DNS of turbulence modulation due to solid particles

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We applied the direct numerical simulation (DNS) to investigate the particle-laden turbulence in fully-developed upward flow in a vertical channel. In this report, particular attention is focused on the influence of particle rotation. Rotating particles are distributed more uniformly in the channel in comparison with irrotational ones. Flow separation from irrotational spheres develops to hairpin vortices in near-wall region, while flow around rotational ones increases small scale turbulence in the mainstream region.

Keywords: Turbulent flow, Two-phase flow, Direct numerical simulation,
Solid particle, Rotation

1 Introduction

Turbulent flows including solid particles are often observed in industry and nature. Solid particles may change the turbulence and accordingly affect the transfer of momentum, heat and mass. However the turbulence mechanism of the particle-laden flows has not been understood. Therefore the theoretical description of turbulence modulation and the particle motion in fluid turbulence have not established yet. The particle rotation can be one of the important factor because the particle distribution, the non-uniformity of density, is influenced by the lift force. The modeling of the exchange of angular momentum between particles and fluid in turbulent flows is poorer than that for translational momentum.

We investigated effects of solid particles on the fully-developed turbulent flow in a vertical channel[1][2]. The agreement between our DNS and experimental data[3] for upward flow was satisfactory for particles of Reynolds number at around 50[1]. In addition, we conducted the DNS for downward flow and found the overall momentum exchange was dominant for turbulence modulation. In this case, the particle distribution was important but the particle rotation was not essential. For larger Reynolds number at around 300[2], each particle shed hairpin-type vortices unsteadily. In the shear flow, the orientation of vortex shedding tended to be fixed. Thus these unsteady vortex shedding caused the production of turbulent shear stress.

In our previous works[1][2], the rotation of solid particles was not considered. But it might affect the particle distribution and, especially for the higher Reynolds number case, the flow around each particle. We recently conducted DNS with the corresponding condition of higher particle Reynolds number, considering the particle rotation.

2 Outline of Computation

The DNS technique was applied to a flow between vertical planes. Since the numerical scheme and computational condition were given in our previous paper[2], they are briefly outlined here. The mainstream direction, which is upward vertical direction, is x, the wall-normal direction is y and the spanwise direction is z, respectively. Considering a fully-developed flow in a two-dimensional channel, the periodic condition is applied to x and z directions. The boundary condition on the solid wall is non-slip for fluid.

The Reynolds number based on the wall-friction velocity u_τ and channel width H is fixed as 300. The number of grid points in each direction is N_x =512, N_y =128 and N_z =256. The grid spacings in wall-unit are Δx^+ =4, Δy^+ =0.74$\sim$3.83 and Δz^+ =4. For single phase flow, the Reynolds number based on the bulk velocity U_m and H became 4,600 and this value was in good agreement with DNS database[4].

Solid particles are assumed to be rigid spheres of a uniform size. The diameter is D_p^+=32 in wall units. The density ratio between solid and fluid is ρ_p/ρ_f =10, which was adjusted so that a particle falls in a stationary fluid with Reynolds number 300. The grid resolution, namely 10 grid points in a diameter, has been confirmed enough to capture the vortex shedding in our previous work. The additional pressure gradient is necessary to maintain the same friction velocity at the wall because higher density particles are mixed. We adjusted it by trial and error and was fixed to be constant value.

The number of solid particle is N_p =36. As the volumetric fraction is about 0.1%, the possibility of particle-particle collision is quite low. Then we use a very simple assumption, that is a fully elastic collision without any exchange of angular momentum. For simplicity, particle-wall interaction is also treated by the same way. Thus, any dissipation due to these interactions are not taken into account in this situation. As an initial condition, particles were randomly distributed in a fully-developed flow obtained by DNS for single phase fluid. The initial velocity of particle was that for fluid velocity at the center and the rotation rate was zero. After confirming the fully developed stage was reached, we continued time-marching and obtained a time-averaged statistics.

Hereafter, the effect of particle rotation is compared. The ‘irrotational particle’ is a virtual case, in which the angular momentum of the particle is always fixed as zero. The detail of computational result has already reported in our previous paper. In addition, the ‘rotational particle’, which is a natural case, is used in this work. Such kind of comparison is possible only in the numerical experiment and we expect it suggest the influence of a particular factor.

