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Effects of the roughness height in turbulent boundary layers over rod- and cuboid-roughened walls

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ABSTRACT

Direct numerical simulations (DNSs) of spatially developing turbulent boundary layers (TBLs) over two-dimensional (2D) rod-roughened walls and three-dimensional (3D) cuboid-roughened walls are conducted to investigate the effects of the roughness height on the flow characteristics in the outer layer. The rod elements are periodically aligned along the downstream direction with a pitch of $p_x/\theta_{in} = 12$, and the cuboid elements are periodically staggered with a pitch of $p_x/\theta_{in} = 12$ and $p_z/\theta_{in} = 3$, where p_x and p_z are correspondingly the streamwise and spanwise pitches of the roughness and θ_{in} is the momentum thickness at the inlet. The first surface roughness is placed $80\theta_{in}$ downstream from the inlet, leading to a step change from a smooth to rough surface. The rod and cuboid roughness height (k) is varied in the range of $0.1 \leq k/\theta_{in} \leq 1.8$ ($13 \leq \delta/k \leq 285$), respectively ($\delta$ is the boundary layer thickness), and the Reynolds number based on the momentum thickness (θ) is varied in the range of $Re_\theta = 300 \sim 1400$. For each case, the self-preservation form of the velocity-defect and the turbulent Reynolds stresses is achieved along the downstream direction. As the roughness height increases, the roughness function (ΔU^+) extracted from the mean velocity profiles increases, although the velocity-defect profiles for the rough-wall cases show good agreement with the profile from the smooth-wall case. The magnitude of the Reynolds stresses in the outer layer increases with an increase of k/δ. The outer layer similarity between the flows over the rough and smooth-walls is found when $\delta/k \geq 250$ and 100 for the 2D rod and 3D cuboid, respectively. The continuous increase of the Reynolds stresses in the outer layer with an increase of k/δ is explained by a large population of very long structures over the rough-wall flows. Because the characteristic width of the structures increases continuously with an increase of k/δ for the rod and cuboid roughness, a wide width of the structures leads to frequent spanwise merging between adjacent structures. The active spanwise merging events with an increase of k/δ increase the streamwise coherence of the structures with the appearance of significant meandering.

1. Introduction

Townsend (1976) stated that surface roughness only exerts a direct influence on the turbulence within a few roughness heights of the wall, and the outer flow is unaffected by the roughness (hereafter, Townsend's wall-similarity). Raupach et al. (1991) and Jiménez (2004) proposed that if the roughness height (k) is relatively low compared to the boundary layer thickness (δ) with a criterion of $\delta/k \geq 40$, the interaction between the inner and outer layers is very weak at a high Reynolds number. A number of studies have shown the establishment of the Townsend's wall-similarity in the outer layer of turbulent boundary layers (TBLs) in the presence of significant topographical three-dimensional (3D) complexity of the surface roughness (Akinlade et al. 2004; Flack et al. 2005; Schultz & Flack 2007; Wu & Christensen 2007, 2010; Mejia-Alvarez et al. 2014; Squire et al. 2016, 2017). In an experimental study of TBLs with sandpaper and mesh roughness for a wide range of roughness sizes ($\delta/k = 16 \sim 110$), Flack et al. (2007) found that the roughness effects are confined to a roughness sublayer defined as 5 k or $3k_s$ irrespective of the height of the 3D irregular roughness, where k_s is the equivalent sand-grain roughness height.

Contrary to previous observations of TBLs over 3D irregular roughness elements, many experimental and numerical studies of TBLs with two-dimensional (2D) surface roughness (i.e., rod roughness) have reported the existence of roughness effects in the outer layer (Krogstad & Antonia 1999; Lee & Sung 2007; Volino et al. 2009, 2011). In a direct numerical simulation (DNS) study, Lee & Sung (2007) showed that the introduction of a rod roughness element ($\delta/k = 20$) affects the turbulent stress not only in the roughness sublayer but also in the outer layer

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