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Monitoring Electrostatic Charges in Fluidized Beds

Xiaotao T. Bi* Aihua Chen†
John R. Grace‡

*University of British Columbia, xbi@chml.ubc.ca
†University of British Columbia, achen@chml.ubc.ca
‡University of British Columbia, jgrace@chml.ubc.ca

MONITORING ELECTROSTATIC CHARGES IN FLUIDIZED BEDS

Hsiaotao T. Bi, Aihua Chen and John R. Grace
Fluidization Research Centre
Department of Chemical and Biological Engineering
University of British Columbia, Vancouver, BC, V6T 1Z4

ABSTRACT

A novel analysis procedure for dynamic collision probes has been developed to monitor the charge density of particles in gas-solids fluidized beds based on the mean and normalized standard deviation of current signals. The contribution from hydrodynamic changes is decoupled from the changes in specific particle charge density based on the principles that the average current is related to charge transfer and/or triboelectrification due to the contact between the probe and particles, whereas the normalized standard deviation of current signals is mainly related to the hydrodynamic changes of the fluidized bed. The correlation between hydrodynamic changes and current signal fluctuations is confirmed from experimental data of both current fluctuations and pressure fluctuations measured from a 0.1 m diameter fluidized bed using polymer particles. Utilizing these findings, dynamic collision probes can potentially be applied in industrial fluidized bed reactors to monitor electrostatic charge build-up.

INTRODUCTION

In commercial gas-solid fluidized beds such as gas-phase polymerization reactors, powder coating and granulation reactors, electrostatic charges can cause agglomeration, nuisance discharges and even explosions. Net particle charge densities in gas-solids fluidized beds and transport lines have been directly measured by withdrawing a small amount of charged particles from the fluidized bed into Faraday cages (e.g. Tardos and Pfeffer, 1980; Fujino et al., 1985; Wolny and Kazmeirczak, 1989; Jiang et al., 1997). This method provides information on average net charges accumulated on particles, but does not clarify whether the charges on particles are bipolar or unipolar, nor does it help understand the mechanism of charge generation and dissipation. The Faraday cup method also suffers from the possibility of sample contamination by additional charging or discharging during sample collection, especially when collecting samples from commercial fluidized bed reactors.

Capacitance probes (e.g. Guardiola et al., 1996) have been used to measure the capacitance between a suspended probe and the metallic distributor as a function of time. The measured voltage is related to the particle charge density in the fluidized bed, as well as to other parameters, reflecting the average behaviour of electrostatic charges in the entire fluidized bed, rather than local information on electrification associated with bubble motion.

Collision-type ball probes measure average charge transfer in gas-solids bubbling fluidized beds (e.g. Ciborowski and Woldarski, 1962) and transport lines (e.g. Zhu and Soo, 1992; Gajewski, 1999). However, the contribution from particle and bubble movement to the charge induction on exposed collision probes has not been considered in the signal analysis. Shielded probes have also been used to measure charge transfer associated with single bubble motion in gas-solids fluidized beds (Boland and Geldart, 1971/1972; Park et al., 2002) and single particles in transport lines (Woodhead, 1992; Armour-Chelu et al., 1998). Signals corresponding to the passage of a single bubble follow the same trend as pressure signals, and have been interpreted by Boland and Geldart (1971/1972) as being associated with polarization of charge distribution around the bubble surface, with a positively charged bubble nose region and a negatively charged wake. Park et al. (2002) showed that the signals corresponding to the passage of a single bubble could instead be explained by induction caused by unipolar particles in the vicinity of a rising bubble.

Although average voltage or current signals measured by collision-type electrostatic probes have commonly been used to monitor electrostatic charge density of particles in gas-solids transport lines and fluidized beds, it is difficult to interpret the recorded voltage or current signals. As predicted by a mechanistic charge induction and transfer model (Park et al., 2002; Chen et al., 2003), the signals received by a collision probe consist of two contributions, one from direct transfer of charges from bed particles to the probe during the collision, and the other due to induction caused by the change of electric field around the probe when charged particles surrounding rising bubbles pass the probe. The current and voltage received from a ball probe therefore not only reflect the particle charge density in the bed, but are also a function of local flow dynamic properties such as bubble size and rise velocity. Thus, the variation of the average current or voltage from a ball probe does not necessarily indicate a change of the bed charge density because it can be caused by changes in local hydrodynamics. The commonly used single collision probe method thus cannot differentiate signal changes caused by charge density changes from those due to hydrodynamic changes in a two-phase flow system. One solution is to couple hydrodynamic measurements with electrostatics measurements, e.g. by combining a local voidage probe with an electrostatic probe. A single probe would greatly simplify the measurement. In this work, we propose a novel dynamic collision probe capable of monitoring charge density as well as hydrodynamic changes based on both time-average and transient dynamic current/voltage signals.