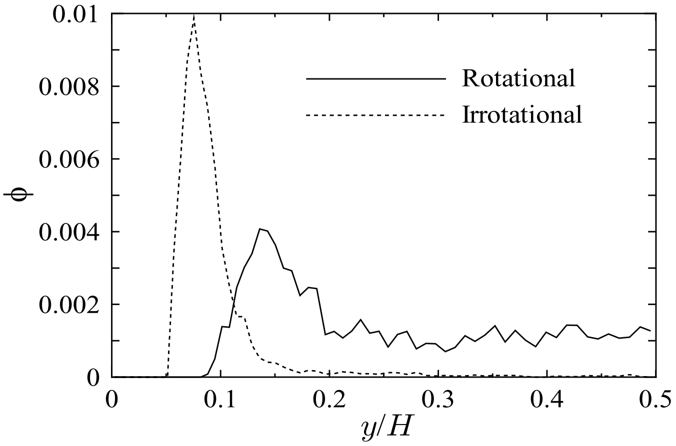


Figure 1: Volumetric fraction of solid phase

3 Results and Discussion

Figure 1 shows the distribution of particles by the volumetric fraction ϕ. It becomes small in the vicinity of the wall since the distance between particle center and wall can not be smaller than the radius. The concentration of irrotational particles shows local maximum at $y^+ \simeq 23$. These particles move up almost along the walls but sometimes they move to the other side in the channel. As a consequence, the distribution is symmetric in a long time average. The direction of fluid force on a sphere fixed in a uniform shear flow was studied by Kurose and Komori[5] and Cherukat, et al.[6]. They said the force was to the higher velocity side for Reynolds number lower than $Re_p \simeq 100$ and opposite for higher Reynolds number. The trend in our simulation with irrotational particles was basically corresponding to their findings. On the other hand, the concentration of rotational particles becomes weak maximum at $y^+ \simeq 45$ but the distribution is more uniform. It is due to the rotation caused in the high shear region near the wall. Particles move into the mainstream region by the lift force and then they may return to the wall region after the decay of rotation.

Figure 2 shows mean velocity profiles. In the particle-laden flow, the upward flow is decelerated in high ϕ region of heavy particles, in comparison with single phase case. This tendency is evident especially by irrotational particles because of the high density in the near-wall region. But the velocity profile recovers the logarithmic layer in low ϕ region. The deceleration is not so significant in the case of rotational particles. The almost uniform addition of particles is in balance with an additional pressure gradient. Therefore, we can conclude the modulation of mean velocity profile is related to the non-uniformity of density.

Figure 3 shows the root-mean-square (rms) values of velocity fluctuation. Irrotational particles increased the intensity of streamwise component u_{rms} in the region from high ϕ to the mainstream. Other components, v_{rms} and w_{rms}, are increased everywhere. These increase from the single phase case are associated with the vortex rings shed from irrotational particles[2]. In contrast, the turbulence intensity is reduced in the near-wall side of the location of maximum ϕ by rotational particles. This reduction of turbulence might be explained by that the particle rotation takes some part of the shear stress. In the mainstream region, turbulent intensity increases because of the disturbance by particles.

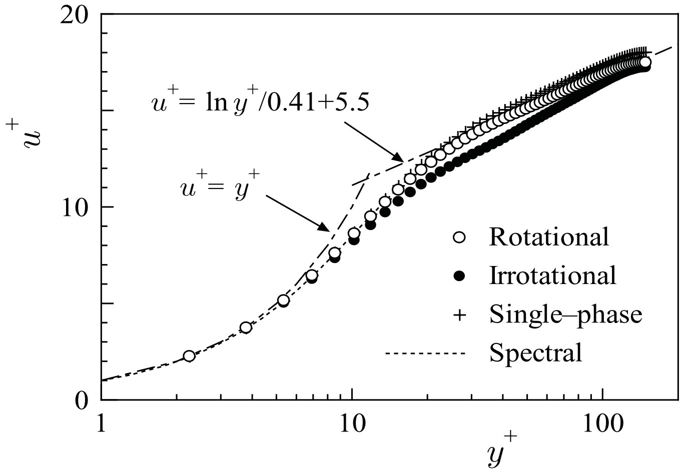


Figure 2: Mean velocity of fluid-particle mixture in upward direction

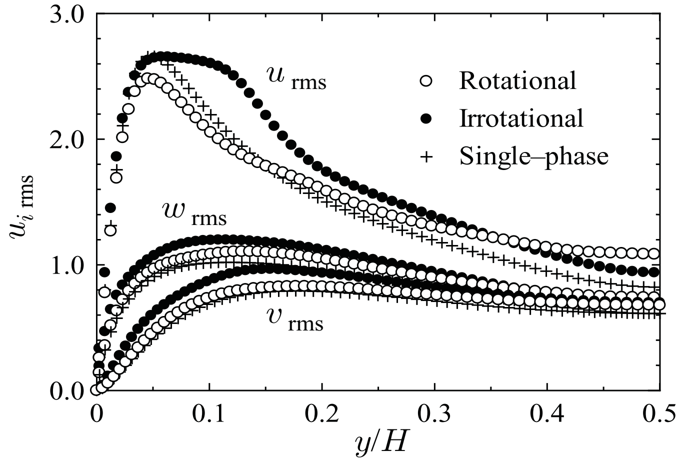


Figure 3: Intensity of velocity fluctuations: u in upward, v in wall-normal and w in spanwise directions

