Powder Technology 362 (2020) 416–427

Contents lists available at ScienceDirect

Powder Technology

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

CFD-DEM study of the effects of direct current electric field on gas-solid fluidization

Guodong Liu [a,b,*], Pengwei Liao [b], Junnan Zhao [b], Shuai Wang [b], Yao Wu [b], Xiaolong Yin [c], Huilin Lu [b,*]

[a] State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, China
[b] School of Energy Science and Engineering, Harbin Institute of Technology, China
[c] Petroleum Engineering Department, Colorado School of Mines, CO, USA

ARTICLE INFO

Article history:
Received 26 April 2019
Received in revised form 28 September 2019
Accepted 25 November 2019
Available online 26 November 2019

Keywords:
Electric field
Gas-solid fluidized bed
CFD-DEM
Numerical simulation

ABSTRACT

Electric fields can make significant impact on meso-scale structures, such as bubbles and clusters, in gas-solid fluidized beds. In this work, a 2-D gas-solid fluidized bed coupled with a DC electric field is established, and numerical simulations are carried out based on CFD-DEM method. Electric-field induced forces are modeled based on a revised point-dipole approximation by considering local-field effects and multipolar interactions. The reason for bubble size reduction and clusters formation is investigated in detail from the perspective of particle motions and forces, respectively. Simulated results show that formation of chains suppress the vortex motion of particles and result in the elimination of bubbles. Although particle-particle interactions are repulsive in the direction normal to the electric field, particles are observed to attach to each other along an oblique angle to form a braided multi-particle chain. Moreover, distributions of particle concentration and velocity become more homogeneous as the field strength increased.

1. Introduction

Gas-solid fluidized beds are widely used in combustions, pharmaceutical processes [1], metallurgy for their good mixing performance and highly efficient heat and mass transfer. However, non-uniform flow structures such as bubbles and clusters generated by interactions among particles and between particles and gas reduce the contact between particles and gas, and can seriously affect the performance of fluidized bed reactors [2]. Previous research suggested that the application of an external electric field can affect the force among particles, exerting control over the formation of inhomogeneous structures and enhancing the performance of fluidized beds. Therefore, it is of great significance to investigate the effect of external electric fields on gas-solid fluidized bed hydrodynamics.

Experimental studies that aim to regulate and control the inhomogeneous structures and thereby enhance the performance of fluidized bed reactors using an external electric field include [3–10]. Johnson et al. [4] investigated the particle fluidization phenomenon in a gas-solid fluidized bed coupled with an electric field and found that particle strings formed along the direction of the electric field. Colver [5] first proposed the concept that the application of an electric field could affect bubble size in the fluidized bed. Kashyap and Gidaspow et al. [11] explored the effect of electric field on the hydrodynamics of nanoparticles experimentally. It was shown that the electric field markedly decreased bed expansion and increased the volume fraction of nanoparticles. Experiment in a 2-D fluidized bed performed by van Willigen et al. [12] showed that an applied electric field could reduce bubble size, and a maximum reduction in bubble diameter of 25% was achieved with small particles (77μm), while for large particles (700μm) the bubble diameter could be reduced by as much as 85%. Yang et al. [13] investigated the effects of DC electric fields on meso-scale structures in a 3-D fluidized bed with electrostatic effects. Their results showed that particles also experienced Coulomb forces besides particle-particle interactions through polarization and these two forces presented a competition effect on the formation of meso-scale structures. Coulomb forces act primarily at lower field strengths to increase bubble size and break up agglomerates. Whereas at higher field strengths, polarization forces act to assist the formation of agglomerates and suppress bubble size.

To date, although the hydrodynamics of fluidized beds with imposed electric fields has been studied qualitatively by experiments, quantitative experimental characterization remains a major challenge. Numerical simulation thus provides a viable alternative to reveal quantitative connections between implemented mechanisms and their consequences. Sun et al. [14] employed a 2-D multi-fluid CFD model coupled with an electrostatic model to simulate the effect of electric field on the hydrodynamics of a fluidized bed. Van Willigen et al. [15] employed the method of DPM (Discrete Particle Model) coupled with CFD to investigate the effect of electric field on bubble size and number. Through

* Corresponding author at: State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, China.
E-mail addresses: gdliu@hit.edu.cn (G. Liu), huilin@hit.edu.cn (H. Lu).

https://doi.org/10.1016/j.powtec.2019.11.096
0032-5910/

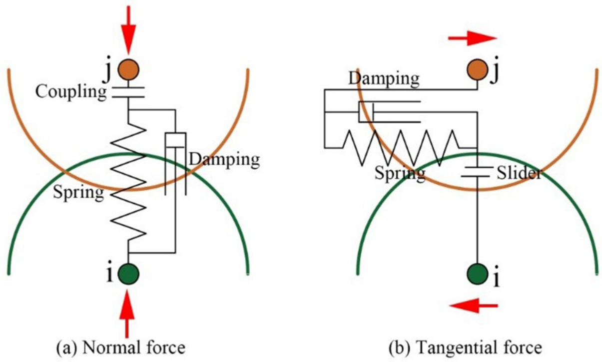

Fig. 1. Model of contact force for particles.

analysis of bubble's behavior, it was concluded that moderate-strength electric fields distributed gas more evenly at the bottom of the bed. As bubbles rose through the bed, the coalescence rate was lower, which resulted in smaller average bubble sizes in the higher region of the bed. Hassani et al. [16] developed a CFD–DEM coupled model to study the effects of electrostatic forces on the hydrodynamics of fluidization. By increasing the charge magnitude on mono-charged particles and adding bipolar charged particles into the bed, bubble size, diffusivity of the solid and voidage distribution were all changed.

