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NUMERICAL ANALISYS OF FLOW CONDITIONER EFFICIENCY

G. Buonanno, M. Dell'Isola*, A. Frattolillo, N. Massarotti, A. Carotenuto

Dipartimento di Meccanica, Strutture, Ambiente e Territorio (Di.M.S.A.T.)
Università degli Studi di Cassino, Via Di Biasio 43, 03043 Cassino, Italia
*E-mail: dellisola@unicas.it

ABSTRACT - The use of flow conditioners becomes necessary in flow measurement applications where the geometry of conduits does not allow complete development of the velocity profile upstream the flowmeter. In this paper the authors present a numerical analysis, based on finite volume technique, for the evaluation of flow conditioner performance under low level perturbation conditions. The use of non structured grids was necessary because of the complexity of the geometry studied. The results of the numerical calculations were used to evaluate the efficiency of different types of flow conditioners. The efficiency was defined on the basis of different parameters that take into account flatness, uni-directionality and asymmetry of the velocity profile downstream the flow conditioner.

KEYWORDS: CFD, flow conditioners, installation effects.

1 INTRODUCTION

Flow measurement is strongly influenced by the velocity profile. Since flowmeters are calibrated and characterised under completely developed flow conditions, perturbations such as swirl, cross-flow, and asymmetry can produce relevant systematic errors [1].

In practical applications the completely velocity profile conditions can hardly be obtained, in fact fluid-dynamic perturbations are caused by the elements of the piping itself, such as elbows, joints and valves. Theoretically it could be possible to reduce the influence of such perturbations using an adequate segment of straight pipe between the disturbances and the instrument. In practice, due to the reduced dimensions of the piping, it is necessary to use adequate flow conditioners [2].

Generally flow conditioners efficiency is not based on the velocity profile produced downstream but on the effects produced on a particular flowmeter. This approach has certainly obstructed the development of a general theory and consequently the optimal design of conditioners [3]. Furthermore the number and the cost of experimental investigations does not allow a comprehensive characterisation of flow conditioners, although very interesting laser Doppler investigations were carried out in the last years [4, 5]. The development of CFD in the last decades [6] has allowed researchers to use this technique for numerical analysis of installation effects [7, 8] and flow conditioners [9, 10].

In the present work the authors carry out a numerical study on several flow conditioners, independently from their effects on a certain type of instrument. The analysis is based on different fluid-dynamic parameters that describe the velocity profile disturbance in a conduct, with respect to fully developed flow conditions. An exhaustive analysis is not achievable because of the variety of both fluid-dynamic perturbations and conditioners. The present work deals with etoile, tube bundle (AGA) e Laws flow conditioners and with low level perturbation. Obviously for each conditioner it would be necessary not only to verify the efficiency with respect to the different types of disturbance and flow conditions but also to validate the results experimentally.

This work is a part of a wider research project for the set up of a procedure for numerical modelling of i) main fluid-dynamic perturbations (e.g. elbows, double elbows, etc) [11]; ii) most common flow conditioners [12] iii) flowmeters most sensitive to installation effects [13].

2 FLOW CONDITIONER’S EFFICIENCY

Efficient flow conditioner should have small pressure losses, reduced axial dimensions and low costs; furthermore it should also be able to reduce the fluid-dynamic disturbances (such as swirl, asymmetry and flatness).

In order to evaluate the flow conditioners’ efficiency, some parameters have been introduced; some of these were already available in literature [14, 15]:

a. Flatness numbers

These parameters measure the flatness of the velocity profile, that is the difference between the effective distorted and the fully developed velocity profile. Flatness is essential for instruments that are easily influenced by velocity profile, such as insertion, turbine and ultrasonic flowmeters.

Two parameters are used: the first, K_f, measures the difference between the effective adimensional flux of axial momentum and the fully developed one; the second, K_{fm}, measures the difference between the effective adimensional flux of angular axial momentum and the fully developed one. The latter is very important for flowmeters affected by the flatness depending on distance from axis such as turbine flowmeters.

