COHERENT STRUCTURES IN A SELF-SIMILAR ADVERSE PRESSURE GRADIENT TURBULENT BOUNDARY LAYER AT THE VERGE OF SEPARATION

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The coherent structures of a self-similar adverse pressure gradient turbulent boundary layer (APG-TBL) at the verge of separation [7, 5] are investigated using a direct numerical simulation (DNS). The axes in the streamwise, wall-normal and spanwise directions are x, y and z. The corresponding velocity fluctuation with respect to the time-averaged mean (U, V, W) are (u, v, w). The APG-TBL achieves a region of constant friction coefficient, pressure velocity and shape factor [3] with turbulence statistics in this region showing a self-similar collapse by using the scaling of the external velocity (U_e) and the displacement thickness (δ_1) and velocity fluctuations in this strong APG-TBL are mainly produced in the outer layer [4]. As shown in figure 1(a), the intense Reynolds stress structures (uv-structures) are detached from the wall and that is true for the fine-scale vortex clusters represented by isosurfaces of the second invariant of the velocity gradient tensor (not shown). Most of events are generated in the outer region of APG-TBL, and the interaction of the local shear and the Reynolds stress (uv-structures) are of great interest, in comparison with those in zero-pressure-gradient TBL, turbulent mixing layer and homogeneous shear turbulence (HST). Ejections (Q2) and sweeps (Q4) are extracted by $\tau^*_{xy} < -Hu^*v^*$, where $\tau^*_{xy} = \langle uv\rangle/(U_e(x)^2)$, $u^* = u/U_e(x)$, $v^* = v/U_e(x)$ and H is a constant threshold. As shown in figure 1(b,c), the volume fraction and the scaled stress conditioned on the uv-structure indicate that ejections and sweeps are balanced at a symmetric point $y/\delta_1 \approx 0.88$ independently of H. Ejections mainly interacts with the free stream at around $y/\delta_1 \gtrsim 1.5$, and on the other hand, sweeps have larger contributions on the Reynolds stress than ejections below the symmetric point. The wall effect is limited within $y/\delta_1 \lesssim 0.5$ and the strong APG-TBL at the verge of separation behaves like a free shear flow. The Corrsin shear parameter [1], $S^* \equiv (\partial U/\partial y)q^2/\varepsilon$, where $q^2 \equiv u^2 + v^2 + w^2$ and ε is the dissipation rate, is $S^* \approx 9$ in the outer layer of the strong APG-TBL in good agreements with both HST [6], turbulent mixing layer and at the top of the logarithmic layer of wall-bounded flows [2]. Further investigations on the coherent structures in the self-similar APG-TBL, in comparison with the other shear flows, will be presented.

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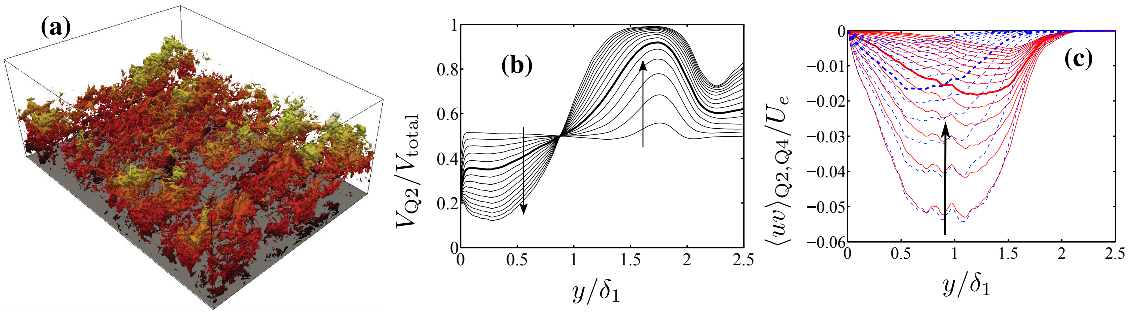

Figure 1. (a) The isosurfaces of intense Reynolds stress in the self-similar APG-TBL. Only the domain of interest (DoI) $[L_{\rm DoI}, 0.27L_y, L_z] = [6.4, 3.43, 8.8]\delta_1(x_{\rm DoI})$ is shown. $x_{\rm DoI}$ denotes the beginning of DoI, where $Re_{\delta 1}(x_{\rm DoI}) \approx 25000$ for the strong APG-TBL, and $L_{\rm DoI} \times L_y \times L_z$ represents the dimensions of DoI. The isosurfaces are $-uv/U_e^2 = 0.016$, coloured by the distance from the wall. The flow is from left to top-right. (b) The volume fraction of ejections (Q2) and sweeps (Q4), conditioned by $\tau^*_{xy} < -Hu^*v^*$. The lines are $H = [0.25 : 0.25 : 4.0]$, and the thick line represents $H = 1.75$. The arrow indicates the increase of H. (c) the Reynolds stress conditioned on the uv-structures; (red solid) Q2; (blue dashed) Q4. The lines are the same with (b).

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