ELECTROSTATIC CHARGING IN GAS-SOLID FLUIDIZED BEDS

by

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B. A. Sc., University of British Columbia, 1998

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Department of Chemical and Biological Engineering)

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
August 2000

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Abstract

Electrostatic charges in fluidized beds, generated through various mechanisms such as triboelectrification, ion collection, thermionic emission, and frictional charging, can cause particle agglomeration and hazardous electrical discharges. In this study, electrostatic charging in gas-solid fluidized beds was investigated by means of a simplified mechanistic model and bubble injection and free bubbling experiments in two-dimensional and three-dimensional fluidized beds.

An electrostatic ball probe measured static charges in fluidized beds, while an optical fiber probe was used to determine the simultaneous movement of the bubbles. Preliminary experiments indicated that a negatively charged object results in a negative voltage peak followed by a positive voltage peak. The opposite pattern occurred for a positively charged object. The current calculated from the voltage output was integrated to estimate the charge induced and transferred. It was shown that the voltage signal can be considered to consist of two components: induced voltage and that due to the direct charge transfer between charged particles and the probe. A simplified model was also developed by applying the method of images to distinguish induced and transferred charges. Spherical bubbles surrounded by a monolayer of charged particles and a medium of dielectric constant 1 were assumed in the models.

Bubble injection experiments in a 2-D bed showed that both 321 μm glass beads and 378 μm polyethylene particles were charged positively, while 318 μm polyethylene particles were charged negatively. As bubble size increased the charge induced and transferred increased accordingly. The model gave reasonable predictions of the charge output.

Increasing the relative humidity of the fluidizing air between 60 % and 80 % reduced the electrostatic charge accumulation by increasing the surface conductivity, enhancing the rate of charge dissipation. Adding group C fines and Larostat 519 reduced or eliminated particle buildup on the inner wall of the fluidization column, but the former
probably also affected other interparticle forces such as Van der Waals forces and altered
the fluidization behaviour. 1 wt % Larostat 519 clearly reduced electrostatic charge
accumulation during free bubbling in a 3-D bed of 318 μm polyethylene particles; within
1.5 hr charge accumulation decreased to an insignificant level.
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Acknowledgments

I would like to express my sincere thanks to Dr. Xiaotao Bi and Dr. John Grace for the encouragement, excellent guidance, and support they provided during the course of this investigation.

It is a pleasure to acknowledge many people in the Department of Chemical and Biological Engineering who contributed to this project. Specifically, I would like to thank Dr. Jim Lim and Dr. Dong-Hyun Lee for their assistance. I would also like to thank the people in the workshop for their help in building and maintaining the equipment, and the store and secretarial staff for their assistance. Finally, I would like to acknowledge my fellow graduate students and friends who listened to me and gave me encouragement during the difficult times.

Most of all, I would like to thank my family for their patience, support and encouragement. I would like to dedicate this thesis to my parents, Jin Park and Hee-Sup Yoon, who believed in me and gave me the opportunity to be who I really wanted to be.
Chapter 1
Introduction

The fluidized bed is a unique device for maximizing contact of solids with gases and/or liquids. Drying processes, crystallization processes, and chemical reactions involving particles can all perform well in fluidized beds.

One of the main problems in the gas-solid fluidized bed is particle agglomeration. There are a number of factors involved in the formation of particle agglomerates, with electrostatic charges one key factor (Jiang et al., 1994). Particle agglomeration tends to be higher when using dielectric materials, e.g. polyethylene and polystyrene particles, due to the generation of electrostatic charges (Katz and Sears, 1969; Wolny and Opalinski, 1983). Electrostatic forces induced by the charges carried by particles change the hydrodynamics of gas-solid fluidized beds (Fan and Zhu, 1998). In addition, unintentional accumulation of electrostatic charges by dielectric materials in a reactor can cause hazardous electrical discharges leading to sparks, fire, and even explosions (Astbury and Harper, 1999). Previous research shows that even the small electrostatic spark experienced after walking across a nylon carpet in a dry environment contains more than sufficient energy to cause electrical breakdown in a gas and to ignite a flammable vapor (Cross, 1987). Table 1.1 lists the charge generated during various industrial processes involving powders.

Table 1.1. Charge generation for medium-resistivity powders $R_e \equiv 10^{12} \Omega m$ (Cross, 1987)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Charge-to-mass ratio [(\mu C \ kg^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieving</td>
<td>$10^2$ to $10^5$</td>
</tr>
<tr>
<td>Pouring</td>
<td>$10^1$ to $10^3$</td>
</tr>
<tr>
<td>Grinding</td>
<td>$1$ to $10^1$</td>
</tr>
<tr>
<td>Micronising</td>
<td>$10^2$ to $10^4$</td>
</tr>
</tbody>
</table>
The accumulated electrostatic charges on powder particles or plastic films inside large commercial fluidized bed reactors can easily interfere with their performance. In spite of these negative effects of electrostatic charging, the mechanism of generation of charges and methods of alleviating electrostatic effects are still poorly understood.

1.1 Charge Generation

The phenomena of particle electrical charge generation are complex. In gas-solid fluidized beds, triboelectrification, ion collection, thermionic emission, and frictional charging are known to generate electrostatic charges. Details of these charging mechanisms and charge transfer modes are discussed in this section.

1.1.1 Triboelectrification

The word *tribo* meaning "to rub," is from Greek (Fan and Zhu, 1998). *Triboelectrification* involves the generation of electrical charges due to rubbing between materials. In fact, surface contact is sufficient to generate triboelectricity, although rubbing processes generally increase charge transfer by increasing contact area (Fan and Zhu, 1998).

The *Fermi energy* is the highest filled energy level at absolute zero temperature (Cross, 1987). When two dissimilar materials are in contact, the difference in their initial Fermi energy levels results in exchange of electron or ion between two surfaces in order to achieve thermodynamic equilibrium by equalizing their Fermi levels (Harper, 1967). Some conducting materials like to gain electrons and become negative, whereas others prefer to give up electrons and become positive. Charge transfer between conducting surfaces occurs by electron redistribution, leading to a leveling of Fermi levels. On the other hand, insulating materials, which have very restricted electron mobility, become charged by redistributing ions rather than electrons across metal-insulator or insulator-insulator interfaces (Boland and Geldart, 1971). Therefore, materials in contact become electrostatically charged when they are separated, with their polarities dependent on the
net change of the charges on their surfaces. A number of authors have reported different "triboelectric series" listing materials in order of tendency to collect different charges. The larger the difference in position on the series, the more charges are transferred from one substance to another. Tables 1.2 and 1.3 reproduce two examples of triboelectric series.

Table 1.2. Triboelectricity series (Cutnell and Johnson, 1992)

<table>
<thead>
<tr>
<th>Positive polarity +</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asbestos</td>
</tr>
<tr>
<td>Rabbit's fur</td>
</tr>
<tr>
<td>Glass</td>
</tr>
<tr>
<td>Mica</td>
</tr>
<tr>
<td>Nylon</td>
</tr>
<tr>
<td>Wool</td>
</tr>
<tr>
<td>Cat's fur</td>
</tr>
<tr>
<td>Silk</td>
</tr>
<tr>
<td>Paper</td>
</tr>
<tr>
<td>Cotton</td>
</tr>
<tr>
<td>Wood</td>
</tr>
<tr>
<td>Lucite</td>
</tr>
<tr>
<td>Sealing wax</td>
</tr>
<tr>
<td>Amber</td>
</tr>
<tr>
<td>Polystyrene</td>
</tr>
<tr>
<td>Polyethylene</td>
</tr>
<tr>
<td>Rubber balloon</td>
</tr>
<tr>
<td>Sulphur</td>
</tr>
<tr>
<td>Celluloid</td>
</tr>
<tr>
<td>Hard rubber</td>
</tr>
<tr>
<td>Vinylite</td>
</tr>
<tr>
<td>Saran wrap</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Negative polarity -</th>
</tr>
</thead>
</table>

This series tells us that when you rub together a neutral polyethylene rod and a piece of neutral saran wrap, for example, the saran wrap becomes negatively charged while the polyethylene rod becomes positively charged. On the other hand, if one rubs a neutral polyethylene rod with a neutral piece of wool, the former ends up negative and the latter positive.
Table 1.3. Triboelectric series (Cross, 1987)

<table>
<thead>
<tr>
<th>Material</th>
<th>Polymer type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>Cellulose</td>
<td></td>
</tr>
<tr>
<td>Nylon</td>
<td>Cellulose</td>
<td></td>
</tr>
<tr>
<td>Viscose</td>
<td>Polymethyl methacrylate</td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>Copolyester of ethylene glycol and terephthalic acid</td>
<td></td>
</tr>
<tr>
<td>Silk</td>
<td>Polyacrylonitrile</td>
<td></td>
</tr>
<tr>
<td>Acetate rayon</td>
<td>Polyacrylonitrile/vinyl chloride</td>
<td></td>
</tr>
<tr>
<td>Lucite or Perspex</td>
<td>Polyvinylidene chloride/vinyl chloride</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl alcohol</td>
<td>Polymethyl methacrylate</td>
<td></td>
</tr>
<tr>
<td>Dacro</td>
<td>Acetate rayon</td>
<td></td>
</tr>
<tr>
<td>Orlon</td>
<td>Acetate rayon</td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td>Acetate rayon</td>
<td></td>
</tr>
<tr>
<td>Dynel</td>
<td>Acetate rayon</td>
<td></td>
</tr>
<tr>
<td>Velon</td>
<td>Acetate rayon</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>Acetate rayon</td>
<td></td>
</tr>
<tr>
<td>Teflon</td>
<td>Acetate rayon</td>
<td></td>
</tr>
<tr>
<td>Polyox</td>
<td>Polyethylene oxide</td>
<td>Union Carbide Chemirad</td>
</tr>
<tr>
<td>Polyethylene amine</td>
<td>Polynvinyl acetate</td>
<td>Colton Chemical</td>
</tr>
<tr>
<td>Gelatin</td>
<td>Polyvinyl acetate</td>
<td>Du Pont</td>
</tr>
<tr>
<td>Vinac</td>
<td>Polyvinyl acetate</td>
<td>Du Pont</td>
</tr>
<tr>
<td>Lucite 44</td>
<td>Polybutyl methacrylate</td>
<td>Rohm and Haas</td>
</tr>
<tr>
<td>Lucite 42</td>
<td>Polyvinyl acetate</td>
<td>Du Pont</td>
</tr>
<tr>
<td>Acryloid A101</td>
<td>Polyvinyl acetate</td>
<td>Cyanamid Eastman</td>
</tr>
<tr>
<td>Zelec Dx</td>
<td>Polyvinyl acetate</td>
<td>Rohm and Haas</td>
</tr>
<tr>
<td>Polyacrylamide</td>
<td>Polyvinyl acetate</td>
<td>BF Goodrich</td>
</tr>
<tr>
<td>Cellulose</td>
<td>Polyvinyl acetate</td>
<td></td>
</tr>
<tr>
<td>Acysol</td>
<td>Polyvinyl acetate</td>
<td></td>
</tr>
<tr>
<td>Carbopol</td>
<td>Polyvinyl acetate</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>Polyvinyl acetate</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl butyral</td>
<td>Polyvinyl acetate</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>Polyvinyl acetate</td>
<td></td>
</tr>
<tr>
<td>Lucite 2041</td>
<td>Methyl methacrylate</td>
<td>Du Pont</td>
</tr>
<tr>
<td>Dapon</td>
<td>Diallyl hthalate</td>
<td>GE</td>
</tr>
<tr>
<td>Lexan 105</td>
<td>Poly-bisphenol-A-carbonate</td>
<td>Monsanto Goodrich</td>
</tr>
<tr>
<td>Formvar</td>
<td>Polyvinyl formal</td>
<td>Du Pont</td>
</tr>
<tr>
<td>Estane</td>
<td>Polyurethane</td>
<td>Durez</td>
</tr>
<tr>
<td>Du Pont 49000</td>
<td>Polyester</td>
<td>Hercules</td>
</tr>
<tr>
<td>Durez</td>
<td>Phenol formaldehyde</td>
<td>Kopper</td>
</tr>
<tr>
<td>Ethocel 10</td>
<td>Ethyl cellulose</td>
<td>Eastman</td>
</tr>
<tr>
<td>Polystyrene 8X</td>
<td>Polystyrene</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>Epoline C</td>
<td>Polystyrene</td>
<td>Du Pont</td>
</tr>
<tr>
<td>Polysulphone P-35000</td>
<td>Polystyrene</td>
<td>Durez</td>
</tr>
<tr>
<td>Hypalon 30</td>
<td>Polystyrene</td>
<td>Hercules</td>
</tr>
<tr>
<td>Cycolac H-1000</td>
<td>Polystyrene</td>
<td>Kopper</td>
</tr>
<tr>
<td>Uncoated iron</td>
<td>Polystyrene</td>
<td>Eastman</td>
</tr>
<tr>
<td>Epon 828/V125</td>
<td>Polystyrene</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>Polysulphone P-1700</td>
<td>Polystyrene</td>
<td>Du Pont</td>
</tr>
<tr>
<td>Cellulose nitrate</td>
<td>Polystyrene</td>
<td>Borg Warner</td>
</tr>
<tr>
<td>Kynar</td>
<td>Polyvinylidene fluoride</td>
<td>Penwalt</td>
</tr>
<tr>
<td>Epon 828/V125</td>
<td>Epoxo amine curing agent</td>
<td>Shell/General Union Carbide</td>
</tr>
<tr>
<td>Polysulphone P-1700</td>
<td>Epoxo amine curing agent</td>
<td></td>
</tr>
<tr>
<td>Cellulose nitrate</td>
<td>Epoxo amine curing agent</td>
<td></td>
</tr>
<tr>
<td>Kynar</td>
<td>Epoxo amine curing agent</td>
<td></td>
</tr>
</tbody>
</table>
These triboelectric series predict the charge polarities of the materials in contact with reasonable accuracy; however, the order can vary depending on other complex factors affecting charge transfer. For example, surface finish, preconditioning, and contamination can change polar relationships (Fan and Zhu, 1998). By varying the manner of rubbing, researchers were able to obtain the following exception of the triboelectric series shown in Figure 1.1. Counting round the figure clockwise, neighbours charge each other so that the second is positive with respect to the first.

![Diagram of triboelectric series](image)

Figure 1.1. Closed triboelectric series (Harper, 1967)

1.1.2 Frictional Charging

In industrial gas-solid fluidized beds, electrostatic charges are known to be primarily generated from surface charge polarization due to friction among gas, particles, and reactor walls. If the reactor is large enough to neglect wall effects, particle-particle interaction is the main cause of charge accumulation. According to Cross (1987), the quantity of charges generated due to friction between two similar materials can be as great as that from dissimilar materials.

As early as 1927, researchers such as Shaw performed experiments to investigate the frictional charging between two identical materials. Figure 2 illustrates the nature of his experiments. Figure 1.2 (a) shows an asymmetrical rubbing, whereas Figure 1.2 (b) illustrates symmetrical rubbing between two rods of insulating material. When two
identical surfaces are rubbed together, they become oppositely charged, suggesting that some asymmetry must be involved in this charging process (Harper, 1967).

Assuming surface symmetry, the rubbing itself must be asymmetric. In other words, the charge polarity of each rod is determined by whether the contact is a point or a line and whether it is rubbed or is doing the rubbing (Cross, 1987). This phenomenon is most likely caused by the temperature effect on the charge transfer (Harper, 1967). Cross (1987) also reported that the amount of charge transferred is influenced more by the energy of rubbing than the nature of materials involved. Therefore, frictional charging is different in nature from triboelectrification, and it is important to distinguish them in order to understand the charging mechanisms in fluidized beds.

Frictional charging is also affected by other factors such as the force of the contact and the rubbing velocity. The amount of charge transferred generally increases as the force of the contact and the speed of rubbing increase (Cross, 1987). An increase in rubbing velocity may also change the polarity of the charge transferred, as shown in Figure 1.3.

The polarity of polymers used to generate Figure 1.3 was also found to be sensitive to the temperature. At temperatures between 90 and 180 °C, when two objects separate, a high electric field is generated between two oppositely charged surfaces, resulting in local ionization of the gas (Cross, 1987). The ions not only neutralize the
surface charge on a polyethylene terephthalate disc, but also tend to overcompensate, to the point that the polarity on that portion of surface reverses itself (Zimmer, 1970). Depending on their surface geometry, frictionally charged materials may contain both positively and negatively charged areas on their surface, while the dominant polarity will determines the net charge of the surface.

Figure 1.3. Charging current plotted against rubbing velocity (Zimmer, 1970) for a Polyethylene terephthalate disc rubbed against a metal brush.

1.1.3 Charging by Ion Collection

Field charging, diffusion charging and corona charging are three distinct charging processes for particles in an electric field. Field charging is the predominant mechanism for particles larger than 1 μm (Fan and Zhu, 1998). For particles smaller than 0.2 μm, the contribution of an external electric field becomes insignificant relative to random motion of ions, so that the diffusion charging starts to play an important role (Fan and Zhu, 1998). In addition, when the electric field is very high and exceeds the breakdown field of the gas, the surrounding gaseous medium is ionized (Cross, 1987). Ions of single polarity or bi-polarities in gaseous medium are then attracted to the different sectors of a particle's surface that are polarized due to the electric field (Cross, 1987). This charging mechanism is called corona charging.
1.1.4 Charging by Thermionic Emission

Another special charging mechanism is thermal electrification. When solid particles are exposed to a high temperature (i.e. \( T > 1,000 \) K) environment, the electrons inside the solid can acquire sufficient energy to overcome the energy barrier (Fan and Zhu, 1998). The particles that lose electrons in such a thermionic emission are then thermally electrified. In the case of charging insulators, electrons do not normally play a role. However, the charge carriers can only be electrons if the temperatures are high enough that the materials are no longer insulators (Harper, 1967). As more electrons escape from a particle, charges build up on the particle. As the charge buildup increases, the attracting Coulomb force between the particle and to-be-freed electron also increases (Fan and Zhu, 1998). The rate of thermal electrification of solid particles in a finite space then eventually approaches an equilibrium value (Fan and Zhu, 1998).

1.1.5 Dielectric Constant or Permittivity of Materials

In order to understand the charging mechanisms of dielectric materials, it is necessary to consider the permittivity, one of the basic properties of insulating materials. Consider parallel plate conductors with voltage applied across the metallic plates as shown in Figure 1.4.

![Figure 1.4. Illustration of induced charge by a dielectric medium (Guy, 1976)](image-url)
The charge $Q$ on the plate surface is given by

$$Q = \Pi A_s \frac{V}{l} = C_P V \quad (1.1)$$

where $A_s$ is the surface area of the plate, $V$ is the voltage applied, $l$ is the distance between the plates, $C_P$ is the capacitance, and $\Pi$ is the permittivity of the medium (Fan and Zhu, 1998). The permittivity of a material is therefore a measure of the extent to which its atoms and molecules polarize (Cross, 1987). The dielectric constant or the relative permittivity of the insulating material, $\Pi_r$, is defined as the ratio of $\Pi$ to $\Pi_0$, where $\Pi_0$ is the permittivity of free space (i.e. vacuum environment) defined by Coulomb's law (Fan and Zhu, 1998). Hence for a vacuum between the plates $\Pi_r$ is one, and it is very close to one for air (Cross, 1987). The dielectric constants of most insulating materials are between 1 and 10, whereas a perfect conductor has an infinite relative permittivity (Cross, 1987). Table 1.4 lists dielectric constants of some common materials.

Table 1.4. Dielectric constants of materials at $10^6$ Hz and 25 °C (Fan and Zhu, 1998)

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric coefficient, $\Pi_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>2.3</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>2.8</td>
</tr>
<tr>
<td>Nylon</td>
<td>3.6</td>
</tr>
<tr>
<td>Porcelain</td>
<td>5</td>
</tr>
<tr>
<td>Mica</td>
<td>7</td>
</tr>
<tr>
<td>Alumina ceramic</td>
<td>9.6</td>
</tr>
</tbody>
</table>

The breakdown strength of the surrounding fluid limits the maximum charge that can be built up on a surface (Jiang et al., 1994). By applying Gauss' law, we can estimate the maximum charge for a spherical particle as (Jiang et al., 1994):

$$q_{\text{max}} = 2.64 \times 10^{-5} \left( \pi \frac{d_p}{r} \right) p \quad (1.2)$$

where $p = 3 \Pi_r / (\Pi_r + 2)$ and $\Pi_r$ is the relative permittivity or dielectric constant of the material.
1.2 Surface Charge Decay

Without continuing charging, the surface charge soon starts to decay. Ohm's law states that the flow rate of charges from the charged material to earth is proportional to the potential of the material. The greater the amount of the charge on the material, the higher the potential of the material (Cross, 1987). Thus, the initial rate of charge flow is highest and this rate falls with time as the charge on the material falls (Cross, 1987). The charge density, \( \sigma \), on the material decays exponentially, i.e.

\[
\sigma = \sigma_0 \exp(-t/\tau)
\]  

(1.3)

where \( \sigma_0 \) is the initial charge density and \( \tau \) is a decay time constant defined as

\[
\tau = \Pi_1 \Pi_2 R_r
\]  

(1.4)

where \( R_r \) is the resistivity. Figure 1.5 illustrates the decay of negative surface charges on poly(methyl methacrylate) graft-copolymerized onto a polypropylene film in air at 20 °C and 60 % humidity.

Figure 1.5. Computer-derived relief maps (1st row) and contour maps (2nd row) of negative charge spreading on a surface of the PMMA/PP film (Hori, 2000). The time intervals are from the moment of contact charging with mercury.
The minimum distance scale in the computer-derived relief maps is uniform at 0.2 mm, whereas the intervals between the charge contours are $1/7$ of the maximum charge densities in each case.

1.3 Scope of Work

The first objective of this thesis project is to understand the mechanisms of charge generation and dissipation in fluidized beds in order to assist in solving static electricity problems. An experimental apparatus was set up to measure and quantify the electrostatic charges generated under different operating conditions. A method of interpreting the output signals had to be developed in order to verify the experimental methods. A simplified mechanistic model of charge induction and transfer is proposed to describe the output signals.

The research also includes an evaluation of different methods of reducing the amount of electrostatic charges in a fluidized bed, in particular by increasing the humidity of fluidizing gas, and adding fine group C particles or an anti-static agent such as Larostat 519. Glass beads as well as polymer resin particles having properties similar to those in commercial polymerization reactors are used to provide insights and possible ways of preventing electrostatic effects. An optical fiber probe is implemented to synchronize the electrostatic signals with the movement of the bubbles.
Chapter 2
Experimental Set-up

2.1 Apparatus

The experiments were carried out in the fluidization system shown schematically in Figure 2.1. The apparatus consists of a fluidized bed column, various probes and instruments, and a data acquisition system. Details are given in the following sections.

Figure 2.1. Schematic diagram showing overall layout of experimental equipment.
2.1.1 Column

The major unit of the experimental apparatus is a three-dimensional cylindrical column made of Plexiglas whose inner diameter is 88.9 mm, while its height above the distributor is 1.213 m.

Figure 2.2. Three-dimensional fluidization column
The fluidizing air is supplied from the main compressed air line of the building. All the major piping is copper of 19.1 mm diameter. As shown in Figure 2.1 the pressure regulator at the air inlet maintains the air pressure at a desired value. The total air flow rate into the windbox at the bottom of the column is monitored by a rotameter located upstream of the air heater. As air leaves the top of the column, a cyclone installed at the exit of the column captures entrained fine particles and recycles them back to the base of the bed.

Fifteen pressure taps are located at various heights in the column at 90 mm intervals in order to measure partial and overall pressure drops. These taps were made by attaching Plexiglas sleeves 30 mm in diameter with drilled 3.2 mm (1/8 inch) NPT taps over the holes on the side of the column for support to 6.4 mm (1/4 inch) plastic fittings. Four ports were installed to accommodate the electrostatic ball probe, an optical fiber probe, and a bubble injector. Above the distributor, a large tap was installed to discharge the bed particles. Figure 2.2 shows the locations of the main taps and ports.

In order to synchronize the signals from the optical fiber probe and the electrostatic ball probe during single bubble injection, the second port for the electrostatic probe is located at the same height as the optical fiber probe port. The first ball probe port was used for free-bubbling experiments.

The distributor has forty-four orifices of diameter 1.09 mm. The pressure drop across the distributor to ensure the uniform distribution of fluidizing air is about 20 to 40% of the total bed pressure drop (Kunii and Levenspiel, 1991). In our system, the overall pressure drop is estimated to be about 3.3 kPa for 2 kg of glass beads in the fluidized bed column, and the pressure drop across the distributor was estimated to be 5.85 kPa, which is sufficient for our experimental purpose. Appendix C provides details of the design of the three-dimensional fluidized bed column. A 35 μm size mesh was glued on top of the distributor to prevent sifting of fine particles through the orifices.
2.1.2 Bubble Injector

During preliminary experiments with freely bubbling beds, it was found that the signals from the electrostatic ball probe were very difficult to analyze. As a result, single bubble injection experiments were carried out to provide basic understanding of the electrostatic signals. For these experiments, a bubble injector was constructed from stainless steel as shown in Figure 2.3.

![Figure 2.3. Schematic diagram of bubble injector](image)

The total volume of the bubble injector was determined to be $101 \times 10^{-6}$ m$^3$ (101 ml), normally sufficient to inject about two bubbles between refills. A pressure gauge was used to measure the pressures before and after bubble injection, and the difference is then used to estimate the volume of the injected bubble. It was therefore important to make the bubble injector as small as possible to improve the accuracy of the measurements.

One needle valve was installed to allow air to enter the bubble injector, while the second needle valve was used to bleed the excess air pressure. Stainless steel tubes of 6.4 mm (1/4 inch) diameter were used for the piping.
The solenoid valve that controlled the bubble injection was located as close as possible to the fluidization column in order to minimize the time delay in bubble injection; the distance was about 160 mm. The end section of the tube inside the column was bent 90° with its opening facing upward. Bubbles were injected inside the three-dimensional fluidized bed 50 mm above the distributor. The solenoid valve was normally closed (i.e. 0 V), and when 5 V was sent from the computer the valve opened.

2.1.3 Relative Humidity and Temperature Control

According to previous work (e.g. Guardiola et al., 1996; Ciborowski, 1962), the relative humidity of the fluidizing gas strongly affects the dissipation of electrostatic charges in fluidized bed reactors. Any change in temperature brings about a change in relative humidity. Therefore, it was very important to control and monitor both the relative humidity and the temperature of the fluidizing gas during the experiments.

An in-line air heater supplied by OMEGALUX (M2157/0495) was installed downstream of the main rotameter to control the temperature of the fluidizing gas. A temperature controller (OMEGA: Model CN76120-PV) regulated the air heater, while a pressure transducer after the first rotameter acted as an alarm. The voltage from the pressure transducer is proportional to the air flow in the system. Therefore, when the voltage output from the pressure transducer is equal to or below the set value, 1 V, it was assumed that there was no air flow and the air heater was turned off automatically in order to protect the air heater from overheating. The actual temperature of the fluidizing gas entering the fluidized bed was measured by a digital hygrometer/thermometer manufactured by TRACEABLE. The accuracy of the thermometer given by the manufacturer was ± 1 °C between 0 °C and 40 °C.

The relative humidity of the fluidizing gas was adjusted using a packed water column and dryer in parallel, as shown in Figure 2.1. The building air was either dried by passing through a column of silica gel or humidified by passing through a counter-current water column, before entering the windbox. A hygrometer/thermometer was located just
upstream of the windbox in order to increase the accuracy of the measurements. The accuracy of the hygrometer given by the manufacture was ±3.5 % between 40 % and 80 % relative humidities. In addition, the rotameter on the dry line was used to monitor the fraction of the flow passing through this side, while the main rotameter (i.e. the rotameter located most upstream in the system shown in Figure 2.1) monitors the total air flow rate.

