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Numerical Analysis of Porous Wall-Bounded Turbulent Flows Based on the Lattice Boltzmann Method

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Abstract - We investigate the effect of two parallel porous walls, consisting of Darcy number and the porosity of porous medium, on behaviour of turbulent shear flows as well as skin-friction drag. The direct numerical simulation of turbulent channel flows with porous surface using lattice Boltzmann method (LBM) was performed. The Darcy-Brinkman-Forcheimer (DBF) acting force term is added in the lattice Boltzmann equation in order to simulate the turbulent flows bounded by porous walls. It is found that there are two opposite trends (enhancement or reduction) for the porous medium to modify the intensities of velocity fluctuations and the Reynolds stresses in near wall region. Meanwhile, the parametric study shows the dependency of flow modification on the Darcy number and the porosity of porous medium. Our results on statistical quantities for flow field show that, with respect to conventional impermeable wall, the degree of turbulence modification does not depend on any simple set of parameters obviously.

Keywords**:** lattice Boltzmann method, porous material, wall-bounded turbulence, Darcy number, drag coefficient

1. Introduction

Fluid flow through porous medium is widely used in many fields of applied science and engineering. At different porosities and Darcy numbers, the effects of porous surface on the modulation of turbulent flows are different. Some reports [1] indicated the velocity and pressure fluctuations around a blunt body wrapped by porous medium were weakened distinctly, but, there are some studies [2] which found the turbulent level and skin friction were to increase rather than to decrease. By now, both points of view are still complementary, and the detailed mechanism remained unclear.

In this work, turbulence modulation in a porous wall-bounded turbulent channel flow is further explored by direct numerical simulation using lattice Boltzmann method. For the flow inside the porous medium, we adopt the volume-averaged method which is governed by the volume-averaged Navier–Stokes equations. We also present how the lattice Boltzmann equation which contains Darcy-Brinkman-Forchheimer acting force term [3] is deduced. Some statistical quantities of impermeable wall-bounded turbulent flow and validations based on the comparison with existing results are given. Then, we perform parametric studies of the influence on the turbulent flow over a range of Darcy numbers and porosities. Furthermore, the turbulent structures of velocity and vorticity instantaneous field are especially shown in order to explain the mechanism for turbulence modification using porous medium.

2. Mathematical formulation

We consider the turbulent channel flow between two parallel planes, shown as Figure 1. The porous layers are sticked to the walls, the porosity of the porous layer is ε, and the permeability is K.

For the isothermal incompressible flow in the porous medium, the governing equations are given as following according to Brinkman–Forchheimer equation[4,5]:

$$\begin{cases} \nabla \cdot \boldsymbol{u} = 0 , \\ \dfrac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)(\dfrac{\boldsymbol{u}}{\varepsilon}) = -\dfrac{1}{\rho}\nabla(\varepsilon p) + \upsilon \nabla^2 \boldsymbol{u} + \boldsymbol{F} , \end{cases} \tag{1}$$

where $\boldsymbol{F}$ is total force which contains the medium resistance and driving force terms,

$$\boldsymbol{F} = -\frac{\varepsilon \upsilon}{K}\boldsymbol{u} - \frac{\varepsilon F_{\varepsilon}}{\sqrt{K}}|\boldsymbol{u}|\boldsymbol{u} + \varepsilon \boldsymbol{G}, \tag{2}$$

In formula (2), $|\boldsymbol{u}| = \sqrt{u_x^{\ 2} + u_y^{\ 2} + u_z^{\ 2}}$, and υ is the kinematic viscosity. According to Ergun empirical formulas[6], the structure function F_z and permeability K are expressed as following,

$$F_{\varepsilon} = \frac{1.75}{\sqrt{150\varepsilon^3}}, K = \frac{\varepsilon^3 d_p^{\ 2}}{150(1-\varepsilon)^2}. \tag{3}$$

According to the LBGK model including forcing term, this work applies the D3Q19 LBE model which solves the 3D porous wall-bounded turbulent flow.

