CFD STUDY OF MIXING AND SEGREGATION OF BINARY GAS-SOLID FLOW IN CFB RISERS WITH EMMS DRAG MODEL

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Abstract – To consider the effects of the existence of different kinds of particles in gas-solid flow, an attempt is made to extend the Energy Minimization Multi-Scale (EMMS) drag model to binary gas-solid system. Four input parameters that can be obtained from CFD simulation, including two slip velocities between gas and each particle phase and two particle concentrations of each phase, are used to solve the proposed EMMS drag model. Heterogeneous indexes, which are used to modify the drag correlation obtained from homogeneous fluidization, are then predicted and fed into multi-fluid model (MFM) to predict the dynamical behavior of mixing and segregation of binary gas-solid flow. Several 3D CFD simulations with various operating conditions are carried out to validate the binary EMMS drag model. Simulation results fit well with the experimental data, which indicates that the EMMS drag model could capture the mixing and segregation characteristics of binary gas-solid flow.

INTRODUCTION

Multiphase flow, particularly gas-solid flow, is a common occurrence in both industry process and natural world, where the particle size distribution plays an important role. The wide particle size distribution (PSD) could lead to significant influences on the hydrodynamics and chemical reactions within the gas-solid CFB (Grace and Sun, 1991; Palappan and Sai, 2008). As a specific situation, the gas-solid flow composed of two different kinds of particles has been studied firstly. Mixing and segregation of binary gas-solid flow at axial and radial directions are usually measured to describe multiphase systems and exposed to further cast some light on the investigation of the wide PSD gas-solid flow.

For the sake of predicting the hydrodynamics and features of the binary gas-solid flow and accounting for the heterogeneous structures at the same time, an extended energy minimization multi-scale (EMMS) drag model for binary gas-solid system was proposed (Zhou and Wang, 2015), based on the EMMS drag model for monodisperse gas-solid flow of Wang et al. (2008). In this paper, the binary EMMS drag model is further explained and several 3D CFD simulations of the binary gas-solid flows are carried out to validate the binary EMMS drag model.

EMMS DRAG MODEL FOR BINARY GAS-SOLID FLOW

A multi-scale structure system is built to consider the mesoscale structure of binary gas-solid flows. The particle clustering in such system represents a mesoscale structure between the particle and system scales of gas-solid mixtures, featuring the interactions at or between three scales (Li and Kwauk, 1994), which includes microscale, mesoscale and macroscale. Microscale embodies two different phases (dense phase and dilute phase) and interaction between individual particles and the fluid both in the dilute phase represented by voidage ε_{pf1} and ε_{pf2}, particle velocity U_{pf1}, U_{pf2} and gas velocity U_f; and in the dense phase represented by voidage ε_{pc1}, ε_{pc2}, particle velocity U_{pc1}, U_{pc2}, and gas velocity U_c. Mesoscale includes interaction between particle clusters and the dilute phase represented by the volume fraction of particle clusters f and its diameter d_{cl}. Macroscale contains interaction between the whole gas-solid mixture and its environment represented by operating conditions such as superficial gas velocity U_g, particle velocity U_{p1}, U_{p2}, and boundary conditions.

The binary EMMS drag model is derived from the multi-scale structure and governed by the principle of compromise in competition between different dominant mechanisms (Li, 1994, 2000; Li et al., 2013; Li and Kwauk, 2001; Li et al., 1988). The system has a tendency to $W_{st} = \min|_{\varepsilon=min}$ as the stability condition of the interaction between gas and solid, which is equivalent to a minimum of $N_{st} = W_{st}/((1-\varepsilon)\rho_p)$ (N_{st} is the energy consumption for suspending and transporting particles with respect to unit mass of particles and ρ_p is particle density).

The multi-scale system composed of two different kinds of particles is described by 16 parameters and 11 equations which are formulated. Because the number of equations is less than the parameters, a stability condition ($N_{st} = W_{st}/((1-\varepsilon)\rho_p) \to min$) is used to close the equation set (Li and Kwauk, 1994). In order to simplify the solving process, some reasonable postulations are made according to previous publications (Wang et al., 2008; Wang and Li, 2007; Zhou and Wang, 2015). The accelerations of particles in dilute phase are assumed to be zero; furthermore, the small and large particles within the clusters tend to move in a collective way, leading to the assumption that the particles in the dense phase share the same acceleration and velocity.

Equations of the model are constructed at different scale of the multi-scale system. First, the equations of continuity and mass conservation of particle 1 and particle 2 can be acquired through the dense and dilute phase.

