Querschnitt-PIV-Analyse in turbulenter Rohrströmung bei hohen Reynolds-Zahlen

Cross-sectional PIV analysis in turbulent pipe flow at high Reynolds number

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Summary

At the Department of Aerodynamics and Fluid Mechanics, Brandenburg University of Technology Cottbus-Senftenberg, the unique pipe facility “CoLa-Pipe” (Cottbus Large Pipe) is designed and built to investigate fully developed pipe flow at high Reynolds numbers ($Re_m \leq 1.5 \times 10^6$). This paper will give a general overview about the cross-section particle image velocimetry (PIV) measurements in CoLa-Pipe. A stereoscopic PIV arrangement is used. Taylor’s hypothesis and proper orthogonal decomposition (POD) is applied to obtain instantaneous fluctuations and turbulent structures. Scaled energy contribution of the first 100 sPOD modes for various Reynolds numbers has been analyzed. The first 10 sPOD modes represent 23% and 25% of the energy for $Re_D \approx$ 83,000 and 140,000, respectively.

Introduction

Most recent results in the literature showed that investigations of LSM and VLSM in pipes are still in progress and there is a lack of definition for the scales of these structures, in particular, at very high Re (Öngüner et al. 2016). Therefore, a quantitative measure of the energy and the Reynolds stresses associated with such scales are to be clearly defined. The LSMs are believed to be created by the vortex packets formed when multiple hairpin structures travel at the same convective velocity, and although the origin of the VLSM is not known for certain. For cross sectional case stereoscopic PIV arrangement is used. Taylor’s hypothesis and proper orthogonal decomposition (POD) is applied to obtain instantaneous fluctuations and turbulent structures.

In terms of making a significant contribution to the turbulent kinetic energy and Reynolds stress VLSM features are highly important in pipe flow research. Balakumar & Adrian (2007) found that 40%–65% of the kinetic energy and 30%–50% of the Reynolds shear stress are accounted for in the long modes with streamwise wavelengths greater than 3δ for boundary layers. Additionally, Mathis et al. (2009) claims that these structures have large radial scales that modulate the near-wall flow, which helps to explain Reynolds number dependent variations in the near-wall Reynolds stress distributions.

Obtaining turbulent structures at high Reynolds numbers optically with PIV requires long laser plane setups in axial direction. First of all a 2D laser plane will be applied in streamwise direction and axial extensions of turbulent structures can be identified. Hellström et al. (2011) is using Taylor's hypothesis and proper orthogonal decomposition (POD) to obtain instantaneous fluctuations and turbulent structures. To extend the investigation to a 3D domain additionally a cross sectional laser plane will be added and with this combination a 3D space can be constructed by using same algorithms as in Hellström et al. (2011).

