XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

NUMERICAL EVALUATION OF DISTORTED VELOCITY PROFILE EFFECTS ON INSERTION FLOW METERS

G. Buonanno, M. Dell'Isola, N.Massarotti
Di.M.S.A.T. - Università di Cassino
via Di Biasio 43 - 03043 Cassino (FR) - Italy

Abstract: Installation effects can not be exhaustively analysed due to the wide variety of plant configurations. On the other hand installation effects are one of the most important causes of flow meters inaccuracy. In the present paper the authors analyse the effects of two important low level perturbations in a downstream straight pipe on insertion flow meters. The aim of the work is to evaluate: i) the minimum distance between the flow meter and the perturbation that makes negligible the installation uncertainty, ii) the systematic error of different insertion flow meters.
Keywords: insertion flow meter, installation effect, elbow

1 INTRODUCTION

One of the main factors that affects the accuracy of flow rate measurements in closed conduit is the real velocity profile inlet to the meter. In fact, flow meters are generally characterised only with respect to fully developed conditions. Unfortunately, such conditions are not very usual in the pipelines because of the presence of perturbation components (i.e. elbows, valves) and the reduced axial dimension of the piping [1, 2].

The most common fluid-dynamic perturbations such as the single and double elbows give rise to: i) the distortion of axial velocity profile with respect to the fully developed one; ii) the deviation of the velocity vector from axial direction (swirl and cross-flow). Other perturbation components (such as valves, convergent and divergent connections, **T** connections) give rise to high level pertubations. Theoretically, it would be possible to reduce the influence of such perturbations by installing a straight pipe of adequate length. This length can be reduced by means of flow conditioners placed between the disturbance component and the flow meter. In any case the upstream straight pipe length depends on the disturbance and the meter sensitivity. In particular, the insertion flow meters present the highest sensitivity to installation effects. In fact, these flow meters are able to measure the average velocity only in particular fluid dynamics conditions [3-5].

In the present paper the authors analyse the effect of several low level perturbations in a downstream straight pipe on insertion flow meters. The aim of the work is to evaluate i) the minimum distance between the flow meter and the perturbation cause that makes negligible the installation uncertainty, ii) the systematic error of different insertion flow meters as the straight length varies.

2 INSERTION FLOW METERS

The measurement of the average velocity U_0 and, consequently, the volumetric flow rate in closed conduit can be performed by means of different insertion flow meters such as the Pitot tube, thermal and vane anemometers, current meters, etc. These meters measure the local velocity, u, at one point. Then, it is possible to evaluate the average velocity on the basis of “a priori” velocity profile imposed in the measurement section. Some insertion flow meters measure the velocity in more than one position using multiple sensors in one probe (annubar, Wilson grid).

Therefore, the measurement methods can be divided in single and multiple point methods on the basis of the number of the measurement points. The first method is based on the velocity measurement in a single point, generally the critical or the axial position defined by the ISO 7145 [3]. In the critical position the local velocity is practically equal to the average velocity; this position is located to $0.242 \pm 0.1r$ (where r is the pipe radius) from the wall. As regards the axial position, the local velocity measurement must be corrected by means of a profile factor to calculate the average velocity.

Different models are proposed in literature for the evaluation of velocity profile in steady state, fully developed turbulent flow and smooth pipe such as those of Nikuradse [6], Pai, Pao [7] and Prandtl [8]. For example, the profile factor evaluated on the basis of the Nikuradse model is:

$$f_p = \frac{U_o}{u} = \left(\frac{2n^2}{(2n+1)(n+1)} \right) \tag{1}$$

where n is a function of the Reynolds number:

$$\begin{aligned} n &= 3.299 + 0.327 \ln Re_D \qquad \text{for } Re_D < 400.000 \\ n &= 5.5365 + (5.498 \cdot 10^6) \ln Re_D \qquad \text{for } Re_D > 400.000 \end{aligned} \tag{2}$$

The one point measurement method specified in the ISO 7145 can be applied in the following conditions: i) fully developed turbulent incompressible flow; ii) steady state conditions; iii) hydraulic resistance coefficient λ less than 0.06; iv) Reynolds number less than $3 \cdot 10^4$ for λ equal to 0.06 (10^6 for λ equal to 0.01); v) pipe diameter greater than 300 mm; vi) axial angle less than 5°; vii) ratio between sensor and pipe diameters less than 2% (11%) for Pitot tube (current meter).