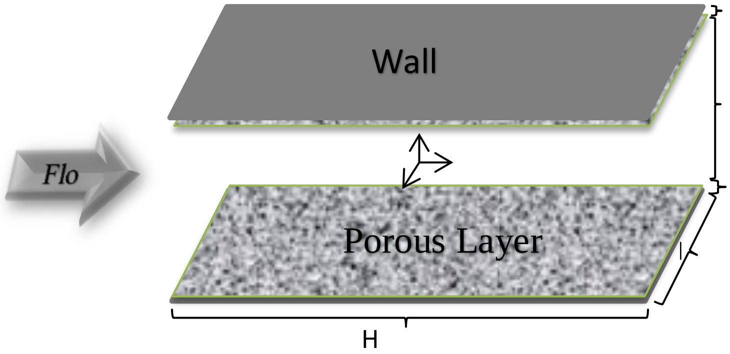
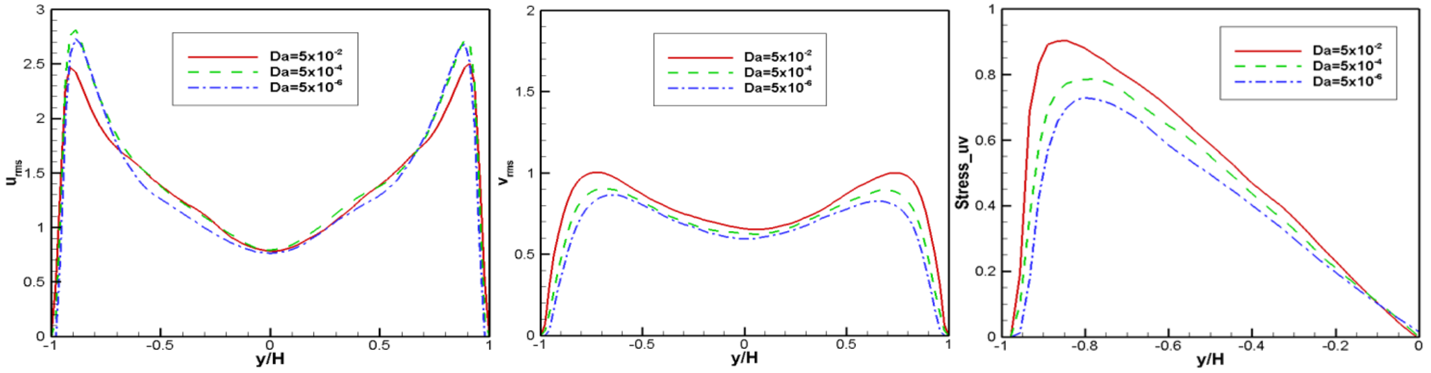


Fig. 1: The model of porous wall-bounded turbulence.

3. Results and Discussion

In this study, the Darcy Brinkman-Forchheimer acting force term was added in the lattice Boltzmann equation in order to simulate the turbulent flows bounded by porous walls. It is found that there are two opposite trends (enhancement or reduction) for the porous medium to modify the intensities of velocity fluctuations and the Reynolds stresses in near wall region.



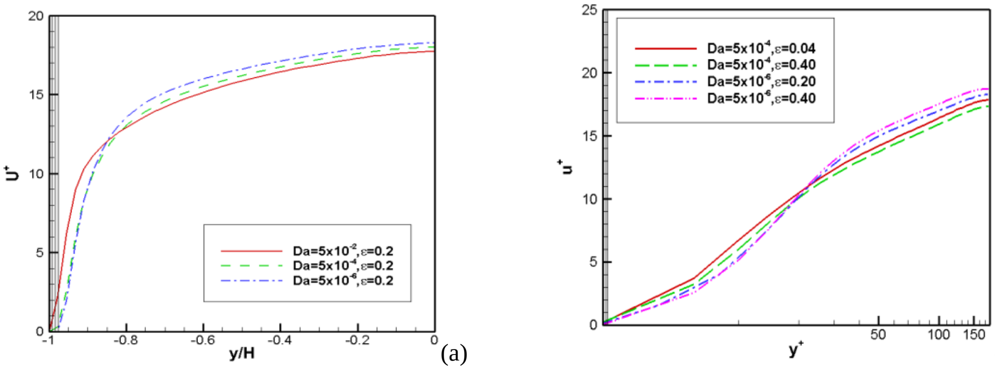
(a) (b) (c)

Fig. 2: Root-mean-square streamwise and wall-normal velocity fluctuations and Reynolds shear stress.

Porous surface can modulate the turbulence intensity and Reynolds shear stresses in near wall region which affect the streamwise coherence of the near wall flow structures. Along with the Darcy number increases, the streamwise velocity fluctuation decreases in near wall region and increases in the far wall area as shown in Figure 2a; and the wall-normal velocity fluctuations in all region increase obviously in Figure 2b. In addition, the Reynolds stress shows the same variation trend (Figure 2c). In the view of physics, the porous medium is essentially to generate an intermediate flow which controls vortex flows and weakens the boundary layer.

