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Direct numerical simulation of fluid–particle heat transfer in fixed random arrays of non-spherical particles

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HIGHLIGHTS

- DNS using IBM for particle–fluid heat transfer for non-spherical particles.
- HTC of random arrays of spherocylinders characterized for a wide parameter range.
- An effective diameter is used to account for the effect of the aspect ratio on the HTC.
- An refitted Gunn correlation describes the simulation results well.

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ABSTRACT

Direct numerical simulations are conducted to characterize the fluid–particle heat transfer coefficient in fixed random arrays of non-spherical particles. The objective of this study is to examine the applicability of well-known heat transfer correlations, that are proposed for spherical particles, to systems with non-spherical particles. In this study the spherocylinders are used to pack the beds and the non-isothermal flows are simulated by employing the Immersed Boundary Method (IBM). The simulations are performed for different solids volume fractions and particle sizes and low to moderate Reynolds numbers. Using the detailed heat flow pattern, the average heat transfer coefficient is calculated for the different operating conditions. The numerical results show that the heat-transfer correlation of spherical particles can be applied to all test beds of spherocylinders by choosing a proper effective diameter. Our results reveal that the diameter of a spherocylinder is the proper effective diameter for characterizing particle–fluid heat transfer.

1. Introduction

During the last decades extensive investigations have been devoted to characterizing heat and momentum transfer in packed and fluidized bed reactors. As a result, a large number of empirical correlations models have been developed to predict pressure drops and the heat transfer coefficients (HTC) in these types of systems. Most of these correlations are obtained for randomly packed beds of spheres.

For example, it is generally accepted that the pressure drop in a porous bed packed with spherical particles can be estimated reasonably well from the Ergun (1952) correlation. The Ergun equation relates the pressure drop to the particle size and the bed porosity. However, the extension of the Ergun equation to a bed packed with non-spherical particles is not straightforward. On the other hand, recent numerical studies (Freund et al., 2012; Guardo et al., 2006; Nijemeisland, 2000) prove that not only the local behavior but also the macroscopic quantities, such as the pressure drop, are significantly affected by local micro structural properties of the bed.

An accepted approach which has its foundation in the Carman–Kozeny approximation (Carman, 1956) is to use an effective diameter for non-spherical particles in the Ergun equation. Nemec and Levec (2005) have fitted the pressure drop for particles of different shapes to the generalized Ergun equation. They concluded that the use of a general effective diameter is not sufficient to capture the effect of non-spherical particle shapes. They proposed to evaluate the constants of the Ergun equation as a function of the particle size.

Our current knowledge of the heat transfer characteristic for these systems follows mainly from experiments obtained for random beds with spherical particles, e.g., by Gunn (1978), Wakao and Kaguei (1982), and Kunii and Levenspiel (1991). Although these well-known correlations are widely used to predict the heat transfer characteristics of packed and fluidized beds, their applicability to structured beds or non-spherical particles has not been assessed yet. Calis et al. (2001) and Romkes et al. (2003) characterized the momentum and heat

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transfer in five different types of composite structured packed beds of spheres using numerical and experimental methods. These results revealed that macroscopic flow and heat transfer characteristics are affected significantly by packing features. Yang et al. (2010) studied the effects of packing form and particle shape on the flow and heat transfer characteristics in uniform packed beds. They found that, with proper selection of packing form and particle shape, the hydrodynamic and thermal performance in structured packed beds can be greatly improved. Their results show that the correlations of momentum and heat transfers extracted from random packings overpredict the pressure drop and HTC for structured packings.

All these results indicate that the heat transfer between fluid and particles is strongly affected by the local fluid–solid flow structure and varies spatially for nonuniform structures. Therefore, the effect of the packing material's shape needs to be considered for accurate prediction of fluid–particle heat transfer characteristics.

In view of the recent advancement in computational power, Direct Numerical Simulation (DNS) can be a promising tool to improve our knowledge about flow and heat transfer processes in porous media encountered in the packed and fluidized beds. DNS provides detailed information at the micro-scale without using the pressure drop or heat transfer correlations. With the availability of detailed information, the macroscopic pressure drop and HTC can be extracted. Therefore, these quantities can be estimated with the aid of numerical experiment as a function of operating conditions. This approach has been used by Hill et al. (2001) and Beetstra et al. (2007) to characterize the pressure drop in beds of spherical particles over a wide range of Reynolds numbers and solids volume fractions.

Recently, this approach has been extended to heat transfer problems (Deen et al., 2012; Tenneti et al., 2013; Tavassoli et al., 2013) and the Nusselt number for stationary arrays of spherical particles was estimated with the aid of DNS. These results show significant deviations between computed Nusselt numbers and predictions on the basis of heat transfer correlations even in beds with spherical particles.

