Direct numerical simulation of turbulent boundary layer with rough wall

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Abstract: The effects of surface roughness on a turbulent boundary layer were investigated by comparing direct numerical simulations over rough and smooth walls. The Reynolds number based on the momentum thickness is Reθ=300~1400. The roughness is composed of periodically arranged 2-D rods and its height is k/δ=0.045~0.125. Along the downstream, the wall friction velocity approaches a constant value and the self-preservation form of mean velocity and turbulent stresses could be obtained. The roughness effects on turbulent stresses were not restricted to the roughness sublayer but were felt throughout the boundary layer. Despite of the increases of turbulent stresses in the outer layer, the effects on the anisotropic Reynolds stress tensor in the outer layer were negligible. The triple products of velocity fluctuations shows vertical turbulent transport strongly depends on the wall roughness. No significant changes are found in the high-order moments of velocity fluctuations between smooth and rough walls, which are similar to the results of anisotropic Reynolds stress tensor.

Many previous studies for turbulent flow over rough wall have supported ‘Townsend wall similarity hypothesis’ - surface roughness effect is primarily felt in a roughness sublayer and outside the roughness sublayer turbulent motions are independent of the wall roughness at sufficient large Reynolds numbers. However, recent experimental study of Krogstad et al. (1999) have shown a significant deviation of turbulent stresses in the outer layer of the boundary layer between smooth and rough walls, making the similarity hypothesis questionable. Recently, some numerical DNS and LES studies have been made in turbulent channel flow with rough wall. However, the significant deviation of turbulent stresses in the outer layer was not observed in those simulations. Krogstad et al. (2005) compared DNS with experimental results in a channel flow and found no difference between smooth and rough walls. They conjectured that the surface roughness effects on the outer layer may be dependent on flow type, i.e., channel flow or boundary layer. A literature survey reveals that no previous DNS data are available now for turbulent boundary layers with rough wall. In the present study, DNSs of turbulent boundary layers with rough and smooth walls were performed. And the effect of roughness effect on the turbulent boundary layer were analyzed in detailed. This new study can provide very important data to elucidate the roughness effect in turbulent boundary layer and the interaction with inner layer and outer layer.

The Reynolds number based on the momentum thickness at the inlet was Reθ=300. As shown in Figure 1, the domain size was 7680_m×900_m×800_m for rough wall and 15360_m×600_m×800_m for smooth wall in the streamwise, wall-normal and spanwise directions, where the corresponding mesh number is 2049×200×257 for rough wall and 2049×150×257. The roughness is composed of periodically arranged 2-D rods whose cross-section is square with a side k=1.50_m and separated in the streamwise direction by λ=8k. The first rod is placed at 800_m downstream from inlet and the surface roughness changes abruptly from smooth to rough. We define this step change position as x=0. Realistic velocity fluctuations at the inlet were obtained by inflow generation. The roughness was numerically treated by the immersed boundary method of Kim et al. (2001) and the governing equations are incompressible Navier-Stokes equations and continuity equation and they were solved with a fully implicit fractional-step method proposed by Kim et al. (2002).

Figure 1. Schematic diagram of computational domain for rough wall.
The friction velocity is obtained using skin frictional drag and form drag and the virtual origin is considered as the centroid of the moment of forces acting on the roughness elements. Near the roughness, turbulent statistics are significantly affected and spatial inhomogeneities exist along the streamwise direction. However, these spatial inhomogeneities of turbulent statistics are restricted only in y<5k. The roughness sublayer can be regarded in this region and the outer layer is over the roughness sublayer. The depth of roughness sublayer is estimated to ζ=5k. Along the downstream direction for rough wall, turbulent stresses increase in outer layer due to the transport of increased turbulent kinetic energy from near the roughness. After 300–400δ (30–40δ) downstream from the first rod, the turbulent stresses profiles of rough wall reach a self-preservation form and are collapsed in the outer layer. These re-established self-preservation form shows that the domain size along the streamwise direction is sufficient to eliminate the step change effect of surface roughness and a fully rough-wall turbulent boundary layer is generated. Figure 2 shows the streamwise mean velocity normalized by the friction velocity between rough and smooth wall. DNS results over smooth and rod-roughened wall are also compared with experimental results of Krogstad et al. (1999). Figure 2(a) shows that the slope of rough wall in log-layer is the same as that of smooth wall. This suggests that the friction velocity and the virtual origin are properly calculated. The present roughness reduces the streamwise mean velocity in the log-layer and the roughness function in the present rod-roughened wall case is ∆U+ = 9.86. Figure 2(b) shows a defect form profile which is normalized by the friction velocity and the boundary layer thickness is collapsed in the outer layer between smooth and rough walls. This suggests that this defect form satisfies the surface similarity in the different surface roughness. In Figure 3, the turbulent stresses of smooth wall normalized by the friction velocity are compared with those of rough wall. DNS results are also compared with experimental results of Krogstad et al. (1999) and Keirsbulck et al. (2002). Streamwise turbulent stress decreases in the roughness sublayer but increases in the outer layer. Wall-normal turbulent stress significantly increases across the entire boundary layer and spanwise turbulent stress and Reynolds shear stress significantly increase similar to the wall-normal turbulent stress. These results show that the surface roughness affects the turbulent stress not only in the roughness sublayer but also in the outer layer. These are consistent with the previous experiments of Krogstad et al. (1999) and so on. Despite the increase of turbulent stresses in the outer layer, the effects on the anisotropic Reynolds stress tensor in the outer layer are shown to be negligible. The triple products of velocity fluctuations normalized by the friction velocity show vertical turbulent transport strongly depends on the wall roughness. The vertical turbulent transport of rough wall near the cavity region is toward wall-ward direction and stronger than that of smooth wall. In outer layer, the vertical turbulent transport is toward outward direction, which is attributed to the increased turbulent stresses in the outer layer. No significant changes are found in the 3rd and 4th order moments of velocity fluctuations between smooth and rough walls, which are similar to the results of anisotropic Reynolds stress tensor.

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