2.2 Probes

Three major types of probes have been employed by previous researchers to measure electrostatic charges in fluidized beds.

2.2.1 Capacitance Probe

Some researchers, e.g. Guardiola et al. (1996), used a capacitance probe to measure the electrostatic charges in fluidized beds. In their technique, the probe and distributor are considered to be parallel metallic parallel plates, while the bed acts as a dielectric medium. The electric probe was made of a copper bar, 5 mm in diameter, coated with silicone rubber. The lower 10 mm of the bar was left bare to maximize direct contact between the probe and the particles and to achieve a high potential difference between the probe and the metallic distributor. The probe was placed along the axis of the column with the exposed surface at a height above the distributor equal to the fixed bed height. This height has been reported by others to correspond to the highest charge buildup region in fluidized beds (Ciborowski and Woldarski, 1962). The probe-distributor voltage drop was then measured as a function of time. This method averages the effect of electrostatic charges in the entire fluidized bed, and therefore it is an indirect method of measuring the degree of electrification during fluidization. However, in order to study the mechanisms of charge generation and dissipation, a direct method of measuring local electrostatic charges is needed.
2.2.2 Induction Probe

Induction probes have also been used by many researchers. There are two main types. One type involves a ball or bar probe with a shielded head. Figure 2.4 shows a probe shielded by a layer of the wall material used by Boland and Geldart (1971).

![Figure 2.4. Probe with shielded tip (Boland and Geldart, 1971)](image)

![Figure 2.5. Detailed representation of induction probe (Armour-Chelu et al., 1998)](image)
Another type of the induction probe, often used in pneumatic conveying systems, is a ring probe. As shown in Figure 2.5, a conducting copper strip is wrapped around a 2 mm thick polyethylene ring (i.e. insulating) section, preventing any direct charge transfer between the copper ring and the conveyed dust particles. These types of induction probes are not directly exposed to the fluidized material. As a result, an induction probe is a non-contacting probe mainly measuring the wall charge, instead of directly measuring the accumulated charges inside the fluidized bed. Particle-wall interactions rather than particle-particle interactions affect the output signals.

2.2.3 Collision Probe

A collision probe is also known as a contacting probe. As the name implies, the probe is inserted inside the fluidized bed in order to make direct electrostatic charge measurements. The most common type of collision probe is an electrostatic ball probe. This was the technique adapted in the present study.

![Electrostatic Ball Probe Diagram](image)

Figure 2.6. Schematic diagram of electrostatic ball probe

Figure 2.6 portrays the electrostatic ball probe used in this study. The design of the electrostatic ball probe with a Faraday Cage (i.e. brass tube shown in Figure 2.6) was similar to that of Gidaspow et al. (1986). A glass sleeve was used to maintain a high resistance to the ground, and this glass tube was then enclosed by a brass tube to reduce the background current by eliminating disturbances due to buildup of charge on the walls of the column. The outer diameter of the probe was 6.7 mm in order to fit into one of the
ports on the column used, while the stainless steel ball at the tip of the probe was 3.2 mm as suggested by Gidaspow et al. Alumel lead wire was then inserted into the small hole drilled on the stainless steel ball, and the connection between the ball and wire was secured by compressing the opening of the hole onto the wire. The portion of the wire outside the glass sleeve was then covered with insulating material in order to prevent charge leakage. This ball probe was connected to a self-amplified electrometer for data acquisition.

Ciborowski and Wlodarski (1962) measured electrostatic charges at various positions in fluidized beds. Their research indicated that the radial position of the probe did not affect the results. On the other hand, as the probe was lowered towards the distributor the potential reading approached zero. Therefore, the optimum position of the ball probe should be just below the surface of the fixed bed to measure maximum charge (Ciborowski and Woldarski, 1962).

### 2.3 Particles

The particles investigated in this research were glass beads and polyethylene (PE I and PE II) particles. The glass beads, which are smooth and spherical, represented ideal particles, whereas the polyethylene particles with non-smooth surfaces provided more realistic experimental conditions. Fine polyethylene particles were also non-spherical. Figure 2.7 shows Scanning Electron Microscope (SEM) images of typical particles.

The key physical properties of the particles are summarized in Table 2.1. The first three sets of particles: clear glass beads and white polyethylene particles (linear low-density polyethylene) were used as the bed materials and the other two sets of particles: white glass powders and black polyethylene particles were to be used as fine additives during experiments. The mean particle diameters of the fine particles were quoted from the manufacturers, since they were extremely fine that sieving would not be a right method to determine their particle diameter. Sedigraph was also recommended for the determination of the particle diameters of the fine particles, however, it was found that
Figure 2.7. SEM micrographs showing surfaces of particles used in this study

Table 2.1. Properties of particles used in experiments

<table>
<thead>
<tr>
<th>Usage</th>
<th>Material</th>
<th>$d_p$ (μm)</th>
<th>$\rho_p$ (kg/m$^3$)</th>
<th>$\rho_b$ (kg/m$^3$)</th>
<th>$\varepsilon_b$</th>
<th>$\Pi_r^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed material</td>
<td>Glass beads (Clear)</td>
<td>321</td>
<td>2458</td>
<td>1478</td>
<td>0.399</td>
<td>5-10</td>
</tr>
<tr>
<td>Bed material</td>
<td>Polyethylene resin PE I (White)</td>
<td>378</td>
<td>715</td>
<td>412</td>
<td>0.424</td>
<td>2.3</td>
</tr>
<tr>
<td>Bed material</td>
<td>Polyethylene resin PE II (White)</td>
<td>318</td>
<td>797</td>
<td>458</td>
<td>0.425</td>
<td>2.3</td>
</tr>
<tr>
<td>Added as fine</td>
<td>Glass powders (White)</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5-10</td>
</tr>
<tr>
<td>Added as fine</td>
<td>Fine polyethylene particles (Black)</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
</tr>
</tbody>
</table>

* The dielectric constants of the glass beads were from Reitz et al. (1993), while those of the polyethylene resin were from Jiang et al. (1994).

this method was very sensitive to particle densities and did not work for the particles used in this project. Therefore, SEM images were utilized to confirm the mean particle
diameter given by the manufacturers. For the other two sets of particles with larger
diameters, sieve analyses were used to determine the Sauter mean diameters of the
particles. The physical properties other than the particle diameters and dielectric
constants for the fine particles were omitted since they were very difficult to measure and
they were not required for this project to evaluate the experimental findings. Both white
and black polyethylene particles were supplied by NOVA Chemicals Ltd.

The Sauter mean particle diameters of bed materials (i.e. clear glass beads and
white polyethylene resin) in Table 2.1 were obtained from sieve analyses using the
following equation.

\[
\overline{d_p} = \frac{1}{\sum \frac{x_i}{d_{pi}}}
\]  

(2.1)

where \( x_i \) is the mass fraction of particles within an average screen aperture size of \( d_{pi} \).
The particle size distribution of the glass beads was narrower than that of the
polyethylene resin. Prior to the sieving process, the polyethylene particles were coated
with anti-static spray in order to reduce adhesion between particles during sieving. The
detailed calculations and plots of cumulative particle size distributions are given in
Appendix D.

The particle densities of the glass beads and the polyethylene resin were
determined using a 100 ml pycnometer. Particles of known mass were added to the
pycnometer and the total combined weight was measured. Water was then added to the
pycnometer to make up the total volume to 100 ml. During the experiment, the
pycnometer was placed in the water bath at 25 °C. The total mass of the pycnometer after
adding the particles and water was measured, and knowing the density of water at 25 °C,
the particle density was then calculated. Since the polyethylene particles were porous,
water, which has a low wetting ability for the polyethylene particles, was used during the
particle density measurements.
The bulk densities of the particles were also obtained in order to determine the loose packed voidage, $\varepsilon_b$, of the bed materials. A graduated cylinder was used to measure the volume of a known mass of particles. In order to create a loosely packed condition with the top end covered, the cylinder was inverted and returned quickly to its upright position before the volume was measured. The loose packed voidage was then calculated from

$$
\varepsilon_b = 1 - \frac{\rho_b}{\rho_p}
$$

Several tests were performed to ensure the reproducibility of these measurements. Also see Appendix D for the detailed calculations.

Finally, the relative permittivities were obtained from the literature for both glass beads and polyethylene resin. According to Jiang et al. (1994), polyethylene particles are dielectric, and therefore, they become electrostatically charged through the triboelectric effect. As shown in Table 2.1 the glass beads used in this project also had a high dielectric constant, resulting in electrostatic charges in the fluidized bed.

![Figure 2.8. Geldart classification of particles for air at ambient conditions; Region A' (Range of the properties for well-behaved FCC catalyst)](Kunii and Levenspiel, 1991)
Glass beads (GB) and the polyethylene resin (PE I and PE II) used as the bed materials were group B particles according to Geldart classification shown in Figure 2.8. However, polyethylene particles (PE I and PE II) showed aeratable (group A) behaviour during fluidization.

2.4 Instrumentation

The instrumentation in this research mainly consisted of an electrometer, pressure transducers, and an optical fibre probe. Figure 2.9 shows the electrometer.

![Schematic diagram of the electric circuit used to measure the electrostatic voltage in a fluidized bed](image)

Figure 2.9. Schematic diagram of the electric circuit used to measure the electrostatic voltage in a fluidized bed

A Keithley Model 616 Digital Electrometer was used to measure the electrostatic potential in a fluidized bed. Its specifications are as follows:

- Range of voltage: \(10^{-6}\) to \(10^2\) V
- Range of current: \(10^{-16}\) to \(10^{-1}\) A
- Total electrostatic charges: \(10^{-15}\) to \(10^{-5}\) C

The magnitude of the resistor was determined to give a reasonable voltage output (i.e. \(-5\) to \(5\) V) after additional amplification (x 10). The electrometer is also self-amplified (up to a factor of 1000), and the electrostatic ball probe is directly connected to the electrometer. The signals from the electrometer were logged into a 486 computer using an A/D converter and Visual Basic software.
Two pressure transducers (OMEGA PX162 and PX142) were used to measure the local and overall pressure drops across the bed. The pressure ranges of these two transducers were from 0 to 34.5 kPa and from 0 to 13.8 kPa, respectively. The voltage outputs of these pressure transducers are between 0 and 5 V.

The PC-4 voidage probe was an optical fiber probe developed by the Institute of Chemical Metallurgy of the Chinese Academy of Science, in Beijing, China. A schematic block diagram of the instrument is shown in Figure 2.10.

![Schematic diagram of fiber optic system](image)

Figure 2.10. Schematic diagram of fiber optic system used to monitor passage of bubbles in fluidized bed (adapted from Pianarosa (1996))

The major components of the fiber optic system are an optical fiber probe, a light source, a photo-multiplier, and an A/D converter. The probe consists of two overlapping bundles of fine optical fibers. One bundle transmits light from the light source to the target (Pianarosa, 1996). The intensity of the light from the light source was adjusted to give a voltage output between 0 and 5 V. The other bundle captures back-scattered light and transmits it to a detector or photo-multiplier. The particle concentration in the path of the transmitted light determines the intensity of the back-scattered light. The back-
scattered light signals are then converted to electrical signals by the photo-multiplier, and the magnitude of the voltage output from the photo-multiplier depends on the intensity of the light (Pianarosa, 1996). Since in this project we were only interested in the position of a bubble relative to the position of the ball probe, it was not necessary to calibrate the optical fiber probe readings. A voltage output close to 5 V was considered to be a fixed bed condition, whereas the bubble was represented by a voltage close to 0 V. In addition, a referential light auto-compensation system stabilizes the signals and eliminates drift caused by changes in ambient temperature and light source (Pianarosa, 1996).

Since all the signals from various electrical instruments were in voltage either between −5 and 5 V or between 0 and 5 V, a DAS08 card was used to log the experimental data. This Visual Basic program was also used to send a 5 V pulse to the solenoid valve to trigger the injection of a single bubble. By setting the duration of the voltage pulse, the size of the injected bubble was controlled. Figure 2.11 is the photograph of the experimental set-up.

Figure 2.11. Photograph of the experimental set-up
Chapter 3
Preliminary Experiments

3.1 Introduction

Since there has been very little direct research into electrostatic charges in fluidized beds, it was not clear what kind of output signals would be obtained using the electrostatic ball probe described in Chapter 2. Previous work is covered when specific topics are discussed in following chapters. Preliminary experiments using a simplified experimental set-up were carried out to determine the ball probe output voltage signals.

When an electrostatic ball probe is inserted into a fluidized bed, the output signals should be a combination of voltage changes due to direct charge transfer and charge induction. In other words, the particles charged through the mechanisms described in Chapter 1 would result in voltage outputs when they move past the probe or make contact with it. The voltage output from direct charge transfer was considered to result in step changes of magnitude equal to the charge transferred at each contact, while the induced voltage was assumed to be caused by changes in electric field around the probe.

There is no literature reviewing a motion-induced voltage or current due to the electric charges. However, it is known that a magnet can produce electric current. An electric guitar, a stereo cassette deck, and a transformer are examples of the use of a magnetic field to create an electric current (Cutnell and Johnson, 1992). The electric charges are analogous to magnetic poles. In both cases, unlike charges or poles attract each other, whereas like charges or poles repel each other. The significant difference between the electric charges and the magnetic poles is that unlike electric charges it is impossible to separate the north and south poles (Cutnell and Johnson, 1992). Cutting a bar magnet into pieces results in smaller magnets with their own north and south poles. Nevertheless, the behavior of the magnetic poles is very similar to that of electric charges.
Like the electric field surrounding electric charges, a magnetic field exists in the space surrounding a magnet (Cutnell and Johnson, 1992). The direction of the magnetic field at any point is away from the north pole and towards the south pole. This is analogous to the electric field lines that are always directed away from positive charges and toward negative (Cutnell and Johnson, 1992). Figure 3.1 shows electric and magnetic fields.

![Electric and Magnetic Field Lines](image)

(a) electric field lines  
(b) magnetic field lines

Figure 3.1. Visualization of electric field lines and magnetic field lines (Cutnell and Johnson, 1992)

There are a number of methods to produce an electric current using a magnetic field. In each case, the key is the change in magnetic field. Figure 3.2 illustrates a simple experiment with a bar magnet and a coil of wire connected to an ammeter. First, the bar magnet is placed near the stationary coil of wire as shown in Figure 3.2 (a). The ammeter reads zero, indicating that there is no current flowing through the coil. On the other hand, in Figures 3.2 (b) and (c) the bar magnet is either moving towards or away from the coil, and the ammeter reads current generated. It should be noted that the direction of the current is opposite for cases (b) and (c). This simple experiment illustrates how the change in magnetic field generates an electric current.
Since the induced current depends on the relative motion between the bar magnet and the coil, a current would also be produced if the coil were moved instead of the bar magnet. In addition, the magnitude of the current depends on the distance between the coil and the bar magnet. As shown in Figure 3.1 (b), the density of the magnetic field lines is higher near the poles of the bar magnet. As a result, a shorter distance from the pole of the magnet to the coil results in a larger change in magnetic field around the coil, leading to a higher induced current.

The direction of the induced current can be determined using Lenz's law which states that the direction of the induced current is such that the induced field either adds to or subtracts from the original field, whichever is necessary to keep the flux from changing (Cutnell and Johnson, 1992). In Figure 3.2 (b) as the north pole of the magnet approaches the coil, a current is created. The magnetic field due to this current then originates from the side of the coil close to the magnet (i.e. acting as the north pole) and balances the increase in magnetic field due to the moving magnet. The reverse process happens in Figure 3.2 (c).

3.2 Experiments

The experimental set-up consisted of an electrometer and an electrostatic ball probe as described in Figure 2.9. The probe was fixed to a table using a clamp. Different
materials such as a plastic ruler, a glass rod and a plastic pen were selected to produce either positive or negative charges.

In order to create a negatively charged object, a plastic ruler was rubbed against hair. According to Table 1.2, the triboelectric series predicts that negative charges will be generated on the plastic ruler when it is rubbed with hair. On the other hand, it was also predicted that the glass rod would be positively charged when it was rubbed against cotton cloth. When the plastic pen and polyethylene powders were rubbed together to charge the pen, the triboelectric series in Table 1.2 could not predict the charge polarity since the type of plastic was unknown.

After the rubbing process, each charged object was then moved from one side of the ball probe to the other as shown in Figure 3.3, and output signals were logged into a computer connected to the electrometer. In these experiments, the induced current was converted to an output voltage (i.e. -5 to 5 V) by adding a resistor to the electric circuit.

![Figure 3.3. Preliminary experiment using a charged object](image)

Six different cases were tested as illustrated in Figure 3.4. The experimental data were logged into a file.
Figure 3.4. Six different movements of the charged object without direct contact between the probe and the object.

In case 1, the charged object was moved vertically with a speed of approximately 30 mm/s from below the probe to above leaving a distance from the probe to the ruler edge at the closest point of 5 mm. In case 2, this procedure was repeated for a larger distance from the probe (i.e. 40 mm). The charged object was then moved faster (i.e. at a speed of approximately 60 mm/s) in case 3, but at the same separation distance as in the first case. In case 4, the object initially approached the probe with a speed of approximately 30 mm/s and stopped for few second when it was aligned with the probe; then it moved quickly (i.e. speed of approximately 60 mm/s) away from the probe. The reverse procedure was performed in case 5. Finally (case 6), the charged object was quickly moved up and down past the probe with speeds of approximately 60 mm/s in both directions. In all cases, the charged object was moved only vertically. The speeds of the objects were approximated values since the charged objects were moved by hand.

These experiments were qualitative rather than quantitative, since their main purpose was to find the nature and relative magnitude of the output signals and to give them physical meaning.

3.3 Experimental Results and Interpretation of Data

3.3.1 Plastic ruler rubbed with hair

From Table 1.2, the plastic ruler is charged negatively when rubbed against hair. We can therefore predict the polarities of the voltage output as illustrated in Figure 3.5.
Figure 3.5. Schematic diagram illustrating the effect of a negatively charged ruler on the voltage output of the electrostatic ball probe.

Figure 3.6. Preliminary experimental results using a negatively charged ruler (i.e. plastic ruler rubbed against hair).
According to the method of images (Reitz et al., 1993), as the negatively charged object moves closer to the probe, the probe connected to ground experiences charges migrating from the tip of the probe to the ground in order to promote the net positive induced charge of the ball probe. Then, since the direction of the current is opposite to the direction of the charges, the sign of the voltage output, which is proportional to the induced current, would be negative. This is only true while the negatively charged object is moving towards the ball probe and the electric fields between the probe and the charged object is being increased. On the other hand, if the negatively charged object were moving away from the ball probe, the electric field density between the probe and the charged object would be decreased. This negative change in the electric field density then results in that the charges migrate back to the tip of the probe, which indicates the positive direction for the current and voltage in Figure 3.5. In summary, these opposite directions of the migrations of the charges through the probe result in negative, followed by positive, voltage readings to the electrometer. The former occurs until the negatively charged object is aligned with the probe, where the voltage output is instantaneously zero, and then the polarity quickly reverses as the object starts to move away from the probe.

This hypothesis is compared with the experimental results in Figure 3.6, with numbers 1 to 6 in Figure 3.6 (a) corresponding to the case numbers in Figure 3.4. As expected, the voltage output changed from negative to positive as the negatively charged ruler vertically moved from below the probe to above. The magnitude of measured voltage was smaller when the distance from the probe to the ruler edge at the closest point was increased (i.e. case 2). Faster movement of the ruler (i.e. speed of approximately 60 mm/s) resulted in a smoother curve for the voltage output since it was harder to keep the moving velocity of the ruler constant at a lower speed (approximately 30 mm/s). However, assuming the charge on the ruler and the distance between the ruler and the probe were constant in cases 1 and 3, the area under the curve should be the same for both cases. In case 4, keeping the ruler motionless right next to the probe led to a zero reading from the electrometer, proving that the change in electric field do causes the induced voltage. As soon as the ruler started to move quickly away from the probe, a
relatively high positive voltage was generated. The fourth case was repeated in reverse in the fifth case. Again, a zero reading was obtained when the ruler was motionless at the same height as the probe. However, as soon as the ruler started to move slowly away from the probe, a positive voltage was detected. The magnitude of this induced voltage was smaller than in case 4, since the speed of the ruler moving away from the probe was slower. Finally, when the ruler was moved up and down past the probe, and the signal varied in an irregular manner due to overlapping of induced signals.

Figure 3.6 (b) shows the results of a second set of experiments where the ruler and probe made contact while the ruler was moved from below to above the probe. The peaks where contacts occurred have higher magnitudes. For example, the negatively charged object would donate the negative charges to the ball probe and this movement of the charged through the probe would generate the current in the negative direction enhancing the first peak of each case in Figure 3.6 (b). In addition, it is suspected that the loss of electrons through the points of contact partially neutralizes the negatively charged ruler so that the magnitude of the induced voltage is lower after the contacts. These direct charge transfers can be quantified by calculating the cumulative charges on the probe by applying the following equations.

\[ I = \frac{V}{R} \]  
\[ Q_{\text{cumulative}} = -\int I(t) \, dt \]

where \( I \) is current, \( V \) is voltage, and \( R \) is resistance (1 MΩ). Also

It should also be noted that the output signals were amplified 1000 times by an internal amplifier of the electrometer and an external amplifier. Figure 3.6 (c) shows the cumulative charges on the probe with and without direct charge transfer. Note that the sign of cumulative charges of the ball probe is opposite to the sign of charges on the object. The cumulative charges for the non-contacting experiments varied due to the induced voltage, but eventually returned to the baseline indicating no permanent charge transfer during the experiments. For case 6, the cumulative charge did not reach the
baseline since there was not enough time for the induced charge to decay before the next charge inducement.

On the other hand, when there was direct charge transfer between the ruler and the electrostatic ball probe, a baseline shift was observed. The difference between the baselines indicates the net charge transfer. Even in this case, peaks occur before the cumulative charge reaches the new baselines, due to charge inducement, since the ruler had to be brought closer to the probe in order to make contact, and it also had to be removed from the probe after contact. The combined charge inducement and charge transfer are important in considering experimental results as discussed in the following chapters. Note that the polarity of the charges on the probe can be determined by observing whether the voltage output curves rise or fall with successive bubbles.

3.3.2 Glass rod rubbed with cotton cloth

In order to produce a positively charged object, a glass rod was rubbed with cotton cloth using the same experimental procedure as for the negatively charged ruler. This system is analogous to the one in Figure 3.5 except that the polarities are reversed. Therefore, as the positively charged glass rod passed the probe, a positive voltage output was detected by the electrometer, followed by a negative voltage output. Figure 3.7 shows similar experimental results.

The numbers 1 to 6 in Figure 3.7 (a) correspond to the numbers in Figure 3.4. As expected the general trend of the voltage output was positive while the positively charged glass rod approached the probe and negative while the glass rod was moving away from the probe. The magnitude of the voltage output was larger as the distance between the probe and the charged object was smaller and/or as the object was moving faster. When there was no relative motion between the glass rod and the probe, there was no voltage detected even when the glass rod was very close to the probe.

In the case of the direct charge transfer, the general trend of the voltage output
Figure 3.7. Preliminary experimental results using a positively charged object (i.e. glass rod rubbed against cotton cloth)

was the same. However, the first peak (i.e. peak with positive polarity) had a higher magnitude and the increase in height corresponded to the charge transferred. Since the experiments shown in Figure 3.7 (b) were performed continuously without recharging the glass rod, the charge on the glass rod decreased as the number of contacts between the rod and the probe increased. This phenomenon is illustrated by the first three peaks in Figure 3.7 (b). The magnitudes of the latter voltage peaks were smaller. Figure 3.7 (c) shows the smaller baseline shifts in the corresponding cases.

Figure 3.7 (c) plots the cumulative charge versus time. The average cumulative charge on the probe was zero when there was no direct charge transfer. The slope of the curves result from the charge inducement. On the other hand, the baseline of the cumulative charge on the probe shifted at each contact between the positively charged glass rod and the probe. The difference between the baselines indicates the net charge
Since the glass rod was positively charged, the electrons were transferred from the probe (which was connected to ground) to the glass rod, resulting in a positive net charge transfer.

### 3.3.3 Plastic pen rubbed with polyethylene powders

After performing experiments with negatively and positively charged objects, an experiment with a charged object of unknown polarity was performed for comparison. A plastic pen was rubbed with polyethylene powders; since these materials are very close in the triboelectric series, it was not clear what polarity the plastic pen would have.

Figure 3.8 summarizes the experimental results. The patterns in Figure 3.8 resemble those in Figure 3.7 rather than Figure 3.6. Therefore, we can conclude that the plastic pen was positively charged when rubbed against polyethylene powders. The difference between the baselines again represents net charge transfer.

![Figure 3.8. Experimental results for plastic pen rubbed against polyethylene powders](image-url)
3.4 Conclusion

Preliminary experiments were performed to aid the interpretation of voltage output signals from the electrostatic ball probe. By observing the change in sign of the voltage output, the polarity of the surface charge on moving objects can be determined. A negatively charged object results in negative voltage readings while the object is approaching the probe, whereas positive voltage readings are detected as the object moves away from the probe. The change in the cumulative charge corresponds to net charge transfer. When there is contact between the charged object and the probe, excess charges on the object are transferred to the probe. This process is reversed if the object is charged positively. Electrons move easily between the charged object and the probe, because the probe is made of highly conductive material (i.e. stainless steel) and connected to the ground.
Chapter 4
Model for Charge Transfer and Inducement

4.1 Introduction

The electrostatic ball probe used in this study is a collision probe. Since this allows direct contacts with charged particles, direct charge transfer takes place between the particles and the probe during the experiments. In addition, it was observed that the motion of the charged particles relative to the ball probe caused some localized disturbance to the electrostatic field in the region of the ball probe, resulting in inducement of charge on the probe, as reported by Woodhead (1992) who used a ring probe (i.e. induction probe).

The signal obtained from the electrostatic ball probe is a combination of induced charge and charge transferred. In order to separate the charges from these two mechanisms, it is first necessary to establish some fundamental understanding of the mechanisms. A basic mechanistic model for the charge inducement helps to provide a basis for the reader.

4.2 Development of Models

When oppositely charged particles are at rest with respect to each other in free space, there is a force of attraction between them. On the other hand, there is a force of repulsion between stationary particles with the same polarity. The forces between these charged particles differ if the particles have different relative velocities with respect to a common reference system (Bohn, 1968). The force acting on a moving charge or charged particle is most conveniently described in terms of electromagnetic field vectors, the electric field intensity, $E$, and the magnetic flux density, $B$ (Bloom, 1993). These field vectors, $E$ and $B$, are related to each other and to the sources of the electromagnetic field, the charge density $\rho$ [C/m$^3$], and the current density $J$ [A/m$^2$], through field
Maxwell discovered two of these equations, and they are known as the *Maxwell equations* (Bohn, 1968). Equations (4.1) and (4.2) are the two Maxwell equations which are postulated to have general validity (Bohn, 1968):

\[
\begin{align*}
\frac{\partial \phi_m}{\partial t} &= -\nu_e, \\
\oint_C \frac{B}{\mu_o} \cdot d\mathbf{r} &= i_T + \frac{d\phi_e}{dt}
\end{align*}
\]  

(4.1)  

(4.2)

where

\[
\phi_m = \int_S \mathbf{B} \cdot \mathbf{n} \, ds
\]

is defined as the magnetic flux along path \( C_S \) which bounds surface \( S \)

\[
\phi_e = \int_S \Pi_o \mathbf{E} \cdot \mathbf{n} \, ds
\]

is defined as the electric flux along \( C_S \), and where

\[
i_T = \int_S \mathbf{J}_T \cdot \mathbf{n} \, ds
\]

is the total current due to the movement of charge through a surface \( S \) bounded by \( C_S \). \( \nu_e \) is the electromotive force, \( \mu_o \) is the permeability of free space, \( \Pi_o \) is the permittivity of free space, and \( \mathbf{J}_T \) is the total current density.

