TURBULENT PIPE FLOW: NEW DNS DATA AND LARGE-SCALE STRUCTURES

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Abstract Large-scale fully resolved direct numerical simulations (DNSs) have been performed with a high-order spectral element method to study the flow of an incompressible viscous fluid in a smooth circular pipe of radius R and axial length $25R$ in the turbulent flow regime at four different friction Reynolds numbers $Re_\tau = 180, 360, 550$ and 1000. The new data is compared to other simulation data sets, obtained in pipe, channel and boundary-layer geometry. The pressure is the variable that differs the most between the cases; a significantly higher mean and fluctuating pressure are observed in boundary layers that is linked to a stronger wake region. Critical assessment of the available DNS data is conducted in order to determine which difference or correspondence between the data sets are real and caused by physics, and which discrepancies are likely due to statistical or numerical inaccuracies. Furthermore, two-dimensional spectra of axial/streamwise velocity show an imprint of the large-scale motions from the outer layer in all canonical flows, however with different amplitude.

INTRODUCTION

In the past years, there have been a multitude of studies aiming at understanding the physical processes in the canonical wall-bounded flows, *i.e.* the fully developed turbulent channel and pipe flow as well as the zero-pressure-gradient (ZPG) turbulent boundary layer (TBL). Although considerable progress has been achieved in this context, there are still many open questions that relate to the similarities and differences between these flow cases. In terms of pressure, the variation with the Reynolds number of the pressure fluctuations in the buffer layer and at the wall is similar between pipes and channels, but lower than that in boundary layers whereas in the wake region the pressure fluctuations and mean axial velocity turn out to be strongest in boundary layers, due to the intermittency between the potential and rotational flow regions, followed by pipes and then channels. For internal flows, it may be that the characteristic curved nature of the pipe, where the circumferential length decreases as the centre is approached, results in this difference with channels and subsequently induces the observed discrepancies in the wake. Other questions concern the large-scale structures and how much are these structures are similar and different between the three flow cases. According to recent experimental studies, very large-scale motions with lengths of $5R$ up to $20R$ have been found in the outer region of fully developed turbulent pipe flow [1]. These structures, being strongest in the outer region, even extend throughout the layer and leave their footprint quite close to the wall and in the log layer ([2, 3]). Very long meandering structures have also been observed in turbulent boundary layer flows and channel flows ([4, 5]). However, there seem to be important differences between the large-scale structures observed in these three cases not only in the outer layer but also in the near-wall region.
In the present study, well-resolved DNSs of turbulent pipe flow have been performed using the spectral element method implemented in `nek5000`. The grid spacing, measured in wall units, is set such that $\Delta r^+_{max} \leq 5$, $\Delta R\theta^+_{max} \leq 5$ and $\Delta z^+_{max} \leq 10$. The largest DNS is being run on about 2.2 billion grid points. Additionally, we rely on in-house as well as literature data on turbulent channel and pipe flows for comparisons [4, 6, 7, 8].

RESULTS

DNS data of turbulent boundary layers have been assessed extensively by Schlatter & Örlü (2010) [9] who highlighted systematic differences between these data sets by calculating, among other quantities, the deviation of the mean streamwise velocity profile from the modified Musker profile. This deviation is displayed in figure $1(a)$ for pipes, channels and boundary layers at $Re_\tau \approx 1000$. The three canonical wall-bounded flows show a rather different behaviour. While the data for channel from [4] and [6] are in very good mutual agreement, the three pipe-flow data sets are surprisingly different from each other; in particular clear negative values close to the wall are only visible in the data set by [7]. This comparison suggests that there are some non-physical discrepancies between the various pipe flow data sets, which should be investigated in more detail. The log-law indicator function $\Xi = y^+ \mathrm{d}U_z^+/\mathrm{d}y^+$, evaluated at $Re_\tau \approx 1000$ is shown in figure $1(b)$. It is apparent that in the near-wall region up to about $y^+ \approx 30$ the curves pertaining to the various flow cases (pipe, channel, boundary layers) agree very well. Only upon reaching the first minimum (maximum in $1/\Xi$ at $y^+ \approx 70$) the pipe flow data appears to be slightly lower, $\Xi = 2.33$, compared to channels and boundary layers, $\Xi = 2.30$ and 2.28; this small but systematic difference is thought to be genuine and not an effect of limited sampling.
The two-dimensional axial/streamwise pre-multiplied spectra in the near-wall region are shown in figure $2(a)$ for the present pipe DNSs at $Re_\tau = 180, 550$ and 1000 and in figure $2(b)$ at $Re_\tau = 550$ together with channel DNS data from [4] at the same Re. It can be observed from these two panels that, as expected, the location of the inner peak, measured in wall units, is independent of the Reynolds number and geometrical configuration. This peak occurs at an axial/streamwise wavelength that is located around 1000, and a spanwise wavelength of 100 corresponding the the spanwise periodicity of streaks. By examining the spectra further, it can be seen that the contours from all the Re_τ cases considered collapse

