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EFFECTS OF MICROSCOPIC DRAG CORRELATIONS AND RESTITUTION COEFFICIENT ON THE CHARACTERISTICS OF MESO-SCALE CLUSTERING STRUCTURES IN RISER FLOWS

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ABSTRACT

It has been widely accepted that meso-scale structures are critical for the hydrodynamic characteristics of gas-solid riser flows. In this article, we study the influence of microscopic drag correlations and/or restitution coefficient on the characteristics of meso-scale structures within the frameworks of EMMS model and filtered two-fluid model. It was found that different microscopic drag correlations and/or restitution coefficient lead to an observable difference in the predicted cluster size, effective inter-phase slip velocity and particle pressure, which characterize the meso-scale structures in EMMS model and filtered two-fluid model, respectively. Therefore, microscopic drag correlations and restitution coefficient should be selected with caution in coarse grid simulation of riser flows.

Keywords: Meso-scale structures; Drag correlation; Restitution coefficient; Fluidization; Multiphase flow; Powder Technology

1. INTRODUCTION

Circulating fluidized beds (CFB) are widely used in modern industry, pyrolysis of coal, gasification of biomass, fluid catalytic cracking and so on. Computational fluid dynamics (CFD) is now widely accepted as a powerful tool in studying the hydrodynamics of CFB risers, and continuum model with coarse computational grids, denoted as coarse grid simulation, is the most popular method for commercial equipments. However, due to the existence of meso-scale clustering structures, the size of which range from several particle diameters to equipment scale, coarse grid simulations with suitable meso-scale (or sub-grid scale) model for constitutive laws are necessary (Agrawal et al., 2001; Yang et al., 2003).

The Energy Minimization Multi-Scale (EMMS) model developed by Li & Kwauk (1994) is one of the suitable meso-scale models, where the drag force term is modified by introducing a heterogeneity index representing the effects of meso-scale structures (e.g. Wang et al., 2008). Another approach is the filtered two-fluid model (e.g. Igci et al., 2008), where the constitutive laws were extracted from the results of two-fluid modeling of gas-solid suspension with sufficient scale resolution.

In both approaches, the drag correlation for homogeneous fluidization, denoted as microscopic drag correlation, is a necessary input in the prediction of meso-scale structures. However, it is unclear how the microscopic drag correlations will affect the meso-scale clustering structures, this is the topic of present study.

2. EMMS APPROACH

The EMMS model was developed in response to the particle clustering structure in CFB risers. Although clusters in risers are amorphous and dynamic in nature, a hydrodynamic equivalent size with the assumption of sphere is used to characterize the meso-scale (or clustering) structure in the EMMS model. Furthermore, the heterogeneous gas-solid flow was decomposed into three homogeneous systems, allowing us to use drag correlations obtained from homogeneous systems to describe the hydrodynamics of heterogeneous gas-solid flow. In the EMMS model, details of which can be found in Li and Kwauk (1994), eight parameters are used to describe the heterogeneous structures in riser flow, that is, superficial gas and solid velocity in dilute phase (U_f, U_{pf}), superficial gas and solid velocity in dense phase (U_c, U_{pc}), voidage of dilute and dense phase (ε_f, ε_c), the volume fraction of dense phase (f) and the size of cluster (d_{cl}). In addition to the drag coefficient of Wen and Yu (1966) which has been implemented in the original EMMS model, four different drag correlations (Gibilaro et al., 1985; Syamlal et al., 1993; Di Felice, 1994; Beetstra et al., 2007) are used to test the effect of microscopic drag models on the characteristics of meso-scale structures. The EMMS model used in present study is summarized in table 1, as listed in table 1, there are only six hydrodynamic equations and continuity equations in the EMMS model. In order to solve the EMMS model, it is substantial to introduce a stability condition into the equation set to constrain the solution. For every pair of macroscopic operating parameters (U_g, U_s), a corresponding d_{cl} can be obtained by solving the EMMS model. In this study, we focus on the effect of the microscopic drag correlation other than operation parameters on the meso-scale structures, presented by the cluster diameter, and forasmuch, we choose the constant U_g = 1.52 m/s and varying U_s as a example. Thus, the data are obtained by keeping the superficial gas velocity constant (U_g=1.52 m/s) and varying the solid circulation flux from 0.01 kg/m^{2}s to about 1000 kg/m^{2}s.

