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LDA MEASUREMENTS OF SWIRLING PIPE FLOWS FOR A WIDE RANGE OF SWIRL NUMBERS

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Abstract

This study concentrates on turbulent swirling flows, which are constrained in a stationary and straight circular pipe. Aim was to determine the sole effect of swirl component and its decay on a developing turbulent pipe flow. For this purpose, velocity statistics of a pipe flow with a Reynolds number of $Re_D = U_m \, D / \nu = 30{,}000$ were measured at several downstream positions up to $z/D = 17.3$. The strength of inlet swirl was adjusted to the desired swirl numbers of $N= 0.3$ and $N = 1.0$. Emphasis was put on generating a solid-body rotation type of swirl while maintaining axisymmetric inlet conditions. Consequently, the determined mean velocity and Reynolds stress profiles showed almost no deviation from axisymmetry. Furthermore, non-zero Reynolds shear stresses were determined. Both findings contradict some results in the literature. Subtle increase in the magnitude of Reynolds stresses was observed as the swirl component decayed partially. At the second stage of this study, the range of swirl numbers were extended up to $N = 4.5$, simply by reducing the Reynolds number to $Re = 8{,}500$. For this extended range, axial velocity profiles were measured at $L/D = 3$. It was observed that the velocity profile first become increasingly concave down with increasing N until $N = 1.5$ where this tendency changed its direction: The profile flattened around $N = 2.6$ and for stronger swirls, it became increasingly concave up.

Introduction

Swirling flows are an important class of flows not only due to their basic features, but also due to their technical relevance for engineering and abundance in nature. However, their challenging complexity poses serious problems in their modeling and understanding (see Jakirlić et al., 2002). Due to this fact, swirling flows have been studied for a long time and many publications can be found in the literature (see Steenbergen 1995, Rocklage-Marliani et al. 2003, Pashtrapanska et al. 2006 for detailed reviews). These studies reveal the fact that, depending on the boundary conditions, swirling flows can undergo totally different scenarios and flow field can exhibit different dynamical features: A great number of these studies concentrate on the effects of swirl, when the swirling flow is created and subjected to gradual or sudden expansion in pipes or injected as a free jet (unconstrained) (Novak et al. 2000, Facciolo et al. 2007, Billant et al. 1998). In these kind of flows, swirl component decays rapidly due to the action of adverse pressure gradient and sometimes *vortex core breakdown* phenomenon occurs (Novak et al. 2000). Other studies consider the case, when the swirl component is created by a rotating pipe and the swirl component is constantly imposed onto the axial flow (Nishibory et al. 1987, Facciolo et al. 2007). In such a flow, a parabolic tangential velocity profile develops and it does not decay along the axis of the pipe.

In contrast to these, present study concentrates on the relatively less studied case (Steenbergen 1995, Pashtrapanska et al. 2006, Rocklage-Marliani et al. 2003, Kito 1984, Kitoh 1991, Genç et al. 2005) when the swirl is generated at the inlet of a straight circular pipe and constrained in it. In such a flow, the swirl component decays gradually due to the action of viscosity. Regarding to this kind of flows, a number of different effects were reported; like stabilizing-destabilizing effect of swirl on turbulence (Kito 1984), effect of swirl decay on breaking of axisymmetry (Pashtrapanska et al. 2006), relaminarization of flow profile (Nishibory et al. 1987), annihilation of Reynolds shear stresses (Rocklage-Marliani et al. 2003).

From the literature survey and our previous experiments (see Genç et al. 2005), it can be concluded that axial velocity distribution and the generation of swirl at the inlet of the pipe determine the downstream distribution of mean and turbulent flow quantities to a great extend. Therefore, in this study, a solid body rotation type of swirling inlet condition was carefully created to maintain axisymmetry at the inlet of the pipe. Aim is to determine the sole effect of swirl and its decay on the statistics of flow quantities along the pipe. The obtained results are evaluated taking into account the above-mentioned effects reported in the literature.

