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Gas–solid flow and heat transfer in fluidized beds with tubes: Effects of material properties and tube array settings

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ABSTRACT

The effects of material properties and tube array settings on gas–solid flow and heat transfer characteristics in fluidized beds with tubes are investigated by the combined approach of computational fluid dynamics and discrete element method, incorporated with heat transfer models. First, the effect of material properties is illustrated by considering cohesive and non-cohesive powders with different particle sizes. The contributions of different heat transfer mechanisms are discussed at two tube temperatures. Significant differences of gas–solid flow between cohesive and non-cohesive powders are observed. The results reveal that conductive heat transfer between a fluidized bed and a tube is dominant for small cohesive particles while convective heat transfer is dominant for large non-cohesive particles. Then, the uniformity of particle velocity and temperature fields is analyzed. It is shown that material properties and gas velocity affect the uniformity of particle velocity and temperature in a complicated manner. Finally, the effect of tube array settings is examined in terms of two geometrical parameters for both in-line and staggered settings. Complicated gas–solid flow and heat transfer characteristics are observed. An effort is made to link macroscopic observations to microscopic information such as local porosity and contact number between fluidized particles and tubes. The findings should be helpful for the optimization of operation and design of fluidized systems with tubes.

1. Introduction

Fluidized bed reactors are widely used in industries mainly due to their high heat and mass transfer capability. Immersed surfaces such as vertical or horizontal tubes, fins, and water walls are usually adopted to control flow and heat transfer. Heat transfer performance is affected by many factors such as material properties of gas and solid phases, geometrical settings and operating conditions. In the past, many macroscopic studies have been carried out in this field, leading to the formulation of various correlations to determine the heat transfer coefficient (HTC) of fluidized beds as, for example, summarized by Kunii and Levenspiel [1] and Molerus and Wirth [2]. These correlations have shown their value in solving some practical problems. However, the predictions by some correlations show significant differences partly due to negligence of certain parameters and unknown experimental set-up and conditions [3]. To produce equations that can be generally applied to different systems, microscopic understanding of flow and heat transfer mechanisms at a particle scale is helpful. Such understanding can be obtained through experimental and/or numerical approaches. In recent years, experimental examination of the heat transfer at a particle scale has been attempted by various investigators, often done by measuring the temperature evolution of a tracing particle [4–6]. The resulting information is useful for fundamental understanding and model validation. To generate a more comprehensive picture of heat transfer, in recent years numerical studies have been carried out for various fluidized systems based on the combined computational fluid dynamics (CFD) and discrete element method (DEM) approach [7–21]. The models developed vary in some details and have different advantages and limitations. However, they all demonstrate that the combined CFD–DEM approach, incorporated with heat transfer models, is an effective technique for investigating heat transfer in fluidized systems at a particle scale.

Fluidization and related heat transfer behaviors vary with the type of powders as classified by Geldart [22]. However, most of the previous investigations are focused on large particles. Only a few investigators studied heat transfer characteristics of fine particles theoretically or experimentally, focusing on macroscopic HTC of packed beds rather than fluidized beds [23–29]. Di Natale et al. [24] found that HTC between a fluidized bed of fine particles and an immersed spherical or cylindrical surface increases with the increase in particle Archimedes number (which is a function of particle density and size, and fluid density and viscosity). Recently, heat transfer between a tube/probe and a fluidized bed has been investigated by the combined CFD–DEM

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approach [11,12,14]. The contributions of different heat transfer mechanisms are discussed [11], and the effects of some material properties such as particle size and particle thermal conductivity are examined [12,14]. In fluidized beds, uniform particle velocity and temperature distributions are often desired for heat transfer and chemical reactions. If the uniformity is not good enough, hot spot, as pointed out by Kaneko et al. [30], could be formed. Somehow, this important issue has not been addressed in detail in the previous studies.

A tube array rather than a single tube is often used in fluidization systems. One major concern is the setting of a tube array, related to heat transfer and tube erosion [31–33]. Previous studies of such systems have been mainly conducted by using two-fluid models [34–36] or by experimental approaches [37–39]. Recent studies on the setting of a tube array are carried out by means of the CFD–DEM approach [40,41]. Some interesting findings are presented, but controversies can also be identified. For example, the significant effect of tube pitch on the erosion has been demonstrated [35]. While no significant difference in terms of bubbling behaviors or heat transfer between different tube settings (in-line and staggered) is observed [34,41], quite different factors underlying heat transfer such as particle impacts and bubble behaviors are predicted by the CFD–DEM approach [40]. A possible reason could be that particle scale interactions are not sufficiently considered. The different observations indicate that there is a need for further investigation of the effect of tube array settings on gas–solid flow behavior. In particular, the effect on heat transfer and the underlying mechanisms should be properly understood.

In this work, in connection with our previous efforts [14,15], two significant concerns relevant to gas–solid flows and heat transfer characteristics are addressed by using the combined CFD–DEM approach. Firstly, the effect of material properties for different types of particles including non-cohesive and cohesive particles is investigated for a fluidized bed with a horizontal tube. The uniformity of velocity and temperature fields is quantified. Secondly, the effect of tube array settings is investigated for a fluidized bed with multiple horizontal tubes. The complicated variation of heat flux between the fluidized bed and tubes is discussed in terms of microscopic information such as local porosity and contact number between particles and tubes. The findings should be useful for better understanding and prediction of heat transfer in gas fluidization.