These parameters can be mathematically written as:

$$K_f = \frac{\iint_A r(U^2 - U_{rif}^2)dA}{prU_m^2 R^2} \tag{1}$$

$$K_{fm} = \frac{\iint_A r(U^2 - U_{rif}^2)r\,dA}{prU_m^2 R^3} \tag{2}$$

where A is the conduit cross sectional area, ρ the density of the fluid, r the radial coordinate, R the conduct radius and U, U_{rif} and U_m are the effective, the fully developed and mean axial velocities respectively.

b. *Axial vortex numbers*

These parameters measure the intensity of axial vortex. Several definition of swirl angle and swirl number are used in literature [14, 18]: swirl number is based on the flux of angular tangential momentum; swirl angle is based on streamline angle with respect to the pipe axis evaluated in relevant points of the section [2, 19]. In this work two parameters are used: the first defined as the nondimensional flux of tangential momentum (such parameter physically represent the tangent of the average swirl angle), the second defined according to Mattingly [4] represents the swirl number:

$$K_v = \frac{\iint_A r\,|U\,V|\,dA}{pr\,U_m^2 R^2} \tag{3}$$

$$K_{vm} = \frac{\iint_A r\,|U\,V|\,r\,dA}{pr\,U_m^2 R^3} \tag{4}$$

where V is the tangential velocity.

c. *Asymmetry number*

The asymmetry number provides the degree of symmetry in the velocity profile and represents a non-dimensional measure of the distance between the centroid of the mass flow and the axis of the pipe section. It can be mathematically expressed as:

$$K_a = \frac{\sqrt{x_s^2 + y_s^2}}{R} \tag{5}$$

where x_s and y_s are the coordinates of the centroid of the mass flow calculated as:

$$x_s = \frac{\iint_A x\, d\dot{m}}{\dot{m}}; \qquad y_s = \frac{\iint_A y\, d\dot{m}}{\dot{m}}.$$

d. *Efficiency parameters*

On the basis of the above mentioned parameters, it is possible to define a relative efficiency of a flow conditioner $_{kl}$, as the ratio:

$$\varepsilon_{K_i}(z) = \frac{K_i^{'}(z) - K_i^{''}(z)}{K_i^{'}(0) - K_i^{'}(z)} \tag{6}$$

where K'_i e K''_i represent the values of the parameter calculated without and with flow conditioner respectively; the coordinate z is evaluated from section z=0 placed immediately downstream the disturbance (Fig. 1-a). Obviously, values of $_{kl}$ greater (lower) than zero show an efficiency of the conditioner greater (lower) than the straight pipe configuration.

3 NUMERICAL MODEL

In all applications analysed in this work, as in most engineering problems, the interest is focused on the mean values of velocity and other variables of turbulent flows, rather than their time fluctuant values. For this reason the governing equations (i.e . the conservation equations) are generally averaged using the well known procedure introduced by Reynolds [20]. The equations are not reported here for the sake of simplicity.

One of the major issues for the solution of the equations is represented by the turbulent or Reynolds stresses that take into account the fluctuating velocity. Several turbulence models for the closure of the problem are available, and some of them were tested [11]. The so-called k-ε model [21] is widely used and it was found to give good results not only for analysis of flow conditioners [9, 10].

For the simulation of viscous layer near the walls simplified models were used that assume some empirical functions based on experimental evidence, the so-called wall functions. The equations for the turbulent flow are solved outside this layer.

For all cases presented, the following boundary conditions were used:

- walls:

$$U = 0;\ V = 0;\ W = 0$$

- inlet:

$$U = U_0 \frac{(n+1)\cdot(2n+1)}{2n^2}\left(1 - \frac{\sqrt{(x^2+y^2}}{D}\right)^{\frac{1}{n}};\ V = 0;\ W = 0$$

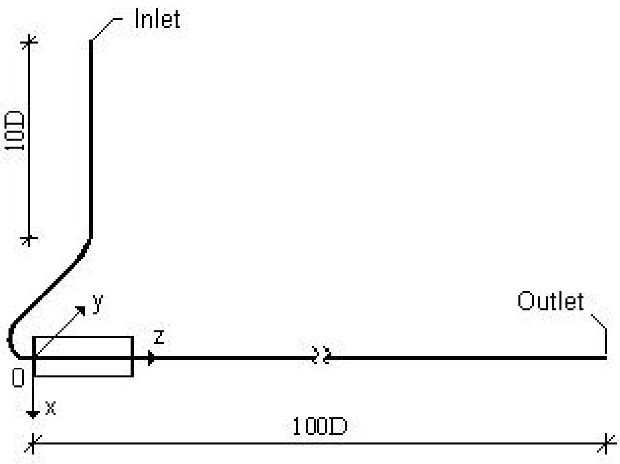
$$k = \frac{3}{2}\left[U_m \cdot 0.16(Re)^{-1/8}\right]^2; \qquad \varepsilon = 0.164\frac{k^{3/2}}{0.07\,D}$$