Continuity equations:

$$U_{p1} = U_{pf1}(1-f) + U_{pc1}f \quad (1)$$

$$U_{p2} = U_{pf2}(1-f) + U_{pc2}f \quad (2)$$

$$U_g = U_f(1-f) + U_c f \quad (3)$$

Mass conservation equations:

$$\varepsilon_{p1} = \varepsilon_{pf1}(1-f) + \varepsilon_{pc1}f \quad (4)$$

$$\varepsilon_{p2} = \varepsilon_{pf2}(1-f) + \varepsilon_{pc2}f \quad (5)$$

As a result of the mixing and the balance of the internal forces, there is only one dense phase for both particle phases composed of different kinds of particles. Momentum conservation is reached within both dilute and dense phase inside the system, which can be described by the following equations.

Momentum conservation equation of particle 1 in dilute phase:

$$\frac{3}{4}C_{df1}\frac{(1-f)\varepsilon_{pf1}}{d_{p1}}\rho_g U_{sf1}^2 = \varepsilon_{pf1}(1-f)(\rho_{p1}-\rho_g)(g+a_f) \quad (6)$$

Momentum conservation equation of particle 2 in dilute phase:

$$\frac{3}{4}C_{df2}\frac{(1-f)\varepsilon_{f2}}{d_{p2}}\rho_g U_{sf2}^2 = \varepsilon_{pf2}(1-f)(\rho_{p2}-\rho_g)(g+a_f) \quad (7)$$

Momentum conservation of dense phase:

$$\frac{3}{4}C_{dc1}\frac{f\varepsilon_{pc1}}{d_{p1}}\rho_g U_{sc1}^2 + \frac{3}{4}C_{dc2}\frac{f\varepsilon_{pc2}}{d_{p2}}\rho_g U_{sc2}^2 + \frac{3}{4}C_{di}\frac{f}{d_{cl}}\rho_g U_{si}^2 = f\varepsilon_{pc1}(\rho_{p1}-\rho_g)(g+a_c) + f\varepsilon_{pc2}(\rho_{p2}-\rho_g)(g+a_c) \quad (8)$$

It is obvious that the equation of dense phase has an extra term (the third term on the left side of equation 3), which represents the drag force of the inter phase of the multi-scale structure. The inter phase drag force is caused by the slip velocity between gas of dilute phase and solid of dense phase. Then a pressure drop balance should be reached at the macroscale between dilute phase, dense phase and inter phase.

Pressure drop balance equation:

$$C_{df1}\frac{\varepsilon_{pf1}}{d_{p1}}\rho_g U_{sf1}^2 + C_{df2}\frac{\varepsilon_{pf2}}{d_{p2}}\rho_g U_{sf2}^2 + \frac{f}{1-f}C_{di}\frac{1}{d_{cl}}\rho_g U_{si}^2 = C_{dc1}\frac{\varepsilon_{pc1}}{d_{p1}}\rho_g U_{sc1}^2 + C_{dc2}\frac{\varepsilon_{pc2}}{d_{p2}}\rho_g U_{sc2}^2 \quad (9)$$

According the previous study, the voidage in dense phase can be calculated as follows (Wang et al., 2008).

$$\varepsilon_c = 1 - \varepsilon_{pc1} - \varepsilon_{pc2} = \varepsilon_g - n\sqrt{\langle \varepsilon_s' \varepsilon_s' \rangle} \quad (10)$$

where the value of n is set as 2.0 and the variance of solids concentration fluctuation $\langle \varepsilon_s' \varepsilon_s' \rangle$ is obtained as:

$$\langle \varepsilon_s' \varepsilon_s' \rangle = \varepsilon_s^2 \frac{(1-\varepsilon_s)^4}{1+4\varepsilon_s+4\varepsilon_s^2-4\varepsilon_s^3+\varepsilon_s^4} \quad (11)$$

The acceleration relation between dilute phase and dense phase is obtained according to previous publication (Wang et al., 2008).

$$a_c - a_f = \frac{\langle \varepsilon_s' \varepsilon_s' \rangle (\rho_{s,ave}-\rho_g)g}{C_{am}(\varepsilon_f-\varepsilon_c)f\rho_{dilute}} \quad (12)$$

where the added mass coefficient (C_{am}), the density of particle mixture ($\rho_{s,ave}$) and the density of dilute phase (ρ_{dilute}) are calculated as:

$$C_{am} = \frac{1+2f}{2(1-f)} \tag{13}$$

$$\rho_{s,ave} = \frac{\varepsilon_{p1}\rho_{p1}+\varepsilon_{p2}\rho_{p2}}{\varepsilon_{p1}+\varepsilon_{p2}} \tag{14}$$

$$\rho_{dilute} = \varepsilon_{pf1}\rho_{p1} + \varepsilon_{pf2}\rho_{p2} + \varepsilon_f\rho_g \tag{15}$$

Finally, a stability condition, referring to the minimization of the energy consumed in suspending and transporting per unit mass of particles, is used to close the equation set (Li and Kwauk, 1994).

