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Simulation gas-solid flow in the downer with new structure-based drag model

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ABSTRACT

To improve the accuracy of simulating the heterogeneous flow in a circulating fluidized bed (CFB) downer, a drag model based on the local structure of the gas-solid flow using the multi-scale method has been developed in this work. New stability conditions according to the characteristics of gas-solid flow in the CFB downer have been derived to solve the non-linear model equations for obtaining structure parameters. New structure-based drag coefficients were incorporated into the two-fluid model (TFM) to simulate the hydrodynamics of the gas-solid flow in the downer. Simulation results showed that the predictions with the new structure-based drag model are more accurate than those with the Wen-Yu drag model. The predictions with the structure-based drag model showed the heterogeneous flow of the gas-solid flow and the cluster phenomenon. The fluctuation of the instantaneous solid fraction of the experiment can be reasonably reproduced by the simulation using the new structure-based drag model, whereas the fluctuation of the instantaneous solid fraction cannot be captured by the Wen-Yu drag model. The experimental data showed that the radial profiles of the solid fraction are a typical core-annular structure, and the simulated results with new structure-based drag model agreed well with experimental data from different cases. The axial profiles of the simulated pressure gradient, solid concentration and particles velocity distinctly exhibit the axial structure of the gas-solid flow in the downer, which agreed with the experimental results.

1. Introduction

Due its advantages of shorter residence time, high uniform distribution of particles and low gas and solids backmixing, the circulating fluidized bed (CFB) downer has drawn attention in the past two decades [1–3]. Many industrial processes, such as fluid catalytic cracking [4,5], coal pyrolysis [6,7], and biomass pyrolysis [8], may benefit from this type of reactor. With the increase of computational ability, computational fluid dynamics (CFD) has become widely used to predict the fluid dynamics [9–10]. For the gas–solid flow, two different approaches, namely the Eulerian–Lagrangian approach, and the Eulerian–Eulerian approach or two-fluid model (TFM), can be used for the calculation. In recent years, increasing researchers have come to favor TFM for simulating the gas–solid flow in CFBs [11–13].

Drag models have significantly affected hydrodynamics simulation with regard to the heterogeneous gas–solid flows in CFBs. Many researchers have adopted drag coefficients based on the average approaches to simulate the gas solid flow, which brought great deviations compared with experimental results [14,15]. Structure-based drag models, which consider the effects of the heterogeneous structures, have been a valuable tool to simulate the hydrodynamics of gas-solid flow in the fluidized bed [16–19]. Yang et al. [20] employed eight structure parameters to describe the local flow in the CFB riser and showed that the drag coefficient calculated from the EMMS model is lower than that from the Wen-Yu/Ergun correlations, which is in reasonable agreement with the commonly accepted conclusion from experiment. The cluster behaviors are captured and core/annulus structure of radial distribution of solids is observed when the EMMs approach is adopted for the simulation. Hou et al. [21] studied the relationship between bed structure parameters and mass and heat transfer in the CFB riser. Results showed that the momentum, mass and heat transfer coefficient from the meso-structure parameters can be more accurately predicted than that from the traditional averaged methods. Lv et al. [22] adopted seven local structural parameters and built the structure dependent coefficient correlations for the bubbling fluidized bed. The axial and radial solid concentration profiles and particle velocity profiles can be well predicted, which agreed with the experimental data.

Numerous simulations have been implemented for the CFB downer [23–26]; however, accurate mathematical modeling is still necessary to provide a quantitative reference to comprehensively understand the hydrodynamics of gas solid flow in the downer [27,28]. Considering the success of the EMMS approach in the CFB riser and bubbling fluidized bed, a similar model needs to be developed to give a theoretical

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description of hydrodynamics in the CFB downer, in which the characteristics of gas solid flow should be counted. For a circulating fluidized bed downer, the gas-solid flow can be divided into the first acceleration section, second acceleration section and developed region as shown in Fig. 1. The drag force between the gas and solid has the same direction as the solid flow in the first section, that pushes the particles downward as an impetus force, whereas it has the inverse direction to the solid flow in the second acceleration section and developed region, thereby impeding the particles that flow downward as a resistance force. Therefore, the stability condition of the CFB downer cannot be directly quoted from the CFB riser.

The first objective of this work is to develop new stability conditions according to the characteristics of gas-solid flow in the CFB downer, and establish the drag model based on the local structure of gas-solid flow using the multi-scale method. The local structural parameters are determined by solving non-linear equations and the structure-based drag coefficient is obtained, which is incorporated into the TMF for simulating the gas–solid flow in the downer. Comparison of the simulation results between this new approach and the Wen-Yu drag correlation are carried out to demonstrate its effectiveness.