The mean velocity increases in the central region and decreases near wall with the Darcy number decreasing. We can find from Figure 3a that here exists a cross point on the curves of the mean profile. In fact, it has significance in the flow of turbulent boundary layer. Usually, its location stands for interface area between viscous sublayer and logarithmic law layer.

Figure 3b shows the streamwise mean velocities at four cases. The red line reveals the largest mean velocity in near wall region and Case of purple line displays the largest velocity in far wall area. It is worth to mentioning that increasing porosity doesn't mean obtaining larger mean velocity with the same Darcy number.

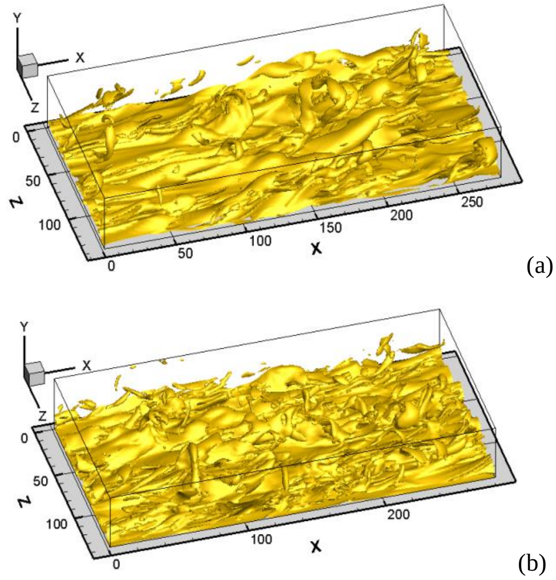


(a) (b)

Fig. 3: Mean velocity in streamwise direction.

When Darcy number is in order of $O(10^{-4})$, the streamwise mean velocities and velocity fluctuations are indeterminate. The present results show that very small porosity may also result in weak velocity fluctuations and Reynolds stresses in near wall region.

Figure 4 shows the vortex structures in near wall region of conventional and porous wall-bounded turbulence. From Figure 4c, we can find the quantity of the coherent structures, as well as the scales and attack angles are all reduced with respect to that from Figure 4a. On the contrary, Figure 4b exactly gets enhancive coherent structures. According to Kolmogorov's K41 theory, the dissipative eddies (small scale magnitude) always dissipate the energy from large scale vortexes. Obviously, since the turbulence of Figure 4c has more micro vortexes than that of Figure 4b, the former will dissipative less energy and then drag reduction can be achieved.



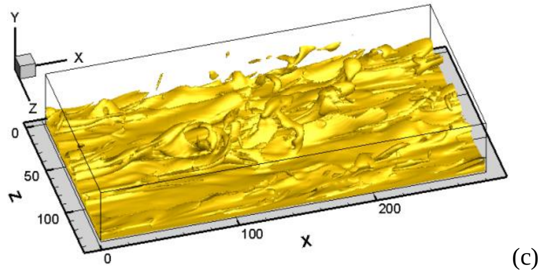


Fig. 4: Vortex structure in near wall region via Q-criterion (Q=0.006)
(a) non porous； (b) Da=5×10^{-2}, ε=0.2； (c) Da=5×10^{-6}, ε=0.4.

4. Conclusion

The characteristics of turbulent flow and the turbulence modulations of porous wall-bounded turbulent flow was investigated by means of direct numerical simulation via lattice Boltzmann method. At different porosities and Darcy numbers, pronounced turbulence modulations have been observed.

1. The porous surface can modulate the turbulence intensity and Reynolds shear stresses in near wall region which affect the streamwise coherence of the near wall flow structures. In the view of physics, the porous medium is essentially to generate an intermediate flow which controls vortex flows and weakens the boundary layer.

2. The mean velocity increases as Darcy number decreasing. In addition, when the Darcy number decreases, the streamwise velocity fluctuation increases in near wall region and the growth trend slows down. As a results, the turbulent anisotropy weaken the wall-normal and spanwise velocity fluctuations and Reynolds stresses.

3. When Darcy number is in order of $O(10^{-4})$, the streamwise mean velocities and velocity fluctuations are indeterminate. The present results show that very small porosity may also result in weak velocity fluctuations and Reynolds stresses in near wall region.

4. The drag coefficient has been damped in the porous wall-bounded turbulent flow when Darcy number is in order of. The streamwise low-speed streaks become longer and more regular than that of impermeable wall-bounded flow and appear stronger velocity correlation in streamwise direction. At the same time, the coherent structures of vorticity field and the scale and attack angles of vortex in near wall region are reduced.

Acknowledgements

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