- outlet:

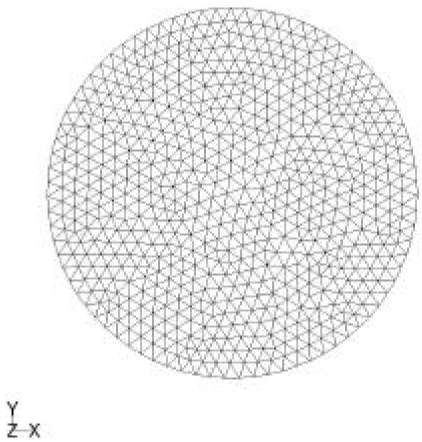
$$\frac{\partial}{\partial z}\left(U, V, W, k, \varepsilon\right) = 0$$

where n is a function of the Reynolds number [20], while k and ε have been evaluated from turbulent intensity and length scale.

The domain studied under the above conditions is sketched in Fig. 1-a.



(a)



(b)

Fig. 1 - Computational domain: a) lay-out; b) inlet section grid

The code adopted for the numerical analysis (FLUENT 5.0) is based on finite volumes technique [22,23]. Finite volumes allow, respect to traditional finite difference schemes, to model complex geometry by using also unstructured grids. This is essential for the simulation of geometry such as the flow conditioners' one.

The discretized algebraic equations obtained from the finite volume procedure were solved using a semi-implicit scheme, SIMPLEC, derived from the algorithm originally devised by Patankar [24]. Second order up-winding schemes were used for all velocity terms in the momentum equation, and second order interpolation was also used for the pressure.

Flow conditioners' geometry was discretized using unstructured grids. Therefore a necessary mesh sensitivity analysis was carried out. Flow in a double elbow configuration was modelled with structured and unstructured grids and the results compared with experimental data [4] showing a good agreement [11].

The mesh used for the flow conditioners was generated using advancing front type of procedure; Fig. 1-b shows the grid used in the inlet section, while in Fig. 3 a-f the different flow conditioners and the grids used their sections. The conditioner is always positioned immediately downstream the second elbow. About 1 million cells have been used for the whole computational domain, but still the solution is mesh sensitive, a finer mesh would certainly improve the results but it would need parallel facilities.

