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A Large-Scale Experiment for the Visualization of Near-Wall Structures in Turbulent Pipe Flow Using Stereoscopic PIV

R. Jäckel[1], B. Owolabi[2,1], B. Magacho[2,1], L. Moriconi[2,1], D. J. C. Dennis[1], J. B. R. Loureiro[1]
[1]Interdisciplinary Center of Fluid Dynamics, Federal University of Rio de Janeiro,
Rio de Janeiro, Brazil.
jbrloureiro@mecanica.coppe.ufrj.br
[2]Instituto de Física, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Abstract **-** Turbulent pipe flow is still an essentially open area of research, boosted in the last two decades by considerable progress achieved both on the experimental and numerical frontiers, mainly related to the identification and characterization of near-wall structures and their possible roles in the statistical features of turbulent fluctuations. However, it has been a challenging task in particle image velocimetry due to various experimental constraints to visualize these structures. To address this issue, this paper presents the setup of a large-scale pipe experiment with a stereoscopic PIV system for flow field characterizations, which allows us to go deep in visualizing the turbulent boundary layer, down to the viscous sublayer, in conditions of fully developed turbulence. Flow measurements of Re = 4298 and Re = 24414 (based on the diameter) are performed. The measured streamwise velocity profiles show excellent agreement with data from the literature. We further detect a number of interesting and still barely understood structures of turbulent pipe flows, namely streamwise vortices and very large-scale motions (VSLMs) formed by long, meandering structures of high and low streamwise momentum, as well as coherent symmetry patterns of streamwise vortices alternating with sweeps and ejections.

Keywords**:** Stereoscopic PIV, Turbulent pipe flow, Streamwise vortices, VLSMs

1. Introduction

Turbulence in pipe flows has been a subject of utmost interest in fluid dynamics, since the very first pioneering experiments of Reynolds in 1883 [1]. A better understanding of its building blocks has been motivation for hot contemporary debates and the elaboration of improved experimental set-ups [2]. The near-wall production and complex dynamics of evolving coherent structures (turbulent puffs, quasi-streamwise and hairpin vortices, etc.) have been the fundamental keywords in these developments. It is clear, however, that a gap in the literature still persists, related to the visualization of near-wall coherent structures in pipe flows, in order to see how they can validate, refine or even suggest alternative perspectives to the ongoing scientific discussions. Here, we provide a first step toward closing this gap, exploring, with the help of particle image velocimetry, the zoo of near-wall structures associated with turbulent regimes in pipe flows. In this paper, we present the setup of a large-scale pipe experiment with a stereoscopic PIV (SPIV) system for flow field characterizations. A unique feature of this setup is the large pipe diameter (6 inches in diameter) which allows us to go deep in visualizing the turbulent boundary layer, down to the viscous sublayer, in conditions of fully developed turbulence. In the next section, we describe in detail the experimental setup. In Sec. 3, first, we validate our measurements by comparing the obtained mean flow profiles with well-established data from the literature. Then, we demonstrate the ability of our large-scape setup to visualize spatially well-resolved vortical structures and VLSMs in the near-wall region. Finally, in Sec. 4, we briefly summarize the key points of our work.

2. Experimental setup

This section presents a setup specially designed for the research on wall turbulence and near-wall structures. The flow loop consists of a horizontal 6-inch diameter, 10 meters long pipe, operating in a closed circuit. Water from a large reservoir is driven by a progressive cavity pump to a Coriolis flow meter before entering the pipe. A settling chamber consisting of a diffuser cone with a 6-degree angle and a 1:3 aspect ratio followed by a honeycomb and a set of screens was employed to reduce the turbulence intensity before the flow enters the rig. The visualization section is shown in Fig.1, showing the principal components by number; a time-resolved SPIV system using two high-speed CMOS cameras

(*Phantom M310)*, arranged horizontally at an angle of 45 degrees to the pipe centerline in order to capture a transversal plane of the flow. The water-filled trapezoidal section is used to minimize optical distortions caused by the pipe curvature. A two-level 15.4 cm diameter calibration target (Fig. 2), visible for each camera through the same angle of 45 degrees relative to the pipe, is located on the measurement plane to calibrate the SPIV system. The flow was seeded with silver-coated hollow glass spheres, 17 microns in size, to accurately follow turbulent fluctuations of the flow field. Estimating the hydrodynamic entrance length L_H for turbulent pipe flow in dependence of the Reynolds number Re (based on the diameter D) by means of eq. (1) [3]:

$$L_H = 1.359\,(\mathrm{D})\,Re^{\frac{1}{4}} \tag{1}$$

we expect the flow to be fully developed long before entering the observation section located at 5.8 meters downstream, namely after 2.61 meters for a flow of Re = 24400.

