Advanced Powder Technology 26 (2015) 563–575

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Effects of external electric field on bubble and charged particle hydrodynamics in a gas–solid fluidized bed

Jingyuan Sun, Jingdai Wang *, Yongrong Yang, Zichuan Zhu

State Key Laboratory of Chemical Engineering, Zhejiang University, Hangzhou 310013, China
College of Chemical and Biological Engineering, Zhejiang University, Hangzhou 310013, China

ARTICLE INFO

Article history:
Received 8 April 2014
Received in revised form 16 September 2014
Accepted 14 January 2015
Available online 28 January 2015

Keywords:
Electrostatics
External electric field
Gas–solid fluidized bed
Multi-fluid model

ABSTRACT

In the gas–solid fluidized bed reactors, the interactions between particles and the wall, the gas, or the other particles always generate electrostatic charges, which affect the flow characteristics significantly. Imposing an external electric field to regulate the particle charging and reactor hydrodynamics is a potential way of process intensification. This work focuses on the incipient gas–solid fluidization under external electric fields of direct current (DC) or alternating current (AC), with each in the form of cross-flow and co-flow respectively. The two-dimensional multi-fluid CFD model coupled with electrostatic model is established to simulate the electric effects on the fluidized bed hydrodynamics. As the particle charge magnitude increases, the bubble size and bubble detachment time are reduced, while the electrostatic force on particle is enhanced obviously. By imposing the DC electric field, the bubble is split in cross-flow field and stretched to be sharper in co-flow field. Meanwhile, the particle self-generating electric field and particle velocity are strengthened around the bubble, distributor and wall. For the application of AC electric field, the bubble deforms in the lower frequency field, and the particle self-generating electric field declines near the wall, which will reduce the particle segregation and agglomeration towards the wall.

1. Introduction

Gas–solid fluidized bed reactors are widely used in various commercial processes including chemical, petroleum, biochemical and food industries because of their large contact areas between different phases which enhance the chemical reactions. Due to the frequent collision and friction between particles and the wall, the gas phase, as well as other particles, the electrostatic charges are easily generated. This phenomenon of charge accumulation on the particles is usually unavoidable and undesirable in most dry particulate systems [1], which can lead to sparks, explosions, particle sheeting, agglomeration and even defluidization. Besides, the electrostatic charge generation will also affect the bubble dynamic behavior (such as size, shape) and the particle elutriation rates [2,3]. Although such phenomenon is unavoidable and usually acts as a disadvantage of fluidized bed operation, we can still try to utilize it and convert the harms to benefits. It is proved that to impose an electric field on the fluidized bed is an efficient way for process intensification. By this way, the bubble size and bubble spatial distribution can be controlled, which facilitates the reactor scale-up and increases the reaction conversion and selectivity [4]. For example, by applying the low-energy (50 W/m^3) alternating electric fields, the interactions between the charged particles could be changed, leading to smaller bubble size in the fluidized bed [5], further improving the gas–solid contacting and mixing efficiency. In order to control the fluidization characteristics and optimize the reactor operation by adding external electric field, it is of great importance to understand the particle charging and its effects on the two-phase hydrodynamics.

It was revealed in the previous works that in some gas–solid systems, all of the particles carried charges of the same sign (unipolar charging), while in others, some particles were positively charged, and others were negatively charged (heteropolar charging) [6–8]. In the latter cases, particles tended to agglomerate and complicated the hydrodynamics [9]. Napier [10] studied the magnitude of charge generation for different dense fluidized bed configurations, and the unloading of different particles by applying a field mill and electrostatic probe. Fang et al. [11] investigated the charge distribution and electric potential in a fluidized bed by experiments. She found that the voltage polarity reversed at the

* Corresponding author at: College of Chemical and Biological Engineering, Zhejiang University, Hangzhou 310013, China.
E-mail address: wangjd@zju.edu.cn (J. Wang).

http://dx.doi.org/10.1016/j.apt.2015.01.006
0921-8831/

bed level and stagnant zone, while the bed-level zones were more prone to form the particle–wall adhesion and wall sheets. Mehrani et al. [12] used a Faraday cage cup method to study the charge generation due to particle–gas contact, showing that the buildup of charge was due to the entrained fines. They also performed experiments to represent the changes of electrostatic behavior after adding fines. Their work supported the theory of bipolar charging.

Based on the studies of particle charging effects on the hydrodynamic behaviors of gas and solid phases, researchers utilized the external electric field to regulate and control the reactor performance by experimental methods [4,13–19], including the cross-flow DC, co-flow DC, cross-flow AC and co-flow AC external electric field applications. The results showed that particles were arranged in chains along the external electric field direction, leading to the deformation of the bubbles. The external electric field also decreased the particle mixing rate, making the fluidized bed deviate from fully mixing status. After reviewing the influences of different electric fields on the fluidized bed hydrodynamics, van Willigen proposed that the low frequency AC fields with strengths of 2–5 kV/cm were optimal for decreasing bubble number in the bed, while the DC fields had more effects but often led to spouting, stringing and cohesion of particles [20]. He then measured the external electric field influences on the bubble size in the fluidized bed by pressure fluctuation method, and proposed the optimized external electric field parameters [5,21]. The bubble size can be efficiently reduced by the external electric field with frequency of 5–20 Hz for smaller particles (77 μm), and with frequency of 20–70 Hz for larger particles (700 μm). For the nanofluidization, Espin et al. [22] and Lepek et al. [23] also found the decrease of particle agglomeration size and the enhancement of fluidization by imposing an alternating electric field.