The uncertainty declared of the method does not exceed the value of 3% with a coverage factor equal to 2. In any case, the uncertainty on the mean velocity must be calculated taking in to account the method uncertainty and all the uncertainty contributions such as the velocity meter repeatability, uncertainty calibration, stem blockage correction, positioning uncertainty, installation effects.

The multiple points method is based on multiple measurements or multiple sensors mounted on the same probe (averaging Pitot tube). The position of these points can be optimised using one of the several methods proposed in literature such as the log-Tchebicheff, the log-linear, Gauss, Newton-Cotes [4, 7]. Therefore, the average velocity can be determined as:

$$U_0 = \sum_i \pi_i \cdot u_i \tag{3}$$

where π_i are the weights related to each location i as reported in Tab. 1.

Table 1 – Location of measurement point for circular section

Number of measurement points for radius	Log-linear		Log-Tchebicheff		Gauss		Newton-Cotes	
	r/R	weight	r/R	weight	r/R	weight	r/R	weight
2	-	-	0.4597 0.8881	1/2	0.4597 0.8881	0.5000 0.5000	0 1	1/2
3	0.3586 0.7302 0.9358	1/3	0.3754 0.7252 0.9358	1/3	0.3357 0.7071 0.9420	0.2778 0.4444 0.2778	0 0.7071 1	0.1667 0.6667 0.1667
4	-	-	0.3314 0.6124 0.8000 0.9524	1/4	0.2635 0.5745 0.8185 0.9647	0.1739 0.3261 0.3261 0.1739	0 0.5774 0.8165 1	0.1250 0.3750 0.3750 0.1250
5	0.2776 0.5658 0.6950 0.8470 0.9622	1/5	0.2866 0.5700 0.6892 0.8472 0.9622	1/5	0.2166 0.4804 0.7071 0.8771 0.9763	0.1185 0.2393 0.2844 0.2393 0.1185	0 0.5 0.7071 0.8660 1	0.0778 0.3556 0.1333 0.3556 0.0778

For the single point meter the ISO [3] suggests a wide length of the straight conduit in order to have a fully developed flow. In table 2 the minimum distance for different kind of disturbance upstream the measurement cross-section are reported.

As regards the multiple point flow meter, the ASHRAE [5] suggests at least 7.5 diameters upstream and 3.0 downstream the cross section. Further specifications, reported in table 2, are given by some manufacturers of multiple points flow meters.

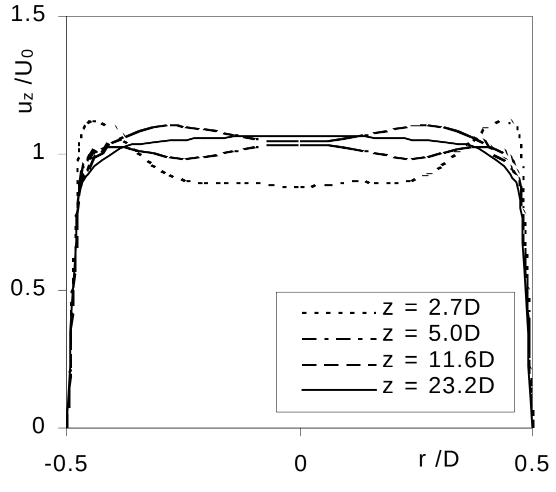
3 INSTALLATION EFFECTS

Two different approaches are possible to the study of installation effect. The first one is numerical and is based on the numerical modelling of both the velocity field and the flow meter by means of CFD codes [9-11]. The second one is experimental and consists in a standard flow rate plant with a suitable perturbation generation system [12-14]. The first method allows to evaluate a wide range of perturbation components and flow meters with reduced costs but it is not very accurate for the actual limits of fluid dynamic codes and the meter simulation codes. For this reason each computational fluid dynamic solution needs an experimental validation. The second method presents the advantage of a direct measurement of installation effects but it is very expensive in terms of cost and time. Furthermore, it is possible to evaluate only stationary problems.

