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Direct numerical simulation of turbulent boundary layer over hemispherical rough walls

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ABSTRACT

Direct numerical simulations (DNSs) were performed to investigate the effects of hemispherical roughness on the properties of the spatially developing turbulent boundary layer (TBL). To resolve the hemispherical roughness element, an immersed boundary method was employed. The hemispheres were staggered in the downstream direction and arranged periodically in the streamwise and spanwise directions with spacing of $p_x/d = 2$, 4, 8 and $p_z/d = 2$ (where p_x and p_z are the streamwise and spanwise spacings of the hemispheres, and d is the diameter). The effects of different streamwise spacing on the turbulent statistics and coherent structures were examined. Inspection of the Reynolds stress profiles shows that the outer-layer similarity is not established for current conditions, and it is significantly dependent on the roughness types. The introduction of the roughness affects the coherent structure and the eject- and sweep-events not only in the roughness sublayer but also in the outer layer. With the decrement of the streamwise spacing, the effects become more obvious. By contrast, the Reynolds stress anisotropic tensor in the outer layer is rarely affected by the surface roughness. The influences mainly concentrate in the roughness sublayer, and are significantly related to the streamwise spacing.

Introduction

Due to the machining, fouling, pitting and deposition, etc., the underlying surface usually cannot be viewed as hydrodynamic smooth under many practical and environmental conditions, especially at high Reynolds number condition. A significant change can be induced by the surface roughness including the momentum and heat transfer, and the particle transport properties (Cheng and Zhu, 2015; De Marchis et al., 2016), which makes them meaningful to be investigated thoroughly. Since the Townsend's wall-similarity hypothesis (Townsend, 1976) was put forward, for several decades, a great number of experimental and numerical studies (Flack et al., 2007; Jimenez, 2004) have been conducted toward understanding the extent that the roughness modifies the turbulent boundary layer. Townsend wall-similarity hypothesis stated that the outer flow was unaffected by the surface conditions when the boundary layer thickness was large compared to the roughness height at high Reynolds number. Many previous 3-D roughness works of various roughness types (Lee et al., 2011; Mejia-Alvarez and Christensen, 2010) have provided results supporting the Townsend wall-similarity hypothesis. They found that the effects of roughness were confined to the roughness sublayer, $y < 5k$ or $3k_s$ (where y is the wall-normal coordinate, k is the height of the roughness and k_s is the sand grain roughness height). The similarity trend was also observed for the large 3-D roughness such as mesh, staggered cubes and gravel chips with $k/\delta < 10$ (δ is the boundary layer thickness) (Castro, 2007). However, the studies of Lee et al. (2011) have showed that the outer-layer similarity was not achieved for their 3-D cube-roughened wall, even though the value of k_s/k was similar to that of the previous studies. They contributed the difference to the effects of the square plane which would induce a stronger blockage effect. Thus, more investigations should be performed to clarify the effects of different geometric shapes on the turbulent boundary layer, particularly the non-square roughness.

Moreover, compared with the 3-D rough wall, the studies of the turbulent boundary layer over 2-D rough wall also exhibit different behaviors and show a strong interaction between the inner and outer layers. Volino et al. (2009) carried out an experimental study in a zero pressure gradient turbulent boundary layer over a 2-D rod-roughened wall ($p_x/k = 8$, $\delta/k \approx 32$). Their results showed that even if the mean flow was not significantly affected by the rough wall, the Reynolds stresses, particularly the wall-normal Reynolds stress $\langle v^{+2}\rangle$ and Reynolds shear stress $\langle -u^+v^+\rangle$, were increased compared with the smooth wall case. The differences between the 2-D and 3-D roughness were attributed to the large-scale turbulent motions emanating from the wall induced by each type of roughness. The large-scale motions induced by the 3-D roughness were

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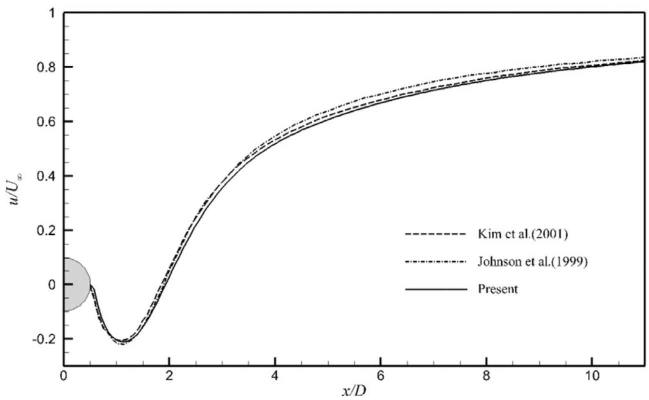

Fig. 1. Time-averaged streamwise velocity along the streamwise direction at $Re_D = 300$.