Although the electrostatic effects on gas and particle behaviors in the particulate systems have been studied qualitatively by experimental detections, their quantitative characterization remains a major challenge to the experimentalists. Numerical simulation provides a viable alternative to study the electrostatic effects in gas–solid fluidized bed. Rokkam et al. [2,24] used the Eulerian–Eulerian multi-fluid model coupled with electrostatic model to simulate the bipolar charging phenomenon in a gas–solid fluidized bed. The magnitude of electrostatic force was calculated based on the Lorentz force equation. The results showed that the negatively charged medium and large particles were in the fluidized zone, while the small positively charged particles resided in the expansion region. The simulation method was also applied to a pilot plant of polymerization. Jalalinejad et al. [25] studied the effect of electrostatic charges on a single bubble in gas–solid fluidized beds by Eulerian–Eulerian CFD model, containing the Coulomb force and particle polarization calculation. It was found that the electrostatic effects led to the bubble elongation and increased the bubble rising velocity. The deformation of the bubble was related to the forces on particles around the bubble. Hassani et al. [26] developed a CFD–DEM coupled model to study the effects of electrostatic forces on the fluidization hydrodynamics. By increasing the charge magnitude on mono-charged particles and adding bipolar charged particles into the bed, the bubble size, the solid diffusivity and the voidage distribution were all changed. van Willigen et al. [27] used the discrete particle model (DPM) to simulate the fluidized bed with external electric field, and explained the reason of bubble size reduction. However, only the particle displacement polarization effect was included in his model, the self-generating electric field of the charged particles was beyond consideration, although it could play an important role in the external electric field effects. Until now, there are still limited simulation works about the electrostatic influences in the gas–solid fluidization systems, especially for the external electric field application.

In this work, we establish a multi-fluid CFD model coupled with the electrostatic model to study the effects of external electric field on the bubble and particle behaviors in a gas–solid fluidized bed, taking both the self-generating electric field of the charged particles and the particle polarization influences into consideration. We focus on the single bubble growing and detaching process to investigate the fundamental hydrodynamics of the gas–solid fluidized bed with electrostatic effects. Firstly, the calculation model is verified by comparison with Kuipers' experimental data [28] and the testing case of unlike charges attracting. Secondly, the bubble characteristic parameters and the forces on particles are analyzed without the external electric field to illustrate the hydrodynamics of reactor filled with the charged particles. Finally, four kinds of external electric fields are imposed on the gas–solid fluidized bed respectively to investigate their influences on the bubble and particle behaviors in the incipient fluidization. This work will provide a deeper understanding of the fluidized bed operation with the utilization of external electric field.

2. Simulation apparatus and materials

In the experiments, the two-dimensional fluidized beds with small depth are often used to study the fluidization phenomenon due to the possibility of visual observation, mainly by photography [28,29]. For the CFD simulation, although the three-dimensional simulation is more realistic, the computing cost for one gas and two solid phases is high. Therefore, in this work, we establish a two-dimensional fluidized bed model for simulation and compare the results with the experimental data. The fluidized bed has a width of 0.57 m and a height of 1.0 m, the same as that in Kuipers' experimental work [28]. Initially, the primary air is injected at the minimum fluidization velocity U_{mf}, while the second air stream at the velocity of $U_{orifice}$ is injected from the central orifice to generate a bubble. The simulation parameters are listed in Table 1.

For the calculation of the external electric field effects on the bubble and particle hydrodynamics, the cross-flow DC, co-flow DC, cross-flow AC and co-flow AC external electric field are exerted on the fluidized bed respectively. The direction of cross-flow electric field is perpendicular to the gas flow direction, while the direction of co-flow electric field is parallel with the gas flow direction.

3. Model description

This work simulated the central jetting fluidized bed with and without external electric field. For the situation without external electric field, one solid phase was considered and the particles of different charge-to-mass ratio were set to investigate the electrostatic effects on flow filed features. When adding the external electric field to the bed, two solid phases with different charge and polarity were considered to approach the real flow situation as mentioned above. Therefore, we used both the Eulerian–Eulerian

Table 1
Simulation parameters.

Parameter	Value	Unit
Bed height, H	1.0	m
Bed width, W	0.57	m
Orifice width, d	0.015	m
Jet velocity, $U_{orifice}$	10	m/s
Minimum fluidization velocity, U_{mf}	0.250	m/s
Minimum fluidization voidage, ε_{mf}	0.402	–
Particle diameter, d_s	500	μm
Particle density, ρ_s	2660	kg/m^3
Gas density, ρ_g	1.2	kg/m^3
Gas viscosity, μ_g	1.85×10^{-5}	Pa s
Static bed height, H_0	0.5	m
Restitution coefficient, e	0.90	–