COMPARISON OF TURBULENT PIPE AND BOUNDARY LAYER FLOWS

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Summary Results from direct numerical simulation of a turbulent pipe flow at Re_D=35000 showed that very long meandering motions exceeding 30R exist in the pipe flow and the streamwise length scale of the structures is increased up to y/R~0.3, while the structures in boundary layer increase up to the edge of the log layer. In addition, it was found that strong swirling motions is more frequently observed in the pipe flow, and this strong swirl is related to the increase of the streamwise length scale in the pipe flow.

RESULTS AND DISCUSSION

Many experimental and numerical studies have shown that large- and very large-scale motions (LSMs and VLSMs) in the logarithmic layer play a crucial role in the turbulent boundary layer (Adrian 2007; Marusic *et al*. 2010). The spatial feature of the very large-scale structures is known as the regime of very long meandering positive and negative streamwise velocity fluctuations and these structures have streamwise length of O (20δ), as described in Hutchins & Marusic (2007). In a DNS study, Lee & Sung (2011) showed that in the log layer, patches with the length greater than 3~4δ account for more than 40% of all the patches and these VLSMs contribute approximately 45% of the total Reynolds shear stress included in all the patches. In addition, they showed that adjacent packet-type structures combine to form the VLSMs via continuous stretching of the hairpins coupled with lifting-up and backward curling of the vortices.

As well as being found in the log and wake regions of the turbulent boundary layer, these structures are also found in pipe and channel flows, while there are some structural differences (Monty *et al.* 2007; Bailey *et al.* 2008). Monty *et al.* (2007) examined the structures of fully developed turbulent pipe and channel flows using hot-wire probes and showed that the very long meandering structures of length up to 25 pipe radii (R) or channel half-height (h) exist in the logarithmic layers of the internal flows and for channel flow, these structures persist at least until y/h=0.56. However, the validity of Taylor's hypothesis to convert temporal to spatial data remains a cause for concern, since its accuracy of Taylor's hypothesis is decreased as the apparent structure size is increased. In addition, although Monty *et al.* (2007) and Bailey *et al*. (2008) showed that the spanwise width scales of the pipe and channel flows based on the two-point correlation of the streamwise velocity fluctuations are approximately twice larger than that observed in the logarithmic layer of the boundary layer, there remains lacking of the streamwise information due to the experimental difficulties to measure the streamwise extent of the structures that are very long with the order of 8~16δ in the turbulent pipe flow.

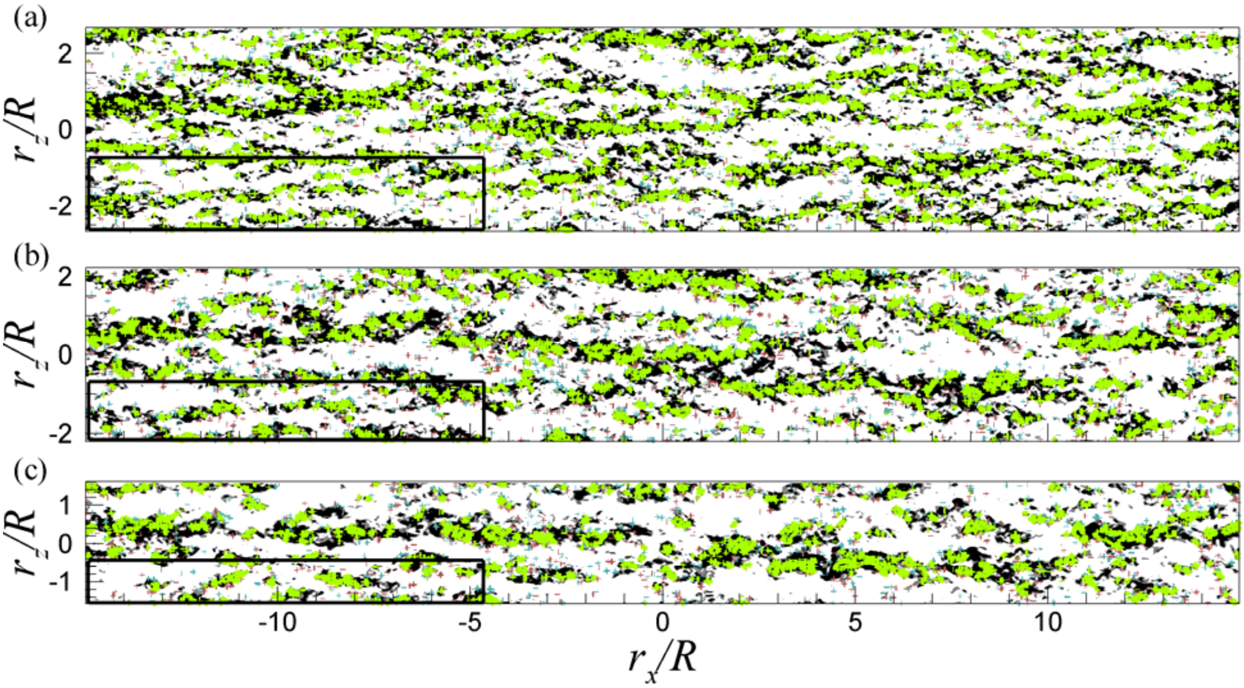

Figure 1. Very large low-momentum regions with 2D signed swirling strength ($\Lambda_{ci}=\lambda_{ci}\omega_x/|\omega_x|$) and second-quadrant Reynolds shear stress. (a) y/R=0.15, (b) y/R =0.3 and (c) y/R =0.5. Blue and red contours indicate the positive and negative Λ_{ci} with magnitude of 30% maximum and minimum values and luminous contour indicates Q2 event with magnitude $5\overline{-uv^+}$.