In a stationary medium the electric field intensity, \( \mathbf{E} \), and the magnetic flux density, \( \mathbf{B} \), are related by the integral forms of the Maxwell equations (Bohn, 1968):

\[
\begin{align*}
\oint_C \mathbf{E} \cdot d\mathbf{r} &= -\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot \mathbf{n} \, ds \\
\oint_C \frac{B}{\mu_o} \cdot d\mathbf{r} &= \int_S \left( \mathbf{J}_T + \Pi_o \frac{\partial \mathbf{E}}{\partial t} \right) \cdot \mathbf{n} \, ds
\end{align*}
\]  

(4.3)  

(4.4)

These equations are then written in differential form with the aid of Stokes' theorem:

\[
\begin{align*}
curl \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
curl \frac{\mathbf{B}}{\mu_o} &= \mathbf{J}_T + \Pi_o \frac{\partial \mathbf{E}}{\partial t}
\end{align*}
\]  

(4.5)  

(4.6)

By taking the divergence of Equations (4.5) and (4.6), we obtain important results concerning the magnetic and electric flux. First, Equation (4.5) becomes
\[ \nabla \cdot (\nabla \times E) = - \frac{\partial}{\partial t} (\nabla \cdot B) = 0 \quad (4.7) \]

since \( \nabla \cdot (\nabla \times E) = 0 \) according to the vector identity which is subsequently used in the development of electromagnetic theory (Bohn, 1968). Integrating the right-hand side of Equation (4.7) with respect to time results in \( \nabla \cdot B = c_1 \), where \( c_1 \) is independent of time. Similarly, the divergence of Equation (4.6) results in

\[ \frac{\partial}{\partial t} (\nabla \cdot \Pi_0 E) + \nabla \cdot J_T = 0 \quad (4.8) \]

where \( \Pi_0 E \) is the electric flux density due to all charges in a given space.

A further equation relating \( J \) and \( \rho \) is called the equation of continuity, obtained from the concept of a charge in motion constituting a current (Bohn, 1968). In addition, the conservation law should be applied, since in a transport process charges are neither created nor destroyed. Therefore, the divergence of the current density is written

\[ \text{div} \ J_T = -\frac{\partial \rho_T}{\partial t}, \quad (4.9) \]

where \( \rho_T \) is the total charge density. Substituting Equation (4.9) into Equation (4.8) leads to

\[ \frac{\partial}{\partial t} (\nabla \cdot \Pi_0 E - \rho_T) = 0 \quad (4.10) \]

As for the Maxwell's first equation, integrating Equation (4.10) with respect to time yields \( \nabla \cdot \Pi_0 E - \rho_T = c_2 \), where \( c_2 \) is independent of \( t \). Let us consider a static situation and let \( J_T \) and \( \rho_T \) slowly approach zero, so that \( B \) and \( E \) also slowly approach zero. This means that the constants \( c_1 \) and \( c_2 \) must be zero. Therefore, two fundamentally important equations are obtained:

\[ \text{div} \ B = 0 \quad (4.11) \]
\[ \text{div} \ \Pi_0 E = \rho_T \quad (4.12) \]

Now we introduce the electric flux density due to free charges, \( D \), defined as

\[ \text{div} \ D = \Pi_0 \ \text{div} \ E \quad (4.13) \]
where \( \mathbf{E} = -\nabla U \) by definition to satisfy the Maxwell equations. Hence, Equation (4.12) becomes

\[
- \text{div} (\Pi \: \nabla U) = \text{div} \mathbf{D} = \rho
\]

where \( \Pi \) is a permittivity of a dielectric medium and \( U \) is the potential.

Assuming that \( \Pi \) is constant and that \( \rho / \Pi \) is a piecewise continuous function of position, we can now write Poisson's equation (Bloom, 1993) as

\[
\nabla^2 U = -\frac{\rho}{\Pi}.
\]

In order to simplify the solution of Poisson's equation, the divergence theorem is now introduced;

\[
\int_v \text{div} \mathbf{D} \: dv = \int_s \mathbf{D} \cdot \mathbf{n} \: ds,
\]

where \( v \) is the volume bounded by a well-behaved surface \( S \) (Bohn, 1968). By substituting \( \mathbf{D}_1 = U \: \nabla V \) and \( \mathbf{D}_2 = V \: \nabla U \) into Equation (4.16) and subtracting the two equations, we derive Green's theorem, which will be used in the solution of Poisson's equation:

\[
\int_v (\nabla^2 U - U \: \nabla^2 V) dv = \int_s \left( V \frac{\partial U}{\partial n} - U \frac{\partial V}{\partial n} \right) ds
\]

Equation (4.17) can be rewritten by letting \( V = 1/r \) and \( \partial / \partial n = - \partial / \partial r \) where \( r \) is the distance between \( P \) (field point) and \( B \) (source point). This leads to

\[
\int_v - \frac{\nabla^2 U}{r} \: dv = \int_s \left( \frac{1}{r} \frac{\partial U}{\partial r} + U \frac{\partial}{\partial r} \frac{1}{r} \right) ds
\]

If we choose a suitable surface point, \( P \), for the surface integral in Equation (4.18) and the volume approaches zero, the rate of change of \( U \) in the direction of the surface normal to \( r \) approaches zero. Combining with Equation (4.15), Equation (4.18) reduces to

\[
\int_v - U \: \frac{\partial}{\partial r} \frac{1}{r} \: dv = \int_s \left( U \frac{\partial}{\partial r} \frac{1}{r} \right) ds
\]

If the surface is spherical with radius \( r_p \), the surface integral in Equation (4.19) further reduces to

\[
\int_s \left( U \frac{\partial}{\partial r} \frac{1}{r} \right) ds = -U(P) \int_s \frac{1}{r_p^2} ds = -U(P) \frac{1}{r_p^2} 4\pi r_p^2 = -U(P) 4\pi.
\]

If we choose a suitable surface point, \( P \), for the surface integral in Equation (4.18) and the volume approaches zero, the rate of change of \( U \) in the direction of the surface normal to \( r \) approaches zero. Combining with Equation (4.15), Equation (4.18) reduces to
By combining Equations (4.19) and (4.20), the potential at the surface point \( P \) can be written

\[
U \equiv U(P) = \frac{1}{4\pi} \int \frac{\rho}{\Pi r} \, dv. \tag{4.21}
\]

The source of the scalar field is defined as \( Q = \int \rho \, dv \), and Equation (4.21) becomes

\[
U_1 \equiv \frac{1}{4\pi r} \int \frac{\rho}{\Pi} \, dv = \frac{Q}{4\pi \Pi r}. \tag{4.22}
\]

This unique solution for Poisson's equation is valid only for the boundary condition \( U = 0 \) at infinity and for free charges embedded in an infinite uniform dielectric medium. However, in most real cases the dielectric has finite dimensions and conductors may be present in the system. As a result, a solution of Laplace's equation

\[
\nabla^2 U_2 = 0, \tag{4.23}
\]

has to be added (Bohn, 1968) to the solution of Equation (4.22) to satisfy the prescribed boundary conditions where the charge density vanishes. The solution of Poisson's equation, Equation (4.15), for given boundary conditions is then \( U = U_1 + U_2 \).

**Boundary Conditions**

![Figure 4.1. Boundary conditions (Bohn, 1968)](image)

Figure 4.1 illustrates the interface, \( S_0 \), for media 1 and 2. For any surface \( S \) that bounds the charge \( Q \), Gauss' law is expressed as

\[
Q = \int \mathbf{D} \cdot \mathbf{n} \, ds. \tag{4.24}
\]
By letting the cylinder length, \( h \), approach zero, we can assume that there is no electric flux through the sides of the cylinder, and Equation (4.24) can be rewritten

\[
\sigma = D_1 \cdot n - D_2 \cdot n = -\Pi_1 \frac{\partial U_1}{\partial n} + \Pi_2 \frac{\partial U_2}{\partial n},
\]

(4.25)

where \( n_1 = -n_2 = n \) and \( \sigma \) is the surface charge density due to free charge embedded in the interface.

Two boundary conditions need to be satisfied. The first states that the normal component of the electric flux density is continuous (Bohn, 1968). Thus from Equation (4.25), \( D_1 \cdot n = D_2 \cdot n \) when \( \sigma = 0 \). In addition, the electric flux density of a conductor is zero. Therefore, if medium 2 is a conductor, Equation (4.25) reduces to

\[
\sigma = -\Pi_1 \frac{\partial U_1}{\partial n}.
\]

(4.26)

The second boundary condition states that for any contour \( C \) the electric field intensity must satisfy Maxwell's first equation in integral form (Bohn, 1968). Using the vector identity employed in deriving Equation (4.7), i.e. \( \nabla \cdot (\nabla \times \mathbf{E}) = 0 \), Equation (4.3) yields

\[
\oint_C \mathbf{E} \cdot d\mathbf{r} = \oint_S \mathbf{n} \cdot \text{curl} \mathbf{E} = \int_v \text{div} \text{curl} \mathbf{E} \, dv = 0.
\]

(4.27)

For a path length, \( l \), short enough to show uniform \( \mathbf{E} \) along the path, we then obtain

\[
E_1 \cdot \mathbf{m} + E_2 \cdot \mathbf{m} = 0
\]

(4.28)

and

\[
-\Pi_1 \frac{\partial U_1}{\partial m} + \Pi_2 \frac{\partial U_2}{\partial m} = 0,
\]

(4.29)

where \( \mathbf{m} \) is a unit vector tangent to \( S_0 \). Hence, \( U_1 = U_2 \) at the interface, \( S_0 \). Two models were developed and tested to aid the understanding of the electrostatic systems.

**4.2.1 Model 1**

The first model assumes that electrostatic ball probe is extremely small compared with the size of injected two-dimensional bubbles so that it is reasonable to consider the probe as a field point, \( P \). Figure 4.2 illustrates the physical system corresponding to Model 1.
Figure 4.2. Bubble situated near a grounded very small conductor

Assume that the bubbles rise with constant velocity, $U_B$, and the probe lies on the axis of the moving bubble. The $y$ component of the center $C$ is then $-L + U_B t$, where $L$ is the distance between the tip of the bubble injector and the ball probe and $U_B$ is the bubble rise velocity. In this experimental set-up, $L$ is $-0.205$ m since the position of the probe fixed on the wall of the fluidized bed was assumed to be (0,0) and the bubble injector was located a distance $0.205$ m vertically below the probe. Using polar coordinates, we can express the position of point $B$ on the bubble surface as

$$(x, y) = (r_B \cos \theta_B, L + U_B t + r_B \sin \theta_B)$$

(4.30)
From Equation (4.30), we can calculate the distance between the probe \( P \) and the source point on the bubble, \( B \), as a function of time, radius of the bubble, and \( \theta_B \):

\[
    r^2 = x^2 + y^2 = (r_B \cos \theta_B)^2 + (L + U_B t + r_B \sin \theta_B)^2
\]

After some algebra, \( r \) is given by

\[
    r = \frac{r_B^2 + (L + U_B t)^2 + 2(L + U_B t)r_B \sin \theta_B}{2(L + U_B t)} \tag{4.31}
\]

Since \( r \) is in radial coordinates, the sign of \( r \) is always positive.

Now assume uniform monolayer charge distribution on the surface of the bubble. Then, the point surface charge density on a two-dimensional cylindrical bubble is expressed as

\[
    \sigma_B = \frac{Q_B}{\pi d_B \delta_B} \left[ \text{C/m}^2 \right] \tag{4.32}
\]

where \( Q_B \) is the total charge on the bubble and \( \delta_B \) is the thickness of the bubble. Take a control surface area around point \( B \). The charge on the control surface is

\[
    \Delta Q_B = \sigma_B \Delta S = \frac{Q_B}{\pi d_B \delta_B} \Delta S
\]

where

\[
    \Delta S = \left( \pi d_B \frac{\Delta \theta_B}{2\pi} \right) \delta_B = \frac{1}{2} d_B \Delta \theta_B \delta_B \tag{4.34}
\]

Substituting Equation (4.34) into Equation (4.33), we obtain

\[
    \Delta Q_B = \frac{Q_B \Delta \theta_B}{2\pi} \tag{4.35}
\]

Take the point charge at \( B \) to be an infinitely small conductor 2, and the electrostatic ball probe to be conductor 1. Consider two different charge distributions \( Q_k \) and \( Q_k' \) on these conductors, respectively. Since the charge densities \( \rho = \rho' = 0 \) within the volume bounded by the conductors and \( \text{div} \, D = \rho \) (Bohn, 1968), we have

\[
    \nabla \cdot D = \nabla \cdot D' = 0 \tag{4.36}
\]

Equation (4.36) can be rewritten

\[
    \nabla \cdot (U D' - U D) = D' \nabla U - D \cdot \nabla U' = 0 \tag{4.37}
\]

Since \( E = -\text{grad} \, U \) (Bohn, 1968), Equation (4.37) becomes
\(- \mathbf{D}' \mathbf{E} + \mathbf{D} \cdot \mathbf{E}' = 0\)  
(4.38)

Applying the divergence theorem

\[ \int_\mathcal{V} \text{div} \mathbf{D} \, d\mathbf{v} = \int_\mathcal{S} \mathbf{D} \cdot \mathbf{n} \, ds \]  
(4.39)

and the expression for the charge on the \(k\)th conductor for the unprimed case

\[ Q_k = \int_{s_k} \mathbf{D} \cdot \mathbf{n} \, ds = \int_{s_k} \sigma_k \, ds \]  
(4.40)

to the above result results in the reciprocity theorem (Bohn, 1968), we obtain

\[ \sum_{k=1}^{n} \sum \left( (U_1 \mathbf{D}' - U_2 \mathbf{D}) \cdot \mathbf{n} \right) ds = \sum_{k=1}^{n} \left( U_k Q'_k - U'_k Q_k \right) = 0 \]  
(4.41)

We now consider two different charge distribution scenarios. For case 1, let

\[ Q_k = 0 \text{ for } k \neq m \text{ and } Q_m \neq 0, \]  
while for case 2, \(Q'_k = 0\) for \(k \neq l\) and \(Q'_l \neq 0\). Also, by choosing point \(P\) on \(S_1, \ldots, S_n\), we obtain equations of the form

\[ U_1 = a_{11} Q_1 + a_{12} Q_2 + \ldots + a_{1n} Q_n, \]
\[ U_n = a_{n1} Q_1 + a_{n2} Q_2 + \ldots + a_{nn} Q_n, \]  
(4.42)

In our system, case 1 corresponds to \(Q_1 = 0\) and \(Q_2 = Q\), while case 2 has \(Q'_1 = Q\) and \(Q'_2 = 0\). Thus, Equation (4.42) for cases 1 and 2 becomes

\[ U_1 = a_{12} Q_2 \]  
(4.43.a)
\[ U'_2 = a_{21} Q'_1 \]  
(4.43.b)

In addition, Equation (4.41) now reduces to

\[ U_1 Q'_1 = U'_1 Q_2 \]  
(4.44)

By substituting Equations (4.43.a) and (4.43.b) into Equation (4.44), we obtain

\[ a_{12} Q_2 Q'_1 = a_{21} Q'_1 Q_2 \]

Therefore,

\[ a_{12} = a_{21} \]  
(4.45)

Let us consider the radius of the ball probe to be \(r_P\) and the distance between the probe and source point \(B\) to be \(r\). When the field point \(P\) is taken on the surface of conductor 1 (i.e. probe), we can express the potential \(U_i\) using Equation (4.22):
\[ U_1 = a_{11}Q_1 + a_{12}Q_2 = \frac{1}{4\pi \Pi_1} \frac{1}{r_p} Q_1 + \frac{1}{4\pi \Pi_2} \frac{1}{r} Q_2 \] (4.46)

where there is no dielectric constant for the ball probe made of conductive material and medium 2 is assumed to be vacuum (i.e. \( \Pi_2 = 1 \)). Since \( U_1 = 0 \) for the grounded ball probe, Equation (4.46) becomes

\[ \frac{1}{4\pi} \left( \frac{1}{r_p} Q_1 + \frac{1}{r} Q_2 \right) = 0 \]

\[ Q_1 = -\left( \frac{r_p}{r} \right) Q_2 \] (4.47)

In our system illustrated in Figure 4.2, the source point \( B \) on the bubble surface represents a control surface area. Therefore, the expressions for charges in Equation (4.47) have to be replaced by their gradient forms such as \( Q_2 = \Delta Q_B \).

\[ \Delta Q_1 = -\left( \frac{r_p}{r} \right) \Delta Q_B \] (4.48)

Then, in order to obtain the total induced charge on the probe \( Q_1 \) from the entire bubble Equation (4.48) is integrated over the surface of the two-dimensional bubble:

\[ \int \Delta Q_1 = -\int \left( \frac{r_p}{r} \right) \frac{Q_B}{2\pi} \Delta \theta_B \]

which reduces to

\[ Q_1 = -\frac{r_p Q_B}{2\pi} \int \frac{1}{r} \Delta \theta_B \] (4.49)

By substituting the expression for \( r \) given by Equation (4.31), we can obtain the total induced charge, \( Q_{\text{induced}} \), as a function of time:

\[ Q_{\text{induced}} = -\frac{r_p Q_B}{\pi} \sqrt{\frac{2}{\sqrt{r_B^2 + (L + U_B t)^2} + 2(L + U_B t)r_B \sin \theta_B}} \] (4.50)

Finally, the induced current can be derived by differentiating the expression of \( Q_{\text{induced}} \), since the definition of current is the rate at which charge is transported through a given surface. Note that the direction of current is opposite to the direction of electrons, i.e.

\[ I_{\text{induced}} = -\frac{dQ_{\text{induced}}}{dt} \] (4.51)
It should be noted that these equations were all derived assuming that the medium is a vacuum.

4.2.2 Model 2 (Application of method of images)

We reconsider the problem posed for Model 1, but now we take into account a potential difference along the outer surface of the electrostatic ball probe. This allows us to apply the method of images to the system in order to obtain an expression for the induced charge on the probe. The method of images states that a point charge $q$ in the vicinity of a conducting sphere requires a single image charge to make the sphere a surface of zero potential (Bohn, 1968). As in Model 1, the ball probe is a grounded ($U = 0$) spherical conductor of radius, $r_p$. A simplified diagram of the system is shown in Figure 4.3.

We first determine the magnitude and location of the image $q'$ which, together with the point charge $q$, produces zero at all points on the surface of the ball probe. The point charge $q$ is at a distance $d$ from the center of the probe $O$. It is apparent from the symmetry of the problem that the image charge $q'$ lies on the line passing through $q$ and $O$. The distance $b$ and the magnitude of $q'$ are to be determined in terms of the specified quantities: $q$, $d$, and $r_p$. The potential at an arbitrary point $P$ due to $q$ and $q'$ is derived using Equation (4.22):

$$U(r, \theta, \phi) = \frac{q}{4\pi \varepsilon_0 r_1} + \frac{q'}{4\pi \varepsilon_0 r_2}$$  \hspace{1cm} (4.52)

where

$$r_1^2 = r^2 + d^2 - 2rd \cos \theta$$  \hspace{1cm} (4.53)

and

$$r_2^2 = r^2 + b^2 - 2rb \cos \theta.$$  \hspace{1cm} (4.54)

Therefore,

$$U(r, \theta, \phi) = \frac{q}{4\pi \varepsilon_0 \sqrt{r^2 + d^2 - 2rd \cos \theta}} + \frac{q'}{4\pi \varepsilon_0 \sqrt{r^2 + b^2 - 2rb \cos \theta}}$$  \hspace{1cm} (4.55)
On the surface of the ball probe which is grounded, \( r = r_p \) and \( U(r_p, 0, \phi) = 0 \) for all \( \theta \) and \( \phi \). Equation (4.52) becomes

\[ \text{Electrostatic Ball Probe} \]

\[ \text{centre of bubble} \]

\[ \text{centre of ball probe} \]

\[ \text{surface of ball probe} \]

\[ q \text{ = charge of source point on bubble surface} \]

\[ q' \text{ = image charge on probe} \]

\[ r_b \text{ = radius of bubble} \]

\[ r_p \text{ = radius of ball probe} \]

\[ \theta \text{ = angle on probe} \]

\[ \theta_b \text{ = angle on bubble} \]

\[ r_1 \text{ = distance between points } q \text{ & } P \]

\[ r_2 \text{ = distance between points } q' \text{ & } P \]

Figure 4.3. Two-dimensional bubble near a grounded ball probe
\[ U(r_p, \theta, \phi) = \frac{q}{4\pi \Pi_1 r_1} + \frac{q'}{4\pi \Pi_2 r_2} = 0 \] (4.56)

In order to satisfy the boundary condition given by Equation (4.56), the following relation is required.

\[ \frac{r_2}{r_1} = \frac{-q'}{q} = \text{constant} \] (4.57)

Let this constant be \(-c\), so that

\[ q' = c q \] (4.58)

and

\[ \frac{r_2}{r_1} = -c \] (4.59)

By substituting Equations (4.53) and (4.54) into Equation (4.59), we obtain

\[ \frac{\sqrt{r^2 + b^2 - 2rb \cos \theta}}{\sqrt{r^2 + d^2 - 2rd \cos \theta}} = -c \]

and since \( r = r_p \)

\[ \frac{r_p^2 + b^2 - 2r_p b \cos \theta}{r_p^2 + d^2 - 2r_p d \cos \theta} = (-c)^2 \]

The above equation can be simplified to

\[ \left( r_p^2 (1 - c^2) + b^2 - d^2 c^2 \right) + 2(r_p d c^2 - r_p b) \cos \theta = 0 \] (4.60)

In order to satisfy Equation (4.60) for all \( \theta \), the following equations must be satisfied.

\[ r_p d c^2 - r_p b = 0 \] (4.61.a)

\[ r_p^2 (1 - c^2) + b^2 - d^2 c^2 = 0 \] (4.61.b)

Equation (4.61.a) reduces to

\[ b = dc^2 \] (4.62)

Then, by substituting Equation (4.62) into Equation (4.61.b), we obtain

\[ r_p^2 (1 - c^2) + d^2 c^2 - d^2 c^2 = (1 - c^2)(r_p^2 - d^2 c^2) = 0 \] (4.63)

Therefore,

\[ c = \pm 1 \text{ or } c = -\frac{r_p}{d} \] in order to satisfy the above equation.
Since $c$ is generally smaller than 1 (i.e. in most cases image charge is greater than the original charge), $c = \frac{-r_p}{d}$ is the solution of the image method. Therefore, Equation (4.57) is written

\[
\frac{q'}{q} = \frac{-r_p}{r_1} = c = \frac{-r_p}{d}
\]

(4.64)

Furthermore,

\[
b = \frac{r_p^2}{d}
\]

(4.65)

These equations serve to specify the location and magnitude of the first image charge.

We now apply Equation (4.26) and differentiate Equation (4.56) at the surface of the ball probe. This results in an expression for the surface charge density.

\[
\sigma = -\Pi \frac{\partial U}{\partial r} \text{ at } r = r_p
\]

\[
\sigma = \frac{1}{4\pi} \left( \frac{(d \cos \theta - r_p)q}{r_1^3} - \frac{(r_p - b \cos \theta)q'}{r_2^3} \right)
\]

(4.66)

Substitution of Equation (4.64) into Equation (4.65) yields

\[
\sigma = \frac{q}{4\pi} \left( -r_p \left( \frac{1 - c}{r_1^3} - \frac{c}{r_2^3} \right) + \left( \frac{d + cb}{r_1^3} \right) \cos \theta \right)
\]

(4.67)

Since

\[
\frac{d}{r_1^3} + \frac{cb}{r_2^3} = \frac{d}{r_1^3} + \frac{cb}{(-cr_1)^3} = \frac{1}{r_1^3} \left( d - \frac{b}{c^2} \right) = \frac{1}{r_1^3} \left( d - \frac{dc^2}{c^2} \right) = 0
\]

(4.68)

and

\[
-r_p \left( \frac{1 - c}{r_1^3} - \frac{c}{r_2^3} \right) = -r_p \left( \frac{1}{r_1^3} - \frac{c}{(-cr_1)^3} \right) = -r_p \left( \frac{1 + 1/c^2}{c^2} \right)
\]

(4.69)

Equation (4.66) reduces to

\[
\sigma = -\frac{q r_p \left( 1 + 1/c^2 \right)}{4\pi} \frac{1}{r_1^3}
\]

(4.70)

where $c = \frac{-r_p}{d}$
Equation (4.70) represents the surface charge density induced by the charge on the control surface of the bubble. It is necessary to integrate this expression over the entire surface of the bubble as in Model 1 assuming a uniform monolayer charge distribution. With the aid of Equation (4.35) and letting \( q \) be \( \Delta Q_B \), Equation (4.70) becomes

\[
\sigma = -\frac{Q_B r_p (1 + (1/c)^2)}{8\pi^2 r_1^3} \frac{1}{r_1^3} \Delta \theta_B
\]  

(4.71)

Therefore,

\[
\sigma_{\text{total}} = -\int_0^{2\pi} Q_B r_p (1 + (1/c)^2) \frac{1}{8\pi^2 r_1^3} d\theta_B
\]  

(4.72)

Also recall that \( r_1^2 = r_p^2 + d^2 - 2r_p d \cos \theta \). Therefore,

\[
\sigma_{\text{total}} = -\int_{-\pi/2}^{\pi/2} Q_B r_p (1 + (1/c)^2) \frac{1}{4\pi^2} \frac{1}{(r_p^2 + d^2 - 2r_p d \cos \theta)^{3/2}} d\theta_B
\]  

(4.73)

where \( d \) is the distance between point \( q \) on the bubble and the centre of the ball probe, and

\[
d^2 = (r_p \cos \theta_B)^2 + (L + U_B t + r_B \sin \theta_B)^2.
\]  

(4.74)

The total surface charge density in Equation (4.73) is in units of Coulomb/m² s.

The total surface charge density is then integrated over the surface of the electrostatic ball probe to obtain the total induced charge at any given time, i.e.

\[
Q_{\text{induced}} = \int \sigma_{\text{total}} ds
\]  

(4.75)

where \( ds = (2\pi r_p \cos \theta)(r_p d\theta) \).