These findings motivate us to examine the heat transfer in a random array of non-spherical particles. According to authors' knowledge, no studies have been published in this area yet and this study provides the first results of heat transfer in such systems. In this study, we employed the Immersed Boundary Method (IBM) to simulate non-isothermal flow through random fixed arrays of spherocylinders. The physical model is constructed by a random distribution of non-overlapping spherocylinders in a cubic domain by a standard Monte Carlo procedure for hard cylinders. Although the particles do not move the results are relevant for fluidized beds because particles do not touch as in a packed bed, but are separated as in a fluidized bed. Based on the predicted flow and temperature fields, the average heat transfer coefficient was computed as a function of particle shape, Reynolds number and porosity.

The paper is organized as follows. First, the governing equations and numerical solution method are explained. Then some well-known heat-transfer correlations are reviewed and the usage of the effective diameter for non-spherical particles is detailed. The computed HTCs for stationary arrays spherocylinders are compared with the correlations and the effect of particle size on HTCs is investigated as well. In the final section the conclusions are provided.

2. Physical model and numerical method

2.1. Physical model

The simulation approach is identical as described in Tavassoli et al. (2013) for stationary arrays of spheres. The non-spherical particle used in present study is the spherocylinder with the diameter D_p and length L_p (see Fig. 1a). Three different aspect ratios of $L_p/D_p = 2$, 3 and 4 are considered to determine the effect of the aspect ratio on the fluid–particle heat transfer.

As shown in Fig. 1b, the computational domain consists of inlet, packed and outlet sections. In these simulations, only the packed section is active in the heat transfer process. This section was created by a random distribution of $N=30$ non-overlapping spherocylinders, with random orientation, in a 3-dimensional duct using a standard Monte Carlo method. The desired solid volume fraction, ϕ, is calculated as the ratio of total volume of particles ($N \times V_p$) to the volume of the packed section ($V_{ps} = L_{ps}^3$) (where L_{ps} is the length of packed section). The length of inlet and outlet sections is equal and set to L_p for all simulations.

The fluid flows through the duct in streamwise direction (x-direction). Periodic boundary conditions are imposed in other directions (y and z) in order to avoid wall effects. The particles are maintained at a constant temperature T_s whereas the temperature of the fluid at the inlet is set at T_0. The Pr number was fixed to 1 for all simulations. So the fluid is in fact a gas. The particle diameter, fluid viscosity and fluid density are set to 1 mm, 10^{-5} kg/(ms) and 1 kg/m^3, respectively, in our simulations. Since the Re number is high enough in this study, natural convection can be neglected. Therefore the density variation is neglected on governing equations.

The Navier–Stokes and thermal energy equations were solved for incompressible fluid flow with constant physical properties

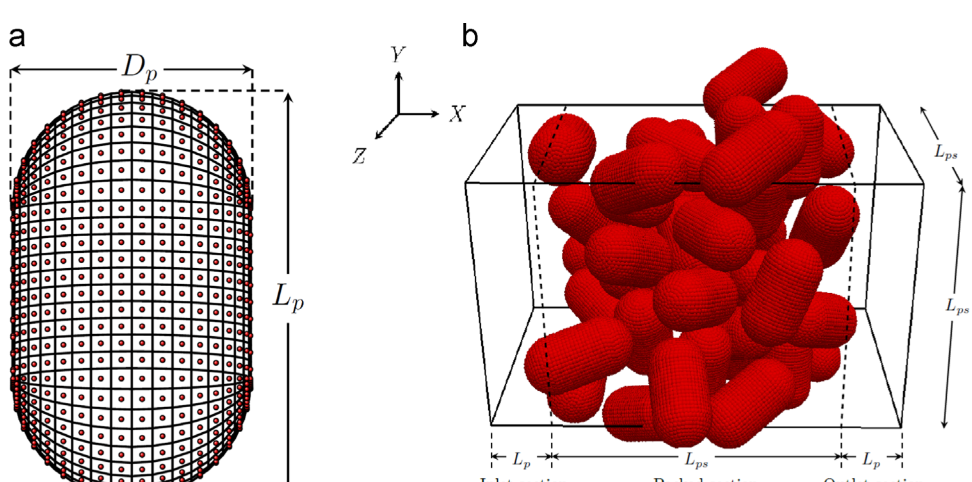

Fig. 1. (a) Representation of a spherocylinder surface with Lagrangian points. (b) A typical particle configuration used in the simulations.