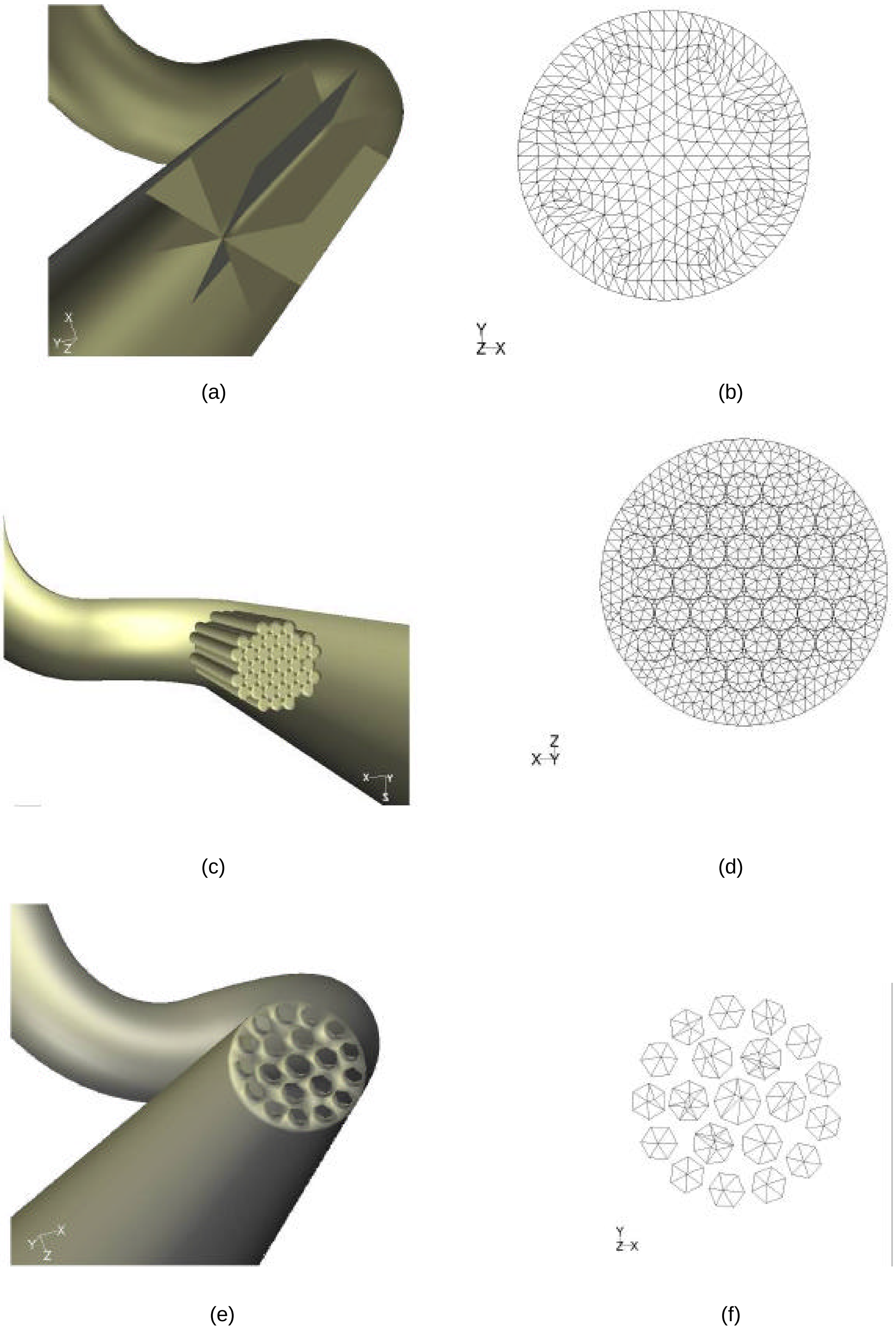


Fig. 3 – Conditioner configurations: a) etoile layout; b) grid in the etoile section; c) tube bundle layout; d) grid in the tube bundle section; e) Laws layout; f) grid in the Laws section.

4 NUMERICAL RESULTS

The numerical procedure introduced in the previous sections has been used to model three types of flow conditioner (etoile, tube bundle e laws), substantially different in geometry.

The disturbance configuration under study is a low level perturbation caused by two elbows on orthogonal plans, with a radius of curvature 1.5 times the diameter of the pipe, smooth walls and Reynolds number equal to 10^5. The fluid considered is water in standard conditions, with density of 998 kg/m^3 and viscosity equal to 1.00×10^{-3} Pa·s.

The results obtained from the calculation have been used to evaluate the parameters for each conditioner. Velocity profiles, along with the parameters calculated in different sections of the pipe downstream the conditioner, are presented in this section.

As regards experimental results, due to the limited number of work available in literature and to the difficulty to retrieve exhaustive results of the experiments, it has not been possible to evaluate the uncertainty of the solution. From a qualitative comparison of analogous configurations it is however possible to estimate the order of magnitude of uncertainty, about 15% in terms of velocity immediately to downstream the disturbance (i.e. the most critical condition) and 10% for the parameters. At the moment it is in progress an experimental research in the LAMI to investigate the velocity pattern for different pipe configuration [24].

4.1 Etoile conditioner

The numerical results are presented in Fig. 4 and 5. In particular Fig. 4a and 4b show the profiles of axial and tangential velocity in different sections downstream the conditioner, with respect to the y-axis. From the figures it is clear that both axial and tangential disturbance have not yet decayed at z=10.5 D. Fig. 5a and 5b show the values of K_i parameters and the related efficiencies ε_{Ki}, with respect to the distance from the disturbance. From these figures it can be noticed that the swirl parameters K_v *and* K_{vm}, decrease quite quickly (Fig. 5a) and the efficiencies, as regards these parameters, are quite good (circa equal to 1 and 4 times greater than the straight pipe downstream the disturbance respectively). The flatness parameters K_f *and* K_{fm} are very high. In fact conditioners generally worsen the profile flatness and the efficiencies ε_{Kf} and ε_{Kfm} are lower than zero. Finally the asymmetry of velocity profile implies a K_a number higher than other conditioners.

