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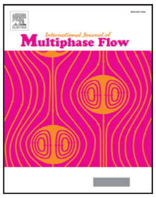

Immersed boundary lattice Boltzmann simulation of turbulent channel flows in the presence of spherical particles

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ABSTRACT

The lattice Boltzmann method (LBM) is used to simulate turbulent channel flows in the presence of spherical particles. In these simulations, the particles' surface is fully resolved by relying on the immersed boundary method (IBM). First, a single-phase turbulent flow at a frictional Reynolds number of $\mathrm{Re}_\tau = 180$ is simulated and used for validation by comparison with published data. The results show very good agreement with reference benchmarks. Starting from these results, a particle-laden flow is considered by direct numerical simulation (LBM-DNS), resolving all relevant scales. Both single-phase and particle-laden flows are modeled at the same frictional Reynolds number by applying the same driving force and initial flow conditions. Particle-to-fluid density ratios of $\rho_r = 1.0$ and 1.2 are considered and the particle radius a is adjusted to either 0.06 or 0.1 times the half-channel height H. The solid phase volume fraction is changed between 0.015 and 0.06. Results of the multiphase cases reveal that the presence of finite-size particles decrease the mean streamwise velocity. In the case of $\rho_r = 1$ and $a/H = 0.1$, the mean velocity reduces by 3.0 and 7.9% for volume fractions of 1.5 and 6%, respectively. Attenuation of turbulence by addition of particles is observed as well. The higher the volume fraction, the larger the degree of attenuation. Moreover, particles decrease the maximum streamwise velocity fluctuations by weakening the large-scale streamwise vortices. The root-mean-square of the streamwise velocity component increases in the region very close to the wall and in the core regions. The spanwise and normal velocity fluctuations are increased close to the wall but show minor changes far from the wall. Small particles ($a/H = 0.06$) cause more reduction of mean streamwise velocity at the same volume fraction in comparison with larger ones. At $\phi = 1.5\%$, the maximum rms of streamwise velocity fluctuations with small particles is lower than that with large particles. Finally, heavy particles lead to different velocity profiles in the upper and lower parts of the domain. In all cases, an equilibrium position close to the wall is observed, at which local particle concentration shows a maximum.

1. Introduction

Particulate suspensions can be found in many environmental, chemical, biological and pharmaceutical applications. In many of these applications the flow regime is turbulent, which tremendously increases complexity compared to a laminar flow. In these cases, the inherent stochastic structure of the carrier-phase together with the random distribution of the particles result in complex particle-fluid interactions.

Addition of small amounts of particles to a turbulent flow can modify the turbulence characteristics significantly. Gore and Crowe (1989) expressed that small particles suppress the turbulent intensity, whereas large particles enhance it. Small particles will attenuate fluid turbulence due to the lagging response of the particles with respect to the turbulent fluctuations. For larger particles, similar effects happen; however, a large particle will additionally cause wake shedding and, therefore, turbulence intensification can be observed. Very small particles (microparticles) may increase the turbulence due to their fast response to changes in the fluid. However, high particle concentrations can lead to a completely different behavior.

Many studies considered experimental investigations of turbulent particulate flows (see for example: Kussin and Sommerfeld, 2002; Sato et al., 1996; Khalitov and Longmire, 2002; Kaftori et al., 1995; Paris, 2001; Hwang and Eaton, 2006; Suzuki et al., 2000). Rashidi et al. (1990) performed experiments with particles of different sizes in an open channel. They found that large particles (1100 µm) increase the turbulence intensities and Reynolds stresses. On the other hand, smaller particles (120 µm) decreased the measured intensities and Reynolds stresses. These effects were

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Nomenclature

a	particle radius
$\mathbf{c}_i$	discrete velocity
c_s	sound speed
d_p	particle diameter
$\mathbf{F}$	Eulerian force
$\mathbf{f}$	Lagrangian force density
f_i^{eq}	equilibrium distribution function
f_i	distribution function
$\mathbf{g}$	gravity
Ga	Galileo number
H	half channel height
I_p	particle mass moment of inertia
L_x, L_y, L_z	domain size
Ma	Mach number
M_p	particle mass
N_x, N_y, N_z	number of nodes
P	pressure
Q	Q criterion
Re_b	bulk Reynolds number
Re_τ	friction Reynolds number
St	Stokes number
$\mathbf{T}$	torque
t	time
$\mathbf{U}$	translational velocity
$\mathbf{u}$	macroscopic velocity
U_0	velocity at channel center
U_b	bulk velocity
u_τ	friction velocity
$\mathbf{v}$	shifted macroscopic velocity
V_p	particle volume
$\mathbf{X}_c$	particle center position
$\mathbf{x}_{i,j,k}$	Eulerian point position
$\mathbf{X}_l$	Lagrangian point position
y	vertical distance from the wall
Δh	grid size
Δt	time step
ϵ	turbulence dissipation rate
ζ	microscopic velocity
κ	von Kármán constant
ν	kinematic viscosity
ρ_f	fluid density
ρ_p	particle density
ρ_r	$=\rho_p/\rho_f$
τ	relaxation time
τ_K	Kolmogorov characteristic time
τ_P	particle-induced stress
τ_p	characteristic time of particle
τ_R	Reynolds stress
τ_V	viscous stress
τ_w	wall shear stress
τ_ν	viscous time scale
ϕ	volume fraction of solid phase
$\boldsymbol{\Omega}$	rotational velocity
ω_i	lattice weights

