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A dynamic cluster structure-dependent drag coefficient model applied to gas-solid risers

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ABSTRACT

A dynamic cluster structure-dependent (CSD) drag coefficient model is proposed to be consistent with the temporal-spatial characteristics of dynamic clusters through the convective accelerations and temporal accelerations of the dense phase and the dilute phase. The CSD drag coefficient is determined by a nonlinear micro-meso-grid scales equation set which consists of three momentum conservation equations, two mass balance equations, one equation for volume fraction balance, and an extreme value of a function in combination with the bivariate extreme value (BEV) theory. Flow behavior of gas and particles is predicted by means of gas-solid two-fluid model coupled with CSD drag model and kinetic theory of granular flow. The distributions of independent variables of dense phase and dilute phase are predicted in the riser. Numerical analysis suggests that the inertial difference between the dense phase and the dilute phase affects flow behavior of dynamically temporal-spatial clusters in risers. The simulated solids volume fraction, cluster existence time fraction and frequency of cluster occurrence are compared to experimental measurements in the literature.

1. Introduction

Gas–solid circulating fluidized beds are widely used in fluid catalytic cracking, coal combustion and gasification, solids waste disposal and biomass energy generation. In gas-solid risers, particles tend to bring individual particles close to each other and form particle clusters with the increase of local volume fractions of particles due to hydrodynamic interactions and collisional interactions of particles. These temporal and spatial clusters dynamically form and break up locally [1]. The formation of particle clusters is significantly affecting the interphase transfer of mass and momentum in gas-solid circulating fluidized beds. The interphase heat and mass transfer with particle clusters are reduced in comparison with those flows where particles are uniformly distributed in fluidized beds [2,3]. These investigations indicate a reduction of gas-particle drag when particle clusters exist in the riser. Therefore, the predictions of flow behavior of gas and particles using computational fluid dynamics (CFD) models relate essentially to the presence of particle clusters in gas-solid circulating fluidized beds.

The filtered models are derived by means of the continuum model equations for unsteady gas-particle flows as a function of solid volume fractions and dimensionless filter size [4–6]. The filtered models have been suggested to consider the presence of small scale structure using sub-grid closures for fluid-particle drag force, solid pressure and viscosity. Simulated results showed that the filtered models can predict flow behavior of large-scale devices with reasonable accuracy and significant computational savings [7]. Comparing to experiments, simulated results using subgird model for drag coefficient suggested that the overestimation of the drag force was linked to the existence of a subgrid drift velocity, which reduced the effective resolved slip velocity [8]. These filtered models mentioned above are the analogue of large-eddy simulation of single-phase turbulent flow [9], where one simulates spatio-temporal patterns occurring at the macro-scale using the conservations of mass and momentum, and then filtered to construct models to account for the effects of meso-scale structures occurring at a scale smaller than the grid size through additional closure relations. The sub-grid models have been extended to simulate hydrodynamics of particles in gas-solids fluidized beds, including jet penetration [10], bubbling bed [11–13], interphase heat transfer [14] and reactive flows [15]. It is noted that the filtered models are more fundamentally sound, and there is still something to be improved for obtaining cluster characteristics of cluster size, cluster mean solids volume fraction, and time fraction of cluster appearance which are important in industrial applications of circulating fluidized beds.

The energy minimization method (EMMS) [16–18], on the other hand, is based on the assumption that the heterogeneous structures contribute to the drag reduction between the gas phase and the solid phase. The static heterogeneous structure is assumed in the form of clusters in the particle-rich dense phase or in the form of dispersed

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particles in the gas-rich dilute phase. The resulting set of equations as the function of ten independent variables is solved by minimizing a function that is called the stability condition for the dilute phase and the dense phase. To calculate ten independent variables, the drag coefficient was solved by a two-step scheme, in which at first the variables of volume fraction of particles in the dense phase and cluster diameter are calculated on the basis of inlet gas velocity and solid mass flux, and the next step the other variables are calculated on the basis of seven equations. There are also some uncertainties about the EMMS models to predict cluster-related properties, such as cluster diameter and accelerations due to assumptions in EMMS models [19,20]. While the EMMS model is still developing in the physics-based model of drag in clustering suspensions.

Recently, the static cluster structure-dependent (CSD) drag model based on the static (spatial) heterogeneous structure of clusters was proposed on the basis of the minimization of energy dissipation by heterogeneous drag [21,22]. The static heterogeneous structure is assumed in the form of static clusters of the dense phase and static dispersed particles of the dilute phase. The effect of convective momentum transport of the dilute phase and the dense phase on the drag coefficient of static heterogeneous structure is considered in the determination of CSD drag coefficient. However, the rate of accumulation of momentum of the dilute phase and the dense phase is neglected. Thus, the CSD drag coefficient is the function of eight independent variables of the dilute phase and the dense phase. The relation between the CSD drag coefficient and flow behavior of particles was investigated in gas-solid risers [23,24], and heat transfer and reactions [25–27]. Keep in mind that in the static cluster structure-dependent (CSD) drag model the convective acceleration of the dilute phase and the dense phase shows the rate of change of velocity due to the change of position of gas and particles in the dilute phase and the dense phase, not due to temporal acceleration or local acceleration which is the rate of change of velocity of gas and particles with respect to time in the dilute phase and the dense phase. Thus, the static heterogeneous structure is resolved into the dense phase and the dilute phase, while the dynamic changes are also resolved into the corresponding fluctuations.

