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Effect of electrostatics on freely-bubbling beds of mono-sized particles

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ABSTRACT

Electrostatic charges influence single bubble shape and rise velocity, as shown in our previous study. This paper extends the previous work to investigate the influence of electrostatic charges on bubbles in freely-bubbling fluidized beds, by simulating a two-dimensional column, with charged mono-sized glass beads supported by air. Simulation results are first compared with experiments in an uncharged system at two superficial gas velocities. The sensitivity of the results to frictional models is investigated, with the model chosen for the rest of the study which gives better predictions. In the second part of this work, the effect of electrostatics on hydrodynamics of freely-bubbling fluidized beds is investigated by comparing bubble diameter, distribution and time-average vertical solid velocities for uncharged and charged cases. The results predict that electrostatic charges decrease bubble size, modify bubble spatial distribution and influence time-average solid velocities.

Introduction

Electrostatic charges generated in gas–solid fluidized beds of dielectric materials can lead to costly shutdowns in the polymer production industries. Efforts are frequently made to reduce the magnitude of charge in fluidized beds, for example by grounding the walls, adding antistatic agents and increasing the humidity (in laboratory studies), but the problem remains unresolved.

Experimental studies in this area are divided into two subcategories: (a) understanding the effects of charge generation (Boland and Geldart, 1971; Mehrani et al., 2005; Chen et al., 2006), and (b) reducing charges inside the bed (Bafrnec and Bena, 1972; Park et al., 2002). Numerical studies by Al-Adel et al. (2002), Rokkam et al. (2010), Jalalinejad et al. (2012) and Rokkam et al. (2013) have demonstrated that electrostatic charges influence the hydrodynamics of risers and dense fluidized beds. Al-Adel et al. (2002) showed that the electrostatic charge on particles could influence the solid distribution in a vertical riser by displacing the particles towards the outer wall. Rokkam et al. (2010) studied the effect of electrostatics on the hydrodynamics of a dense fluidized bed of polymer particles by applying a Two Fluid Model (TFM). Electrostatics were predicted to change the particle distribution inside the bed and expansion region, thereby affecting fines entrainment. Jalalinejad et al. (2012) predicted the effect of charges on a single bubble in dense fluidized beds of mono-sized particles based on a TFM. Bubble elongation was predicted in the vertical direction in the charged system, with the extent of elongation a function of the particle charge density. These qualitative findings were independent of the frictional model adopted. Rokkam et al. (2013) found good agreement between simulation results for charged particles and experimental results for poly-dispersed polymer particles in terms of the degree of segregation and height of wall-coating in the bubbling and slugging flow regimes.

Electrostatics often cause major operating problems in the freely-bubbling flow regime of fluidization. This flow regime is widely used in gas-phase polymerization reactors. In this regime, the bubble size and spatial distribution determine the internal solids circulation and consequently the efficiency of gas and solid contact. Key properties like heat transfer, mass transfer and reactor efficiency are related to bubble motion and the distribution of gas flow between the bubble and emulsion phases. One of the early models to predict the flow behavior is the “two-phase theory”, which assumes that the gas flow to emulsion phase remains that needed to keep the particles at minimum fluidization, with any excess gas beyond that forming bubbles. Experimental results have shown that this “theory” is an oversimplification, resulting in over-prediction of visible bubble flow. As explained by Grace and Clift (1974), some researchers suggest that this is because of a greater interstitial dense phase velocity than U_{mf}/ε_{mf}, while others attribute it to throughflow inside bubbles. Grace and Harrison (1969) showed that the velocity of a bubble in a swarm of bubbles is higher than for isolated bubbles of the same size. Since trailing bubbles tend to enter the wake of leading ones, causing them to elongate, this is expected to increase the throughflow for the trailing bubbles, as well as to increase the average bubble rise velocity.

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The true distribution of gas flow between the phases remains unclear. Computational Fluid Dynamics (CFD) can shed light on the flow distribution, but CFD models need extensive validation for their predictions to be quantitatively reliable.

