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Effects of granular temperature on inter-phase drag in gas-solid flows

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ABSTRACT

Direct numerical simulations with a second-order immersed boundary-lattice Boltzmann method are used to investigate the effect of particle fluctuation on flows in fixed random arrays of spheres at low and moderate particle Reynolds numbers. Random velocities obeying the isotropic Maxwellian distribution are imposed to all particles in the computational domain to mimic the granular temperature due to particle collisions. The simulation results show that the effect of particle fluctuation on the drag force is significant especially when the solid volume fraction and the particle Reynolds number are small. The drag increment due to the particle fluctuation increases with the increase of the granular temperature-based Reynolds number, however, it decreases with the increase of the solid volume fraction and the particle Reynolds number. On the basis of the simulation results, a new drag force relation based on the stationary drag in random arrays of spheres for arbitrary solid volume fractions, granular temperature-based Reynolds numbers, and particle Reynolds numbers is formulated. The fluctuations of the drag force on individual particles with respect to the mean drag are also analyzed. It is found that the drag on individual particles can differ up to 40% from the mean at small granular temperature-based Reynolds numbers and the difference increases rapidly with the increase of the granular temperature-based Reynolds number, indicating the particle fluctuation can affect the individual drag force significantly. The present results also show the drag force on individual particles well follows Gaussian distribution. The mean relative deviation is found to increase with the increase of the granular temperature-based Reynolds number and the solid volume fraction but is not affected much by the particle Reynolds number.

1. Introduction

Gas-solid flows have been attracting more and more attention due to their widespread use and popularity in various industrial processes, such as coal gasification, food production, pharmaceutical processing, environmental and energy industries, and so on. In the past two decades, computational fluid dynamics (CFD) has become an acknowledged tool for predicting the behavior of gas-solid flows. In CFD simulations, of critical importance is the gas-solid drag correlation that describes the interaction between gas phase and solid phase. Among the various CFD methods, the particle-resolved direct numerical simulation (PR-DNS) has been widely used in understanding the fundamental physics in these flows [1]. Many researchers [2–8] have performed PR-DNSs of flows past static random configurations of particles to obtain the drag correlations. In their simulations, particles are fixed in space and have no relative motion whatsoever, thus, the effects of a common phenomenon, particle fluctuations, are indeed not accounted for.

Particle fluctuations considered here solely represent the fluctuations of particle translational velocity. Their magnitude is usually measured by granular temperature T given by

$$T = \langle(\boldsymbol{U}_p - \langle\boldsymbol{U}_p\rangle)\cdot(\boldsymbol{U}_p - \langle\boldsymbol{U}_p\rangle)\rangle/3, \tag{1}$$

where $\boldsymbol{U}_p$ is the velocity of an individual particle and angular brackets denote the average over all particles in the system. Granular temperature is a statistical quantity well defined in kinetic theory for granular flows. It gives the energy contained in the particle velocity fluctuations analogous to the energy (temperature) in random motion of gas molecules. Based on granular temperature, a Reynolds number which represents the ratio between viscous and inertial forces due to particle fluctuations, can be defined as

$$Re_T = \frac{\rho d T^{1/2}}{\mu}, \tag{2}$$

where d is the diameter of the sphere, and ρ and μ are the density and the dynamic viscosity of the gas, respectively. Replacing $T^{1/2}$ in this definition with $|\boldsymbol{U}|$, where $\boldsymbol{U}$ is the steady-state superficial gas velocity

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relative to the solid phase, another important dimensionless parameter widely used in gas-solid flows can be obtained. It is usually termed as the particle Reynolds number and simply reads

$$Re_p = \frac{\rho d |\boldsymbol{U}|}{\mu}. \qquad (3)$$

Tartan and Gidaspow [9] reported their measurement of granular temperature in a fully developed riser. They fitted the ratio of granular temperature to the square of the mean particle velocity to a least square equation, from which it can be seen that, with the isotropic assumption of granular temperature, the magnitude of fluctuating velocities can reach up to around 88% of the mean particle velocity. Other researchers [10–14] also measured granular temperature experimentally and found that it was significant and played an important role in gas-solid flows.

Researchers also performed quantitative investigation of the effect of granular temperature on drag correlations via PR-DNSs. The first authors to do this are believed to be Wylie et al. [15]. They considered an array of particles with a Maxwellian distribution of velocities under the assumption of high Stokes numbers via a lattice Boltzmann Method (LBM). Simulations were mainly executed at a single solid volume fraction ($c = 0.2$) with a wide range of values for the Reynolds numbers Re_T and Re_p. Their results shown that particle fluctuations led to an increase in the mean drag force. To propose a model for the observation, they considered a test particle moving relative to its fixed neighbors with a fluctuating velocity and accounted for the additional drag force on the test particle caused by the mean flow of the gas. The final drag model was obtained through averaging over the Maxwellian distribution of the fluctuating velocity, and has been adopted in the investigation of turbulence modulation due to particles [16] and also in the field of kinetic-theory (KT)-based simulations for gas-solid flows [17–18].

Later, Kriebitzsch et al. [19] performed PR-DNSs of a gas-fluidized bed of 2000 particles using the immersed boundary method (IBM) combined with traditional CFD. It was found that the average computed drag force from the PR-DNSs was about 50% larger than the value from direct element method (DEM) closures, which, typically, were obtained from PR-DNSs or experiments with beds of fixed particles. This finding is consistent with that reported by Wylie et al. [15]. They also clearly pointed out that one of the key parameters modifying the gas–solid force for dynamic fluidized systems was the local granular temperature.

