DYNAMICS OF HOMOGENEOUS SHEAR TURBULENCE LADEN WITH FINITE-SIZE PARTICLES

Mitsuru Tanaka[1] & Takayuki Wazaki [1]
[1]*Dept. of Mech. and System Engng., Kyoto Institute of Technology, Kyoto JAPAN*

Abstract Particulate turbulent flows are encountered in many natural and industrial situations. 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 in order to understand how the presence of particles modulates turbulence. We focus on the situation where the particle diameter is a few times larger than that of the vortex core in turbulence. An immersed boundary method is adopted to represent the spherical finite-size particle. Numerical results show that the particles activate the generation of longitudinal vortex tubes leading to the formation of the clusters of vortex tubes in zero-gravity situation. In finite gravity, the particles also cause the breakdown of vortex tubes and the clusters of vortex tubes are less noticeable.

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, 5]. 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 particles are a few times larger than that of the vortex core in the turbulence.

COMPUTATIONAL METHOD

We consider the motions of solid particles falling in homogeneous turbulence subjected to a uniform mean shear, which is in the x_1 direction and is a linear function of x_2, $\overline{\boldsymbol{u}} = (Sx_2, 0, 0)$, where S is the shear rate. The gravitational force is directed in the x_1 direction. 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[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.[2]. The 2nd-order Adams-Bashforth and Adams-Morton methods are used for the particle velocity and position, respectively. Although the accuracy and efficiency of this scheme have been extensively examined by Uhlmann[6], we have conducted an additional test for rotational motions of particles considering their importance in the shear flow. The angular velocity of a freely rotating particle in a simple shear flow is found to agree quite well with that obtained by a pseudo-spectral method[4] (see Fig.1).

The simulations are performed in a computational domain of $4\pi \times 2\pi \times 2\pi$ with $256 \times 128 \times 128$ 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 as in Kida and Tanaka[3]. The grid resolution is about 1.5 times higher than that in [3]. Twenty particles whose diameter is about 30 times larger than the Kolmogorov length are introduced at the initiall instance. The particle volume fraction is 0.52×10^{-2} and the density ration is 2.0. The strength of the gravity is set at $g^+ = 0$ and $g^+ = 1$, where g^+ denotes the gravitational acceleration normalized by the Kolmogrov scales. A computation without particles is also performed for comparison.

RESULTS

Figures 2 show the time development of turbulence kinetic energy and enstrophy of the carrier fluid. The turbulence energy in the single-phase flow increases exponentially in time. In spite of the small volume fraction, the injection of the particles causes a considerable augment of the turbulence energy and enstrophy, namely, the growth of turbulence is enhanced by the particles. The effect of gravity further enhances the the growth of turbulence energy. The enhancement of the growth of enstrophy due to the gravity is less pronounced. In Figs. 3, vortex tubes are visualized by using the isosurfaces of $Q/S^2 = 3.0$, where Q denotes the second invariant of the velocity-gradient tensor. Comparing Figs. 3(a) and 3(b), we notice that the generation of vortex tubes are activated by the presence of particles in the case of $g^+ = 0$. The clusters of vortex tubes are formed at a later time in zero gravity as is shown in Fig. 3(c). The enhancement of vortex generation is also observed in the case of $g^+ = 1$. When we focus on the particle marked by a circle in Fig. 3(d) and compare it with the corresponding particle in Fig. 3(b), we notice that the vortex tubes are weakened around the particle due to the effect of gravity. It is also seen that the clusters of vortex tubes are less noticeable in finite gravity.

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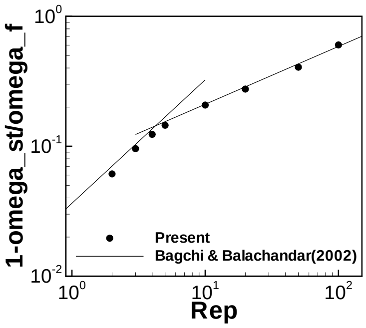

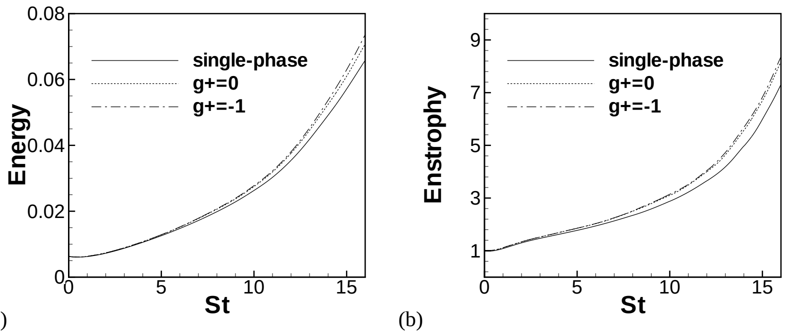

(a) (b)

Figure 1. Angular velocity of a particle in a simple shear flow as a function of Reynolds number base on slip velocity.

Figure 2. Time evolution of (a) turbulence energy and (b) enstrophy. Solid, dashed, and dotted lines represent single-phase flow and multiphase flows in zero and finite gravities, respectively.

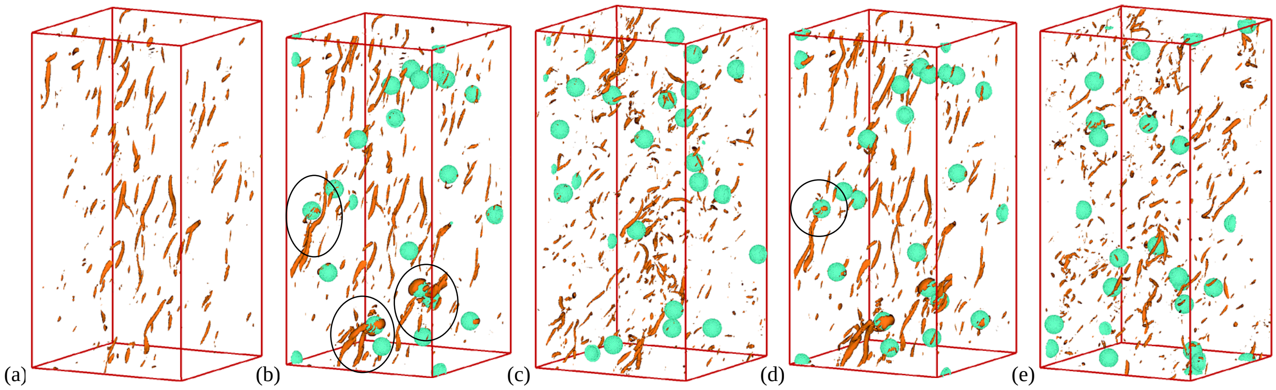

Figure 3. Isosurfaces of $Q/S^2 = 3.0$ in (a) the single-phase flow at $St = 8$ and in the multiphase flows in the case of $g^+ = 0$ at (b) $St = 8$, (c) $St = 16$ and in the case of $g^+ = 1$ at (d) $St = 8$, (e) $St = 16$.