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Original Research Paper

Study of hydrodynamic characteristics of particles in liquid–solid fluidized bed with modified drag model based on EMMS

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ABSTRACT

Flow behavior of solid phases is simulated by means of Eulerian–Eulerian in a liquid–solid fluidized bed with modified drag model based on energy-minimization multi-scale (EMMS) method. The modified EMMS drag coefficient is characterized by the treatment of the particle-rich dense phase and the liquid-rich dilute phase as the two interpenetrating continua. It was shown that the modified EMMS drag coefficient can predict reasonably the solid concentration profiles in a liquid–solid fluidized bed. The distributions of solid velocity, granular temperature and granular pressure are predicted. The phenomenon of back-mixing near the wall is found in the liquid–solids fluidized beds.

1. Introduction

Liquid–solid fluidized beds continue to attract increasing attention due to their inherent versatility for several industrial applications in hydrometallurgical, biochemical, environmental and chemical process industries [1]. Liquid–solid flow is of great importance in process engineering, where the presence of multi-scale heterogeneous structures may seriously affect liquid–solid contacting and transport processes, and hence must be considered in the designing, scaling-up or optimization of industrial liquid–solid systems. However, the fundamental understanding of liquid–solid fluidized beds is still limited on account of the existence of the complex flow structures resulting from the interactions between the liquid and solid phases [2]. Several researchers made significant contributions to improve the understanding of the hydrodynamics of liquid–solid fluidized beds through experimental and theoretical investigations [3–5]. Circulation phenomena of solids have been observed to be dominant in liquid fluidized beds due to non-uniform solid holdup profiles and solid velocity profiles. For these reasons, computational fluid dynamics (CFD) has been promoted as a useful tool for understanding hydrodynamics of liquid and solid phases and for reliable design and scale up [6].

In order to know of detailed flowing trends of the liquid and particle, an Eulerian–Eulerian two-fluid modeling approach has been applied. To our best knowledge, almost all of simulations on liquid–solid fluidization use two-fluid model [7–12]. This approach describes both phases as interpenetrating continua where the local instantaneous equations are averaged in a suitable way to allow coarser grids and longer time-steps being used in numerical simulations. However, the averaging approach introduces extra unknowns into the system and additional expressions are needed to close the set of equations. For liquid–solid systems these closure laws most commonly include a description of the interaction between the phases at the interface, in addition to a description of the internal momentum transfer in the solid phase [13]. A closure problem therefore arises, which usually cannot be solved analytically and has to be overcome by means of empirical expressions. The drag force model plays a significant role in the two-fluid model simulation as a closure equation. This force, in compliance with Newton's third law of mechanics features, with opposite sign, in the linear momentum equations of conservation pertaining to both phases [14]. For drag coefficient different correlations are available in the literature. The models like Syamlal–O'Brien model [15], Gidaspow model [16] and Huilin–Gidaspow model [17] are frequently used. These four drag models as described above are used and the results are compared to assess their capability in predicting the hydrodynamic behavior of fluidized beds. At the same time, these correlations mentioned above are originally developed on the basis of experiments with homogeneous systems, and may lose their validity for simulating heterogeneous flow since they do not take into account the structure of particle clusters in the fluidized beds [18–20]. Considering the

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Nomenclature

a	acceleration, m/s^2
C_{am}	coefficient of virtual mass force of cluster
C_{dc}	drag coefficient of dense phase
C_{df}	drag coefficient of dilute phase
C_{di}	drag coefficient of interphase
D	riser diameter, m
d_{cl}	cluster diameter, m
d_p	particle diameter, m
e	coefficient of restitution of particles
U_p	particle velocity, m/s
U_{pc}	particle velocity in dense phase, m/s
U_{pl}	particle velocity in dilute phase, m/s
U_{sc}	superficial slip velocity in dense phase, m/s
U_{sf}	superficial slip velocity in dilute phase, m/s
U_{si}	superficial slip velocity of interphase, m/s
f	volume fraction of dense phase
F_d	drag force, N
g	gravitational acceleration, m/s^2
g_o	radial distribution function
H	axial distance from the bottom, m
$\mathbf{I}$	unit tensor
N_{st}	suspension and transportation energy, W/kg
P	liquid pressure, N/m^2
u_l	liquid velocity, m/s
x	radial distance, m