Another set of massive PR-DNSs of fluidized beds was executed by Luo et al. [20]. Particularly, they investigated a laboratory bubbling fluidized bed of 9240 particles via the immersed boundary method coupled with a soft-sphere model (For details of the numerical method, see [21,22]). Favorable agreement with experimental measurements was achieved. However, surprisingly, the newly computed PR-DNS drag force was found to be larger by up to an order of magnitude or more compared to the prevailing CFD-DEM drag correlations. Specifically, they reported that even if the granular temperature was in the range of $0 - 0.02\ \mathrm{m}^2/\mathrm{s}^2$, which is a range of relatively low values, the PR-DNS drag force was still eight times greater than the drag correlation obtained by Koch and Hill [2].

Most recently, using the IBM-CFD, Tang et al. [23] systematically performed a series of PR-DNSs in periodic suspensions of spherical particles. The particles were allowed to move freely under the influence of particle-fluid interactions and elastic particle-particle collisions. The drag force, granular temperature and particle Reynolds number were obtained after the dynamic systems reached the statistical steady-state. Significant differences have been reported between the obtained "dynamic" drag force and the forces computed in static arrays available in the literature [4,5,24,25]. It is found that the drag increase caused by particle fluctuations is linearly dependent on granular temperature and, surprisingly, that the drag increase is virtually unaffected by various particle Reynolds numbers. Finally, based on the results of the PR-DNSs, Tang et al. [23] proposed the first drag correlation accounting for the effects of granular temperature for a wide range of particle Reynolds numbers and solid volume fractions.

Studies in the literature as shown above arrive at a consistent conclusion that the drag force increases in systems considering velocity fluctuations compared to that in systems absent of velocity fluctuations. However, these studies do not agree with each other quantitatively in terms of the drag increase between dynamic and stationary systems. The reasons for this are twofold. First, it is nontrivial to accurately calculate the local solid volume fractions, local particle Reynolds number and granular temperature in a dynamic system allowing particle to move freely. The errors in calculations will all go into the drag models they proposed. Second, the grid resolution adopted by previous researchers may be insufficient to resolve the details of the flow around particles. The typical grid spacing h in previous studies are around $\frac{d}{12}$, where d is the diameter of the spheres in mono-disperse systems, however, recent studies by Van Der Hoef et al. [3], Tenneti et al. [5], Breugem [26] and Zhou and Fan [6] all show that the grid spacing needs to be at least $\frac{d}{20}$ to obtain a mesh-independent solution for a dilute suspension. For denser systems, the required grid resolution becomes even stringent, which usually is finer than $h = \frac{d}{30}$. In this regard, Van Der Hoef et al. [3] have reported that using a grid of $d = 24.4h$ for a system with the solid volume fraction of 0.5, the predicted drag force still had a significant deviation compared to the more accurate value obtained via an extrapolation method. Therefore, in the present study, even finer meshes are adopted to reduce the error caused by insufficient grid resolution. Besides, the Richardson extrapolation method similar to that adopted by Van Der Hoef et al. [3] is used to produce the final results for the drag force. The final results at grids with infinite resolutions are extrapolated from the results obtained at three grid resolutions. It is found that, for dense systems, the drag forces at $h = \frac{d}{40}$ still deviate from the results calculated using Richardson extrapolation by around 10%. Thus, the adoption of Richardson extrapolation is indeed essential in terms of obtaining mesh-independent results for the drag force. Also, in the present study, static particle assemblies are adopted to remove the error caused by inaccurate calculation for the local solid volume fractions. This ensures a homogeneous distribution of solid particles within the computational domain. To reflect the effects of granular temperature, random velocity fluctuations obeying Maxwell-Boltzmann distribution are imposed on all particles. Systems with constant solid volume fractions and particle fluctuations obeying Maxwell-Boltzmann distribution are realizable especially when the Stokes number characterizing particle inertia is high [1]. Using the idea of static configurations, many drag models without considering particle fluctuations have been proposed in the past decade [3–8]. The present work, by imposing random fluctuations on fixed particles, makes a step forward towards understanding the inter-phase interactions in more realistic systems. It should be mentioned that, in real-world gas-solid flows, particles also tend to form clusters due to the nonlinear dependence of the drag force and the inelastic particle-particle collisions [1,18,27]. In the dynamic systems simulated by Tang et al. [23], no obvious clustering at the statistically steady state was observed, indicating that even larger computational domain is required to reproduce this phenomenon. To explore the effects of clustering, Mehrabadi et al. [28] executed PR-DNSs of particle configurations generated by DEM simulations of homogeneous cooling gas systems. Meanwhile, Tenneti et al. [29], using PR-DNSs, developed a particle acceleration model that was able to correctly predict the evolution of granular temperature, which is closely associated with particle clustering. Most recently, Liu et al. [30] succeeded in performing PR-DNSs of a gas-solid system with the number of spheres up to around 28,800. Distinct clusters were observed in the fully resolved simulations and their impact on granular temperature was discussed. Clearly, the investigation of the effects of particle clustering on the drag force and other salient properties of gas-solids needs more future efforts and will not be discussed in the present paper.