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Discrete particle simulations of an electric-field enhanced fluidized bed

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Abstract

Reducing the size of gas bubbles can significantly improve the performance of gas–solid fluidized reactors. However, such a control of bubbles is difficult to realize without measures that either use a lot of energy or deteriorate the fluidization behavior. In this paper, we present the results of discrete particle simulations of an electric-field enhanced fluidized bed, and compare these results to experimental data.

The simulations show a significant effect on the size of bubbles, both with horizontal and vertical electric-fields applied. When the field strength is increased to values higher than those used in the experiments, the particles are found to form strings in the direction of the electric field. At very high field strengths, defluidization is observed, consistent with the experiments.

Through the analysis of the bubble behavior, it is concluded that moderate strength electric fields distribute gas more evenly at the bottom of the bed. As the bubbles rise through the bed, the coalescence rate is lower because of the guiding paths, or resistance, the particles form due to the field. This results in a smaller average bubble size in the higher region of the bed. The simulations presented here show *how* and *why* the electric fields reduce bubble size in electric-field enhanced fluidized beds.

Keywords: Fluidization; Electric-field enhanced fluidized beds; Dipole force; CFD; Discrete particle model; Bubble size reduction

1. Introduction

The application of electric fields to fluidized beds has experimentally been shown to enhance the fluidized bed behavior [1]. Using low-energy (50 W/m^3) alternating electric fields, the interaction of particles in the bed is changed, leading to a smaller average size of the bubbles in the fluidized bed. While the agitation by bubbles in a normal fluidized bed generally enhances the solids mixing of the system, the gas contained in bubbles rises quickly through the bed with little interaction with the solid catalyst particles. Therefore, control and reduction of bubble size is desirable since it leads to improved gas–solids contacting in fluidized bed reactors.

When particles in a fluidized bed are subjected to alternating electric fields, they experience a periodically oscillating attractive or repulsive interparticle force, depending on their relative orientation. It has been shown experimentally that this leads to smaller bubbles in both pseudo two-dimensional as well as in circular cross-section beds. Such properties as the size of bubbles, the number of bubbles, their rise velocity, and the total bubble hold-up when electric fields are applied have been measured with a variety of techniques. Although an understanding of the phenomenon of the reduced bubble size and increased hold-up has been reached, the mechanism leading to smaller bubbles is not yet clear.

That varying the interparticle forces between particles has a large effect on fluidization phenomena is well-known — it has been investigated both experimentally and in simulations. Experimentally, the interparticle force has been influenced via liquid bridge forces [2] and magnetic forces [3], showing artificially induced homogeneous fluidization in Geldart B material, or cohesive behavior in Geldart A systems. Molerus [4] has suggested that it is the ratio of interparticle van der Waals force to fluid drag forces that defines the Geldart B/A and A/C transitions in the Geldart classification, although other

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interparticle forces may also have a significant influence on fluidization behavior.

Artificially changing the interparticle forces in discrete particle simulations has revealed [5,6] qualitatively that an increased cohesive interparticle force helps promote homogeneous fluidization for systems that normally would not show such a behavior. Typically, a system that displays homogeneous fluidization behavior at lower flow rates will form smaller bubbles at higher flow rates than a system in which no homogeneous fluidization is possible. Larger interparticle forces lead to cohesive behavior, whereby large agglomerates of particles build up.

However, the control of interparticle forces in experiments is difficult. On a small scale, in a controlled environment, and at high energy costs, such methods as liquid bridging using thin oil films [7] and magnetic fields [3,5] can be used, but these methods are often not practical in a large scale system.

The application of electric fields is an alternative method of altering the bubble behavior in fluidized beds. However, the interparticle force induced by the electric fields differs from the cohesive forces discussed above in that the electric-field induced force is either attractive or repulsive depending on the particle orientation. In addition, because the applied field is alternating, the force it induces also varies periodically.

The aim of this work is to incorporate the microscopic electric-field induced interparticle forces into a discrete particle CFD model (DPM) to study the impact on bubble behavior. Specifically, we want to know *why* the electric field, and the interparticle forces it induces, leads to a reduction in bubble size.

2. Electric-field induced forces

In an electric-field enhanced fluidized bed, an applied electric field induces electric dipoles in the particles, leading to electric-field induced interparticle forces. When a non-conductive particle is placed in an electric field, a charge separation occurs and the particle becomes polarized (cf. Fig. 1). This charge separation can originate from the scale of electrons or molecules to the scale of particles, depending on the conditions. Note that such a charge separation does not lead to a build-up of charge on the particle, as, for example, triboelectric charging of the particles with the walls can. The particles in our application and simulations remain electrostatically neutral.