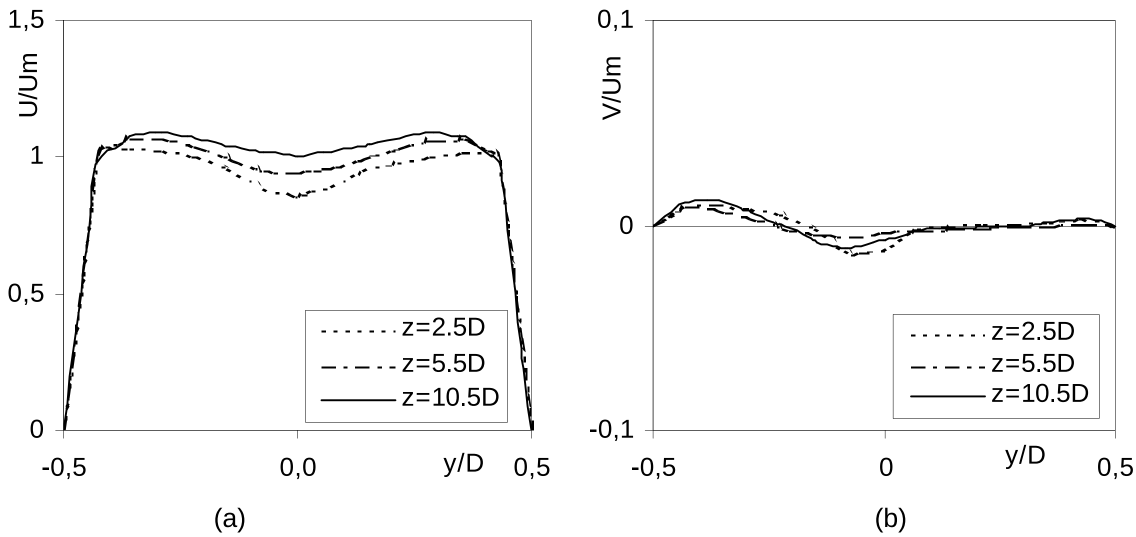


Fig. 4 – Velocity profiles downstream the conditioner: a) axial velocity U; b) tangential velocity V

