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LDA MEASUREMENTS IN A STRONGLY SWIRLING PIPE FLOW

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Abstract

Detailed measurements were carried out using laser-Doppler anemometry (LDA) in a swirling flow through a pipe. A 30 mW He-Ne laser generator was used as a coherent light source. To provide optical access into the pipe, the pipe and walls of the rectangular test section was made up of Duran glass. The refractive index of the working fluid was matched with the Duran glass by mixing two similar fluids with slightly different refractive indices, and a fluid temperature control system was employed to eliminate the thermal effects on the refractive index of the fluid and keep it constant within a certain degree of accuracy. To decrease the size of the control volume and thus, to reach a good resolution especially in the near wall region, the original laser beam diameter was expanded and collimated. The LDA system utilizes frequency shifting using a pair of Brag-Cells placed after the beam splitter, which enables accurate measurements in the regions where the velocities are very small or change their signs. Computer controlled stepper motors were used to traverse the measuring volume from point to point to enable profile measurements. A TSI counter was used to filter the signals and eliminate the effect of noise on the signals. The measured profiles for velocity and statistical moments yield insight into the behavior of turbulence subjected to swirl. The decay of swirl and the corresponding change in the turbulence structures have been investigated in the entrance region, up to approx. 20 diameters downstream of the pipe.

Introduction

Swirling flows find their applications in many fields of Engineering. During the past decades, great effort has been spend to understand and model the effect of swirl on the turbulent quantities (Jakirlić et al., 2002). However, in these studies, it was concluded that the addition of a tangential shear component to the main flow direction makes the modeling of swirling flows rather complex. The major difficulty arises from the fact that the turbulent stress tensor, being a symmetric tensor, has to be modeled in terms of the strain tensor, which is basically anti-symmetric due to the contribution from the rotation. Therefore, in the case of swirling flows, the constitutive relations become more complex than in purely strained flows.

Flows in a straight pipe with decaying swirl were experimentally studied by Baker (1967), Fejer et al. (1968), Wolf et al. (1969), Murakami et al. (1976), Kitoh (1991), Li and Tomita (1994), Steenbergen (1995) and Rocklage-Marliani et al. (2003). These investigations have proven the failure of the standard two-equation models, which fail to account for the anisotropy of turbulence pronounced in case of swirl flows. It is however known in the literature that the Reynolds stress models have the theoretical advantage of modelling the turbulent stresses in each direction separately, and make it possible to include the effects of anisotropy. Therefore, for better turbulence predictions, a Reynolds stress model appears to be promising for the case of swirling flows. However, in spite of their potential, no satisfactory Reynolds stress model for the case of swirl flows has been reported (Jakirlić et al., 2002).

The objective of this paper is to present the experimental facility built for the investigation of swirling pipe flows in LSTM-Erlangen and discuss the implementation of the LDA measuring technique to measure turbulence statistics. Recently obtained experimental data for the mean velocity and second-order turbulence statistics in the axial flow direction will be presented. New data is thought to complement the previous results obtained on the setup (Miras et al., 2004) and yield further insight into the characteristics and thus the modeling of turbulence subjected to swirl.

The Experimental Facility and Measuring Technique

The experimental work is carried out on the facility shown in Fig. 1, which was described in detail by Durst et al. (1995).