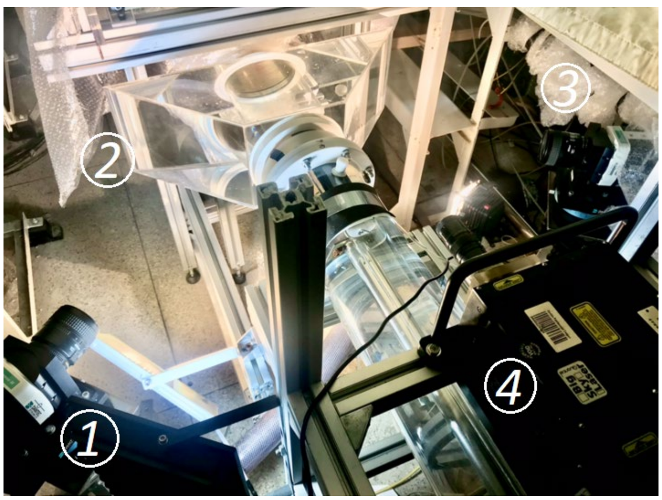

Fig. 1: Visualization section, numbers indicate the positions of cameras (1 & 3), Laser (4) and trapezoidal water-box (2).

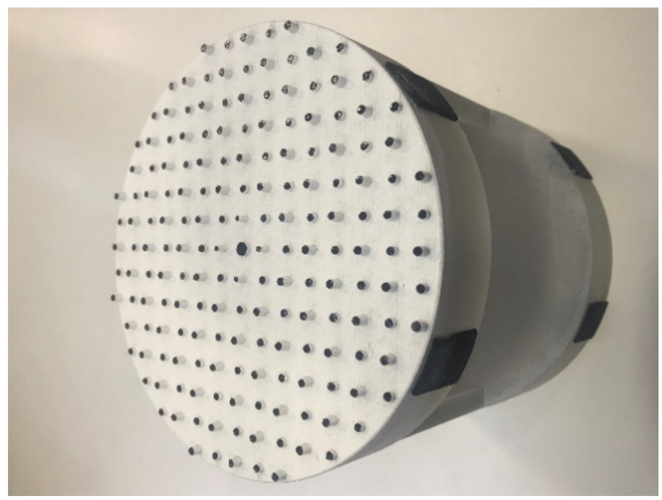

Fig 2.: Two-level calibration target used for the spatial calibration of the SPIV system, as seen by the right camera.

3. Results

3.1. Validation of turbulent statistics

In order to validate the experimental setup, water measurements of Re = 4298 and Re = 24414 are presented in this section, based on 10000 and 12000 vector field acquisitions, respectively. The results for the mean streamwise velocity profiles show excellent agreement with data from DenToonder & Nieuwstadt [4] and Eggels et al. [5], down to the viscous sublayer, as demonstrated in Fig. 3. Further, the profiles clearly resemble earlier observations of the Reynolds number effect [4], i.e. the Reynolds number dependence of the log region at low to moderate Reynolds number flows.

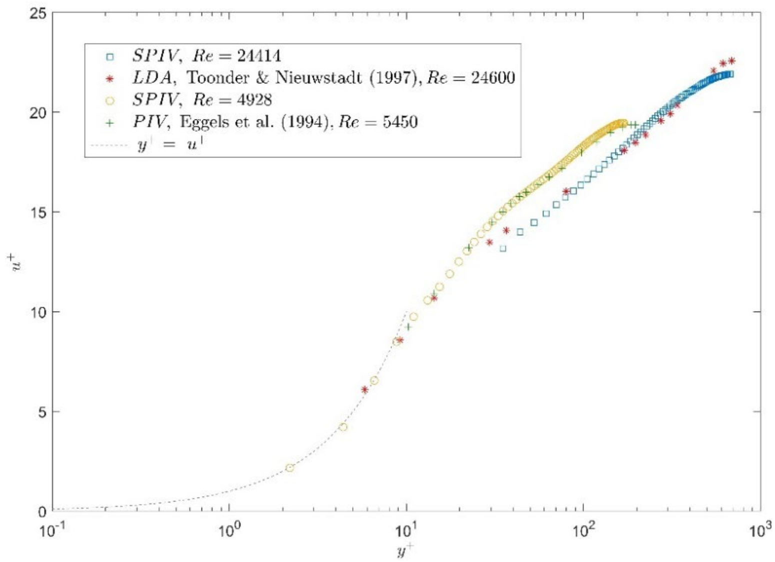

Fig. 3: Mean streamwise velocity profiles in inner units at Reynolds numbers of 4928 and 24414 obtained with SPIV, compared with the results of DenToonder & Nieuwstadt [4] and Eggels et al [5].

