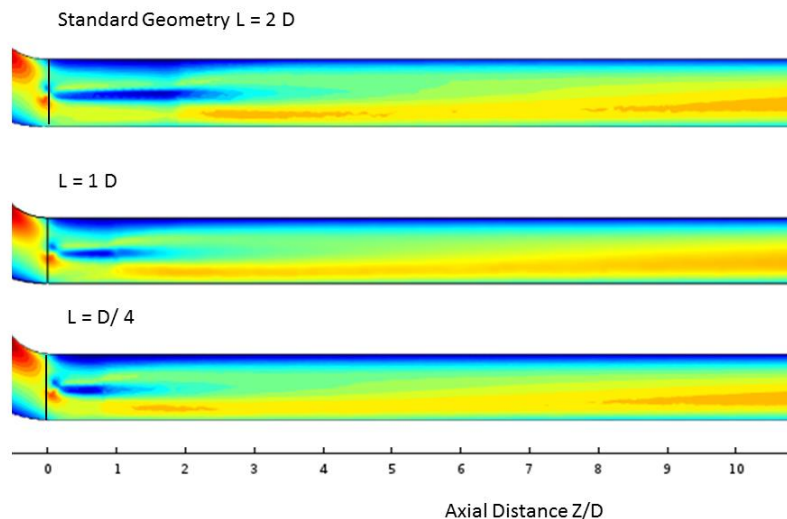
Fig. 2: Predicted flow development downstream the three flow conditioner configurations

It can also be seen from these Figures that though the flow at the vicinity of the flow conditioner depends on the conditioner geometry (Length), at a downstream distances of 10 diameters it does not seem to attend the fully developed profile. The effect of the flow distortion and the swirl still exist after that distance of straight flow development. Early experimental work presented by Laws and Ouazzane (1994) and Brown and Griffith (2013) showed that there is a possibility to produce fully developed flow condition within such manageable and economical distance. However, the authors believe that a standards flow conditioner with this excellent performance is not yet designed. More research

would be needed towards that purpose. In the present paper we were interested to assess the effectiveness of the standard (2D length) Etoile flow straightener on the flow distortion and swirl attenuation towards the fully developed flow condition. Also, the question of the effect of the length of the Etoile on its performance was examined. Though, five configurations were tested during the project (flow straightener with length of 2D, D, D/2, D/8 and D/16), in the present study, only the results of L=2D, D, and D/2, will be presented and discussed. The predicted axial velocity profiles downstream the flow straightener are shown on Fig. 3 at different axial distance (Z/D=4, 8, and 12) and compared to the fully developed profile predicted at Z/D=90. This Figure shows clearly that the flow distortion generated by the double bend is still

