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Effect of tube shape on the hydrodynamics and tube-to-bed heat transfer in fluidized beds

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ABSTRACT

In the present work, the multiphase flow dynamics in fluidized beds is modelled using the Two-Fluid Model (TFM) where the characteristics of a granular solid phase are described by the Kinetic Theory of Granular Flow (KTGF). A drag function and heat transfer coefficients are used to describe the interaction and heat exchange between different phases, respectively. The effective thermal conductivity is defined as a function of phase volume fraction and thermal properties and is used to calculate the heat transfer coefficient from immersed tube to fluidized beds. The effects of different tube shapes on the flow characteristics and local heat transfer coefficients are investigated and the time-averaged heat-transfer coefficient is compared with the experimental data in the literature. The simulated results show that the heat transfer processes are significantly influenced by the reintroduction of solid particles around the immersed surfaces and the heat transfer coefficients vary sensitively with the distribution of the solid phase. The simulated heat transfer coefficients are in the same order as the experimental data which indicates that it can be quantitatively employed to aid the configuration of heating tubes during industrial design of the fluidized bed reactors.

1. Introduction

Bubbling fluidized beds have been widely utilized in the industrial sector for decades because of their high heating rates, uniform temperature distributions and scale-up potential [1]. Empirical and numerical studies have been carried out but computational multiphase flow models are the preferred method to analyze the interactions between the gas and the solid particles. During fluidization the transition and formation of bubbles in the vicinity of heat exchangers are important factors in understanding the heat transfer between phases. Unfortunately, industrial processes cannot be easily measured, due to the relative small scale or complicated operational conditions, so numerical methods have been considered as a useful tool to display details that cannot be obtained directly from the experiments.

Although the mass and heat transfer between two-phase-flow have been studied for years, accuracy in the prediction of multiphase flow characteristics and heat transfer coefficient in fluidized beds with immersed surface is expected to be improved. Several empirical correlations have been developed to determine the heat transfer coefficients between wall-to-bed and tube-to-bed reactors. Mickley and Fairbanks [2] suggested that the particle-wall contact time was an important factor for calculating the heat transfer coefficients between the wall and fluidized beds, as packets of particles contacting with the wall frequently could enhance the heat exchange. Although the theoretical work is reasonable and can be verified experimentally, the correlation is just suitable for the specific experimental conditions on which they are based. Di Natale et al. [3] presented a range of heat transfer coefficients from experiments using different shaped immersed tubes within a fluidized bed. The findings highlighted the strong influence surface shape has on the heat transfer coefficients rather than just thermal properties alone.

Two-Fluid Model (TFM) is the preferred method for simulating fluidized beds and has been effectively used for the studies of the heat transfer processes in fluidized beds. The granule–granule and granule–droplet collision rates were investigated by analyzing the corresponding collision time scale in fluidized bed melt granulation by Chua et al. [4], the granule behaviour in a spray fluidized bed had been clearly identified by TFM & KTGF. Kuipers et al. [5] numerically studied the wall to bed heat exchange to determine the influence of bubble motion on the heat transfer. Patil et al. [6] considered a range of different operating conditions and two different closure models, the constant viscosity model (CVM) and the presently used

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Table 1
Governing equations.

Volume fraction:

$$\alpha_g + \alpha_s = 1 \quad (1)$$

Conservation of mass:

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\right) = 0 \quad (2)$$

$$\frac{\partial}{\partial t}(\alpha_s\rho_s) + \nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\right) = 0 \quad (3)$$

Conservation of momentum:

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{v}_g\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right) = -\alpha_g\nabla p + \nabla\cdot\bar{\bar{\tau}}_g + \alpha_g\rho_g\vec{g} + \vec{R}_{sg} \quad (4)$$

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s\vec{v}_s\right) + \nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\vec{v}_s\right) = -\alpha_s\nabla p - \nabla p_s + \nabla\cdot\bar{\bar{\tau}}_s + \alpha_s\rho_s\vec{g} + \vec{R}_{gs} \quad (5)$$

Phase stress–strain tensor:

$$\bar{\bar{\tau}}_g = \alpha_g\mu_g\left(\nabla\vec{v}_g + \nabla\vec{v}_g^{\,T}\right) + \alpha_g\left(\lambda_g - \frac{2}{3}\mu_g\right)\nabla\cdot\vec{v}_g\bar{I} \quad (6)$$

$$\bar{\bar{\tau}}_s = \alpha_s\mu_s\left(\nabla\vec{v}_s + \nabla\vec{v}_g^{\,T}\right) + \alpha_s\left(\lambda_s - \frac{2}{3}\mu_s\right)\nabla\cdot\vec{v}_s\bar{I} \quad (7)$$

$$\vec{R}_{sg} = -\vec{R}_{gs} = K_{sg}\left(\vec{v}_s - \vec{v}_g\right) \quad (8)$$

Conservation of energy:

$$\frac{\partial\left(\alpha_g\rho_g\psi_g\right)}{\partial t} + \nabla\cdot\left(\alpha_g\rho_g\psi_g\vec{v}_g\right) = -\alpha_g\frac{\partial p_g}{\partial t} + \bar{\bar{\tau}}_g : \nabla\vec{v}_g - \nabla\cdot q_g + S_g + \vec{Q}_{sg} \quad (9)$$

$$\frac{\partial(\alpha_s\rho_s\psi_s)}{\partial t} + \nabla\cdot\left(\alpha_s\rho_s\psi_s\vec{v}_s\right) = -\alpha_s\frac{\partial p_s}{\partial t} + \bar{\bar{\tau}}_s : \nabla\vec{v}_s - \nabla\cdot q_s + S_s + \vec{Q}_{gs} \quad (10)$$

$$\vec{Q}_{gs} = -\vec{Q}_{sg} = h_{gs}(T_g - T_s) \quad (11)$$

Table 2
Constitutive correlations.