Table 2 - Minimum distance for single and multiple point measurements

Type of perturbation component	**Single point in critical position** [ISO 7145]	**Single point in axial position** [ISO 7145]	**Multi-point in Tchebicheff position**
90° elbow or t-bend	50	25	8-10
Several 90° coplanar bends	50	25	11-16
Several 90° non-coplanar bends	80	50	23-28
Convergent pipe	30	10	12
Divergent pipe	55	25	18
Butterfly valve (fully opened)	45	25	30
Plug valve (fully opened)	30	15	30

In [9], the authors have evaluated the velocity field for some typical perturbation component by means of a code based on finite volume method. The solutions were validated by comparing the numerical results with the experimental data available in literature [11]. The differences between the numerical and experimental data were always less than 3-5% of the mean velocity and they depend on the grid type, the turbulence model and the perturbation cause. In particular, as regards the downstream single elbow velocity field (90° elbow, radius curvature equal to 1.5 D, smooth pipe, Re= 10^5). Figure 1 shows the velocity (dimensionless respect to the average velocity U_0) as the axial co-ordinate z increases in the plane orthogonal to the elbow one. We can see that the disturbance of axial and tangential velocity components suddenly decay (the disturb is practically negligible for z > 23 D). For a double elbow orthogonal planes, Fig. 2 shows the velocity in the plane orthogonal to the last elbow as the axial co-ordinate z increases. In this case, we can see that the disturbance of axial and tangential velocity components decay very slowly (the disturbance is practically negligible only for z > 93D).



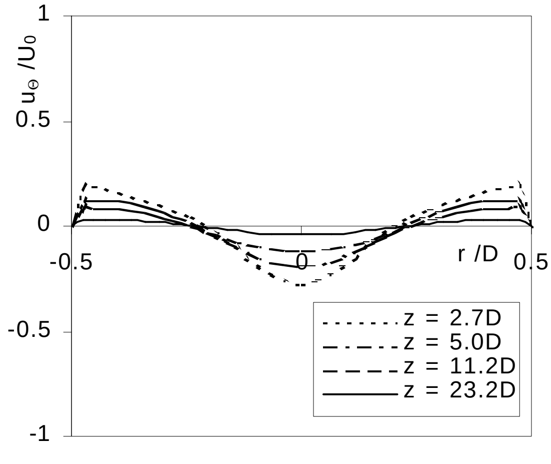


Fig. 1 – Velocity field downstream a single elbow:a) axial velocity u_z; b) tangential velocity u_Θ.

4 VELOCITY PROFILE EFFECTS ON INSERTION FLOW METERS

Hereinafter velocity profile effects caused by single and double elbow on the insertion meters are reported. In particular, two different kind of meters are considered: i) single point insertion flow meters (such as Pitot tubes, vane and thermal anemometers) placed either in central position or in critical position and ii) multi-point ones (such as Annubars) also placed in different position.

The velocity profile was obtained on the basis of the numerical methodology above described. The anemometer measurement was simulated on the basis of standards [3-5] or manufacturer specifications. The velocity percentage error was evaluated as:

