## Bubble Size Reduction in Electric-Field-Enhanced Fluidized Beds

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### Introduction

The applications of gas-solids fluidized bed reactors are widespread in chemical and physical processes. Their liquid-like behavior and continuous movement of particles allow for good heat transfer and temperature control. However, the appearance of gas bubbles lowers the mass transfer in bubbling fluidized beds. A reduction of the bubble size by a factor of four can almost double the conversion (Levenspiel, 2002). Moreover, in case of parallel and/or series reactions (which is the case in almost every realistic situation) smaller bubbles lead to a higher selectivity for the desired product (Kaart *et al.*, 2002). A number of (more or less practical) methods are available to reduce bubble diameters and increase phase contact, such as internal baffles (Van Dijk *et al.*, 1988), pulsed or fractal gas injection (Coppens and van Ommen, 2003), mechanical vibration (Kwauk, 1992), and magnetic fields (Hristov, 2002). Here, an alternative to these often energy-intensive methods is proposed: the application of electric fields as a means to control bubble size in bubbling fluidized beds.

The application of electric fields is a way to decrease the bubble size in fluidized beds at low energy costs. In this work, thin wire electrodes were placed in the fluidized bed, perpendicular to the flow. When fluidizing semi-insulating glass particles by air and applying an electric field of moderate strength (0-5 kV/cm) and low frequency (1-100 Hz), a significant decrease of gas bubble sizes can be observed. We will show that for both Geldart A and B materials, bubble size and number of bubbles decrease. This was determined using analysis of pressure fluctuations and video analysis of 2-D columns. We stress that fluidization of the emulsion phase is maintained – particles are still free to move.

First, the underlying mechanism of polarization under the influence of electric fields, and the resulting interparticle forces in fluidized beds, will be described. This is followed by the experimental results and discussion.

### Theory

The influence of small variations in interparticle forces on fluidization behavior has been shown both experimentally (*e.g.* liquid bridges (Seville and Clift, 1984), magnetic forces (Saxena and Wu, 1999)) and in discrete element models (*e.g.* Rhodes *et al.*, 2001). In this work, the interparticle forces are the result of the polarization of particles. The degree of polarization, $P$, of the particles (diameter $d_p$) in a fluidized bed is a function of the electrical conductivity, $\sigma$, and dielectric constants of particle and continuous phase ($\varepsilon_p$ and $\varepsilon_c$), as well as the electric field strength, $E_0$.

$$P = f\,(d_p^3, \varepsilon_p, \varepsilon_c, \sigma(\mathrm{RH}), E_0) \qquad (1)$$

The conductivity of the system is strongly influenced by the relative humidity, RH, of the fluidizing gas.

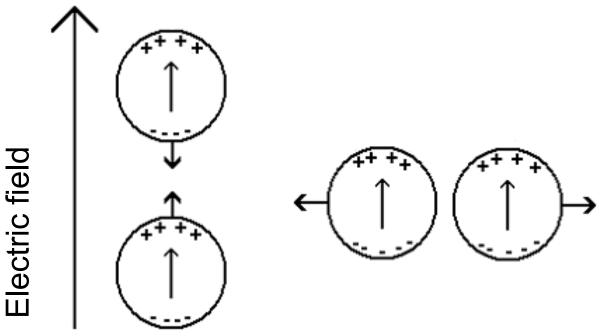


Figure 1. Interparticle forces between polarized particles.

The interparticle force, $F_{el}$, between two polarized particles, $P_i$ and $P_j$, separated by a distance *a* between their centers of mass may then be calculated as follows:

$$F_{el} = \frac{6 \cdot P_i \cdot P_j}{4 \cdot \pi \cdot \varepsilon_0 \cdot a^4} \qquad (2)$$

$\varepsilon_0$ denotes the permittivity of free space. Clearly, these interparticle forces are strongly dependent on the separation distance and may be attractive or repulsive (*cf.* Fig. 1). The maximum magnitude of these forces, as they are created in the experiments described in this paper, ranges from $10^{-10}$ to $10^{-8}$ N per particle for Geldart A particles. This is comparable to the typical fluidization forces, such as drag and buoyant weight. For larger particles, *i.e.* Geldart B, the ratio between electrical interparticle forces and fluidization forces becomes much smaller. This is illustrated by the ratio between electrical forces and fluidization forces (drag, gravity) as a function of particle diameter. The electrical interparticle force, as seen from Eqns. 1 and 2, scales roughly with the square of the particle diameter. Note that the center-to-center particle separation distance, *a*, is closely related to $d_p$ (Eqn. 3). The fluidization forces, on the other hand, scale with the particle diameter to the third power (Eqn. 4).

$$F_{el} \propto \frac{P_i \cdot P_j}{a^4} \propto \frac{d_p^3 \cdot d_p^3}{a^4} \approx d_p^2 \qquad (3)$$

$$F_{fluidization} \propto d_p^3 \qquad (4)$$

This interpretation of electrical interparticle forces considers closely spaced particles under the constant influence of electric fields. While particle separation distances in bubbling fluidized beds are generally very small, the electric fields applied in the current design are oscillating – typically sine waves with a mean of 0 V/m and a frequency ranging from 0.5 to 200 Hz. The electrical interparticle forces are thus periodic. Every sine period the interparticle forces relax twice, but their sign never changes: positive charges attract negative charges as strongly as vice versa.

