Chemical Engineering Science 191 (2018) 156–168

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Critical comparison of electrostatic effects on hydrodynamics and heat transfer in a bubbling fluidized bed with a central jet

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HIGHLIGHTS

- Phase fraction, bubble properties were compared in the charged and uncharged system.
- Jet region, bubble generation region and free space were found in the simulation.
- Interphase heat transfer coefficient was gained by corrected gas throughflow.
- Charged system had weaker particle fluctuation velocity and more chaotic behavior.

ARTICLE INFO

Article history:
Received 25 January 2018
Received in revised form 20 June 2018
Accepted 24 June 2018
Available online 26 June 2018

Keywords:
Bubble behavior
Particle fluctuation
Electrostatics
Heat transfer
Fluidization

ABSTRACT

In many industrial processes, electrostatic charges are inevitable and affect the hydrodynamic behavior and heat transfer ability of chemical equipment. A comprehensive study of the electrostatic effect on bubble behavior, particle fluctuation velocity and heat transfer coefficient in the fluidized bed with a central jet has been evaluated in this paper by Eulerian-Eulerian two-fluid model coupled with electrostatic model and energy model. The simulated voidage profiles at different positions, bubble detachment time and initial bubble diameter are compared with experimental results from the literature without charge. The bubble behaviors including bubble frequency and bubble numbers, combined with particle fluctuation parameters are analyzed in both charged and uncharged system. The electrostatic effect on two kinds of heat transfer coefficients is quantitatively compared, namely bubble to emulsion phase heat transfers based on the gas throughflow velocity and gas-solid local heat transfer coefficient. Simulation results show that electrostatic charges decrease bubble numbers and granular temperature, whereas the averaged heat transfer coefficients are enhanced. Overall, the electrostatic effect on the hydrodynamic and heat transfer characteristics can be revealed.

1. Introduction

Gas-solid fluidized beds are capable of handling huge particle volumes and thus possess exceptionally high heat transfer and mixing efficiency finding a wide range of applications including petroleum processing, environmental protection, food processing and pharmaceutical production etc. Gas-solid suspensions exhibit randomness and structural instability due to the existence of bubble agitation, particle motion and gas-solid interaction resulting in a typical nonlinear transient system. The time-averaged parameters, such as voidage, pressure fluctuation, bubble properties are mostly reported in the study of fluidized beds (Jung et al., 2006; Patil et al., 2005; van der Schaaf et al., 2002). In addition, these parameters can also reveal the dynamic behavior, flow structure and heat and mass transfer abilities (Acosta-Iborra et al., 2011; Patil et al., 2014; Zi et al., 2017).

However, the electrostatic phenomenon is inevitable in many industrial fluidization processes, such as ethylene polymerization, due to particle-particle and particle-wall collision and friction. The excessive accumulation of charges on the surface of the insulating particles will result in wall sheeting, particle agglomeration, or even shutdown of the plant (Sun and Yan, 2017). Moreover, electrostatic and hydrodynamic effects are interdependent. Charged

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https://doi.org/10.1016/j.ces.2018.06.069
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Nomenclature

List of symbols

A, B, P, Q	parameters in parameterized Syamlal O'Brien
C_D	drag coefficient
$\langle C_i C_i \rangle$	laminar particle stress
c_{ik}	instantaneous velocity of particle k
D	electric displacement
D_a	equivalent bubble diameter
E	electric field intensity
f_b	bubble frequency
g	gravitational acceleration
g_0	radial distribution function
h	local heat transfer coefficient
H_{be}	interphase heat transfer coefficient
H_s, H_g	enthalpy of the solid phase and gas phase
I_{2D}	second invariant of the deviatoric stress tensor
K	effective thermal conductivity
P	induced polarization
p_{fr}	frictional pressure
p_s	solid pressure
q_{be}	gas interchange
q_m	specific charge
q_v	charge density based on bulk volume of solid
q_m	charge density based on mass of solid
Re_s	particle Reynolds number
Nu	Nusselt number
$\mathbf{u}_s$, $\mathbf{u}_g$	velocity of the solid phase and gas phase
u_{bh}, u_{bv}	horizontal and vertical bubble velocity
u_{gh}, u_{gv}	horizontal and vertical gas velocity
u_{px}, u_{py}	particle velocity in x-direction and y-direction
U_{th}	throughflow velocity
U^*	corrected velocity
V_{jet}	jet velocity
$v_{r,s}$	terminal velocity correlation for the solid phase
α_s, α_g	volume fraction of the solid phase and gas phase
β_{gs}	momentum exchange coefficient
ρ_s, ρ_g	density of fluid of solid phase and gas phase
χ_e	electric susceptibility
$\in_m$	relative permittivity
φ_e	electrostatic potential
ϕ_s	angle of internal friction
$\theta_{laminar}$	laminar granular temperature
$\overline{\overline{\tau}}$	stress tensor
Θ_s	granular temperature
$k_{\Theta s}$	diffusion coefficient for granular energy
$\gamma_{\Theta s}$	collisional dissipation of energy
κ_s, κ_g	thermal conductivity of solid and gas phase
μ_s, μ_g	shear viscosity of solid and gas phase
λ_s, λ_g	bulk viscosity of solid and gas phase