$$e\% = \frac{\left(f_p \cdot u - U_0\right)}{U_0} \cdot 100 \qquad (4)$$

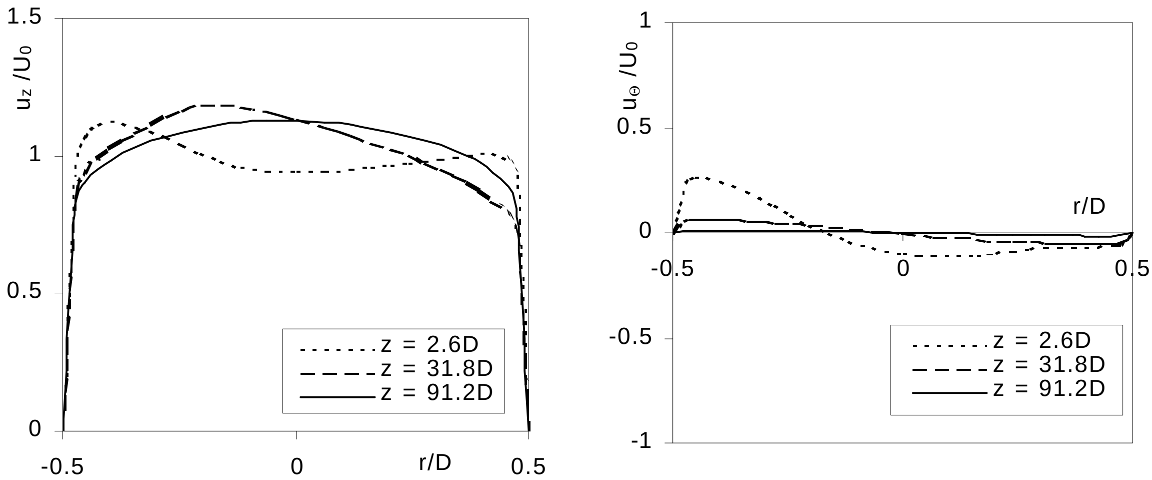


Fig. 2 – Velocity field downstream a double elbow: a) axial velocity u_z; b) tangential velocity u_Θ.

4.1 Single point numerical results

In the case of single measurement point, critical and axial positions were examined as the axial and angular co-ordinates (z, Θ) vary. As regards the influence of the meter on radial and tangential velocity components, it can be neglected because of the low values of these components respect to the axial component.

In figure 3 the error trend in the average velocity measurement using a local velocity sensor placed in axial position downstream a single elbow (a) and a double elbow (b) is reported. In particular, the profile factor is evaluated on the basis of the velocity profile proposed by Nikuradse [6], Prandtl [8] and the numerical model analysed [9]. The figure shows i) an error greater than 5% for z/D less than 20, ii) an exponential error decay, iii) a difference of the residual error between the numerical model and the Nikuradse model equal to 2-3%, iv) a negligible error (less than 1%) for z/D>35 (z/D>50) in the single elbow case (double elbow case). In figure 3 is also reported the error trend in the average velocity measurement using a local velocity sensor placed in critical position downstream a single elbow (c) and a double elbow (d) as the axial and angular (defined as the angle between the axial plane containing critical point and the axial plane orthogonal to the last elbow) co-ordinates vary. The figure shows that i) the error is less than the corresponding value determined in the axial position in the first 10-15 z/D, ii) on the contrary the decay is slower, iii) the error meaningfully depends on the angular co-ordinate making more complex a measurement correction, iv) the residual error for fully developed condition in both solutions is wide (3-4%) due to a difference between the numerical velocity values and the ones assumed by ISO in critical position. The oscillation of the residual error as the angular co-ordinate varies only depends on the numerical model and, in particular, on the mesh type adopted (Cartesian mesh). Furthermore, a residual error of 1-2% for fully developed condition was found respect to the Prandtl solution.

4.2 Multiple point sensor numerical results

As regards the average velocity measurement using multiple point methods, the Log-Tchebicheff method is analysed considering 2, 3, 4 and 5 measurement points per radius [4].

In figure 4 the error trend of average velocity measurement using different numbers of measurement point is reported. In particular the figure shows that: i) the maximum error is always less than the axial and critical position ones and less than 10% (also very close to the perturbation and with only 2 measurement points), ii) the residual error depends on the angular co-ordinate and on the number of measurement points; iii) also in this case the residual error for fully developed profile is wide (2-4%) for both single and double elbow. Furthermore, a residual error of 1-2% for fully developed condition for both solutions was found respect to the Prandtl solution.

