International Journal of Multiphase Flow 67 (2014) 118–131

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Behavior of particles in turbulence over a wavy boundary

Hea Eun Lee [a], Changhoon Lee [a,b,*]

[a] Department of Computational Science and Engineering, Yonsei University, Seoul 120-749, South Korea
[b] Department of Mechanical Engineering, Yonsei University, Seoul 120-749, South Korea

ARTICLE INFO

Article history:
Received 16 September 2013
Received in revised form 20 March 2014
Accepted 20 August 2014
Available online 9 September 2014

Keywords:
Turbulent wavy channel flow
Particle-laden turbulence
Direct numerical simulation
Virtual boundary method

ABSTRACT

Understanding the mechanism controlling the particle motion in flow over a complex boundary is of great importance for many engineering fields. It is well known that fluid flowing over a wavy boundary creates turbulence that is remarkably different from the flow over a flat wall. Previous studies have presented the role of vortical structures over a wavy boundary, which is associated with particle clustering near the boundary. In this study, behavior of particles in turbulence over a wavy wall is investigated by direct numerical simulation of a turbulent wavy channel flow with laden particles. Our investigation shows that particles interact selectively with vortical structures and accumulate in a specific region along the wavy wall. Active deposition and resuspension occur in the upslope region where streamwise vortices are concentrated. Depending on the particle Stokes number and waviness of the wall, a strip or streak pattern of particle clustering near the wall is observed due to the combined effect of the wavy wall and vortical structures. However, due to the particle inertia, particle velocity and its fluctuation do not change as much as fluid velocity along the wavy boundary. Statistics and relevant physical interpretations of particle motion are presented.

Introduction

Particle motion in turbulence plays an important role in many physical processes in rivers, and sometimes leads to environmental and economical issues such as sediment transport, and stability of artificial structures. While most boundary conditions of particle-laden turbulence are rough in real practice, most studies on particle motion have focused on the particle-laden flow over a flat boundary. As near-wall particle motion in turbulence is known to be dependent on the near-wall flow structures, the wall geometry naturally affects particle motion. Therefore, understanding the mechanism controlling the particles in turbulence along a rough boundary is of major importance. Although some attempts to investigate particle motion near a fully rough wall such as Breuer et al. (2012) have been made, our interest is restricted to wavy walls. Several studies on flow over a wavy boundary have been experimentally performed (Nakagawa et al., 2003; Hudson et al., 1996; Kuzan et al., 1989). Especially, the mean velocity profiles of Hudson et al. (1996) and Kuzan et al. (1989) were used in numerical studies for validation.

There have been several numerical studies on the characteristics of turbulence over a wavy wall. De Angelis et al. (1997) performed direct numerical simulation and confirmed the results from experiments by observing separation in a downslope region and recirculation in a trough region extracted from the mean velocity profile. Also, they found that streamwise vortices and low-speed streaks mainly develop along the upslope region with a lengthscale based on the wavelength of the wavy surface. More recently, numerical studies presenting similar but detailed results were performed (Cherukat et al., 1998; Calhoun and Street, 2001).

Only a few studies have been performed on the particle behavior in turbulence over a wavy wall. For example, Boersma (2000) performed direct numerical simulation on a flow over a wavy boundary without separation to investigate particle motion. He found that large longitudinal vortices similar to Langmuir vortices were generated, and there was no strong relation between particle concentration and shear stress along the wavy boundary. Marchioli et al. (2006) and Widera et al. (2009) also discussed discordance of maximum and minimum locations of shear stress and particle concentration in their simulations. Marchioli et al. (2006) observed that particles move opposite to the streamwise direction from the trough to the downslope region due to recirculation. Also, after the reattachment point, a large number of particles hit the wall and were entrained by ejection due to quasi-streamwise vortices. The roles of vortical structures on entrainment and resuspension of

* Corresponding author at: Department of Computational Science and Engineering, Yonsei University, Seoul 120-749, South Korea.
E-mail address: clee@yonsei.ac.kr (C. Lee).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.08.009
0301-9322/

particles near wavy boundary were investigated by Chang and Scotti (2003). They initially distributed particles uniformly over the wavy surface, and the particles were allowed to move in the location where bed shear stress exceeded the critical value. Strong vortical structures near the upslope boundary entrain particles to the particle cloud. In Marchioli et al. (2006), snapshots of instantaneous particle distribution over a wavy boundary provided some clues on the interaction between particles and the structures. Although they calculated the number of particles hitting each location of the wavy wall, other statistics of particle motion were not fully discussed. Moreover, most research focused on Lagrangian particle tracking in turbulence over wavy boundary were based on LES (Marchioli et al., 2006; Widera et al., 2009; Chang and Scotti, 2003). Their simulations could not capture the essential turbulent scales observed near the wavy boundary, particularly detailed motion of particles.

In this study, particle motion in turbulent flow over a wavy boundary is investigated in a fully resolved direct numerical simulation of turbulent wavy channel flow using a spectral method. To impose the no-slip condition at the wavy boundary, the virtual boundary method proposed by Goldstein et al. (1995) is used. Focusing on the distinct characteristics from a flat boundary, turbulence in three wavy boundaries with different length scales is investigated. Also, behavior of particles over these three wavy geometries is discussed in comparison to one over a flat wall in terms of the statistics of particle motion for various Stokes numbers.