Experimental Facility

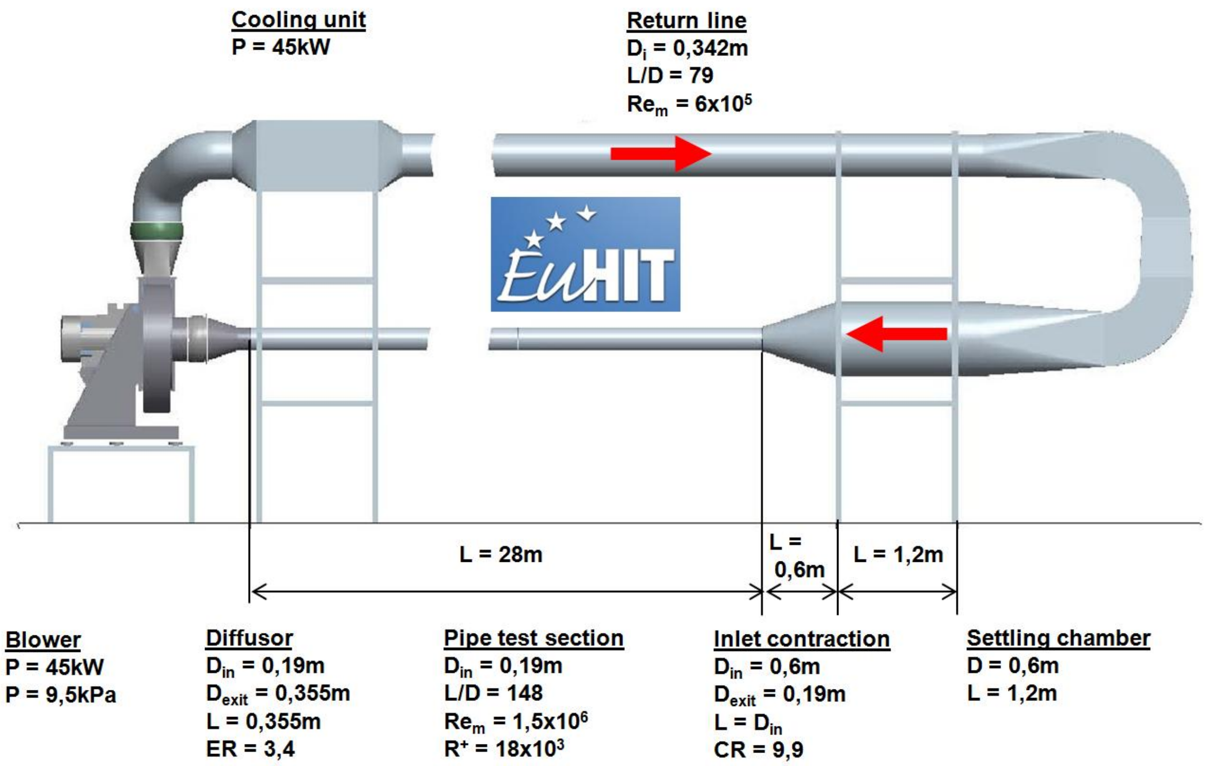


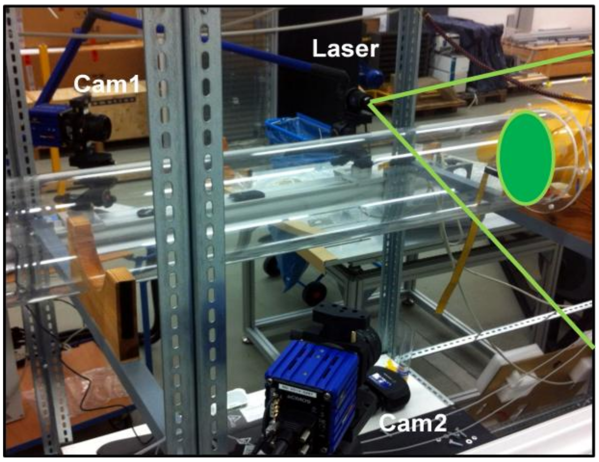
Figure 1: CoLa-Pipe facility at Brandenburg University of Technology (BTU)

The main objective of the CoLa-Pipe as a high Reynolds number test facility is to conduct fundamental research, e.g. a contribution to understanding the physical processes and dynamics of turbulence, as well as for supporting industrial projects. In this chapter all the relevant components described, i.e. test section, settling chamber, inlet contraction, tripping devices, power assembly and cooling unit. A detailed description can be found in König et al. (2014).