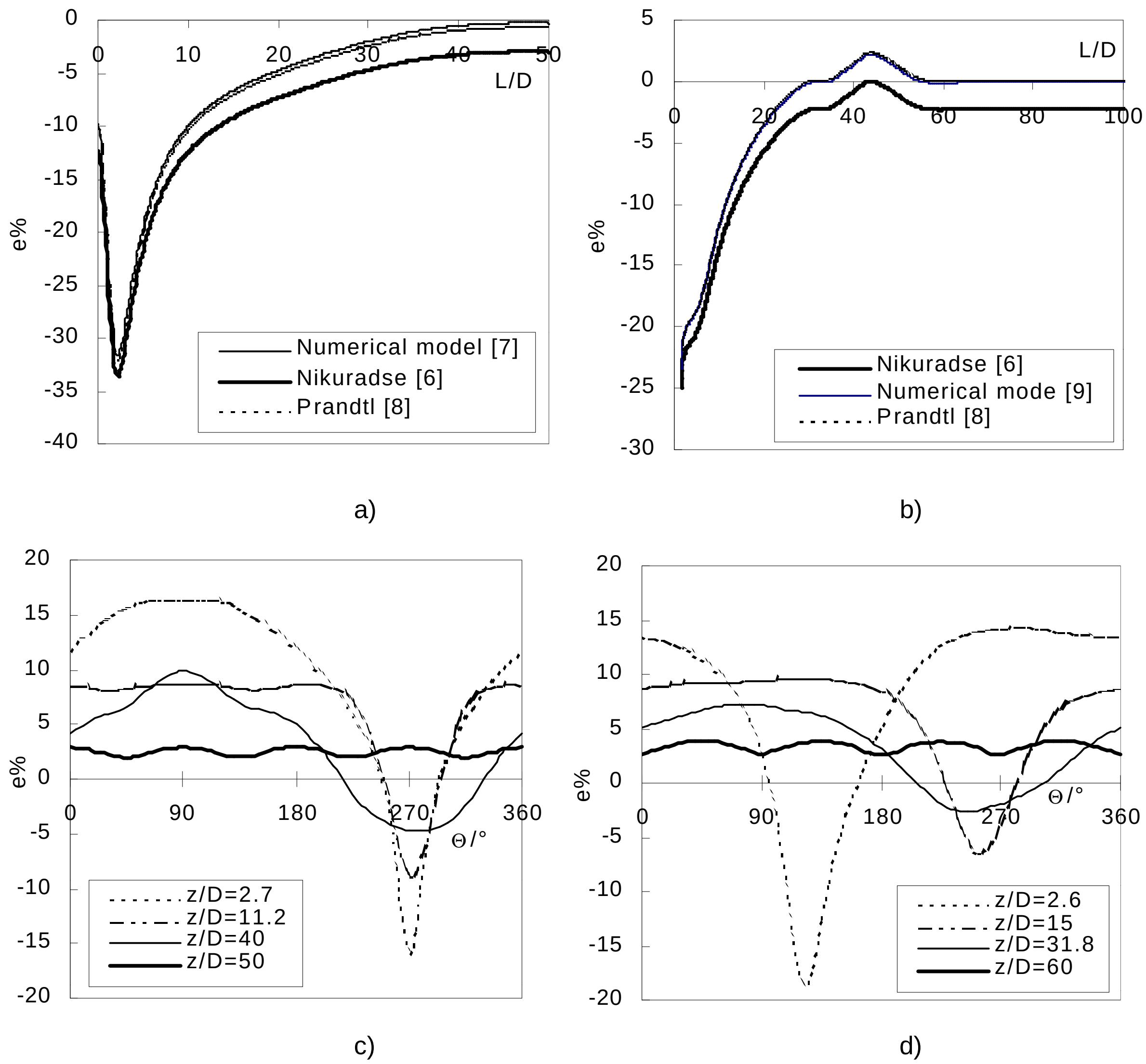


Fig. 3 – Single point error trend: a) axial position - single elbow; b) axial position - double elbow; c) critical position - single elbow; d) critical position - double elbow