MODELING THE TRANSIENT BEHAVIOUR OF A DYNAMIC COLLISION PROBE

The same model developed earlier by Park et al. (2002) and Chen et al. (2003) for single bubbles is used for the dynamic simulation of the dynamic collision probe. To simplify the simulation, the following assumptions are made with respect to the distribution of the specific particle charge density surrounding a bubble:

a. The total charge received by the probe consists of two components: induction from bubble passage and transfer and separation from tribo-electrification during probe-particle collision.
b. Each bubble is assumed to have a spherical shape, with its radius (R_B) remaining constant while the bubble rises at a uniform bubble velocity, U_B, after

injection.

c. Particle hold-up inside the bubble is negligible, so that there are no charges inside the bubble. The specific charge is distributed uniformly outside the bubble.

Charge induction: As in Park et al. (2002), consider a bubble approaching a grounded ball probe (with potential U_P=0) from below with both the bubble wake and drift being ignored. The bubble is assumed to rise at a constant velocity, U_B. With the centre of the probe on the axis of the rising bubble, the total induced charge can be written (Chen et al., 2003) as

$$Q_{induced} = \frac{-q_{m0}(1-\varepsilon)\rho_s R_P^2}{4\pi\Pi_r}\int_0^{R_B}\int_0^{2\pi}\int_{-\pi/2}^{\pi/2}\int_0^{2\pi}\int_{-\beta_0}^{\beta_0} r_B'^2\cos\theta\cos\beta\left(\frac{1}{r_1^2}\frac{\partial r_1}{\partial r}+\frac{c}{r_2^2}\frac{\partial r_2}{\partial r}-\frac{1}{r_2 d}\right)d\beta d\gamma d\theta d\phi dr_B' \quad (1)$$

where q_{m0} is the specific particle charge density, ε the bed voidage, ρ_s the particle density, R_p the probe radius, Π_r the permitivity of particles and r_B' the radial distance from the centre of the bubble. The induced current can then be calculated from

$$I_{induced} = -\frac{dQ_{induced}}{dt} \quad (2)$$

Charge transfer and separation: In addition to charge induction, direct charge transfer takes place when charged particles collide with the probe. Zhu and Soo (1992) estimated the electric current through a ball probe due to collisions between the probe and particles in a pneumatic transport line as

$$I_{transferred} = K(1-\varepsilon)\rho_s V_s^{8/5}\, e^{-k_c\left(\rho_s(1-\varepsilon)/V_s\right)} \quad (3)$$

where V_s is the particle velocity. K is a dimensional constant related to the ball probe characteristics, particle surface characteristics, specific charge of particles and particle properties. K_c is related to local voidage and particle velocity. It was shown (Park et al., 2002; Chen et al., 2003) that

$$I_{transferred} = -\frac{dQ_{transferred}}{dt} = K' q_m h_{ePs}\rho_s(1-\varepsilon)\left[\frac{U_B R_B^2}{(-L+U_B t)^2}\right]^{8/5}/\Pi_r \quad (4)$$

where h_{ePs} is the effective conductivity of the dense phase, U_B the bubble rise velocity, R_B the radius of the bubble, L the original separation distance between the bubble and probe centres, t the time and K' a constant. While the bubble encloses the probe, the transfer current $I_{transferred}$=0.

Vertical chain of bubbles: In freely bubbling fluidized beds, randomly moving bubbles can be approximated by vertical chains of bubbles. In the present simulation, only a single chain of bubbles rising in close alignment with the collision probe is considered (Chen and Bi, 2003). The following assumptions are made:

a. Bubbles are of spherical shape, with an equivalent diameter of $D_B = 2R_B$. Bubble wakes and drift are not considered in the calculation;
b. Bubbles in large-scale fluidized beds are divided into chains, with bubbles aligned vertically in each chain and surface-to-surface separation distances of L_B;
c. The dense phase expansion is negligible.

SIMULATION RESULTS FOR SINGLE BUBBLE AND BUBBLE CHAINS

The average current, which represents the average charge transferred per unit time to the probe from particles contacting with the probe, is shown in **Figure 1** as a function of bubble size and frequency. The average total current is seen to increase almost linearly with increasing bubble frequency and bubble size.