(4.76)

By substituting Equations (4.72) and (4.75) into Equation (4.74) we obtain

\[
Q_{\text{induced}} = \int_{-\pi/2}^{\pi/2} \sigma_{\text{total}} (2\pi r_p^2 \cos \theta) d\theta
\]

\[
Q_{\text{induced}} = \int_{-\pi/2}^{\pi/2} \left( \int_{-\pi/2}^{\pi/2} Q_B r_p (1 + (1/c)^2) \frac{1}{4\pi^2} \frac{1}{(r_p^2 + d^2 - 2r_p d \cos \theta)^{3/2}} d\theta_B \right) (2\pi r_p^2 \cos \theta) d\theta
\]

(4.77)

Differentiation of \( Q_{\text{induced}} \) yields the current induced by the bubble, \( I_{\text{induced}} \), i.e. Equation (4.51).
If there is direct charge transfer between the bubble and the ball probe, Equation (4.77) becomes

\[ Q_{\text{total}} = Q_{\text{induced}} + Q_{\text{transferred}} \tag{4.78} \]

It is difficult to estimate the charge transferred by collision. The electric current through the ball probe is given (Zhu and Soo, 1992) by

\[ I_{\text{transferred}} = A \rho_p U_p^{9/2} e^{-C_c (\rho / U_p)} \tag{4.79} \]

where \( \rho_p \) is the particle density and \( U_p \) is the particle velocity. The radial component of the particle velocity in two-dimensional fluidized beds is given by Davidson and Harrison (1963)

\[ U_r = -U_b \left( 1 - \frac{r^2}{r^*} \right) \cos \theta \tag{4.80} \]

The bubble is moving vertically and the ball probe lies on the axis of the moving bubble, and therefore, only the nose of the bubble and the bubble-wake interface experience the direct charge transfer. As a result, the particle velocity is the same as the radial velocity at these regions. The term \( \cos \theta \) will equal one since the angles are either 0° or 180°. In addition, Equation (4.80) was derived assuming that the bubble was stationary. Therefore, the bubble velocity has to be added to Equation (4.80), and Equation (4.80) becomes

\[ U_p = U_b \frac{r_p^2}{r^2} \tag{4.81} \]

where the distance between the centres of the bubble and the probe, \( r = L + U_b t \). The bubble rise velocity for isolated single bubbles in three-dimensional fluidized bed is given as,

\[ U_b = 0.711 \sqrt{g d_B} \tag{4.82} \]

while for single bubbles in two-dimensional fluidized bed,

\[ U_b = 0.511 \sqrt{g d_B} \tag{4.83} \]

\( A \) in Equation (4.79) is a constant related to the ball probe characteristics and the effects of surface contamination and nonsphericity. Therefore, \( A \) should be determined experimentally and its units are \([Cs^{3/2} m^{3/2} / kg]\) (Zhu and Soo, 1992). \( C_c \) is a
dimensional factor \([m^4/kg s]\) which should also be determined experimentally. For example, according to Zhu and Soo (1992), for the specific ball probe used in their experiments, \(A = 0.022 \, Cs^{3/2} \, m^{7/2} / kg\), and typical values of \(C_c\) for glass beads with mean diameters of 100, 200, and 450 \(\mu m\) were 0.05, 0.06, and 0.075 \(m^4/kg s\), respectively. The constant \(C_c\) can be also obtained if the particle mass flux data is available. The relationship between these parameters is (Fan and Zhu, 1998)

\[
J_p = \frac{U_p^2}{C_c} = \rho_p \left(1 - \varepsilon\right) U_p
\]  

(4.84)

Therefore, the constant \(C_c\) can be expressed as

\[
C_c = \frac{U_p}{\rho_p \left(1 - \varepsilon\right)} \left[ \frac{m/s}{kg/m^3} \right]
\]  

(4.85)

Then, Equation (4.79) becomes

\[
I_{\text{transferred}} = A \rho_p U_p^{5/2} e^{-t/(1-\varepsilon)}
\]  

(4.86)

![Figure 4.4](image)

**Figure 4.4.** Relative positions of the bubble to ball probe.

Figure 4.4 (a) corresponds to the moment when the nose of the bubble collides with the tip of the ball probe. In case (b), there is negligible direct charge transfer to the probe since the concentration of the solids inside the bubble is very small (typically 0.2 – 1.0 % by volume (Kunii and Levenspiel, 1991)). Finally, when the bubble-wake interface collides with the probe as in Figure 4.4 (c), there is significant charge transfer between the charged particles around the bubble and the electrostatic ball probe.
4.2.3 Agreement of models 1 and 2 in the limit

Consider the limiting case when the distance between the probe and the bubble is very large. Then, Equation (4.73) reduces to

\[ \sigma_{total} = -\frac{Q_B r_p (1 + 1/(r_p/d)^2)}{4\pi^2} \left( \frac{1}{r_i^3} \right) (\pi) = -\frac{Q_B (r_p^2 + d^2)}{4\pi r_p r_i^3} \]  

(4.87)

Hence,

\[ Q_p = \sigma_{total} \Delta S = \sigma_{total} \left( 4\pi r_p^2 \right) = -\frac{Q_B r_p (r_p^2 + d^2)}{r_i^3} \]

(4.88)

where \( r_i^2 = r_p^2 + d^2 - 2r_p d \cos \theta \). If \( d \gg r_p \), then \( r_i \approx d \) and also \( r_p^2 + d^2 \approx d^2 \).

Therefore, Equation (4.88) becomes

\[ Q_p = -\frac{Q_B r_p d^2}{d} = -\left( \frac{r_p}{d} \right) Q_B \]

(4.89)

This equation is the same as the one from Model 1 (Equation (4.47)), verifying that the methods for Model 1 and Model 2 agree with each other in the limiting case.

The analytical evaluations of Equations (4.50) and (4.77) were not easily achieved, and therefore computer program code was developed to carry out the integrations numerically. The MatLab programs are listed in Appendix E. During the simulations, the surface charge density induced by the charges around the bubble was integrated over the surface of the bubble, except for the small portion at the top and bottom of the bubble in order to avoid the overlap of the probe and the bubble, which is physically impossible. However, the gap left out during the integration was very small so that the error in the total value of induced current was assumed to be insignificant. The size of the gap corresponds to the diameter of the probe.

4.3 Results of simulation (1)

The first set of simulations was carried out to compare Models 1 and 2 using MatLab programs. In this section, only the induced charge on the probe was considered
during simulations without direct charge transfer between the bubble and the electrostatic ball probe to simplify the comparison. A two-dimensional fully circular bubble with a surface layer of positively charged particles with total surface charge of $1 \times 10^{-10}$ C was used in each of these simulations. Since the distance between the tip of the bubble injector and the probe was 0.205 m in the experimental set-up, the simulation covered the interval where the centre of the bubble moves from $-0.205$ to $0.205$ m, with the centre of the probe adopted as the origin of the coordinates. The bubble rise velocity, calculated using Equation (4.83), was 0.358 m/s for a bubble of diameter 50 mm.

4.3.1 Results of simulation for Model 1

Equation (4.50) was used in the simulations to generate the induced charge curve for the system. The induced current was then obtained by differentiating the charge over time period.

![Graph showing induced charge and current](image)

Figure 4.5. Charge inducement without direct charge transfer versus time for Model 1 ($Q_b = 2 \times 10^{-10}$ C, $d_B = 50$ mm, $A = 0$): (a) Charge induced on electrostatic ball probe by single bubble; (b) Current induced on probe by single bubble.
Figure 4.5 shows the simulated results. The curve on Figure 4.5 (a) represents the induced charge on the probe due to the motion of the positively charged bubble. Since it is assumed that there is no direct charge transfer, the induced charge eventually approaches zero with a minimum reached when the bubble is closest to the probe. The increment in the charge close to time zero indicates that even at the initial distance between the bubble and the probe, there is significant charge inducement. The lowest peaks occur when the nose of the bubble and the bubble-wake interface pass the probe since the shortest distance between the probe and the fastest moving (rim) particles are achieved. The small dip between two peaks is caused by the geometry and size of the bubble. Since the bubble is much larger than the ball probe, only small portions of the bubble are intercepted by the probe. Therefore, the total induced charge is considerably less than the total surface charge on the bubble at all times.

The current curve in Figure 4.5 (b), obtained by differentiating the induced charge, increases as the positively charge bubble approaches the ball probe from below. Then, as the bubble passes the ball probe, the polarity of the current signal switches to negative. The magnitudes of the positive and negative peaks are the same since the charge on the bubble is assumed to be constant throughout the period, with no net charge transfer between the bubble and the probe. The secondary peaks between the two main curves are caused by the dip in the induced charge curve.

### 4.3.2 Results of simulation for Model 2

For Model 2 all parameters (e.g. total charge on the bubble, bubble shape and diameter, and bubble rise velocity) were the same as for Model 1. The curve shapes in Figure 4.6 are very similar to those in Figure 4.5. As a positively charged bubble moves closer to the ball probe, the magnitude of the induced charge on the probe increases. The magnitude of the induced charge then decreases slightly while the probe is inside the bubble, since the distance between the probe and the particles on the rim of the cylindrical bubble is closest when either the nose of the bubble or the bubble-wake interface pass the probe. As soon as the bubble-wake interface passes the ball probe, the
induced charge starts to decay. Model 2 is slightly more sensitive than Model 1 when the
distance between the point on the bubble surface and the probe is very small (i.e. < 10
mm), since in Model 2 the finite dimension of the probe was applied instead of treating
the electrostatic ball probe as a single point. Therefore, Model 2 was chosen for further
simulations.

The differentiation of the induced charge resulted in the smooth current curve
shown in Figure 4.6 (b). Secondary peaks between the main peaks are observed for
Model 2, as for Model 1.

Figure 4.6. Charge inducement without direct charge transfer versus time for Model 2
\(Q_B = 2 \times 10^{-10} \text{ C}, d_B = 50 \text{ mm}, A = 0\): (a) Charge induced on electrostatic ball
probe by single bubble; (b) Current induced on probe by single bubble.
4.4 Results of Simulation (2): Charge distribution on bubbles

It has generally been agreed that charges on particles enhance the agglomeration process in fluidized beds, but there have been many debates regarding the polarities of charged particles. Wolny and Kazmierczak (1989) suggested two hypotheses: (1) a small portion of the fluidized bed particles are positively charged and act as active agglomeration centres, while the rest of the bed is negatively charged; (2) the particles are heteropolar, having some surface area charged positively and other portions of the surface charged negatively. Earlier studies by Katz and Sears (1969), similar to Wolny and Kazmierczak (1989), reported that fluidized bed particles are heteropolar, with the positive end of one particle aligned next to the negative end of an adjacent particle resulting in agglomeration. On the other hand, Boland and Geldart (1971) argued that different charging mechanisms exist in different parts of the fluidized bed, causing particles to be charged with different polarities. In particular, they postulated that when a single bubble is injected into a fluidized bed of glass beads, the nose and wake regions produce charges of opposite signs as a result of different charge transfer mechanism. Other arguments have also been advanced, e.g. that the particle size determines the polarity of particles (Ali et al., 1998).

In this section, three cases are simulated with different charge distributions on bubbles. In Figure 4.7, the positions of positive and negative charges can be reversed.

![Figure 4.7](image_url)

Figure 4.7. Charge distributions on bubble surface in fluidized beds: (a) uniform charge distribution; (b) half/half distribution; (c) distribution suggested by Boland and Geldart (1971).
All the simulations were performed using Model 2 assuming the dielectric constants of vacuum throughout the system. Figure 4.6 shows the results of a simulation assuming a bubble of uniform positive charge distribution. An inverted profile would result if the bubble were instead assumed to be charged negatively.

Figure 4.8. Charge and current induced on electrostatic ball probe by single bubble versus time without direct charge transfer for different charge distributions charge distributions on bubble surface in fluidized bed: Uniform charge distribution (solid line \(-\), \(Q_B = 2 \times 10^{-10} \text{ C}, d_B = 50 \text{ mm, } A = 0\)), half/half charge distribution (dash line \(-\), \(Q_{B,\text{top}} = 1 \times 10^{-11} \text{ C}, Q_{B,\text{bottom}} = -1 \times 10^{-11} \text{ C}, d_B = 50 \text{ mm, } A = 0\)), and distribution suggested by Boland and Geldart (1971) (dotted line \(...\), \(Q_{B,\text{top}} = 50 \times 10^{-12} \text{ C}, Q_{B,\text{bottom}} = -50 \times 10^{-12} \text{ C}, d_B = 50 \text{ mm, } A = 0\)).

Figure 4.8 portrays the results of simulations for cases (a), (b) and (c) in Figure 4.7. The results for cases (b) and (c) are very different from those for case (a). The induced current initially increased as the bubble approaches the ball probe, but decreases...
as soon as the top portion of the bubble passes the probe. The negative charge induced by the upper portion of the bubble and the positive charge induced by the negatively charged lower hemisphere of the bubble cancel each other out so that the induced charge curves switch their polarities when the center of the bubble is coincident with the probe. The asymptotic value of the induced charge also has a negative value instead of zero, although direct charge transfer between the bubble and the probe was not allowed during simulations. Therefore, cases (b) and (c) are incomplete modeling representations of single bubble injections in fluidized beds. Moreover, the simulation results for the Boland and Geldart charge distribution differs from their experimental results reproduced shown in Figure 4.9.

![Diagram of charge induction](image)

Figure 4.9. Single bubble injection traces from fluidized bed of 200-300 \( \mu \)m lead glass ballotini (Boland and Geldart, 1971)

Woodhead (1992) simulated induced charge against horizontal distance between the point charge and electrode centre line, and his result is shown in Figure 4.10. He assumed that the sensing ring in the column wall (i.e. induction probe) is a strip of the equipotential line. His results do not include a dip at the top of the induced charge curve, since he assumed a point charge moving in a homogeneous medium. In addition, the units were not given by the author. However, it is clear that the general trend is the same for the charge inducement.
The theoretical induced charge was also simulated by Armour-Chelu et al. (1998), and their results are reproduced in Figures 4.11 and 4.12. In this case only one particle is charged with a charge of 1 C and it is located on the horizontal axis of a column of diameter 26.5 mm. These simulated results are also very similar to our results, although they used a ring-type induction probe instead of the electrostatic ball probe used in this project. In Figure 4.12, the curve of the induced charge was found to be concave down since the particle was charged with 1 C.
Figure 4.12. Theoretical induced charge from a charged particle (1 C) 0.01 m above a finite conducting strip (Armour-Chelu et al., 1998): See Figure 2.5 for the detailed experimental set-up.

4.5 Results of Simulation (3): Total charge on bubble surface

In previous sections, we developed models simulating the charge induced by a single bubble in a fluidized bed. The total charge on the bubble surface was assumed to be 2E-10 C. We now take different values of total charges on the bubble surface to investigate their effects on the induced charge on the probe using Model 2. As shown in Equation (4.77), the total induced charge is proportional to the total charge on the bubble surface.

Figures 4.13 and 4.14 summarize the results for positively charged bubbles. As expected, while $Q_B$ is increased from 2E-10 to 6E-10 C, the magnitudes of induced charge and current signals increased three times. The simulated results for a negatively charged bubble shown in Figures 4.15 and 4.16 are very similar to those for the positively charged bubble, except that polarities of the signals are reversed.
Figure 4.13. Simulated charge output due to charge inducement by a positively charged bubble surface for various values of total surface charge

\[ Q_b = \begin{align*} 
6.0 \times 10^{-10} \text{ C} \\
4.0 \times 10^{-10} \text{ C} \\
3.2 \times 10^{-10} \text{ C} \\
2.4 \times 10^{-10} \text{ C} \\
2.0 \times 10^{-10} \text{ C} 
\end{align*} \]

\[ (d_{b0} = 50 \text{ mm}, A = 0 \text{ } C^s m^{3/2} / \text{kg}) \]
Figure 4.14. Simulated current output due to charge inducement by a positively charged bubble surface for various values of total surface charge

\[ d_B = 50 \text{ mm}, A = 0 \ C s^{3/2} m^{7/2} / \text{kg} \]
Figure 4.15. Simulated charge output due to charge inducement by a negatively charged bubble surface for various values of total surface charges

\[ (d_B = 50 \text{ mm}, A = 0 \ C s^{3/2} m^{3/2} / \text{kg} ) \]
Figure 4.16. Simulated current output due to charge inducement by a negatively charged bubble surface for various values of total surface charge

\( (d_B = 50 \text{ mm}, A = 0 \ C s^{3/5} m^{7/5} / \text{kg} ) \)
4.6 Results of Simulation (4): Charge inducement and transfer

By adding direct charge transfer to the previous simulation results, we can now simulate the signals from the collision probe (electrostatic ball probe) which was inserted into the fluidized bed of glass beads during our bubble injection experiments. Equation (4.86) was used to create two step changes of direct charge transfer illustrated in Figure 4.4. In real experiments, most of the charge transfer takes place when the nose and tail of the bubble reach the probe. The first major charge transfer occurs when the nose reaches the ball probe, while the second major charge transfer occurs when the bubble-wake interface strikes the probe. In addition, there are also minor charge transfers due to other interactions, e.g. due to upward particle motion during bubble injection and particle showering inside the bubble onto the probe. By applying the particle velocity, i.e. Equation (4.80), to Equation (4.86), we can include the direct charge transfer due to the movement of particles near the probe.

4.6.1 Positively charged bubble surface

Assuming that the total initial surface charge on the bubble is $2E-10$ C and its surface charge density is uniform, Equation (4.86), together with Equation (4.80), results in Figure 4.17 (a). Since the particle velocity near the probe increases as the bubble approaches the probe, the current due to the charge transfer also increases. However, while the probe is inside the bubble, the current reading due to the direct charge transfer is almost zero since the solid concentration inside the bubble is very low, typically 0.2 to 1.0 % by volume (Kunii and Levenspiel, 1991).

The current curve in Figure 4.17 (a) is then integrated over time to generate the charge transfer curve shown in Figure 4.17 (b). The charge transfer comes from the particles around the ball probe. Therefore, the total charge in the fluidized bed is changing, and the total charge on the bubble surface has to be adjusted accordingly. The MatLab program was then designed to subtract the amount of charge transferred from the
Figure 4.17. Predicted charge inducement and transfer by a positively charged bubble surface (initial $Q_B = 2E-10$ C, $d_B = 50$ mm, $A = 2E-13 \ C \frac{s}{m^{3/2}} / kg$):

(a) Current due to direct charge transfer between particles and probe; (b) Charge due to direct charge transfer; (c) Total current output due to charge transfer and inducement; (d) Total charge output.

Initial total charge on the bubble surface (i.e. $2E-10$ C) at any given time. Using these corrected values of $Q_B$, Equation (4.77) generates the total induced charge on the probe. Note that while the charge transfer most occurs at the nose and latter the wake, the charge is assumed to be uniformly distributed around the bubble surface at all times. Combining the total induced charge and charge transfer then yields the results shown in Figure 4.17 (d). Since the current at time zero has a finite value, the total charge at time zero also
shows a non-zero value. In order to obtain the zero reading of current at time zero, the
distance between the probe and the bubble injector should be much larger than 0.205 m.
Nevertheless, unlike Figure 4.6 (a), the charge curve does not return to the initial value at
the end of the simulation. Instead the final charge subtracted by the total charge at time
zero indicates the total charge transferred during the simulation. The simulated charge
curve is then differentiated to predict the overall current output as shown in Figure 4.17
(c). As expected, the maximum positive peak is higher due to charge transfer, whereas
the minimum of the negative peak is reduced by the charge transfer.

Five different values of the constant $A$, between 0 and 3E-13 $C s^{\frac{3}{2}} m^{\frac{1}{2}} / kg$, were
adopted to investigate the effect of direct charge transfer on the output signals. Figures
4.18 and 4.19 show the changes in charge on the ball probe and the current signal for
different values of $A$. From Equation (4.86), the amount of transferred charge is
proportional to $A$. $(L+U_B t)$ is the instantaneous vertical distance between the centres of
the probe and bubble. Thus, $(L+U_B t) = 0$ indicates that the centre of the bubble coincides
with the centre of the ball probe. Since the bubble injector in the experiments is located
0.205 m below the probe, the initial position of the centre of the bubble is taken as –0.205 m.

As shown in Figure 4.18, the magnitudes of the asymptotic (long term) values and
the maxima of the charge curves increase as $A$ increases from 0 to 3E-13 $C s^{\frac{3}{2}} m^{\frac{1}{2}} / kg$, i.e. as the direct charge transfer is increased. The differences between the curves while
the bubble is below the probe are quite small indicating that most of the charge transfer
occurs when the rim of the bubble is directly in contact with the ball probe. Figure 4.19
was obtained by differentiating the curves in Figure 4.18. As the direct charge transfer
(i.e. $A$ increases) the maximum of the positive current peak increases, while the minimum
of the negative peak is reduced. Since it is assumed that there is no direct charge transfer
between the particles and the probe while the ball probe is inside the bubble, the portions
of the curves within the bubble are very close to each other.
Figure 4.18. Cumulative charge output due to charge inducement and transfer by a positively charged bubble surface in fluidized bed for various $A$ values (in $Cs^{\frac{3}{5}}m^{\frac{7}{5}}/kg$): Initial $Q_B = 2E-10$ C; $d_B = 50$ mm.
Figure 4.19. Current output due to charge inducement and transfer by a positively charged bubble surface in fluidized bed for various $A$ values (in $Cs^{3/2}m^{3/2}/kg$): Initial $Q_B = 2E-10$ C; $d_B = 50$ mm.
4.6.2 Negatively charged bubble surface

In the previous section, we investigated the changes in charge and current caused by the relative motion of positively charged bubble. Now we assume that the injected bubble is negatively charged with the same magnitude of charge (i.e. \( Q_B = -2 \times 10^{-10} \text{ C} \)).

As shown in Figures 4.20 and 4.21, the predictions for a negatively charged bubble are the same as those for the positively charged bubble considered previously, except that the polarities of the signals are reversed.

Figure 4.20. Cumulative charge output due to charge inducement and transfer by a negatively charged bubble surface in fluidized bed for various \( A \) (in \( C s^{\frac{3}{2}} m^{\frac{1}{2}} / \text{kg} \)): Initial \( Q_B = -2 \times 10^{-10} \text{ C} \); \( d_B = 50 \text{ mm} \).
Figure 4.21. Current output due to charge inducement and transfer by a negatively charged bubble surface in fluidized bed for various $A$ (in $C s^{3/2} m^{7/2}/kg$):

Initial $Q_B = -2E-10$ C; $d_B = 50$ mm.

4.7 Results of Simulation (5): Relative permittivity of medium

The previous simulations were performed using Equations (4.50) and (4.77) developed assuming that the medium is a vacuum. However, the experiments were performed in two-dimensional fluidized beds of glass beads or polyethylene particles. Since the relative permittivities of glass beads, polyethylene particles and air all differ from that of a vacuum, the equations were modified to accommodate the respective relative permittivities. As mentioned in Chapter 1, a dielectric reduces the effective surface charge density. The effective induced current, $Q_{e,induced}$, on the metallic ball probe surface is given by
Q.e,induced = \frac{1}{\Pi_r} Q_{\text{induced}} \tag{4.90}

where \( \Pi_r = \Pi / \Pi_o \) and \( \Pi_o \) is the permittivity for vacuum. Combining Equations (4.77) and (4.90) leads to

\[
Q_{\text{e,induced}} = -\frac{1}{\Pi_r} \int_{\pi/2}^{\pi} \left( \frac{Q_o r_p (1 + 1/c^2)}{8\pi^2} \frac{1}{(r_p^2 + d^2 - 2r_p d \cos \theta)^{3/2}} \right) d\theta \left( 2\pi r^2 \cos \theta \right) d\theta \tag{4.91}
\]

The dielectric constants of air and polyethylene particles at 1 atm are 1.00059 and 2.3, respectively, whereas the dielectric constant of glass beads ranges from 5 to 10 (Reitz et al., 1993). The range of values in the latter case reflects variations in the chemical composition of different glasses.

Three cases are considered. In case 1, the dielectric constant of air is used for the entire system, and since the dielectric constant for vacuum is too close to the one of air to be distinguished, a case for vacuum was omitted. In case 2 the dielectric constant of glass beads is used throughout the simulation. Since the specific information on the dielectric constant of glass beads used in our project is unavailable, an average value, 7.5, is chosen. Finally, in case 3, the media in a fluidized bed were assumed to be ideal mixtures. Therefore, from the volumetric factions of solid and gas inside and outside the bubble, separate permittivities were estimated inside and outside the bubble, with in each case

\[
\Pi_{r,\text{mix}} = \Pi_{r,\text{gas}} \epsilon + \Pi_{r,\text{solid}} (1 - \epsilon) \tag{4.92}
\]

where \( \Pi_{r,\text{mix}}, \Pi_{r,\text{gas}}, \) and \( \Pi_{r,\text{solid}} \) are the relative permittivities of the mixture, gas, and solid, respectively, while \( \epsilon \) is the volume fractions of gas. Since the dielectric constant of a mixture must be obtained experimentally, this assumption can be only used as a very rough estimation\(^1\). In practice, the dielectric constant of a fluidized bed is extremely difficult to measure or predict, since the bed (a mixture of gas and solid particles) is not stationary like a fixed bed. According to Kunii and Levenspiel (1991), bubbles contain

\(^1\) Dr. Erik V. Bohn, personal communication
0.2 to 1.0% solids by volume. The fraction of gas outside the bubble was assumed to be the void fraction of the loose packed bed since all bubble injection experiments were performed at the minimum fluidization velocity. For glass beads, the bed voidage does not change appreciably until the minimum bubbling velocity is reached, which is almost the same as the minimum fluidization velocity. In our system, the void fraction $\varepsilon_{mf}$ in a bed of glass beads at $U_{mf}$ was 0.399. Simulated results appear in Figure 4.22.

Figure 4.22. Effect of dielectric constant on charge induced by single bubble

\[ (Q_B = 2\times10^{-10} \, C, d_B = 50 \, mm, A = 0 \, C \, s^{3/2} \, m^{7/2} / kg ) \]

According to the results in Figure 4.22, there is a large difference between using $\Pi_{r,air}$ and $\Pi_{r,\text{glass beads}}$. $\Pi_{r,mix}$ shows a combination of the two. The magnitude of the induced charge is higher for case 1 than for case 3, while case 2 resulted in lowest induced charge on the ball probe. As expected, case 3 follows the trend of case 2 until the nose of the bubble reaches the probe, and then while the probe is inside the bubble the induced charge curve for case 3 behaves like that for case 1. After the tail of the bubble
passes the probe, the induced charge decreases rapidly to values slightly higher than for case 2. These simulated results are then differentiated to predict the current output induced by a bubble rising in a fluidized bed.

Figure 4.23. Effect of dielectric constant on current induced by single bubble

\( Q_B = 2E-10 \text{ C, } d_B = 50 \text{ mm, } A = 0 \)

As shown in Figures 4.23, the effect of distance remains the same when the relative permittivity is changed. The rate of increase in current in case 3 is slower than for case 1, but slightly faster than for case 2 until the bubble reaches the ball probe. On the other hand, when the nose of the bubble or the bubble-wake interface reaches with the probe there is an extremely high current. It is difficult to show the trend for all three cases on one scale. The small window in Figure 4.23 shows how high the current of case 3 was compared to the other cases. The results found during the preliminary experiments (Chapter 3) lie between the predictions for case 1 and case 3.
In order to compare case 1 and case 3 in detail, simulations were performed using the mixture relative permittivity. Figure 4.24 shows the charge output due to charge transfer and inducement. As $A$ increases, the charge transfer (represented by the differences between the asymptotes) also increases. The magnitude of the peak increases as well. The discontinuity in the dielectric constant in the system still results in the extreme change in induced charge near the nose and tail of the bubble. These patterns also bring about unreasonably high current outputs as shown in Figure 4.25. Since the curves overlap, it is difficult to identify each. However, it is clear that for the application of the dielectric constant of the mixture, the induced current is dominant over the direct charge transfer.

![Figure 4.24](image.png)

Figure 4.24. Effect of dielectric constants and charge transfer on charge output

(Q_B = 2E-10 C, d_B = 50 mm)
Figure 4.25. Effect of dielectric constants and charge transfer on current output

\(Q_B = 2E-10 \text{ C}, \ d_B = 50 \text{ mm}\)
Chapter 5
Bubble Injection in Fluidized Beds

5.1 Introduction

High surface conductivity is one of the main characteristics of static charges (Boland and Geldart, 1971). In addition, although a large voltage is produced due to the accumulation of the electrostatic charges in fluidized beds, the actual current available from such a source is extremely low since most of the voltage is induced. Therefore, it is very difficult to measure the current in order to determine the degree of static accumulation in fluidized beds.

