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CFD Modeling of Heat Transfer in Gas Fluidized Beds

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Abstract

This work aims to study heat transfer from a heated wall in a gas fluidized bed using the Eulerian-Eulerian approach. A two dimensional simulation of a bubbling bed at ambient conditions with a heated wall at 333 K is carried out on the in-house code FLOTRACS-MP-3D. Two approaches are used to model the solid phase thermal conductivity. The first approach is that of Kuipers et al. [7] who used an empirical expression for thermal conductivity of gas-solid bulk based on particles arrangement in a packing while the second approach is attributed to Natarajan and Hunt [12] model consisting of a kinetic conductivity due to particle streaming and a molecular conductivity due to collisions. The effect of bubble rise on the heat transfer coefficient comes to the fore, thus indicating that heat transfer and hydrodynamics at the wall are closely interwined. Comparisons of numerical predictions against experimental data for the effect of gas velocity and particle size on wall to bed heat transfer coefficient are also presented. However, this is a preliminary study and needs further investigation.

Nomenclature

c_p	heat capacity, J/kg K.
d_p	diameter of particle, m
g_0	radial distribution function
h	enthalpy, J/Kg
k	thermal conductivity, W/m K
T_b	bulk temperature , K
T_w	wall temperature, K
u	velocity, m/s
W	width of the bed, m
W_0	width of the jet, m

Greek Letters

α	heat transfer coefficient, W/m^{2}K
ε	volume fraction
μ	laminar viscosity of the gas, kg/m s
ρ	density, kg/m^3
Θ	granular temperature, m^2/s^2

Subscripts

av	time averaged value
coll	collisional component
b	bed
g	gas
i	instantaneous value
j	x,y,z direction of velocity
kin	kinetic component
l	laminar component
m	microscopic value
mf	minimum fluidization
n	phase, gas or solid
R	reference value
s	solids
tur	turbulent component
w	wall

Dimensionless Numbers

Nu	Nusselt number, $\alpha d_p / k_{gm}$
Pr	Prandtl number, $\mu c_{p,g} / k_{gm}$
Re_p	Particle Reynold's number, $\rho_g u d_p / \mu$

1. Introduction

Fluidized beds become a good choice in gas solid operations involving heat transfer due to high heat transfer rates attributed to vigorous solid motions. As a consequence, fluidized bed heat transfer has been a subject of intense research in order to arrive at reliable models for prediction of bed to wall heat transfer coefficients. Many mechanistic models [1-3] and empirical models [4-6] have been proposed. However, mechanistic models are limited 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 arrival of high speed computers has opened new vistas for numerical calculations of bed to wall heat transfer which is otherwise difficult to quantize. In the past decade, Kuipers et al. [7] and Schmidt and Renz [8] have calculated bed to wall heat transfer coefficient in a two dimensional bubbling fluidized bed by the Eulerian-Eulerian approach which treats the solid phase as a continuous fluid. The main focus of [7] and [8] was to investigate the coupling between the heat transfer and the hydrodynamics prevailing in the bed. The goal of this work is to study the influence of parameters like gas velocity and particle size on heat transfer in a bubbling fluidized bed .

2. CFD model

Mathiesen et al. [9] incorporated a multiphase Eulerian-Eulerian model hydrodynamic model for one gas phase and N solid phases into the in-house CFD code, FLOTRACS-MP-3D. The solid phase pressure and viscosity were modeled by the kinetic theory of granular flow while a sub grid scale model was used for gas phase turbulence. The hydrodynamic model is presented in [9].