5. CONCLUSIONS

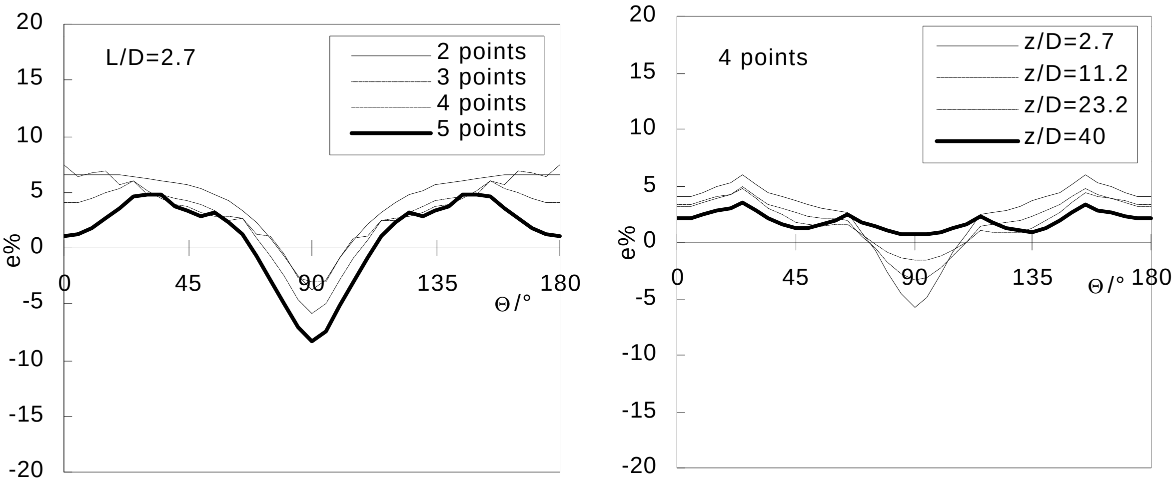
The following considerations can be drawn from the present work:

- the comparison between the experimental and numerical velocity fields shows a good agreement;
- for the single point method, the systematic error is very wide in the first 10-20 L/D and the decay presents an exponential law;
- as regards the multiple point method, the systematic error is not negligible even if less than about 5%; in this case it decays slowly;
- the lengths suggested by ISO and by the numerical method are comparable even if the numerical solutions present a residual error probably due to the velocity field numerically evaluated;
- numerical solutions obtained are self consistent but the results were only partially experimental validated.

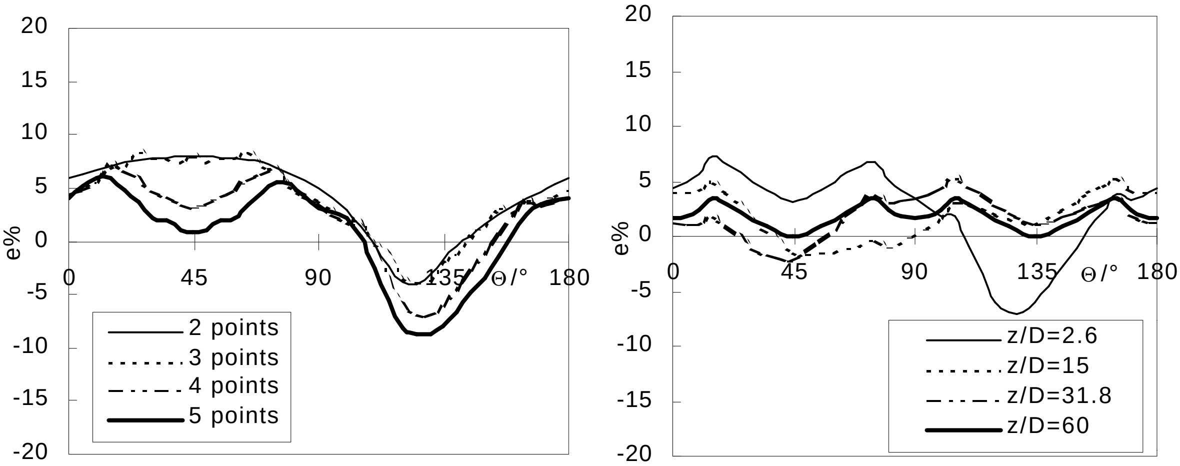
These calculations validate the proposed approach to evaluate the distance from the perturbation element even if the presented calculations need a further experimental validation.

