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Numerical and Experimental Study of Effects of Upstream Disturbance on Accuracy of Vortex-Shedding Flow Meter

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Abstract - In the present investigation, the problem of accurate determination of volumetric flows by means of the so-called vortex-shedding flow meter in the case of upstream disturbances caused by several versions of bends has been studied. To this end, the flow about the bluff body used in the presently studied vortex-shedding flow meter was investigated experimentally and numerically for the case of incompressible fluid flow (water). The disturbances considered presently were generated by a single 90-degree bend, in-plane double bend and a three-dimensional 90-degree out-of-plane double bend. Additionally, the distance of the bluff body from the disturbance source was varied. The computations were carried out for a limited number of cases using the three-dimensional unsteady incompressible solver of the Navier-Stokes equations as included in the Fluent commercial program.. The effects of turbulence were modelled by using the realizable k-ε turbulence model. The resulting flow fields were analyzed using various methods, including visualization, evaluation of several of their global features and DFT of properly chosen variables. The numerical results were validated by comparisons of the simulated k-factor with the measured one. The effect of the disturbances was assessed by comparison with the undisturbed reference case. Depending on the configuration investigated and the distance of the meter from the bend outflow location, the change of the k-factor from the undisturbed reference case was noticeable. The difference of the simulated and measured deviations was in some cases less than 0.2 %.

Keywords: Vortex Flow Meters, Flow Simulation, Experimental Flow Metering, Accuracy. Upstream Disturbance.

1. INTRODUCTION

Many chemical and environmental processes found in the corresponding industries require volume- or mass flow data for their completion. Number of promising new methods for flow rate measurement have been recently developed. One relatively simple flow measurement device is the so-called vortex-shedding flow meter, in which the volumetric flow is determined by observing the relationship between the vortex-shedding frequency from a bluff body attached inside a channel, and the corresponding mean velocity about it. The bluff body causes production of a system of periodic vortices (von Karman vortex street), whose frequency can be correlated with the mean flow velocity and, therefore, the volumetric flow. This procedure assumes a regular and well defined vortex structure as well as shedding mechanism, resulting mostly in linear dependency of the volumetric flow on the shedding frequency over a wide range of Reynolds numbers.

In principle, the vortex-shedding flow meters use the separation frequency of vortices behind a bluff body to measure the mean flow velocity of a fluid flow. Downstream of the bluff body, von Karman vortex street develops; its width D and distance T between the vortices depend on this frequency, and therefore on the bluff body's shape. Preferably, the vortex-shedding frequency should depend linearly on the mean flow velocity for a wide Reynolds number range. The dependency of the vortex frequency f, the mean flow (bulk) velocity u_m and the width of the bluff body D is expressed by the dimensionless Strouhal number Sr:

$$Sr = (D \cdot f) / u_m$$

or the dimensional k-factor:

$$k = f / Q$$

with Q being the volumetric flow.

By now, commercial vortex flow meters use a large variety of bluff body shapes, test sections (conical inflow and outflow, constrictors of various shapes) and signal detection systems (pick-up). The corresponding flow fields have been studied by, among others, Johnson [4], Fureby [1] and Madabhushi et. al. [5] using mostly numerical simulations. The signal detection and processing have been discussed by Hans et. al. [2] and [3]. The potential for improvement of signal quality by modifying the shape of the bluff body was investigated by von Lavante et al. [6]), It has been also observed that a slight uncontrolled modification of the assumed geometry of a particular vortex-shedding flow meter, e.g. shape, location relative to the surrounding casing and change of shape due to wear caused by particles suspended in the metered fluid, could cause a shift of its characteristic frequencies, leading to

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unreliable volumetric flow data. The influence of the manufacturing tolerances on the accuracy of vortex-shedding flow meters and abrasion by particles suspended in the metered fluid has been investigated in [7] and [8] by von Lavante et al. A detailed study of the flow field in small size commercial vortex-shedding flow meters with inflow and outflow conditioned by a Venturi nozzle and a diffusor has been published by von Lavante et al. in [9].

In the present investigation, the effects of upstream disturbances caused by three kinds of bends were studied using numerical simulation as well as experimental work. In most real world applications, the flow meter is installed such that it can be easily monitored and maintained, implying the use of bends and other flow disturbing elements in the pipeline. Every manufacturer supplies recommendations for the installation of their meter, including upstream and downstream straight pipe length required for the decay of the disturbances, measuring typically 10 D upstream and 5 D downstream. It is the aim of the present work to first gain knowledge about the mechanism of generation of deviations in vortex-shedding frequency, allowing subsequent development of measures to reduce the straight pipe length and, if possible, reduce the required length of the upstream upstream and downstream straight pipe. The emphasis was put on experimental work, the numerical simulation providing detailed information in few configurations, where the deviation from the undisturbed flow meter was the most significant. In all cases, the metered fluid was water.