2. Model description

2.1. Governing equations for solid phase

Here, gas fluidization is considered to be composed of a discrete solid phase and a continuum gas phase. The solid phase is described by DEM, originally proposed by Cundall and Strack [42]. At any given time t, the equations governing the translational and rotational motions of particle i can be written as:

$$m_i \mathrm{d}\mathbf{v}_i/\mathrm{d}t = \sum_j \left(\mathbf{f}_{e,ij} + \mathbf{f}_{d,ij} + \mathbf{f}_{v,ij}\right) + \mathbf{f}_{pf,i} + m_i\mathbf{g}, \tag{1}$$

and

$$I_i \mathrm{d}\boldsymbol{\omega}_i/\mathrm{d}t = \sum_j \left(\mathbf{T}_{t,ij} + \mathbf{T}_{r,ij}\right), \tag{2}$$

where the equation for the van der Waals force is written as:

$$\mathbf{f}_{v,ij} = -\frac{\frac{H_a}{6} 64 R_i^3 R_j^3 \left(h + R_i + R_j\right)}{\left(h^2 + 2R_i h + 2R_j h\right)^2 \left(h^2 + 2R_i h + 2R_j h + 4R_i R_j\right)^2} \cdot \mathbf{n}. \tag{3}$$

The forces involved are: particle–fluid interaction force $\mathbf{f}_{pf,i}$, the gravitational force $m_i\mathbf{g}$ and the forces between particles (and between particles and walls) which include the elastic force $\mathbf{f}_{e,ij}$, the viscous damping force $\mathbf{f}_{d,ij}$ and the cohesive force $\mathbf{f}_{v,ij}$. Note that the cohesive force $\mathbf{f}_{v,ij}$, considered here is the van der Waals force given by Eq. (3), which depends on the Hamaker constant H_a and the separation h of the interacting surfaces along the line joining the centers of particles i and j. R_i and R_j are the radii of particles i and j respectively. A minimum separation h_{min} is used in the calculation of $\mathbf{f}_{v,ij}$ to represent the physical repulsive nature and avoid the singular attractive force when $h = 0$. This treatment has been proved to be valid for particles down to 1 μm [43–45]. The torque acting on particle i due to particle j includes two components: $\mathbf{T}_{t,ij}$ which is generated by the tangential force and causes particle i to rotate, and $\mathbf{T}_{r,ij}$ which, commonly known as the rolling friction torque, is generated by asymmetric normal contact forces and slows down the relative rotation between contacting particles [46,47]. If particle i undergoes multiple interactions, the individual interaction forces and torques are summed up for all particles interacting with particle i. The equations used to calculate the particle–particle interaction forces and torques, and particle–fluid interaction forces have been well established as, for example, reviewed by Zhu et al. [48]. The equations used for the present work are the same as those used in our previous studies [20,49].

The heat transfer between particle i and its surroundings have three modes: convection with fluid, conduction with other particles, tubes or walls, and radiation with its local environment. According to the energy balance, the governing equation for particle i can be written as [10]:

$$m_i c_{p,i} \mathrm{d}T_i/\mathrm{d}t = \sum_j \dot{Q}_{i,j} + \dot{Q}_{i,f} + \dot{Q}_{i,rad} + \dot{Q}_{i,wall} + \dot{Q}_{i,tube}, \tag{4}$$

where $\dot{Q}_{i,j}$ is the conductive heat exchange rate between particles i and j; $\dot{Q}_{i,f}$ is the convective heat exchange rate between particle i and its local surrounding fluid; $\dot{Q}_{i,rad}$ is the radiative heat exchange rate between particle i and its local surrounding environment; $\dot{Q}_{i,tube}$ is the conductive heat exchange rate between particle i and tubes; and $\dot{Q}_{i,wall}$ is the conductive heat exchange rate between particle i and wall. Mathematically, Eq. (4) is the same as the so-called lumped-capacity formulation, where the thermal resistance within a particle is neglected [50]. This condition is valid when the Biot number, defined as $h \cdot (V_i/A_i)/k_{pi}$, is less than 0.1, where h is the heat transfer coefficient; V_i is the particle volume; A_i is the particle surface area; and k_{pi} is the particle thermal conductivity. However, as noted by Zhou et al. [10], Eq. (4) is established on the basis of energy balance at the particle scale. So, the values of parameters (e.g. m_i, c_{pi}, T_i, and k_{pi}) involved should be the representative properties of the particle at this scale, which may need further studies in the future. So is the case for the equations used to calculate heat exchange rates involved.

The equations to calculate heat exchange rates in Eq. (4) are listed in Table 1, and the treatments for heat transfer between a tube and a fluidized bed have been discussed and used in the previous studies [10, 13–15]. Four conductive heat transfer mechanisms are considered in the present work, including the conduction through particle–fluid–particle path: (1) between non-contacted particles, or (2) between contacted particles; and the conduction through particle–particle path: (3) between particles in enduring contact, or (4) between particles in collisional contact. Note that Eq. (c) in Table 1 is for the conductive heat transfer mechanisms (1) and (2) between particles i and j; and Eqs. (d) and (e) are for the conductive heat transfer mechanisms (3) and (4), respectively.

The treatments of a tube are outlined below. A tube is treated as walls because its size is much larger than a particle or a computational cell used in CFD; otherwise, it can be treated as a particle. The conduction between a tube and a particle is considered in a similar manner to that between particles. The equation used for evaluating the local convection heat transfer between the tube and fluid is the same as those between a wall and fluid. For the present study, the domain size for the radiative heat transfer between particles is the same as a computational cell $2d_p$. The definition of bed temperature (T_{bed}) and tube environmental temperature (T_e) is the same as $T_{local,i}$. The local porosity