Two pipe test sections are available. The lower one is connected to the blower suction side and the other one is mounted at the delivery side of the blower called return line. Both pipe test sections are critical components in the present facility in terms of circularity, degree of surface roughness, straightness, alignment and optical accessibility for special measuring devices such as Laser-Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV). The inner pipe diameter of the lower side test section is D_i = 190± 0.23mm which has a deviation of less than 0.12%. The total length of the suction side, L = 28m, provides a test section length-to-diameter ratio of $L/D_i \approx 148$. The return line has an inner diameter of D_i = 342 ± 0.32mm and a total length of L = 27m as well, providing a length-to-diameter ratio of $L/D_i \approx 79$. Both test sections interior surfaces have a measured surface roughness of approximately 3µm being in terms of wall units 0.6 for the maximum Reynolds number of 1.5×10^6. The height of the centerline of the lower pipe test section is 1.55m from the ground, in order to support an easy access to the test section while the operator is standing on the floor of the laboratory and the height of the upper line is 4.55m from the ground, which definitely requires a working platform (Figure 1).

Measurements & Results

The experiments were performed during the same campaign described by Öngüner et al. (2015). The results presented in this paper were obtained at Reynolds numbers $Re_b = U_bD/\nu \approx$ 83.000 and 140.000 and the working fluid was air at room temperature. The corresponding friction Reynolds numbers are $Re_\tau = u_\tau R/\nu$ = 2036 and 3483, respectively. A stereoscopic PIV arrangement is used in collaboration with LaVision GmbH (Figure 2).



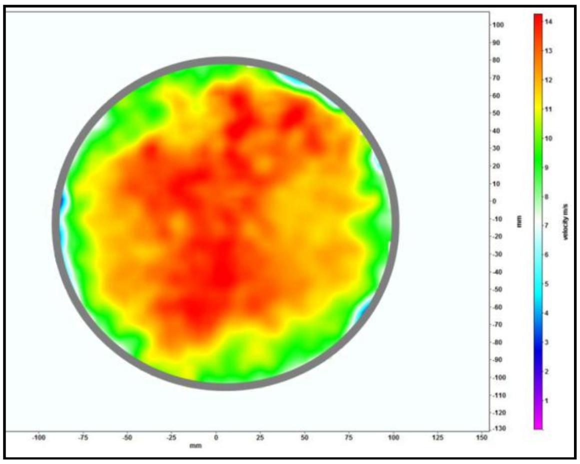


Figure 2: Stereo PIV configuration using 2 cameras
Figure 3: Snapshot of mean streamwise velocity at $Re_b \approx 140000$ for cross-sectional configuration

The stereo PIV system consisted of two LaVision Imager sCMOS cameras and a Nd:YAG Dual Cavity pulsed laser with a wave length of 532nm and frequency of 15 Hz, generating a 1 mm thick laser sheet that was used to illuminate a cross section of the pipe. The cameras were operated at 15 Hz with an interframe time of 30 and 60 µs for Reynolds numbers of for $Re_b \approx$ 83.000 and 140.000, respectively.

Snapshot POD was performed on the three dimensional fluctuating velocity data. The relative energy contents of the first 100 modes at 2 different Reynolds number ranges are given in Figure 4. The modal energy is distributed over a large number of modes and comparing to Hellström et al. (2014) these modes do not appear to occur in pairs with similar energy content. Every single mode seems to contain its own energy and non-pairwise energy distribution can be observed. The first 10 sPOD modes represent 23% and 25% of the energy for $Re_b \approx$ 83.000 and 140.000, respectively (Figure 4).