Despite the aforementioned studies, numerical simulations of fludidization with electric fields are still rare and needed, because quantitative models for electrically induced forces are difficult to develop. Parthasarathy et al. [17] suggested a point-dipole approximation, which assumed that each dielectric particle was only polarized by the external electric field but could not be affected by the particles around it. Based on this approximation, they acquired a formula to calculate the dipole moment and the force between polarized particles. Martin et al. [18] investigated the influence of local-field on particle's polarization based on the point-dipole approximation. They divided the electric field acting on particles into two parts: applied electric field and dipole electric field generated by other particles. With the consideration of multipolar interactions, Huang et al. [19,20] revised the polarization factor of the point-dipole approximation by employing the Multiple Image Method. No previous simulations, however, have taken both local-field effects and multipolar interactions into account.

In this work, a 2-D numerical model of a gas-solid fluidized bed with imposed DC electric field is built using the CFD-DEM method. This article aims to correlate the influence of external electric field on the inhomogeneous structures such as bubbles and clusters to particle motions and forces. In our model, we considered both local-field effects and multipolar interactions.

2. Simulation method

The equations governing a gas-solid multiphase system were derived from a multiphase flow theory [21,22], which used the Discrete Element Method to simulate particle flows and CFD to simulate the Navier-Stokes equation of gas flow. The in-house DEM and CFD codes

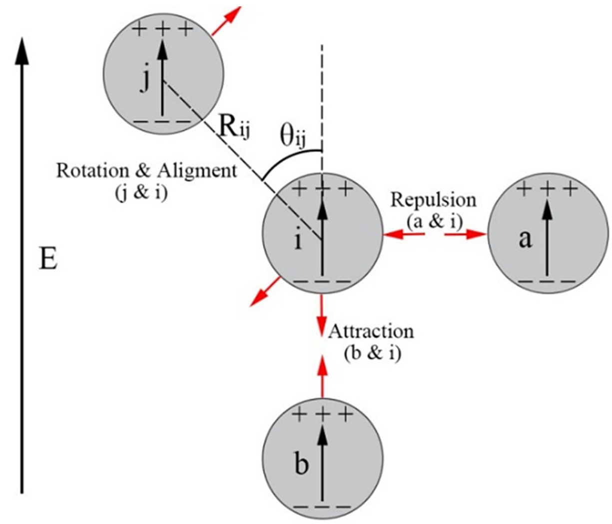

Fig. 2. Polarization force model among particles in a direct current electric field.

[23] were employed for the numerical simulations presented here. Detailed expressions of CFD for gas phase and DEM for the solid particles used in this work are as follows.

2.1. Gas phase

Continuity equation:

$$\frac{\partial\left(\rho_g\varepsilon_g\right)}{\partial t}+\nabla\cdot\left(\rho_g\varepsilon_g\mathbf{u_g}\right)=0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial\left(\rho_g\varepsilon_g\mathbf{u_g}\right)}{\partial t}+\nabla\cdot\left(\rho_g\varepsilon_g\mathbf{u_g}\mathbf{u_g}\right)=-\varepsilon_g\nabla p+\varepsilon_g\nabla\cdot\boldsymbol{\tau}_\mathbf{g}+\varepsilon_g\rho_g\mathbf{g}+\mathbf{f_{int}} \tag{2}$$

In the above equations, ε_g is voidage; ρ_g is the density of gas phase; $\boldsymbol{u_g}$ is the velocity of gas phase; p is the pressure of gas phase; $\boldsymbol{\tau_g}$ is the viscous stress tensor of the gas; $\boldsymbol{g}$ is gravity acceleration; $\mathbf{f_{int}}$ is the interphase force between the two phases.

2.2. Solid phase

According to Newton's second law of motion, equations governing the motion of the solid particles include one for translation and another for rotation.

Table 1
Input parameters of simulations.

DEM parameters	Value	CFD parameters	Value	Simulation parameters	Value
Particle diameter	2 mm	Gas viscosity	1.8×10^{-5} Pa·s	Grid number	28 × 168
Particle density	2500 kg/m^3	Gas density	1.2 kg/m^3	Grid size	5 × 5 mm × mm
Normal stiffness	700 N/m	Dielectric constant	1	Time step size	1×10^{-4} s
Tangential stiffness	200 N/m	Superficial velocity	2 m/s	Convergence criterion	1×10^{-5}
Damping coefficient	0.05	Conductivity	5.0×10^{-15} S/m		
Friction coefficient	0.15				
Dielectric constant	7				
Conductivity	1.0×10^{-10}				