In this chapter, the experimental results of charge inducement and transfer due to bubble injection performed in two-dimensional and three-dimensional fluidized beds are discussed, while the output of the electrostatic ball probe is presented in voltage. The experimental results using the two-dimensional fluidized bed are then compared with the simulation results in Chapter 4, for charge inducement and transfer by individual moving bubbles in a two-dimensional gas-solid fluidized bed.

In addition, several methods of reducing/eliminating electrostatic charge accumulation in fluidized beds are investigated by interpreting the static charge signals in fluidized beds in terms of charge inducement and transfer.

5.2 Experiments

Two experimental set-ups were prepared to perform bubble injection experiments: a two-dimensional and a three-dimensional fluidization column. Both columns shared the main air line and the humidifier/dryer section described in chapter 2. Also, the same instrumentation was utilized.
5.2.1 Two-dimensional fluidization column

The two-dimensional column was 0.307 m wide, 0.022 m thick, and 1.24 m in height from the distributor as shown in Figure 5.1. There were three sets of circular ports at various heights. Each pair of removable measuring ports was located at the same height on the front and back of the bed. This set-up allowed the signals from the electrostatic ball probe and the optical fiber probe to be synchronized. The initial location of the hygrometer/thermometer was above the bed as shown in Figure 5.1, but at low superficial gas velocities, the meter was found less effective. As a result, the hygrometer/thermometer was moved to the upstream of the windbox.

Figure 5.1. Schematic diagram of two-dimensional fluidization column
5.2.2 Three-dimensional fluidization column

Since the inside thickness of the two-dimensional fluidization column was only 0.022 m, particle-wall interactions may affect the output signals. Therefore, it was important to conduct experiments in a three-dimensional fluidization column to investigate whether bubbles gave rise to charging in a similar manner. Figures 2.1 and 2.2 describe the experimental set-up. Since the ratio of the diameter of the column to the mean particle diameter is much larger than 20 (Appendix C), wall effects were assumed to be much smaller than in the two-dimensional bed.

5.2.3 Noise elimination

Since the actual current through the electrostatic ball probe was very small, it was important to ensure that there was no significant level of noise in the system interfering with the experimental signals. There were many electronic components, which could be sources of noise. First, the voltage output was obtained at 0 m/s superficial gas velocity. As shown in Figure 5.2, the fluctuation of the voltage output even at 0 m/s is significant.

![Figure 5.2. Voltage output at 0 m/s superficial gas velocity (sampled at 100 Hz)](image-url)
In order to determine the noise level of each electronic component, a series of noise tests was carried out as given in Appendix D. For each set of experimental data, using the computer software ORIGIN a Fast Fourier Transformation (FFT) was performed to check the level of noise and the frequency of the signals of interest. Each data set consisted of time as the independent variable (X dataset) and voltage output as the dependent variable (Y dataset). Therefore, the X axis for the FFT graph window is scaled in units of Hz (frequency). Figure 5.3 shows the FFT graph of the voltage output corresponding to Figure 5.2.

![FFT Graph](image)

**Figure 5.3.** FFT (Fast Fourier Transformation) of the voltage output in Figure 5.2.

There are two prominent peaks at 20 and 40 Hz (these frequencies adding up to 60 Hz). Since most electronic instruments have an input frequency of 60 Hz, this is a good indication that there is significant noise in the system. The voltage output obtained at a frequency higher than 120 Hz would result in a high peak at 60 Hz. The large peak around 2 Hz is likely associated with the bubble frequency in the bubbling fluidized bed.

One of the suspected sources of the noise was the A/D card. The A/D card converts analog signals to digital signals as shown in Figure 5.4.
Analog signal (single)  
V = 0 V  

Digital signal (12 bits)  
D0  
D11  

Figure 5.4. Mechanism of A/D card (DAS08)

Since the A/D converter has a maximum output of 5 V, the error in the A/D card can be estimated as

\[
\frac{5000 \text{ mV}}{(4096-2048)} = 2.4 \text{ mV}
\]

To minimize the measurement error, the signal tracked by the A/D card has to be greater than 2.4 mV. The noise due to other components in the system is not as easily calculated as above. The series of experiments were carried out as listed in Appendix D and the results are shown in Figure 5.5.

As suggested from the above calculation, the noise level for the A/D card was found to be quite small. Also, the noise from the electrometer was not significant regardless of the amplification. However, the noise caused by the amplifier was up to 30 times higher than that due to other components in the system. Therefore, the amplifier circuit was modified by adding a capacitor of 1000 F to reduce the amplifier noise.

Figures 5.6 and 5.7 show the voltage signals and its corresponding FFT, respectively after the modification of the amplifier. There are no peaks at either 20 or 40
Hz in Figure 5.7, while the major peak is still around 2 Hz. This implies that the charge inducement and transfer are closely associated with the bubbles. Therefore, the minimum sampling frequency was suggested to be an order of magnitudes higher, i.e. 20 Hz. During the bubble injection experiments, the sampling frequency was set at 100 Hz in order to capture details of the bubble passage.

![Graph showing standard deviation from noise test at 0 m/s superficial gas velocity](image)

Figure 5.5. Standard deviation from noise test at 0 m/s superficial gas velocity
Figure 5.6. Voltage output of electrostatic ball probe at $U_g = 0.067$ m/s (x10 amplification, 100 Hz)

Figure 5.7. FFT graph of voltage signal in Figure 5.6
5.3 Results and Discussion for 2-D Bubble Injection

5.3.1 Base case

5.3.1.1 Single bubble injection

Single bubble injection experiments were carried out in a two-dimensional fluidized bed of glass beads as described in Chapter 2 and section 5.2.1. The distance between the bubble injector and the probes was 0.205 m, and the static bed height was 0.45 m. Since any air bubbles generated from the distributor would interfere with the signals due to the single bubble injection, the background superficial gas velocity was set just below the minimum bubbling velocity. Figure 5.8 illustrates the images taken by a digital camera, and Figure 5.9 shows typical results obtained from single bubble injection in a two-dimensional bed of glass beads without any additives.

Figure 5.8. Images taken by digital camera during single bubble injection in 2-d bed of 321 μm glass beads ($U_g = 0.122$ m/s, $d_B = 46$ mm)
The circular port on the front face of the column holds the optical fiber probe while the electrostatic ball probe is located on the back of the column at the same level. The probes were located just below the surface of the static bed as suggested by Ciborowski and Woldarski (1962).

The voltage output in Figure 5.9 (a) is very similar to the charge traces obtained by Boland and Geldart (1971) shown in Figure 4.9. They also used a Keithley electrometer (610A – vacuum tube) to measure the voltage and current through the ball probe. They selected a standard resistance of $10^9$ ohms in order to obtain measurable voltage readings. However, they used a Visicorder to determine the location of the bubble as a function of time, which is less accurate than the optical fiber probe. This may explain why, although the positions of the bubble relative to the ball probe are indicated on Figure 4.9, their results differ from ours. In their case, the units of the axis are not even clear. Synchronization of the signals from the electrostatic ball probe and the optical fiber probe is likely to be more accurate. Regardless of the size of the bubble, the maximum of the first peak corresponded to when the centre of the bubble was lined up with the centre of the ball probe. In Figure 5.9, "nose" indicates the alignment of the nose of the bubble with the centre of the probe, whereas "bubble-wake interface" represents the moment the bubble-wake interface comes in contact with the probe.

Another main difference between their experimental set-up and ours was that the ball probe was shielded as the layer of the wall material retained at the tip of the probe in their case, whereas we used a collision probe without any shield. The thickness of the shield was approximately 0.8 mm (Boland and Geldart, 1971). Therefore, the portion of the voltage readings due to direct charge transfer would be smaller for their case than ours. In our case, the probe was directly installed into the two-dimensional fluidization column in such a manner that the stainless steel ball at the tip of the probe interacted freely with charged particles.

From Figure 4.9, Boland and Geldart (1971) concluded that most electrostatic charges are generated around the perimeter of rising bubbles, particularly in the wake
region, since this is the region of the most intense particle activity. Moreover, the nose and wake regions were said to generate voltages of opposite sign as a result of different charge transfer mechanisms at the nose and wake. However, they could not explain the charging mechanisms. Wolny and Kazmierczak (1989) reported that the generation and dissipation rate of electrostatic charges in a fluidized bed is much higher than in a fixed bed. This indicates that charge generation and dissipation are influenced by the frequency of formation and breaking of particle surface contacts, suggesting that the charge generation and dissipation should be larger in the wake region.
Figure 5.10 shows photographs of bubble injection in a two-dimensional fluidized bed containing +150/-120 mesh opaque lead glass ballotini and +52/-36 mesh blue lead glass ballotini, incipiently fluidized with air of 60 % relative humidity (Boland and Geldart, 1971). The dark black in Figure 5.10 corresponds to the large particles while the gray represents fine particles and the white is the bubble itself. Whereas the bulk of the bed exhibits a uniform black shade, remarkable gray streaks were observed in the area at the rear of the bubble, particularly the wake region (Boland and Geldart, 1971). Boland and Geldart (1971) argued that this confirmed that the wake region generates higher charge than the nose region. However, since the relative humidity of the fluidizing gas was 60 %, it is hard to conclude that bubble streaking was solely caused by electrostatic charges. It could instead be due to other interparticle forces such as Van der Waals forces which are known to be most significant for fine particles.

As shown in Chapter 4, it is clear in our case why the voltage reading changes its sign before and after the ball probe. This occurs because when the bubble is approaching the probe, the intensity of electromagnetic field between the bubble and the probe increases, while the opposite happens when the bubble moves away from the probe. As a result, a bubble surface consists of particles charged with one sign produces two voltage
peaks of opposite sign. The sign of the first voltage peak is the same as the sign of the charges on the particles around the bubble. In addition, as shown in Figure 5.9 the magnitude of the second peak was always smaller than the first peak, since the part of the charges on the particles around the bubble was neutralized each time the bubble periphery reached the ball probe. This results in the decreased magnitude of the induced voltage after the collisions. Also, during each collision the bubble surrounded by positively charged particles would gain negative charges (i.e. electrons) from the grounded probe and the sign of the voltage output would be positive corresponding to the direct of charge movements. The sign of the voltage associated with charge transfer is discussed in detail in Chapter 4. The voltage readings caused by the direct charge transfer influence the overall voltage output and result in the higher first peak and smaller second peak. The solenoid valve used in bubble injection was only on when a 5 V voltage signal was fed to it. The program written in Visual Basic for data acquisition was also capable of sending such a voltage signal to the solenoid valve. The third curve with step change in Figure 5.9 represents the period when the bubble was injected. The initial disturbance in voltage signal resulted from the rise in the bed near the ball probe during the bubble injection period. Since the ball probe is made of stainless steel, there is continuous charge transfer between the probe and the particles surrounding it in order to balance their Fermi energy levels discussed in Chapter 3. This charge transfer is enhanced when the particles are in motion.

Boland and Geldart (1971) could not further interpret the voltage readings from their bubble injection experiments to obtain the amount of charge on the bubble and the charge transfer. Woodhead (1992) and Armour-Chelu et al. (1998) tried to develop a model to predict the induced current through a finite conducting strip by a passing charged particle. However, these models were designed for pneumatic transport in a circular pipe, and also they assumed the particle to be a single point charge which is much smaller than the strip probe. Therefore, it is not valid to compare their results (see Figure 4.10) with our results shown in Figure 5.9 (b).
Since the experimental data obtained were in voltage and the size of the resistor and the total amplification are known, we can write

\[ I_{\text{total}} = \frac{V}{1000 R} \]  

(5.1)

where \( V \) is the voltage output, \( R \) is 10 Mohm, and the total amplification is 1000. By definition, current is the rate at which charge is transported through a given surface (Bohn, 1968). Note that we adopt the convention that the direction of current is opposite to the direction of electron motion. Hence, the charge on the ball probe, \( Q_p \), is given by

\[ Q_p = -\int I_{\text{total}} \, dt \]  

(5.2)

Figure 5.9 (b) was obtained by integrating the current calculated from voltage readings. Note that this is the charge on the ball probe, not on the particles around the bubble. Since the charge on the particles surrounding the bubble is not the same as the induced charge when the distance between the bubble and the probe is large, it is important to note that the charge in Figure 5.9 (b) is on the ball probe. In addition, the charges on the bubble induce charges on the probe of opposite sign. For example, the negative charge in Figure 5.9 (b) indicates that the charges on the probe were induced by a positively charged bubble. The asymptotic value represents the direct charge transfer between the probe and the particles. As indicated in Figure 5.9 (b), there are six main parameters could be used to illustrate the characteristics of electrostatic charges in fluidized beds: \( V_{\text{max}}, V_{\text{min}}, C_{\text{max}}, Q_{\text{transfer}}, \) and half height times for the first and second peaks. These parameters are used throughout this thesis.

Using the base case shown in Figure 5.9, we now fit our modeling results. Figure 5.11 shows the experimental and model simulation outputs. Using equations developed in Chapter 4, the parameter \( Q_B \) (1.8 E-8 C) was obtained by fitting \( C_{\text{max}} \) of the model simulation results to the experimental results. Then, by applying the different values of parameter \( A \) into Equation (4.79), we find the value of \( A \) (1.8 E-11 C s\(^{3/5}\) m\(^{7/5}\) / kg), which allows the same amount of charge transfer. By differentiating the modeling results, we obtain the corresponding current reading which was further modified for the size of resistor and the amplification to convert current to the voltage. The final modeling
results in voltage are then compared with the voltage signals obtained experimentally in Figure 5.12.

The experimental and modeling results do not agree very well. However, the trend and patterns in the signals are quite similar. The two main peaks in modeling results lined up with the two dotted lines, indicating the moments that the nose of the bubble and bubble-wake interface pass the probe.

Figure 5.11. Experimental base case \( (U_g = 0.122 \text{ m/s}, \text{R.H.} = 17 \%, T = 20 ^\circ \text{C}) \) and model simulation \( (Q_B = 1.8E-8 \text{ C and } A = 1.8E-11 \text{ C s}^{3/5} \text{ m}^{7/5} / \text{ kg}) \) charge accumulation due to bubble injection in two-dimensional fluidized bed of 321 \( \mu \text{m} \) glass beads.
Figure 5.12. Experimental base case ($U_g = 0.122$ m/s, R.H. = 17 %, $T = 20$ °C) and model simulation ($Q_B = 1.8E-8$ C and $A = 1.8E-11$ C s$^{3/5}$ m$^{7/5}$ / kg) voltage output due to bubble injection in two-dimensional fluidized bed of 321 μm glass beads.

**Limitations of the model**

There are some limitations in the model that cause the differences between the experiments and predictions in Figures 5.11 and 5.12. First, the dielectric constant used to obtain the modeling results was 1.00059, the value for air at 1 atm. However, it is clear that the dielectric constants of the medium both inside and outside the bubble were much larger, since the permittivity of glass beads is 7.5. The dielectric constant of air was used, because as discussed in Chapter 4, it is impossible to quantify the dielectric
constant of a mixture, particularly when the mixture is in motion. Consequently, $V_{\text{max}}$ from the model is much larger than the experimental values.

Secondly, the charge transfer between the probe and the particles may not be instantaneous and also the charge induced or transferred to the ball probe would not decay instantaneously. From Chapter 1, the charge decays exponentially (Equation (1.3)). This may explain why the experimental signals lag the modeling results.

The shape of the bubble was also assumed to be perfectly spherical, whereas real bubbles are kidney shaped with a wake occupying up to 30% of the sphere volume. Another limitation in our model was that charged particles around the bubble were assumed to form a monolayer on the surface, although the charged particles near the probe, regardless of whether they are on the surface of the bubble, all influence the voltage reading. In addition, the layer of charged particles on the inner wall of the fluidization column affected the voltage output, while the probe was inside the bubble.

Despite these limitations of the model, the model helps understand the effect of charge inducement and transfer during bubble injection. The following sections discuss the experimental findings from bubble injections in fluidized beds.

**Effect of polyethylene shield**

As already noted, Boland and Geldart (1971) used a ball probe with a 0.8 mm thick shield. However, even then it was impossible to entirely eliminate direct charge transfer between the probe and the particles. The non-zero asymptotic voltage in Figure 4.9 indicates that there was a net charge transfer. Experiments were therefore performed in this work using a plastic cover of 0.5 mm thickness covering the ball probe as shown in Figure 5.13. The cover was made of a polyethylene sheet, and a box opened one side was constructed and fixed onto the probe with the electrical tape.
As shown in Figure 5.14, the polyethylene shield reduced the direct charge transfer. However, it was very difficult to eliminate the charge transfer. When the probe was located inside the polyethylene cover with 2 mm of gap between them as shown in Figure 5.13 (b), the charge transfer was reduced by half.

Figure 5.13. Polyethylene covers for electrostatic ball probe

![Polyethylene covers](image)

Figure 5.14. Effect of partial insulation on the electrostatic ball probe for bubble injection in two-dimensional fluidized bed of 321 μm glass beads ($U_g = 0.122$ m/s, R.H. = 17%, T = 20 °C): (a) Voltage output; (b) Charge inducement and transfer.
5.3.1.2 Multiple bubble injection

Figure 5.15 shows the experimental results of multiple bubble injection in a two-dimensional fluidized bed of 321 μm glass beads. Within 15 second, three bubbles of the same size were injected and the output signals were continuously collected. It was found that the signals were quite repeatable. The differences between the asymptotes represent the charge transfers due to each bubble. The charge transfer from the charged particles around the bubble to the ball probe was found to be constant during multiple bubble injection.

![Figure 5.15](image)

Figure 5.15. Multiple bubble injection into two-dimensional fluidized bed of 321 μm glass beads ($U_g = 0.122$ m/s, R.H. = 14 %, T = 20 °C): (a) Voltage output; (b) Charge inducement and transfer.
Figure 5.16 shows the typical voltage output for multiple bubble injection in a two-dimensional bed of polyethylene particles. Since interparticle forces including electrostatic forces in the bed are extremely high, it was impossible to form bubbles. Polyethylene particles were attached to each other and did not move freely, even at high superficial gas velocities. When the air was injected into the bed by the bubble injector, it formed a thin square-nosed slug and moved up very slowly.

Figure 5.16. Multiple air injections into two-dimensional fluidized bed of 378 µm polyethylene resin: Typical results of base case
\( U_g = 0.125 \text{ m/s}, \text{ R.H.} = 17 \%, \text{ T} = 20 ^\circ \text{C}. \)
5.3.1.3 Effect of bubble size

The electrostatic charges produced by different sizes of two-dimensional bubbles are compared in Figure 5.17. The bubble volumes plotted are injected volumes of air calculated using the pressure difference in the bubble injector before and after the bubble injection. Since the gas bubble in a gas-solid fluidized bed does not have a definite interface, some portion of the air injected likely penetrated into the dense phase resulting in smaller actual bubble sizes. The volume of the bubble was approximately 8.5 vol. % less than the injected volume of air. The degree of charging increased with the bubble size, since bubble rise velocity increases with bubble diameter and consequently the particle velocities in the region of the bubble are larger. This observation agrees with those of previous researchers who found that maximum charging occurred near the bed surface which is where the largest bubbles occur (Boland and Geldart, 1971).

Figure 5.17. Effect of bubble size for single bubble injection into two-dimensional fluidized bed of glass beads on voltage output, and charge inducement and transfer ($U_g = 0.122$ m/s, R.H. = 17 %, $T = 20 ^\circ C$).
When the volume of the injected bubble was increased from 13 ml to 39 ml, the magnitudes of both negative and positive peaks slightly increased. The absolute values of $C_{\text{max}}$ and charge transfer also increased, indicating that larger bubbles produce not only higher charge transfer but also higher charge inducement. In subsequent experiments, the injected bubble volume was fixed at around 40 ml. The bubble size appeared to remain constant while the bubble rose up to the surface of the bed. The error bars were generated by applying student $t$ distribution, after rejecting approximately 70 % of bubble injection experimental data sets due to the different bubble sizes or non-vertical bubble trajectory.

5.3.2 Reduction/elimination of electrostatic charge accumulation

The major goals of this thesis were to understand the mechanisms of charge generation and to develop a method of quantifying and interpreting the electrostatic charge signals in fluidized beds. A secondary purpose was to investigate methods of reducing/eliminating accumulation of electrostatic charges in fluidized beds.

In the past, there have been efforts to prevent the accumulation of electrostatic charges in fluidized beds. However, there has been little direct research into electrostatic charges in commercial reactors. As a result, the factors causing electrostatic charging and mechanisms of reducing electrostatic charge accumulation are still poorly understood.

A review of the literature suggests that there are five methods of preventing electrostatic charge accumulation in a fluidized bed: increasing humidity of the fluidizing gas, adding an anti-static agent, grounding the column, coating the inner wall of the column, and adding fine Geldart group C particles.

Grounding is the simplest method to reduce electrostatic charging. However, grounding the column has been found to be generally ineffective, because the method is based on the assumption that electrostatic charges are primarily generated from surface
charge polarization due to friction between the particles and the vessel wall. However, most electrostatic charges in large commercial units result from particle-particle and particle-gas interactions.

Ally and Klinzing (1985) reported that at the same operating conditions, the charge-to-mass ratio of copper particles in a glass tube is $10^2$ times higher than that in a plexiglas tube, because glass can extract electrons from copper particles better than Plexiglas. The diameters of the vessels used were quite small (i.e. 0.0254 m), so that it is reasonable to assume that most electrostatic charge was generated from friction between the particles and the wall. According to Ally and Klinzing (1985), the relative ability to release electrons is: copper > plexiglas > glass.

However, in large columns a larger portion of electrostatic charges is produced due to particle-particle and particle-gas interactions. In contrast to the findings by Ally and Klinzing (1985) using a 0.0254 m diameter column, Gidaspow et al (1986) reported that the effect of the materials of construction on the triboelectric charge was insignificant in a two-dimensional fluidized bed of 0.0254 m thickness. Since the rate of transfer of electrostatic charges to the wall is limited without the aid of either humidity or an anti-static agent, grounding is ineffective for reducing electrostatic charging in large fluidized bed reactors.

Another method of preventing the adhesion of particles is to coat the inner surface of the column with another substance such as cellotape or Scotch tape (Grace and Baeyans, 1986). Although this method has been used widely, the mechanism is unclear.

The other three methods were investigated in this project, i.e. humidifying air, adding fine group C particles, and adding anti-static agents. Grounding the unit was excluded since it is known to be ineffective in large units, while coating the inner wall of the column with Scotch tape was too difficult to apply.
5.3.2.1 Increasing humidity of the fluidizing gas

Adding moisture is a well-known method of reducing electrostatic charges. The moisture content of the fluidizing stream does not change the rate of charge generation but increases the rate of electrostatic charge dissipation (Ciborowski and Wlodarski, 1962). Therefore, the cumulative charge is insignificant in fluidized beds when the fluidizing gas is humidified. Katz and Sears (1969) reported that moisture in the fluidizing gas results in rapid dissipation of charges by increasing surface conductivity by factors of $10^6$. Injecting inert liquid hydrocarbons has also been suggested to decrease the electrostatic adhesion of the polymer granules by Mitsubishi Petrochemical Company (US Pat. 3,944,534). However, more research is needed on the effectiveness and mechanism of this method.

Unfortunately, introducing moisture to the fluidized bed to reduce electrostatic charges has been found to be ineffective at temperatures $> 80$ °C, although most polymerization processes take place between 60 and 100 °C (Ciborowski and Wlodarski, 1962). In addition, when the relative humidity of the fluidizing gas exceeded 70 %, the fluidized bed was found to be quite unstable due to capillary forces (Wolny and Kazmierczak, 1989).

Ciborowski and Wlodarski (1962) found that the minimum fluidization velocity decreased as the moisture content in the fluidizing air increased. This is because the bed is easier to fluidize when interparticle forces are reduced, and adding moisture is a well-known method of reducing electrostatic charges. The moisture content of the fluidizing stream increases the rate of electrostatic charge dissipation, thereby decreasing the minimum fluidization velocity (Ciborowski and Wlodarski, 1962). A considerable charge leakage was observed for the system of the ambient carrier gases with high humidity. Results are shown in Figure 5.18 (Guardiola et al., 1996). The voltage measured between the probe and distributor at 50 % relative humidity of fluidizing gas is ten times higher than for 70 % relative humidity.
Ciborowski and Wlodarski (1962) also reported that the electrode reached lower potentials for greater humidity of the surrounding air. However, the electrode potential increased rapidly as the humidity increased beyond 4 g/kg of fluidizing gas (Ciborowski and Wlodarski, 1962). This may be due to an increase in capillary force in the fluidized beds. However, according to Psychrometric chart at 20 °C the corresponding relative humidity is only about 30 % for 4 g/kg dry air. According to Vanecek et al. (1967), the minimum fluidization velocity increased rapidly as the moisture content increased from 1 wt % (i.e. 70 % relative humidity) to 4 wt % (i.e. supersaturated) due to capillary forces.

Figure 5.18. Variation of probe-distributor voltage with time for $d_p = 350$ and 420 μm and $u_f/u_{mf} = 2.5$ (Guardiola et al., 1996)

Figures 5.19 to 5.23 show voltage outputs from the current study as the relative humidity of the fluidizing air was increased from 6 % to 98 % by controlling the proportion of air passing through the humidifier and dryer columns. Before each measurement, there was a 2 h waiting period to ensure that steady state had been achieved. The bubble size and superficial gas velocity were kept constant throughout the experiments. Bubble injection at each relative humidity was repeated three times.
Figure 5.19. Voltage output of bubble injection in two-dimensional fluidized bed of 321 μm glass beads at R.H. = 6 % ($U_g = 0.122$ m/s, $T = 20 ^\circ$C)

Figure 5.20. Voltage output of bubble injection in two-dimensional fluidized bed of 321 μm glass beads at R.H. = 43 % ($U_g = 0.122$ m/s, $T = 20 ^\circ$C)
Figure 5.21. Voltage output of bubble injection in two-dimensional fluidized bed of 321 μm glass beads at R.H. = 72 % ($U_e = 0.122$ m/s, $T = 20$ °C)

Figure 5.22. Voltage output of bubble injection in two-dimensional fluidized bed of 321 μm glass beads at R.H. = 92 % ($U_e = 0.122$ m/s, $T = 20$ °C)
Figure 5.23. Voltage output of bubble injection in two-dimensional fluidized bed of 321 μm glass beads at R.H. = 98 % ($U_g = 0.122$ m/s, $T = 20^\circ$C)

Each run generated a figure similar to Figure 5.19. Voltage outputs were integrated using Equations (5.1) and (5.2) to obtain the charge curves at each condition. The six experimental parameters: $V_{max}$, $V_{min}$, $C_{max}$, $C_{min}$, and half height times for the first and second peaks, were obtained from those figures, and the results were then plotted against the relative humidity.

Two sets of experiments were performed to investigate the effect of increasing relative humidity in fluidizing air. Figure 5.24 plots the results of the first set of experiments. As shown in Figure 5.24, while the relative humidity increased from 6 % to about 35 %, $V_{max}$, $V_{min}$, $C_{max}$, and $C_{transfer}$ all decreased. These parameters were nearly constant between 35 % and 90 % relative humidities. However, when the relative humidity increased beyond 90 % the magnitudes of the parameters decreased further. The error bars were generated using the "student t distribution" from the replications (Newbold, 1991).
During the first set of experiments, the location of the hygrometer/thermometer was above the fluidized bed. However, it was found that the hygrometer/thermometer was not sufficiently sensitive to detect the humidity of air at low velocities. Therefore, the hygrometer/thermometer was relocated to upstream (i.e. below) of the column as shown in Figure 5.1. The results in Figures 5.25 to 5.27 are for the second set of experiments.

