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Numerical simulations of flow structure and heat transfer in a central jet bubbling fluidized bed

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ABSTRACT

An attempt has been made to model the flow structure and to predict heat transfer coefficients in a gas–solid bubbling fluidized bed operated with a central jet using a two fluid model with closures from the kinetic theory of granular flow. Quantities such as the fluid-to-particle heat transfer coefficient are not easily obtained practically from experiments with a high degree of accuracy thereby making computational methods attractive. The CFD model has been verified using experimental bubble properties obtained from the literature. Axial and lateral normal Reynolds stresses, energy spectra and granular temperatures have been computed. The simulations show that the maximum local instantaneous fluid-to-particle heat transfer coefficient occurs in the wake of the bubble. Heat transfer coefficients at the center of the bed exhibit high oscillations compared to the near wall region. However time averaged values in the near wall region are larger compared to the bed center. The average heat transfer coefficient exhibits a maximum value with the variation of the jet velocity.

1. Introduction

Compared to other modes of contacting, fluidized bed reactors offer high rates of heat and mass transfer between the fluid and solid phases. It is not surprising therefore that fluidized bed technology is widely employed in chemical, petrochemical, metallurgical and energy industries [1]. The excellent features of these reactors are largely attributed to the presence of bubbles [2] and in industrial scale fluidized bed reactor bubbles emerge from discrete holes or other types of orifices in the gas distributor plate. Kuipers et al. [3] note that bubble characteristics are dependent on the initial bubble generated from the orifice. They further state that mass and heat transfer processes are seriously affected by the mechanism of bubble formation. Numerous studies (experimental and theoretical) have been conducted on the formation of bubbles from a single orifice. Harrison and Leung [4] are perhaps one of the first authors to develop a model for the formation of gas bubbles at a single orifice in a fluidized bed. However their model assumed the non-existence of gas leakage at the bubble surface into the emulsion phase an assumption which was later proved otherwise by Nguyen and Leung [5]. Other models describing the formation of gas bubbles at a single orifice are due to Yang et al. [6] and Caram and Hsu [7]. The model of Yang and co-workers postulates that the superficial velocity of gas leakage at the bubble-emulsion boundary is equal to the minimum fluidization velocity while that of Caram and Hsu postulates that the superficial exchange velocity is dependent of the pressure gradient.

Increased computational capabilities coupled with reduction in hardware costs have given rise to the use of computational fluid dynamics (CFD) in the modeling and simulation of multiphase systems. Therefore for the last two decades or so studies on the formation of bubbles at a single orifice have been executed using CFD. Two basic approaches namely Eulerian–Eulerian (granular flow models) and Eulerian–Lagrangian (discrete particle models) are commonly used to model gas–solid flows. Kuipers and co-workers [3] used a two fluid model (TFM) to study the theoretical bubble formation at a single orifice in a two dimensional bed. The model predicted bubble sizes, formation times and shapes satisfactorily and the results were in good agreement with experimental results and approximate models. Later Nieuwland et al. [2] extended the work of Kuipers and co-workers to investigate the effect of particle properties on the bubble growth process for Geldart B particles. They came to a conclusion that the hydrodynamic model gives a satisfactory good description of the bubble growth process for several particle types. Bokkers et al. [8] used a discrete particle model (DPM) to study the extent of mixing and segregation induced by a single bubble in a monodisperse and bidisperse fluidized bed at incipient conditions and in freely bubbling fluidized beds in addition to experimental studies. They observed that the bubble size predicted by

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the DPM and the extent of segregation induced by a single bubble in a bidisperse fluidized bed strongly depends on the drag model used. Patil et al. [9] compared the constant viscosity model (CVM) with the kinetic theory of granular flow (KTGF) in the study of bubble formation at a single orifice with experimental data. Their study revealed that bubble growth is mainly determined by the drag experienced by the gas percolating through the bubble-emulsion boundary. Recently Kumar et al. [10] used the Eulerian–Eulerian modeling approach to study the effect of the wall on the shape of the bubble, bubble wake during formation and the bubble rise for both symmetric and asymmetric injections. In addition to the modeling and simulation of bubble behavior from a single orifice, several other modeling and simulation studies [11–13] have been reported focusing the wall-to-bed heat transfer coefficients in bubbling fluidized beds in which the orifice is located near a heated wall and the bulk of the bed is kept at a constant temperature. Results from such simulations agreed reasonably well with experimental results from carefully controlled experiments.

