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Analysis of interphase forces and investigation of their effect on particle transverse motion in particle-laden channel turbulence

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ABSTRACT

The current study attempts to investigate the relative importance of interphase forces and their effect on particle transverse motion in a particle-laden channel turbulence using the four-way coupled direct numerical simulation based on the point-particle model. The theoretical methods including the frequency analysis and the dimensional analysis were also derived to estimate the relative importance of interphase forces. Meanwhile, the calculation method of the Basset force was also investigated. It was found that the relative importance of different forces obtained by theoretical method and that obtained by numerical simulation can agree well with each other. The integration time scale should not be shorter than the particle relaxation time and the integration time step can be set as the mean Kolmogorov time scale when calculating the Basset force. The Basset force and lift force were found significant relative to the drag force while the added mass force, the Magnus lift force and the pressure gradient force were negligible. The particle transverse motion was confirmed to be the main reason for flatter particle velocity profile. The effects of different interphase forces on particle transverse motion were investigated in detail. In addition, the combined effects of different forces were also researched.

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1. Introduction

Particle-laden flow is widely applied in industrial and environmental practice such as the spray burning, fluidized beds and two-phase flow in dedusting equipment (Wang et al., 2009; Lei et al., 2008). The flow of nanofluid also belongs to this flow type and it is thought to improve the heat transfer efficiency (Bahiraei and Hangi, 2014). Thus the particle-laden flow has been researchers' object of study for several decades. The Euler–Lagrange approach is widely employed to investigate the particle-laden flow especially in the dilute conditions (Pan and Banerjee, 1996; Bahiraei and Hangi, 2013). In particular, the Euler–Lagrange approach with direct numerical simulation (DNS, hereafter) is proved to be an effective tool in the research of particle-laden turbulence (Nasr et al., 2009; Vreman, 2015).

By adopting the Euler–Lagrange DNS on particle-laden flow, the continuous flow field is obtained with the Navier–Stokes equation solved without any turbulence model, while the particle is tracked by Newton's second law of motion under the Lagrange Coordinates based on the particle-source in cell (PSIC) model (Li et al., 2001). Obviously, description of the particle motion and of the interaction between the two phases depends on correct calculation of the forces acting on the particles. However selections of interphase forces differ in different researchers. Some forces occurring in the process were neglected before being evaluated and therefore it is necessary to analyze the interphase forces comprehensively.

To our knowledge, most calculations of the particle motion in the literature were based on the formula proposed by Maxey and Riely (1983). The equation can be expressed as follows:

$$m_p \frac{du_{pi}}{dt} = F_{Di} + F_{Bi} + F_{AMi} + F_{Pi} + F_G \tag{1}$$

where m_p is the mass of the particle which defined as $\pi \rho_p d_p^3/6$, d_p refers to the particle diameter and ρ_p is the particle density. u_{pi} refers to particle velocity and t is the time. The terms on the right side of the equal sign refer to the drag fore, Basset history force, the force due to added mass, pressure gradient force and body force respectively. In addition, there are lift forces acting on particles moving in turbulence, for example the shear-induced lift force, wall-induced lift force and Magnus lift force. The lift force may also have significant influence on particle motion in the shear flow field such as wall turbulence. Thus many researchers took the lift force into consideration when tracking the particle (Zhang and Ahmadi, 2000; Nasr et al., 2009; Lain, 2013). Armenio and Fiorotto (2001) analyzed the importance of the forces that act over an ensemble of particles in a turbulent channel flow by direct numerical

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Table 1
Forces considered in the simulations of particle-laden turbulence.

Literature	Drag	Gravity	Lift	Magnus lift	Pressure gradient	Basset	Added mass	Collision
McLaughlin (1989)	√	–	√	–	–	–	–	–
Chen and McLaughlin (1995)	√	–	√	–	–	–	–	–
Pan and Banerjee (1996)	√	√	–	–	√	–	–	–
Chen et al. (1998)	√	√	√	–	–	–	–	√
Zhang and Ahmadi (2000)	√	√	√	–	–	–	–	–
Li et al. (2001)	√	√	√	–	–	–	–	√
Yamamoto et al. (2001)	√	√	√	√	–	–	–	√
Dragan and Loth (2004)	√	√	–	–	–	–	–	–
Vance et al. (2006)	√	–	–	–	–	–	–	–
Marchioli et al. (2008)	√	–	–	–	–	–	–	–
Nasr et al. (2009)	√	–	√	–	–	–	–	√
Chen et al. (2011)	√	–	–	–	–	–	–	√
Kuerten et al. (2011)	√	–	–	–	–	–	–	–
Kubik and Kleiser (2011)	√	√	√	–	–	–	–	–
Lain (2013)	√	√	√	√	–	–	–	√
Nicolai et al. (2014)	√	–	–	–	–	–	–	–
Lee and Lee (2015)	√	–	–	–	–	–	–	–
Richter (2015)	√	–	–	–	–	–	–	–
Vreman (2015)	√	–	–	–	–	–	–	√