The standard deviation of the total current, which is mostly caused by induction, normalized by the average current, which is related to the charges transferred by collision, is shown in **Figure 2** as a function of bubble size and frequency. It can be seen that the standard deviation of total current/average current decreases with increasing bubble frequency, while there is less influence of bubble size. From Equations (1) and (2) for the induced current and Equation (4) for transferred current, normalization of the induced current by the transferred current leads to cancellation of the specific charge density (q_m). The resulting normalized standard deviation of the current fluctuation signals then mainly reflects local hydrodynamics. Although both the average current and its standard deviation increase monotonically with increasing specific charge density, the normalized standard deviation remains unchanged if the local hydrodynamics remain the same. On the other hand, if both the average current and the normalized standard deviation vary, this does not necessarily indicate a change of specific charge density because the local hydrodynamics are also varying. The normalized standard deviation of transient current fluctuation signals at a sampling frequency of at least a few Hz, in combination with the average current, commonly utilized by industry for long-term electrostatics monitoring, can thus be used to monitor specific charge densities in fluid-particle heterogeneous flow systems, with the average current reflecting charge transfer, whereas the normalized standard deviation provides information on changes in local hydrodynamic behaviour around the probe.

DYNAMIC SIGNALS FROM BALL PROBE IN A FREELY BUBBLING FLUIDIZED BED OF POLYETHYLENE PARTICLES

Experiments were carried out in a cylindrical column, 89 mm inner diameter and 1.2 m tall, constructed of Plexiglas, as shown in **Figure 3**. The column is equipped with an external cyclone to collect entrained particles and return them to the bottom of the bed. The static bed height was always 0.35 m. The particles were porous polyethylene resin beads with a mean diameter of 0.378 mm and a particle density of 715 kg/m^3.

Both the relative humidity and the temperature of the fluidizing air were monitored during the experiments. An in-line air heater and a temperature controller maintained the temperature of the fluidizing gas at desired levels, while the relative humidity of the fluidizing air was regulated by a packed bed water-spray column and a packed silica gel column in parallel. The bed was operated at atmospheric pressure and room temperature in the bubbling bed regime, with ($U-U_{mf}$) ranging from 0 to 0.4 m/s.

A collision ball probe, also known as a contacting probe, was inserted into the fluidized bed to make direct electrostatic charge measurements. A glass sleeve maintained a high resistance to the ground, while a brass tube enclosing the glass tube reduced the background current by eliminating disturbances due to build-up of charges on the column walls. The diameter of the stainless steel ball at the tip of the probe was 3.2 mm. Alumel wire was securely fastened into a small hole drilled into the stainless steel ball. The electrostatic ball probe was connected directly to a Keithley Model 616 Digital Electrometer using a coaxial connector to minimize distortion of the electrostatic potential field. The ball probe was installed 0.3 m above the distributor, with the ball intruding slightly beyond the column inner wall. A differential pressure transducer, Omega PX-164, was installed across an interval of the column to measure local pressure fluctuations. Signals from both the electrometer and pressure transducer were logged into a computer using an A/D converter and a Visual Basic data acquisition program at a sampling frequency of 50 Hz for 100 s intervals. In the bubble injection test, a pressurized cylinder and solenoid valve were used to inject bubbles and an optical fibre probe (PC-4) was used to monitor bubbles passing the ball probe. The optical probe was installed at the same height and lateral position as the ball probe, with its tip a few millimetres from the ball probe.

The direct relationship between bubble motion (i.e. local hydrodynamics) and dynamic signals from the ball probe was examined by comparing ball probe signals and differential pressure fluctuations. Local differential pressure fluctuations measured over a vertical interval in fluidized beds are mainly caused by passing bubbles, with most pressure waves from outside the interval filtered out, and hence are indicators of local bubble behaviour. As shown in **Figures 4**(a) and (b), the power spectra of signals, obtained by Fast Fourier Transformation (FFT) analysis from the ball probe and pressure transducer are very similar, confirming that fluctuations of the ball probe signals are closely correlated with local hydrodynamics induced by the bubble passage.

The correlation between local hydrodynamics and the current fluctuations from the ball probe was further examined by varying the superficial gas velocity. In freely bubbling fluidized beds, the average bubble size and rise velocity increase as the superficial gas velocity increases. As a result, the amplitude of pressure fluctuations represented by the standard deviation of pressure fluctuations, increases with increasing superficial gas velocity. Similarly, the amplitude of ball probe signals can be characterized by the standard deviation. As shown in **Figure 5**, standard deviations of both pressure fluctuations and ball probe signals increase with increasing superficial gas velocity, indicating an increase in induced charge due to larger and faster bubbles, as well as changes in specific particle charge density.