One of the experimental studies used in this work to compare with CFD predictions was that of Laverman et al. (2008), who investigated the hydrodynamics of a two-dimensional bubbling fluidized bed, by combining Particle Image Velocimetry (PIV) with Digital Image Analysis (DIA) to measure bubble size and solids velocity at different superficial gas velocities. The influence of electrostatics was minimized by grounding the column with Aluminum strips and using humid air. Li et al. (2010) simulated the experiments of Laverman et al. (2008) using MFIX (open-source Multiphase Flow with Interphase eXchange code originated by the U.S. Department of Energy), with the S–R–O frictional model to investigate the effect of the wall slip boundary condition on the freely-bubbling flow regime. It was found that the specularity coefficient, δ, a measure of wall roughness, influences the bed height, solid velocity profile and bubble diameter, while the influence of particle–wall restitution coefficient was small. Overall, the model predictions are in reasonable agreement with experimental results.

In this study we investigate the effect of electrostatics on a freely-bubbling bed of mono-sized particles, by comparing simulation results for uncharged and charged fluidized beds of 500 μm glass beads. To compare with experimental results, the geometry of the system matches that of Laverman et al. (2008). The Two Fluid Model implemented in MFIX is applied to the hydrodynamics, while the interaction between the electrical field and fluid dynamics is modeled by solving the electrical governing equation and adding the resultant electrical force to the solids momentum equation.

As mentioned above, Li et al. (2010) simulated the same case as us without the influence of electrostatic charge with the same code as used here (MFIX), comparing model predictions with experimental results of Laverman et al. (2008) for different model parameters. Therefore, here we extended their work by investigating the influence of different frictional models and then moved to study the effects of electrostatics on the hydrodynamics.

The Srivastava and Sundaresan (2003) (S–S) frictional model was previously used to see the effect of electrostatics on single bubbles in fluidized bed, showing better agreement with experimental results than the Syamlal et al. (1993) (S–R–O) model (see Jalalinejad et al., 2012). In this paper, both of these frictional models are employed, with the one which works better retained to determine how the inclusion of electrostatics modifies the average bubble diameter, bubble spatial distribution and solids velocities.

Model equations

Two Fluid Model (TFM)

The Two Fluid Model treats both the gas and solid phase as interpenetrating continua. The conservation equations for each phase take the forms

$$\frac{\partial \varepsilon_m \rho_m}{\partial t} + \nabla \cdot (\varepsilon_m \rho_m \boldsymbol{U_m}) = 0 \tag{1}$$

$$\varepsilon_g \rho_g \left(\frac{\partial \boldsymbol{U_g}}{\partial t} + \boldsymbol{U_g} \cdot \nabla \boldsymbol{U_g} \right) = \varepsilon_g \nabla \cdot \boldsymbol{\sigma_g} + \varepsilon_g \rho_g \boldsymbol{g} - \beta_{gs}(\boldsymbol{U_g} - \boldsymbol{U_s}) \tag{2}$$

$$\varepsilon_s \rho_s \left(\frac{\partial \boldsymbol{U_s}}{\partial t} + \boldsymbol{U_s} \cdot \nabla \boldsymbol{U_s} \right) = \nabla \cdot \boldsymbol{\sigma_s} - \varepsilon_s \nabla P_g + \varepsilon_s \rho_s \boldsymbol{g} + \beta_{gs}(\boldsymbol{U_g} - \boldsymbol{U_s}) + \boldsymbol{f_e} \tag{3}$$

where ε, ρ and $\boldsymbol{U}$, P are the voidage, density, velocity and pressure. Subscript m refers to either the gas or solid phase. β_{gs} denotes the gas–solid momentum exchange coefficient, calculated based on the Gidaspow (1994) drag relation in our studies. $\boldsymbol{f_e}$ in the solid momentum equation is the electric force density for charged particles. This is where the effect of electrostatics is introduced to the system. $\boldsymbol{\sigma_g}$ and $\boldsymbol{\sigma_s}$ in the above equations are the gas and solid phase stress tensors defined by

$$\boldsymbol{\sigma_g} = \mu_g \left[\nabla \boldsymbol{U_g} + \nabla^T \boldsymbol{U_g} \right] - \left[P_g + \frac{2}{3} \mu_g \nabla \cdot \boldsymbol{U_g} \right] \boldsymbol{I} \tag{4}$$

$$\boldsymbol{\sigma_s} = \mu_s \left[\nabla \boldsymbol{U_s} + \nabla^T \boldsymbol{U_s} \right] + \left(-P_s + \left(\eta \mu_b - \frac{2}{3} \mu_s \right) \nabla \cdot \boldsymbol{U_s} \right) \boldsymbol{I} \tag{5}$$