$$N_{st} = \frac{(m_{f1}F_{f1}+m_{f2}F_{f2})U_f+(m_{c1}F_{c1}+m_{c2}F_{c2})U_c+m_iF_iU_f(1-f)}{(1-\varepsilon_g)\rho_{s,ave}} \rightarrow min \tag{16}$$

In order to combine with the multi-fluid models (MFM) to simulate the large scale gas-solid flows, the effective drag coefficients of particle 1 and 2 are derived from the EMMS model (Zhou and Wang, 2015).

$$\beta_1 = \frac{\varepsilon_g^2}{U_{slip1}}\left[(1-f)\varepsilon_{pf1}(\rho_{p1}-\rho_g)(g+a_f) + f\varepsilon_{pf1}(\rho_{p1}-\rho_g)(g+a_c)\right] \tag{17}$$

$$\beta_2 = \frac{\varepsilon_g^2}{U_{slip2}}\left[(1-f)\varepsilon_{pf2}(\rho_{p2}-\rho_g)(g+a_f) + f\varepsilon_{pf2}(\rho_{p2}-\rho_g)(g+a_c)\right] \tag{18}$$

The particulate phase stresses and the inter-phase drag force between different particle phases of the MFM are closed by the kinetic theory for binary gas-solid flow (Chao et al., 2011), which is recommended by the work of Zhou and Wang (2015), where details of the used multi-fluid model and kinetic theory of granular flow can be found.

SIMULATION RESULTS

3D CFD coarse-grid simulations were performed using commercial software ANSYS FLUENT to validate the effectiveness of the EMMS drag model discussed above. The governing equations of the multi-fluid model were solved with finite-volume method, and the continuity and momentum equations are discretized using second-order upwind scheme and QUICK scheme, respectively. The gas-particle drag coefficients were predicted by the binary EMMS drag model to account for the effects of particle clusters. The experimental data of Bai et al. (1994) are used as the criterion for simulations in this paper.

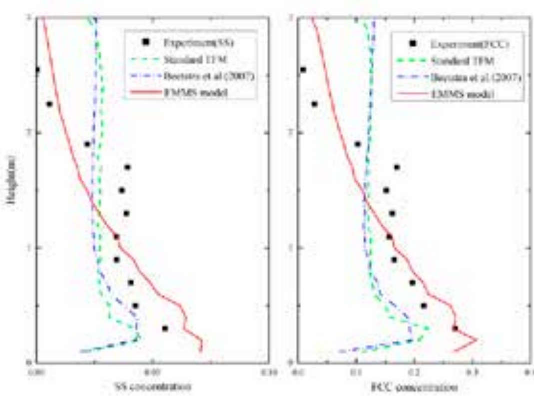

Fig. 3. Time-averaged axial solids distributions predicted using different drag models at gas velocity of 2.5 m/s, solids circulation rate of 53.9 kg/m^{2}s, in which the experimental data is from Bai et al. (1994).

The abovementioned EMMS drag model, Standard TFM (ad hoc Gidaspow's model) and Beetstra el al. (Hoef et al., 2005) were used to simulate the experiments of Bai et al. (1994) so as to compare the effectiveness of the these models. It can be seen from Fig. 3 that the axial distributions predicted using the binary EMMS drag model fit the experimental results better than other models. It is obvious that the experimental data presents a heterogeneous structure with a dilute upper part and a dense lower part throughout the CFB riser. However, the drag models without the consideration of mesoscale structure can barely predict such heterogeneous structure. In contrast, the EMMS model is derived from multi-scale system and takes the effect of the mesoscale structure into consideration, which promises to fitting better with the heterogeneous experimental results.