2. EXPERIMENTAL WORK

In the experimental approach, a commercial vortex-shedding flow meter manufactured by Krohne Messtechnik GmbH was subjected to investigation in the modified testing facility at Krohne Messtechnik GmbH. The fluid being metered was water at pressures up to 5 bar; the measuring section of the meter was DN15 with inflow and outflow areas corresponding to DN20.

The test section has been changed to include a simple setup to allow a quick change of the configuration tested. The undisturbed reference case consisted of the basic flow meter with the prescribed upstream and downstream sections of 10 D length of straight pipe. There were 2 basic configurations investigated: a simple 90-degree single bend and an in-plane 2-dimensional double bend, each having radii of curvature of 50, 100 and 200 mm. The distance between the bend outlet and the bluff body was also varied, being 92, 192 and 292 mm or approximately 5 D, 10 D and 15 D. The resulting matrix of possible geometrical configurations included 18 entries. In all cases, the piping could be considered hydraulically smooth. Some combinations of parameters displayed no significant difference to the reference case and were, therefore, excluded from the investigation. All the tested configurations are shown in Table 1, together with the resulting deviation of the measured frequency from the reference case. Each configuration was studied at bulk velocities of approximately 0.5, 1.0, 1.5, 3.0 and 5.0 m/s. The corresponding Reynolds numbers Re_D were between 7500 and 75000. The facility included two pumps of different size that were differentially controlled by a CPU using signals from the reference meter (MID). The resulting deviations from the basic reference case without any upstream disturbances were between 0.1 % and almost 2.5 %. The measuring section is shown in Fig. 1.

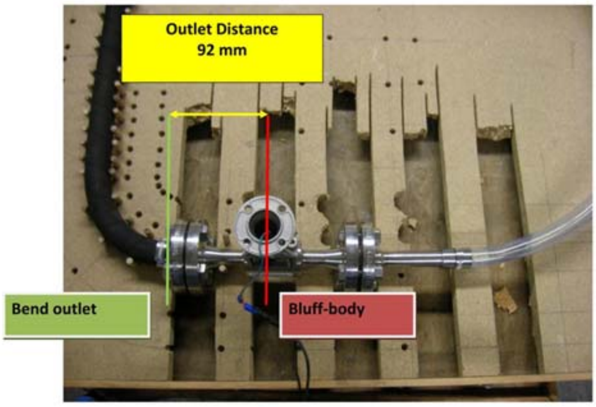


Fig. 1: Experimental test section.

The systematic nomenclature of the different configurations first indicated the number of bends, then the radius of curvature and after that the distance of the bend outlet to the bluff body. 2-R100-92 means for example double bend, radius of curvature 100 mm and distance from measuring section 92 mm.

The effect of the radius of curvature of the double bend on the reduced frequency of vortex shedding is shown in Fig. 2. Interestingly but not unexpectedly, the strongest deviation from the reference case was observed for the smallest radius of curvature, R=50 mm at 2.45%, see also Table 1. At larger radii, the deviation was rather small, not exceeding 0.3%. Imposing the same distance between the bend outlet and the meter for single bend resulted in the same tendency, the maximum deviation being 1.93% for the smallest radius of curvature. Fig. 3 displays the difference between the two bend configurations for different flow velocities. The deviation from the reference case gradually increases with increasing velocity.

Geometry	Radius	Downstr. Distance	Deviation
Double Bend	50	92	-2,45%
Simple Bend	50	92	-1,93%
Double Bend	50	192	-1,61%
Simple Bend	100	292	0,35%
Simple Bend	200	92	0,30%
Double Bend	100	92	-0,30%
Double Bend	100	192	-0,30%
Simple Bend	100	192	0,29%
Simple Bend	50	192	-0,27%
Double Bend	200	92	-0,16%
Simple Bend	100	92	-0,11%

Table 1: Experimentally investigated combinations of geometries, radii and distances from the bend outlet to the bluff body

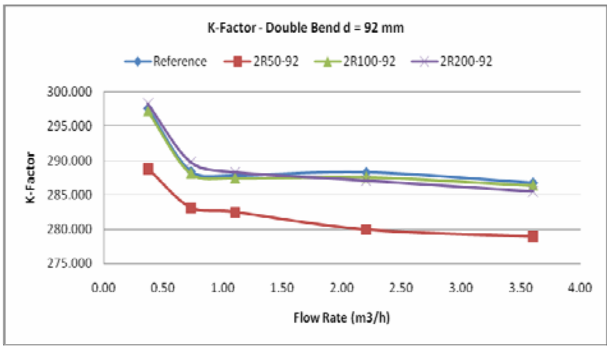


Fig. 2: Effect of radii of curvature on the resulting Strouhal number (k-factor)