more pronounced by increasing the particle loading. Kussin and Sommerfeld (2002) experimentally investigated a turbulent channel flow with a wide range of particle sizes. They stated that, large glass beads particles (0.625 and 1 mm) show a turbulence augmentation in the core of the channel. However, near the wall, turbulence reduction was observed.

Considering the continuous increase in computational power, numerical simulations of turbulent flows attract increasing attention. In general, the presence of particles in a fluid flow can be numerically modeled by three approaches: Eulerian (two-fluid) method, Lagrangian point-particle method, or fully-resolved simulation (Balachandar and Eaton, 2010; Crowe et al., 2011; Elghobashi, 1994).

The first approach is the *Eulerian (two-fluid)* method, in which both fluid and particles are treated as continuous medium and the interaction between the two phases is described by drag force correlations. This approach does not fully model all details of particle-particle and particle-fluid interactions (see for example Fevrier et al., 2005)

The second approach is the *Lagrangian point-particle* model. This method is appropriate when the particle size is smaller than the Kolmogorov length scale and the particle phase is dilute. This method fails to give an accurate prediction of the flow behavior when these conditions are not met. In this respect, Pan and Banerjee (1996) considered a dilute particle-laden turbulent channel flow ($\phi < 10^{-4}$) with a free surface. They used a pseudo-spectral method and point-particles were modeled in a Lagrangian framework. They observed that particles smaller than the dissipative length scale reduce turbulence intensity and Reynolds stress.

Mallouppas and van Wachem (2013) carried out large eddy simulation (LES) of point-particles dispersed in a horizontal channel flow with the gravity acting perpendicular to the main flow direction. The results were in consistency with the experimental measurements of Kussin and Sommerfeld (2002).

Most studies concerning turbulent particle-laden flows belong to the first or second category discussed above. The third approach uses *fully-resolved simulations*. In this case, interactions are modeled directly and the fluid motion around each moving particle is numerically resolved. Pan and Banerjee (1997) modeled the presence of large particles in an open channel flow. Particles radius was $a = 0.05H$ or $0.1H$ with H being the half-channel height. Solid phase volume fraction was $\phi \sim 10^{-4}$, which still belongs to the dilute regime. They reported that the presence of large particles alters the turbulence properties, particularly in the near-wall region. They found that particles increase turbulence intensities and Reynolds stress; this observation was more dominant for larger particles. Lashgari et al. (2015) studied laminar to turbulent transition in a channel flow in the presence of small amounts of finite-size particles. They found that the critical Reynolds number beyond which laminar to turbulent flow transition occurs is reduced as compared to a single-phase flow. Kajishima et al. (2001) simulated an upward turbulent flow in a vertical channel including solid particles ($d_p/H = 0.125,\ \phi \sim 10^{-3}$). They reported a strong modification of velocity and vorticity fluctuations. It was observed that, particles tend to move up mostly in the region close to the wall. It was also seen that the particles hinder the upward flow motion by reducing the mean velocity. On the other hand, velocity fluctuations showed an increase. Uhlmann (2008) performed DNS of fully-resolved particles in a vertical channel flow ($\phi = 4.2 \times 10^{-3}$). Formation of large-scale elongated streak-like structures was reported. It was mentioned that turbulence intensity and the normal stress anisotropy were strongly increased with respect to the single-phase flow at the same bulk Reynolds number. This enhancement was attributed to increase of the streamwise velocity fluctuations.

If the solid phase volume fraction is increased beyond the dilute regime, in the so-called dense regime, a four-way coupling model is required to accurately model all interactions. Corresponding studies are very challenging and, therefore, limited in number. Shao et al. (2012) used a direct-forcing fictitious domain (DF/FD) method and simulated a horizontal turbulent channel flow with finite-size solid particles at up to 7% solid-phase volume fraction.