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Direct numerical simulation of a turbulent Couette–Poiseuille flow: Turbulent statistics

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ABSTRACT

The direct numerical simulation of a fully developed turbulent Couette–Poiseuille flow is performed to investigate the modification of turbulent statistics on the bottom and top walls compared to those in a pure Poiseuille flow. The streamwise mean velocity profile shows that an extended logarithmic layer for a Couette–Poiseuille flow is developed from each wall to the centerline. In addition, the turbulent intensities and Reynolds shear stress on the bottom wall are found to be larger than those in the Poiseuille flow, whereas it is reversed on the top wall due to reduction of the velocity shear. The quadrant analysis of the Reynolds shear stress reveals that large Q2 and Q4 event motions are continuously created throughout the entire flow near the centerline, leading to active momentum transport between the bottom and top walls for the C-type. Inspection of the pre-multiplied streamwise and spanwise energy spectra shows that distinct secondary outer peaks are created for all velocity components and a plateau, called the k_x^{-1} region, is presented in the logarithmic region. Based on an analysis of the net force spectra, three spectral ranges in the wavelength space, corresponding to small- ($\lambda_x/\delta \le 1$), large- ($1 \le \lambda_x/\delta \le 10$) and very-large-scale ($\lambda_x/\delta \ge 10$) motions for a Couette–Poiseuille flow, are proposed, and very-large-scale structures are highly energetic and contribute more than half of the streamwise turbulent kinetic energy and Reynolds shear stress, where λ_x is the streamwise wavelength and δ is the channel half height.

1. Introduction

For several decades, turbulent Couette flows or Couette–Poiseuille flows have received much attention in the area of fluid mechanics because such flows are present whenever a wall moves toward the flow direction (e.g., turbulent bearing films). These flows are known to be beneficial because they show more efficient diffusion, less resistance, and greater turbulence kinetic energy than Poiseuille flows (Orlandi et al., 2015).

Many important features of turbulent statistics in turbulent plane Couette flows have been clarified thus far (Tillmark and Alfredsson 1998; Tsukahara et al., 2006; Kitoh and Umeki 2008; Avsarkisov et al., 2014; Pirozzoli et al., 2014; Orlandi et al., 2015; Lee and Moser 2018). In general, the maximum mean streamwise velocity was shifted from the channel centerline to the upper moving wall due to the moving wall condition at the top (Tsukahara et al., 2006). In addition, the mean streamwise velocity profile of the Couette flow had a non-zero mean velocity gradient in the channel centerline. Although a minor difference in the turbulent intensities and the Reynolds shear stress between Couette and Poiseuille flows was reported near the wall, those of the Couette flows were significantly increased in the channel centerline (Tillmark and Alfredsson 1998; Komminaho et al., 1996). Recently, Avsarkisov et al. (2014), Pirozzoli et al. (2014) and Lee and Moser (2018) examined the Reynolds number dependency of turbulent statistics in Couette flows. They found that turbulent intensities in the outer layer are noticeably different as the Reynolds number increases (Re_τ = 125–986) due to the increased large-scale energy imparted to the near-wall region, similar to the trends in Poiseuille flows (Hoyas and Jiménez 2006; Bernardini et al., 2014). Based on DNS data over a very wide range of Reynolds numbers for Poiseuille and Couette flows, Orlandi et al. (2015) showed that friction coefficient and overall kinetic energy decrease for both Poiseuille and Couette flows with an increase of the Reynolds number. Furthermore, they found that the near-wall region where most energy production is created is more important in Poiseuille flows than in Couette flows due to the large cumulative kinetic energy distribution in the outer region of the Couette flow. Pirozzoli et al. (2011) concluded that Couette flows can provide further evidence with which to understand the inner and outer layer interactions in Poiseuille flows, as the characteristics of low Reynolds number Couette flows appear to be similar to those of high Reynolds number

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Poiseuille flows.

In turbulent plane Couette flows, study of coherent structures, especially very long high- and low-speed streaks in the core region, has been actively performed thus far (Komminaho et al., 1996; Tsukahara et al., 2006; Avsarkisov et al., 2014; Pirozzoli et al., 2014; Lee and Moser 2018). Based on an energy spectrum analysis, Komminaho et al. (1996) found a prominent low-frequency peak associated with very large structures in a DNS study. In addition, they showed that the streamwise correlations for Couette flows increase continuously up to the channel centerline from the wall, whereas those in Poiseuille flows decrease above the logarithmic region. In a DNS study of turbulent Couette flows at $Re_\tau = 252$, Tsukahara et al. (2006) found that an outer peak occurs at a wavelength range of $\lambda_x/\delta \approx 40$–$60$ in the channel centerline using the pre-multiplied one-dimensional (1-D) energy spectra of the streamwise velocity fluctuations. Furthermore, they showed that low-speed near-wall streaks in an instantaneous field are clustered beneath low-speed large-scale structures near the centerline. Avsarkisov et al. (2014) reported that the longest structures in the channel centerline appear to be organized in the form of counter-rotating pairs of rolls with high vorticity. Pirozzoli et al. (2014) showed that a secondary outer peak which emerges at the pre-multiplied spanwise energy spectra of the streamwise velocity fluctuations is closely associated with the considerable excess turbulent production responsible for the formation of long streaky structures and roll modes, although they were not able to confirm an outer peak in the streamwise energy spectra due to the relatively short streamwise domain. Pirozzoli et al. (2014) suggested that the core flow is mainly organized into ‘towering eddies’, which are attached to both walls. Finally, Lee and Moser (2018) reported that the large-scale vortices have much greater streamwise coherence length with an increase of the Reynolds number.

