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Original Research Paper

Cluster structure-dependent drag model for liquid–solid circulating fluidized bed

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ABSTRACT

The formation of clusters in liquid–solid circulating fluidized beds effects on momentum transfer between phases. In this article, a cluster structure-dependent drag model is proposed to take the effect of clusters on momentum transfer between dispersed phase and clusters into account by means of an Eulerian–Eulerian two-fluid model. The momentum and energy balances that characterize the clusters in the dense phase as well as dispersed particles in the dilute phase are described by the multi-scale resolution approach. The proposed model of cluster structure-dependent (CSD) drag coefficient is on the basis of the minimization of energy dissipation by heterogeneous drag (MEDHD) as a function of Reynolds number. The CSD drag coefficient model is incorporated into the two-fluid model to simulate flow behavior of liquid and particles in a liquid–solid riser. Predicted volume fraction and particle velocity distributions are in good agreement with experimental data published in the literature.

1. Introduction

Liquid–solid circulating fluidized bed reactors are widely used in various industrial processes, such as biochemical engineering, food, chemistry and wastewater treatment. Design, scaling and control of such reactors require detailed information of the liquid and solid flow hydrodynamics. With the development of computer and computation method, computational fluid dynamic (CFD) has become a viable tool for simulating the dynamic processes that take place in circulating fluidized bed (CFB). CFD method can also provide amount of flow information which can hardly be obtained by modern measuring techniques. In the CFD modeling, most studies employ the Eulerian–Eulerian two-fluid model (TFM) which assumes the liquid phase and solid phase as continuous and fully interpenetrating within each control volume. Among various attempts in formulating the particulate flow, the kinetic theory of granular flow (KTGF), an extension of the classical kinetic theory of gases to dense particulate flows, is widely used in fluidization [1]. This approach describes the fluctuation energy of particles by introducing the concept of granular temperature. The granular temperature equation can be expressed in terms of the production of fluctuations by shear stress, dissipation by kinetic and collisional energy, dissipation due to inelastic collisions, production due to fluid turbulence, and dissipation due to interaction with the fluid. As a result, the flow behavior of particles can be predicted in combination with the kinetic theory of granular flow in the two-fluid model. A number of studies have shown the capability of the KTGF approach for modeling fluidized beds [2–7].

In the Eulerian–Eulerian TFM, the interphase momentum transfer between fluid and particle phases is one of the most significant terms in the momentum equations of both phases. Thus, a compatible closure law for fluid-particle interactions is required. Generally, the interaction terms in liquid–solid flow system include the drag force, the virtual mass force and the history force except that the pressure gradient and the gravity force. The momentum exchange is mainly represented by the drag force [8]. Hence, the drag force models are important in simulating the interphase momentum transfer between the liquid and solid phases. Traditionally, the drag force models are average-based in the literature [9,10]. Most of these correlations are originated on the basis of experiments in homogeneous flow systems. Thus, they may lose validity in a heterogeneous flow system, because they do not take the structure of particle clusters into account. Hence, the effect of clustering of particles needs to be accounted for in the drag force correlations [11].

Liang et al. [12] and Zheng et al. [13] took liquid–solid circulating fluidization process as heterogeneous due to the radial non-uniformity structure of particles they detected in the riser. The

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Nomenclature

a	acceleration, m/s^2
C_D	drag coefficient
d_s	particle diameter, m
d_c	cluster diameter, m
e	restitution coefficient
f	volume fraction of dense phase
F_k	drag force, N/m^3
g	gravity, m/s^2
g_o	radial distribution function at contact
G_s	solid mass flux, kg/m^2 s
I_{2D}	second invariant of the deviatoric stress tensor
k_s	conductivity of fluctuating energy, kg/m s
n_{den}	number of particles in the dense phase per unit volume
n_{dil}	number of particles in the dilute phase per unit volume
N_{df}	energy dissipation, W/kg
P	fluid pressure, Pa
P_s	particle pressure, Pa
Re	Reynolds number
u_l	liquid velocity, m/s
u_s	particle velocity, m/s
U	superficial liquid velocity, m/s
U_{den}	superficial slip velocity in dense phase, m/s
U_{dil}	superficial slip velocity in dilute phase, m/s
U_{int}	superficial slip velocity of interface, m/s
U_{mf}	minimum fluidization velocity of particles, m/s
V_{den}	volume of dense phase in the control volume, m^3
V_{dil}	volume of dilute phase in the control volume, m^3
x	transverse distance from axis, m
z	vertical distance, m