The oscillation of the AC fields has the advantage over constant (DC) electric fields that agglomeration of particles is unlikely. Yet, the net effect of the electric fields is a decrease in the number and size of gas bubbles in the fluidized bed. The presence of the electric interparticle forces, acting in x-, y-, and z-directions, can prevent or reduce the instability that may lead to bubble formation (*cf.* Rietema and Piepers, 1990, Ye *et al.*, 2004).

## Experimental

In the description given above a reasonable case has been made for how interparticle forces resulting from non-homogeneous, oscillating electric fields can lead to a decrease in the bubble formation in a fluidized bed while maintaining the fluid-like behavior of the system. This has been demonstrated experimentally in both circular cross-section and so-called 2-dimensional columns. Measurements were conducted in two Plexiglas columns (2-D cross-section: 200 $\times$ 15 mm$^2$, 3-D inner diameter: 80mm) by pressure fluctuation analysis and/or video analysis. The electrodes consist of a regular wire pattern strung through the column, passing through the bed, as shown schematically in Fig. 2. The sintered porous distributor plate is grounded, and therefore serves as one of the electrodes. The wire electrodes are alternately, both horizontally and vertically, grounded or connected to a Trek 20/20c high-voltage power amplifier. The nichrome wires have a diameter of 250 µm. The holes on the outer walls through which the wires pass were sealed. An influence of these wires on bubble behavior is not measurable with the employed techniques. The experiments were conducted in a temperature-controlled cabinet, and the settled bed height was typically 300 mm. Glass beads of Geldart group A ($d_p$ = 77 µm, $u_{mf}$ = 1.0 cm/s, $u_0$ = 3 $u_{mf}$) and Geldart group B ($d_p$ = 700 µm, $u_{mf}$ = 33 cm/s, $u_0$ = 1.5 $u_{mf}$) were studied.

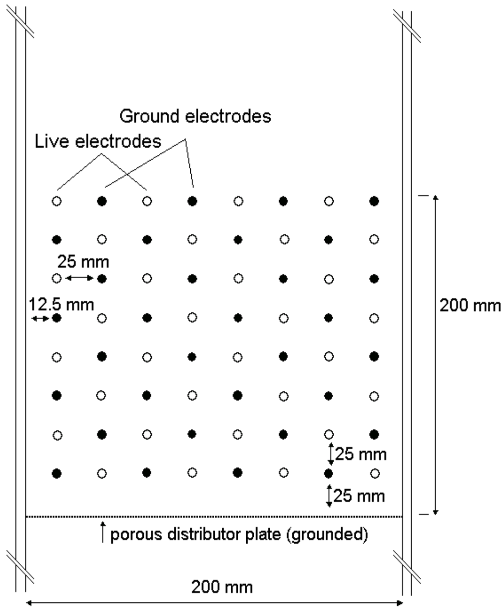

Figure 2. Schematic of the 2-D column design.

## Results

Results are shown as a fractional decrease in the bubble diameter. This change in bubble diameter is based on analysis of pressure fluctuation time series before, during, and after the application of the electric field. The quantitative relation between the visually observed bubble diameter and the bubble diameter derived from pressure fluctuations has been shown by Kleijn van Willigen *et al.* (2003).

Figure 3 shows the results of applying electric fields to reduce bubble size for both Geldart A and B material. During fluidization with and without electric field, it was observed both visually and in pressure fluctuation data that the behavior of the emulsion phase is very similar and that fluidity (particle movement) is conserved. However, whereas the state of the emulsion phase does not change, the bubble behavior changes considerably. The fine powder (Fig. 3a) shows a decrease in bubble diameter of about 25%, while bubbles in the larger beads (Fig. 3b) decrease by as much as 85%! Experiments with Geldart A material carried out in the 3-D column show almost identical results, albeit that at a field strength greater than 3.5 kV/cm it was seen that the decrease in bubble size is somewhat less than at lower field strength.