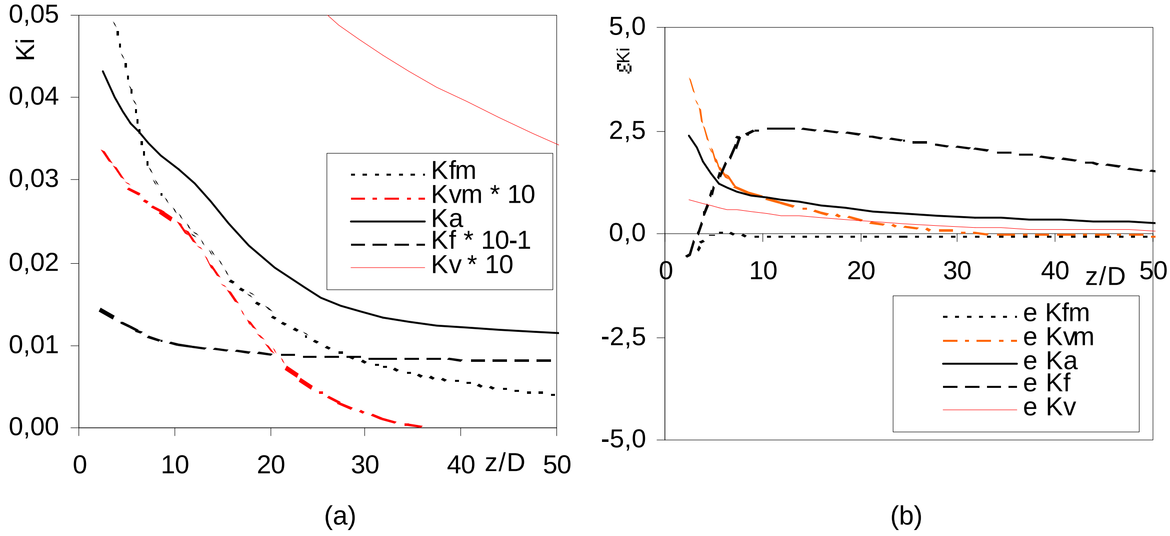


Fig 5 – Etoile conditioner: a) parameters K_i; b) efficiency $_{kI}$

4.2 Tube Bundle conditioner

The numerical results are presented in Fig. 6 and 7. In particular Fig. 6a and 6b show that the axial and tangential disturbance, although symmetric respect to the conduct axis, is greater than that produced downstream the etoile conditioner. In any case these disturbances decay quickly even though are relevant immediately downstream the conditioner. Fig. 7a and 7b show that the swirl parameters K_v *and* K_{vm}, decay more rapidly than the etoile case (Fig. 7a), the efficiency for these parameters is almost equal to etoile conditioner (circa equal to 1 and 4 times greater than the straight pipe downstream the disturbance respectively). Symmetry instead is better than in the previous conditioner (the related efficiency is almost 5 immediately downstream the conditioner). Flatness numbers K_f *and* K_{fm} are worse than the etoile, and their efficiencies, immediately downstream the conditioner, are both negative and very low (circa equal to –11 and –5 respectively).

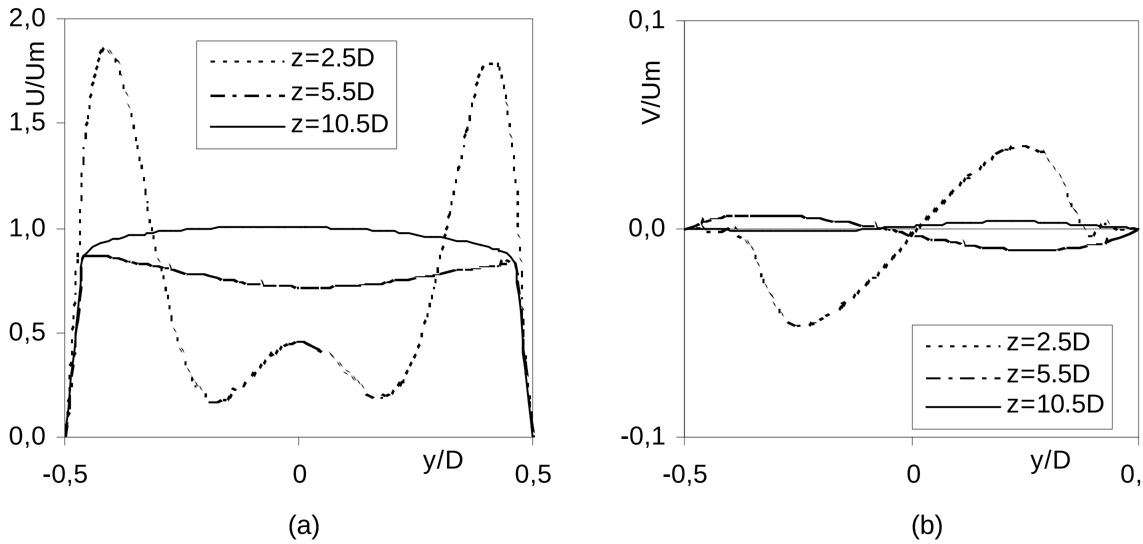
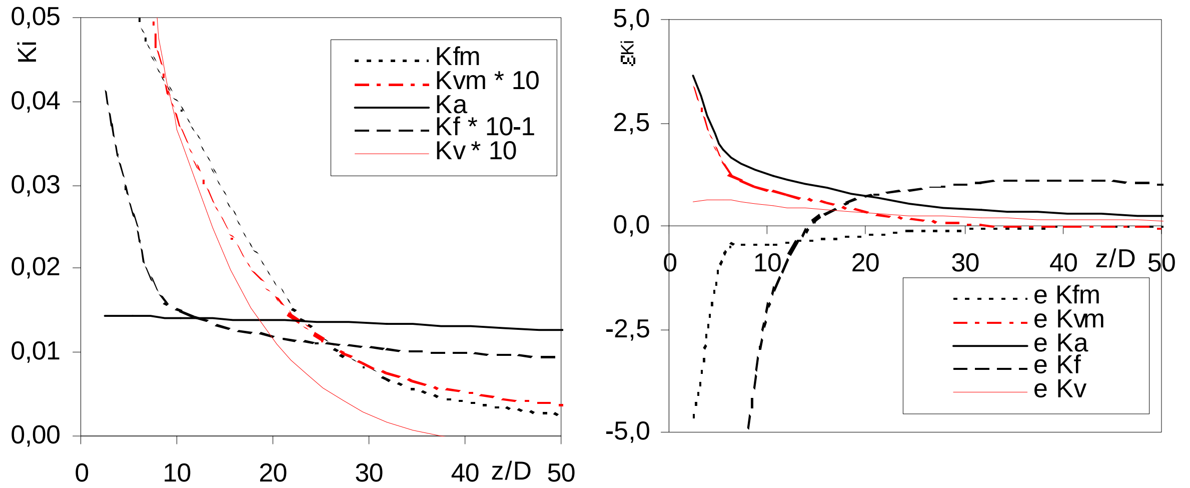