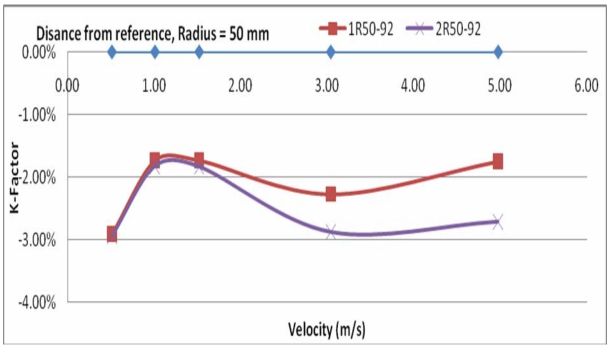


Fig. 3: Comparison of the deviation measured for single bend and double bend configurations at different bulk velocities.

The effect of change of distance between the bend outlet and the metering section can be seen in Fig. 5 for the radius of curvature of R=100 mm. At the smallest distance of 92 mm, the deviation was small and negative (-0.11%), increasing with increasing distance to positive values of up to 0.35% at the largest distance. This tendency seemed first to be inconsistent with the physics of the flow field. The expected behaviour would rather display a reduction of the disturbances with longer distance due to viscous effects causing a decay of their amplitude. A closer examination of the flow field behind the single bend revealed a strong rotational component of the induced secondary flow (see also the section Numerical Simulation).

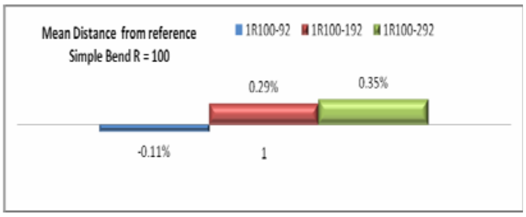


Fig. 4: Deviation of the measured k-factor with increasing distance between the bend outlet and the meter, single bend.

One possible explanation of the the above behaviour is that due to the rotation of the flow field, the asymmetric velocity profile changes its orientation relativ to the bluff body, influencing the deviation stronger than the viscous decay of the disturbance in the inflow. In order to test this presumption, a test configuration with the bluff body rotated 90° to its horizontal position was investigated experimentally. The resulting change in nondimensional vortex shedding frequency was determined to be up to -1.3%, the maximum found at the lowest velocities. The deviation from this test case is significantly larger than for the same double bend with the bluff body oriented horizontally. Evidently, an efficient flow straightener capable of strongly reducing the rotational component of the flow field would have an positive (or at least consistant) effect on the meter accuracy in presence of the bends.

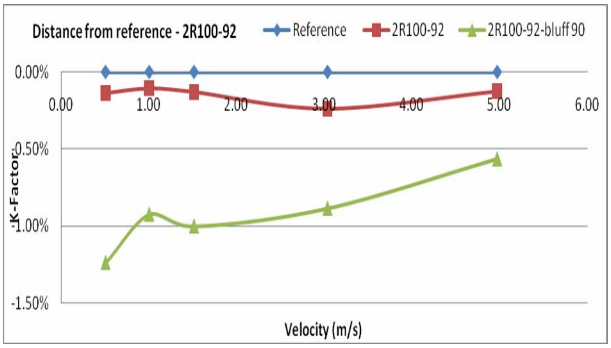


Fig. 5: Deviation of the k-factor for different orientations of the bluff body

3. NUMERICAL SIMULATION

The numerical flow simulations were carried out for limited number of cases for a DN25 vortex flow meter, as the high resolution computational grid required approximately 4 weeks of run times for each case. The computations were performed by using the commercial flow solver Fluent in its segregated, incompressible form. The flow was assumed to be turbulent, with the RNG k-ε turbulence model used for approximation of the Reynolds-averaged turbulence effects. Three bend-configurations were considered in addition to the reference case: simple 90-degree bend, in-plane double bend and 90-degree out-of-plane 3-dimensional bend. The corresponding grids for all four cases are shown in Fig. 6. Normally, the computational grid would include the upstream bends as well as the central part with the metering section. However, this configuration would consist of at least 1.6 10^6 cells, resulting in extremely long computational times. In the current application, the metered fluid was water, which is nearly perfectly incompressible. Therefore, in absence of pressure waves travelling at finite velocities, any pressure disturbances generated at the bluff body would propagate instantaneously, decaying quickly. It was therefore decided to compute the bends separately and to use the outflow as inflow boundary condition for the meter, which was basically the reference meter.