Here μ_g, P_g, μ_s and P_s are viscosity and pressure for gas and solid respectively and $\eta \mu_b$ refers to the bulk viscosity for inelastic particles. The solid phase shear stress tensor is defined as a sum of kinetic and frictional terms, denoted by superscripts k and f, as presented in Table 1. The kinetic part of the stress in MFIX is based on the model of Lun et al. (1984), modified to account for the effect of interstitial gas on particle phase viscosity through terms with an asterisk superscript (Agrawal et al., 2001), such as μ^* in Eq. (1.7) in Table 1. Replacing μ^* by μ recovers the Lun et al. (1984) model, where μ is the shear viscosity for perfectly elastic particles with dilute concentrations.

The frictional part of the stress is implemented in MFIX by two methods, S–R–O and S–S models. The S–R–O model is based on plastic flow of a granular material, and it allows for compressibility near the packing limit. The frictional stress from this model is only non-zero when the solid volume fraction exceeds ($\varepsilon_s^{\max}$). The critical pressure is a power law function of voidage (Syamlal et al., 1993), and the frictional viscosity is proportional to the critical solid pressure, as proposed by Schaeffer (1987) and as shown in Eq. (1.11) in Table 1. ϕ, I_{2D} and $\mu_s^{\max}$ in this equation denote the angle of internal friction, second invariant of the deviator of the strain rate tensor for solid phase and the maximum solid viscosity limit, set to 100 kg/m s by default in MFIX. ($\varepsilon_s > \varepsilon_s^{\max}$) is a Boolean expression that equals 1 or 0 when the expression is true or false, respectively.

The S–S model is based on compressible granular flow, with the frictional stress starting to play a role at lower solid volume fraction (ε_s^{min}) than for the S–R–O model. The S–S model includes the fluctuation in strain rate associated with the formation of shear layers, proportional to the root of granular temperature over particle diameter, $\Theta_s^{0.5}/d_p$, preventing numerical singularity in regions where the magnitude of strain tensor, denoted by ($\sqrt{\mathbf{S}:\mathbf{S}}$), is zero, as shown in Eq. (1.13) in Table 1. In this equation, $\mathbf{S}$ is the strain rate tensor and ($\varepsilon_s > \varepsilon_s^{min}$) is a Boolean expression acting as explained above. The critical solid pressure in this model is calculated in the same way as in the S–R–O model when the solid volume fraction exceeds $\varepsilon_s^{\max}$, but it is based on the Johnson et al. (1990) empirical correlation between ε_s^{min} and $\varepsilon_s^{\max}$, and it equals zero when the solid volume fraction falls below the minimum solid volume fraction, ε_s^{min}, needed to account for the frictional effect.

The conservation equation for the granular temperature, Θ, takes the form

$$\frac{3}{2} \rho_s \varepsilon_s \left[\frac{\partial \Theta}{\partial t} + \boldsymbol{U_s} . \nabla \Theta \right] = -\boldsymbol{\sigma}_s^k : \nabla \boldsymbol{U_s} + \nabla \cdot (\kappa_s \nabla \Theta) - J_{coll} - J_{vis} \tag{6}$$

where J_{coll}, J_{vis} and κ_s refer respectively to the loss of granular temperature due to inelastic particle–particle collisions, interaction between gas and particles and the granular conductivity of inelastic particles for high concentrations. These terms are defined in Table 2, with κ, κ^* and κ_s referring to granular conductivity for inelastic particles in dilute concentration, proposed by Lun et al. (1984), the