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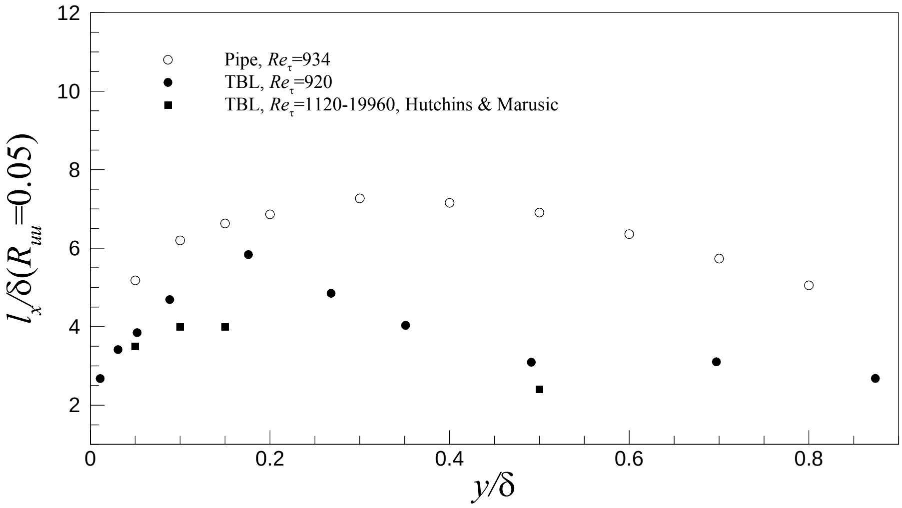

Figure 2. Variation of the characteristic streamwise length scale based on the streamwise two-point correlation R_{uu}=0.05.

In the present study, DNS of a fully-developed turbulent pipe flow at Re_τ=934 were conducted to investigate the spatially coherent structures associated with VLSMs, compared to boundary layer data (Lee & Sung 2011). Figure 1 shows the very large-scale low-momentum regions with signed 2D swirling strength ($\Lambda_{ci}=\lambda_{ci}\omega_x/|\omega_x|$) and second-quadrant Reynolds shear stresses (u<0, v>0; Q2 events). The wall-normal heights considered are y/R=0.15, 0.3 and 0.5 and black contour indicates the low-momentum regions with u^+=-0.5. In figure 1(a), it is shown that the large- and very large-scale streamwise-aligned structures are populated in the logarithmic layer and these structures are closely associated with the strong swirling strength and Q2 Reynolds shear stress, indicating that the long structures are created by the coherent alignment of the groups of the hairpin vortices: counter-clockwise vortices (red) appear on the right of the low-speed region and clockwise vortices (blue) appear on the left. What is quite distinctive feature compared to the boundary layer is that these structures continuously grow up to y/R=0.3, as shown in figure 1(b). Note that in the boundary layer, the streamwise spatial coherence and organization of the structures are broken beyond the log-layer (Ganapathisubramani *et al*. 2003; Lee & Sung 2011). Another important aspect of the figures is variations of the strength of the signed swirling strength in the turbulent pipe flow, compared to the boundary layer. To evaluate the quantities along with the strength, we have computed the probability density functions (p.d.f.s), although not shown here. The results show that strong swirling motions related to hairpin legs component is more frequently occurred in the pipe flow than the boundary layer. This strong swirl is associated with the increase of the streamwise length scale in the pipe flow, because it induces the positive and negative momentum regions more strongly, resulting in highly elongated regions of momentum deficit (Ganapathisubramani *et al*. 2003).

Figure 2 shows variation of the characteristic streamwise length scale based on the two-point correlation of the streamwise velocity fluctuations with threshold 0.05. To compare with the boundary layer data, we employed the previous numerical and experimental data from Lee & Sung (2011) and Hutchins & Marusic (2007). The result shows that the streamwise length scale in the pipe flow is larger than that in the boundary layers both in the log and wake regions. Especially, it is obvious that the length scale is continuously increased up to y/R=0.3 in the pipe flow, while the structures in the boundary layer increase up to y/δ=0.15 and decrease above it. Although not shown here, population trend of the momentum regions shows that the increase of the length scales are due to a great population of long structures in the pipe flow and increase of the maximum length (~30R) of the structures than that of the boundary layer (~18δ). More detailed results and further analysis on streamwise pre-multiplied spectra and time-resolved instantaneous fields will be given in the future.

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