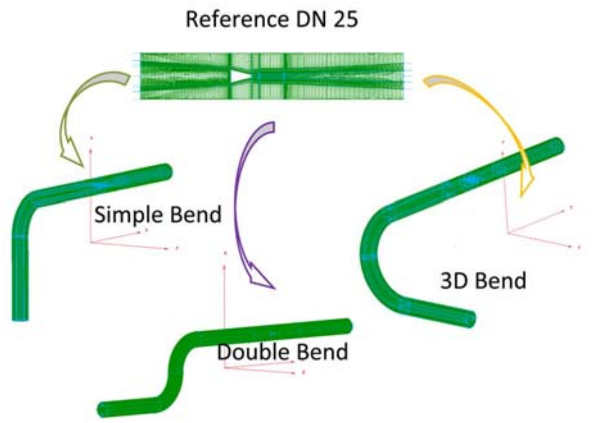
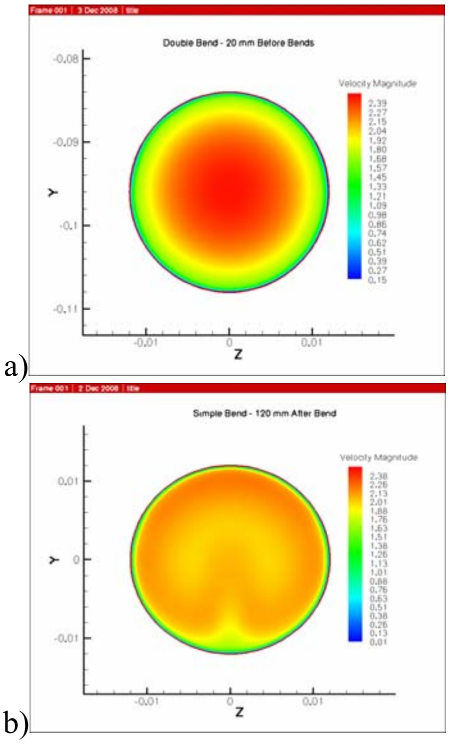
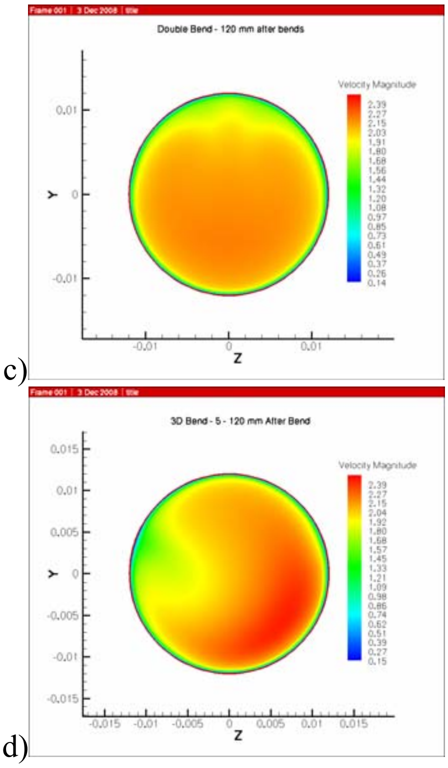


Fig. 6: Configurations for numerical simulations.

The velocity profiles obtained from the three types of bends are shown in Fig. 7. The flow fields agree well with the generally well known secondary flow profiles in these devices.





a) undisturbed inflow b) single bend c) 2-D double bend d) 3-D double bend

Fig. 7: Velocity profiles at the outflow from the bends.

Although only limited number of cases were simulated, the resulting vortex shedding frequencies agreed very well with the experimental data, verifying the numerical results as realistic and making the computation a useful tool for predictions of the corresponding flows.

The resulting deviation of the predicted k-factors from the reference case is shown in Table 2 for all three types of bends that were simulated. The largest deviation was produced by the three-dimensional double bend configuration.

NUMERICAL RESULTS		
		Deviation
Simple Bend :		**-1,18%**
Double Bend (2D) :		**-1,34%**
Double Bend (3D) :		**-6,43%**
Radius of Curvature	50 mm	
Bend outlet/Bluff Body Distance	160 mm	
DN	25	
pipe	24 mm	
Speed	2m/s	

Table 2: Resulting deviation of the k-factor from the reference case obtained from numerical simulations.

The comparison of the numerically simulated deviations of the k-factor from the reference case with the corresponding experimental results can be seen in Table 3 below.

	Deviation, simple bend	Deviation, double bend
Simulation	1,74%	1,88%
Test	1,93%	2,45%
Simulation error	- 0.19%	- 0.57 %

Table 3: Comparison of experimental and numerical results in terms of the deviation of the k-factor

4. SUMMARY

In the present work, several configurations incorporating a vortex-shedding flow meter and one of three selected bend geometries were investigated numerically as well as experimentally. The resulting k-factors were compared, leading to conclusions regarding distance of the meter from the source of disturbance and minimum radius of curvature of the bends. The potential for reduction in the prescribed straight pipe section upstream of the meter has been demonstrated. The numerical simulations required extensive computational times, but delivered results that were in very good qualitative as well as quantitative agreement with the experimental data. The difference between the two was typically less than 1.0 %.

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