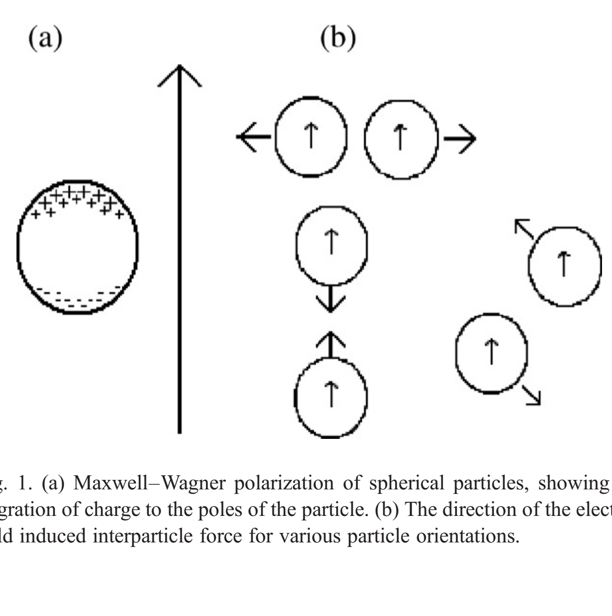

Fig. 1. (a) Maxwell–Wagner polarization of spherical particles, showing the migration of charge to the poles of the particle. (b) The direction of the electric-field induced interparticle force for various particle orientations.

The particles used in electric-field enhanced fluidized beds are insulating particles (e.g., glass beads, silica or alumina catalyst particles) with a slightly conductive bulk and/or surface layer (since the fluidized air is slightly humidified), and the electric field alternates at frequencies ranging from 1 to 100 Hz. The dielectric response of such a system can be described by the Maxwell–Wagner theory of interfacial polarization (see e.g. [8]). This means that the degree of polarization, and the ensuing particle interaction, is not dictated by the particle and gas permittivities, but rather by the particle and gas conductivities. The polarization is now not primarily due to dipoles on the atomic or molecular scale, but rather due to the migration of charges in the particle, often restricted to a thin layer within or on the particle, aided by absorbed moisture. For charges to migrate over such large distances, rather slowly oscillating electric fields are required, i.e. the 1–100 Hz alternating fields previously mentioned. At higher frequencies, only the (significantly smaller) effect of the material dielectric permittivity on the polarization is active. In the simulations described in this paper, the field frequency effect on the degree of polarization of a particle (e.g. the dynamics of the Maxwell–Wagner polarization) is ignored — it has been described before [9], and the focus here is on the motion of the particles.

The relative dielectric constant (ε_p) is a measure for the degree of charge separation in a particle in an electric field. When the electric field has induced a small movement of positive and negative charges in opposite directions, the particle has become an electric dipole, quantized in the electric dipole moment p situated at the center of the particle. It is related to the electric field E by:

$$p = 1/2\pi\varepsilon_0 K d_\mathrm{p}^3 E \tag{1}$$

where ε_0 is the permittivity of free space, d_p the particle diameter, and K the Clausius–Mossotti function, which provides a measure of the strength of the effective polarization in a spherical particle:

$$K = (\varepsilon_\mathrm{p} - \varepsilon_\mathrm{air})/(\varepsilon_\mathrm{p} + 2\varepsilon_\mathrm{air}). \tag{2}$$

The relative permittivity of the particle is ε_p, the relative permittivity of air is approximately $\varepsilon_\mathrm{air}=1$.

For the approximation of the electric-field induced interparticle force between two particles, $\overrightarrow{F_{ij}}$, the assumption of interaction between point dipoles is made [10]:

$$\overrightarrow{F_{ij}} = C \cdot \frac{3}{16} \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_\mathrm{air} \cdot d_\mathrm{p}^2 \cdot K^2 \cdot E^2 \cdot \left(\frac{d_\mathrm{p}}{a_{ij}}\right)^4 \cdot [(3\cos^2\theta_{ij} - 1)\overrightarrow{e_r} + (\sin 2\theta_{ij})\overrightarrow{e_\theta}] \tag{3}$$

where C is the multipole correction factor, a_{ij} is the center-to-center separation distance, θ_{ij} is the angle between the center-to-center particle axis and the electric field, and $\overrightarrow{e_r}$ and $\overrightarrow{e_\theta}$ are the unit vectors in the r and θ directions respectively (cf. Fig. 2).

Particles oriented with their centers aligned in the direction of the electric field will attract, while particles with their centers perpendicular to the field will repel one another. Particles in any