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Drag coefficient and averaged Nusselt number of a scalene prolate ellipsoid

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ABSTRACT

A cold fluid flowing past a hot stationary scalene prolate ellipsoid is numerically studied via a three-dimensional immersed boundary-lattice Boltzmann model (IB-LBM). First, axisymmetric ellipsoids are considered for verification purposes, and good agreement is found between obtained drag coefficient (C_d) and averaged Nusselt number (Nu) and previously reported results. Subsequently, 81 case studies are conducted by changing shape ($2 \leq Ar1, Ar2 \leq 6$) and incident angle ($0^\circ \leq \theta \leq 90^\circ$) of the ellipsoid as well as the Reynolds number ($25 \leq Re \leq 200$). In this study, we particularly consider scalene prolate ellipsoids with unequal $Ar1$ and $Ar2$, which have not been studied in detail before. Effects of different factors on momentum and heat transfer characteristics between solid and fluid phases are understood based on the analysis of numerical results. Available formulas reported in the literature are also briefly reviewed. Finally, new correlations for both C_d and Nu are developed using the most important factors with average deviations of 3.875% for C_d and 1.598% for Nu, respectively. These proposed correlations can be used to facilitate the phase coupling in the multi-phase flow modelling.

1. Introduction

1.1. Background

Particulate–fluid interaction systems are widely encountered in various industrial applications such as energy utilisation, environmental protection, chemical engineering and process metallurgy. Most, if not all, of the particles in these systems are non-spherical which exhibit much more complex behaviour than spherical ones [1]. In addition to the difficulty in the direct experimental measurement of such systems [2], the lack of knowledge of drag coefficient (C_d) and averaged Nusselt number (Nu) for non-spherical particles has in some way limited the capability of advanced computational techniques (like CFD-DEM) [3,4] to assist in examining relevant mechanisms. These two non-dimensional parameters (C_d and Nu) are extremely important for coupling fluid and particle phases in numerical simulations irrespective of whether they are based on Eulerian–Eulerian or Eulerian–Lagrangian schemes. Therefore, the proper evaluation of these parameters is of course one of essential aspects to prevent unphysical or inaccurate predictions. It should be stressed that to evaluate C_d and Nu correctly, several key factors must be appropriately considered including local fluid flow property, particle size/shape/orientation and

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Nomenclature

a, b, c	principal semi-axes of the ellipsoid along X-, Y-, and Z-directions
A	front area
Ar	aspect ratio
C_d	drag coefficient
C_l	lift coefficient
$Corr_{Cd}$	correlation for the drag coefficients
$Corr_{Nu}$	correlation for the averaged Nusselt number
d_p	volume-equivalent sphere diameter
$\mathbf{e}_\alpha$	lattice velocity
$\mathbf{f}_d$	drag force
f_α	fluid density distribution function
f_α^{eq}	fluid equilibrium density distribution function
F_α	external force
F_x, F_y, F_z	component of $\mathbf{F}_f$ in the X-,Y-, and Z-direction
g_α	fluid temperature distribution function
g_α^{eq}	fluid equilibrium temperature distribution function
G_α	external heat source
L_c	characteristic length
Nu	averaged Nusselt number
Pr	Prandtl number
$\mathbf{r}$	fluid space position vector
Re	Reynolds number
S	total area of the particle surface
t	present time
T_c	low temperature
T_f	local fluid temperature
$\tilde{T}_f$	normalised fluid temperature
T_h	high temperature
T_s	local particle temperature
$\tilde{T}_s$	normalised solid temperature
u_0	characteristic velocity
$\mathbf{X}_l$	solid coordinate

Greek letters

α	LBM index (subscript)
δ_t	fluid discrete time step
Δ_{s_l}	area that each Lagrangian point occupies on the particle surface
ϵ	local voidage
κ	thermal conductivity coefficient
ϕ	sphericity
$\phi_\perp$	crosswise sphericity
$\phi_\parallel$	lengthwise sphericity
ρ	fluid macro density
τ_f	fluid non-dimensional relaxation time of the density evolution
τ_g	fluid non-dimensional relaxation time of the temperature evolution
θ	incident angle

relative motion/temperature difference between solid and fluid phases. Otherwise, inaccurate drag force and heat transfer could influence on movement and energy exchanges of each individual particle which could then modify overall particle and temperature distributions and hence the whole technological process. This study aims to help fill this knowledge gap.

1.2. Previous work

Because required experimental studies are expensive and difficult to repeat on an unbiased basis, particle-scale numerical simulations are good alternatives to achieve the goal. Those well-known numerical methods summarized in Table 1 can be briefly classified into two categories: lattice Boltzmann method (LBM) [5,6] and direct numerical simulation (DNS). Past numerical studies show that the former type of method is primarily performed based on in-house codes, whereas the latter is mainly conducted using commercial packages. It is worthwhile mentioning that available correlations for C_d can be