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Simulation of a high-density circulating fluidized bed riser with EMMS-based two-fluid model

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Abstract: The gas-solid flow in circulating fluidized bed riser is characterized by the coexistence of particle-rich dense phase and gas-rich dilute phase. Our preliminary study has shown that an EMMS-based two-fluid model (1) is able to correctly capture the main features of the hydrodynamics of riser flows, where the particle-rich dense phase and the gas-rich dilute phase representing the physical realizations of particle-dominated and gas-dominated mechanisms are treated as the two interpenetrating continua, instead of treating the gas and solid phases as the two interpenetrating continua as in traditional two-fluid models. In this study, we show that from application point of view the model can be simplified by assuming that the dilute phase contains gas only, owing to the fact that the key gas-solid interaction at meso-scale is still properly described by the simplified EMMS-based two-fluid model. It was shown that the experimental hydrodynamics of a high-density riser can be reproduced reasonably well by the simplified EMMS-based two-fluid model, which further proves the feasibility of EMMS-based two-fluid model.

Keywords: Meso-scale interaction; stability condition; Fluidization; EMMS model

1. Introduction

Given the good performance of mass and heat transfer and continuous handling ability of solid particles, circulating fluidized bed reactors have been widely used for various aspects of modern industry, such as pyrolysis of coal, gasification of biomass, fluid catalytic cracking, and combustion of low-grade coal (2). However, the particles in fluidized beds experience nonlinear dynamic interactions at multiple spatio-temporal scales, which lead to the non-uniform distribution of particles or the formation of streamers and clusters. These meso-scale clustering structures have a profound effect upon various aspects of the hydrodynamics of gas-solid flow and prompt the requirement of suitable meso-scale models for considering the effects of meso-scale structures on the constitutive laws of two-fluid models (3,4). There are many methods available in literature to consider the effect of meso-scale clustering structures on the constitutive laws of two-fluid models where the gas and solids are described as two interpenetrating continua, such as the Energy Minimization Multi-Scale (EMMS) model (5,6) and filtered two-fluid model (3,7).

Recently, our preliminary study (1) has shown that instead of treating the gas and solids as the two interpenetrating continua as in most of previous studies, it is possible to describe the particle-rich dense phase and the gas-rich dilute phase, representing the physical realizations of particle-dominated and gas-dominated mechanisms, as the two interpenetrating continua in continuum modeling of heterogeneous gas-solid flow in CFB risers. The idea results in the so-called EMMS-based two-fluid model. In this study, the EMMS-based two-fluid model is simplified and used to simulate the hydrodynamics of a high-density CFB riser.

2. Summary of the EMMS-based two-fluid model

Based on the work of Wang et al. (1), the governing equations of EMMS-based two-fluid model are summarized as follows:

- Continuity equation of dilute phase

$$\frac{\partial}{\partial t}\left[(1-f)\rho_{dilute}\right]+\nabla\cdot\left[(1-f)\rho_{dilute}\mathbf{u}_{dilute}\right]=\Gamma \tag{1}$$

- Continuity equation of dense phase

$$\frac{\partial}{\partial t}\left(f\rho_{dense}\right)+\nabla\cdot\left(f\rho_{dense}\mathbf{u}_{dense}\right)=-\Gamma \tag{2}$$

- Momentum equation of dilute phase

$$\begin{aligned}&\frac{\partial}{\partial t}\left[(1-f)\rho_{dilute}\mathbf{u}_{dilute}\right]+\nabla\cdot\left[(1-f)\rho_{dilute}\mathbf{u}_{dilute}\mathbf{u}_{dilute}\right]=-(1-f)\nabla p\\&+\nabla\cdot\left[(1-f)\boldsymbol{\tau}_{dilute}\right]+(1-f)\rho_{dilute}\mathbf{g}-\mathbf{F}_d\end{aligned} \tag{3}$$

- Momentum equation of dense phase

$$\frac{\partial}{\partial t}\left(f\rho_{dense}\mathbf{u}_{dense}\right)+\nabla\cdot\left(f\rho_{dense}\mathbf{u}_{dense}\mathbf{u}_{dense}\right)=-f\nabla p+\nabla\cdot\left(f\boldsymbol{\tau}_{dense}\right)+f\rho_{dense}\mathbf{g}+\mathbf{F}_d \tag{4}$$

- Drag force between dense phase and dilute phase

$$\mathbf{F}_d=\beta\left(\mathbf{u}_{dilute}-\mathbf{u}_{dense}\right) \tag{5}$$

$$\begin{aligned}&\beta=\left(\frac{17.3}{Re}+0.336\right)\frac{\rho_{dilute}f(1-f)\left|\mathbf{u}_{dilute}-\mathbf{u}_{dense}\right|}{d_{cl}}(1-f)^{-2.8}\\&Re=\frac{(1-f)\rho_{dilute}\left|\mathbf{u}_{dilute}-\mathbf{u}_{dense}\right|d_{cl}}{\mu_{dilute}}\end{aligned} \tag{6}$$

