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Original Research Paper

# Effect of electrostatics on interaction of bubble pairs in a fluidized bed

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ABSTRACT

Electrostatic charges can influence the hydrodynamics of gas–solid fluidized beds. In our previous work (Jalalinejad et al., 2012), it was shown that high charge density modified the single bubble shape in fluidized beds. In this study, we investigate the effect of electrostatics on interaction of bubbles by simulating pairs of bubbles in vertical and horizontal alignment in uncharged and charged particles. The geometry simulated is based on the experiment of Clift and Grace (1970), with simulation results compared with their experiments for bubbles in vertical alignment. The model predicts the overall coalescence pattern, but the trailing bubble splits in simulations, unlike experiment.

The effect of electrostatics is modeled by solving electrical equations and adopting the Two Fluid Model in MFIX (an open source code). Comparison of uncharged and charged cases for bubbles in vertical alignment shows different bubble coalescence behaviour, with greater asymmetry in the charged case, leading to larger resultant bubble. For bubbles in horizontal alignment, electric charges cause the side bubble to migrate towards the axis of the column, reversing the leading-trailing role of the two bubbles, which led to the decrease in the height of complete coalescence.



## 1. Introduction

Electrostatics cause serious challenges for the polymer production industries [3]. There have been several attempts to understand and control this phenomenon, mostly experimental [4–11]. In recent years, some numerical studies predict that electrostatics can modify the solids spatial distribution in risers and dense beds [12–14]. Our previous study showed elongation of single bubbles in the presence of electrostatics, accompanied by an increase in their rise velocity [1]. However, the influence of electrostatic charges on bubble interaction has not been previously investigated.

Pair-wise bubble interaction and coalescence play key roles in determining not only the distribution of bubble size, but also overall bed properties. They also strongly influence how much gas rises as bubbles and passes through bubbles in the bubbling regime of gas-fluidized beds. In this regime, many bubbles can be interacting/coalescing at any time.

Coalescence of obliquely-aligned pairs of bubbles proceeds via the following steps: (1) relative motion to give near vertical alignment of the two bubbles; (2) acceleration and elongation of the trailing bubble; (3) the trailing bubble overtakes the leading one; (4) rupture of the thin film of particles separating the two bubbles. The interaction of pairs of bubbles in vertical alignment was investigated by Clift and Grace [2] experimentally and theoretically by approximating the solids flow around bubbles as potential flow. It was shown that the velocity of a bubble could be approximated by adding the bubble velocity in isolation to the velocity the continuous (dense) phase would have at the position of the nose if the bubble were absent. This postulate predicted the acceleration of the trailing bubble, and the results were in good agreement with experiments, even though the flow around the bubble was approximated with a flow around a cylinder (two dimensions) or sphere (three dimensions).

The model by Clift and Grace [2] was extended to predict the multiple pair-wise interactions between leading and tailing bubbles [15,16]. Because the trailing bubble did not affect the leading bubble significantly, Farrokhalaee [17] adopted a simplification which gave good agreement with experimental results. This simplified model predicted the bubble behaviour with only slight deviation from the more complicated model proposed by Clift and Grace [2]. The model by Farrokhalaee [17] was later adopted as one of the closure methods in the Discrete Bubble Model (DBM) to predict the interaction of bubbles [18,19].

In this work, the effect of electrostatics is investigated on the interaction of pairs of bubbles in vertical and horizontal alignment by simulating the Clift and Grace [2] setup for uncharged and

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**Nomenclature**

| | |
|---|---|
| $d_p$ | particle diameter (m) |
| $e_p$ | particle–particle restitution coefficient (–) |
| $e_w$ | particle-wall restitution coefficient (–) |
| $E$ | electric field (N/C) |
| $f_e$ | electrical force density (N/m$^3$) |
| $g_0$ | radial distribution (–) |
| $I$ | unit vector (–) |
| $J_{coll}$ | loss term due to particle-particle collision (kg/m s$^2$) |
| $J_{vis}$ | loss term due to interaction of gas and particles (kg/m s$^2$) |
| $\boldsymbol{n}$ | unit normal vector (–) |
| $P$ | pressure (N/m$^2$) |
| $P_c$ | critical pressure (N/m$^2$) |
| $q_m$ | charge density based on mass of solids (C/kg) |
| $\boldsymbol{S}$ | strain rate tensor (s$^{-1}$) |
| $t$ | time (s) |
| $\boldsymbol{U}$ | velocity vector $\boldsymbol{U} = (U,V)^T$ (m/s) |
| $V_{j,v}$ | vertical jet velocities (m/s) |
| $V_{j,h}$ | horizontal jet velocities (m/s) |
| $X$ | Cartesian coordinates in horizontal direction (m) |
| $Y$ | Cartesian coordinates in vertical direction (m) |

