ERCOFTAC
European Drag Reduction and Flow Control Meeting – EDRFCM 2024
September 10^{th}–13^{th}, 2024, Turin, Italy

TURBULENT CHANNEL FLOW – A MEASUREMENT TECHNIQUE COMPARISON

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INTRODUCTION

The evaluation of drag reduction in internal flows in experimental set-ups either relies on global pressure drop measurements or on the direct measurement of the wall-shear stress. The latter allows to asses local wall shear stress information, which is particularly interesting for control approaches, where the control effort results in spatially non-uniform near-wall flow conditions. Direct measurements of the skin friction can rely on oil-film interferometry on smooth wall surfaces, which can, however, not be applied in many control scenarios including riblets or plasma-based actuation. In addition, the drag behaviour in non-equilibrium flow conditions is of interest such that a direct evaluation of the skin friction drag is required, since no fitting of the measurement data to a generic velocity profile (which requires outer layer similarity) is applicable.

A variety of techniques exists, that allow the direct measurement of the wall shear stress (cp. [8]). In general, this resorts to a determination of the near-wall mean velocity gradient and the dynamic viscosity. Due to the small spatial scales of near-wall velocity gradients high spatial resolution and the determination of the wall location are of utter importance. In the present contribution we focus on optical measurement methods. For those techniques, a precise localisation of the wall is a non-straightforward, but often an iterative process, where different means exist – from the reflections within the raw data image to the shifting of the extracted velocity profile.

We aim at identifying the measurement technique that enables the best assessment of skin-friction drag along with (possibly simultaneous) flow field measurements across the entire channel flow. To asses the measurement quality in a turbulent channel flow while excluding the challenge of the correct wall localisation, the diagnostic plot introduced by Alfredsson and Örlü [1] is employed. The present contribution takes the findings of several optical measurements conducted at the turbulent channel measurement facility located at ISTM in Karlsruhe and compares them to each other, regarding their suitability and practicability, the retrieved findings and their costs in terms of time and money. The techniques under consideration are *Stereo Particle Image Velocimetry* (Stereo-PIV), *Laser Doppler Velocity Profile Sensor* (LDV-PS), *Defocusing Particle Tracking Velocimetry* (DPTV) and Lagrangian Particle Tracking measurements with the *Shake-the-Box* (STB) method.

EXPERIMENTAL SET-UP AND METHODOLOGY

Figure 1 shows the experimental facility with physical dimensions, where all four measurements techniques came into operation. The coordinate x serves as streamwise direction, while y represents the wall-normal coordinate. The channel dimensions are set to a height H of 25.2 mm (semi channel height $h = 12.6$ mm), a width w of 300 mm and an entire length of 4000 mm. As test case a low Reynolds number is chosen, for the possibility to compare with numerical data and to receive a viscous length scale with a certain acceptable spatial extent. As centerline velocity a value of $U_{\text{cl}} = 8.4$ m/s is chosen, which corresponds to a channel Reynolds number $Re_{\text{cl}} = U_{\text{cl}}h/\nu \approx 7,000$. The viscous scaling could be quantified with the velocity $u_\tau = \sqrt{\tau_{\text{w}}/\rho} = 0.42$ m/s and a friction Reynolds number of $Re_\tau \approx 350$. The viscous length scale δ_ν can consequently be stated as $\sqrt{\nu/u_\tau} = 36\,\mu$m. Given by these parameters we expect a viscous region to be located within the first half millimetre of the wall distance.

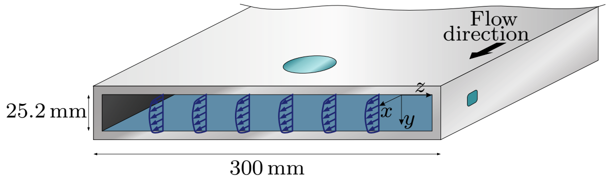

Figure 1: Sketch of the experimental facility with the used coordinate system $\{x, y, z\}$, the physical dimensions and optical accesses.

A window in the top plate with an open diameter of 90 mm, serves as access for the cameras and the LDV-laser, while a window on the side acts as entrance for the laser during PIV and STB measurements. For the Stereo-PIV measurements the cameras were positioned close to the outlet. As seeding fluids di-ethyl-hexyl-sebacate (DEHS) and PIV-light are used, which both lead to a typical droplet diameter in the range of $\approx 1\,\mu$m. A summary of the technical equipment used for the different experimental campaigns is given in Table 1.