Figure 5.24. Effect of relative humidity of fluidizing gas on bubble injection in two-dimensional fluidized bed of 321 μm glass beads ($U_g = 0.122$ m/s, $T = 20 ^\circ$C): (a) Voltage output; (b) Charge inducement and transfer.
Figure 5.25. Effect of relative humidity of fluidizing gas on Voltage output of bubble injection in two-dimensional fluidized bed of 321 μm glass beads

($U_g = 0.122$ m/s, $T = 20^\circ$C)
Figure 5.26. Effect of relative humidity of fluidizing gas on charge inducement and transfer of bubble injection in two-dimensional fluidized bed of 321 µm glass beads ($U_g = 0.122$ m/s, $T = 20 {}^\circ$C)
Figure 5.27. Effect of relative humidity of fluidizing gas on half height time of bubble
injection in two-dimensional fluidized bed of 321 μm glass beads
($U_g = 0.122$ m/s, $T = 20$ °C)
The results shown in Figure 5.25 are quite similar to those shown in Figure 5.24 (a). The difference is that the magnitudes of the maximum voltage values are almost twice larger in Figure 5.24 (a) than in Figure 5.25. Since the electrostatic charging is such a complex process, it was quite difficult to reproduce the absolute values of the voltage output when different batches of particles were used. Even small amount of impurities in the bed could bring about a difference in the experimental results. However, despite the changes in the batch of the particles and the location of the hygrometer/thermometer, the patterns of the experimental results were quite reproducible as shown in Figures 5.24 (a) and 5.25. Both figures show an initial decrease in $V_{\text{max}}$ and a constant value of $V_{\text{max}}$ at the relative humidities higher than 40 %, while $V_{\text{min}}$ was quite constant throughout the entire range of the relative humidity. In case of the parameters, $C_{\text{max}}$ and $C_{\text{transfer}}$, the second set of the experimental results shown in Figure 5.26 reached a constant value at a lower relative humidity (20 %) than the first set (40 %) shown in Figure 5.24 (b). This difference may be caused by the location of the hygrometer/thermometer as discussed previously. Since the second set of experiments was performed after the relocation of the hygrometer/thermometer, those results were believed to be more representative and reliable.

The parameters, $V_{\text{max}}$, $V_{\text{min}}$, $C_{\text{max}}$, and $C_{\text{transfer}}$, are affected by many factors such as the magnitude of the charges on the particles around the bubble, the bubble rise velocity, the background superficial gas velocity and the location of the probe in the bed. Therefore, all factors except the relative humidity were maintained constants throughout the bubble injection experiments in the two-dimensional fluidized bed of 321 µm glass beads. The injected bubble volume and the superficial gas velocity were kept at 40 ml and 0.122 m/s, respectively.

As shown in Figures 5.25 to 5.27, the results obtained for the second set of experiments were distinguished in five major zones: A, B, C, D, and E. Zone A corresponds to the region between 0 % to 20 % relative humidity (i.e. R.H.), with typical results shown in Figure 5.19. In this zone, the maximum voltage ($V_{\text{max}}$) decreased while the minimum voltage ($V_{\text{min}}$) was constant as the R.H. increased. According to Figure
5.26, the maximum charge ($C_{\text{max}}$) and charge transfer ($C_{\text{transfer}}$) also decreased as the relative humidity of the fluidizing air increased. There was some disturbance in voltage during the bubble injection, but the magnitude of the disturbance was small compared to the overall voltage signal. Figure 5.27 shows that the half height times for the first and second peaks were quite constant at a low value when the relative humidity increased up to 20%. The half height time for the first (positive) peak is a function of bubble residence time, whereas the half height time for the second (negative) peak is proportional to the time required for charge dissipation. In other words, the rate of charge dissipation did not change as the relative humidity of the air increased up to 20%. The low values of half height time for the negative peak indicate that due to low humidity, the surface conductivity of the particles was low resulting in limited dissipation of electrostatic charges from the bed through the probe and high accumulation of static charges in the fluidized bed.

In zone B, the voltage output pattern was very similar to that in zone A. The disturbance during bubble injection seemed larger, but the minimum voltage, maximum charge and charge transfer were quite constant when the relative humidity increased from 20% to 40%. Particularly, the charge transfer was found to be minimal. On the other hand, as shown in Figure 5.25, the maximum voltage slightly increased as the R.H. increased. This may be due to the slight increase in surface conductivity caused by humidity in the fluidizing air which allowed higher charge transfer between the metallic ball probe and the particles, and among particles. According to Figures 5.26 and 5.27, at relative humidities between 20% and 40%, the time required to dissipate charges through the ball probe was almost the same as in zone A, while the charge accumulation (charge transfer) was lower due to the increase in surface conductivity.

Zone C extends from 40% to 60% relative humidity. The typical voltage output is given in Figure 5.20. In this zone, the maximum charge was fairly constant, whereas the magnitudes of both the minimum and maximum voltage decreased. The charge transfer was almost zero, indicating that there was no significant static charge accumulation in the fluidized bed. The main characteristic of this zone was that the
charge dissipated over long periods of time. In other words, the relative humidity of the fluidizing air was sufficient to increase the surface conductivity of the dielectric particles. As a result, even after a bubble burst at the bed surface the accumulated charges around the ball probe were still dissipated through particle contacts. Since the slope of the second peak was very small, the error bars were found to be quite large for the negative peak.

Zone D lies between 60 % and 80 % relative humidity. Most parameters were very similar to those in zone C. However, as shown in Figure 5.27, the half height times in zone D were much smaller than in zone C. In addition, the magnitude of the minimum voltage slightly increased as the relative humidity increased beyond 60 %, because high humidity significantly increased surface conductivity so that less time was required to dissipate the charges in the bed. The signal tended to be unstable showing a slight discontinuity when the nose of the bubble reached the probe. The absolute values of the charge transfer were slightly positive. This may mean that the charges even farther away from the probe were neutralized through particle contacts, resulting in overcompensation of charges.

Finally, there was an unstable zone E at R.H. > 80 % as shown in Figures 5.21, 5.22, and 5.23. Particularly, at 98 % relative humidity, a square-nosed slug was formed instead of an air bubble. In zone C the rate of charge dissipation was quite slow, although the relative humidity between 40 % and 60 % resulted in insignificant charge accumulation when a single bubble was injected. Therefore, it is suspected that the charges that continuously generated in a free bubbling fluidized bed may not be dissipated sufficiently to prevent the charge accumulation at this humidity. Consequently, the relative humidity between 60 % and 80 % is recommended to reduce the electrostatic charge accumulation in gas-solid fluidized beds.

It is well known that humidity in fluidizing gas reduces electrostatic charges in fluidized beds by increasing the surface conductivity of the dielectric particles in fluidized beds. However, the mechanism of such process is not clearly stated in literature.
yet. As mentioned in Chapter 1, charging between materials is not only caused by electron transfer but also positive- or negative-ion transfer. This is called the "ionic theory" (Cross, 1987). According to the supporters of the ionic theories, real surfaces of metal or insulators contain charged double layer or adsorbed layers of impurities, which are frequently ionic in nature (Cross, 1987). Depending on the nature of the adsorbed impure layer, the material may be charged positively or negatively (Shaw and Jex, 1928).

All the forces of the molecules or ions in the surface of a solid are not balanced by union with other particles. This force imbalance causes the solid surfaces to attract and retain gases in order to satisfy their residual forces (Maron and Prutton, 1965). This process of concentration of a substance on the surface of a solid is called adsorption. Adsorption differs from absorption, where the substance is not only retained on the surface, but penetrates through the interface to become distributed throughout the body of a solid (Maron and Prutton, 1965). Since the particles used in this study were glass beads and polyethylene resin, only adsorption is considered.

There are two types of adsorption: physical (or van der Waals) adsorption and chemical (or activated) adsorption (Fan and Zhu, 1998). Physical adsorption is established rapidly and is reversible since it requires only a low heat of adsorption (Fan and Zhu, 1998). On the other hand, chemical adsorption, which forms stronger attachment bonds between the gas and the solid surface, is accompanied by much higher heat changes (Maron and Prutton, 1965). In many cases, materials adsorb gas molecules physically at low temperatures and chemically at higher temperature (Maron and Prutton, 1965).

Unlike chemical adsorption, physical adsorption is not specific in nature, since Van der Waals forces are not specific in nature (Maron and Prutton, 1965). Therefore, all solids generally adsorb gases to some extent. However, porous materials such as silica gel and charcoals have larger surface area for a given mass, and therefore, they are particularly effective as adsorbing agents (Maron and Prutton, 1965). A rough guide of the classification of common adsorbents is given in Table 5.1.
Table 5.1. Classification of common adsorbent (Perry and Green, 1997)

<table>
<thead>
<tr>
<th></th>
<th>Amorphous</th>
<th>Structured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrophobic</td>
<td>Activated carbon Polymers</td>
<td>Carbon molecular sieves</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silicalite</td>
</tr>
<tr>
<td>Hydrophilic</td>
<td>Silica gel</td>
<td>Common zeolites: 3A (KA), 4A (NaA), 5A (CaA), 13X (NaX), Mordenite, Chabazite, etc.</td>
</tr>
<tr>
<td></td>
<td>Activated alumina</td>
<td></td>
</tr>
</tbody>
</table>

The degree of adsorption is also determined by the gas pressure. As relative humidity of fluidizing gas increases, the partial pressure of water vapor also increases. Therefore, the physical adsorption of water vapor onto the glass beads and polyethylene particles increases. According to Cross (1987), most surfaces of solid particles in air covered by a layer of water ranging in thickness between a monolayer to a macroscopic thin film. Shinbrot (1985) reported the thickness of the adsorbed water layer to be around 10 nm. As adsorbed moisture forms a continuous film on the solid surface, the water provides a medium for dissociation of ions (Cross, 1987).

The adsorbed moisture also reduces the surface resistivity. Figure 5.28 illustrates the change in electrical resistivity as functions of temperature and moisture content. At 38 °C, as the moisture content in gas stream entering the electrostatic precipitator increases from 1 % to 3 % by volume, the resistivity of a fly ash decreases by 1/5 (Figure 5.27 (b)). However, at temperatures beyond 149 °C, the effect of humidity in reducing the resistivity decreases. In other words, surface conduction through a surface film adsorbed on the particles is the predominant mechanism of electric charge transfer for temperatures below 149 °C, whilst above 149 °C, volume or intrinsic conduction is dominant (Wark et al., 1998). Since intrinsic conduction requires passage of electric charge through the particles, the temperature and composition of the particles play important roles. In general, electrical resistivity, \( p_e \), with intrinsic conduction is expressed by an Arrhenius-type equation,

\[
p_e = A' \exp \left( -\frac{E}{kT} \right) \tag{5.1}
\]
where $A'$ is a constant, $E$ is the electron activation energy (a negative value), and $k'$ is the Boltzmann constant.

The electrical conductivity is defined as the quantity of electricity transferred across unit area per unit potential gradient per unit time. Table 5.2 lists the conductivities of common materials including glass and polyethylene. According to Cross (1987), the typical electrical conductivity of glass is around $10^{10}$ Ω$^{-1}$m$^{-1}$, while the conductivity of glass at 50% relative humidity is approximately $10^9$ Ω$^{-1}$m$^{-1}$. The electrical conductivity of polyethylene is much lower than that of glass.

Figure 5.28. Effect of temperature and moisture content on electrical resistivity of dusts: (a) Moisture conditioning of cement kiln dust; (b) Effect of gas humidity in increasing conductivity of a typical fly ash (White, 1974).
Table 5.2. Conductivities of common materials \( \Omega^{-1} \text{m}^{-1} \) (Cross, 1987)

<table>
<thead>
<tr>
<th>Conductivity (( \Omega^{-1} \text{m}^{-1} ))</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{9} )</td>
<td>Silver, Copper</td>
</tr>
<tr>
<td>( 10^{6} )</td>
<td>Graphite, Mercury</td>
</tr>
<tr>
<td>( 10^{3} )</td>
<td>Carbon black composites</td>
</tr>
<tr>
<td>( 1 )</td>
<td>Silicon, Germanium</td>
</tr>
<tr>
<td>( 10^{-3} )</td>
<td>Ivory, Concrete, Wood</td>
</tr>
<tr>
<td>( 10^{-6} )</td>
<td>Cotton at 50 % R.H.</td>
</tr>
<tr>
<td>( 10^{-9} )</td>
<td>Glass at 50 % R.H.</td>
</tr>
<tr>
<td>( 10^{-12} )</td>
<td>Nylon, Perspex</td>
</tr>
<tr>
<td>( 10^{-15} )</td>
<td>Amber, Sulphur</td>
</tr>
<tr>
<td>( 10^{-18} )</td>
<td>Mica, Dry fused quartz</td>
</tr>
<tr>
<td></td>
<td>Polyethylene, PTFE</td>
</tr>
</tbody>
</table>

5.3.2.2 Adding fine Group C particles

According to Wolny (1983) fine group C particles act as spacers as shown in Figure 5.28 and increase the contact area of the particles. As a result, the dissipation rate of electrostatic charges in a fluidized bed is increased. Jean et al. (1992) also reported that adding up to 15 % of fine polyethylene powders to Group B polyethylene bed improved the fluidization quality (i.e. higher bed expansion).

Unlike Jean et al. (1992), Guardiola et al. (1992) performed experiments with a fine material whose electric nature differs from the bed material. The addition of a conducting material such as steel reduced the charge on the bed of a dielectric material such as glass ballotini. Wolny and Opalinski (1983) reported that for drying of polystyrene beads, the effect of fine additives was independent of the electric nature of the added fines. The fine materials should be stable at the operating temperature and be
acceptable in the system. Active coal powder (conductor), titanium dioxide powder (semiconductor), and powder of pigment A-extra (dielectric), which are general additives in many polymer processes, were used as added fine materials in the experiments of Wolny and Opalinski (1983).

In this study, 5 wt % of fine glass beads of 17 \( \mu \)m diameter were added to the group B glass beads used for the base case. The relative humidity and temperature were kept at 15 % and 20 °C, respectively. The minimum bubbling velocity then decreased from 0.122 m/s to 0.056 m/s. Also, the fluidized bed was visually stable. Initially, there was about 40 mm high particle buildup on the inner wall of the two-dimensional fluidization column. After the addition of fine glass powders, 321 \( \mu \)m glass beads used as the main bed material stopped sticking to the inner wall of the column. However, the column wall was covered with a thin layer of fine glass powders. It was difficult to determine whether the fine glass powders were charged. The bed seemed quite dense, and it was impossible to inject a bubble even at an injector pressure of 30 psig. When up to 15 wt % of fine glass beads were gradually added to the bed, instead of forming a large single bubble, the air injected from the bubble injector broke into many small bubbles which rose vertically. Figure 5.30 shows an example voltage and charge output. Since the bubble injection time was still 0.1 second, the total volume of injected air was almost
the same. Unlike the previous plots (e.g. base case in Figure 5.30 (a)), there was no change in voltage output sign. In other words, the induced charge was insignificant compared to the direct charge transfer. This may be due to the fact that the bubbles were extremely small and the continuous movement of the small bubbles resulted in a continuous increase in the magnitude of the voltage so that after all the bubbles had passed the probe the charge started to decay exponentially. The arrow on Figure 5.30 (a) indicates the time when the last bubble passed the ball probe. Note that the polarity of the bed seemed to be changed to negative after adding the fine glass powders. As a result, there is a positive charge transfer through the ball probe as shown in Figure 5.30 (b). Note also that segregation between the larger and smaller glass beads occurred during fluidization, with some portion of the fine glass migrating to the surface of the fluidized bed forming a layer of approximately 5 mm thick.

Figure 5.30. Voltage and cumulative charge output of bubble injection in two-dimensional fluidized bed of 321 μm glass beads with/without 15 wt % of 17 μm fine glass powder at R.H. = 15 % ($U_g = 0.056$ m/s, $T = 20$ °C)
According to Jean et al. (1992), the addition of fines to act as spacers was not effective for particles with rough surface structures, since group C particles tended to be lodged between nodules. Also, particles with non-spherical surface structures are hard to neutralize, since the average surface charge densities are higher in regions with more curvature resulting in a non-uniform distribution of surface charges (Bailey, 1984). The polyethylene particles used in this project were, according to their SEM pictures shown in Figures 2.7 (b) and (c), very rough compared to the surfaces of glass beads. In other words, the addition of fines is not recommended to reduce electrostatic charging in a fluidized bed of polyethylene particles. For the glass beads, as shown in Figure 2.7 (a), the surface was very smooth and the particles were spherical.

The probe used in the experiments of Guardiola et al. (1992) was a capacitance probe, i.e. they measured the electrostatic characteristics of the entire fluidized bed, while our probe measured very localized charges. Therefore, it may not be appropriate to compare the results. Although there is no conclusion from this test, it is believed that the addition of fine powders may not only affect the electrostatic forces but also other interparticle forces such as Van der Waals forces.

5.3.2.3 Adding anti-static agents

This method is commonly used in laboratory scale fluidized beds. There are two different types of anti-static agents: internal and external antistats (Cross, 1987). Internal antistats are compounded into the polymer matrix, whereas external antistats are applied to the surface of the final product, usually by spraying or by dipping the product into a dilute (0.1 % to 2.0 %) solution of the antistats in water or alcohol. The internal antistats have a longer influence since external antistats may be removed by contact with solvents or other particles. The external antistats tend to hydrosopic. Therefore, these chemical antistats are usually surfactants (i.e. cationic, anionic, and non-ionic compounds) (Cross, 1987).

Since static electricity is a surface phenomenon, static charges may be best
dissipated by decreasing the surface resistivity by adding anti-static agents (Zhang et al., 1996). In case of internal antistats, the solid anti-static agents are mixed with the molten polymer. Since the antistats are not soluble in polymer, they migrate to the top of the melted surface positioning the hydrophilic portion of the molecules facing up (Ciba Specialty Chemicals Canada Inc., 2000). The hydrophilic functional group, e.g. amine, then picks up water molecules from the ambient atmosphere, forming a thin layer of water, and increasing the rate of charge dissipation. Only about 0.1 to 0.2 wt % of internal antistats are required to reduce electrostatics significantly, since the surface coverage of the polymer is important, not its thickness (Ciba Specialty Chemicals Canada Inc., 2000). External antistats also reduce the surface resistivity for ion conduction through the formation of a thin (approximately 10 nm thick), invisible layer of water on the surface of the plastic particle (Cross, 1987). In order to create the water layer on the surface of the particles, it is important to well cover the particles with the anti-static powders or solution. Hence, the anti-static powder must be much finer than the main particles. In addition, when the relative humidity of the fluidizing gas is lower than 10 %, these surfactant antistats will become ineffective in reducing the electrostatic charges (Cross, 1987).

It has been reported that the addition of 1.5 wt. % of sodium chloride fines to a polystyrene bed fluidized by dry air dramatically reduced electrostatic charges (Wolny and Kazmierczak, 1989). Zhang and Yang (1996) also reported a great reduction in particle agglomeration when 1 wt. % Larostat powders was added to the bed. This method was also found to result in more uniform radial voidage and velocity profiles (Zhang and Yang, 1996). This method is commonly used in laboratory scale fluidized beds, but its mechanism and the longevity of the anti-static benefit are unknown.

According to White (1974), when small amounts of SO$_3$ or NH$_3$ are added to an electrostatic precipitator (ESP) at intermediate temperatures, they are adsorbed on the particles and act as electrolytes. This process sharply reduces resistivity and enhances surface conduction. It was claimed that these two substances, and compounds closely related to them, are the only antistats that are economically and technically feasible in
commercial practice for electrostatic precipitators. Figure 5.30 shows the effect of H$_2$SO$_4$ and SO$_3$ on the reduction of surface resistivity. As the amount of injected SO$_3$ increased from 10 to 30 ppm, the fly ash resistivity decreased by a factor of 10.

![Figure 5.30: Effect of H$_2$SO$_4$ and SO$_3$ on fly ash resistivity](image)

In this study, we have used a cationic surfactant, Larostat 519 powder, which is made of quaternary ammonium compound and supplied by PPG Industries Inc., Gurnee, Illinois, USA (Issangya, 1996). Larostat is a nonflammable white powder with a bulk density of 520 kg/m$^3$. Many researchers used this product to control static electricity in circulating fluidized beds with fine FCC particles. Larostat particles also act as slip agents, lowering the friction between particles and between particles and the wall (Zhang et al., 1996). The recommended dosage is 0.05 wt % (Issangya, 1996). In order to account for the entrainment of fine anti-static powders, the addition of 1 wt % Larostat 519 powder to glass beads and polyethylene particles was tested in the present work for reducing the static buildup in fluidized beds.

![Figure 5.31: Effect of conditioning on fly ash resistivity](image)

Figure 5.31. Effect of conditioning on fly ash resistivity: (a) H$_2$SO$_4$ fume and (b) SO$_3$ injection into the flue gas (White, 1974).
Figure 5.32 shows the voltage output of the bubble injection in a two-dimensional fluidized bed of glass beads containing 1 wt % Larostat 519 powder. The magnitudes of the peaks are much smaller than those for the base case (no anti-static agent added). In addition, Figure 5.32 (b) shows insignificant charge transfer for the case of adding 1 wt % Larostat compared to the base case. However, during the bubble injection, at the same condition the size of bubble injected was much smaller. In addition to the reduction of electrostatic charges by Larostat, this could be another reason for smaller magnitudes of the peaks, since the charge induction and transfer are proportional to the bubble size. It was very difficult to inject a single bubble, and the results were not highly reproducible. Single bubble injection in a two-dimensional fluidized bed of polyethylene particles containing 1 wt % Larostat 519 was also very difficult.

Figure 5.32. Voltage output for bubble injection into two-dimensional fluidized bed of 321 μm glass beads with 1 wt % Larostat 519 powder at R.H. = 17 % 
($U_g = 0.056 \text{ m/s, } T = 23^\circ\text{C}$)
During 2 h fluidization, glass beads generated a buildup on the column wall for a height of about 55 mm above the bed surface, while polyethylene resin created a buildup of 155 mm. For the case of polyethylene particles, initially there was a stagnant particle layer on the wall of the column, but it was visually confirmed that particles in contact with the inner surface of the column were moving freely. As soon as Larostat was added to the two-dimensional bed, the particle buildup on the wall of the fluidization column disappeared. Figures 5.33 and 5.34 illustrate the particle buildup on the inner wall of the fluidization column for different conditions.

Figure 5.33. Digital picture of glass bead buildup on the inner surface of Plexiglas two-dimensional fluidization column above the bed surface.

Figure 5.34. Digital pictures of polyethylene particle buildup on the inner surface of Plexiglas two-dimensional fluidization column before (a) and after (b) addition of 1 wt % Larostat 519 powder
5.3.2.4 Entrainment of anti-static agents and fine Group C particles

Since both methods, adding group C particles and adding anti-static agents, involve fine particles, there is a possibility of losing the additives through entrainment during fluidization. However, many researchers, e.g. Jean (1992) and Briens (1992), argued that the elutriation of Group C fine particles was not significant, since they tended to adhere strongly to the larger Group B particles due to van der Waals and electrostatic forces while acting as spacers. However, it was visually confirmed in the previous work that there was significant entrainment of fines, especially when 15 wt % fine glass powder was added to the group B glass beads, where the amount of fines collected in the filter bag was approximately 100 ml within 5 min.

5.4 Results and Discussion for 3-D Bubble Injection

Since the results obtained in the two-dimensional fluidized beds contained substantial wall effects, the bubble injection experiments were repeated in a three-dimensional fluidized bed. In 1971, Boland and Geldart reported the current trace from a three-dimensional fluidized bed shown in Figure 5.35, confirming static charges arise in three-dimensional beds. However, they could not provide detailed information on charging mechanisms. In the following sections, the bubble injection performed in a three-dimensional fluidized bed of glass beads or polyethylene resin is presented and discussed.

![Figure 5.35. Current trace from 3-D bed (Boland and Geldart, 1971)]
5.4.1 Glass beads

Figure 5.36 shows an example of the voltage output for single bubble injection in the three-dimensional column of diameter 88.9 mm described in Chapter 2. The electrostatic ball probe and the optical fiber probe were again fixed at the same height (0.3 m above the distributor). Due to the location of the measuring ports, the two probes were inserted towards the centre of the column perpendicular to each other without touching. The shortest distance between the probes was 10 mm.

![Graph showing voltage and charge output](image)

Figure 5.36. Voltage and charge output for bubble injection in three-dimensional fluidized bed of 321 μm glass beads at R.H. = 20 % \((U_g = 0.085 \text{ m/s}, d_B = 28 \text{ mm}, T = 23 ^\circ\text{C})\)
Since bubbles were not visible in this case until they burst into the freeboard region, it was difficult to determine whether the two probes were interfering with the bubbles. However, signals from the optical fiber probe indicated that bubbles did exist as distinct entities at least until they passed the probes.

The signal shown in Figure 5.36 differs slightly from that shown in section 5.3.1 for the two-dimensional fluidized bed. However, for both cases when the centre of the bubble was aligned with the centre of the probe, the voltage output produced its maximum. The center of the optical fiber probe peak was considered to correspond to the moment when the centres of the bubble and the optical fiber probe were aligned. After the bubble passed the probes, there was charge decay very similar to that found in the two-dimensional bed. The positive curve lined with the optical fiber probe peak indicates that the glass beads in three-dimensional bed were again charged positively. The only difference between the three-dimensional and two-dimensional fluidized bed results was that during the actual bubble injection, the disturbance of the bed was much more significant.

Figure 5.37 illustrates the effect of bubble size. As expected, larger bubbles lead to higher magnitudes of the peaks. In addition, the time required for charge decay was longer. The volumes given in Figure 5.37 are again the injected volumes of air, not the exact volumes of the bubbles. For each case, the charge plot similar to Figure 5.36 (b) was generated and the parameters, $V_{max}$, $V_{min}$, $C_{max}$, and $C_{transfer}$, were collected and summarized in Table 5.3. According to Table 5.3, the charge transfer is very small for all three injected bubble volumes. This may be due to the relative humidity and the size of the bubble. 20% relative humidity is at the borderline of rapid decrease in charge transfer as shown in Figure 5.26. In addition, the size of the bubbles injected was much less than that for the base case (40 ml). The magnitudes of other parameters, $V_{max}$, $V_{min}$, and $C_{max}$, increased as the bubble injection volume increased.

Figure 5.38 illustrates the effect of multiple bubble injection. The voltage output was very repeatable during the bubble injection.
Figure 5.37. Effect of bubble injection volumes for single bubble injection in three-dimensional fluidized bed of 321 μm glass beads ($U_g = 0.085$ m/s, $T = 23$ °C)

Table 5.3. Effect of bubble injection volumes for single bubble injection in three-dimensional fluidized bed of 321 μm glass beads ($U_g = 0.085$ m/s, $T = 23$ °C)

<table>
<thead>
<tr>
<th>bubble injection volume [ml]</th>
<th>$V_{max}$ [V]</th>
<th>$V_{min}$ [V]</th>
<th>$C_{max}$ [C]</th>
<th>$C_{transfer}$ [C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>0.718</td>
<td>-0.146</td>
<td>-1.947 x 10^{-10}</td>
<td>5.501 x 10^{-11}</td>
</tr>
<tr>
<td>6.9</td>
<td>1.210</td>
<td>-0.149</td>
<td>-2.401 x 10^{-10}</td>
<td>5.109 x 10^{-11}</td>
</tr>
<tr>
<td>13.8</td>
<td>1.335</td>
<td>-0.173</td>
<td>-4.119 x 10^{-10}</td>
<td>-2.5001 x 10^{-11}</td>
</tr>
</tbody>
</table>
Figures 5.38 to 5.42 show the effect of relative humidity on the electrostatic charging in three-dimensional fluidized beds. The large negative disturbance curve is seen to disappear as the relative humidity increased beyond 41%. Figures 5.41 and 5.42 are very similar to the results obtained for the two-dimensional fluidized bed. Generally, the magnitudes of the peaks decreased as the relative humidity increased. When the relative humidity of the fluidizing air increased beyond 67%, the signal became irregular.