Experimental measurements of the frequency of appearance of particle clusters showed that flow behavior exhibits the spatio-temporal fluctuations of velocity and volume fraction through clusters [28–30]. Positively, the local accelerations or temporal acceleration of gas and particles result when the flow of the dilute phase and the dense phase is unsteady, and the formation and breaking up of clusters changes dynamically in gas-solid risers. These temporal acceleration and convective acceleration of dynamically heterogeneous structure of clusters contribute to momentum transport in the dilute phase and the dense phase. In present study, a dynamic (non-static) cluster structure-dependent (CSD) drag coefficient model is proposed with the combination of convective accelerations and temporal accelerations of gas and particles in the dilute phase and the dense phase. The drag coefficient model is incorporated into the two-fluid model. The gas-solid flow behavior in the riser is simulated and compared with experimental results published in the literature.

2. Dynamic cluster structure-dependent drag model

It is assumed that the riser consists of gas and particles with uniform size and the same density. For a volume V (grid cell) with the volumes of the dense phase V_{den} and the dilute phase V_{dil}, which are the function of time t. The motion of particles is in the form of dynamic clusters in the dense phase or in the form of dynamic dispersed particles in the dilute phase, seeing in Fig. 1. The definition of the volume fraction of dense phase is $f = V_{den}/V$. The porosities of the dense phase and the dilute phase are $\varepsilon_{den} = V_{g,den}/V_{den}$ and $\varepsilon_{dil} = V_{g,dil}/V_{dil}$, where $V_{g,den}$ and $V_{g,dil}$ are the gas volumes of the dense phase and the dilute phase in the volume, respectively. The heterogeneous structure is described by independent variables of the gas superficial velocity of the dilute phase $U_{g,dil}$ and the dense phase $U_{g,den}$, superficial velocity of dispersed particles in the dilute phase $U_{s,dil}$ and the dense phase $U_{s,den}$, and cluster size d_c. For the grid cell, the gas velocity u_g, velocity of solids phase u_s, gas volume fraction ε_g, and gas pressure p are obtained from simulated solution of two-fluid model (TFM). In order to establish a mathematical model for both dense phase and dilute phase, we make the following assumptions: (1) The dense phase exists as spherical clusters. (2) Particles in the dilute phase are uniform. (3) Particles within the clusters and the clusters in a control volume are homogeneously dispersed. (4) The mass transfer of particles between the dilute phase and the dense phase are neglected. The mass transfer between the dilute phase and the dense phase is mainly contributed to the gas shear forces and the inelastic collisional interactions between cluster and dispersed particles. The mathematical dynamic cluster structure-dependent drag model can then be formulated as the following set of non-linear equations.

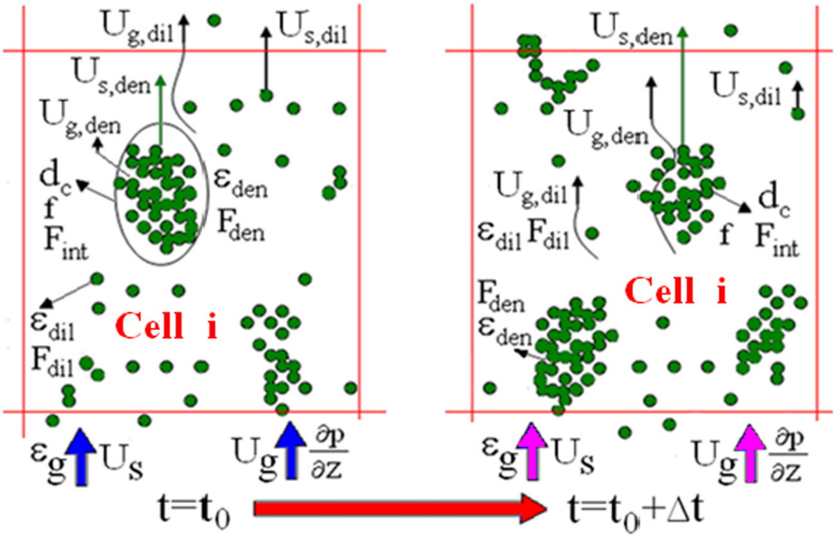

Fig. 1. Eight independent variables and three scales of interactions in the grid cell.