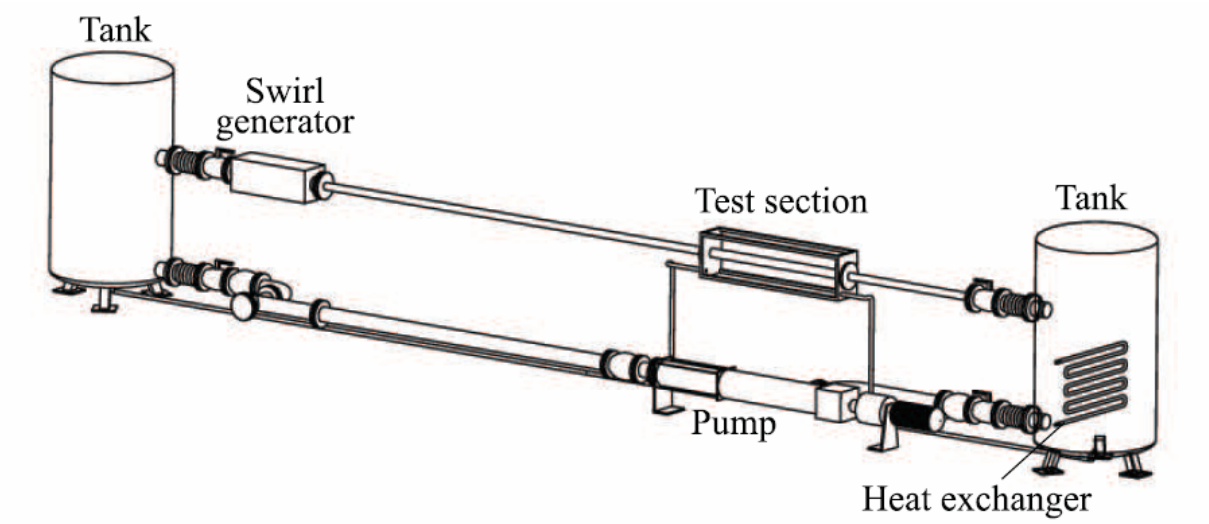

Fig. 1: Sketch of the Experimental Setup

The facility is basically a closed-loop pipe flow installation driven by a screw conveyer pump operating in suction mode. The diameter *D* and the length *L* of the pipe were 50 mm and about 7 m respectively. A swirl generator, which is basically a piece of pipe of 0.5 m length and filled with a tightly packed bank of thin tubes of outer diameter 4 mm, was installed just before the inlet of the pipe. So this device having a honeycomb structure (see Fig. 2) and mounted on two bearings, was used to create swirling flows of desired strengths when rotated at different angular speeds. The swirl generator was rotated by using a three-phase AC motor controlled by a frequency converter, which allowed the adjustment of the rotation rate from 0 to 1130 rpm. To provide optical access into the pipe for LDA measurements and to enable refractive index matching, the walls of the rectangular test section were made of the same glass material (Duran-50 glass) as the pipe wall. Therefore, when the test section is filled with the working fluid (diesel oil), it provides an optically uniform medium which enables the laser light to penetrate through the pipe without any deflection. In addition to this, a fluid temperature control system was employed to eliminate the thermal effects on the refractive index of the fluid and keep the index constant within a certain degree of accuracy.

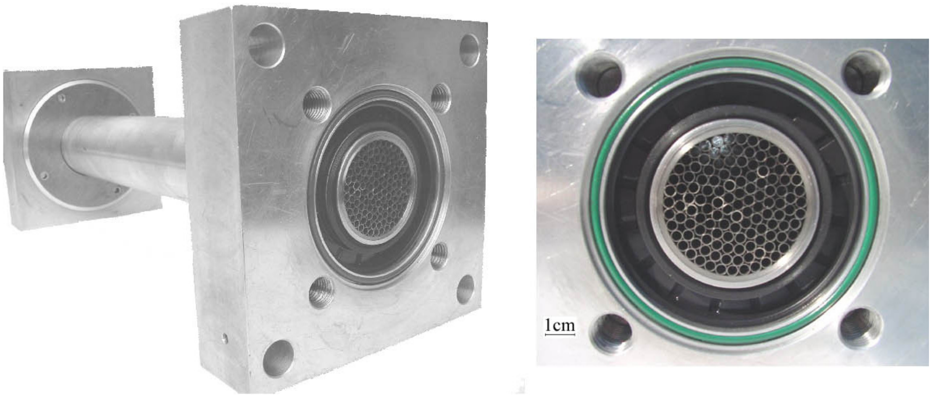

Fig. 2: The Swirl Generator and the Honeycomb Structure

Measuring technique

A specially designed laser-Doppler system was used for the present measurements. The arrangement of the optical system is shown in Fig. 3.