Figure 5.38. Multiple bubble injection in three-dimensional fluidized bed of 321 μm glass beads at R.H. = 20 % (\(U_g = 0.085\) m/s, T = 23 °C)
Figure 5.39. Voltage output of bubble injection in three-dimensional fluidized bed of 321 μm glass beads at R.H. = 15 % ($U_g = 0.122$ m/s, $T = 20 ^\circ$C)

Figure 5.40. Voltage output of bubble injection in three-dimensional fluidized bed of 321 μm glass beads at R.H. = 21 % ($U_g = 0.122$ m/s, $T = 20 ^\circ$C)
Figure 5.41. Voltage output of bubble injection in three-dimensional fluidized bed of 321 μm glass beads at R.H. = 41 % ($U_g = 0.122$ m/s, $T = 20 ^\circ C$)

Figure 5.42. Voltage output of bubble injection in three-dimensional fluidized bed of 321 μm glass beads at R.H. = 67 % ($U_g = 0.122$ m/s, $T = 20 ^\circ C$)
Using the voltage output given in Figures 5.39 to 5.42, the charge curves were derived. The parameters obtained from those figures are summarized in Table 5.4. According to Table 5.4, $C_{\text{max}}$ and $C_{\text{transfer}}$ were generally decreased as the relative humidity of the fluidizing gas was increased. As expected, the magnitudes of $V_{\text{max}}$ and $V_{\text{min}}$ also decreased as the relative humidity increased.

Table 5.4. Effect of relative humidity for single bubble injection in three-dimensional fluidized bed of 321 μm glass beads ($U_g = 0.122$ m/s, $T = 23$ °C)

<table>
<thead>
<tr>
<th>relative humidity [%]</th>
<th>$V_{\text{max}}$ [V]</th>
<th>$V_{\text{min}}$ [V]</th>
<th>$C_{\text{max}}$ [C]</th>
<th>$C_{\text{transfer}}$ [C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.933</td>
<td>-0.904</td>
<td>-8.563x10^{-10}</td>
<td>-5.106x10^{-10}</td>
</tr>
<tr>
<td>21</td>
<td>1.404</td>
<td>-0.153</td>
<td>-4.153x10^{-10}</td>
<td>-7.132x10^{-10}</td>
</tr>
<tr>
<td>41</td>
<td>1.195</td>
<td>-0.329</td>
<td>-6.864x10^{-10}</td>
<td>-4.186x10^{-10}</td>
</tr>
<tr>
<td>67</td>
<td>0.708</td>
<td>-0.263</td>
<td>-3.464x10^{-10}</td>
<td>-0.978x10^{-10}</td>
</tr>
</tbody>
</table>

5.4.2 Polyethylene resin

The bubble injection experiment was then repeated in the three-dimensional bed using 378 μm polyethylene particles (PE I). With a large particle buildup on the inner surface of the column, it was found to be very difficult to inject single bubbles. The injected air formed a large square-nosed slug. Figure 5.43 is a typical voltage and charge output for the bubble injection in a three-dimensional fluidized bed of polyethylene particles. The signal from the optical fiber probe indicates that the voidage of the bed increased slightly while the injected air rose through the bed, but there was no definite indication that there was a bubble. The initial disturbance in voltage output was quite significant as for the glass beads. Figure 5.43 (b) was obtained by integrating the current calculated from the voltage output in Figure 5.43 (a). Although significantly high electrostatic charge accumulation was assumed for the polyethylene fluidized bed, the charge transfer was found to be quite small during experiments, likely due to very small bubble size and rise velocity.
Figure 5.43. Voltage output of bubble injection in three-dimensional fluidized bed of polyethylene particles at R.H. = 20 % ($U_e = 0.124 \text{ m/s}$, $T = 23 ^\circ \text{C}$)

Figures 5.44 and 5.45 illustrate the effects of bubble size and relative humidity of the fluidizing air on the electrostatic charge accumulation in the three-dimensional fluidization column. The patterns of these figures are very similar to the ones found in Figures 5.37 to 5.42 (bubble injection in the fluidized bed of glass beads). The initial disturbance negative peak only disappeared at 85 % relative humidity.

The experimental results are then tabulated in Table 5.5. As the bubble injection volume increased the maximum voltage, minimum voltage and charge maximum were all increased. However, the effect of the bubble size on the charge transfer was not as obvious as on other parameters. Nevertheless, the general trend led to the conclusion that the polyethylene particles were also charged positively.
Figure 5.44. Effect of bubble sizes for single bubble injection in three-dimensional fluidized bed of 378 μm polyethylene particles at R.H. = 20 %

\((U_g = 0.124 \text{ m/s, } T = 23 ^\circ \text{C})\)

Table 5.5. Effect of bubble sizes for single bubble injection in three-dimensional fluidized bed of 378 μm polyethylene particles at R.H. = 20 %

\((U_g = 0.124 \text{ m/s, } T = 23 ^\circ \text{C})\)

<table>
<thead>
<tr>
<th>bubble injection volume [ml]</th>
<th>(V_{\text{max}}) [V]</th>
<th>(V_{\text{min}}) [V]</th>
<th>(C_{\text{max}}) [C]</th>
<th>(C_{\text{transfer}}) [C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0.689</td>
<td>-0.138</td>
<td>-1.760\times10^{-10}</td>
<td>7.115\times10^{-11}</td>
</tr>
<tr>
<td>8.6</td>
<td>1.213</td>
<td>-0.142</td>
<td>-2.524\times10^{-10}</td>
<td>0.729\times10^{-11}</td>
</tr>
<tr>
<td>12.1</td>
<td>1.363</td>
<td>-0.170</td>
<td>-3.936\times10^{-10}</td>
<td>-1.893\times10^{-11}</td>
</tr>
</tbody>
</table>
Figure 5.45. Effect of relative humidity of fluidizing air for single bubble injection in three-dimensional fluidized bed of 378 μm polyethylene particles

\(U_g = 0.124 \text{ m/s, } T = 23 \degree\text{C}\)

Table 5.6. Effect of relative humidity for single bubble injection in three-dimensional fluidized bed of 378 μm polyethylene particles \((U_g = 0.124 \text{ m/s, } T = 23 \degree\text{C})\)

<table>
<thead>
<tr>
<th>relative humidity [%]</th>
<th>(V_{\text{max}}) [V]</th>
<th>(V_{\text{min}}) [V]</th>
<th>(C_{\text{max}}) [C]</th>
<th>(C_{\text{transfer}}) [C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>1.117</td>
<td>-0.233</td>
<td>-9.038x10^{-10}</td>
<td>-5.818x10^{-10}</td>
</tr>
<tr>
<td>48</td>
<td>0.331</td>
<td>-0.024</td>
<td>0.366x10^{-10}</td>
<td>1.280x10^{-10}</td>
</tr>
<tr>
<td>79</td>
<td>0.126</td>
<td>-0.132</td>
<td>-0.383x10^{-10}</td>
<td>1.515x10^{-10}</td>
</tr>
<tr>
<td>85</td>
<td>0.053</td>
<td>-0.038</td>
<td>-0.233x10^{-10}</td>
<td>0.684x10^{-10}</td>
</tr>
</tbody>
</table>
According to the results in Figure 5.45, as the relative humidity increased from 35\% to 48\%, the magnitude of the positive peak decreased by 2/3. Since polyethylene particles have a very porous structure, if the pores were larger than the water molecules, their large exposed surfaces can take up appreciable volume of moisture. This may be why the degree of charge reduction with increasing relative humidity was higher for the polyethylene particles than for the glass beads. The comparisons between the cases for the polyethylene particles and the glass beads are shown in Figures 5.46 and 5.47. Since the bubble size used for both cases was the same, we can conclude that the effect of relative humidity in reduction of electrostatic charges was greater for the polyethylene particles than for the glass beads.

Figure 5.46. Effect of relative humidity of fluidizing gas on voltage output for single bubble injection in three-dimensional fluidized beds of 321 \( \mu \)m glass beads and 378 \( \mu \)m polyethylene particles.
Figure 5.47. Effect of relative humidity of fluidizing gas on charge output for single bubble injection in three-dimensional fluidized beds of 321 μm glass beads and 378 μm polyethylene particles.
Chapter 6
Free Bubbling in Three-Dimensional Fluidized Bed

6.1 Introduction

Since most commercial fluidized beds operate in the bubbling or turbulent flow regimes, it was necessary to perform the experiments in free bubbling three-dimensional fluidized bed in order to gain a better understanding of the nature of the electrostatic phenomena. One goal of this set of experiments was to verify the technique developed based on single bubble injection by analyzing the experimental results obtained from the three-dimensional bubbling fluidized bed. Also, the effect of solid anti-static agents on the electrostatic accumulation was investigated.

6.2 Experiments

Polyethylene particles are known to accumulate larger static charges in fluidized beds. The polyethylene particles (PE I) used in this set of experiments were different from those used in the previous experiments (PE II). See Chapter 2 for the size distribution and physical properties (Table 2.1). These polyethylene particles were finer than the previous particles and manufactured through a slightly different process. The experiments were performed using the three-dimensional fluidization column described in Chapter 2.

Before starting the actual data acquisition, it was necessary to determine the stabilization time to ensure steady state operation during the experiments. Therefore, a longevity experiment was performed by fluidizing the polyethylene particles for 300 min, while taking measurements periodically. The results are shown in Figure 6.1.
Figure 6.1. Longevity experiments using a three-dimensional fluidized bed of 378 μm polyethylene particles (PE I) at $U_g = 0.158$ m/s

Figure 6.1 plots the mean voltage versus time. It is seen that it takes about 2 hours for the system to reach steady state. This longevity experiment was performed using PE I. However, it gave a rough idea of how long is needed to reach steady state. There is a possible problem with entrainment of fine particles including the Larostat particles. As a result, an intermediate superficial gas velocity (0.158 m/s) was chosen to perform the experiments.

6.3 Experimental Results and Discussion

6.3.1 Base case

In order to quantify the electrostatic charge in the fluidized bed, a base case was investigated by fluidizing the polyethylene powders (PE II) without any additives at various superficial gas velocities. A typical voltage output is shown in Figure 6.2 (a).
Figure 6.2. Base case of 318 μm polyethylene fluidized bed without additive at:

\[ U_g = 0.158 \text{ m/s (R.H. = 19 %, T = 26.3 °C)} \]

Most previous researchers used the mean values of the voltage output to represent the electrostatic charge accumulation in fluidized beds. However, throughout our experiments it was found that the integration of the current calculated from the voltage output represents the direct charge transfer, while the standard deviation of the voltage output is proportional to the magnitude of charge inducement.

From the voltage output, we calculate the rate of charge transfer between the ball probe and the fluidized particles using Equations (5.1) and (5.2). There are two components in voltage output: induced voltage and voltage due to direct charge transfer. The induced voltage does not affect the net charge output, since there is no direct charge transfer. Therefore, the slope of the curve in Figure 6.2 (b) gives the rate of direct charge transfer.
transfer, $I_{\text{transfer}}$, between the probe and the particles, while the small bumps on the curve are caused by induced voltage. The positive slope in Figure 6.2 (b) indicates that the ball probe was charged positively and accepted electrons from the particles. In other words, the particles in the fluidized bed were generally charged negatively. The experimental results at various superficial gas velocities are summarized in Table 6.1.

Table 6.1. Effect of superficial gas velocity for base case 1 (R.H. = 19 %, T = 26.3 °C)

<table>
<thead>
<tr>
<th>$U_g$ [m/s]</th>
<th>$V_{\text{avg}}$ [V]</th>
<th>standard deviation of $V$ [V]</th>
<th>$I_{\text{transfer}}$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.099</td>
<td>-0.01007</td>
<td>0.52119</td>
<td>0.0110x10^-9</td>
</tr>
<tr>
<td>0.124</td>
<td>-0.02452</td>
<td>0.75822</td>
<td>0.0250x10^-9</td>
</tr>
<tr>
<td>0.158</td>
<td>-0.06171</td>
<td>1.30182</td>
<td>0.0575x10^-9</td>
</tr>
</tbody>
</table>

According to Table 6.1, as the superficial gas velocity was increased, the mean value and the standard deviation of the voltage output, and $I_{\text{transfer}}$ also increased. The magnitude of the standard deviation of the voltage output is proportional to the magnitude of the charge induced on the surface of the electrostatic ball probe.

The base case was repeated to check the reproducibility of the measurements. The patterns of the experimental plots were very similar to the base case 1, as one compares Tables 6.1 and 6.2. The base case results were quite reproducible. The results from two repeated sets of base case were combined and their average values are reported in Table 6.3.

Table 6.2. Effect of superficial gas velocity for base case 2 (R.H. = 15 %, T = 23.0 °C)

<table>
<thead>
<tr>
<th>$U_g$ [m/s]</th>
<th>$V_{\text{avg}}$ [V]</th>
<th>standard deviation of $V$ [V]</th>
<th>$I_{\text{transfer}}$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.124</td>
<td>-0.00619</td>
<td>0.83723</td>
<td>0.0288x10^-9</td>
</tr>
<tr>
<td>0.158</td>
<td>-0.05434</td>
<td>1.40857</td>
<td>0.0588x10^-9</td>
</tr>
</tbody>
</table>
Table 6.3. Summary of Base cases

<table>
<thead>
<tr>
<th>$U_g$ [m/s]</th>
<th>$V_{avg}$ [V]</th>
<th>standard deviation of $V$ [V]</th>
<th>$I_{transfer}$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.124</td>
<td>-0.0154</td>
<td>0.7977</td>
<td>0.0269x10^-9</td>
</tr>
<tr>
<td>0.158</td>
<td>-0.0580</td>
<td>1.3552</td>
<td>0.0582x10^-9</td>
</tr>
</tbody>
</table>

6.3.2 Effect of anti-static agents: Larostat 519

1000 ppm of Larostat 519 was added to the three-dimensional bubbling fluidized bed of 318 μm polyethylene particles. Since it was not known how quickly Larostat would start to reduce electrostatic charges in a fluidized bed at 16 % relative humidity, periodic measurements were carried out. An example of the experimental results is shown in Figure 6.3.

![Figure 6.3](image)

Figure 6.3. Voltage output and calculated charge of the polyethylene fluidized bed with 1 wt % of Larostat 519 at $U_g = 0.124$ m/s (R.H. = 16 %, $T = 23.1$ °C): 84 minutes after the addition of Larostat 519.
Figure 6.4. Effect of adding 1000 ppm of Larostat 519 into the polyethylene fluidized bed at \( U_g = 0.124 \text{ m/s} \) (R.H. = 16 %, \( T = 23.1 \text{ °C} \)): Larostat powder were added at time = 0.

Since Larostat was added to the top of the fixed bed, there was an unstable mixing period at the beginning. However, it is clearly shown in Figure 6.4 that within 1.5 hours, the static in the fluidized bed was reduced to an insignificant level. Moreover, there was no particle buildup observed on the wall of the fluidized bed, even 1 minute after the addition of Larostat powders, and the probe was not covered with the particles. It was remarkable that the addition of 1 wt % of Larostat 519 completely eliminated the particle buildup, which was up to 125 mm (height of particle buildup on the column wall above the bed surface). The initial values of \( I_{\text{transfer}} \) in Figure 6.4 are mostly positive, indicating that the ball probe was charged positively by negatively charged particles until Larostat reduced the static in the bed. Since PE I particles described in Chapter 5 and 6 were
charged positively, this may mean that one batch of the polyethylene particles (either PE I or PE II) had different surface characteristics or was contaminated.

Figure 6.5 illustrates the change in the mean and standard deviation of the voltage output. While $I_{\text{transfer}}$ in Figure 6.4 represents the direct charge transfer, these values, particularly the standard deviation of the voltage output, represent the amount of voltage induced. As expected, the magnitude of induced voltage decreased as the charge accumulation decreased.
7.1 Conclusions of This Work

A study of electrostatic charging in gas-solid fluidized beds was carried out by developing a simplified mechanistic model and performing bubble injection and free bubbling experiments in two-dimensional and three-dimensional fluidized beds.

Preliminary experiments performed using a negatively charged ruler, and a positively charged glass rod and plastic pen showed that the voltage signal comes from a combination of induced voltage and the voltage due to direct charge transfer between the charged object and the probe.

A simplified mechanistic model was developed by applying the method of images and by assuming that the bubble is a perfect sphere, the dielectric constant of the fluidized bed is 1, and charge induction is caused by a monolayer of charged particles around the bubble. In addition, the exponential charge decay term is considered to be instantaneous. The model simulation shows that when a bubble of negatively charged surface approaches the probe, positive voltage output will be induced with the maximum peak corresponding to the moment when the bubble nose is aligned with the centre of the probe. The voltage output starts to decrease and becomes negative when the bubble center passes the probe, and therefore, a negative peak is obtained when the probe is aligned with the bubble wake. The magnitudes of the maximum peak values are proportional to the bubble rise velocity and the charge density on the bubble surface. Charge transfer occurs when particles surrounding the bubble move at relatively high velocity and collide with the probe. The charge transfer rate will be proportional to particle velocity and the charge density around the bubble.
Bubble injection experiments in a two-dimensional fluidized bed were carried out using both glass beads and polyethylene particles. Both 321 μm glass beads and 378 μm polyethylene particles were charged positively, while 318 μm polyethylene particles were charged negatively. Larger bubbles resulted in higher charge inducement and transfer. The results from the glass beads were compared with the model predictions. Despite the limitations in model assumptions, the model simulations give reasonable predictions of the charge. Boland and Geldart (1971) speculated that the nose and wake of the bubble are oppositely charged. However, for our model a uniform charge distribution on the surface of the bubble resulted in better agreement with experimental data.

Increasing the relative humidity reduced the electrostatic charge accumulation by increasing the surface conductivity, thereby enhancing charge dissipation. For less than 20 % relative humidity, the charge inducement and transfer decreased as the relative humidity increased. For 20 % to 40 % R.H., there was a rapid reduction in electrostatic charging. For 40 % to 60 % R.H., the accumulation of static charges was insignificant. Finally, for R.H. > 80 %, the signals from the electrostatic ball probe were irregular likely due to capillary forces. The half height time for the negative peak at various relative humidities represented the rate of charge dissipation. According to the experimental results, relative humidities higher than 60 % result in sufficient charge dissipation to prevent charge accumulation in gas-solid fluidized beds. These patterns could change depending on many factors such as the surface characteristics of the particles, however, the order of the zones and the patterns within the zones would not change.

The addition of 15 wt % group C fines reduced the particle buildup on the inner wall of the fluidization column, but this may not have been due to the reduction in electrostatic charges in the bed. The addition of 1 wt % Larostat eliminated particle buildup on the column wall and resulted in reduced voltage output during bubble injection. However, since the bubble size was smaller when Larostat was added than for the base case, the reduction in voltage output was not solely caused by the addition of Larostat. The addition of 1 wt % Larostat 519 into a three-dimensional bubbling fluidized bed of 318 μm polyethylene particles clearly showed that the rate of charge
transfer decreased rapidly and approached zero within 1.5 hr, indicating significant reduction of charge accumulation in the bed.

7.2 Recommendations for Future Work

- The charge decay term expressed in Equation (1.3) and the kidney shape of the bubbles should be accounted for in the model.

- The technique of data evaluation using the integration method has been verified using the experimental results obtained from the two-dimensional fluidized bed. Therefore, more free bubbling experiments are recommended to investigate the effects of increasing the relative humidity of the fluidizing gas and adding fine particles on reducing charge accumulation in a three-dimensional bubbling fluidized bed.

- The effect of electrostatic charges on the hydrodynamics of fluidized bed should be investigated.

- Since most of commercial units operate in the turbulent flow regime, it would be interesting to collect data at higher superficial gas velocities. In order to operate at higher velocities, a higher capacity cyclone is required.
Nomenclature

\( a \) = coefficient
\( A \) = constant, \( C \cdot s^{3/5} \cdot m^{7/5} / kg \)
\( A' \) = constant
\( A_S \) = surface area, \( m^2 \)
\( b \) = distance between the centre of probe and image charge \( q' \), \( m \)
\( B \) = magnetic flux density, \( \text{Wb/m}^2 \)
\( B \) = source point
\( c \) = constant
\( c_1 \) = constant
\( c_2 \) = constant
\( C \) = centre of bubble
\( Cc \) = constant, \( (\text{m/s})/((\text{kg/m}^3)) \)
\( C_{\text{max}} \) = maximum magnitude of the charge curve, \( C \)
\( C_P \) = capacitance, \( \text{F} \)
\( C_S \) = path bounding surface \( S \)
\( C_{\text{transfer}} \) = charge transfer, \( C \)
\( d \) = distance between the centre of probe and point charge \( q \), \( m \)
\( d_B \) = bubble diameter, \( m \)
\( d_P \) = probe diameter, \( m \)
\( \bar{d}_p \) = Sauter mean diameter, \( \mu\text{m} \)
\( d_{pl} \) = average screen aperture size, \( \mu\text{m} \)
\( D \) = electric flux density due to free charges, \( \text{C/m}^2 \)
\( E \) = electric field intensity, \( \text{V/m} \)
\( E \) = electron activation energy, \( \text{J} \)
\( g \) = gravitational acceleration, \( 9.81 \text{ m/s}^2 \)
\( h \) = cylinder height, \( m \)
\( i_T \) = total current, \( \text{A} \)
\( I \) = current, \( \text{A} \)
\( I_{\text{induced}} \) = induced current, A
\( I_{\text{transferred}} \) = current due to direct charge transfer, A
\( J \) = current density, A/m\(^2\)
\( J_p \) = mass flux, kg/m\(^3\)
\( J_T \) = total current density, A/m\(^2\)
\( k' \) = Boltzmann constant = 1.38 \times 10^{-23} \text{ J/K}
\( l \) = distance, m
\( L \) = distance between the electrostatic probe and the tip of bubble injector, = 0.205 m
\( \mathbf{m} \) = unit vector tangent to \( S_0 \), m
\( \mathbf{n} \) = unit vector normal to \( S_0 \), m
\( O \) = centre of probe (0,0)
\( p \) = constant = \( 3 \pi r / (\pi r + 2) \)
\( p_e \) = electrical resistivity with intrinsic conduction, \( \Omega \) m
\( P \) = surface field point
\( q \) = point charge, C
\( q' \) = image charge, C
\( q_{\text{max}} \) = maximum charge for a spherical particle, C
\( Q \) = charge, C
\( Q_B \) = total charge on bubble, C
\( Q_{\text{cumulative}} \) = total cumulative charge, C
\( Q_{\text{induced}} \) = total induced charge, C
\( Q_P \) = total charge on the probe, C
\( Q_{\text{total}} \) = total charge, C
\( Q_{\text{transferred}} \) = total direct charge transfer, C
\( \mathbf{r} \) = surface normal vector, m
\( r \) = distance between field point and source point, m
\( r_1 \) = distance between the field point \( P \) on the probe and the point charge \( q \) on the bubble, m
\( r_2 \) = distance between the field point \( P \) on the probe and the image charge \( q' \) in the bubble, m
\( r_B \) = bubble radius, m
\( r_p \) = probe radius, m
\( R_r \) = resistivity, \( \Omega \) m
\( R \) = resistance, \( \Omega \)
R.H. = relative humidity, %
\( S \) = surface
\( S_o \) = interface for medium 1 and medium 2
\( t \) = time, s
\( T \) = temperature, °C
\( U \) = electrical potential, V
\( U_B \) = bubble rise velocity, m/s
\( U_g \) = superficial gas velocity, m/s
\( U_{mf} \) = minimum fluidization velocity, m/s
\( U_p \) = particle velocity, m/s
\( U_r \) = radial component of particle velocity, m/s
\( v \) = volume bounded by \( S \), m\(^3\)
\( V \) = voltage, V
\( V_{avg} \) = average voltage, V
\( V_{max} \) = maximum voltage of positive peak, V
\( V_{min} \) = minimum voltage of negative peak, V
\( x_i \) = mass fraction

Greek symbols

\( \varepsilon \) = voidage
\( \varepsilon_0 \) = loose packed voidage, = \( 1 - (\rho_b/\rho_p) \)
\( \sigma \) = surface charge density, C/m\(^2\)
\( \sigma_0 \) = initial surface charge density, C/m\(^2\)
\( \sigma_{total} \) = total surface charge density, C/m\(^2\)
\( \delta_B \) = thickness of bubble, m
\( \Pi \) = permittivity of medium, F/m
\( \Pi_0 \) = permittivity of free space, \( 8.854 \times 10^{-12} \) F/m
\( \Pi_r \) = relative permittivity, ratio of \( \Pi \) to \( \Pi_0 \)
\( \Pi_0 \varepsilon \) = electric flux density due to all charges in a given space, C/m²
\( \phi \) = angle for points on the probe, radian
\( \phi_m \) = magnetic flux along path \( C_S \) which bounds surface \( S \), Wb
\( \phi_e \) = electric flux along \( C_S \), C
\( \theta \) = angle for points on the probe, radian
\( \theta_B \) = angle for points on the bubble, radian
\( \mu_0 \) = permeability of free space = \( 4\pi \times 10^{-7} \) H/m
\( \nu_e \) = electromotive force, N
\( \rho \) = charge density, C/m³
\( \rho_b \) = bulk density, kg/m³
\( \rho_p \) = particle density, kg/m³
\( \rho_T \) = total charge density, C/m³
\( \tau \) = decay time constant, = \( \Pi_r \Pi_0 R \)
References


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Appendix A

Air Rotameter Calibration Curves
Calibration of the main air rotameter with the smallest floater
(0 - 3.17 scfm)

Table A.1. Calibration results of the main rotameter for air

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.1</td>
<td>74.65</td>
<td>0.0000</td>
<td>0.000E+00</td>
<td>0.000</td>
</tr>
<tr>
<td>1</td>
<td>0.3</td>
<td>44.77</td>
<td>0.3350</td>
<td>1.581E-04</td>
<td>0.025</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>24.46</td>
<td>0.6133</td>
<td>2.895E-04</td>
<td>0.047</td>
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<td>1.4267</td>
<td>6.733E-04</td>
<td>0.108</td>
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<tr>
<td>6</td>
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<td>17.75</td>
<td>1.6901</td>
<td>7.977E-04</td>
<td>0.129</td>
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<tr>
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<td>14.99</td>
<td>2.0017</td>
<td>9.447E-04</td>
<td>0.152</td>
</tr>
<tr>
<td>8</td>
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<td>12.48</td>
<td>2.4038</td>
<td>1.134E-03</td>
<td>0.183</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>11.13</td>
<td>2.6948</td>
<td>1.272E-03</td>
<td>0.205</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>9.67</td>
<td>3.1024</td>
<td>1.464E-03</td>
<td>0.236</td>
</tr>
</tbody>
</table>

diameter of the column = 3.5 in = 0.0889 m

cross sectional area of the column (Ac) = 0.006207 m^2

Figure A.1. Calibration of Air Rotameter with smallest floater at 25.7 °C
Figure A.2. Rotameter reading versus Superficial gas velocity for the main air rotameter (smallest floater)

\[ y = 0.0228x - 0.0012 \]

\[ R^2 = 0.9963 \]
Appendix B

Calibration Curves for Pressure Transducers
Calibration of the Pressure Transducer (1)

Table B.1. Calibration Results for Pressure Transducer - PX162-030G5V

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.43379</td>
<td>3.0</td>
<td>1.2</td>
<td>293.9</td>
<td>0.043</td>
</tr>
<tr>
<td>1.4453</td>
<td>6.3</td>
<td>2.5</td>
<td>612.3</td>
<td>0.089</td>
</tr>
<tr>
<td>1.46849</td>
<td>13.1</td>
<td>5.1</td>
<td>1278.5</td>
<td>0.185</td>
</tr>
<tr>
<td>1.47459</td>
<td>14.8</td>
<td>5.8</td>
<td>1449.9</td>
<td>0.210</td>
</tr>
<tr>
<td>1.48864</td>
<td>18.7</td>
<td>7.4</td>
<td>1832.0</td>
<td>0.266</td>
</tr>
<tr>
<td>1.50361</td>
<td>23.2</td>
<td>9.1</td>
<td>2272.9</td>
<td>0.330</td>
</tr>
<tr>
<td>1.51069</td>
<td>25.4</td>
<td>10.0</td>
<td>2488.4</td>
<td>0.361</td>
</tr>
<tr>
<td>1.52663</td>
<td>30.1</td>
<td>11.8</td>
<td>2944.0</td>
<td>0.427</td>
</tr>
<tr>
<td>1.55848</td>
<td>39.4</td>
<td>15.5</td>
<td>3860.0</td>
<td>0.560</td>
</tr>
<tr>
<td>1.60098</td>
<td>51.5</td>
<td>20.3</td>
<td>5045.4</td>
<td>0.732</td>
</tr>
<tr>
<td>1.62758</td>
<td>59.3</td>
<td>23.3</td>
<td>5809.5</td>
<td>0.843</td>
</tr>
<tr>
<td>1.65753</td>
<td>68.3</td>
<td>26.9</td>
<td>6691.2</td>
<td>0.970</td>
</tr>
<tr>
<td>1.68701</td>
<td>76.7</td>
<td>30.2</td>
<td>7514.2</td>
<td>1.090</td>
</tr>
</tbody>
</table>

Therefore, \( P[\text{Pa}] = 28559.22 \times \text{voltage} - 40662.76 \)
Calibration of the Pressure Transducer (2)

Table B.2. Calibration Results for Pressure Transducer - PX142-030D5V

<table>
<thead>
<tr>
<th>Voltage [V]</th>
<th>DP [psig]</th>
<th>DP [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.40367</td>
<td>0.000</td>
<td>0.0</td>
</tr>
<tr>
<td>2.29449</td>
<td>1.500</td>
<td>10342.1</td>
</tr>
<tr>
<td>3.06353</td>
<td>4.700</td>
<td>32405.4</td>
</tr>
<tr>
<td>3.72999</td>
<td>7.400</td>
<td>51021.2</td>
</tr>
<tr>
<td>4.27849</td>
<td>9.500</td>
<td>65500.2</td>
</tr>
<tr>
<td>4.65633</td>
<td>11.100</td>
<td>76531.8</td>
</tr>
</tbody>
</table>

$y = 27879.99x - 53335.10$

$R^2 = 1.00$

Therefore, $P[Pa] = 27879.99 \times \text{voltage}-53335.10$
Appendix C
Design of Fluidized Bed Column
1.1 Column diameter

1) Particle diameter = 300 μm (PE)

2) Guide line: \( \frac{D_c}{d_p} \geq 20 \)
\[
D_c = 3.5" = 0.0889 \text{ m}
\]
\[
\frac{D_c}{d_p} = \frac{0.0889 \text{ m}}{300 \times 10^{-6} \text{ m}} = 296.3 \geq 20
\]
Therefore, the column diameter is suitable for the system.