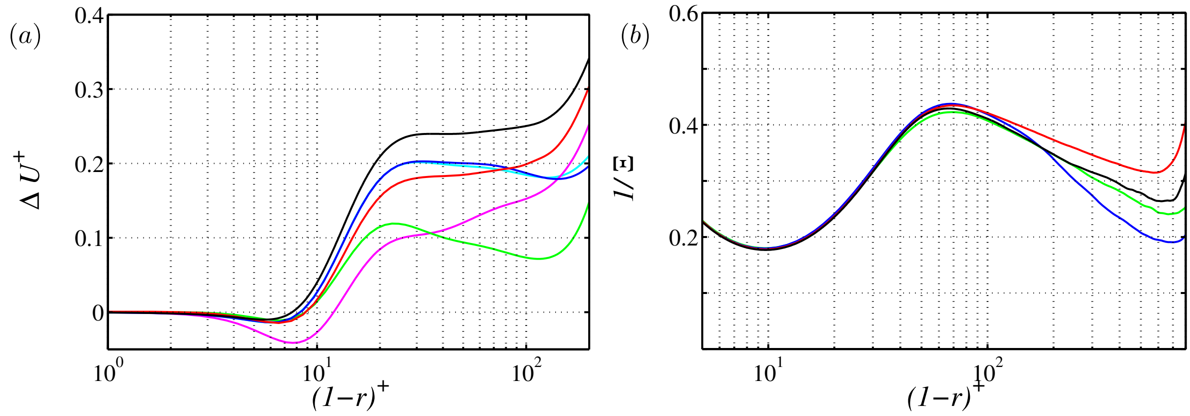

Figure 1. (a) Deviation ΔU^+ of the mean velocity profile from the modified Musker profile as a function of $(1-r)^+$. ——, Present pipe; ——, pipe, [8] ; ——, channel, [6] ; ——, boundary layer, [9] ——, pipe, [7] ; ——, channel, [4] . (b) Log-law indicator function $1/\Xi$ as a function of $(1-r)^+$ for wall-bounded flows. ——, Present pipe; ——, channel, [6]; ——, boundary layer, [9] ——, pipe, [7].

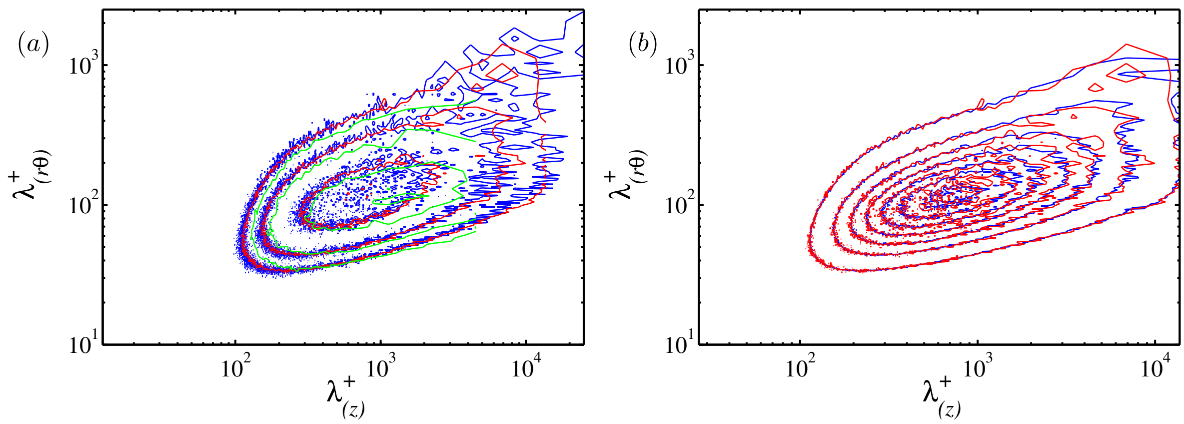

Figure 2. Pre-multiplied two-dimensional spectra at $(1-r)^+ = 15$. (a) Present pipe flow DNS: $Re_\tau = 1000$; $Re_\tau = 550$; $Re_\tau = 180$. (b) $Re_\tau = 550$: present pipe; channel, [4].

well apart from $Re_\tau = 180$ which can be attributed to a low Re effect. It is worthwhile to note that the two-dimensional spectra at $Re_\tau = 180$ are similar for pipes and channels (not shown here). The outer peak is observed at high wavelength in the spectrum for $Re_\tau = 500, 1000$, but appears to be stronger for the pipe than for the channel. The amplitude for the boundary layer will be added as well.

In the final paper we intend to perform a more detailed comparisons between the three canonical wall-bounded flows with a focus on the pressure statistics and wake parameters. In addition, we will quantify the spectral composition of the three canonical flows at the various Reynolds numbers in an effort to deduce Re-trends for the various cases. Inner-outer interaction and amplitude modulation shall also be considered and compared.

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