Our preliminary experimental results confirm that local dynamic signals from a collision ball probe mainly correspond to local two-phase hydrodynamics. Their normalized standard deviation can be used to monitor local flow changes in two-phase heterogeneous flow systems such as bubbling fluidized bed reactors.

CONCLUSIONS

A single collision probe monitoring time-average voltage or current in two-phase heterogeneous flow systems fails to differentiate local hydrodynamic changes from those directly caused by the change of charge densities on bed particles, because the charge transferred from particles to the ball probe is affected by both the particle charge density and the collision speed and frequency between particles and the probe. These collisions are strongly affected by local two-phase flow properties such as bubble size, bubble rise velocity and solids concentration.

A mechanistic model based on charge induction and transfer between moving particles and a stationary ball probe reveals that a dynamic collision probe with a

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sampling frequency of 10 Hz or less can capture dynamic changes induced by local electric field variations corresponding to changes in two-phase flow properties such as bubble motion and void fraction. Standard deviations of fluctuating ball probe signals thus reflect changes in local hydrodynamics, as well as in particle charge density. When normalized by the average values to cancel out the particle density term, the dimensionless standard deviation is an excellent indicator of local hydrodynamics. Local particle charge density and hydrodynamic behaviour can thus be monitored simultaneously by a single dynamic ball probe based on the time-average signals (current or voltage) and the normalized standard deviation.

Preliminary experimental data from a miniature ball probe in a fluidized bed of polyethylene resin particles confirm the direct relationship between dynamic current signals from a ball probe and dynamic pressure fluctuation signals from a differential pressure transducer, both directly reflecting local two-phase flow behaviour.

NOTATION

- d = distance between centre of probe and image charge, m
- d_s =particle diameter, m
- f_B =frequency of bubble passing through a surface, Hz
- r_1, r_2 = distance between a point on the probe and image charges, m
- RH =relative humidity, %
- U =superficial gas velocity, m/s
- U_{mf} =minimum fluidization velocity, m/s
- z =vertical distance above the distributor, m
- z_{probe} =vertical distance of probe above distributor, m

Greek letters

- $\beta,\phi,\gamma,\lambda,\theta$ =angles, degrees

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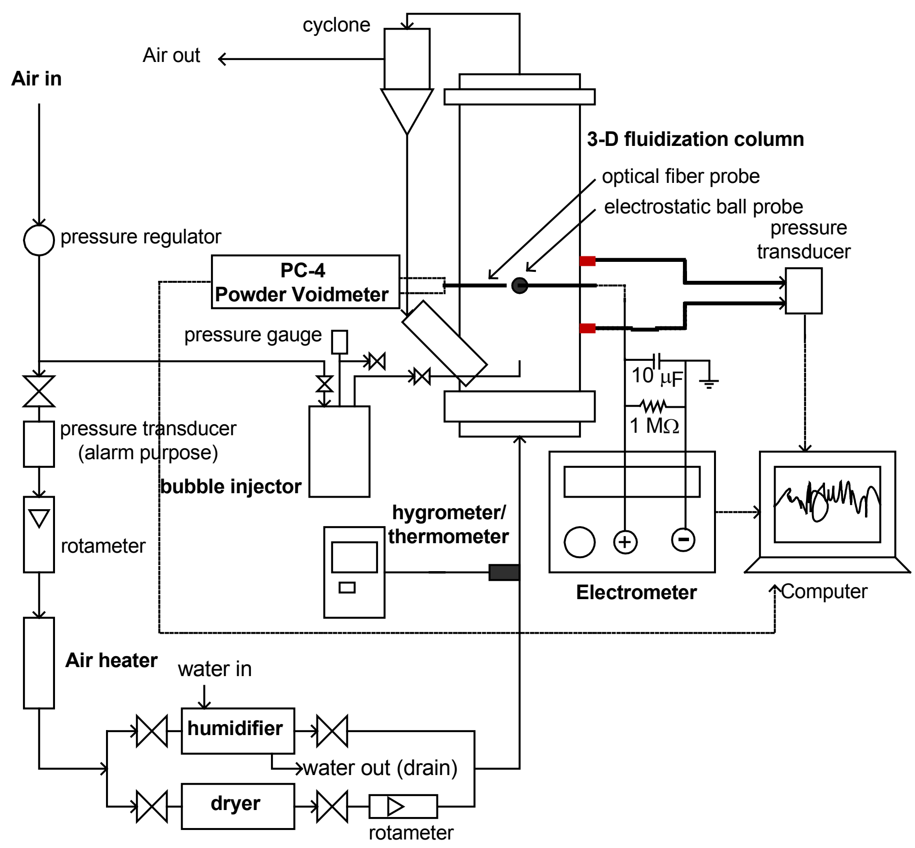

Figure 3. Schematic of 89 mm diameter Plexiglas column and supporting equipment.

