EFFECTS OF PARTICLE SIZE AND SOLID-TO-FLUID DENSITY RATIO ON THE DYNAMICS OF PARTICLE-LADEN HOMOGENEOUS SHEAR TURBULENCE

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Abstract Particulate turbulent flows are encountered in many natural and industrial situations. In the present study, we numerically investigate how the dynamics of particle-laden homogeneous shear turbulence depends on the particle size and solid-to-fluid density ratio in order to deepen the understanding of the interaction between particles and turbulent shear flows. We consider the situation where the particle diameter is five to ten times larger than the Kolmogorov scale of turbulence with a solid-to-fluid density ratio between 0.5 and 10. An immersed boundary method is adopted to represent the spherical finite-size particle. Numerical results show that small particles enhance the viscous dissipation inside viscous layers surrounding particles, which leads to the suppression of the growth of homogeneous shear turbulence. The viscous dissipation is further enhanced through the modification of turbulence structure. The enhancement of the viscous dissipation depends strongly on the solid-to-fluid density ratio as well as particle size. In the cases of high density ratio, the generation of vortex tubes is activated around the particles, which leads to the modification of vortex layers and the enhancement of the viscous dissipation.

INTRODUCTION

Particulate flows are encountered in many natural and industrial situations, such as riser flows and polymer suspensions. Many studies have been carried out to understand the turbulence modulation due to particles. Turbulence is modulated through the interactions between the particles and coherent flow structures in addition to the direct effects of particles such as the enhancement of dissipation and generation of velocity fluctuations due to wake shedding. Some studies have been conducted for the turbulence modulation in homogeneous turbulent shear flow, which is one of the simplest flows that have a generation mechanism of turbulence. Previous studies have found that the presence of particles in zero gravity suppresses the growth of turbulence energy of the fluid flow and that the effect of gravity can enhance or suppress the growth of turbulence [1, 2]. However, these results were obtained for heavy particles whose diameter is much smaller than that of the smallest flow scales and the modulation mechanisms for finite-size particles have not been fully understood at the present. In the present study, we examine the dynamics of homogeneous shear turbulence laden with spherical finite-size particles by the use of fully resolved direct numerical simulations to clarify the modulation mechanisms. Here, we focus on the situation where the particle diameter is five to ten times larger than the Kolmogorov scale with a solid-to-fluid density ratio between 0.5 and 10.

COMPUTATIONAL METHOD AND RESULTS

We consider the motion of spherical solid particles in homogeneous turbulence subjected to a uniform mean shear, which is in the x_1 direction and is a linear function of x_2, $\boldsymbol{u} = (Sx_2, 0, 0)$, where S is the shear rate. The turbulent flow is assumed to be periodic. Due to the presence of the uniform mean shear, the shear-periodic boundary condition, $f(x_1, x_2 + L_2, x_3) = f(x_1 - StL_2, x_2, x_3)$, is applied for the x_2 direction, where L_2 denote the domain size in the x_2 direction.
The numerical method employed in this study is based on an immersed boundary method (IBM) developed in Uhlmann[5] and Kempe and Fröhlich [6]. IBM solves a single set of continuity and momentum equations in the entire domain including the particulate phase, without any internal boundary conditions. Instead, the force distribution effectively imposes constraints on the fluid motion that approximate the boundary conditions. The regularized delta function is used to obtain smoother and less oscillatory boundary force. The position, velocity and angular velocity of the bubble are obtained by solving the equations of the translational and rotational motions of the particles. The Navier-Stokes equations are solved by using finite difference schemes on a staggered grid with cubic grid cells. The time-integration is based on a fractional-step method. The second-order central difference scheme based on the interpolation method is applied in the finite differencing of the convection terms of the momentum equations. The second-order central difference scheme without the interpolation method is applied for the viscous terms. The advection due to the mean shear flow is solved separately by Fourier approximation as in Gerz et al. [3]. A variety of numerical tests have been performed to validate the method including a falling particle in still fluid and a freely rotating particle in a simple shear flow.
The simulations are performed in a computational domain of $4\pi \times 2\pi \times 2\pi$ with $896 \times 448 \times 448$ cubic grid cells. The initial velocity field for the carrier fluid is given with Fourier coefficients with random phase and with a prescribed energy spectrum. The initial Reynolds number and shear rate parameter are set at 16 and 8, respectively [4]. The grid

resolution is about 5 times higher than that in [4]. We have introduced 819 (or 1222) particles whose diameter is about 6.4 (or 4.8) times larger than the Kolmogorov length at the initial instance. The particle volume fraction is 0.5×10^{-2} and the solid-to-fluid density ration is in the range between 0.5 and 10. A computation without particles is also performed for comparison. Hereafter, we focus on the cases of the larger particles with the density ratio of 0.5, 1.0 and 5.0.