- Viscosity of dense phase

$$\mu_{dense}=\mu_g\left(1-\frac{\varepsilon_{s,k}}{\varepsilon_{s,max}}\right)^{-2.5\varepsilon_{s,max}},\varepsilon_{s,max}=0.63 \tag{7}$$

- Density of dense phase

$$\rho_{dense}=\varepsilon_{gc}\rho_g+\left(1-\varepsilon_{gc}\right)\rho_s \tag{8}$$

- Density and viscosity of dilute phase

$$\rho_{dilute}=\rho_g,\mu_{dilute}=\mu_g \tag{9}$$

Note that the density and viscosity of dilute phase is simplified as that of gas, which is different with our previous study (1). As there is no particle in dilute phase (i.e. assuming the particles are always in dense phase), the mass transfer between dilute phase and dense phase is approximately zero, i.e. $\Gamma=\Gamma_s+\Gamma_g\approx 0$. More details can be found in (1). The reasons for this simplification are twofold, one is that we believe the physical model should be as simple as possible, provided that the experimental results are properly reproduced; the other is that with this approximation, a physical model for inter-phase mass transfer rate is no more required.

3. Results and discussion

The numerical simulation was based on the standard two-fluid model of commercial software Fluent 6.3.2. Owing to the nature of present governing equations, which are similar to the model for gas-liquid flow, the kinetic theory of granular flow is not required.

3.1. Simulation layout

Fig. 1 shows the schematic geometry of the simulated riser, which corresponds to the riser part of circulating fluidized bed facility used in the experiment of Issangya et al. (8). Initially, the bed is empty and the gas and solid flow into the bed through three jets, because Peng et al (9) have shown that the adopted inlet boundary condition is more realistic than uniform inlet boundary condition. The physical properties and setting parameters used in simulations are summarized in table 1.

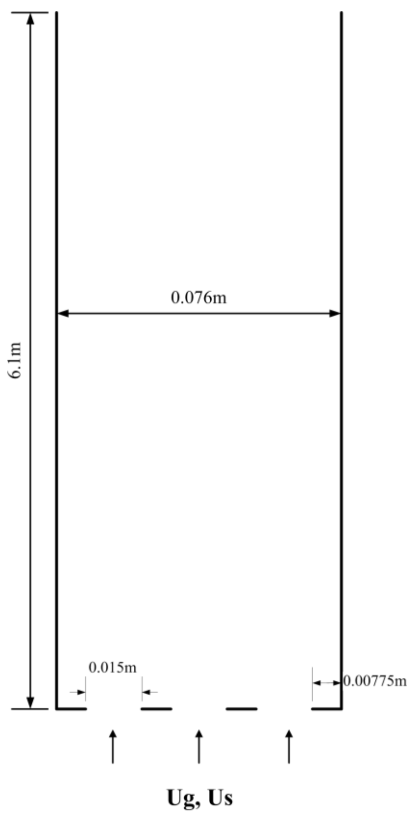

Figure 1. Schematic diagram of the 2-D riser

Table 1. Physical properties and parameters used in simulations

Particle density, ρ_s	1600 kg/m^3		
Particle diameter, d_p	70 μm		
Air density, ρ_g	1.2 kg/m^3		
Air viscosity, μ_g	1.7894×10^{-5} kg/(m.s)		
Gas velocity, U_g	8m/s		
Solid flux, G_s	163kg/m^{2}s	225kg/m^{2}s	323kg/m^{2}s
Number of grids	40×700		

3.2. Simulation results

All the results reported here are obtained by averaging the data obtained from t=20 s to t=30 s, because we have monitored the solids hold-up in the bed and found that they are oscillating around constant values after t=20s, meaning that the simulations have reached statistically steady states.

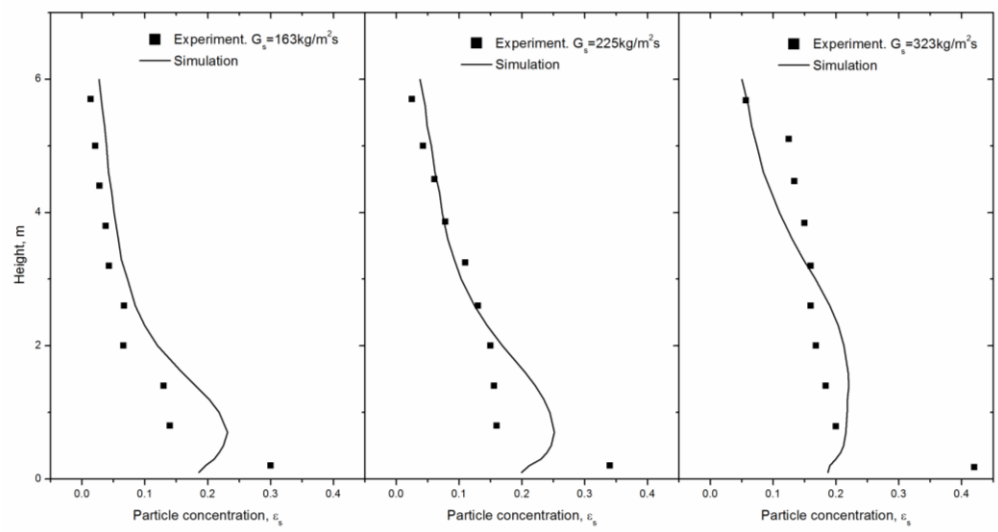

Figure 2 Comparison of simulated axial solid concentration profiles with experiment data under different solid fluxes

