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Turbulence modulation and heat transfer enhancement in channels roughened by cube-covered surface

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ABSTRACT

Direct numerical simulations are carried out to study turbulence modification and heat transport augmentation in rough channels with minor cubes on one wall. To account for the effect of the cubes on momentum and heat transfer in wall-bounded turbulent flows, the lattice Boltzmann method which is based on a double-distribution-function and D3Q19 model is applied to perform the numerical computation. The present study focuses on the modulations of the temperature field and heat transfer process by rough wall with different cube heights. Some typical dynamic and thermal statistics, such as the mean velocities, mean temperature, velocity fluctuations, the Reynolds stresses, and turbulent heat flux are analyzed. The similar trend of temperature and velocity roughness functions illustrates there is strong correlation between the heat transfer augmentation and a drag increase in rough channel flows. A significant heat transfer enhancement (26%, by taking into account the drag consumption) is obtained with the medium-height cubes.

1. Introduction

Turbulent flows over rough surfaces are often encountered in applied science and engineering, because the boundaries cannot be treated as absolutely smooth, especially at high Reynolds numbers. Recently artificial roughness structures are widely used to increase heat transfer [1]. For example rib arrays are used to enhance heat transfer in heat exchangers, cooling of turbine blades, cooling of electronic devices, etc.

Over the decades, a number of researchers [2-6] have carried out the direct numerical simulation (DNS) of turbulent thermal channel flows with smooth walls. The thermal statistics such as temperature variance, turbulent heat flux and turbulent Prandtl number are studied in detail. It is found that the thermal characteristics are correlated with streamwise velocity fluctuations, especially in the near wall region but have a weak dependence on the boundary conditions and on the Prandtl and Reynolds [7] numbers. Recently, lots of studies have focused on the modification of velocity field and thermal field by the roughness elements. Given the correlation between the thermal field and the dynamic behaviors observed on smooth wall, the increased velocity fluctuations in a rough wall will lead to the heat transfer augmentation. The effects of large-scale structure induced by the roughness on heat transfer were discussed by Miyake et al. [8], they found that the mixing is enhanced due to the strong downwash induced by the rough wall. They also found that the heat transfer augmentation is associated with drag increase. This is consistent with the study carried out by Nagano et al. [9], they further analyzed the net heat transfer increment considering the drag consumption. Moreover, several studies have been performed when the shape and the height of the roughness varied [7,9-11], and shown that the heat transfer is enhanced by inducing ejections at the leading edge of the roughness elements and the circular rods and the angled ribs are more effective in increasing heat transfer. Until now, most of the researchers focus on the modulations of relatively higher two-dimensional roughness elements (usually greater than 0.1 channel half width) and on the dynamic and thermal behaviors. However, in many practical cases, the height of roughness elements is much smaller and roughness geometry is much more complex. It is of interest to find whether the dynamic and thermal behaviors have the same trend when the cubes are relatively lower. In this study, in order to examine the effects of roughness on the statistical quantities in velocity and thermal fields, and to investigate further the mechanism of increasing heat transfer and flow drag, direct numerical simulations based on the lattice Boltzmann method (LBM) of heat transfer in turbulent channel flows with cubes roughness have been performed by varying cube height.

The LBM appears to be an attractive approach to compute complex flows, such as turbulence and micro-scale flow [12]. Instead

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Nomenclature

α	pressure gradient $-dp/dx$
c_p	specific heat
C_{fr}	friction coefficient at rough wall, $2\tau_{wr}/\rho\langle U\rangle_r^2$
d	interval from the rough wall to the maximum velocity location
E	total energy
f_i	distribution function for velocity
h	height of cube roughness (see Fig. 1)
h_i	distribution function for total energy
k	turbulent kinetic energy, $u_i'u_i'/2$
Nu_r	Nusselt number at rough wall, $q_{wr}d/\lambda(T_h-\langle T\rangle_d)$
p	pressure
Pr	Prandtl number
q_{wr}, q_{ws}	heat flux at rough and smooth walls
Re_τ	Reynolds number based on the friction velocity and channel half width, $u_\tau\delta/\upsilon$
T_h, T_c	temperatures at rough and smooth walls
$\langle T\rangle_d$	mean temperature at the location where the mean velocity becomes maximum.
$T_{\tau r}$	friction temperature at rough wall, $q_{wr}/\rho c_p u_{\tau r}$
$\langle \boldsymbol{U}\rangle_r$	bulk mean velocity at rough wall side, $\int_0^d\langle u\rangle dy/d$
U_m	bulk mean velocity, $\int_0^{2\delta}\langle u\rangle dy/2\delta$
u_i	velocity component in x_i direction
u', v', w'	fluctuating velocity component in $x-, y-$ *and* $z-$ directions
$u_{\tau 0}$	mean friction velocity, $\sqrt{a(\delta/\rho)}$
u_τ	friction velocity $\sqrt{\tau_w/\rho}$
x, y, z	streamwise. wall-normal and spanwise coordinates