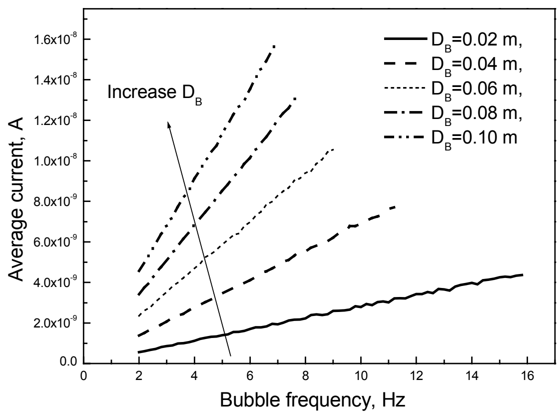

Figure 1. Simulated variation of average current with bubble size and frequency (q_{m0}=-1 C/kg, K'=-1.95x10^2 $\Omega m^{17/5}s^{3/5}$, ρ_S=715 kg/m^3 , d_s=378 μm, R_P=1.25 mm, z_{probe} =10 cm, Π_r=3, U=1.1U_{mf}, U_{mf} =0.041m/s)

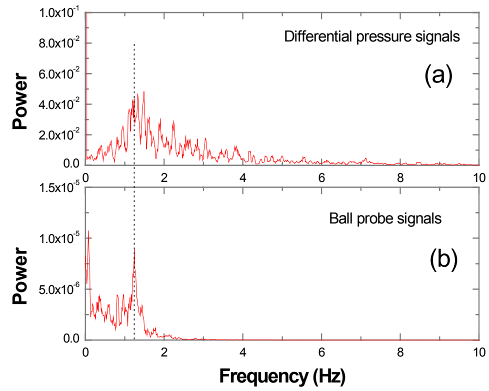

Figure 4. Power spectrum of (a) differential pressure signals, and (b) electric current signals from ball probe. U=0.24 m/s, RH=33%, T=22^{o}C.

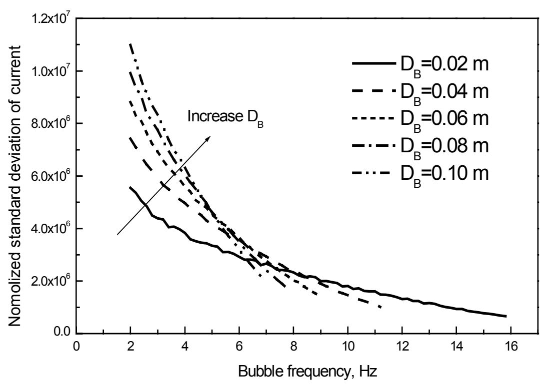

Figure 2. Simulated standard deviation of total current normalized by the average current as a function of bubble size and frequency (q_{m0}=-1 C/kg, K'=-1.95x10^2 $\Omega m^{17/5}s^{3/5}$, ρ_S=715 kg/m^3, d_s=378 μm, R_P=1.25 mm, z_{probe} =10 cm, Π_r=3, U=1.1U_{mf}, U_{mf} =0.041m/s)

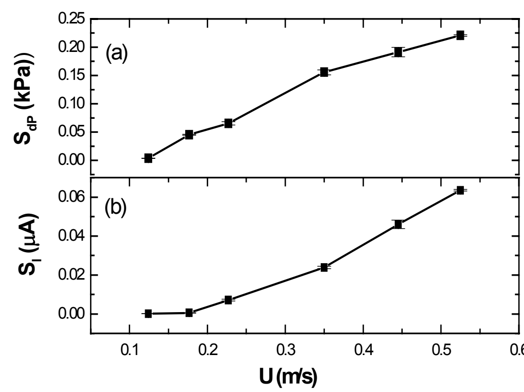

Figure 5. Standard deviations of (a) differential pressure fluctuations and (b) current signals from ball probe as a function of superficial gas velocity. RH=33%, T=22^{o}C.