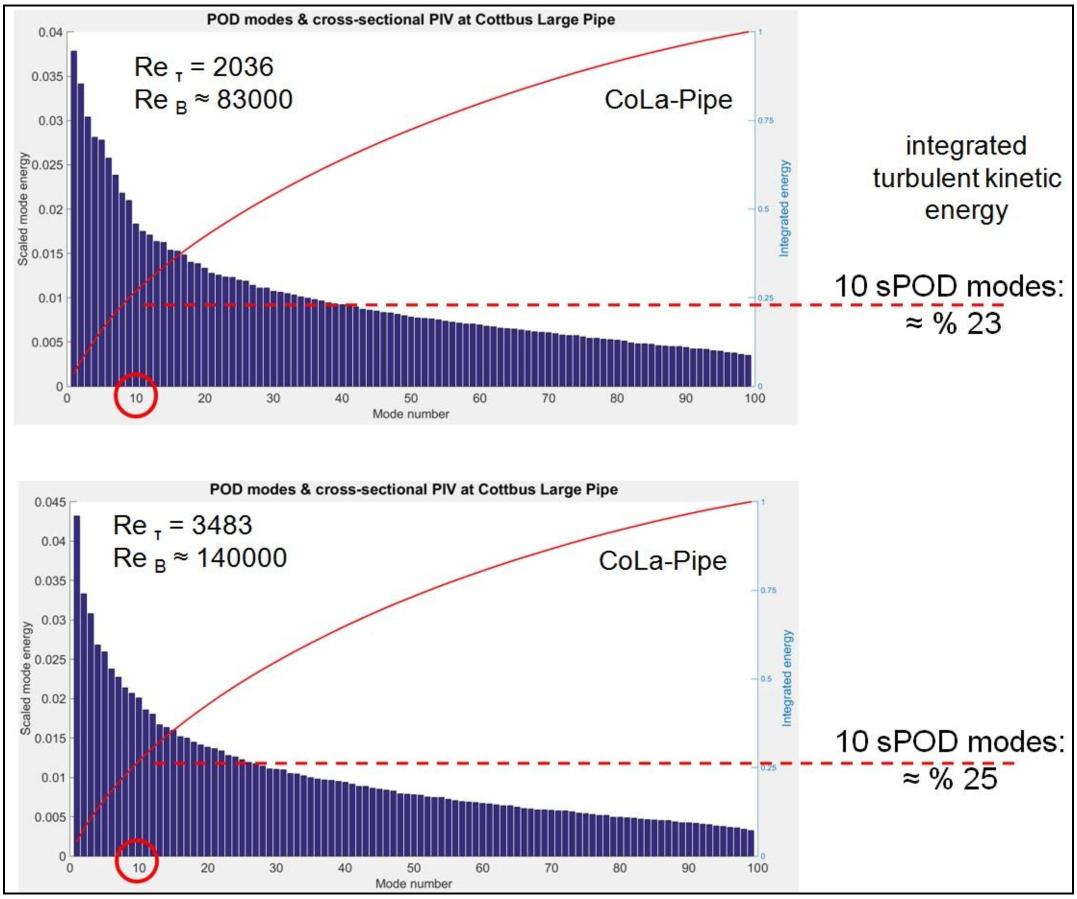


Figure 4: Integrated turbulent kinetic energy at $Re_b \approx 83000$ and $Re_b \approx 140000$

The first eight POD modes for $Re_b \approx 83000$ (Figure 5) show that the azimuthal mode number m is changing drastically. Due to the less number of PIV snapshots (100 pairs for each Reynolds number) energetic modes contain less resolution in comparison to Hellström et al. 2014. Azimuthal mode numbers for the first four POD modes are: 4, 2, 3, 3; which show the energetic patterns of velocity fluctuations.