From Figure 3 it is also clear that an optimal regime of electric fields exists: the applied fields should range from 400 to 2000 V/cm for Geldart A material, although a positive effect is observed even at low field strengths. The frequencies are optimal between 5 and 20 Hz. For Geldart B material, the upper limit for the field strength is not found, and the frequency range is a bit higher, 20 - 70 Hz. The limits seen on the frequency range can be understood in a qualitative manner: at low frequencies, the bed characteristics change to a DC-like behavior, eventually resulting in compaction and agglomeration. This leads to a (partially) frozen bed. At high frequencies, there is not enough time for the macroscopic charge separation to develop – confer the relaxation times calculated by Colver (2000). It is not yet understood why the experimental frequency range for the larger particles is higher than for the smaller particles, and this will be studied in more detail. At the lower voltage limit, the electric interparticle forces are too small to play a role in the bubble behavior. At too high field strengths, it is likely that the particles stick together too strongly, resulting in more cohesive fluidization with its associated gas voids.

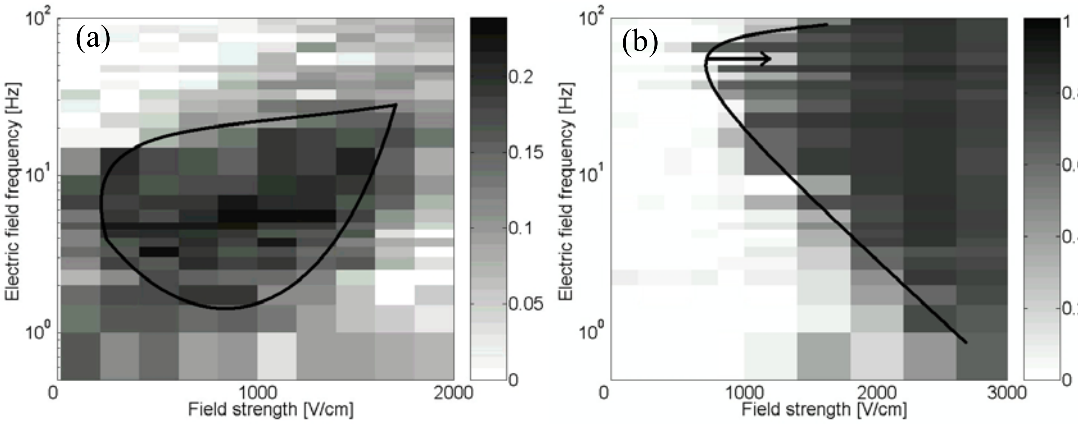


Figure 3. Bubble size decrease at 190 mm (63% of bed height). The grayscale shows the fractional change in bubble diameter as a function of frequency and field strength. Bed material: (a) 77 μm glass beads, (b) 770 μm glass beads. Black lines denote the region of optimal electric field strength and frequency.

To determine the change in bubble size distribution and total bubble volume, bubbles were injected in a 2-D fluidized bed of Geldart B particles slightly above $U_{mf}$. Video analysis demonstrated that in the electrified region the bubbles are broken up, resulting in an increase in average number of bubbles, and that the bubble diameter and the total bubble volume decrease significantly. In the out-of-field top region, the number of bubbles is not changed when compared to the no-field situation, but the bubble diameter, and thus the total bubble volume, is still much lower with the electric field on. A small horizontal elongation of the bubbles is noticed. With this confirmation of a decrease in total volume, and the observation in the bubbling experiments described above that the bed volume does not change, we speculate that the interstitial gas flow is increased. Further experiments will be carried out to confirm this.

If the electric field enhanced fluidized bed is to find industrial application, the energy consumption will be an important criterion. The electric energy consumption during typical experiments amounts to approximately 50 W/m$^3$ of fluidized bed – comparable to a single light bulb. This low energy consumption compares very favorably with the parallel field of magnetically assisted fluidization, where the energy requirements are typically three orders of magnitude greater (Geuzens, 1985).

## Conclusions

In this paper, results were reported on the use of electric fields as a low energy method to control bubble sizes in bubbling fluidized beds. In order to maintain smooth fluidization, co-flow AC-fields with a relatively low frequency are optimal. A proper balance between conductivity of the system (through RH control) and the electric dipole constant of the particle yields an optimal polarization of the particle. The periodic interparticle forces thus created between particles ensures this smooth optimization while yielding an optimal reduction in bubble size.

Analysis of pressure fluctuation time series demonstrates that the bubble diameter decreases by about 25% in the case of Geldart A material, and up to 85% for Geldart B particles. Video recordings demonstrate that the average number of bubbles increases, which means that, in combination with the unchanged expanded bed height, the smaller volume of gas in bubbles results in a larger amount of interstitial gas.

The large decreases in bubble sizes while fluidizing either Geldart A or B material are accomplished with electric fields with an energy consumption of approximately $50 W/m^3$. For Geldart A material, the method has been successfully applied to both 2-D and 3-D columns; for Geldart B material, results in 3-D columns will be reported on shortly.

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