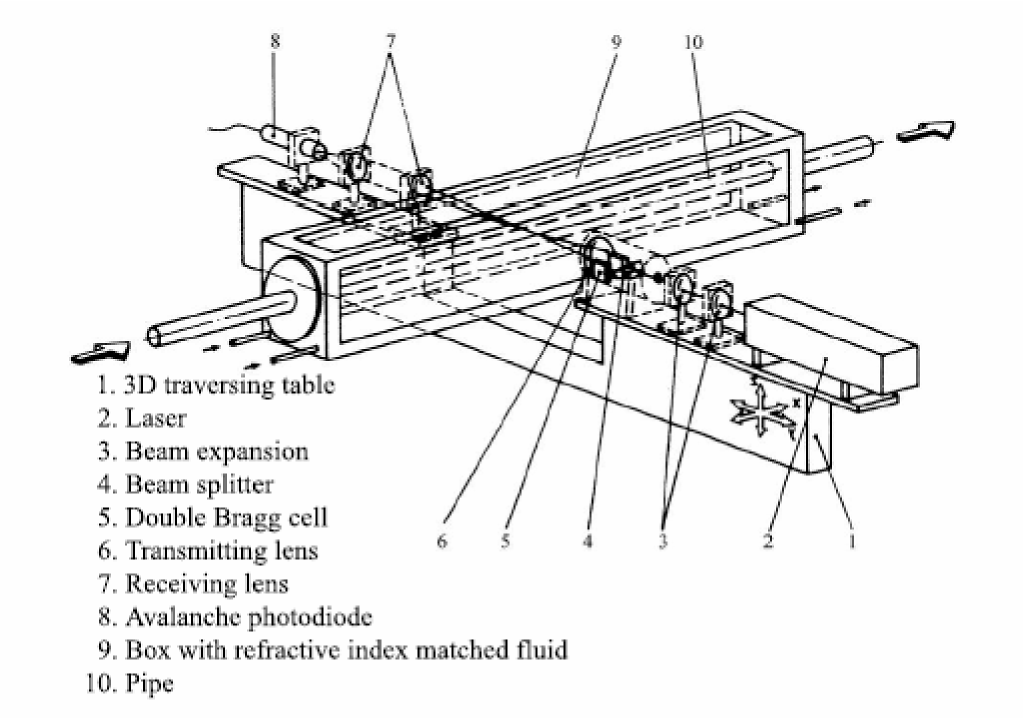

Fig. 3: The LDA System and the Test Section

The system utilizes a 30 mW He-Ne laser generator which was used as a coherent light source. To decrease the size of the control volume and thus, to reach a good resolution especially in the near wall region, the original laser beam diameter was expanded and collimated. The LDA system utilizes frequency shifting using a pair of Brag-Cells placed after the beam splitter, which enables accurate measurements in the regions where the velocities are very small or change their signs. Computer controlled stepper motors were used to traverse the measuring volume from point to point to enable velocity profile measurements at different locations downstream of the pipe. An avalanche photodiode, mounted in the forward scattering direction, was used to detect the light scattered from the particles in the diesel oil. Due to the self contamination of the diesel oil, no additional seeding particles were necessary. A TSI counter was used to filter the signals coming from the photo diode and eliminate the effect of noise. At each measuring position at least 20,000 samples were acquired. According to the sampling considerations, the statistical uncertainty in the measurements was estimated to be around ±0.5% and ±1,5% for the mean value and second order moments, respectively.

The experiments were carried out for a flow rate corresponding to a Reynolds number of 25×10^3, based on the pipe diameter D and bulk velocity U_B. The measurements were performed at 9 different measuring locations, designated with the symbol L, corresponding to *L/D* = 3.3, 5.3, 7.3, 9.3, 11.3, 13.3, 15.3, 17,3 and 19.3 diameters downstream of the pipe. Two different swirl speeds corresponding to swirl numbers of N=1.0 and N=1.57, were applied. The first swirl rate was chosen to match with the one used in the previous work on the setup by Mira et al., 2002, whereas the higher swirl rate is thought to be useful to parameterize the effect of swirl. This choice of swirl speeds and measuring locations was thought to complement these results and see the effect of swirl on turbulence structures more in detail.