simulation. The density ratio in their simulation had a wide range ($2.65 < \rho < 2650$). It is observed that the added mass force is always negligible compared to the Stokes drag. The pressure gradient force is relevant for density ratios $O(1)$ and the Basset force is appreciable for the whole density ratio range investigated. Armenio and Fiorotto (2001) also indicated that the magnitude of the lift force was significant for particles moving within the viscous sublayer.

Although some researchers have tried to evaluate the importance of the interphase forces acting on particles in turbulent flows (Elghobashi and Truesdell, 1992; Armenio and Fiorotto, 2001), the choice of the interphase forces in the equation of particle motion is still somewhat subjective. The forces considered in the high accuracy simulations of particle-laden shear turbulence were listed in Table 1. The inter-particle collision is also included in Table 1 because it can be regarded as non-continuous force acting on the particles. From Table 1, it can be seen that different researchers included various forces in the equation of particle motion. In general, most of the researchers took the drag force and gravity into consideration, while the pressure gradient force, Basset force and virtual mass force were always neglected. Moreover, many investigators included the lift force into the equation of particle motion, while only a few researchers considered the effect of Magnus lift force.

Usually, the researchers choose interphase forces prudently according to their research objects and aims. Pan and Banerjee (1996) neglected the Basset force and added mass force because they thought these two forces were relatively small compared with the drag force. In the large eddy simulation conducted by Wang et al. (1997), forces associated with virtual mass, buoyancy and history effects were neglected because these forces were deemed substantially smaller than the drag force. Lain (2013) neglected the Basset history force, added mass force and pressure gradient force due to high ratios of particle to gas density. In the simulation of Bahiraei and Hosseinalipour (2013), besides the gravity, drag force and Saffman's lift force, the Brownian force and thermophoretic force were also considered in the equation of particle motion because the particle was very small and there existed temperature gradient in the continuous phase. Vreman (2015) only considered the drag force because the focus of his study is the effect of wall roughness on particle-induced turbulence attenuation. However, it can still be seen that the importance of different interface forces has not yet been known clearly. Therefore it is necessary to investigate all the interphase forces in detail and set up criteria for selection of these forces. This study is designed to evaluate the importance of different interphase forces through theoretical analysis and numerical calculation.

As it has been discussed above, the Basset force was neglected almost in all simulations. By a frequency analysis, Pan and Banerjee (1996) evaluated the contribution of the Basset force and concluded that it was much smaller than the quasi-steady Stokes drag force. However, Elghobashi and Truesdell (1992) considered all interphase forces in their direct numerical simulation of particle dispersion in a decaying isotropic turbulence. They indicated that the drag force and gravity were significant in the gravity direction, while the drag and Basset forces were the main forces in the lateral directions although the drag force was one order of magnitude larger than the Basset force. Armenio and Fiorotto (2001) also pointed out that the Basset force was considerable compared with the Stokes drag. Aartrijk and Clercx (2010) studied the dispersion of light inertial particles in statistically stationary stably stratified turbulence by means of direct numerical simulation. It was found that the Basset force played a considerable role in the vertical dispersion of light particles and neglecting the Basset force resulted in an overprediction of the vertical dispersion. The findings indicated the importance of the Basset force and thus it should be investigated in detail. Furthermore, the use of numerical method to calculate the Basset force also needs discussion because most researchers neglected the Basset force in their simulations. The main procedure in calculating the Basset force is to solve an integral, making it necessary to investigate the selections of integration time and integration time step.

The transverse migration of particle is significant in the particle-laden vertical channel flow. In the experiments operated by Kulick et al. (1994) and Paris (2001), it was noted that the particle velocity profile was flatter than the gas phase profile in vertical channel which means that particles at the center of the channel move slower than the gas while the particles near the wall move faster than the gas. In addition, the simulations conducted by Li et al. (2001), Vance et al. (2006) and Vreman (2015) also showed similar findings. This phenomenon was presumed to be caused by transverse migration of particle but was not deeply analyzed. It is obvious that the interphase forces play an important role on transverse migration of particle, and the contribution of different forces was made clear through investigating the effect of different interphase force on transverse migration.

In the present work, particle-laden turbulence in a vertical channel is simulated by a series of DNS based on PSIC. The focuses

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