In order to calculate heat transfer coefficient, the code is extended by adding energy balance equation to each phase. The energy balance equations can be written as

GasPhase:

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g h_g\right)+\frac{\partial}{\partial x_j}\left(\varepsilon_g \rho_g u_{j,g} h_g\right) = \frac{\partial}{\partial x_j}\left(k_s \frac{\partial T_g}{\partial x_j}\right)+\alpha_v\left(T_s - T_g\right) \tag{1}$$

Solid Phase:

$$\frac{\partial}{\partial t}\left(\varepsilon_s \rho_s h_s\right)+\frac{\partial}{\partial x_j}\left(\varepsilon_s \rho_s u_{j,s} h_s\right) = \frac{\partial}{\partial x_j}\left(k_s \frac{\partial T_s}{\partial x_j}\right)+\alpha_v\left(T_g - T_s\right) \tag{2}$$

where,

$$h_n = \int_{T_R}^{T} c_{p,n}\, dT_n \tag{3}$$

In order to close the energy balance equations, expressions for effective phase thermal conductivities, and interphase volumetric heat transfer coefficient are required.

2.1 Effective thermal conductivities of the phases

The effective phase thermal conductivity will be different from the respective phase microscopic thermal conductivity due the presence of other phase. Based on the model of Zehner and Schluender [10], Kuipers et al [7] used the following expressions for effective thermal conductivities:

$$k_{g,l} = \left(1-\sqrt{1-\varepsilon_g}\right)k_{gm} / \varepsilon_g \tag{4}$$

$$k_s = \sqrt{1-\varepsilon_g}\left(\omega a + (1-\omega)C\right)k_{gm} / \varepsilon_s \tag{5}$$

where,

$$C = \frac{2}{1-\frac{a}{b}}\left[\frac{a-1}{\left(1-\frac{b}{a}\right)^2}\frac{b}{a}\ln\frac{a}{b} - \frac{b-1}{1-\frac{b}{a}} - 0.5(b-1)\right] \tag{6}$$

$$a = k_{sm} / k_{gm} \tag{7}$$

$$b = 1.25\left(\frac{1-\varepsilon_g}{\varepsilon_g}\right)^{10/9} \tag{8}$$

$$\omega = 7.26 * 10^{-3} \tag{9}$$

Eq.(4) corresponds to laminar thermal conductivity of gas phase. However, owing to a sub-grid scale turbulence model, the effective thermal conductivity of gas phase will also have a turbulent component. Hence, the total effective gas phase thermal conductivity is expressed as:

$$k_g = k_{g,l} + k_{g,tur} \tag{10}$$

where,

$$k_{g,tur} = \frac{0.7}{\mu_{tur} c_{p,g}} \tag{11}$$

where, the turbulent Prandtl number is taken as 0.7.

In addition to the approach used by [7], the solid phase thermal conductivity can also be modeled by the kinetic theory of granular flows where thermal conductivity can be expressed as a function of granular temperature. Based on kinetic streaming of particles and neglecting collisions, Hunt [11] presented a mechanistic model for effective solid phase thermal conductivity:

$$k_s = \frac{\rho_s c_{p,s} d_p \pi^{3/2} \Theta^{1/2}}{32 g_0} \tag{12}$$

where, g_0 is the radial distribution function. Natarajan and Hunt [12] argued that for dense systems, collisions cannot be neglected, hence effective thermal conductivity should have two components, viz. collisional and kinetic. Based on their argument, they expressed the effective solid phase thermal conductivity as:

$$k_s = k_{s,coll} + k_{s,kin} \tag{13}$$

where, $k_{s,coll}$ is obtained from an empirical expression given by Gelperin and Einstein [4] as:

$$\frac{k_{s,coll}}{k_{gm}} = 1 + \frac{\varepsilon_s\left(1-\frac{k_{gm}}{k_{sm}}\right)}{\frac{k_{sm}}{k_{gm}} + 0.28(1-\varepsilon_s)^{0.63*(\frac{k_{gm}}{k_{sm}})^{0.18}}} \tag{14}$$

while, $k_{s,kin}$ can be given by eq.(12)

The Natarajan and Hunt [12] model hence combines the empirical and mechanistic approaches.