Turbulent Pipe Flow with weak and strong Swirl

The results in this part present the effect of swirl on mean axial flow velocities and their rms values. These velocity data are normalized with the bulk velocity, whereas the distance from the pipe center r is normalized using the diameter *D*. The location of the downstream edge of swirl generator is taken as the reference position (*L/D*=0) for the measurement locations along the pipe axis. The mean velocity profiles for initially strong swirl are presented in Figure 4. To see the effect of swirl better, these profiles are plotted together with the profiles obtained without any swirl.

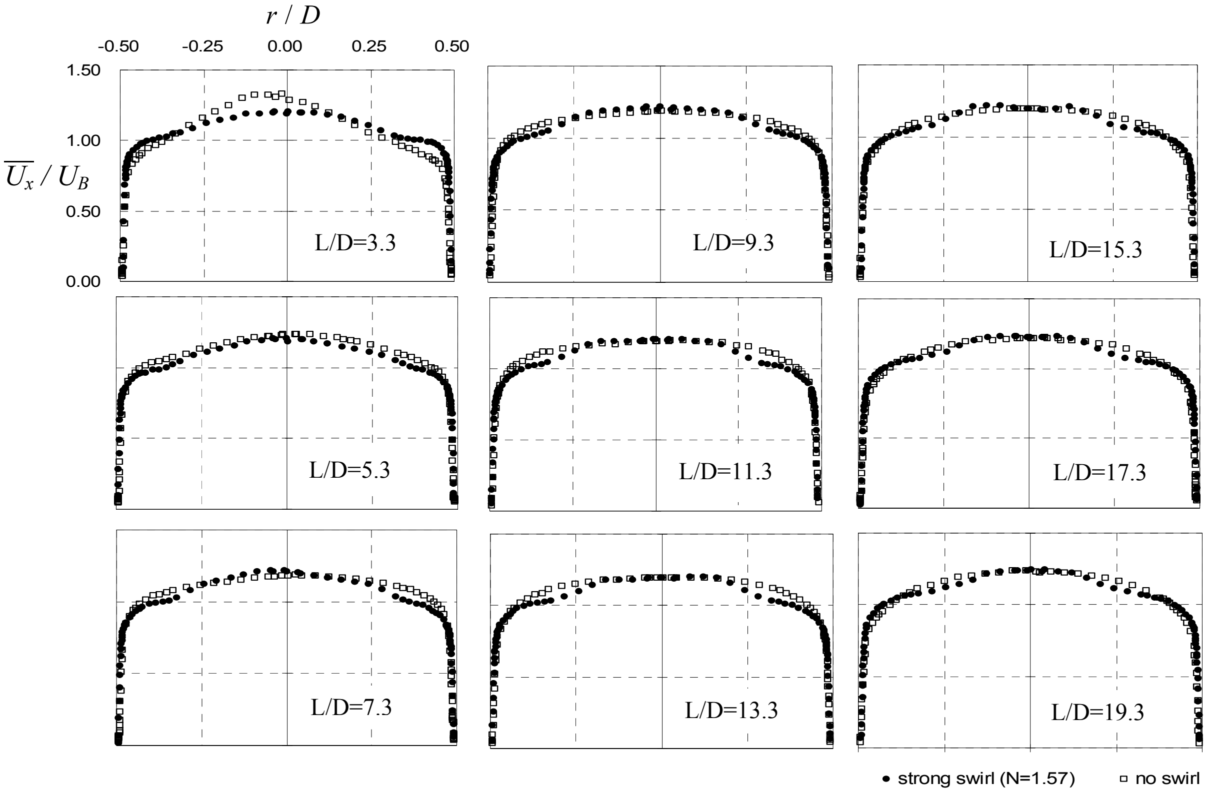

Fig. 4: Normalized Mean Velocity Distributions in a Pipe Flow with Strong Swirl and without Swirl. (Note that the scales are the same for all presented data)

For the case where there is no swirl, the slight asymmetry at the very first profile is thought to be because of the effect of the tripping ring used just after the swirl generator. This tripping ring is used to decrease the development length of the pipe flow. The distributions for the case of weak swirl inlet condition look very much similar to the ones with strong swirl presented in Fig. 4; therefore they are not included in this paper. Actually, for both swirl rates, the effect of swirl is barely seen on the mean velocity profiles. It is known in the literature that for very high swirl rates, even flow reversals can occur. From here it is concluded that in any swirl rate, the net effect of swirl is a transfer of momentum from the axial direction to the radial, due to centrifugal effects. So this tendency is slightly seen in the present profiles.