particles influence the bubble size and particle velocity, and ultimately the performance of the equipment in relation to heat and mass transfer ability. Conversely, changes in hydrodynamic properties i.e. the bubble size, particle velocity and phase fraction distribution, etc., also affect the electrostatic potential distribution of the fluidized bed. Using induction probes, Chen et al. (2006) detected the charge distribution around a rising single bubble. By comparing the predicted values from simulations and values from three theoretical models, they found that the charge density inside the bubble was zero and the particles were predominantly negatively charged in the bubble wake in comparison to the emulsion phase. Rokkam et al. (2010) introduced the electrostatic models in the CFD simulation for the first time, in which they studied entrainment of fine powder and charged particles. They pointed out that when the catalyst was negatively charged, the amount of entrainment decreased, which was in accordance with the experimental results. Hassani et al. (2013) investigated the effect of the electrostatic forces on bubble and particle motions and inferred that when the particles were unipolar charged, the bubble size and the axial diffusion coefficient of the particles decreased. Applying CFD to study the effect of electrostatic charges on hydrodynamics, thereby predicting the heat transfer, mass transfer and fluctuation characteristics will be useful for the regulation of fluidized bed.

The bubble shape in a three-dimensional fluidized bed is difficult to characterized and pressure signal analysis is mostly applied as an intermediate way to capture the bubble size, which includes the standard deviation and incoherent analysis of pressure fluctuations. The two-dimensional fluidized bed, because of its simple structure, easy observation, is widely used in both experiment and numerical simulations. Bouillard et al. (1991) compared the experimental and simulation results for a fast bubble and calculated the pressure profile around it based on Davidson model (Davidson and Harrison, 1963). Nieuwland et al. (1996a) then used a combination of experiment and numerical simulation to predict bubble growth and detachment time. Different researchers have studied the effects of the bubble on heat transfer (Lungu et al., 2015), electrostatics (Sun and Yan, 2016), modified computational model (Chang et al., 2016) and even scale-up effect (Knowlton et al., 2005). However, for the fluidized bed with continuous gas jet, experiments and simulations have mainly focused on phase distribution, bubble parameters, and pressure signal analysis. Studies of the electrostatic effect on interphase heat transfer, local heat transfer and particle fluctuation are, as yet, rather scarce.

In this work, the gas phase fraction distribution and its fluctuation at different positions with various specific charges are studied. Simulation results are compared with the experimental data from the literature to validate the hydrodynamic model (Kuipers et al., 1992; Nieuwland et al., 1996b). Distribution of bubble diameter along the bed height and the total number of bubbles with and without charges are calculated. The gas exchange rate and interchange coefficient, as the extension of the two-phase theory, is further investigated. The effect of electrostatics on the gas exchange rate, which is an important parameter for calculating the interphase heat transfer coefficient is discussed. Moreover, other than interphase heat transfer coefficient, the local heat transfer coefficient, and particle fluctuation parameters are analyzed. The results indicate that the electrostatic effect on the time-averaged parameters and the spatial distribution of those parameters is significant.

2. Equations of the model

Two basic approaches namely Eulerian-Eulerian (granular flow models) and Eulerian-Lagrangian (discrete particle models) are commonly used to model gas-solid flows and solve the problems of different scales. In the Eulerian-Eulerian approach, also known as the two-fluid model, each phase is considered to be completely interpenetrating with other phases with its own set of conservation and constitutive equations. Since the solid phase does not have a state equation in the continuum medium assumption of the two-fluid model (TFM), a series of closure equations are needed to describe the momentum exchange inside the particle phase, such as the radial distribution function, kinetic viscosity, bulk