Classification of Previous Studies using Swirl Intensity and Reynolds Numbers

In the above mentioned swirl flow studies in straight pipes, in addition to Reynolds number, two other non dimensional parameters were appropriately introduced to quantify the strength of tangential (swirl) component in relation to the axial flow component: These are the swirl intensity, denoted with S and the swirl number, denoted with N. Swirl intensity is defined as the ratio of angular momentum flux (through the pipe cross-section) to the axial momentum flux times the radius and it is expressed as:

$$S = \frac{2\pi\rho \int_0^R r^2\, \overline{U_z}\, \overline{U_\theta}\, dr}{\pi\rho R^3\, \overline{U_m}^2}$$

Swirl intensity is useful to calculate the strength of swirl from the measured tangential and axial profiles at downstream positions after swirl component partially decays. On the other hand, the swirl number, denoted with N, is expressed as follows:

$$N = (\overline{U_\theta})_{max}/U_m$$

In the present study, swirl number was used because it could easily be determined at the inlet using the rotational speed of the honeycomb, which was controlled accurately by an AC motor. However, since most experiments in the literature used other type of swirl generators like guide vanes, the determination of the swirl strength right at the inlet was not directly possible. Therefore, the measured swirl intensities at the first measurement cross-sections were projected using exponential decay laws in order to find out the strength of the inlet swirl. This step was necessary in order to be able to compare the swirl strengths of several cases in the literature. In present study, the swirl number was converted to swirl intensity simply by dividing the swirl number by 2, where this simple relation comes from integration of the triangular inlet velocity profile, determined by rotational speed of the honeycomb. In this manner, comparison of different cases found in the literature together with the present study is given on the plot in Fig. 1.

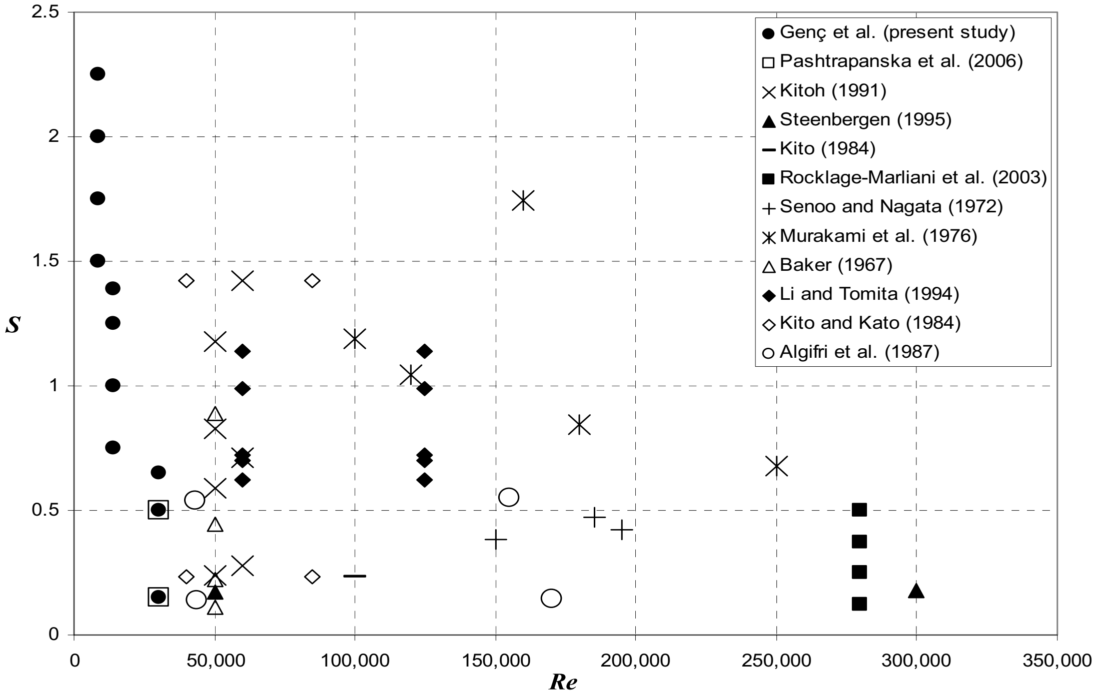

Fig. 1: Swirl Intensity (S) vs. Reynolds Number (Re) plot of present study and other swirl flow experiments in the literature, which are also carried out in straight circular pipes

