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An experimental and computational study of wall to bed heat transfer in a bubbling gas–solid fluidized bed

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ABSTRACT

The Eulerian–Eulerian approach is used to predict wall to bed heat transfer coefficient in a gas–solid fluidized bed with a jet by a heated wall. The constant viscosity model (CVM) and kinetic theory of granular flows (KTGF) are used to describe the solid phase rheology. A solid phase molecular thermal conductivity model specifically developed for the near wall region is used in the present work since wall to bed heat transfer occurs through the particle layer in contact with the wall. A comparison of the predicted and measured heat transfer coefficient is presented for different jet velocities, particle sizes and particle types and good agreement is observed between the predicted and measured values. It is observed that the predicted heat transfer coefficient is not affected significantly by the drag model or solid phase rheology model (CVM or KTGF) provided all other model parameters and operating conditions are same. Additionally for KTGF, over-prediction of heat transfer coefficient is observed in the case where solid phase thermal conductivity is expressed in terms of granular temperature rather than molecular conduction. Inclusion of particle rotation in the KTGF model reduces this over-prediction by around 17%.

1. Introduction

Fluidized beds are deemed to be a good choice in gas–solid operations involving heat transfer due to high heat transfer rates caused by vigorous solid motions and large specific interfacial area of solids. As a consequence, fluidized bed heat transfer has been a subject of intense research in order to find reliable models for the prediction of bed to wall (or wall to bed) heat transfer coefficients. In the past, many mechanistic and empirical models for bed to wall heat transfer have been proposed in literature. A review of selected models is presented in Yusuf et al. (2005). However, mechanistic models are constrained by the assumptions on which they were based, while empirical models work well only within the range of experimental data based on which the model was arrived at. The limitations associated with the mechanistic and empirical models have led researchers to an emerging and a more promising approach that is computational fluid dynamics (CFD). By using the CFD approach, numerical calculation of bed to wall (or vice versa) heat transfer coefficient is carried out by solving the Navier Stokes equation along with the thermal energy balance equation.

Syamlal and Gidaspow (1985) performed numerical simulation of heat transfer in a fluidized bed with a jet by the heated wall by using the Eulerian–Eulerian CFD approach which treats the gas and solid phases as interpenetrating continua. More details of this approach are available in Gidaspow (1994). Syamlal and Gidaspow (1985) observed that the time averaged heat transfer coefficient predicted by their model was in better agreement with the experimental data than the one predicted by an empirical model. Later, Kuipers et al. (1992) predicted heat transfer coefficient for the case of a single and multiple bubbles rising along the heated wall. They observed that the maximum value of the local instantaneous heat transfer coefficient occured in the bubble wake and thus concluded that fluid dynamics and heat transfer in the bed were coupled to each other. Schmidt and Renz (2000) carried out numerical calculation of heat transfer coefficient for a more complex geometry which involved a heated horizontal tube immersed in a bubbling fluidized bed. Similar to Kuipers et al. (1992), their study revealed that fluid dynamics and heat transfer around the tube were closely linked. They further observed that the predicted local instantaneous heat transfer coefficient around the tube was much higher than the measured values.

The application of Eulerian–Eulerian approach to heat transfer requires the constitutive equations for the thermal conductivities of the gas and solid phase in the bed bulk and in the near wall region. While the thermal conductivities in the bulk are needed for calculating the conduction fluxes through the respective phases, near wall conductivities are required for imposing the heat flux transferred from the wall boundary to the bed. The thermal conductivity of the solid phase in the bulk and in near wall region

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can differ significantly from the true thermal conductivity of the material due to particle–particle contacts in the bulk and particle–wall contacts in the near wall region. All the aforementioned studies on wall to bed heat transfer have obtained gas and solid phase thermal conductivities in the bulk and the near wall region from Zehner and Schluender (1970) model for gas–solid bulk thermal conductivity in the core of a packed bed for a random packing of spheres. Zehner and Schluender model (1970) calculates the thermal conductivity of the gas–solid bulk as a function of bulk voidage and the true thermal conductivities of gas and solid particles on the basis of a unit cell in the bulk of the packed bed.

Studies on packed bed by Benenati and Borsilow (1982) and Korolev et al. (1971) have shown that the voidage in the near wall region is a function of particle size and distance from the wall as opposed to the bed bulk where a constant value is observed. According to Patil et al. (2006), the aforementioned studies neglect this effect by evaluating the thermal conductivities on the basis of bulk voidage rather than the actual voidage in the near wall region. Patil et al. (2006) have tried to correct this fallacy by evaluating gas and solid phase thermal conductivities on voidage obtained from Martin's (1978) correlation for porosity (voidage) distribution near the wall where the near wall porosity is expressed as a function of distance from the wall and particle size. By incorporation of near wall porosity profile into the thermal conductivities from Zehner and Schluender (1970) model, Patil et al. (2006) observed that the predicted local instantaneous heat transfer coefficient for the case of a pulsating jet by the heated wall showed improvement and better agreement with the experimental values as compared to previous studies where no such porosity profile was considered.