2. Drag model based on local structure of CFB downer

2.1. Mathematical model

Eight parameters were employed to describe the local structure of the heterogeneous flow in the downer, which were ε_c, U_{fc}, U_{pc}, d_c, and f for the dense phase and ε_d, U_{fd}, and U_{pd} for the dilute phase as shown in Fig. 1. Moreover, an average acceleration for particles in the control volume, a, was considered for this model. To solve these structural parameters, eight independent equations built by mass conservation equation and empirical correlations, are employed as follows:

2.1.1. Force balance of particles in the cluster

Force balance of particles in the cluster includes the drag force between the particles and gas in the cluster, the drag force of the whole cluster and its surrounding gas, the collision force between the cluster and particles in the void phase and the particle gravitation in the cluster.

$$F_{Dcn} + F_{Dcf} + F_{pdc} + F_{cg} = \frac{\pi}{6} d_c^3 (1-\varepsilon_c)(\rho_p - \rho_f) a \quad (1)$$

The drag force between particles and gas in the cluster is:

$$F_{Dcn} = F_{Dc} n = \frac{\pi}{8} C_{Dc} \rho_f d_p^2 U_{sc} |U_{sc}| (1-\varepsilon_c) \left(\frac{d_c}{d_p}\right)^3 \left(1 - 2\frac{d_p}{d_c}\right) \quad (2)$$

C_{Dc} is the drag coefficient between gas and particles and U_{sc} is the superficial slip velocity between gas and particle in the cluster.

$$U_{sc} = U_{fc} - U_{pc} \frac{\varepsilon_c}{1-\varepsilon_c} \quad (3)$$

When $\varepsilon_c \geq 0.8$, the proposed equation by Wen and Yu is employed as follows:

$$C_{Dc} = C_{Do} \varepsilon_c^{-4.7} \quad (4)$$

When $\varepsilon_c < 0.8$, the drag coefficient is estimated by Ergun equation:

$$C_{Dc} = 200 \frac{(1-\varepsilon_c)\mu_f}{\varepsilon_c^3 \rho_f d_p |U_{sc}|} + \frac{7}{3\varepsilon_c^3} \quad (5)$$

The drag force between the whole cluster and its surrounding gas is:

$$F_{Dcf} = C_{Di} \rho_f \frac{1}{2} U_{si} |U_{si}| \frac{\pi}{4} d_c^2 \quad (6)$$

C_{Di} is the drag coefficient between the gas and particles and U_{si} is the superficial slip velocity between the cluster and its surrounding gas.
when

$$\varepsilon_i = \varepsilon_d (1-f) \geq 0.8$$

$$C_{Di} = C_{Do} \varepsilon_d^{-4.7} (1-f)^{-4.7} \quad (7)$$

when

$$\varepsilon_i = \varepsilon_d (1-f) < 0.8$$

$$C_{Di} = 200 \frac{(1-\varepsilon_i)\mu_f}{\varepsilon_i^3 \rho_f d_c |U_{si}|} + \frac{7}{3\varepsilon_i^3} \quad (8)$$

$$U_{si} = \left[U_{fd} - U_{pc} \frac{\varepsilon_d}{1-\varepsilon_c}\right](1-f) = \left[\frac{U_{fd}}{\varepsilon_d} - \frac{U_{pc}}{1-\varepsilon_c}\right] \varepsilon_d (1-f) \quad (9)$$

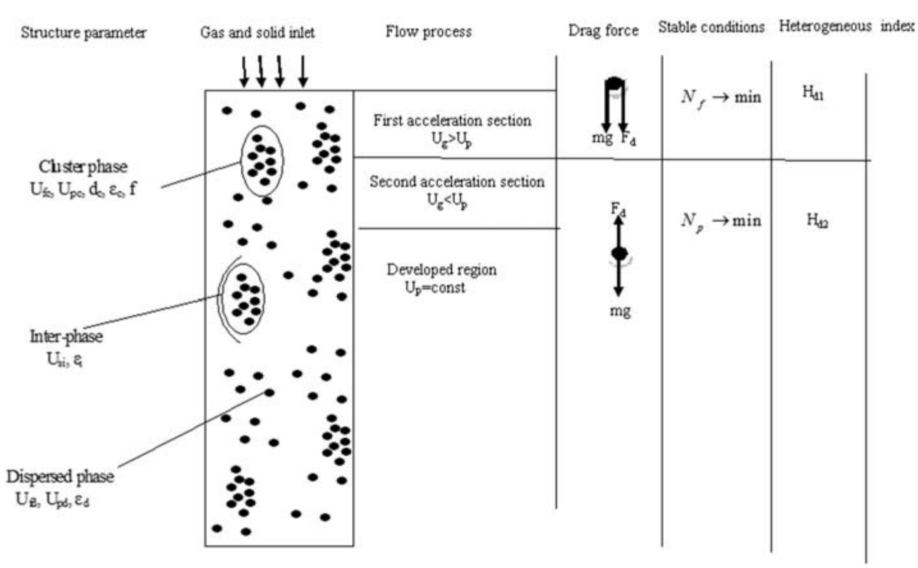

Fig. 1. Structure parameter of gas-solid flow in the downer.