In Section 'The numerical model', the problem is defined and numerical methods are described with validation. Flow characteristics over the wavy boundaries with different waviness are shown in Section 'Flow characteristics'. Section 'Behavior of particles' presents the particle distribution and the statistics related to particle motion in the flow over a wavy boundary. Section 'Conclusion' provides the conclusions of the study.

The numerical model

Numerical method for continuum phase

The Navier–Stokes equations for a Newtonian, incompressible fluid normalized by the wall-shear velocity (u_τ), kinematic viscosity (ν), and channel half-gap (δ) with continuity are considered in the forms

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re_\tau}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + F_i \tag{1}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

with external force F_i acting on the virtual boundary points. Fourier and Chebychev expansions are used in homogeneous directions and the wall normal direction, respectively. The time advancement is carried out by Crank–Nicolson scheme for viscous terms and a third-order Runge–Kutta scheme for nonlinear terms.

The virtual boundary method is a simple method which determines F_i such that the fluid motion is brought to rest at the boundary. The virtual forcing F_i is a kind of feedback forcing based on the velocity at the virtual surface U_i and its integration over time (Goldstein et al., 1995; Saiki and Biringen, 1996; Lee, 2002),

$$F_i(t) = \alpha \int_0^t U_i(t')dt' + \beta U_i(t) \tag{3}$$

where α and β are negative gains so that the virtual forcing is acting in the opposite direction to the virtual surface velocity. As the surface velocity eventually converges to zero, the first term on the right-hand side converges to a certain value which represents forces acting on fluid. Suggested by the stability analysis for the third-order Runge–Kutta scheme (Lee, 2002), we choose $-\alpha\Delta t^2_{max} = 40.0$ and $-\beta\Delta t_{max} = 4.0$. Velocity at virtual points U_i are determined by a tri-linear interpolation. A similar forcing scheme was previously used in the simulation of a turbulent flow over a rough wall (Lee, 2003).

Fig. 1 shows the computation domain of channel flow over a wavy boundary. Between two infinitely wide flat walls separated by 2δ, the sinusoidal wavy boundary is placed above the bottom wall. The flow domain (L_x, L_y, L_z) is set to be $(7.6, 2, 4\pi/3)\delta$ in size, and the number of grid, $N_x \times N_y \times N_z$, is $144 \times 257 \times 192$. The average distance between the top flat wall and the bottom wavy wall is 1.9δ, and the number of virtual boundary points to impose the no-slip condition at the wavy interface is $8 \times N_x \times 4 \times N_z$ including additional virtual boundary points placed under the wavy boundary to produce zero velocity under the wavy boundary. All test cases were initialized by a fully developed turbulent flow field at $Re_\tau = 180$, and after applying the virtual boundary effect, the flow condition in Table 1 were obtained by increasing the pressure gradient. All parameters with the superscript '+' are nondimensionalized by the wall shear stress u_τ of the lower wavy wall. Re_τ^{top} and Re_τ^{bottom} are determined by wall shear stress u_τ of the upper and lower wavy walls, respectively. The characteristic lengths defining Re_τ^{top} and Re_τ^{bottom} are the distance between each wall and the flow center ($\tau = 0$). If waviness is defined as the ratio of the height and wavelength of a wave ($2a^+/\lambda^+$ in Table 1), W1 is a case with strong waviness with $\lambda^+ = 624$ and $2a^+/\lambda^+ = 0.1$, while W2 ($\lambda^+ = 1165, 2a^+/\lambda^+ = 0.05$) and W3 ($\lambda^+ = 1081, 2a^+/\lambda^+ = 0.025$) cases correspond to moderate and weak waviness, respectively.

Particle tracking

Movement of spherical heavy particles is determined by taking account of the Stokes drag only by the following equations.

$$\frac{dX_i}{dt} = V_i \tag{4}$$

$$\frac{dV_i}{dt} = \frac{1 + 0.15Re_p^{0.687}}{\tau_p}(u_i - V_i) \tag{5}$$

where X_i and V_i are the particle location and velocity, and u_i is fluid velocity at the particle location. The parameter Re_p is the particle Reynolds number based on the magnitude of the slip velocity and diameter of a particle, and τ_p $(= \rho_p d_p^2/18\mu)$ is the particle relaxation time with ρ_p, d and μ denoting density and diameter of a particle and viscosity of fluid, respectively. To obtain velocities at a certain particle position, four-point Hermite interpolation and six-point Lagrange interpolation are used in the homogeneous and wall-normal directions, respectively (Choi et al., 2004). If the particle is

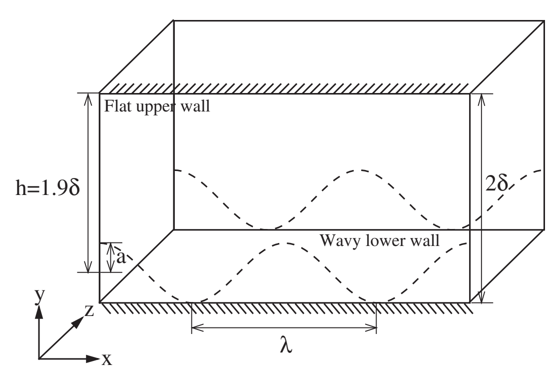

Fig. 1. Schematic diagram of channel flow over a wavy bottom wall.