Papadikis et al. (2008, 2009) have presented an advanced CFD model for fast pyrolysis modelling in bubbling fluidized bed reactors where mass, momentum and heat transport between the fluidized bed (fluidizing gas and fluidized sand) and a discrete biomass particle are modelled. However, the aforementioned approach is not the focus of present work where CFD modelling of heat transfer between a heated surface and the fluidized bed are addressed.

As mentioned earlier, Zehner and Schluender (1970) model is developed on the basis of a solid assembly in the bulk of the bed. Legawiec and Ziolkowski (1994) have reported that heat conduction is much more efficient in the bulk of the bed than in the near wall region because for a given voidage the number of contacts between the solid particles in the bulk are higher than the number of contacts between the particles and the wall. This implies that the incorporation of near wall porosity profile into Zehner and Schluender (1970) model will still predict higher thermal conductivity for the solid phase in the near wall region as this model is based on particle–particle contacts in the bulk rather than in the near wall region. The high solid thermal conductivity will in turn lead to higher values of the predicted heat transfer coefficient in comparison to the measured values.

The above discussion underscores the point that the extension of Zehner and Schluender (1970) model to the near wall region is fundamentally flawed as this model caters to the physical background that governs heat conduction in the bulk of the bed. A fundamental approach that is based on the physical background of heat transfer in the near wall bed region is needed to obtain solid phase thermal conductivity in the vicinity of the wall.

Fluidized bed operations use a variety of particles like sand, fluid cracking catalyst, coal, etc. Different particles have different thermophysical properties which can affect bed hydrodynamics and wall to bed heat transfer. No studies on the effect of thermophysical properties of particles on heat transfer have been reported in previous works on numerical modelling of wall to bed heat transfer. A study with different particle types is thus deemed necessary in order to assess the ability of Eulerian–Eulerian models in capturing the effect of thermophysical properties on heat transfer.

In the Eulerian–Eulerian approach, the particle–particle interactions can be modelled through the constant viscosity model (CVM) or through the kinetic theory of granular flows (KTGF). The CVM assigns a constant viscosity to the solid phase while in KTGF, the solid phase viscosity is modelled in terms of a granular temperature. Both the approaches are studied in this work. The KTGF also provides a means to model the solid phase thermal conductivity in terms of granular temperature (Hunt, 1997). Both Schmidt and Renz (2000) and Patil et al. (2006) have demonstrated that the model of solid phase thermal conductivity based on granular temperature grossly over-predicts the heat transfer coefficient. Patil et al. (2006) cite the over-prediction of the granular temperature in the near wall region as the cause of the high heat transfer coefficients. Till date, no study has explored the fundamental cause behind the over-predicted granular temperature and hence this area requires further attention.

The above discussion brings forth the point that ample scope exists in the improvement of numerical modelling of wall to bed heat transfer in fluidized beds as only few studies have been carried out so far and numerous areas require attention. The present study aims at enhancing the knowledge on numerical modelling of fluidized bed heat transfer by scouring the areas where potential for improvement exists. With this aim in sight, a detailed investigation is first carried out into the effect of near wall thermal conductivity of the phases on the predicted heat transfer coefficient. Thereafter, the influence of particle size, jet velocity, particle type, bed height and drag model on heat transfer is investigated. Finally, the role of solid phase rheology models (CVM vs. KTGF), and the consequences of modelling the solid phase conductivity in terms of a granular temperature on the basis of KTGF. The system chosen for study is a laboratory scale pseudo 2-dimensional fluidized bed with a jet by the heated wall. The model predictions are compared against measured values obtained from an experimental setup specifically developed for this study.

2. Experimental

The experimental system chosen for the present study is a simple pseudo 2-dimensional fluidized bed with a jet near the heated wall where a continuous stream of bubbles is introduced due to a jet velocity much higher than the minimum fluidization velocity (Fig. 1). The dimensions of the bed are 0.2 m × 0.7 m × 0.025 m and the width of the jet is 0.005 m. The heated side wall by the jet is made of copper and three heaters each 0.233 m long are placed inside the wall. The wall temperature is measured by resistance temperature detector (RTD) sensors which are connected to PID controllers that maintain the wall temperature at a constant value of 333 K. The local heat flux from the wall to the bed is measured by using heat flux sensors from RdF Corporation (Product No. 20450-1). Three sensors are mounted on the wall at a height of 0.1165, 0.3495 and 0.5825 m above the distributor. The heat flux sensor is a thermopile device where the temperature difference across the two faces of the sensor is measured in terms of voltage which is further correlated to the heat flux as

$$h = \frac{Q_h}{T_w - T_b} = \frac{V}{R(T_w - T_b)} \tag{1}$$

where h is the local instantaneous heat transfer coefficient, Q_h is the heat flux, V is the voltage drop across the sensor, and, T_b and T_w are the bed bulk temperature and wall temperature respectively, and R is the sensitivity of the sensor (6×10^{-9} V m^2/W) which was provided by RdF corporation. The time constant of the heat flux sensor is 20 ms. The signal from the sensor was logged to a computer by