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On the drag coefficient and averaged Nusselt number of an ellipsoidal particle in a fluid

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ABSTRACT

The paper aims to improve existing correlations for the drag coefficient and averaged Nusselt number of an ellipsoidal particle in a fluid by additionally considering its orientation. To do so, three-dimensional Immersed Boundary-Lattice Boltzmman Method (IB-LBM) simulations were carried out on a classical problem where a hot stationary ellipsoidal particle was passed by continuous cold fluid flows. By changing the shape ($0.25 \leq Ar \leq 2.5$) and incident angle ($0^\circ \leq \theta \leq 90^\circ$) of the solid particle as well as the Reynolds number ($10 \leq Re \leq 200$), the momentum and heat transfer between the solid and fluid phases were quantitatively evaluated and the drag coefficient and averaged Nusselt number were numerically quantified. Then, based on the obtained data, correlations for the drag coefficient and averaged Nusselt number were established by considering Ar, θ and Re as the key influencing factors. Proposed correlations were proven to hold promising prediction capabilities and would be useful to be enclosed in those complex multiphase coupling calculations.

1. Introduction

1.1. Background

Particulate-fluid interaction systems are ubiquitous in various industrial processes whereas present extremely complex momentum and heat transfer characteristics. Available knowledge of these characteristics to date is far from being enough which generates great difficulty in the scaling design and configuration optimization. For the sake of revealing the underlying mechanisms, there are briefly three research hotspots of particular interest at distinct scales, those are particle scale research, device (macroscopic) scale research and meso-scale research between them [1]. On the one hand, all the tuning operations by the engineers are only possible to conduct at the device scale, and then the effect will be eventually imposed on each single particle through complex meso-scale interactions. On the other hand, all the events (*e.g.* turbulence, exchange of momentum and energy, chemical reaction, phase change and deformation of solid particles) taking place at the particle scale form various unpredictably macroscopic phenomenon also via the meso-scale interactions. Therefore, to optimize the operating parameters and energy efficiency, questions remaining open at each level must be answered. In this context, accurate modelling at the particle scale is of paramount importance for preventing irrational predictions.

Recently, Zhong et al. [2,3] have reviewed the state-of-the-art theoretical developments and applications of the combined modelling techniques for particulate-fluid flows. As indicated by the authors [2,3], the drag coefficient C_d and averaged Nusselt number Nu are the key parameters in the coupled calculations because they are responsible for evaluating the drag force and heat transfer, respectively. Eq. (1) gives the typical formula of the drag force and heat flux on a single particle while multi-particle systems can be readily considered via an additional term of voidage. In Eq. (1), $\mathbf{f}_d$ is the drag force, A is the front area, ρ is the fluid density, u_c is the uniform inlet field velocity far from the particle, q is the heat flux, h_e is the convective heat transfer coefficient of the fluid, S is the surface area, κ is the thermal conductivity coefficient of the fluid, d_p is the volume-equivalent sphere diameter, and T_s and T_f are the temperature of the solid and fluid, respectively. Note that Nu should be obtained prior to the calculation of q since h_e is unknown.

$$\begin{cases} \mathbf{f}_d &= \frac{1}{2} C_d A \rho u_c^2; \\ q &= h_e S \left(T_s - T_f\right); \\ Nu &= h_e d_p / \kappa. \end{cases} \tag{1}$$

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It is stressed that the drag coefficient and averaged Nusselt number should be evaluated correctly enough by considering many important factors such as the local fluid flow property, particle size/shape/orientation and relative motion/temperature difference between the solid and fluid [4]. To establish accurate correlations for them, several previous studies were carried out aiming to take as many factors as possible into account. However, numerous defects exist in these contributions and hence much further work is still needed. The current study focuses on researching the effect of particle shape and orientation on the drag coefficient and averaged *Nu* at low Reynolds numbers. The investigation is motivated by the facts that [2,3]:

- Majority of the solid particles are not regularly spherical in modern industries (over 70%).
- Morphology plays key roles in the particle scale heat and mass transfer characteristics.
- Fundamentals governing the above interactions are not well established.

1.2. Previous work

For spherical particles, the correlations of drag coefficients have been well archived and surveyed in the previous literature [4,5]. However, these correlations for spherical particles have been proven to produce large deviations when applied to non-spherical ones [3]. Hottovy and Sylvester [6] measured the settling velocity of several irregularly shaped particles and found that the drag coefficient for the non-spherical particle is comparable with the spherical one when $Re < 100$ but significantly higher in the rest testing range of Reynolds number ($100 < Re < 3000$). It is worthwhile noting that sedimentations of irregular particles in fluids (laminar or turbulent, Newtonian or non-Newtonian) were usually used for experimentally determining their drag coefficients [6–12]. Among these works, Wang et al. [11] and Ren et al. [12] established the correlations of drag coefficients specially for the cuboid with square base and cylinders, respectively. In the meantime, various shape factors were also defined in different studies, such as the sphericity, particle circularity, Corey shape factor and aspect ratio. These parameters were employed to describe how far the irregular particle deviates from a spherical one and help those general correlations of drag coefficients proposed [9,10,13-15] without specifying the exact particle morphology or orientation.