Experimental Facility

In this study, the refractive-index-matched pipe flow facility of LSTM-Erlangen was used (for a 3-D schematic view, see Fig. 2). The working fluid in the pipe was diesel oil. A refractive-index-matched test section with a length of 1 m, filled with diesel oil, provided optical access for the simple 1-C laser Doppler anemometer (LDA) system, which was mounted on a traversing table (see Fig. 2). The swirl generator used in previous studies (Pashtrapanska 2006, Genç 2005) was reconstructed to obtain axisymmetric flow conditions at the inlet. A 300 mm long polycarbonate honeycomb insert was carefully machined into a cylindrical form to obtain an axisymmetric distribution of its cells. This insert was then tightly fitted into a piece of pipe out of steel, which could be rotated with an AC Motor and as such the strength of the inlet swirl could exactly be adjusted to the desired swirl numbers $N = (U_\theta)_{max} / U_m$ up to ca. $N = 1.3$.

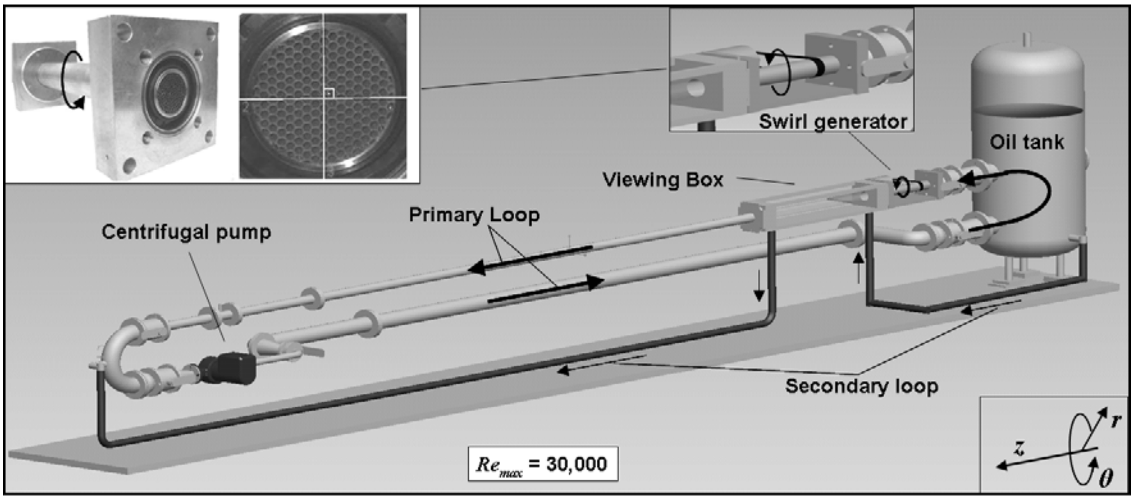

Fig. 2: The refractive-index-matched turbulent pipe flow facility of LSTM-Erlangen with a close up view of the swirl generator and its honeycomb insert. Cylindrical coordinates are used, where z denote the axial direction