Fig. 6 – Velocity profiles downstream the conditioner: a) axial velocity U; b) tangential velocity V

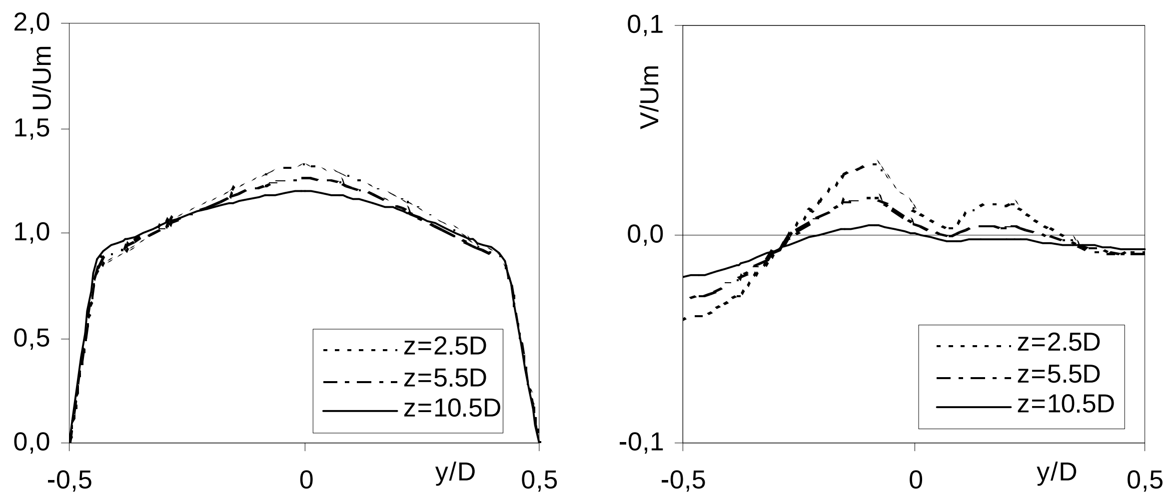


(a) (b)

Fig 7 – Tube bundle conditioner: a) parameters K_i; b) efficiency $_{kI}$

4.3 Laws conditioner

Numerical results are presented in Fig. 8 and 9. Fig. 8a and 8b show that the axial disturbance is greater than that produced downstream the etoile conditioner, but it is lower than that of the tube bundle, while the tangential velocity decays as in the tube bundle. Fig. 9a and 9b show that the swirl parameters decay less than the two previous conditioner (Fig. 9a), although the efficiency is comparable. The profile is more asymmetric than that of the two previous cases, with an efficiency lower than 2 immediately downstream the conditioner. Flatness numbers result worse than the etoile, but better than the tube bundle conditioner; the related efficiencies ε_{Kf} and ε_{Kfm}, immediately downstream the conditioner, are both negative and lower than –6 e –2 respectively.



(a) (b)

Fig. 8 – Velocity profiles downstream the conditioner: a) axial velocity U; b) tangential velocity V