2.2 Volumetric interphase heat transfer coefficient

The energy balance equations for the two phases are connected through the interphase volumetric heat transfer coefficient, α_v which can be can be expressed as :

$$\alpha_v = \frac{6(1-\varepsilon_g)\alpha_{gp}}{d_p} \tag{15}$$

where, α_{gp} is the gas-particle heat transfer coefficient given by Gunn [13] as:

$$\frac{\alpha_{gp} d_p}{k_{gm}} = \left(7 - 10\varepsilon_g + 5\varepsilon_g^{\,2}\right)\cdot\left(1 + 0.7\,\mathrm{Re}_p^{0.2}\,\mathrm{Pr}^{1/3}\right) + \left(1.33 - 2.4\varepsilon_g + 1.2\varepsilon_g^{\,2}\right)\cdot \mathrm{Re}_p^{0.7}\,\mathrm{Pr}^{1/3} \tag{16}$$

3. Numerical set-up

This study is based on the fluidized bed system used by Wunder [14] to study heat transfer from an immersed vertical tube. Wunder's system consists of a 0.2 m diameter bed with varying initial solids height and different lengths of immersed tubes. In order to reduce computation time, the system is modified as 0.1 m wide 2-D bed with a jet near a heated constant temperature wall. The boundary conditions for a bed with a jet are depicted in Fig.1. Minimum fluidiztion state at 298 K and 1 bar are used as the initial conditions for all simulations. A no slip boundary condition is used for both the phases. The time step is calculated from Courant criterion. The thermophysical properties of gas and solid phase are given in Table 1.

In order to resolve near wall temperature gradients, a very fine grid is placed normal to the heated wall. The grid size increases with distance from the wall. The cell next to the heated wall is divided into subcells as suggested by Kuipers et al. [7] till a grid independent solution is obtained. It is observed that 7 subcells with a smallest subcell size of 0.000078125m is sufficient to obtain a grid independent solution. A total of 26*60 computational cells are used The overall instantaneous heat transfer coefficient at the wall is defined as:

$$\alpha_i = \frac{\left|\frac{\varepsilon_g k_g \partial T_g}{\partial x}\right|_w + \left|\frac{\varepsilon_s k_s \partial T_s}{\partial x}\right|_w}{T_w - T_b} \quad (17)$$

Table 1. Thermophysical Properties of phases

Gas Phase	Solid Phase
ρ_g : 1.2 kg/m^3 k_{gm}: 0.026 W/m^2-K c_p : 1006 J/kg ϵ_{mf} : 0.40	ρ_s : 2490 kg/m^3 k_{sm} : 1 W/m^2-K c_p : 840 J/kg d_p : 140*10^{-6} m, 400*10^{-6} m

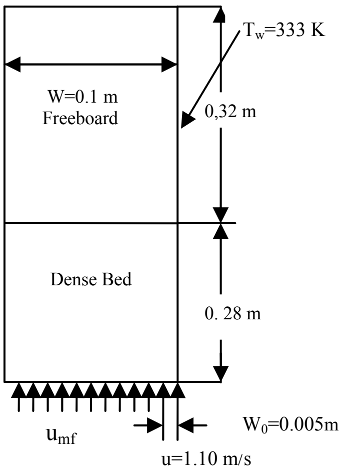

Fig .1 Outline of a typical numerical setup.

4. Results and Discussion

Wunder [14] carried out experimental studies for heat transfer in freely bubbling beds. In order to investigate the coupling between hydrodynamics and heat transfer at the wall, one of Wunder's [14] experiment is simulated as a bed with a jet near the wall. The jet has a velocity of 1.10 m/s which leads to bubble formation in the vicinity of wall. Thermal conductivity of solid phase is obtained from the model of Kuipers et al. [7]. Fig.2 shows the contours of the rising bubble in the bed. It takes around 1 second for the bubble to leave the bed. Fig. 3a and 3b show the temporal variation of solid volume fraction and heat transfer coefficient at a height of 0.15m, respectively. Initially, the heat transfer coefficient is very high as the bed comes in contact with the heated wall. The heat transfer coefficient decays with time until bubble passage leads to particle refreshment which causes a sudden surge in heat transfer coefficient. Thereafter, heat transfer coefficient exhibits an oscillatory behaviour as bubbles keep passing through the bed. This phenomena is in agreement with the study of Mickley and Fairbanks [1] who argued that continuous solids renewal at the wall is responsible for high bed to wall heat transfer coefficients.

