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Lattice Boltzmann direct numerical simulation of interface turbulence over porous and rough walls

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ABSTRACT

To discuss the turbulent flow physics over porous walls, direct numerical simulation (DNS) of a porous-walled channel flow at the bulk Reynolds number of 3000 is performed by the D3Q27 multiple-relaxation time lattice Boltzmann method. The presently considered porous layer, whose porosity is 0.71, consists of interconnected staggered cube arrays. For understanding the influence of the wall permeability on turbulence, DNS of an impermeable rough walled channel flow is also conducted. By two-point auto-correlation, one-dimensional energy spectrum and proper orthogonal decomposition (POD) analyses, the existence and characteristics of the transverse pressure waves induced by the Kelvin–Helmholtz (K–H) instability over the porous and rough walls are elucidated. The structure, wave lengths and power spectra of the transverse waves are discussed in detail. The influence of the K–H instability on turbulence is also clarified.

1. Introduction

Flows around and inside a permeable porous layer are often encountered in industrial devices and environmental fields such as catalytic converters, metal foam heat exchangers, vegetation and urban canopies. For enhancing the heat and mass transfer performance of industrial devices and alleviating urban heat island effects, understanding flow physics over porous media is a primarily important issue. Since flows over porous media are very different from impermeable-wall flows, many studies have been historically performed to understand the reason why such difference occurs.

Beavers and Joseph (1967) firstly performed friction measurements over porous media in laminar flows. They measured mass flow rates in laminar channel flows whose bottom wall was made of a porous material. They found that the mass flow rate was enhanced compared with that of a smooth walled channel flow, which meant that the friction over a porous medium tended to be smaller than that over a smooth wall due to the effective slip velocity on the porous surface. Many other experimental, numerical and theoretical studies of laminar flows over porous media were reported (e.g., Gupte and Advani, 1997; Rudraiah, 1985; Sahraoui and Kaviany, 1992; Ochoa-Tapia and Whitaker, 1995; James and Davis, 2001; Suga and Nishio, 2009). Through those studies, understandings on flows over various porous structures were accumulated and boundary condition models such as that by Beavers and Joseph (1967) and the equation by Brinkman (1949) for the porous/fluid interface region were intensively examined.

Although it was reported that the friction over porous media decreased in laminar flows, this tendency was overturned in turbulent flows. Zagni and Smith (1976) conducted pitot tube experiments in turbulent open-channel flows over porous media. They found that the friction over a porous medium became higher due to the effects of the wall permeability and the wall roughness. Kong and Schetz (1982) carried out similar experiments of the turbulent boundary layer over a sintered metal, perforated titanium sheets and bonded screen sheets to examine the effects of the wall porosity and roughness. They also confirmed that the friction increase was due to the combined effects of the wall roughness and porosity. By hot wire measurements, Zippe and Graf (1983) reported that the flows over porous beds became more turbulent than those over impermeable rough walls.

Recently, particle image velocimetry (PIV) experiments have made it possible to discuss flow physics in more detail. Pokrajac and Manes (2009) measured turbulent flows over a porous layer composed of uniform spherical beads. They discussed the momentum exchange near the porous/fluid interface and concluded that, due to the effect of the wall permeability, the energetic turbulent sweeps penetrated into the pores. The authors' group also systematically investigated the effect of the wall permeability on turbulence (Suga, 2016; Suga et al., 2010, 2011). As the wall permeability increased, the wall-normal Reynolds stress was enhanced whilst