Meas. technique	Equipment
Stereo-PIV [2]	2 × *Photron* SA4 cameras, *Quantronix Darwin Duo* high-speed Laser
LDV-PS [6, 7]	ILA R&D LDV-PS system with Bragg-shift
DPTV [4]	1 × *PCO Edge* 5.5 camera, *Quantel Evergreen* laser
STB [3]	4 × *Phantom* v1840 camera, *Photonics Industries* high speed laser (DM2-100-532-DH)

Table 1: Overview of the different techniques and the employed equipment used for the present comparison. When data were already published, the related reference is cited.

RESULTS

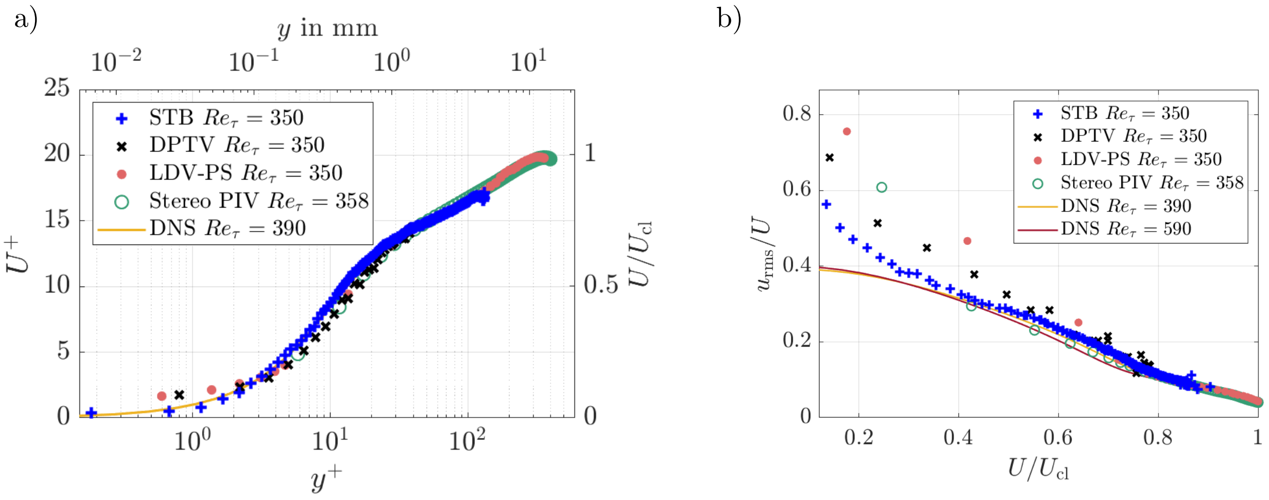

Figure 2: Experimental results: a) ensemble-averaged velocity distribution converted in viscous units with additional physical coordinates on the upper and right axes. b) Diagnostic plot for all compared techniques of ensemble-averaged velocity profiles shown in 2a) and two direct numerical simulations (DNS) [5] as reference.

Figure 2 shows the mean velocity in stream-wise direction u over the wall distance y with a viscous unit normalisation and a diagnostic plot, where the local stream-wise velocity u is normalised with the centerline velocity U_cl on the abscissa and the root mean square (rms) of the fluctuations is normalised with the local stream-wise velocity u on the ordinate. Figure 2a) shows that all measurement techniques are able to properly depict the mean flow in viscous units. The achieved plus-unit range of the results demonstrate a general applicability of all considered techniques, since both the logarithmic layer and – at least partially – the viscous sublayer of the turbulent channel flow could be resolved in terms of spatial extent. The STB-technique, due to the large amount of samples, is able to depict statistically-converged data for values of $y^+ = 1$. For the Stereo-PIV measurements the closest spatial point is at $y^+ = 5$, caused by the interrogation-window size, but the technique is able to depict the entire half-channel, including a precise determination of the centerline velocity U_cl. Figure 2b) reveals the quality of a precise estimation of the fluctuating movement in a statistical sense. Below $U/U_\mathrm{cl} < 0.4$ the results of all experimental techniques reveal an (artificially) increased rms-level, which is caused by an increased contribution of measurement uncertainty close to the wall. The STB-results start to deviate significantly at $U/U_\mathrm{cl} < 0.25$. The DPTV-results show an overall slightly increased fluctuating level, which might be accounted for with a finer ensemble-averaging.

The LDV-PS results show velocity-dependent uncertainties, which become particularly noticeable in proximity of the wall where the velocity is low, as already discussed in detail by [7]. This leads in consequence to an comparably early deviation from the DNS data set.

These observations and limitations consequently deserve further investigation so as to uncover their origin and consequences for the evaluation of turbulent channel flows. The presentation will include more detailed data close to the wall to bring these data sets in relation to underlying physical phenomena. Furthermore, a detailed analysis of additionally acquired information for each technique will be given.

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