Figure 1 shows the effects of microscopic drag correlations on the cluster size of an air-FCC system (ρ_g=1.2 kg/m^3, μ_g=1.8×10^{-5} Pa.s, dp=54 μm and ρ_p=930 kg/m^3). It is can be seen that microscopic drag model has a considerable impact on the cluster size, amongst the drag correlations we tested, the one proposed by Syamlal et al. (1993) results in the largest cluster size and the Gibilaro et al's drag correlation (1985) predicts the smallest cluster size when the solid concentration is less than about 0.2. For a mean solid soncentration of 0.05-0.1, the ratio of cluster size using different drag correlations can be as high as 1.7, indicating the importance of microscopic drag correlations. Note that different cases have been tested, the results, which are not reported in the article, are similar with the one presented in Figure 1.

Therefore, the conclusion is that the microscopic drag correlation should be selected with caution when EMMS model is used, since it leads to a significant difference in meso-scale clustering structures, which in turn will possibly cause a considerable difference in the predicted hydrodynamic characteristics of gas-solid suspension. Note that we do not test what will happen when present studies are coupled with two-fluid model, this however will be the topic of a future study.

3. FILTERED TWO-FLUID MODEL

Following the study of Agrawal et al.(2001), fine grid simulations of gas-solid suspension (ρ_g=1.3 kg/m^3, μ_g=1.8×10^{-5} Pa.s, dp=75 μm, ρ_p=1500 kg/m^3 and time step=10^{-4} s) in double periodic domain with kinetic theory of granular flow (Gidaspow, 1994) are carried out to study the effect of microscopic drag correlations on the characteristics of meso-scale structures, details of the model are not shown here but can be found in FLUENT's theory guide. The momentum and granular temperature equations are discretized using second-order upwind scheme and the QUICK scheme for volume fraction equation. A grid size of 0.2mm×0.2mm and a domain size of 30mm×120mm are selected according to previous studies (Wang, 2008; Wang et al., 2009) to offer sufficient scale resolution and to make sure that the averaged slip velocity and particle pressure is independent on domain size, respectively.

Only three drag correlations (Gibilaro et al., 1985; Syamlal et al., 1993; Gidaspow, 1994) are tested to save computational cost, for each of which, a series of simulations with averaged solid concentrations ($\overline{\varepsilon}_s$) of 0.01, 0.0175, 0.025, 0.0375, 0.05, 0.1 and 0.2 are carried out. All simulations last 10s, where the first two seconds are excluded in the calculation of time-averaged values. Furthermore, we also test the effect of restitution coefficient adopting Gidaspow's drag model.

Figure 2 shows the effects of microscopic drag correlations on the Favre-averaged axial slip velocity (U_{slip}) and Favre-averaged solid phase pressure, which are calculated following the definition of Igci et al. (2008). Note that (I) it takes about 1 second to reach the statistical steady state and the reported data are obtained by averaging the transient data from t=2s to t=10s; (II) the effective drag coefficient can be calculated as follows: $\bar{\varepsilon}_s\bar{\varepsilon}_g\left(\rho_s-\rho_g\right)g\big/U_{slip}$ and Favre-averaged solid phase pressure represents the meso-scale particulate phase stresses With increasing solid volume fraction, averaged axial slip velocity is first increasing and then falling with a maximal value at a solid volume fraction of around 0.05, the trend is consistent with the result of Agrawal et al (2001). More importantly, different drag correlations have an observable effect on the averaged axial slip velocity, the drag correlations of Gibilaro et al.(1985) and Syamlal et al.(1993) respectively predicts maximal and minimal averaged axial slip velocities with the one predicted by Gidaspow (1994) in between. The maximal difference can be as high as 17.4%, since extensive studies have shown that CFD simulations of gas-solid fluidization are very sensitive to the drag correlations, the effect of microscopic drag correlations can not be neglected. With respect to the particle phase pressure, in cases of $\bar{\varepsilon}_s \le 0.1$, solid phase pressures from these three drag correlations are nearly the same, while in case of $\bar{\varepsilon}_s = 0.2$, the difference is observable, the one obtained from Gibilaro et al. (1985) is about 12% higher than that of obtained from Gidaspow (1994).

Figure 3 shows the effects of restitution coefficient on the averaged axial slip velocity and solid phase pressure, both of which obviously decrease with increasing restitution coefficient. Varying e=0.98 to e=0.7, the resulted differences are 33.3% and 33.7% for averaged axial slip velocity and solid phase pressure, respectively. The reason for such an observation is that larger restitution coefficient causes less energy dissipation due to particle-particle inelastic collision, which in turn will lead to a more homogeneous system and less intensity of oscillation due to meso-scale structure, resulting in the decrease of averaged axial slip velocity and solid phase pressure. It however should be noted that the kinetic theory used in present study (Gidaspow, 1994) is only validated when restitution coefficient is close to unity, it is unclear if it is still validated when e=0.7, we simply perform parametric studies supposing the validation of kinetic theory.