Drag function:

$$K_{sg} = 150\frac{\alpha_s^2\mu_g}{\alpha_g d_s^2} + 1.75\frac{\rho_g\alpha_s\left|\vec{v}_s - \vec{v}_g\right|}{d_s} \quad \alpha_g < 0.8 \quad (12)$$

$$K_{sg} = \frac{3}{4}C_D\frac{\alpha_s\alpha_g\rho_g\left|\vec{v}_s - \vec{v}_g\right|}{d_s}\alpha_g^{-\ .65} \quad \alpha_g > 0.8 \quad (13)$$

$$C_D = \frac{24}{\alpha_g Re_s}\left[1 + 0.15(\alpha_g R_s)^{0.687}\right] \quad (14)$$

$$Re_s = \frac{\rho_g d_s\left|\vec{v}_s - \vec{v}_g\right|}{\mu_g} \quad (15)$$

Kinetic theory of granular flow:

$$\mu_s = \mu_{s\cdot\mathrm{col}} + \mu_{s\cdot\mathrm{kin}} + \mu_{s\cdot\mathrm{fr}} \quad (16)$$

$$\mu_{s\cdot\mathrm{col}} = \frac{4}{5}\alpha_s\rho_s d_s g_0(1+e)\left(\frac{\theta_s}{\pi}\right)^{1/2} \quad (17)$$

$$\mu_{s\cdot\mathrm{kin}} = \frac{10 d_s\rho_s\sqrt{\theta_s\pi}}{96\alpha_s(1+e)g_0}\left[1 + \frac{4}{5}\alpha_s g_0(1+e)\right]^2 \quad (18)$$

$$\mu_{s\cdot\mathrm{fr}} = \frac{p_s\sin\varphi}{2\sqrt{I_{2D}}} \quad (19)$$

$$\lambda_s = \frac{4}{3}\alpha_s\rho_s d_s g_0(1+e)\left(\frac{\theta_s}{\pi}\right)^{1/2} \quad (20)$$

$$p_s = \alpha_s\rho_s\theta_s\cdot(1 + 2g_0\alpha_s\cdot(1+e)) \quad (21)$$

$$g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{\alpha_{s\cdot\max}}\right)^{\frac{1}{3}}\right]^{-1} \quad (22)$$

Granular temperature:

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha_s\rho_s\theta_s) + \nabla\cdot\left(\alpha_s\rho_s\theta_s\vec{v}_s\right)\right] = \left(-p_s\bar{I} + \bar{\bar{\tau}}_s\right) : \nabla\vec{v}_s + \nabla\cdot(k_{\theta_s}\nabla\theta_s) - \gamma_{\theta_s} - 3K_{gs}\theta_s \quad (23)$$

$$k_{\theta_s} = \frac{150 d_s\rho_s\sqrt{\theta_s\pi}}{384(1+e)g_0}\left[1 + \frac{6}{5}\alpha_s g_0(1+e)\right]^2 + 2\alpha_s^2 d_s\rho_s g_0(1+e)\sqrt{\frac{\theta_s}{\pi}} \quad (24)$$

$$\gamma_{\theta_s} = \frac{12(1-e^2)g_0}{d_s\sqrt{\pi}}\rho_s\alpha_s^2\theta_s^{\frac{3}{2}} \quad (25)$$

Heat transfer coefficient:

$$h_{gs} = h_{sg} = \frac{6k_g\alpha_g\alpha_s Nu_s}{d_s^2} \quad (26)$$

$$Nu_s = \left(7 - 10\alpha_g + 5\alpha_g^2\right)\left(1 + 0.7\mathrm{Re}_s^{\frac{1}{5}}\mathrm{Pr}^{\frac{1}{2}}\right) + \left(1.33 - 2.4\alpha_g + 1.2\alpha_g^2\right)\mathrm{Re}_s^{\frac{7}{10}}\mathrm{Pr}^{\frac{1}{3}} \quad (27)$$

$$Pr = \frac{Cp_g\mu_g}{k_g} \quad (28)$$

kinetic theory of granular flow (KTGF) model. They found that the KTGF model captured better transitions of the bubbles compared to the CVM model. Unfortunately the heat transfer coefficient was over predicted compared to the experimental results, particularly when the effective solid thermal conductivity included the influence of particle kinetic conductivity. Armstrong et al. [7] extended the simulations over a longer period of time and found that the heat transfer coefficient decreased as the bed dynamics eventually formed a regular dynamic pattern which was more realistic as experiments are performed over long durations compared to the several seconds that simulations are run for.

Tube-to-bed heat transfer was considered by Schmidt and Renz [8] using a TFM with a symmetrical bed. The results provided a good representation of the bubbling dynamics around the tube however Armstrong et al. [9] showed that a symmetrical bed does not represent the heterogeneous behaviour of the particles. Furthermore they found that increasing the number of tubes lead to the breakup of bubbles causing a more heterogeneous bed which increased particle motion providing better heat transfer. Yusuf et al. [10] considered the effects of the effective solid thermal conductivity and highlighted a model that reduced the heat transfer coefficient considerably compared to previous attempts. Based on the progresses achieved by previous studies