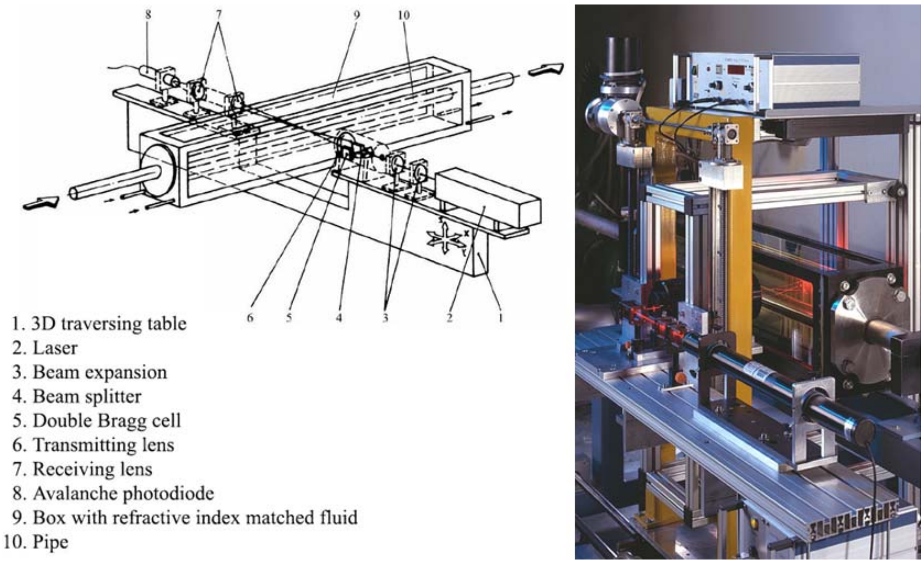

Fig. 3: Schematic and photographic views of the LDA System and the test section

Results and Conclusions

All results were normalized with avg. axial velocity $U_m = 2.34$ m/s. For swirl with $N = 1$, the mean velocities depict some typical effects of swirl, which were also observed in the literature, like bringing the axial mean flow profiles to a shape resembling a laminar profile (Fig. 4). Reynolds stresses substantially increase, especially when the strong swirl component decays along the pipe (Fig. 5, Fig. 6). As can be seen from the plots, this observed increase of Reynolds stresses is most pronounced in the near-wall region and penetrates into the center of the pipe at downstream locations. Apart from $\overline{u_r u_z}$ component, magnitude of Reynolds stresses increase with increasing swirl number owing to the increased shearing of flow in θ-direction.

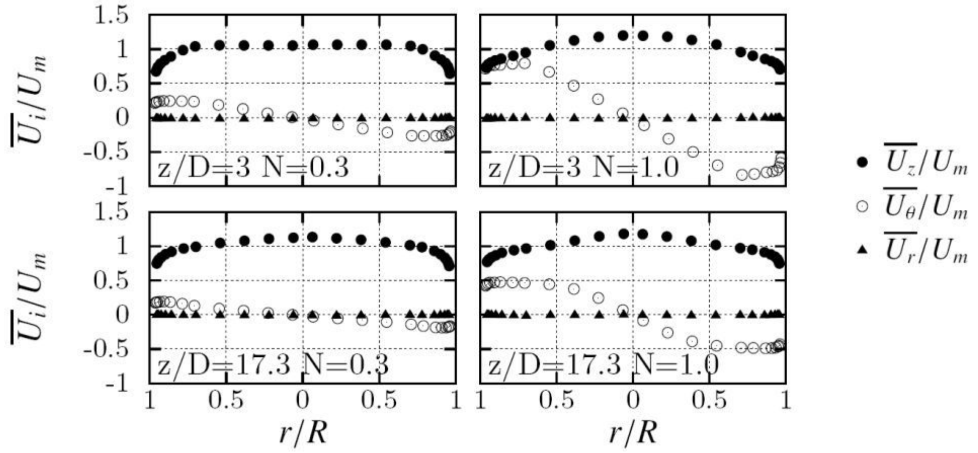

Fig. 4: Mean velocity profiles at $z/D = 3$ and 17.3 for swirl numbers $N = 0.3$ and 1.0