present after 12 D of flow development for the tested straightener configurations (2D, D, D/2, D/8 and D/16). The velocity profiles still exhibit the asymmetry and the wake and the shear flow is still present. This can be seen from Fig. 4 where axial velocity profiles and swirl angle were plotted at different axial plans and compared to the fully developed profiles. From these observations, it can be suggested that the length of the Etoile flow straightener would not have a great effect on its performance in reducing flow distortions and disturbances. Hence it is recommended that the standards Etoile flow straightener would be used in industrial settings with flow meters. Early experimental work by Laribi et al. (2003) agree with this conclusion.
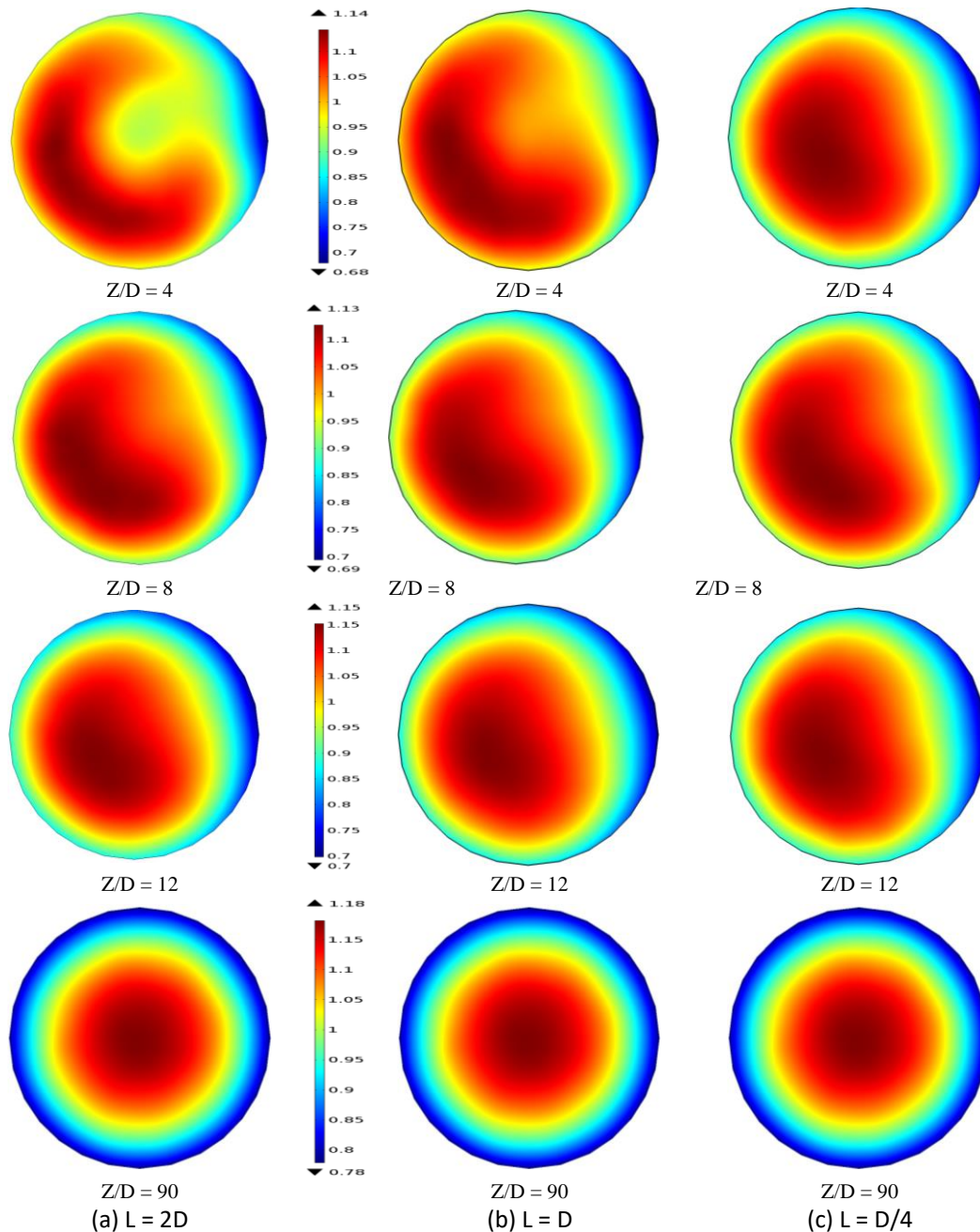