Greek letters

β	interface momentum transfer coefficient, kg/m^2 s^2
ε	energy dissipation of liquid , kg m^{-3} s^{-1}
ε_c	concentration of particles in dense phase
ε_f	concentration of particles in dilute phase
ε_l	porosity
ε_p	concentration of particles
$\varepsilon_{p,\max}$	maximum solid volume fraction
ε_{mf}	porosity at minimum fluidization
θ	granular temperature , m^2 s^{-2}
γ_p	energy dissipation , kg m^{-3} s^{-1}
μ_l	viscosity of liquid, Pa s
μ_p	particle viscosity, Pa s
τ_p	particle stress tensor,
τ_k	kinetic stress tensor
τ_f	frictional stress tensor
τ_l	viscous stress tensor
ρ_l	liquid density, kg/m^3
ρ_p	particle density, kg/m^3

Subscripts

l	liquid phase
p	particle phase
w	wall

formation of clusters in the liquid–solid two-phase system, the flow structure consists of the flow of dispersed particles and the flow of clusters in the bed. This results in the reduction of drag force between the liquid phase and the solid phase, and effects on the interaction between phases. A multi scale interfacial drag coefficient is proposed to determine effects of particle clusters on the mesoscale structure, by taking momentum and energy balance of dense phase, dilute phase and interphase into account [21]. Based on the transportation and suspension energy-minimization method, the multi scale interfacial drag coefficient model is combined with an Eulerian–Eulerian two fluid model to simulate the heterogeneous behaviors of liquid–solid circulating fluidized bed. Liu et al. [22] simulated the hydrodynamics of gas–liquid–solid fluidized bed with the macro-scale EMMS model coupling with a two-fluid method (TFM). It also suggested a general approach to speed up dynamic simulation in the multi-scale paradigm of computation. Jin [23] presented a multi-scale model for gas–liquid–solid three-phase fluidized beds based on the principles of the EMMS model. The model was solved and checked with the experimental data available in several references which cover a broad range of operating conditions from the conventional expanded fluidized bed to the circulating fluidized bed, indicating that the model is capable of describing the global hydrodynamics of the complex flow in the three-phase system with acceptable accuracy.

In present study, the interphase momentum transfer coefficient between liquid and particle phases is obtained from basic the principle of energy minimization multi-scale (EMMS) model [24]. The relation between drag coefficient and the meso-scale structure parameters is investigated. Present approach is incorporated into the Eulerian–Eulerian two-fluid model. The kinetic theory of granular flow which uses a function to describe the turbulent kinetic energy of particles by introducing the concept of granular temperature of particles is employed for closure. Comparisons between CFD prediction and experimental data by Razzak et al. [25] are presented.

2. Liquid–solid flow model with EMMS-based modified drag model

2.1. Two-fluid model of liquid–solid flow

The Eulerian approach is used for both liquid phase and particles phase within a liquid–solid riser, taking into account all possible intra- and interphase interactions. In this work, it is assumed that flow is to be isothermal. The liquid phase is incompressible, and particles are spherical and uniform in size. The governing equations for the conservation of mass and momentum for each phase and the constitutive relations are given in Table 1. In addition to the mass and momentum conservation equations for the solid phase, a fluctuation kinetic energy equation, Eq. (T1-5), is also solved to account for the conservation of the fluctuation energy of particles phase, through the implementation of the kinetic theory of granular flow [16]. In principle, the kinetic theory of granular flows has been derived from the kinetic theory of dense gases [26], where the thermodynamic temperature is replaced by the granular temperature, θ, defined as: $\theta = \langle c \rangle^2/3$, where c is the particle fluctuating velocity. The granular temperature expresses the macroscopic kinetic energy of the random particle motion. A more complete discussion of the implemented kinetic theory model can be found in Gidaspow [16]. The stresses of liquid phase are shown in Eq. (T1-6) where $\mu_{eff} = \mu_l + \mu_t$ is the effective liquid viscosity. The turbulent viscosity is determined from a k–ε turbulent model and expressed by $\mu_t = C_\mu \rho_l k^2/\varepsilon$, where the equations of turbulent kinetic energy and turbulent kinetic energy dissipation rate are expressed by Eqs. (T1-7) and (T1-8). The empirical