In addition to the studies for pure Couette flows, significant efforts to the study of turbulent Couette–Poiseuille flows have been performed thus far (Kuroda et al. 1993; Thurlow and Klewicki 2000; Nakabayashi et al., 2004), because an additional degree of freedom (moving wall) in Poiseuille flow allows not only study of possible dynamic effects of mean shear rate on near-wall turbulence but also more complete understanding for generation of coherent structures with interaction between inner and outer layers. El Telbany and Reynolds (1980) performed experimental measurements of the velocity in turbulent Couette–Poiseuille flows to achieve universal scaling of the velocity fluctuations and showed the moderate success of scaling using the local total shear stress in the core region. Furthermore, based on an experimental study of fully developed turbulent plane Couette–Poiseuille flow, Thurlow and Klewicki (2000) found that the fluid momentum exchange between the top and bottom walls increases when one of the walls is put into motion, because active motions originating from the high stress wall convect towards the low stress wall. Recently, Pirozzoli et al. (2011) performed DNSs of turbulent Couette–Poiseuille flows by gradually increasing the top wall velocity in Poiseuille flow to the flow direction. When the ratio of the shear stress at the two walls becomes approximately 1 (i.e., Couette-like flow), they showed that turbulent production and dissipation terms in the kinetic energy budget are much larger than those of Poiseuille flows near the channel centerline. In addition, they found the occurrence of streaky patterns of spanwise alternating high and low momentum with 50 to 100 local viscous units in the channel centerline and that the channel centerline velocity has a strong modulating influence on both the stationary and moving walls, implying an imprint imparted by large-scale events in the channel centerline onto the near-wall motions.

In the present study, the DNS of a turbulent Couette–Poiseuille flow with a very long domain size is conducted to examine the modification of the turbulent statistics both on the bottom and top walls compared to those in a pure Poiseuille flow. All of the parameters to achieve the turbulent Couette–Poiseuille flow, such as the moving wall velocity and Reynolds number, are identical to those from the previous study of Pirozzoli et al. (2011). We first analyze one-point statistics of the mean velocity, mean velocity shear, turbulent intensities and Reynolds shear stress, and we discuss difference of the quantities on the bottom and top walls compared to those in the Poiseuille flow. Next, we examine energy spectra maps of the velocity fluctuations throughout the entire wall layer for understanding complete energy distribution with respect to the wavenumber. Although large-scale and very-large-scale structures are quite important with respect to turbulent quantities such as turbulent kinetic energy and Reynolds shear stress in Poiseuille flow (Guala et al., 2006; Balakumar and Adrian 2007), much less is known about energy contribution from different scales in Couette–Poiseuille flow. This work focuses on determining the contribution of large-scale and very-large-scale motions to the kinetic energy and most importantly to the Reynolds shear stress in the outer region of Couette–-Poiseuille flow. For the purpose of the present discussion, it is convenient to define large-scale motions (LSMs) as streamwise wavelengths up to 10δ and define very-large-scale motions (VLSMs) as longer wavelengths for a Couette–Poiseuille flow based on the net force spectra (Section 3.2), similar to the method of Guala et al. (2006), Chin et al. (2014) and Hwang et al. (2016) in a pure Poiseuille flow. Furthermore, motions with wavelengths less than 1δ are defined as small-scale motions (Mathis et al., 2009). It should be noted that although this criterion is nominal, it may be subject to change in light of future findings.

2. Numerical method

For an incompressible flow, the non-dimensional governing equations are

$$\begin{aligned} \frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} &= -\frac{\partial \tilde{p}}{\partial x_i} + \frac{1}{Re_{c,o}} \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} \quad and \\ \frac{\partial \tilde{u}_i}{\partial x_i} &= 0, \end{aligned} \tag{2.1}$$

where x_i denotes the Cartesian coordinates and $\tilde{u}_i$ represents the corresponding velocity components. The notation adopted is such that x, y, and z denote the streamwise, wall-normal, and spanwise coordinates, respectively, and that $\tilde{u}$, $\tilde{v}$ and $\tilde{w}$ denote the corresponding velocity components. All variables are normalized by the laminar channel centerline velocity (U_{co}) and the channel half height (δ). The governing equations are integrated over time using the fractional step method along with the implicit velocity decoupling procedure (Kim et al., 2002). A block LU decomposition based on approximate factorization is applied to achieve both velocity-pressure decoupling and the decoupling of the intermediate velocity components. In this approach, the terms are initially discretized in time using the Crank-Nicholson method, and then the coupled velocity components are solved without iteration. All terms are resolved using a second-order central difference scheme in space with a staggered mesh. The mean pressure gradient is dynamically adjusted to maintain a constant mass flow rate.

Fig. 1 shows a schematic of the computational domain for a turbulent plane Couette–Poiseuille flow. Note that the wall-normal (vertical) coordinate y is measured from the bottom wall ($0 \le y/\delta \le 2$). The bottom wall ($y/\delta = 0$) is stationary with $\tilde{u}_S/U_{co} = 0$ and the top wall at $y/\delta = 2$ moves along the streamwise direction by forcing a constant value $\tilde{u}_M/U_{co} = 1.3$, consistent with that of Pirozzoli et al. (2011) for a turbulent Couette–Poiseuille flow. The ratio of the shear stress on the bottom wall to that on the top wall is 0.98, i.e., Couette-like flow. The subscripts ‘S’ and ‘M’ indicate the stationary wall and the moving wall, respectively. The velocities at both walls are set to zero in the wall-normal and spanwise directions. The computational domain sizes, mesh resolutions and flow parameters for pure Poiseuille and Couette–Poiseuille flows are summarized in Table 1, where P-type and C-type indicate Poiseuille flows and Couette–Poiseuille flows, respectively. The streamwise and spanwise domains adopted here are sufficiently long because a previous numerical study by Tsukahara et al. (2006)