The turbulence energy in the single-phase flow increases exponentially in time. Figure 1 shows the time evolution of the ratio of turbulence kinetic energy in the particulate flow to that in the single-phase flow. In the case of the high density ratio, the injection of the particles causes considerable suppression in the growth of turbulence energy. The change of the energy ratio is relatively small for the density ratios of 0.5 and 1.0. We examine the increase rate of the turbulence kinetic energy. The positive contribution from the production and interphase-interaction terms, and the negative contribution from the dissipation term are shown in figure 2. The dashed lines represent the corresponding single-phase flows. The magnitude of the production term exceeds that of the dissipation term, which indicates an increase in turbulence kinetic energy. We notice that the magnitude of the dissipation term is noticeably increased due to the presence of particles with high density ratio. The relative magnitude of the dissipation term is further increased after *St* = 10, which leads to the significant suppression of turbulence energy. The increase in the viscous dissipation is associated with the modification of vertical structures due to particles. Figure 3 shows the distributions of λ_2 around the particles, which is related with vortex tubes near the particles. The regions of large negative λ_2, where the swirling fluid motion is predominant, is represented by red. It is clearly seen that the regions of large negative λ_2 are distributed on the right and left sides of the particle (as indicated by circles). This suggests that vortex tubes are generated there due to the effects of wake flows induced by the particle. It is found that this leads to the modification of vortex layers and the enhancement of the viscous dissipation (figures omitted).

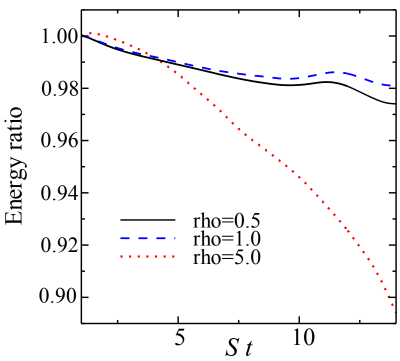

Figure 1. Time evolution of the energy ratio.

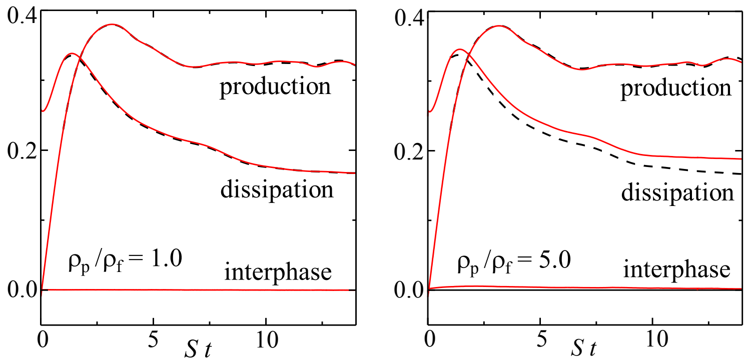

Figure 2. Time evolution of the contributions to the increase rate of turbulence energy.

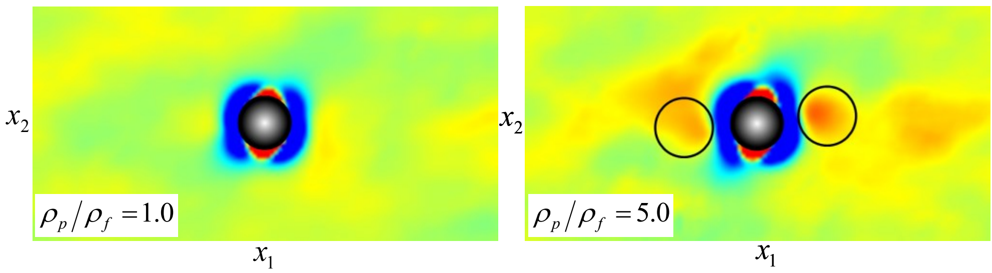

Figure 3. Average value of λ_2 around particles.

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