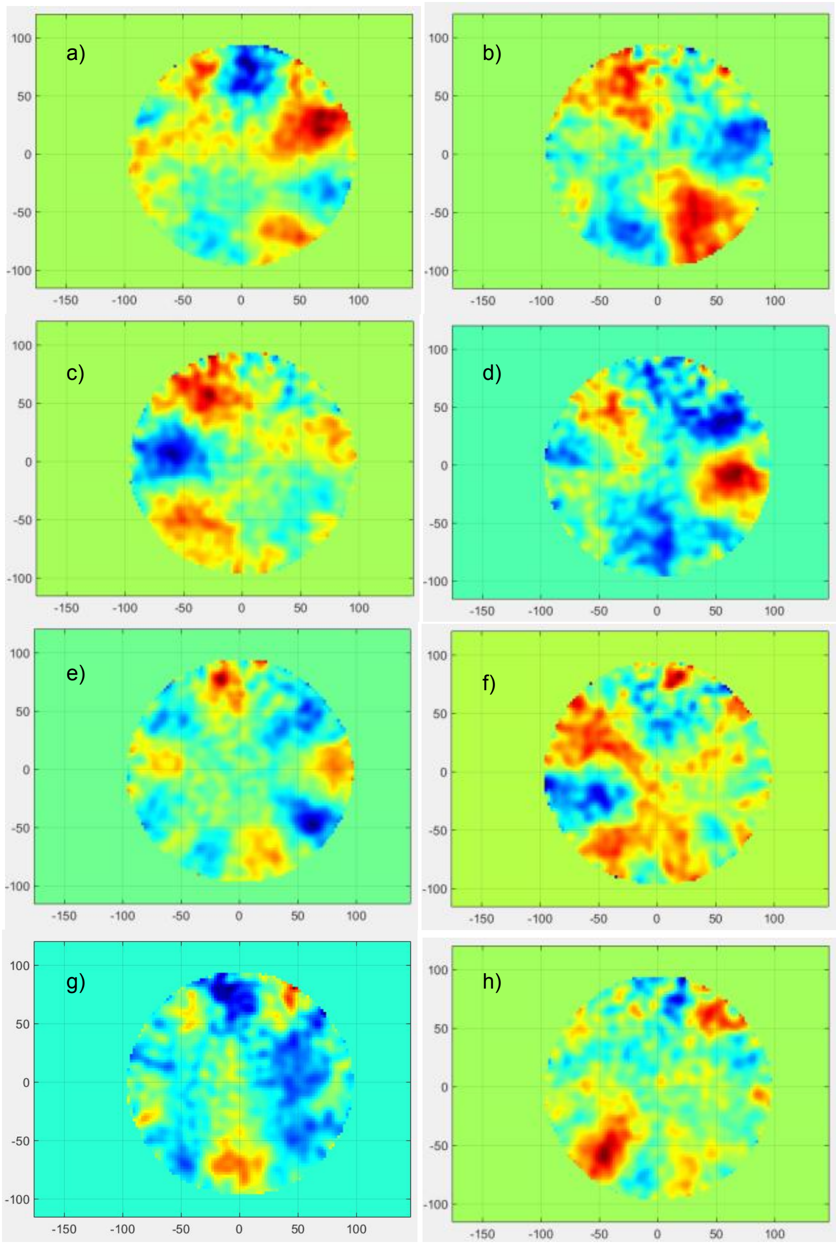


Figure 5: The first eight POD modes for $Re_b \approx 83000$. The colormap represents the streamwise velocity fluctuations, where red and blue represent positive and negative streamwise velocities, respectively: (a) Mode 1, (b) Mode 2, (c) Mode 3, (d) Mode 4, (e) Mode 5, (f) Mode 6, (g) Mode 7 and (h) Mode 8.

Scaled energy contribution of the first 100 sPOD modes for various Reynolds numbers has also been analyzed (Figure 6 and 7). These figures show the azimuthal mode energy for the first 15 POD eigenvalues where each columns represent the energy integrated over all frequencies normalized by the total energy. As seen in Figure 6 for $Re_b \approx 83.000$, the first POD and azimuthal mode numbers (n=1, m=1) and the first POD mode with the third azimuthal mode (n=1, m=3) are corresponding to a close energy content and associated with the most energy where a similar phenomena can be observed for $Re_b \approx 140.000$ (Figure 7).