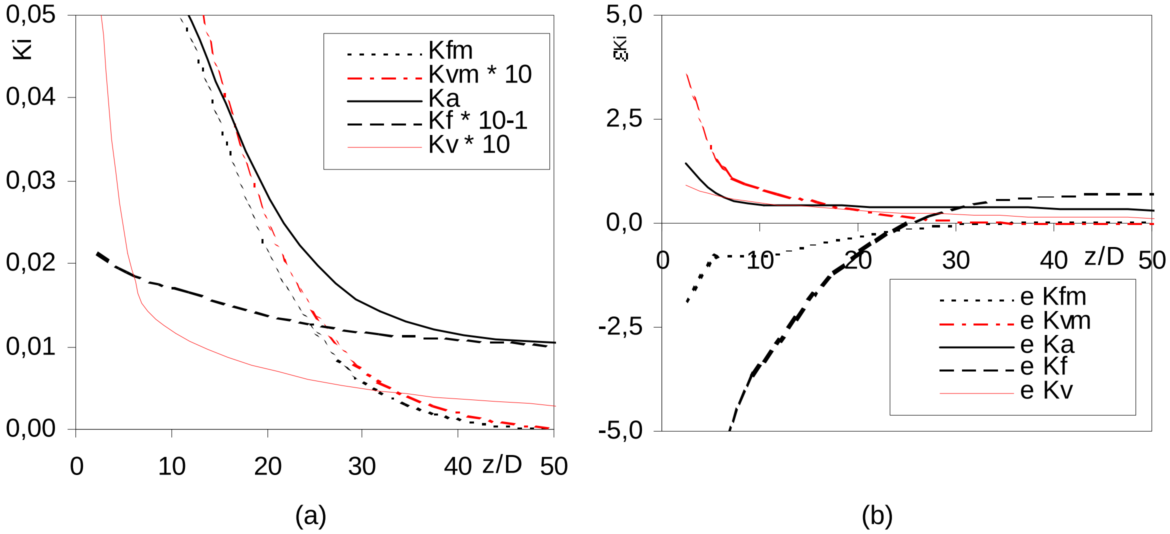


Fig. 9 – Laws conditioner: a) parameters K_i; b) efficiency $_{kI}$

5 CONCLUSIONS

The present work describe a methodology for the numerical simulation of etoile, tube bundle and Laws flow conditioners. The results achieved show that these conditioners have different performances in term of flatness, swirl and asymmetry. In particular:

- the etoile presents good characteristics in term of swirl, but the flatness and asymmetry efficiencies are not very high;
- the tube bundle is very good in term of symmetry but shows a large flatness disturbance;
- the Laws is very interesting for the profile produced far downstream the double bend, although the efficiency immediately downstream is not the best.

The calculated efficiencies allow a comparison between the three conditioners as well as the evaluation of their optimal position depending on flowmeter sensitivity to the different types of disturbance. However the accuracy of fluid-dynamic numerical codes does not allow to perform a very accurate calculation of the velocity field. For this reason it is always necessary to validate the code at least for most complex configurations.

In authors' opinion the numerical methodology developed can still be improved. Therefore it is in progress an analysis of different grids and turbulence models. As regards experimental results, due to the limited number of work avalaible in literature and to the difficulty to retrieve exhausitve results of the experiments, it has not been possible to estimate the uncertainty of the solution. From a qualitative comparison of analogous configurations it is however possible to estimate the order of magnitude of uncertainty, about 15% in terms of velocity immediately to downstream the disturbance (i.e. the most critical condition) and 10% for the parameters. At the moment it is in progress an experimental research in the LAMI to investigate the velocity pattern for different pipe configuration.

NOMENCLATURE

A area of the cross section [m^2]
D pipe diameter [m]
r radial coordinate [m]
R pipe radius [m]
U axial velocity [ms^{-1}]
V tangential velocity [ms^{-1}]
W radial velocity [ms^{-1}]
x co-ordinate [m]
x_s co-ordinate of the centroid of mass [m]
y co-ordinate [m]
y_s coordinate of the centroid of mass [m]
z co-ordinate [m]
k turbulent kinetic energy [m^2s^{-2}]
K_f flatness parameter
K_{fm} momentum of flatness parameter

K_v swirl angle parameter
K_{vm} swirl parameter
K_a asymmetry parameter
$\dot{m}$ mass flow rate [kg/s]
Re Reynolds number ($Re = ñ U_m D/ì$)
U_m average axial velocity [ms^{-1}]
U_0 maximum axial (inlet section) [ms^{-1}]
U_{rif} local velocity (fully developed flow) [ms^{-1}]

Greek symbols
ε turb. energy dissipat. rate [m^2 s^{-3}]
ε_{Ki} efficiency (6) for the K_i parameters
μ dinamic viscosity [Pa·s]
ρ fluid density [kg/m^3]

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