Another important observation is that the measured profiles show almost no sign of deviation from axisymmetry, at least until the measured downstream position $z/D = 17$ (Fig. 4, Fig. 5, Fig. 6). This contradicts some results for similar cases in the literature, in which the swirl was hold responsible for the appearance of asymmetries in the profiles of flow quantities (Pashtrapanska et al. 2006, Steenbergen 1995, Kito 1984. It was therefore concluded that the inlet conditions should first carefully be checked for axisymmetry, before any claim can be made about the effect of swirl. Furthermore, contrary to another investigation (Rocklage-Marliani 2003) no annihilation of Reynolds shear stresses was observed and even the Reynolds stresses increased in magnitude (Fig. 6). No evidence of vortex core breakdown phenomenon could be observed (like tendency to flow reversal in the center) and properties did not change abruptly along the pipe (Pashtrapanska 2006). The swirl component of flow decayed gradually along the pipe.

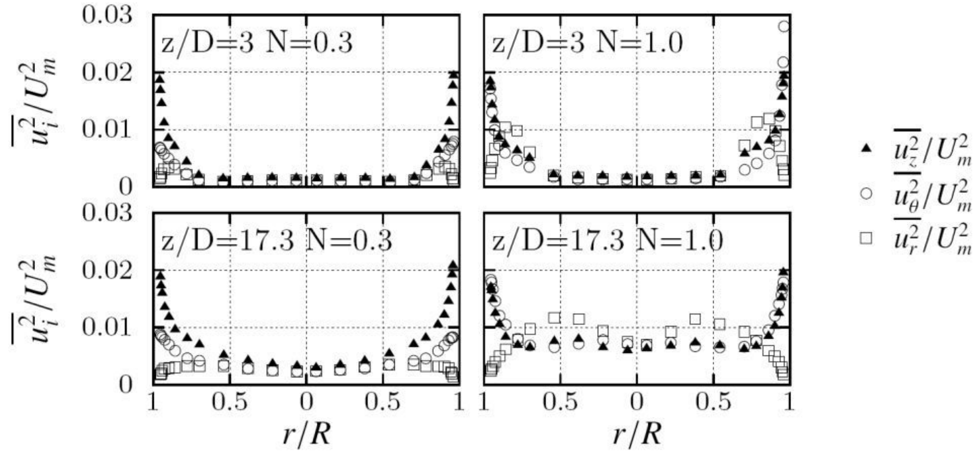

Fig. 5: Reynolds normal stress profiles at $z/D = 3$ and 17.3 for swirl numbers $N = 0.3$ and 1.0

The results of the measurements for the extended swirl rates can be seen in Fig. 7. The measurement cross-section was kept at $z/D = 3$ and axial velocity profiles were measured for different swirl numbers ranging from 0.3 to 4.5. It was observed that the velocity profile first becomes increasingly concave down with increasing N until $N = 1.5$, where this tendency changed its direction: The profile flattened around $N = 2.6$ and for stronger swirls, it became increasingly concave up, showing a tendency to flow reversal. This effect was thought to be due to a complex interaction between the boundary layer and the pressure gradient in the radial direction.