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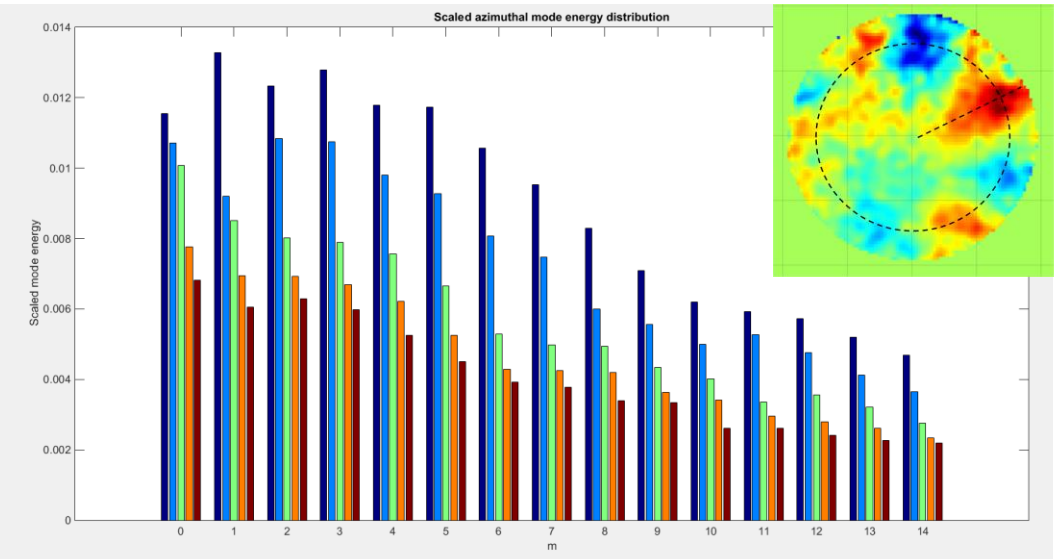

Figure 6: Scaled azimuthal energy distribution at $Re_b \approx 83000$, most energetic case: m=1, n=1.
Third azimuthal mode (m=3, n=1) is shown in contour plot.
(Columns stand for different n-modes: 1<n<4)

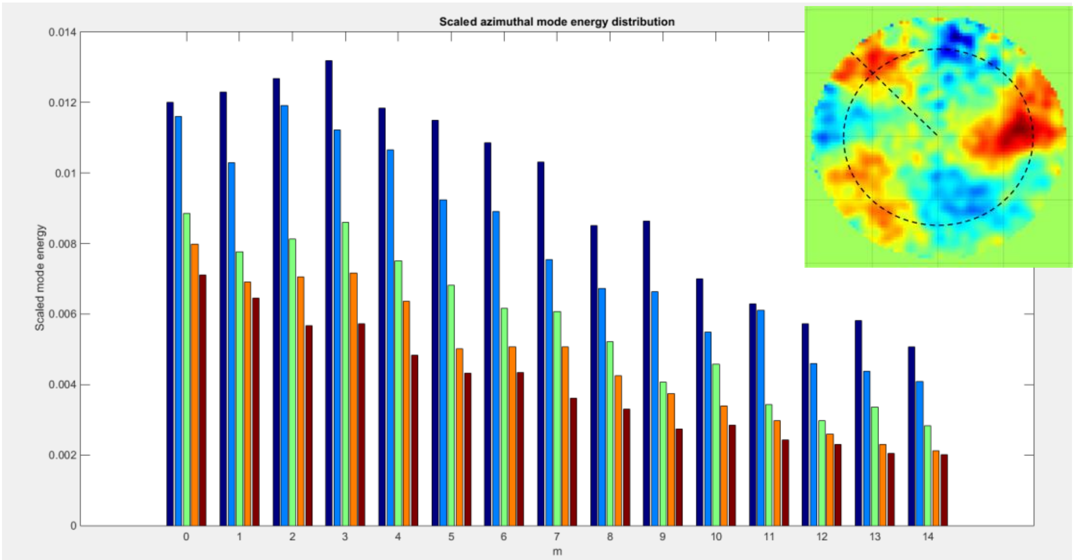

Figure 7: Scaled azimuthal energy distribution at $Re_b \approx 140000$, most energetic case: m=3, n=1.
(Columns stand for different n-modes: 1<n<4)

Acknowledgments

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