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A new structural parameters model based on drag coefficient for simulation of circulating fluidized beds

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ABSTRACT

This work presented a new scheme to establish structural parameters model, and the model was used to solve structural parameters based on the available structure-based drag model. By combining with the Eulerian two-fluid model, the hydrodynamics of circulating fluidized beds (CFBs) was simulated. Different combinations of clusters properties, including the cluster voidage and diameter, were adopted to fit for Geldart A and B particles and to close the insufficient solving equations, respectively. The simulated solid mass flux, radial and axial voidage profiles were in agreement with the experimental data. The dilute-top/dense-bottom and the core-annular flow structure were also captured. Moreover the spatiotemporal fluctuation of clusters can be observed from those simulations. Simulation results showed the combination of the structural parameters model with the available structure-based drag model can predict well the hydrodynamics for Geldart A and B particles in CFBs.

1. Introduction

Circulating fluidized beds (CFBs) are widely used in various modern industrial processes, such as fluid catalytic cracking and coal combustion. Because of high flow rate of gas–solid and intensive contacting, CFBs have favorable hydrodynamics, reactions and heat transfer characteristics. Understanding of the hydrodynamic characteristics is the key to design and the scale-up of such reactors. With the increase of the computational ability, computational fluid dynamics (CFD) has been a valuable tool to predict the fluid dynamics, which is of vital importance to the scale-up of CFBs.

For heterogeneous gas–solid flows in CFBs, drag models have a significant effect on the simulation of bed hydrodynamics [1–3]. The competition and compromise in different spatiotemporal scales lead to the formation of multiscale structures [4,5]. Conventional drag models, such as Gidaspow [6] and Syamlal-O'Brien [7], have been proved to over-predict the drag coefficient because they neglect the multiscale structures [5,8,9] in CFBs. Multiscale structures of CFBs are characterized by clusters, and heterogeneous flows can be divided into the cluster phase, the dispersed phase and the inter-phase which are usually defined by 8–10 structure parameters [10–12]. Because conventional two-fluid drag models assume homogeneous conditions inside the control volume, they cannot predict structure parameters. Structure-based drag models have already been successfully developed to understand the multiscale nature of heterogeneous two-phase flows in CFBs [13]. The key to solve structure-based drag models is to solve the structural parameters. Due to the lack of enough number of equations to solve these parameters, many researchers adopted minimization stability condition to close the insufficient solving equations, such as the energy minimization multi-scale model (EMMS) [12] and the cluster structure-dependent (CSD) drag coefficient model [14]. Adopting other measures to close the equations of structural parameters models has received much less attention and remains a challenge for the complex heterogeneous flows of CFBs.

With respect to the system of multiscale structures, clusters play a dominant role in gas–solid interaction [15–17]. Clusters have two major properties, including diameter and voidage; equations of clusters properties have been used by many researchers to improve drag models. Gao et al. [15] adopted the cluster diameter, derived from the experimental particles terminal velocity, to replace the particle diameter of Gidaspow drag model, and the simulation results were in agreement with experimental data. Lu et al. [18] used equations of clusters properties to modify Gidaspow drag model and conservation equations of the kinetic theory of granular flow. As for EMMS model, Nikolopoulos et al. [19] claimed that the predicted cluster diameter was smaller than the diameter of a single particle or negative for averaged solid volume fraction ε_s less than 0.01 or greater than 0.44, respectively, and introduced Gu and Chen's [20] correlation of the cluster diameter to confront these problems. Wang et al. [10] extended EMMS model from Geldart A to Geldart B particles by integrating the equation of the cluster voidage. Therefore, clusters properties are of prime importance to the simulation

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of CFBs, and an improved structural parameters model should be able to describe the heterogeneous multiscale structures caused by the clusters.

In the present work, a new structural parameters model was established incorporating with equations of clusters properties, which can not only close the insufficient solving equations but also take into consideration the effect of clusters. By incorporating it into an Eulerian two-fluid model, the gas–solid flow hydrodynamics of CFBs was simulated by using CFD software (FLUENT6.2.16). Simulation results were compared with the experimental data available in literature to validate its feasibility.