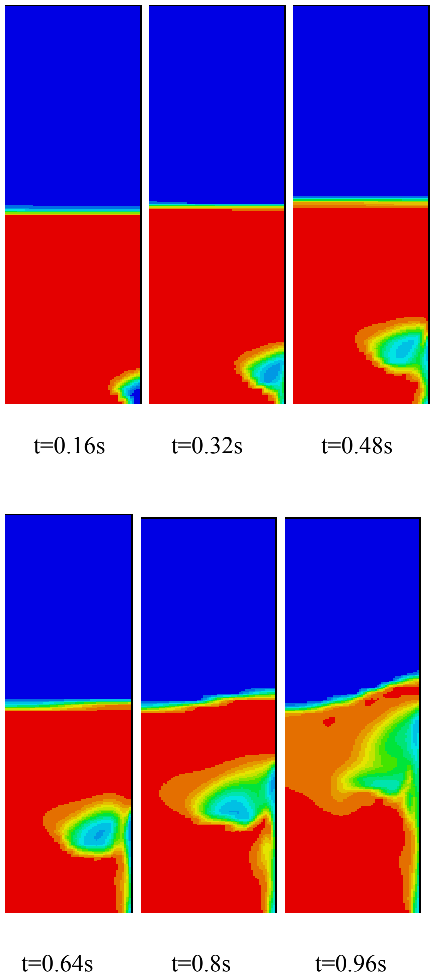

Fig.2 Contours of solid volume fraction in the bed.

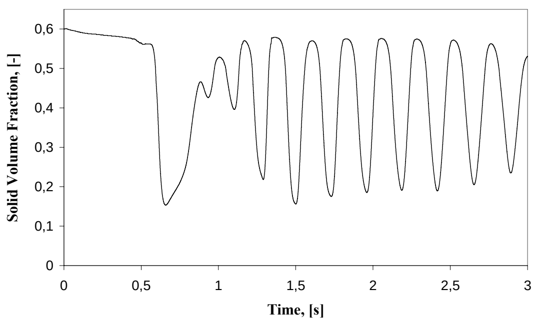

Fig. 3a Temporal variation of solid volume fraction at a height of 0.15 m above the distributor.

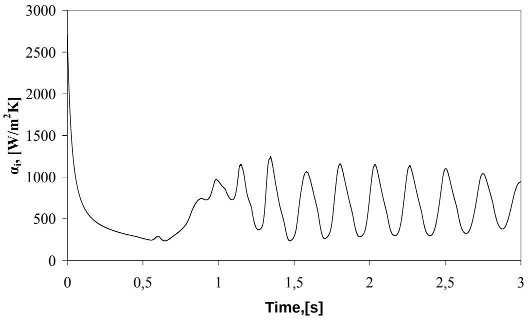

Fig. 3b Instantaneous heat transfer coefficient at a height of 0.15 m above the distributor.

4.1 Effect of solid phase thermal conductivity model

Figs .4a and 4b show the instantaneous and time averaged heat transfer coefficients at a height of 0.15 m for the solid phase thermal conductivity models of Kuipers et al. [7] and Natarjan and Hunt [12]. It is evident from Figs. 4a and 4b that for the first 0.5 s, the Natarajan and Hunt Model [12] gives lower heat transfer coefficient than Kuipers' et al [7] model. This is expected as the kinetic component of thermal conductivity remains low initially due to high solid volume fractions which tends to curb the fluctuating kinetic energy of solid particles. After 0.5 s, as the effect of rising bubbles is felt at a height of 0.15 m, solid volume fraction decreases thus increasing kinetic component of solid phase thermal conductivity. Thereafter, instantaneous and average heat transfer coefficients predicted by the two models are of the same order.

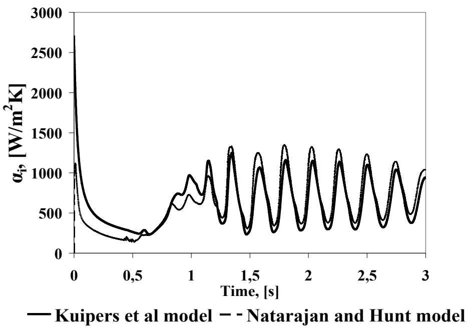

Fig. 4a Comparison between two solid phase thermal conductivity models.