The main limit of the proposed model is the unreliability of the numerical solution in the wall region (in particular for a distance from the wall near to 0.1·r). For this reason the numerical model present a wide uncertainty for 3 or 4 point location methods.

In order to validate the numerical results, in the LAMI Laboratory an experimental study using the thermal anemometry is in progress. Furthermore, the authors are extending this study also to high level perturbation cases.



a)



b)

Fig. 4 – Multiple point error trend: a) single elbow; b) double elbow

ACKNOWLEDGEMENTS

This work is developed in the 60% MURST research program. The authors wish to thank G. Cignolo of IMGC of Turin and Prof. P. Vigo of the Cassino University for their helpful advises.

REFERENCES

[1] Halsey D.M., Flowmeters in Swirling Flows, *J. Phys. E., Sci. Instrum*., 1987, 20, 1036-1040.
[2] Cascetta, F., Vigo, P., *Flowmeters: A comprensive survey and a guide to the choice*, Instrument Society of America, USA, 1988.
[3] ISO 7145, Determination of flowrate of fluids in closed conduits of circular cross-section – method of velocity measurement at one point of the cross-section, Geneve, 1982.
[4] ISO 3966, Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes, Geneve, 1977
[5] *ASHRAE Handbook - Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1997
[6] Nikuradse, J., VDI-Forschungsheft, 356, 1, 1932.
[7] Miller, R.W., *Flow Measurement Engineering Book*, McGraw-Hill Company, New York, 1989
[8] Prandtl, L.Z., Ver. deut Ing., 77, 107, 1933
[9] Dell'Isola M., Massarotti N., Vanoli L., Analisi Numerica Dei Disturbi Fluidodinamici Prodotti Da Curve All'interno Di Condotti Chiusi Circolari, *54° Congresso ATI*, 1999

[10] Halttunen J., 1990, Installation effects on ultrasonic and electromagnetic flowmeters: a model-based approach, *Flow Meas. Inst.*, vol.1, n.4, 287-292.
[11] Hilgenstock A., Ernst R., 1996, Analysis of Installation Effects by Means of Computational Fluid Dynamics, *Flow Meas. Instrum.,* vol.7, n. 3/4**,** 161-171.
[12] Mattingly, G. E., Yeh, T. T., Flowmeter Installation Effects, 5th International IMEKO- Conference on Flow Measurements, *FLOMEKO*, VDI Berichte Nr. 768, 1989, 65-73.
[13] Mattingly G.E., Yeh T.T, 1991, Effects of pipe elbows and tube bundles on selected types of flowmeters, *Flow Meas. Instrum*, vol 2, n.1, 4-13.
[14] Wendt G., Mickan B., Kramer R., Dopheide D., 1996, Systematic investigation of pipe flows and installation effects using laser Doppler anemometry, *Flow Meas. Instrum*, vol. 7, n.3/4, 141-149.

AUTHOR(S): Marco DELL'ISOLA, Associate Professor - Dipartimento di Meccanica Strutture Ambiente e Territorio, Università di Cassino, via Di Biasio 43, 03043 Cassino (FR) - Italia, Ph. ++39 (0) 776/299670, Fax ++39 (0) 776/310812, E-mail: dellisola@unicas.it