4. CONCLUSION

A parametric study has been performed to test the role of microscopic drag correlation and restitution coefficient in characterizing meso-scale clustering structures. It was shown that they have an observable effect on the predicted cluster size using EMMS model and on the effective axial slip velocity and particle pressure using filtered two-fluid model. In view of the reported sensitivity of CFD results on the inter-phase drag force, the conclusion suggests that the microscopic drag correlations should be selected with caution and be seriously tested in coarse grid simulations of riser flows. This will be the focus of our future study.

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Table 1. Summary of EMMS model

Momentum balance for the dense phase:

$$\frac{3}{4}C_{Dc}\frac{(1-\varepsilon_c)}{d_p}\rho_g U_{sc}^2 = (1-\varepsilon_g)(\rho_s-\rho_g)g$$

Momentum balance for the dilute phase:

$$\frac{3}{4}C_{Df}\frac{(1-\varepsilon_f)}{d_p}\rho_g U_{sf}^2 = (1-\varepsilon_f)(\rho_s-\rho_g)g$$

Momentum balance for the meso-scale interface:

$$\frac{3}{4}C_{Di}\frac{f}{d_{cl}}\rho_g U_{sf}^2 = f(\varepsilon_g-\varepsilon_c)(\rho_s-\rho_g)g$$

Mass balance for the gas phase:

$$U_g = fU_c + (1-f)U_f$$

Mass balance for the solid phase:

$$U_s = fU_{pc} + (1-f)U_{pf}$$

The hydrodynamic equivalent diameter of cluster:

$$d_{cl} = \frac{gd_p\left[\frac{U_s}{1-\varepsilon_{\max}} - (U_{mf} + \frac{\varepsilon_{mf}U_s}{1-\varepsilon_{mf}})\right]}{N_{st}\frac{\rho_s}{\rho_s-\rho_g} - (U_{mf} + \frac{\varepsilon_{mf}U_s}{1-\varepsilon_{mf}})g}$$

Stability condition:

$$N_{st} = \frac{3}{4(1-\varepsilon)\rho_s}[C_{Df}\frac{1-\varepsilon_f}{d_p}\rho_g U_{sf}^2 U_f(1-f) + C_{Dc}\frac{1-\varepsilon_c}{d_p}\rho_g U_{sc}^2 U_c f + C_{Di}\frac{f}{d_{cl}}\rho_g U_{si}^2 U_f(1-f)] \to \min$$

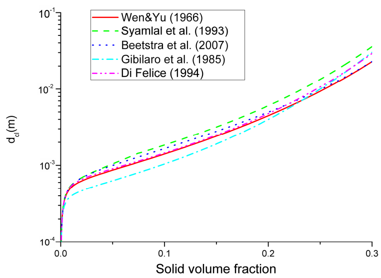
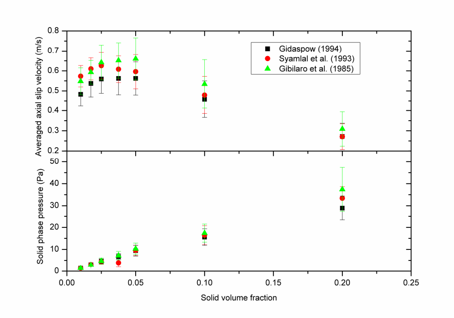


Figure 1. Cluster diameter predicted by EMMS model with different microscopic drag correlations



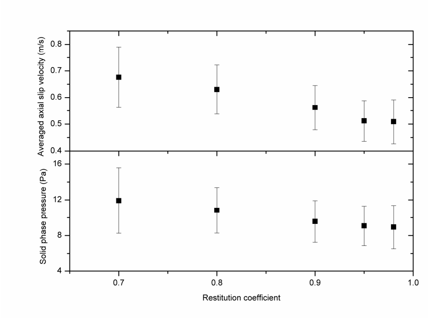


Figure 2. Comparison of averaged axial slip velocity and solid phase pressure obtained from different microscopic drag models.

Figure 3. Comparison of averaged axial slip velocity and solid phase pressure obtained from different restitution coefficients. $\overline{\varepsilon}_s = 0.05$.