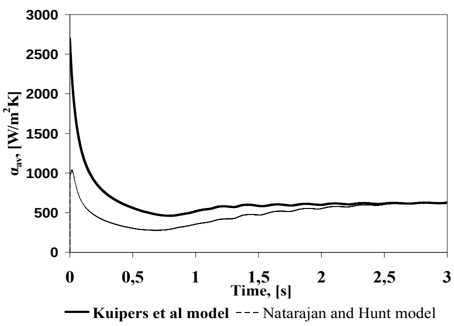

Fig. 4b Comparison between two solid phase thermal conductivity models.

4.2 Effect of gas superficial velocity on Heat Transfer Coefficient

Fig. 5 shows the effect of gas superficial velocity on wall to bed heat transfer coefficient for 400 micrometer particles. All simulations reported here onwards are run for 3s of real time. Time averaged heat transfer coefficients are obtained for the last 2 seconds. As seen in the figure, the heat transfer coefficient increases with gas velocity upto a certain point before levelling down. Both simulations and experiments conform to this trend. The quantitative values however, are different. This is expected as the simulations are carried out on a simplified 2-D modification of Wunder [14] 3-D set up. Moreover, longer averaging times may be required to obtain a more accurate prediction.

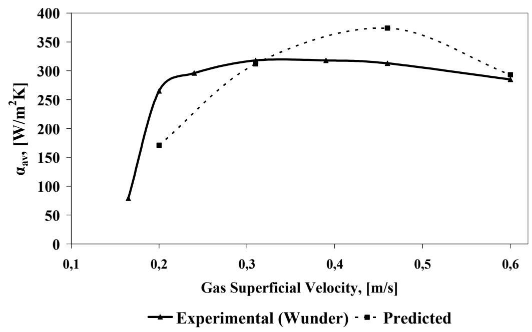

Fig. 5 Effect of gas velocity on wall to bed heat transfer coefficient.

4.3 Effect of particle size

Fig. 6 shows the variation of heat transfer coefficient with gas velocity for two different particle sizes. As seen in Fig. 6, for a given gas velocity, smaller particles give higher heat transfer coefficient. Such a behavior is expected since smaller particles have larger specific interfacial area which is favourable to heat transfer. The quantitative difference between predictions and measurements persist due to reasons cited before. Nonetheless, predictions follow the qualitative phenomena exhibited by the measurements.

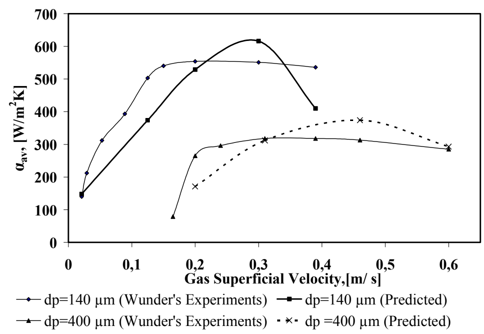

Fig. 6 Effect of particle size on wall to bed heat transfer coefficient.

5. Conclusions

An Eulerian-Eulerian approach is used to predict heat transfer coefficient from a heated wall to bed in a 2-D bubbling fluidized bed. The heat transfer coefficient is closely linked to the solids volume fraction and hence to the hydrodynamics in the vicinity of the wall. Two approaches viz. Kuipers' et a.l [7] and Natarajan and Hunt [12] are used to model the solid phase thermal conductivity. It seems that the semi empirical approach of Natarajan and Hunt [12] can be used as an alternative to the purely empirical approach of Kuipers' et a.l [7]. A study of the effect of gas velocity and particle size on heat transfer coefficient indicates that the qualitative performance of the predictions against experimental data is fair. Three dimensional simulations of Wunder's[14] experiments are planned in order to fully vindicate the capability of the developed code in predicting the wall to bed heat transfer phenomena for immersed surfaces.

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