Greeks

δ	channel half width
ΔT_w	temperature difference between rough and smooth wall, T_h-T_c
κ, κ_θ	Kármán constant for velocity and temperature
λ	thermal diffusivity
υ	kinematic viscosity
θ	temperature normalized by the temperature difference between rough and smooth walls, $(T_h-T)/\Delta T_w$
θ'	fluctuating temperature
τ_{wr}, τ_{ws}	shear stress at rough and smooth wall.
ρ	fluid density

Subscripts and superscripts

$()_r$, $()_s$	value at rough and smooth wall
$()_{rms}$	root mean square value
$()^+$	normalization by inner variables, $u_\tau, \upsilon, T_{\tau r}$
$\langle\rangle$	xz-plane space averaged quantities

of solving Navier–Stokes equations, a more direct approach is to solve discrete-velocity distribution function, which is governed by the lattice Boltzmann equation. In general, the propagation and collision of dummy particles is the main interpretation process of above procedure. What appeals to us most is that this method has great advantages in dealing with complex boundaries. Moreover, it is a rather efficient, robust method which is very easy to implement.

In this paper, the physical model and mathematical formulation including the fundamentals of the lattice Boltzmann model are described in Section 2. Some statistical quantities of turbulent flows with rib arrays and validations based on the comparison with existing results are given in Section 3.1. Then, we carry out a direct numerical investigation of turbulence modulation in a turbulent channel flow with three-dimensional cubes using LBM. Some statistics results and instantaneous fields are given in order to explain the mechanism for heat transfer augmentation and drag increase in Sections 3.2–3.5. Lastly, a summary is followed in Section 4.

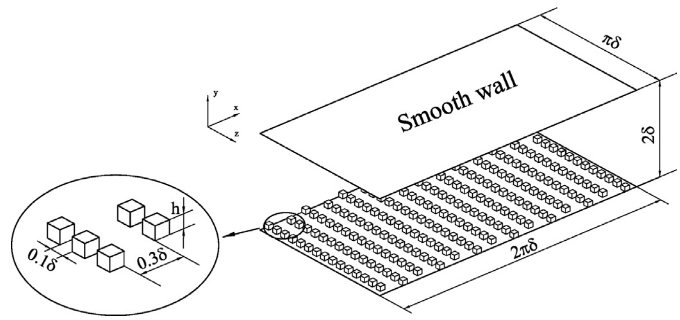

Fig. 1. Model of roughness wall-bounded turbulence.

2. Mathematical formulation and simulation method

2.1. The governing equation and boundary conditions

As shown in Fig. 1, in this work, we consider the turbulent flow between two parallel planes with roughness cubes on the bottom wall.

The velocity field is governed by imcompressible Navier-Stokes equation and the continuity equation. They can be written as follows:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=0, \tag{1}$$

$$\frac{\partial\boldsymbol{u}}{\partial t}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=-\frac{1}{\rho}\nabla p+\upsilon\nabla^2\boldsymbol{u}+\boldsymbol{a}, \tag{2}$$

where $\boldsymbol{\alpha}$ is the pressure gradient to maintain a constant flow rate, p is the pressure, υ is the kinematic viscosity.

The energy equation is

$$\frac{\partial T}{\partial t}+\nabla\cdot(\boldsymbol{u}T)=\nabla\cdot(\lambda\nabla T), \tag{3}$$

T is the temperature and λ is the thermal diffusivity.

The boundary conditions for velocity field are peridic in x- and z-directions and non-slip on the smooth and rough walls. As for the temperature field, both smooth and rough walls are isothermal and the temperature of rough wall is fixed to T_h, and that of smooth wall, to T_c. The temperature is normalized to θ as $\theta=(T-T_h)/\Delta T_w$ with temperature difference $\Delta T_w=T_c-T_h$, then the boundary conditions of the temperature θ are $\theta=0$(rough wall), $\theta=1$(smooth wall).

2.2. The lattice Boltzmann model

The double-distribution-function method is widely used in simulation of thermal problems [13], in our simulation, the total energy distribution function model is put into use. The model utilizes two different distribution functions, one for the velocity field and the other for the total energy field. In fact, it has second order accuracy in time and space if the flow is incompressible and the numerical viscosity can be absorbed into physical viscosity [14].

According to the total energy distribution function model, this paper deduces the D3Q19 lattice Boltzmann equation model which solves the 3D turbulent thermal flow as following:

$$\begin{aligned} &f_i(\boldsymbol{x}+\boldsymbol{c_i}\delta_t, t+\delta_t)-f_i(\boldsymbol{x},t)\\ &=-\omega_f\Big(f_i(\boldsymbol{x},t)-f_i^{(eq)}(\boldsymbol{x},t)\Big)+\delta_t\Big(1-\frac{\omega_f}{2}\Big)F_i, \end{aligned} \tag{4}$$