In addition to the direct experimental measurements, particle-scale numerical simulations have also been carried out for expanding the database of the drag coefficient. Unlike the experimental studies, flow over solid obstacles is the popular case for the numerical investigations. It is reported by Bokkers et al. [16] that, with respect to predicting the bubble formation in fluidized beds, using the drag coefficient derived from the lattice Boltzmann method (LBM) simulation [17] produces even better results than using the experiment-based ones [18,19]. This is not a representative fact showing that experimental can be entirely replaced by numerical simulation. Whereas the comparison results greatly enhance the reliability of the latter technique without doubt. Nowadays, the LBM modelling has been increasingly used to develop the correlations of drag coefficients both for spherical [20–27] and non-spherical [28–30] particles. Pioneer studies can be found from Hill et al. [20,21] who proposed a set of drag correlations by considering flow passing through random arrays of spheres in a cubic. Later, Van Der Hoef et al. and Beetstra et al. investigated flows passing through mono- and bidisperse arrays of spheres at low [22] and moderate [23] Reynolds numbers, respectively. Rong et al. carried out similar simulations based on more representative packed structures and proposed novel correlations [24,25]. Zhou and Fan examined the effect of spherical particle rotation on flows in ordered and random arrays of monodisperse spheres at low [26] and moderate [27] Reynolds numbers, respectively. As for non-spherical particles, Hölzer and Sommerfeld considered six particle shapes as well as particle rotation in uniform and shear flows and numerically determined the drag, lift and moment coefficients [28]. Rong et al. simulated the fluid flow through packed beds of uniform ellipsoids and improved the accuracy of the existing correlations [29]. Guan et al. [30] examined the fluid-particle interaction for non-spherical particles at high Reynolds numbers ($0.1 < Re < 3000$) also via the LBM. Besides the LBM simulations, Saha [31] solved three-dimensional unsteady Navier Stokes and energy equations to study the wake of a cube placed in a uniform flow. Kishore and Gu [32] used similar numerical methods to examine the momentum transfer phenomena of spheroid particles in an unbounded Newtonian fluid and developed correlations of drag coefficient ($1 < Re < 200$). Richter and Nikrityuk performed numerical simulations and proposed correlations of drag coefficients for cuboidal and ellipsoidal particles [33] with considering angles of attack [34].

Numerical simulations investigating the heat transfer characteristics of non-spherical particles in a fluid were relatively less reported. Wen and Jog numerically studied the effects of *Re*, particle morphology and other variable properties on the drag coefficient and averaged Nusselt number [35]. Saha examined the transition schemes of flow and thermal field behind a stationary cube by solving the Navier Stokes and energy equations [31]. Kishore and Gu [32] examined the heat transfer phenomena of spheroid particles in an unbounded Newtonian fluid and developed correlations of averaged Nusselt number ($1 < Re < 200, 1 < Pr < 1000$). Then, Reddy and Kishore investigated the effects of wall confinement and the power-law fluid behaviour index on momentum and heat transfer phenomena of confined spheroid particles within the same range of *Re* and *Pr* [36].

1.3. Motivation and summary of the present work

From the literature survey, it can be seen that the numerical modelling has emerged as a promising method to evaluate drag coefficients and averaged Nusselt number for non-spherical particles. However, available data on the typical morphology is still limited especially for heat transfer though several correlations were proposed before. For example, previous correlations were mainly based on two-dimensional simulation results [32,35,36] which need a considerable simplification on the actual particle shape and thus lacked applicability. Richter and Nikrityuk conducted three-dimensional numerical simulations [33,34] but a systematic study on the difference between oblate and prolate spheroids has not been done. This may be among the reasons why Gan et al. [37] adopted the correlation proposed from two-dimensional simulations to investigate the heat transfer in three-dimensional packed and fluidized beds of ellipsoidal particles. Therefore, there is a great need to fill this knowledge gap.

The current paper conducts three-dimensional LBM simulations to investigate the momentum and heat transfer characteristics of ellipsoidal particles in a uniform flow field. By changing the shape ($0.25 \leq Ar \leq 2.5$) and incident angle ($0^\circ \leq \theta \leq 90^\circ$) of the solid particle as well as the Reynolds number ($10 \leq Re \leq 200$), the drag coefficient and averaged Nusselt number under a wide range of conditions are quantified and previous correlations are improved. The rest of the paper is organized as follows. Section 2 briefly gives the mathematics of the LBM and Immersed Boundary Method (IBM) [38]. Section 3 introduces the details of particle generation and calculation platform. In Section 4, validation simulations are carried out. In Section 5, 125 case studies are tested and new correlations for the drag coefficients and averaged Nusselt number are proposed based on the numerical results. At last, some conclusions are drawn in Section 6.