Despite the great advantages offered by CFD very few studies have been reported on fluid-to-particle heat transfer modeling. Probably this is due to the fact that simulation results from such studies are difficult to validate against experimental data. Inaccuracies in the measurement of particle and gas temperatures have made the determination of fluid-to-particle heat transfer coefficients difficult to measure. Furthermore due to the complex flow pattern in fluidized beds, the fluid-to-particle heat coefficients reported in literature vary a great deal depending on the flow assumption used [14]. In addition there are currently no experimental techniques for obtaining energy profiles in fluidized beds without perturbing the system thereby rendering computational methods attractive [15]. The objective of the present work is to analyze the flow structure including the turbulent properties such as the Reynolds stresses, granular temperatures and energy spectra and how they affect the predicted fluid-to-particle heat transfer coefficients at different positions in the bed. Such an approach would give valuable information concerning the coupling between the bed hydrodynamics and the heat transfer coefficients. CFD as a complementary tool to experimentation and reactor models [16] can greatly help in the understanding of transport mechanisms in the reactor and obtain useful information. The flow structure in the fluidized beds can be described in detail using properties such as the solid volume fraction distribution, void fraction distribution and laminar granular temperature as well as turbulent properties such as the turbulent granular temperature and the energy spectra. Examination of the flow structure can give an idea about regions of high and low heat transfer which is necessary for the optimal design and scale up of fluidized bed reactors. The granular temperature gives information about the fluctuation or oscillation of individual particles, bubbles and clusters [17]. Moreover the temporal variation of the heat transfer coefficients at specific positions in the bed can be analyzed and related to the oscillatory behavior of the individual particles, bubbles and/or clusters. Such an approach enables a better and clear understanding of the coupling between the bed hydrodynamics and the predicted heat transfer coefficients.

The paper is organized as follows. Section 2 gives the continuum governing equations and constitutive relations. Section 3 describes the simulation set-up together with the procedure for processing the data from the simulations. Section 4 is the results and discussion section. Firstly the model is validated using experimental data and the initial-startup bubble properties are considered for this purpose. The simulated results are also compared with the theoretical model according to Caram and Hsu [18]. A study on the choice of the drag model used has also been done. Next the flow structure of the bed is investigated including turbulent properties such as the turbulent granular temperature and energy spectrums. Finally predicted local and time averaged heat transfer coefficients are discussed with relation to the flow structure. In Section 5 the summary and conclusions of the present work are given.

2. CFD model

The continuum governing equations, constitutive relations and boundary conditions for a monodisperse system are presented below:

2.1. Governing equations

Mass conservation for phase k ($k = $ g for gas and s for solid phase)

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \mathbf{u}_k) = 0 \tag{1}$$

in each computational cell the total volume fraction of all phases must be equal to unity, i.e.

$$\sum_{k=1}^{n} \alpha_k = 1. \tag{2}$$

Momentum conservation for solid phase:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s \mathbf{u}_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{u}_s \mathbf{u}_s) = -\alpha_s \nabla p - \nabla p_s + \nabla \cdot \bar{\bar{\tau}}_s + \alpha_s \rho_s \mathbf{g} + \beta_{gs}\left(\mathbf{u}_g - \mathbf{u}_s\right) \tag{3}$$

Momentum equation for gas phase:

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g \mathbf{u}_g\right) + \nabla \cdot \left(\alpha_g \rho_g \mathbf{u}_g \mathbf{u}_g\right) = -\alpha_g \nabla p + \nabla \cdot \bar{\bar{\tau}}_g + \alpha_g \rho_g \mathbf{g} - \beta_{gs}\left(\mathbf{u}_g - \mathbf{u}_s\right) \tag{4}$$

Thermal energy conservation for solid phase:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s H_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{u}_s H_s) = -\nabla \cdot \alpha_s \kappa_s \nabla T_s + h_{sg}\left(T_g - T_s\right) \tag{5}$$

Thermal energy conservation for gas phase:

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g H_g\right) + \nabla \cdot \left(\alpha_g \rho_g \mathbf{u}_g H_g\right) = -\nabla \cdot \alpha_g \kappa_g \nabla T_s - h_{sg}\left(T_g - T_s\right) \tag{6}$$

2.2. Granular temperature equation

The algebraic form of the granular temperature transport equation was adopted after an initial study to save computational cost and maintain accuracy of results. It is applicable for dense fluidized beds where the convection and the diffusion term can be neglected under the premise that production and dissipation of granular energy are in equilibrium.

$$0 = \left(-p_s \bar{\bar{I}} + \bar{\bar{\tau}}_s\right) : \nabla \mathbf{u}_s - \gamma_s - 3\beta_{gs}\Theta_s \tag{7}$$

2.3. Constitutive equations for interphase momentum transfer

Syamlal O'Brien [19]:

$$\beta_{gs} = \frac{3}{4}\frac{\alpha_s \alpha_g \rho_g}{v_{rs}^2 d_s} C_D\left(\frac{\mathrm{Re}_s}{v_{rs}}\right)\left|\mathbf{u}_g - \mathbf{u}_s\right| \tag{8}$$

$$C_D = \left(0.63 + \frac{4.8}{\sqrt{\mathrm{Re}_s / v_{rs}}}\right)^2, \mathrm{Re}_s = \frac{\rho_g \left|\mathbf{u}_g - \mathbf{u}_s\right| d_s}{\mu_g} \tag{9}$$