2. Mathematical model

2.1. Structural parameters model

Fig. 1 shows multiscale resolution of structure and gas–solid interaction proposed by Wang et al. [10]. The complex heterogeneous flow structures of CFBs can be divided into three simple homogeneous phases, including the cluster phase, the dispersed phase and the inter-phase. Based on the homogeneous assumption and Matsen's [21] investigation, the voidage in dispersed phase ε_d is defined as 0.9997. The heterogeneous structures have 9 unknown parameters, namely, U_{fd}, U_{pd} and α_d for the dispersed phase, ε_c, d_c, U_{fc}, U_{pc}, f and α_c for the cluster phase. The solving equations can be detailed as follows, and the related variables involved in these equations are summarized in Appendix A.

(1) Force balance in cluster phase

The forces on the cluster include cluster-fluid drag force F_{Dcn} inside cluster phase, cluster-fluid drag force F_{Dcf} outside cluster phase, the collision force F_{pdc} from particles in the dispersed phase outside cluster phase and apparent gravity.

The drag force F_{Dcn} equals to the drag force of single particle multiplying the effective number of particles inside cluster phase.

$$F_{Dcn} = nF_{Dc} \tag{1}$$

The drag force of single particle F_{Dc} can be expressed by

$$F_{Dc} = \frac{\pi}{8} d_p^2 C_{Dc} \rho_f |U_{sc}| U_{sc} \tag{2}$$

The force on the particles of outside surface of the cluster is different from those inside the cluster. The former force is caused by high gas velocity from the dispersed phase, and the latter force derives from low gas velocity of the cluster phase which means only half of particles of outside surface are relatively effective. Therefore, the effective number of particles inside cluster phase is calculated by

$$n = \frac{\frac{\pi}{6} d_p^3 (1-\varepsilon_c)}{\frac{\pi}{6} d_p^3} - \frac{1}{2} \frac{\pi d_c^2 (1-\varepsilon_c)}{\frac{\pi}{4} d_p^2} = (1-\varepsilon_c) \left(\frac{d_c}{d_p}\right)^3 \left(1 - 2\frac{d_p}{d_c}\right) \tag{3}$$

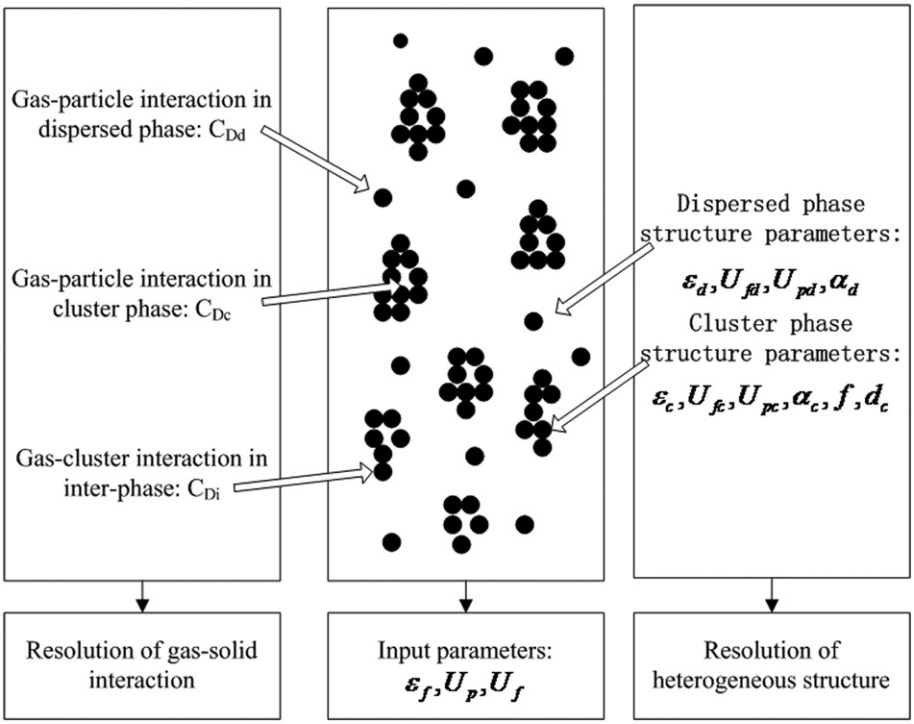

Fig. 1. Resolution of structure and gas–solid interaction proposed by Wang [10].