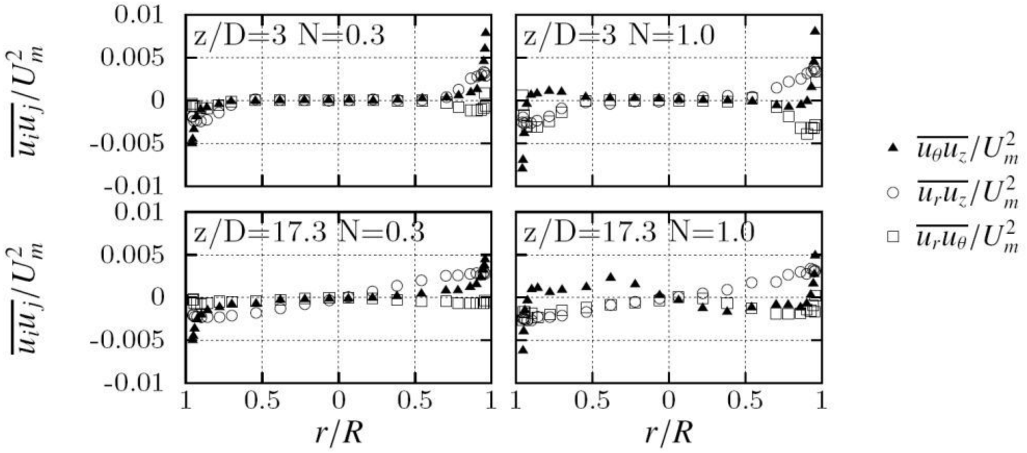

Fig. 6: Reynolds shear stress profiles at $z/D = 3$ and 17.3 for swirl numbers $N = 0.3$ and 1.0

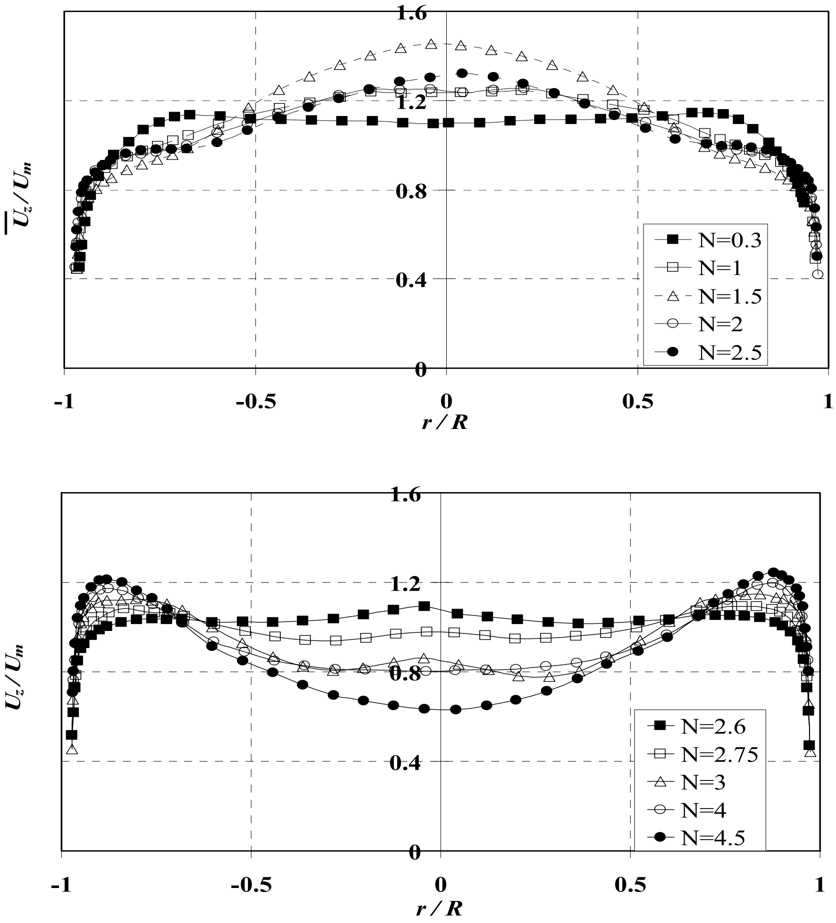

Fig. 7: Mean axial velocity profiles at $z / D = 3$ for swirl numbers ranging from $N = 0.3$ to 4.5 for $Re = 8{,}500$. Profiles are drawn in two separate graphs for convenience.

In the second stage of the study for higher swirl rates, it was observed that, depending on the amount of swirl, opposing tendencies can be observed in the flow field. Therefore it was concluded that, in addition to the shape of the initial swirl profile, the swirl strength was observed to be a sensitive parameter: It plays such an important role in changing the flow field downstream, that it could reverse the tendencies in the flow.

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