Contrary to the results for mean velocities, the effect of increased swirl is clearly seen in the rms profiles of axial velocity, shown in Figures 5 and 6. The swirl initially tends to suppress the fluctuations and stabilize the flow, possibly due to centrifugal effects, but later on, especially after approx. 7 diameters downstream, the intensity values tends to exceed the ones for the case of no swirl. This effect is somewhat retarded to approx. 10 diameters downstream for the case of strongly swirling pipe flow. In both cases once this increase starts, the intensities tend to increase constantly without any cessation. In the previous work by Mira et al., 2004, this tendency is observed until approx. 30 diameters downstream from the inlet. This fact is thought to be due to complete dissolving of the vortex core after approx. 30 diameters downstream of the pipe. However, the detailed measurements show that the increase in the intensities is not in an explosive fashion, even in the case where a higher swirl number has been used (N=1.57). It can be concluded that the energy of the vortex core, which gradually diminishes, is transmitted to the small scale turbulent fluctuations due to the mechanism of dissipation. It must however be noted that to reach a full conclusion, complete measurements for all components of Reynolds stress tensor should be carried out.

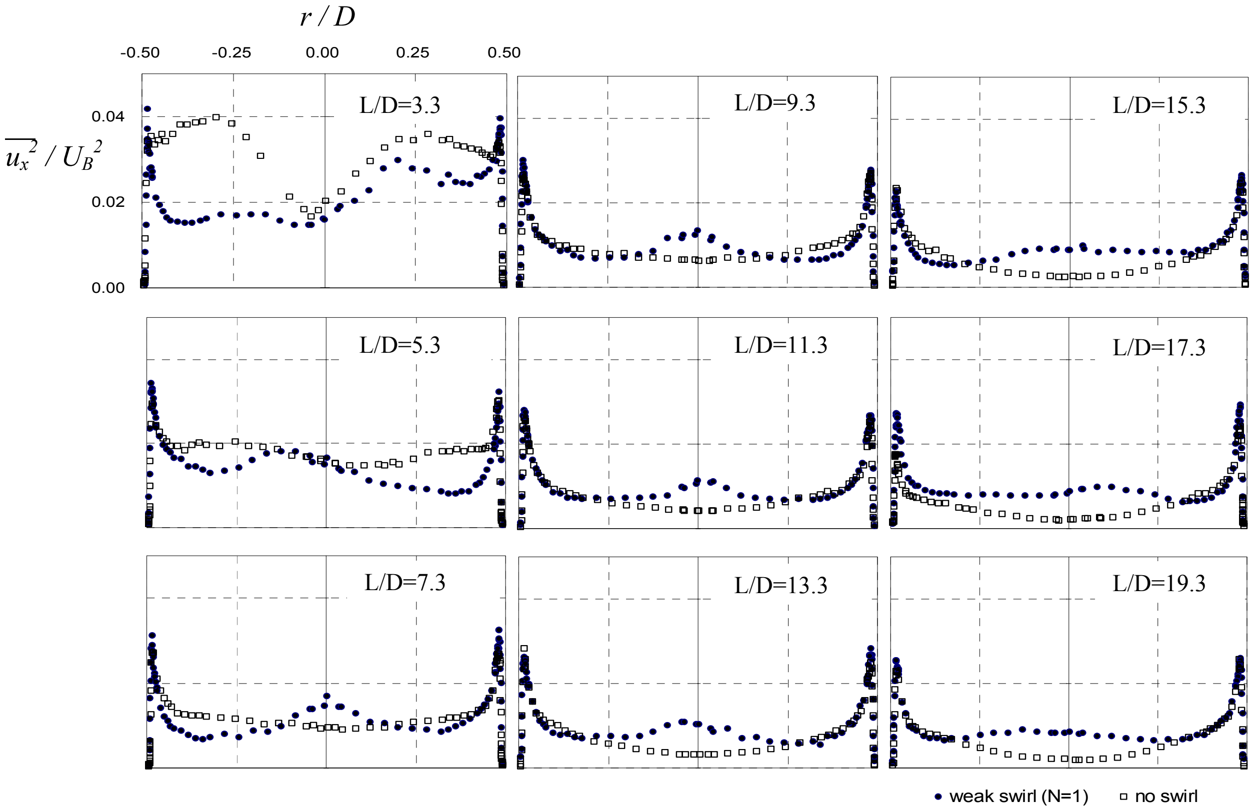

Fig. 5: Normalized Distributions of Axial Component of Reynolds Stress Tensor for a Weakly Swirling Pipe Flow Compared with the Distributions for the Case of no Swirl

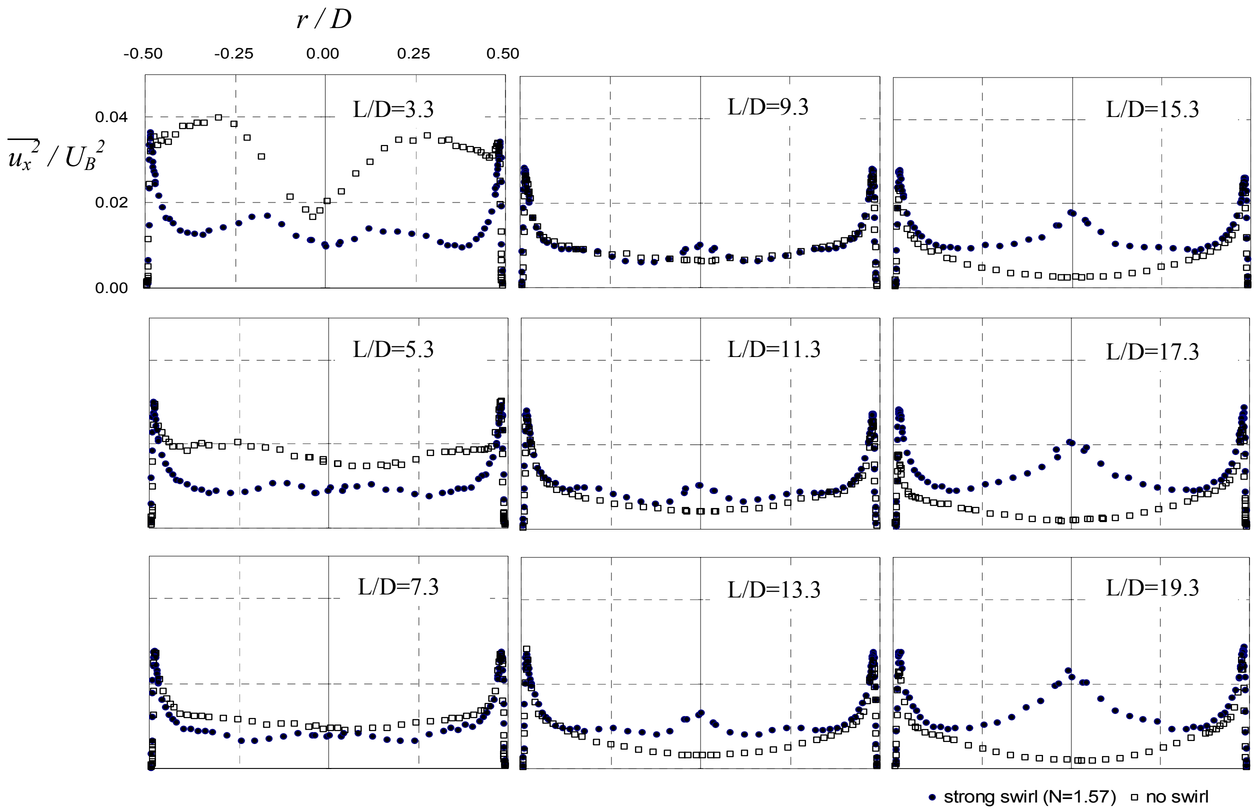

Fig. 6: Normalized Distributions of Axial Component of Reynolds Stress Tensor for a Strongly Swirling Pipe Flow Compared with the Distributions for the Case of no Swirl

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