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A Direct Numerical Simulation (DNS) Study on the Effect of Particle Configuration on Drag

Yi Mo[1,2], Zichao Long[2] and Pingwen Zhang[2,*]

[1] *Aero Engine Academy of China, Beijing 101304, P.R. China.*
[2] *School of Mathematical Sciences, Peking University, Beijing 100871, P.R. China.*

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Abstract. Drag correlations are very important in particle-laden two-phase flow simulations. Some statistical studies have investigated extracting particle configuration factors from simulation data to improve drag correlations. However, little attention has been paid to studying particle configuration effects on drag from the perspective of the flow mechanism. In this paper, a direct numerical simulation (DNS) method based on the second-order accurate immersion interface method is developed to provide highly reliable data. Then, the 'shielding' effect of the two-particle configuration on drag is comprehensively analysed under different angles, distances, and Reynolds number (*Re*) values, revealing that the complex configuration dependence of the drag influence is attributed to the dominant flow mechanism, such as the 'pressure region unit', 'nozzle', and 'wake' effects. Moreover, we study the 'superposition' effect of the three-particle configuration on drag in a finite *Re* range. The results show that when the surrounding particles do not directly shield each other, the drag influence calculated by pairwise linear superposition is close to the drag influence revealed by DNS. Otherwise, when the shielding phenomenon of the surrounding particles is obvious and the *Re* is high, the drag influence of the nearest particle can represent the DNS result.

AMS subject classifications: 35Q30, 76D05, 76M20, 76T15

Key words: Particle-laden two-phase flow, direct numerical simulation, particle configuration, drag, flow mechanism.

1 Introduction

Particle-laden two-phase flow systems are widely encountered in nature and engineering. Computational fluid dynamics methods based on the two-fluid model (TFM) [3, 15,

*Corresponding author. *Email addresses:* `pzhang@pku.edu.cn` (P. Zhang), `moyi1002@163.com` (Y. Mo), `zlong@pku.edu.cn` (Z. Long)

37] and discrete particle model (DPM) [35,39] are the most prominent tools for studying this system. Generally, the computational grid size of these methods is much larger than the particle size, and the interaction between the particles and fluid needs to be solved by empirical drag correlations. Therefore, drag correlations are of great significance to the simulation of such a system and have become a popular research topic.

In most two-phase flow simulations, the drag f is correlated to the particle-based Reynolds number (*Re*) and average void fraction [6,7,12,14,32,33,38,46]. However, in a heterogeneous system, these correlations cannot accurately reflect the effect of irregular particle configurations on drag and usually lead to a loss of simulation accuracy. Some studies have been devoted to extracting the particle configuration factors from simulation or experimental data to improve drag correlations. Beetstra et al. [5] measured the drag of four irregularly shaped particle clusters and studied the effect of interparticle distance on the drag. Then, they modified the drag coefficient of a single particle using three intuitive parameters da, dn and c, where da is the diameter of a sphere with equal projected surface area, dn is the diameter of a sphere with equal volume and c is the circularity.Yang et al. [45] used an energy-minimization multi-scale model [19] to solve an optimization problem and extract the non-uniform structure parameters. As a result, the accuracy of the drag in mesoscale simulation is greatly improved. Mehrabadi et al. [24] performed a particle-resolved direct numerical simulation (DNS) to quantify the drag on clustered particle configurations and proposed a drag correlation over a range of *Re* values and void fractions that provides a smooth transition between the uniform and clustered states. Zhou et al. [47] revealed the strong structural dependence of drag in both a simple case of two particles and a typical case with stepwise heterogeneity, demonstrating the necessity for a structure-dependent drag description, and then constructed a drag correlation for system with a specific linear heterogeneity. Liu et al. [21,22] revealed that the complex scale dependence of drag is attributed to the multi-scale effects of heterogeneous structures and particle fluctuating velocity and proposed a new drag correlation as a function of the Froude number with consideration of the scale dependence.

These statistical fitting drag correlations have yet to be studied for a heterogeneous system. However, little attention has been paid to studying and explaining the effect of particle configurations on drag from the perspective of the flow mechanism, which could provide some essential enlightenment and a foundation for the improvement of drag correlations. In this paper, we plan to pursue the following questions for finite *Re* values ranging from ten to one hundred: first, how can the mutual 'shielding' effect of two-particle configurations on the drag be explained by the flow mechanism. And then, can the pairwise linear superposition of the 'shielding' effect of two-particle configurations be used to approximate the 'superposition' effect of multiple particles on the drag of the target particle.

Current studies on the 'shielding' effect are limited to several special configurations of two particles. Zhu et al. [48] developed an experimental system to visualize the flow past two particles arranged longitudinally and found that the effect of the heading par-