Fig. 3: Predicted axial velocity at different axial positions Z/D downstream the flow conditioner with three different geometries (L) compared to the fully developed profile
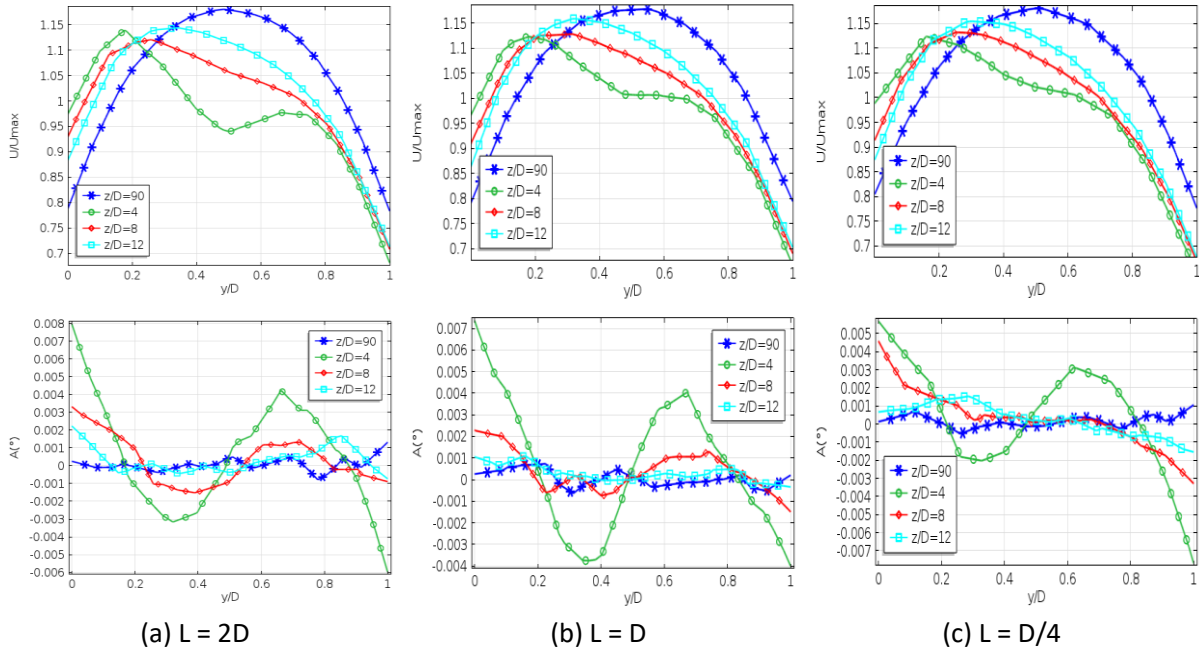
(a) L = 2D	(b) L = D	(c) L = D/4

Fig. 4: Velocity profiles and Swirl Angle simulated at different axial position Z/D for different Length of the Etoile Straightener

3. Conclusion

Measurement of flow rate in non-standards flow conditions remains a problem of highly practical interest from both its technological and economic 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 flow conditioners working under severe flow distortions. The performance to produce fully developed flow condition was investigated numerically. The tested flow conditioner was the Etoile flow straightener described in the standards ISO5167:2003 and ANSI/API 2530 AGA 3.

The effect of the length of the Etoile flow straightener with ((2D as described by the ISO 5167 standards), D, D/2, D/8 and D/16) on the flow performance was also investigated. The predictions show that the mean flow distortions were not removed after 12 D of flow development for the 5 straightener configurations (2D, D, D/2, D/8 and D/16) while the swirl seem to be removed by the straightener within the ISO limits of ±2 degrees. This indicates that the length of the Etoile flow straightener would not have a great effect on the flow performance, suggesting that the standard configuration of the Etoile flow straightener would be recommended for accurate industrial flow metering purposes.

Acknowledgment

Nomenclature

C_1, C_2, C_3	turbulent model constant
D_h	Hydraulic diameter
K	Turbulent kinetic energy, m²/s²
p	pressure, Pa
Re	Reynolds number,
u_i	velocity component in i-direction, m/s
u	velocity component in radial direction, m/s
v	velocity component in circumferential direction, m/s
w	velocity component in flow direction, m/s
x_i	Cartesian coordinate in i-direction
	Greek symbols
Pr_ε	inverse effect Prandtl number for ε
Pr_K	inverse effect Prandtl number for K
ε	dissipation ratio of turbulent kinetic energy, m²/s²
δ_{ij}	Dirac delta function
μ	dynamic viscosity of fluid, kg/(m s)
ρ	density, kg/m3
	Subscripts
i	inlet condition
o	outlet condition
t	turbulent quantity
w	wall condition

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