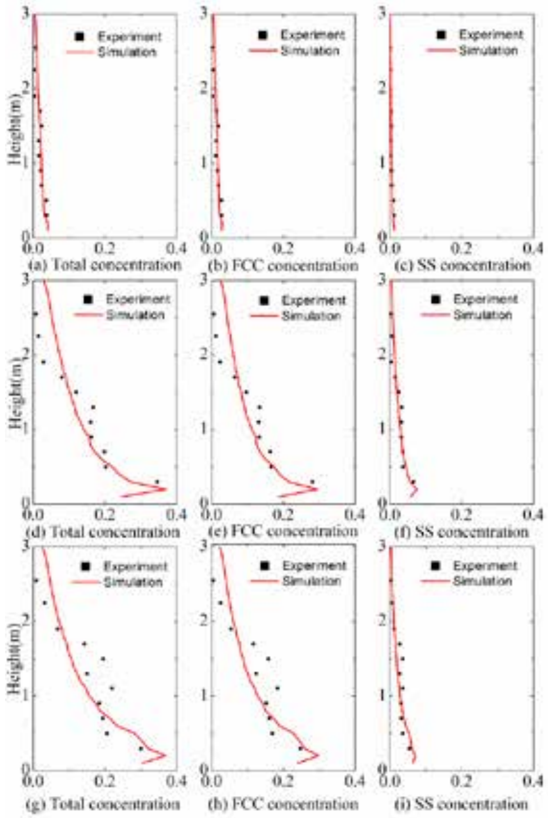

Fig. 4. Comparison of predicted time-averaged axial distributions with experiment of total, FCC and SS particles holdups at gas velocity of 3.0 m/s, solids circulation rate of (a) to (c) is 35.2 kg/m^{2}s, (d) to (f) is 62.2 kg/m^{2}s, (g) to (i) is 128 kg/m^{2}s, in which the experimental data is from Bai et al. (1994).

In addition to the better prediction of the total concentration (the sum of the two kinds of particles), the binary EMMS drag model also captures the mixing and segregation inside the binary gas-solid system. As shown in Fig. 4, the simulation results of both FCC and SS particles throughout the CFB riser fit well with the experimental data as well as the total concentration for various operating conditions. FCC particles take a larger portion along the CFB riser and reveal different patterns compared with SS particles. The binary EMMS model constructs different solid phases for two different kinds of particles separately contributes to the better presentation of the mixing and segregation of the particles. Combined with the multi-fluid model, it leads to an advantage that can describe the different solid phases separately.

CONCLUSION

The binary EMMS drag model has taken the unresolved mesoscale structure into consideration, which is supposed to simulate the features within the binary gas-solid systems better. Then the EMMS drag model is combined with the MFM model to simulate the pilot scale experiments. The 3D simulation results indicate that the mixing and segregation characteristics are well predicted by the binary EMMS drag model.

NOTATION

ε	average voidage
ε_c	voidage in dense phase
ε_{pc1}	voidage in dense phase of particle 1
ε_{pc2}	voidage in dense phase of particle 2
ε_{pf1}	voidage in dilute phase of particle 1
ε_{pf2}	voidage in dilute phase of particle 2
ε_{p1}	overall concentration of particle 1
ε_{p2}	overall concentration of particle 2
ε_{pc1}	concentration of particle 1 in dense phase
ε_{pc2}	concentration of particle 2 in dense phase
ε_{pf1}	concentration of particle 1 in dilute phase
ε_{pf2}	concentration of particle 2 in dilute phase
ε_s	concentration of particles
ρ_{dilute}	density of dilute phase, kg/m^3

ρ_g gas density, kg/m^3
ρ_p particle density, kg/m^3
$\rho_{s,ave}$ density of particle mixture, kg/m^3
a_c acceleration of particles in dense phase, m/s^2
a_f acceleration of particles in dilute phase, m/s^2
C_{dc1} effective drag coefficient for particle 1 in dense phase
C_{dc2} effective drag coefficient for particle 2 in dense phase
C_{df1} effective drag coefficient for particle 1 in dilute phase
C_{df2} effective drag coefficient for particle 2 in dilute phase
C_{di} effective drag coefficient for inter phase
d_{cl} diameter of particle clusters, m
d_{p1} diameter of particle 1, m
d_{p2} diameter of particle 2, m
f volume fraction of particle clusters
F_{f1} drag force in dilute phase of particle 1, N
F_{f2} drag force in dilute phase of particle 2, N
F_{c1} drag force in dense phase of particle 1, N
F_{c2} drag force in dense phase of particle 2, N
m_{c1} particle mass in dense phase of particle 1, kg
m_{c2} particle mass in dense phase of particle 2, kg
m_{f1} particle mass in dilute phase of particle 1, kg
m_{f2} particle mass in dilute phase of particle 2, kg
N_{st} the energy consumption for suspending and transporting particles with respect to unit mass of particles, J
U_c superficial gas velocity in dense phase, m/s
U_f superficial gas velocity in dilute phase, m/s
U_g superficial gas velocity, m/s
U_{pc1} velocity of particle 1 in dense phase, m/s
U_{pc2} velocity of particle 2 in dense phase, m/s
U_{pf1} velocity of particle 1 in dilute phase, m/s
U_{pf2} velocity of particle 2 in dilute phase, m/s
U_{p1} velocity of particle 1, m/s
U_{p2} velocity of particle 2, m/s
U_{sc1} slip velocity between gas and particle 1 in dense phase, m/s
U_{sc2} slip velocity between gas and particle 2 in dense phase, m/s
U_{sf1} slip velocity between gas and particle 1 in dilute phase, m/s
U_{sf2} slip velocity between gas and particle 2 in dilute phase, m/s
U_{si} slip velocity between gas of dilute phase and solid of dense phase, m/s
W_{st} the energy consumption for suspending and transporting particles with respect to unit volume, J

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