Fig. 2 demonstrates that under different solid circulating fluxes, the experimentally found axial solid concentration profiles are successfully predicted by EMMS-based two-fluid model. As for the case of G_s=163 kg/m^{2}s, the predicted solid concentration on the top is a little larger than experimental data, and lower at the bottom. As for the deviation of simulated particle concentration in the bottom dense region, it is due to the simplified inlet boundary of gas and solid phase, which is different from the real geometry of experimental system. The case of G_s=225 kg/m^{2}s gives a similar result. While in the case G_s=323kg/m^{2}s, the simulated axial profile of solid concentration, compared with another two results, becomes flatter as in the experiments, meaning the increase of solid fluxes leads to the expansion of dense bottom region. The results obtained from model predictions and experimental data are in good agreement, although quantitative discrepancies still exist.

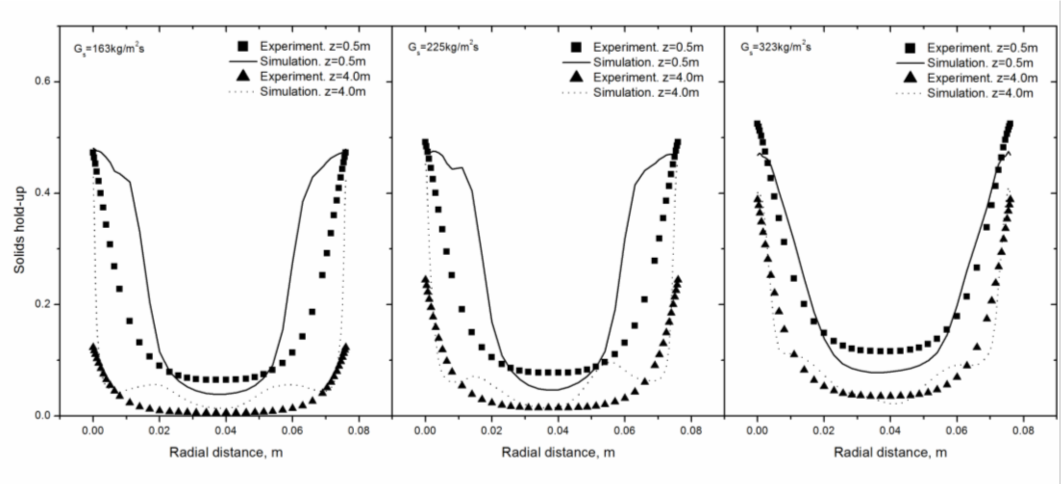

Figure 3 Comparison of time-averaged radial solid concentration profiles at two heights predicted by EMMS-based two-fluid model with experimental data under different solid fluxes

The radial distribution of particles in high-density riser is different with that in low density riser. As shown in Fig. 3, solid is accumulated along the wall so that the solid concentration can be as high as 0.5 and in the center the solid volume fraction is low, the value of which are normally less than 0.1. In the case of G_s=163kg/m^{2}s, the simulated local particle concentration remains relatively flat over a considerable radial distance before rising sharply near the wall, and while increasing solids flux from 163kg/m^{2}s to 323kg/m^{2}s, the dilute region in the core becomes narrower and contains more particle. It is interesting to note that the simulated solid volume fraction in the core region is fluctuating around a constant value, which maybe own to the deficiency of present model. When comparing to experiment data, which is estimated from the correlation obtained from the experiments (10), it is found that good agreement is obtained, though in the cases of G_s=163kg/m^{2}s and 225kg/m^{2}s, the solid concentration near the wall of height z=4.0m is overestimated.

4. Conclusion

The EMMS-based two-fluid model is simplified by assuming that the dilute phase contains gas only. With this simplification, model for the mass transfer rate between dense phase and dilute phase is no more required. We found that the main features of a high-density CFB riser can be predicted reasonably well by the simplified EMMS-based two-fluid model. Extensive validations by simulating various high-density and/or high-flux CFB risers are ongoing.

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Notation

d_p	particle diameter, m
f	volume fraction of dense phase
$\mathbf{F}_d$	drag force, N
g	gravitational acceleration, m/s^2
G_s	solids circulating flux, kg/m^{2}s
p	pressure, Pa
Re	Reynolds number
u	real velocity, m/s
z	height, m
Greek letters	
ε	voidage
μ	viscosity, $Pa \cdot s$
ρ	density, kg/m^3
Γ	mass transfer, kg/m^{3}s
Subscripts	
c	dense phase
f	dilute phase
g	gas phase
s	solid phase
gc	dense-phase gas
gf	dilute-phase gas
sc	dense-phase solid
sf	dilute-phase solid

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