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Nomenclature

c	particle velocity: $\Delta/\delta t$
c_s	sound speed of the LBM
C_f	friction factor of the porous wall
C_f^t	friction factor of the smooth wall
d	zero-plane displacement
D	cube size
D^*	$L/2$
$E_{u_iu_i,x}$	one-dimensional streamwise spectrum of u_i'
$E_{u_iu_i,z}$	one-dimensional spanwise spectrum of u_i'
$\boldsymbol{f}$	distribution function
$\boldsymbol{f}^{eq}$	equilibrium distribution function
h	porous or rough wall thickness
h_r	roughness height
H	channel height
K	permeability
L	pitch of the cube rows
$\boldsymbol{M}$	transformation matrix
p	pressure
R_{ij}	plane averaged Reynolds stress: $[\overline{u_i'u_j'}]^f$
$R_{u_iu_i,x}$	streamwise two-point autocorrelation of u_i'
$R_{u_iu_i,z}$	spanwise two-point autocorrelation of u_i'
Re_b	bulk Reynolds number: U_bH/ν
Re_τ	friction Reynolds number of the porous or rough wall: $u_\tau\delta/\nu$
Re_τ^t	friction Reynolds number of the top solid wall: $u_\tau^t\delta^t/\nu$
t	time
u_i	velocity
u_τ	friction velocity on the porous or rough wall
u_τ^t	friction velocity on the solid wall
U_b	bulk mean velocity
x	streamwise coordinate
y	wall normal coordinate
z	spanwise coordinate
II	second invariant of the velocity gradient tensor: $-2(\frac{\partial u_i'}{\partial x_j}\frac{\partial u_j'}{\partial x_i})$
δ	boundary layer thickness of the porous or rough wall
δ^t	boundary layer thickness of the top solid wall
Δ	grid spacing
Δ^c	coarser grid spacing
Δ^f	finer grid spacing
κ	Kármán constant
κ_x	streamwise wave number
κ_z	spanwise wave number
λ_x	streamwise wavelength
λ_z	spanwise wavelength
ν	kinematic viscosity
$\boldsymbol{\xi}_\alpha$	discrete velocity
ρ	fluid density
φ	porosity
ϕ	variable
w_α	weight parameter
$\overline{\phi}$	Reynolds averaged value of ϕ
ϕ'	fluctuation of ϕ : $\phi-\overline{\phi}$
$[\phi]^f$	plane averaged value of ϕ
$()^+$	normalized value by the friction velocity of the porous or rough wall
$()^{t+}$	normalized value by the friction velocity of the top solid wall

the streamwise component was not and this led to the increase of the turbulent shear stress resulting in higher friction factors over porous media. Their discussions by the quadrant analysis revealed that the contribution of sweeps became most dominant whilst ejections tended to lose their strength very near the porous media. Superimposed effects of those motions and the Kelvin–Helmholtz type of instability were considered to result in shortening the longitudinal vortical structures and the low-speed elongated streaks.

From those experimental studies, it is understood that although the friction over porous media decreases in laminar flows, it increases in turbulent flows. Due to the effect of the wall permeability, the wall-normal Reynolds stress over porous media is intensified whilst the streamwise component is not. The intensified wall-normal Reynolds stress enhances the turbulent shear stress resulting in higher friction factors.

However, those measurement data are limited to the clear flow regions because of the difficulty in measurements inside porous media. Therefore, turbulent flow physics including three-dimensional vortical structures around and inside the porous/fluid interface region was not precisely discussed. Accordingly, several direct numerical simulation (DNS) studies have been attempted. However, since enormous computational costs are required to resolve the complex porous structures, some numerical approaches which model turbulence over a porous wall have been considered. The simplest approach is the specification of the wall-boundary conditions. Jimenez et al. (2001) proposed a boundary condition for turbulence on porous walls. It imposed the non-slip conditions for the streamwise and spanwise velocities whereas it set the wall-normal velocity to be proportional to local pressure fluctuations. They found that the friction increased by up to 40% over porous walls, which was associated with the presence of large spanwise rollers, originating from linear instability related to the K–H instability of shear layers. Hahn et al. (2002) applied an extended version of the boundary condition by Beavers and Joseph (1967). They applied slip velocity conditions in the streamwise and spanwise directions and set the wall-normal velocity to zero. They reported that vortical structures were weakened over porous media and the Reynolds stresses simultaneously decreased reducing the friction factors.

Since those approaches did not consider the flows inside porous media, they could not reproduce the momentum exchange process inside the porous media and thus controversial results appeared in Jimenez et al. (2001) and Hahn et al. (2002). To treat flows inside porous media with reasonable computational demands, Breugem et al. (2006) applied the volume averaged Navier–Stokes (VANS) equations of Whitaker (1986, 1996) to the porous region of porous walled channel flows. It was found that elongated streaky structures and the associated quasi-streamwise vortices were absent near a highly permeable wall and significantly enhanced turbulence was dominant with relatively large vortical structures, which were supposed to be originated from the K–H instability. They concluded that this phenomenon enhanced the Reynolds shear stress and led to strong friction. However, since their VANS equations included a model of a drag force term and they neglected the effect of the dispersion, turbulence phenomena around and inside the porous layers were not precisely reproduced. Moreover, their comments on the K–H instability were not based on direct evidences. Recently, Chandesris et al. (2013) performed a full DNS study for a low Prandtl number ($\mathrm{Pr} = 0.1$) heat transfer field with the same flow conditions as those of Breugem et al. (2006). Although they resolved the model porous structure, it was an unrealistically revitating cube array structure. Since their focus was on heat transfer, they did not provide any further information on turbulent flow physics than that by Breugem et al. (2006).

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