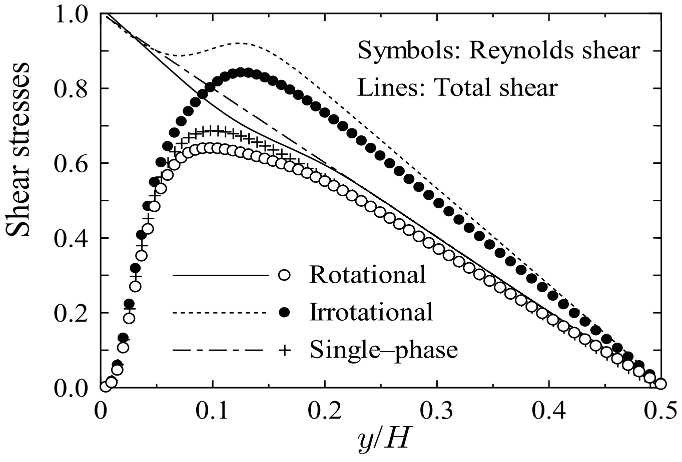
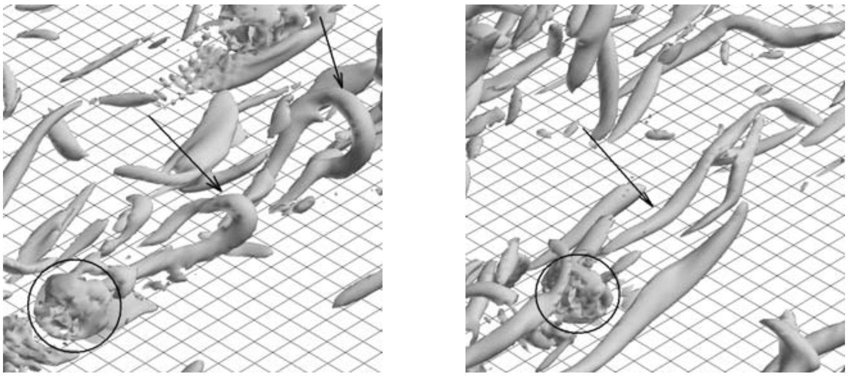


Figure 4: Shear stress: Reynolds shear stress and the total of turbulent and viscous stresses

Figure 4 shows the shear stress profiles; the turbulence shear stress by plots and the total of turbulence and viscous shear stresses by lines. In the single-phase turbulence, the total shear has constant gradient, as shown in the dot-dashed line in Fig. 4, to be balance with the pressure gradient. In the particle-laden case, the shear stress profile might be also linear if particles would be distributed uniformly. However, the result is not so because of non-uniformity in particle distribution. The shear stress gradient can be smaller in the region of high concentration of heavy particles. In the sparse region, on the other hand, the shear stress gradient should be larger to be balance with added pressure gradient to maintain the flow including heavy particles. Thus the dotted line of irrotational case has large gradient in the mainstream region.



(a) Irrotational particles (b) Rotational particles

Figure 5: Shed vortices from spherical particles: visualization by $\nabla^2 p$

To observe the structure in particle wakes, Fig 5 gives a typical example of vortices around particles in the vicinity of the wall. The figure shows instantaneous iso-surfaces of $\nabla^2 p$. Vortex rings shed intermittently from irrotational particles are elongated in the strong shear layer near the wall. Then they form hairpin-like eddies as indicated by arrows shown in Fig. 5(a), and they move toward the central portion of the channel while carried downstream. Legs of these hairpin-like eddies contribute to the energy production increase through increases in turbulence shear stress [2]. But the actual particle obtains angular momentum from the high shear. Thus, in the flow field shown in Fig 5(b), vortices that produces Reynolds shear stress directly can not be observed around rotational particles.

4 Conclusions

The turbulent flow including spherical particles was directly simulated. The mean flow is upward in a vertical channel. In our computation, flow around each particle was successfully resolved by a simple immersed-boundary method. In this study, particular attention was focused on the influence of particle rotation. To this end, we conducted a numerical experiment by accounting for or switching off the equation of angular momentum.

The irrotational (virtual) particle has a lift force towards the wall. This is corresponding to the recent literatures but opposite to the Saffman's model. The rotational (natural) particle, on the other hand, has a Magnus lift force in the near wall region, which is away from the wall. Thus particles distribute uniformly in the latter case.

In the practical computation using a point-force model for particles often ignores their rotation. Otherwise, the model for angular momentum equation has not adequately verified. Our DNS result suggests the rotational motion of particles in turbulent flow field affect seriously to the reliability on the predictions of particle distribution and mean-velocity profile.

The situation that a particle released in fluid flow is irrotational is not realistic. It is possible only in the numerical simulation and useful for parameter analysis. Actually, aside from the present work, we have elucidated dynamics of particle clusters in a homogeneous flow [7] and the influence of particle rotation for it [8] by the DNS including more than 2000 particles.

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