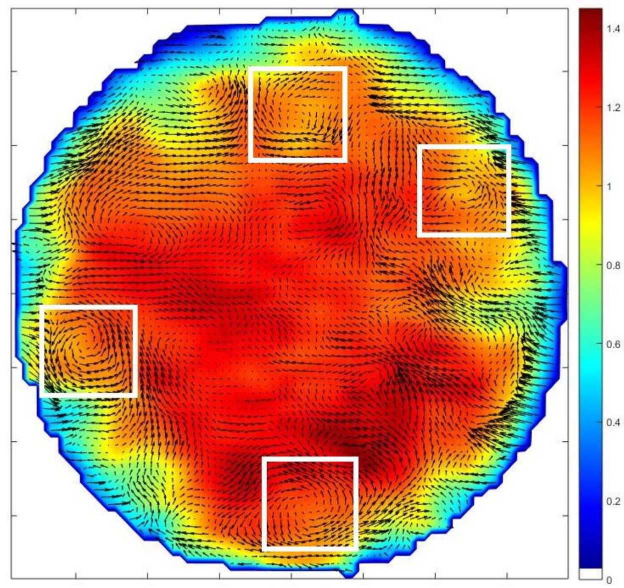

Fig. 4: Instantaneous vector field of Re = 24414 with highlighted streamwise vortices. Colors indicate the magnitude of the streamwise velocity component normalized by the bulk velocity.

3.2. Vortex structures

As demonstrated in Fig. 4, the large-scale pipe setup is well-suited for the visualization of the near-wall vortical structures in an instantaneous vector field with remarkable resolution. The presented flow field allows the identification of at least 4 streamwise vortices, highlighted in white squares. The colors indicate the magnitude of the streamwise velocity component normalized by the bulk velocity, which was derived from the flow meter.

3.2. Very Large Scale Motions (VLSMs)

To visualize the structures along the main stream direction Taylor's hypothesis of frozen turbulence was used to post-process the two-dimensional SPIV flow field data as done by Dennis and Nickels [6]. This method can be employed to obtain pseudo-3D velocity fields by converting temporal experimental measurements into a spatial domain, as illustrated in Fig. 5. By plotting the isocontounters for velocities above 1.1 and below 0.9 times the local mean velocity magnitude along a streamwise-circumferential plane, it is possible to visualize VLSMs in form of meandering structures of streaks associated to high and low streamwise momentum. From Fig. 5, a long high-speed streak that extends over 3 pipe radii can be clearly identified.

3.3. Detection of coherent organizational states

By applying an azimuthal correlation function hoovering along the circumference at a reference radius with respect to a fixed reference point (both at $r_0 = 0.78R$) in order to correlate for positive and negative streamwise velocity fluctuations, we were able to detect 10 coherent symmetry patterns (1-fold up to 10-fold symmetries) of alternating high and low-speed streaks for both Reynolds numbers. Ensemble averaging the associated in-plane vector fields for each of these modes, we found symmetry patterns of ejections and sweeps (Q_2- Q_4 quadrant motions) together with well-defined streamwise vortices alternating along the pipe azimuth.

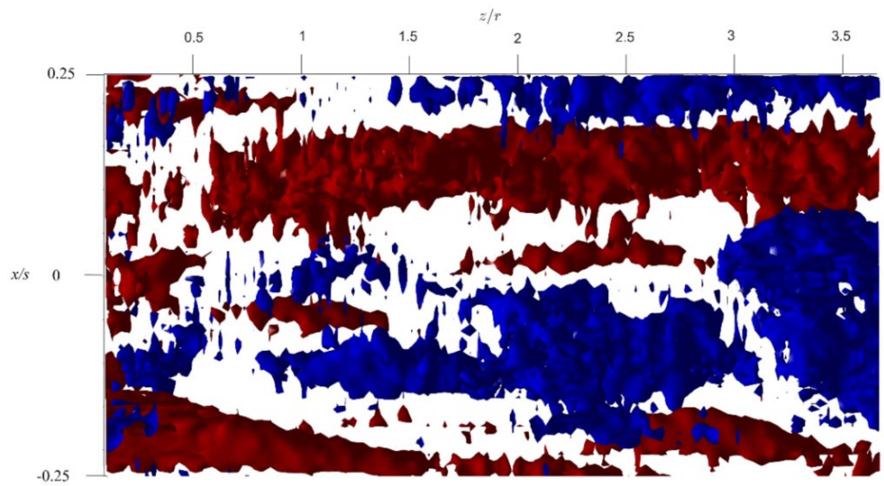

Fig. 5: Velocity fluctuations along the mean flow direction (flow from left to right) obtained at Re = 4928, where the red isocontours show velocities above 1.1 times the local U_{mean} (the turbulent U profile of all acquisitions), while the blue isocontours represent velocities below 0.9 times the local U_{mean}.

4. Conclusions

A customized 6-inch diameter pipe flow loop has been presented to investigate a number of interesting open issues in the physics of turbulent pipe flows, related to the organization of near-wall structures. The measured mean velocity profiles resemble data from literature closely. It was shown that the SPIV system is suitable to visualize in-plane vortex structures and VLSMs with high resolution in the near-wall region. Further, we detected 10 coherent symmetry states (1-fold up to 10-fold symmetries) using an azimuthal correlation function, showing patterns of streamwise vortices alternating with sweeps and ejections. The presented setup will be able to provide experimental data covering regions of the flow so far unexplored, providing relevant information to close the gaps in phenomenological understanding of the laminar-turbulent transition and fully developed turbulent flow.

Acknowledgements

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