Greek letters

β	drag coefficient, kg/m^3 s
γ	collisional energy dissipation, kg/m s^3
ε_l	liquid volume fraction
$\varepsilon_{l,den}$	liquid volume fraction in the dense phase
$\varepsilon_{l,dil}$	liquid volume fraction in the dilute phase
$\varepsilon_{s,den}$	solid volume fraction in the dense phase
$\varepsilon_{s,dil}$	solid volume fraction in the dilute phase
ε_{max}	maximum liquid volume fraction for particle aggregating
ε_{mf}	liquid volume fraction at minimum fluidization
ε_s	solids volume fraction
$\varepsilon_{s,max}$	solids volume fraction at packing
θ	granular temperature, m^2/s^2
μ_l	liquid viscosity, kg/m s
μ_s	solids viscosity, kg/m s
ρ_l	liquid density, kg/m^3
ρ_s	density of solid phase, kg/m^3
τ_l	liquid stress tensor, Pa
τ_s	particle stress tensor, Pa
ϕ	specularity coefficient
φ	angle of internal friction, deg
δ	error of velocity or solids volume fraction
Γ	energy dissipations, kg/m s^3

Subscripts

c	cluster
den	dense phase
dil	dilute phase
l	liquid phase
s	particles phase

radial non-uniformity distribution of particle concentrations was later confirmed by Razzak et al. [14] with both electrical resistance tomography (ERT) and optical fiber probe (OFP) at different liquid superficial velocities. Roy et al. [15] measured the time-averaged cross-sectional distribution of particle concentrations at several elevations by employing gamma-ray computed tomography, the heterogeneous flow structure was also found, and the particle back mixing at the wall was found according to the negative component of time-averaged particle velocity. Similar flow structures were also been reported in the literature [16–19] through experiments.

Numerous CFD models were applied to the simulation of dynamic processes that took place in the liquid–solid circulating fluidized beds. Roy and Dudukovic [20] used TFM model combining with the KTGF to simulate the flow behaviors in liquid–solid circulating fluidized beds. The model was shown to be capable of predicting the liquid and particles residence time distributions in the riser as well as the particle velocity and concentrations. Razzak et al. [21] employed the KTGF based on TFM to simulate the particle viscosity and particle pressure, and a drag model proposed by Wen and Yu was adopted for liquid–solid interactions. Cheng and Zhu [22,23] made a comprehensive study on the modeling and simulation of hydrodynamics in liquid–solid circulating fluidized beds using both similitude method and CFD technique. There were also other models [24,25] which had played important roles in simulating the flow behaviors in liquid–solid risers. However, all these works used the average-based drag correlations.

Some studies took the local heterogeneity of the liquid–solid flow in a CFB into account for the computation of the drag force. Liu et al. [26] showed that with the consideration of meso-scale clusters structure effect, multi-scale drag coefficient model predicted better distribution of particle concentration distributions compared with experimental data. Dynamic evolution of clusters was reproduced and the mechanism behind the S-shaped profile of liquid concentration was proposed based on numerical evidences. The simulation showed that the reduction in drag coefficient was an important factor for the simulation of cluster formation. Later, a modified multi-scale drag model was proposed [27] with the consideration of the effect of walls on the particle clusters.

In our previous multi-scale drag models, the superficial slip velocities of clusters and dispersed particles were restricted at Reynolds number less than 1000 ($Re < 1000$). However, equations at $Re > 1000$ were not included, especially for the liquid–solid flow system. Therefore, this multi-scale drag model was likely to be restricted to flow regions far away from high Reynolds number. As a result, equations to determine the superficial slip velocities of clusters and dispersed particles at high Reynolds number were needed. In present work, the cluster structure-dependent (CSD) drag coefficient model is proposed in the full range of Reynolds number, i.e., from $Re < 1000$ to $Re \geqslant 1000$ in liquid–solid circulating fluidized beds. The relationship between the CSD drag coefficient and the meso-scale structure parameters has been further investigated. The CSD drag coefficient model is incorporated into the TFM combining with KTGF. Simulated results are compared with the Ergun/Wen-Yu correlations and experimental data was published in the literature.

2. Liquid–solid two-fluid model

In the present work, an Eulerian–Eulerian two-fluid model, which considers the conservation of mass and momentum for