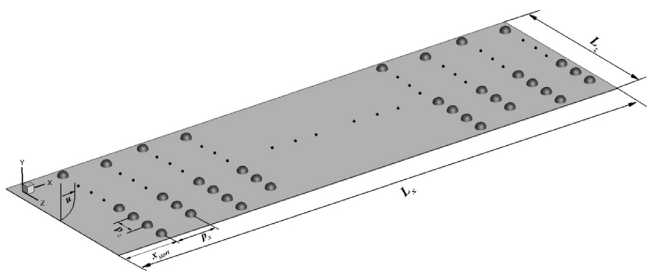

Fig. 2. Schematic diagram of the computational domain and the hemispherical roughness elements.

Table 1
Comparison of quantitative data with previous results.

$Re_D = 300$	C_d	C_L	St
Kim et al. (2001)	0.657	0.067	0.134
Johnson and Patel (1999)	0.656	0.069	0.137
Constantinescu and Squires (2000)	0.655	0.065	0.136
Present	0.659	0.065	0.137

Table 2
Parameters for DNS of turbulent boundary layer.

L_x/θ_{in}	L_y/θ_{in}	L_z/θ_{in}	N_x	N_y	N_z	Δx^+	Δy^+_{min}	Δz^+
128	60	32	1025	129	257	4.25	0.5	4.25

Table 3
Flow parameters over the hemispherical rough wall.

	Re_θ	u_τ	k/δ	$\triangle U^+$	k^+	$k_s{}^+$
Case 1	1005	0.0521	0.047	3.2	20.8	13.8
Case 2	1018	0.0643	0.048	6.7	25.7	57.8
Case 3	1023	0.0682	0.048	8.1	27.3	102.8

on the order of roughness height, while the 2-D roughness generated much larger motions owing to the width of 2-D roughness. Similar differences were also observed for small 2-D transverse bars with a height of only 11 viscous units ($\delta/k = 160$) by Volino et al. (2011). They found that the differences were not simply due to the thickening of the roughness sublayer. Even though the periodic disturbance and recovery of the boundary layer played some role in modifying the outer flow, the blockage caused by the 2-D roughness had a larger effect than the periodic disturbance alone. In addition, the effects of different streamwise spacing on the turbulent statistics and coherent structures were investigated by Lee et al. (2012). They found that the flow statistics for 2-D rough walls were strongly dependent on p_x/k. Except for $p_x/k = 2$ and 3, the effects of the roughness extended into the outer layer and the magnitude of the Reynolds stress increased with the p_x/k. They also found that the wall-normal fluctuation $v_W{}^+$ on the crest of the roughness element was a suitable parameter to predict the outer layer similarity with square-edged roughness. The effects of larger streamwise spacing on the spatially developing turbulent boundary layers were also studied by Nadeem et al. (2015) using direct numerical simulation methods. The roughness elements were arranged periodically in the streamwise direction with spacing of $8 \le p_x/k \le 128$. The inspection of Reynolds stresses showed that the outer layer similarity was established for $p_x/k \ge 32$. The relation between the wall-normal fluctuation $v_W{}^+$ and the roughness function $\triangle U^+$ was almost linear for $p_x/k \le 10$ and non-linear for larger p_x/k.

Because the generation of realistic turbulent inflow data for flow over the rough wall is difficult (Lee et al., 2011; Lee and Sung, 2007), the majority of numerical studies have examined the turbulent channel flows. However, due to the different boundary condition, the spatially developing boundary layer flows behave differently from the channel flows covered with one- or two-side roughened walls (Ashrafian et al., 2004; Burattini et al., 2008; Krogstad et al., 2005; Leonardi et al., 2003). Different from previous studies of TBL flow over rod- and cube-roughened wall (Lee et al., 2011; Lee and Sung, 2007), in present studies, we carried out direct numerical simulations of TBL flow with hemispherical roughness elements which appears in various energy systems such as boilers and nuclear reactors. The effects of the streamwise spacing with spacing of $p_x/d = 2$, 4 and 8 on the flow characteristics were investigated by examining the turbulent statistics and the turbulent structures. The paper is organized as follows. Firstly, the numerical methods of the governing equations and the immersed boundary method are introduced in the Section 2. Then, the effects of the hemispherical rough wall on the turbulent statistics and coherent structures are analyzed in the Section 3. Finally, the main conclusions are presented in the Section 4.

Numerical method

Numerical procedure

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

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i \tag{2}$$

where x_i are the Cartesian coordinates, u_i are the corresponding velocity components and p is the fluid pressure. Re is the Reynolds number ($Re = U_\infty \theta_{in}/v$, U_∞ is the freestream velocity, θ_{in} is the momentum thickness at the inlet, v is the kinetic viscosity). f_i is an external body force field which is designed to enforce the proper boundary conditions on the immersed boundary in the present studies.

The governing equations are solved with the fractional step method given by Perot (1993). The diffusion term in the wall-normal direction is treated implicitly, whereas other terms are treated explicitly. For time advancement, a low-storage three-step Runge–Kutta scheme is used for the terms treated explicitly, and a second-order Crank–Nicolson scheme is used for the terms treated implicitly. A fourth order accurate finite difference is employed to discretize the convective terms on staggered grids whereas the Lagrange polynomials are used to discretize the viscous terms(Desjardins et al., 2008; Shukla et al., 2007). In order