*Greek letters*

| | |
|---|---|
| $\alpha$ | constant (–) |
| $\beta_{gs}$ | gas–solid momentum exchange coefficient (N s/m$^4$) |
| $\varepsilon$ | volume fraction (–) |
| $\epsilon_1$ | electrical permittivity of background fluid (F/m) |
| $\epsilon_2$ | electrical permittivity of solids (F/m) |
| $\epsilon_0$ | electrical permittivity of free space (F/m) |
| $\epsilon_{ave}$ | average relative permittivity of mixture (F/m) |
| $\varepsilon_s^{min}$ | minimum threshold to account frictional stress in S–S frictional model (–) |
| $\varepsilon_s^{max}$ | maximum solid packing volume fraction (–) |
| $\kappa$ | granular conductivity (W/m k) |
| $\varphi$ | electric potential (V) |
| $\phi$ | angle of internal friction degree |
| $\delta$ | specularity coefficient (–) |
| $\rho$ | density (kg/m$^3$) |
| $\mu$ | viscosity (kg/m s) |
| $\mu_b$ | bulk viscosity (kg/m s) |
| $\eta$ | constant (–) |
| $\sigma$ | stress tensor (N/m$^2$) |
| $\boldsymbol{\Theta}$ | granular temperature (m$^2$/s) |

*Subscripts*

| | |
|---|---|
| $g$ | gas |
| $s$ | solids |
| $sup$ | superficial |
| $sl$ | slip |

*Superscripts*

| | |
|---|---|
| $k$ | kinetic component of stress |
| $f$ | frictional component of stress |

charged monosized particles. The simulation results for vertical alignment are then compared with experimental results.

## 2. Model equations

### 2.1. Two Fluid Model

The Two Fluid Model is used in this work, with gas and solids treated as interpenetrating continua (see [23] and [27] for more details). The governing and constitutive equations for this model are listed in Tables 1 and 2. In this study, the Gidaspow [20] drag relation and Srivastava and Sundaresan (S–S) [21] frictional model, which gave better predictions for a single bubble in our previous work, are employed (see [1] for details).

To model electrostatic charges, we assume that fluidized particles have reached a charge saturation level, usually requiring in practice about 1 h of fluidization [5,22,23]. At this stage, the total amount of charge in the system is assumed to be constant, implying that the magnitudes of charge generation and dissipation are equal.

We also assume that particles are mono-sized and carry the same magnitude of charges, regardless of particle–particle and particle–wall collisions (in line with experimental observation for bed of narrow-sized glass beads [6]). Although neglecting influence of particle–wall and particle–particle interaction may not represent what exactly happened in the system, however from engineering stand point it is a good assumption to predict the overall behaviour of charged system at this level of model development.

Therefore, the electric field is a function of particle volume fraction and collisions are assumed to not change the electric field, except by changing the particle concentration. As explained above, in the Two-Fluid Model, the gas and solid phases are considered to be interpenetrating continua. The solid phase can be thought of as a compressible medium (whose solid volume fraction can change). Therefore when particles are charged, we have a charged continuum and the intensity of the electric field in each control volume depends on the particle volume fraction. The movement of particles changes the charge distribution of this medium, causing the electric forces on particles to change. At the same time, the change in electrical forces changes the movement of particles. The net result is a coupling between the electric field and particle movement, which can be called electrohydrodynamics.

Predicting electric force in a dense continuum is challenging, since only for a very dilute medium subject to an imposed field can these forces be calculated from first principles. However, for dense media, another approach based on virtual work is required [24] which combines the effect of free charge and polarization. In our previous work, we derived electric forces for a compressible dense medium based on this approach, presented as $\boldsymbol{f}_e$ in Table 1. (See [1,24,25] for more details on the derivation).

### 2.2. Boundary conditions

Atmospheric constant pressure is assumed as the top boundary condition, while uniform gas velocity is adapted at the distributor, except over a central orifice and side orifice, where transient jet boundaries are applied. The no-slip boundary condition for the gas phase, and partial-slip for the solid phase are employed at the side walls. The partial slip boundary conditions based on Johnson and Jackson [26] take the form

$$\frac{\boldsymbol{U}_{sl}}{|\boldsymbol{U}_{sl}|}\cdot(\boldsymbol{\sigma}_k+\boldsymbol{\sigma}_f).\boldsymbol{n}+\frac{\delta\pi\rho_s\varepsilon_s g_0\sqrt{\Theta_s}}{2\sqrt{3}\varepsilon_s^{\max}}\boldsymbol{U}_{sl}+(\boldsymbol{n}.\boldsymbol{\sigma}_f.\boldsymbol{n})\tan\phi=0 \qquad (1)$$

$$-\boldsymbol{n}.\kappa_s\nabla\Theta_s=\frac{\delta\pi|\boldsymbol{U}_{sl}|^2\rho_s\varepsilon_s g_0\sqrt{\Theta_s}}{2\sqrt{3}\varepsilon_s^{\max}}-\frac{\sqrt{3}\pi\rho_s\varepsilon_s g_0(1-e_w)^2}{4\varepsilon_s^{\max}}\Theta_s^{3/2} \qquad (2)$$