1.2 Column height

Static bed height, \( H_B = 0.21 \text{ m} \)

\[
\frac{H_B}{D_c} = \frac{0.21 \text{ m}}{0.0889 \text{ m}} = 2.362 \leq 5.0
\]

Expended bed height = 2.5 \( \times \) \( H_B \) = 0.53 m

Therefore, Working total height, \( H_T = 0.53 \text{ m} \)

1.3 Distributor

Experimental conditions: \( \rho_s = 700 \text{ kg/m}^3 \), \( \rho_g = 1.2 \text{ kg/m}^3 \), \( U_g = 0.4 \text{ m/s} \), \( W_s = 0.5 \text{ kg} \).
\( \Delta p_{\text{bed}} = \frac{W_s g}{A_c} = (0.5 \text{ kg}) (9.81 \text{ m/s}^2) / (\pi (0.0889 \text{ m})^2/4) = 790.2 \text{ Pa} \)
\( \Delta p_{\text{dist}} = \max (0.1 \Delta p_{\text{bed}}, 35 \text{ cm H}_2\text{O}) = 35 \text{ cm H}_2\text{O} = 3.43 \text{ kPa} \)
Check the size and number of orifices

\( U_g = \) superficial gas velocity = 0.4 m/s

\( N_{or} = \) number of orifices = 44

\( D_{or} = \) diameter of orifices = 1.092 mm

\( C_d = \) drag coefficient

\( D_c = \) column diameter = 0.0889 m

\( \rho_g = \) gas density = 1.2 kg/m³

\[
N_{Re} = \frac{\rho_g U_g D_c}{\mu_g} = \frac{(1.2 \text{ kg/m}^3)(0.4 \text{ m/s})(0.0889 \text{ m})}{(1.8 \times 10^{-5} \text{ kg/ms})} = 2370.7
\]
For Reynolds number, $N_{Re} = 423.3$ from Kunii and Levenspiel (1991)

<table>
<thead>
<tr>
<th>$N_{Re}$</th>
<th>100</th>
<th>300</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>&gt; 3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_d$</td>
<td>0.68</td>
<td>0.70</td>
<td>0.68</td>
<td>0.64</td>
<td>0.61</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Therefore, $C_d = 0.61$

\[
d^2 N_{or} = U_g \frac{D^2}{C_d} \sqrt{\frac{\rho_g}{2\Delta p_{dist}}}
\]

\[
= (0.4 m/s)(0.0889 m)^2 \sqrt{\frac{(1.2 kg/m^3)}{2(3.43 \times 10^3 Pa)}}
\]

\[
= 4.0143E-3 \sqrt{\Delta p_{dist}}
\]

\[
= 52.468E-6 m^2
\]

Then, $\sqrt{\Delta p_{dist}} = 13.07E-3$ and $\Delta p_{dist} = 5.85E3$ Pa

Therefore, there is an enough pressure drop across the distributor.

\[
U_{or} = \frac{A U_g}{A_{or}} = \frac{\pi/4 (0.0889 m)^2 (0.4 m/s)}{44(\pi/4 (1.092 \times 10^{-3} m)^2)} = 60.25 m/s
\]

The line velocity through the orifice is also suitable.

1.4 Air vent line

Maximum $U_g = 0.5 m/s$

\[
Q = \frac{\pi}{4} (0.0889 m)^2 (0.5 m/s) = 3.104 \times 10^{-3} m^3 / s = 3.104 l / s
\]

\[
\frac{\pi}{4} D_{vent}^2 U_{vent} = 3.104 \times 10^{-3} m^3 / s \text{ where } D_{vent} = 2 \text{ inch} = 0.0508 \text{ m}
\]

\[
\frac{\pi}{4} (0.0508 m)^2 U_{vent} = 3.104 \times 10^{-3} m^3 / s
\]

Therefore, $U_{vent} = 1.531 m/s$

Friction factor, $F$

\[
F = K_e \frac{V^2}{2g_c}
\]
\[
\frac{A_2}{A_1} = \frac{\pi/4 (0.75\text{"})}{\pi/4 (3.5\text{")}} = 0.214
\]

From Perry's handbook 5-34, Table 5-13

\[K_c = 0.444\]

\[\Delta P_{vent} = F p_g = 0.444(1.2\text{kg/m}^3)(1.531\text{m/s})^2 = 0.624\text{kg/m}^2 = 0.624\text{Pa}\]

Therefore, \(\Delta P_{vent}\) is negligible.

1.5 Design summary

1) Column diameter, \(D_c = 3.5\text{"} = 0.0889\text{ m}\), Plexiglas column
2) Column height, \(H_T = 0.53\text{ m}\), working height
3) Gas distributor, \(d_{or} = 1.092\text{ mm}\), \(N_{or} = 44\)
4) Air vent line, \(D_{vent} = 0.0191\text{ m}\)
Appendix D

Physical Properties of Particles
Table D.1. Sauter mean diameter of glass beads

<table>
<thead>
<tr>
<th>mean sieve opening, dsi [µm]</th>
<th>weight [g]</th>
<th>mass fraction x_i</th>
<th>mass fraction / mass sieve opening x_i/dsi</th>
</tr>
</thead>
<tbody>
<tr>
<td>655</td>
<td>0.1</td>
<td>0.000</td>
<td>0.0000</td>
</tr>
<tr>
<td>508.5</td>
<td>5.2</td>
<td>0.007</td>
<td>0.0000</td>
</tr>
<tr>
<td>358.5</td>
<td>647.9</td>
<td>0.827</td>
<td>0.0023</td>
</tr>
<tr>
<td>240</td>
<td>123</td>
<td>0.157</td>
<td>0.0007</td>
</tr>
<tr>
<td>121.5</td>
<td>4.9</td>
<td>0.006</td>
<td>0.0001</td>
</tr>
<tr>
<td>31.5</td>
<td>2.3</td>
<td>0.003</td>
<td>0.0001</td>
</tr>
<tr>
<td>sum</td>
<td>783.4</td>
<td>1.000</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

Sauter mean diameter (ds) of glass beads

\[ ds = \frac{1}{\sum x_i/dsi} = 321 \text{ µm} \]

Figure D.1. Size Distribution of Glass Beads
Table D.2. Sauter mean diameter of PE I

<table>
<thead>
<tr>
<th>mean sieve opening, (d_{si}) ([\mu m])</th>
<th>weight ([g])</th>
<th>mass fraction (x_i)</th>
<th>mass fraction / mass sieve opening (x_i/d_{si})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1190</td>
<td>16.3</td>
<td>0.075</td>
<td>0.0001</td>
</tr>
<tr>
<td>1090</td>
<td>15.6</td>
<td>0.071</td>
<td>0.0001</td>
</tr>
<tr>
<td>855</td>
<td>34</td>
<td>0.155</td>
<td>0.0002</td>
</tr>
<tr>
<td>655</td>
<td>19.8</td>
<td>0.091</td>
<td>0.0001</td>
</tr>
<tr>
<td>550</td>
<td>20</td>
<td>0.091</td>
<td>0.0002</td>
</tr>
<tr>
<td>458.5</td>
<td>23.6</td>
<td>0.108</td>
<td>0.0002</td>
</tr>
<tr>
<td>358.5</td>
<td>40.9</td>
<td>0.187</td>
<td>0.0005</td>
</tr>
<tr>
<td>240</td>
<td>37.5</td>
<td>0.171</td>
<td>0.0007</td>
</tr>
<tr>
<td>90</td>
<td>11</td>
<td>0.050</td>
<td>0.0006</td>
</tr>
<tr>
<td>sum</td>
<td>218.7</td>
<td>1.000</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

Sauter mean diameter (\(d_s\)) of PE I

\[
\bar{d}_s = \frac{1}{\text{sum}(x_i/d_{si})} = 378 \ \mu m
\]

Figure D.2. Size Distribution of PE I particles
Table D.3. Sauter mean diameter of PE II

<table>
<thead>
<tr>
<th>mean sieve opening, dsi [µm]</th>
<th>weight [g]</th>
<th>mass fraction x_i</th>
<th>mass fraction / mass sieve opening x_i/dsi</th>
</tr>
</thead>
<tbody>
<tr>
<td>755</td>
<td>10.1</td>
<td>0.038</td>
<td>0.0001</td>
</tr>
<tr>
<td>655</td>
<td>12.3</td>
<td>0.047</td>
<td>0.0001</td>
</tr>
<tr>
<td>550</td>
<td>26.6</td>
<td>0.101</td>
<td>0.0002</td>
</tr>
<tr>
<td>458.5</td>
<td>45.7</td>
<td>0.174</td>
<td>0.0004</td>
</tr>
<tr>
<td>358.5</td>
<td>79.8</td>
<td>0.303</td>
<td>0.0008</td>
</tr>
<tr>
<td>240</td>
<td>76.1</td>
<td>0.285</td>
<td>0.0012</td>
</tr>
<tr>
<td>121.5</td>
<td>13.6</td>
<td>0.052</td>
<td>0.0004</td>
</tr>
<tr>
<td>sum</td>
<td>263.2</td>
<td>1.000</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

Sauter mean diameter (ds) of PE II

\[ ds = 1 / \sum(x_i/dsi) = 318 \text{ µm} \]

Figure D.3. Size Distribution of PE II particles
Table D.4. Density measurement using Pycnometer for GB

<table>
<thead>
<tr>
<th>Trial #1</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W(bottle)</td>
<td>32.8741 g</td>
<td>W(GB)</td>
</tr>
<tr>
<td>W(bottle+GB)</td>
<td>92.6631 g</td>
<td>W(water)</td>
</tr>
<tr>
<td>W(bottle filled with GB)</td>
<td>180.7191 g</td>
<td>T(water)</td>
</tr>
<tr>
<td>W(bottle+GB+water)</td>
<td>168.2628 g</td>
<td>density (water @15°C)</td>
</tr>
<tr>
<td>V(water)</td>
<td>W(water) / density(water)</td>
<td>75.675 ml</td>
</tr>
<tr>
<td>Vtotal</td>
<td>100.000 ml</td>
<td>V(GB)</td>
</tr>
<tr>
<td>Vtotal(filled)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V(GB) = Vtotal - V(water)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

particle density (GB) = W(GB) / V(GB) = 2.458 g/ml
bulk density (GB) = (W (bottle filled with GB) - W (bottle)) / Vtotal = 1.478 g/ml

Table D.5. Density measurement using Pycnometer for PE I

<table>
<thead>
<tr>
<th>Trial #1</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W(bottle)</td>
<td>16.0204 g</td>
<td>W(PE)</td>
</tr>
<tr>
<td>W(bottle+PE)</td>
<td>23.1426 g</td>
<td>W(water)</td>
</tr>
<tr>
<td>W(bottle+PE+water)</td>
<td>38.1686 g</td>
<td>T(water)</td>
</tr>
<tr>
<td>W(bottle filled with PE I)</td>
<td>49.6204 g</td>
<td>density (water @15°C)</td>
</tr>
<tr>
<td>V(water)</td>
<td>W(water) / density(water)</td>
<td>15.041 ml</td>
</tr>
<tr>
<td>Vtotal</td>
<td>25.000 ml</td>
<td>V(PE)</td>
</tr>
<tr>
<td>V(PE) = Vtotal - V(water)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

particle density (PE) = W(PE) / V(PE) = 0.715 g/ml
bulk density (GB) = (W (bottle filled with GB) - W (bottle)) / Vtotal = 0.410 g/ml

<table>
<thead>
<tr>
<th>Trial #2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W(bottle)</td>
<td>16.0331 g</td>
<td>W(PE)</td>
</tr>
<tr>
<td>W(bottle+PE)</td>
<td>22.9854 g</td>
<td>W(water)</td>
</tr>
<tr>
<td>W(bottle+PE+water)</td>
<td>38.7786 g</td>
<td>T(water)</td>
</tr>
<tr>
<td>W(bottle filled with PE I)</td>
<td>51.4331 g</td>
<td>density (water @15°C)</td>
</tr>
<tr>
<td>V(water)</td>
<td>W(water) / density(water)</td>
<td>15.841 ml</td>
</tr>
<tr>
<td>Vtotal</td>
<td>25.000 ml</td>
<td>V(PE)</td>
</tr>
<tr>
<td>V(PE) = Vtotal - V(water)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

particle density (PE) = W(PE) / V(PE) = 0.759 g/ml
bulk density (GB) = (W (bottle filled with GB) - W (bottle)) / Vtotal(filled) = 0.416 g/ml
### Trial #3

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>W(bottle)</strong></td>
<td>16.0202 g</td>
<td><strong>W(PE)</strong></td>
<td>6.5411 g</td>
</tr>
<tr>
<td><strong>W(bottle+PE)</strong></td>
<td>22.5613 g</td>
<td><strong>W(water)</strong></td>
<td>15.9285 g</td>
</tr>
<tr>
<td><strong>W(bottle+PE+water)</strong></td>
<td>38.4898 g</td>
<td><strong>T(water)</strong></td>
<td>20.5 °C</td>
</tr>
<tr>
<td><strong>W(bottle filled with PE I)</strong></td>
<td>52.6202 g</td>
<td><strong>density (water @15°C)</strong></td>
<td>0.998 g/ml</td>
</tr>
</tbody>
</table>

\[
V(\text{water}) = \frac{W(\text{water})}{\text{density(\text{water})}} = \frac{15.9285 \text{ g}}{0.998 \text{ g/ml}} = 15.960 \text{ ml}
\]

\[
\text{Vtotal} = 25.000 \text{ ml}
\]

\[
\text{Vtotal(filled)} = 89.000 \text{ ml}
\]

\[
\text{V(PE)} = \text{Vtotal} - \text{V(water)} = 9.040 \text{ ml}
\]

\[
\text{particle density (PE)} = \frac{W(\text{PE})}{\text{V(PE)}} = \frac{6.5411 \text{ g}}{9.040 \text{ ml}} = 0.724 \text{ g/ml}
\]

\[
\text{bulk density (GB)} = \frac{(W(\text{bottle filled with GB}) - W(\text{bottle}))}{\text{Vtotal(filled)}} = \frac{0.411 \text{ g/ml}}{0.411 \text{ g/ml}}
\]

**Therefore,**

- **average particle density of PE I** = **0.715 g/ml**
- **average bulk density of PE I** = **0.412 g/ml**

### Table D.6. Density measurement using Pycnometer for PE II

### Trial #1

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>W(bottle)</strong></td>
<td>1.619 g</td>
<td><strong>W(PE)</strong></td>
<td>9.100 g</td>
</tr>
<tr>
<td><strong>W(bottle+PE)</strong></td>
<td>16.200 g</td>
<td><strong>W(ethanol)</strong></td>
<td>9.1000 g</td>
</tr>
<tr>
<td><strong>W(bottle filled with PE)</strong></td>
<td>41.719 g</td>
<td><strong>T(ethanol)</strong></td>
<td>15.5 °C</td>
</tr>
<tr>
<td><strong>W(bottle+PE+ethanol)</strong></td>
<td>25.3 g</td>
<td><strong>density (ethanol @15°C)</strong></td>
<td>0.790 g/ml</td>
</tr>
</tbody>
</table>

\[
\text{V(ethanol)} = \frac{W(\text{ethanol})}{\text{density(\text{ethanol})}} = \frac{9.100 \text{ g}}{0.790 \text{ g/ml}} = 11.519 \text{ ml}
\]

\[
\text{Vtotal} = 22.519 \text{ ml}
\]

\[
\text{Vtotal(filled)} = 87.5 \text{ ml}
\]

\[
\text{V(PE)} = \text{Vtotal} - \text{V(ethanol)} = 11.000 \text{ ml}
\]

\[
\text{particle density (PE)} = \frac{W(\text{PE})}{\text{V(PE)}} = \frac{9.100 \text{ g}}{11.000 \text{ ml}} = 0.827 \text{ g/ml}
\]

\[
\text{bulk density (GB)} = \frac{(W(\text{bottle filled with GB}) - W(\text{bottle}))}{\text{Vtotal(filled)}} = \frac{0.458 \text{ g/ml}}{0.458 \text{ g/ml}}
\]

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### Trial #2

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W(bottle)</td>
<td>1.619</td>
<td>W(PE)</td>
<td>6.7</td>
</tr>
<tr>
<td>W(bottle+PE)</td>
<td>8.319</td>
<td>W(ethanol)</td>
<td>6.8810</td>
</tr>
<tr>
<td>W(bottle+PE+ethanol)</td>
<td>15.2</td>
<td>T(ethanol)</td>
<td>15.5</td>
</tr>
<tr>
<td>W1(bottle filled with PE)</td>
<td>6.6735</td>
<td>density (ethanol @15°C)</td>
<td>0.999</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
V(\text{ethanol}) &= \frac{W(\text{ethanol})}{\text{density (ethanol)}} = 15.215 \text{ ml} \\
V(\text{total}) &= 23.715 \text{ ml} \\
V(\text{total1 (filled)}) &= 90.5 \text{ ml} \\
V(\text{PE}) &= V(\text{total}) - V(\text{ethanol}) = 8.500 \text{ ml}
\end{align*}
\]

particle density (PE) = \frac{W(\text{PE})}{V(\text{PE})} = 0.788 \text{ g/ml}

bulk density (PE) = \frac{(W (\text{bottle filled with PE}) - W (\text{bottle}))}{V(\text{total})} = 0.477 \text{ g/ml}

### Trial #3

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W(bottle)</td>
<td>1.619</td>
<td>W(PE)</td>
<td>6.97</td>
</tr>
<tr>
<td>W(bottle+PE)</td>
<td>8.59</td>
<td>W(ethanol)</td>
<td>41.7700</td>
</tr>
<tr>
<td>W(bottle+PE+ethanol)</td>
<td>32.7790</td>
<td>T(ethanol)</td>
<td>15.5</td>
</tr>
<tr>
<td>W2(bottle filled with PE)</td>
<td>35.8</td>
<td>density (ethanol @15°C)</td>
<td>0.999</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
V(\text{ethanol}) &= \frac{W(\text{ethanol})}{\text{density (ethanol)}} = 32.812 \text{ ml} \\
V(\text{total}) &= 41.812 \text{ ml} \\
V(\text{total2 (filled)}) &= 78 \text{ ml} \\
V(\text{PE}) &= V(\text{total}) - V(\text{ethanol}) = 9.000 \text{ ml}
\end{align*}
\]

particle density (PE) = \frac{W(\text{PE})}{V(\text{PE})} = 0.774 \text{ g/ml}

bulk density (PE) = \frac{(W (\text{bottle filled with PE}) - W (\text{bottle}))}{V(\text{total})} = 0.438 \text{ g/ml}

Therefore,

average particle density of PE II = 0.797 g/ml

average bulk density of PE II = 0.458 g/ml
Appendix E

Experimental Plan for Noise Test
Testing for the noise in the system

**Step 1-1**
- Power source (2 V) → Voltmeter → A/D → Computer

**File Name**
- test11.dat

**Step 2-1**
- Power source (0.2 V) → Voltmeter → Amplifier (x10) → A/D → Computer

**File Name**
- test21.dat

**Step 2-2**
- Power source (0.02 V) → Voltmeter → Amplifier (x10) → A/D → Computer

**File Name**
- test22.dat
Step 4

probe (1 Mohm) → resistor → electrometer → amplifier → A/D → Computer

A/D → Computer

voltmeter

Step 5

probe → resistor (different sizes of resistors) → electrometer → amplifier → A/D → Computer

A/D → Computer

voltmeter

Step 6

probe → resistor

Add capacitor → electrometer → amplifier → A/D → Computer

A/D → Computer

voltmeter
Appendix F

MatLab Computer Codes for Models 1 and 2
%--------------------------------------------------------
% Model 1
%
% Charge Inducement without Direct Charge Transfer
%
% This program calculates the cumulative charge on the electrostatic ball probe due to
% the relative motion of a bubble.
%
% Assumption:
% Since the probe is much smaller than the bubble, consider the probe itself as a field
% point.
%--------------------------------------------------------

clear
clc

% set variables
QB=+1E-10; % QB = overall charge on the bubble
% (assuming uniform charge distribution around the bubble for now)
dB=50E-3; % dB = diameter of the bubble
rB=0.5*dB; % rB = radius of the bubble
dP=3.2E-3; % dP = diameter of the probe
rP=0.5*dP;
L=0.205; % L = initial distance between centres of the bubble and probe

UB=(round(1000*0.511*(9.81*dB)^0.5))/1000; % UB = bubble rise velocity

% set the time boundaries
% t = initial time
% tf = final time

% set the initial counting number and time & angle increments
j=1;
stept=0.001;
steptheta=0.001*pi;
gap=0.08*pi; % gapB = the gap to avoid the overlap of the probe and the bubble

% set initial values
% tdata = time
% Idata = total instantaneously induced charge (i.e. current)
% Qdata = total cumulative charge

tdata(1)=t;
Idata(1)=0;
Qdata(1)=0;

% integration of current over time to obtain the cumulative charge
while t <= tf
    j=j+1
    t=t+stept;
end
tdata(j)=t;
Qptotal=0;  % positive component of I (i.e. current)

% since the bubble is symmetrical, integrate over the right side of the bubble and
% multiply by 2
theta=pi/2+gap;

% integration over the bubble surface to obtain the total induced current
while theta<=pi/2-gap
theta=theta+steptheta;
y=L+UB*t+rB*(sin(theta));
rl=((rB*(cos(theta)))^2+(L+UB*t+rB*(sin(theta)))^2)^0.5;
Qp=-rP*QB/(pi*rl);
Qptotal=Qptotal+Qp*steptheta;
end
Qtotal=Qptotal;
Qdata(j)=Qtotal;
end

for r=2:length(Qdata)
Idata(r)=(Qdata(r)-Qdata(r-1))/stept;
end

Currentdata=Idata';
Chargedata=Qdata';

save IdataM1 Currentdata -ascii
save QdataM1 Chargedata -ascii

%Plot the graphs
subplot(2,1,1)
plot(tdata,Idata)
xlabel('Time [s]')
ylabel('Current [A]')
title('(a)')

subplot(2,1,2)
plot(tdata,Qdata)
xlabel('Time [s]')
ylabel('Induced Charge [C]')
title('(b)')
This program calculates the cumulative charge on the electrostatic ball probe due to the relative motion of a bubble and direct charge transfer.

Assumption:
The probe is a spherical conductive ball with radius of $r_P$.

```
clear
clc

% set parameters
QBi=+1E-10;  % QB = overall charge on the bubble
            % (assuming uniform charge distribution around the bubble for now)
 dB=50E-3;   % dB = diameter of the bubble
 rB=0.5*dB;  % rB = radius of the bubble
 dP=3.2E-3;  % dP = diameter of the probe
 rP=0.5*dP;  % rP = radius of the probe
 L=-0.205;   % L = initial distance between centres of the bubble and the probe

Pdensity=2471.1;  % Pdensity = particle density
                  % (i.e. Glass beads = 2471.1 kg/m$^3$ & PE = 958.8 kg/m$^3$)

erair=1.00059;  % erair = relative permittivity of air
erp=7.5;        % erp = relative permittivity of particle
er1=erp*(1-0.402)+erair*0.402;
% er1 = er of medium(i.e. particles) while the probe is not inside the bubble
er2=erp*0.01+erair*0.99;
% er2 = er of medium(i.e. air) while the probe is inside bubble

UB=(round(1000*0.511*(9.81*dB)^0.5))/1000;  % UB = bubble rise velocity
UP=UB;

A=1e-13;  % constant(related to the ball probe characteristics and the effects of surface contamination and nonsphericity)
          % Cc = dimensional concentration factor (m$^4$/kg*s)

% set the time boundaries
ti=0;  % t = initial time
tf=(round(-2*L/UB*1000))/1000;  % tf = final time
t=tf;
```
% set the initial counting number and time & angle increments
j=1;
stept=0.001;
steptheta=0.01*pi;
gapB=0.08*pi; % gapB = the gap to avoid the overlap of the probe and the bubble

% set initial values
tdata(l)=t; % tdata = time
Idata(l)=0; % Idata = total instantaneously induced charge (i.e. current)
Qdata(l)=0; % Qcumulateddata = cumulative charge on the probe induced by bubble

% Calculate the directly transferred charges

I2data1(1)=0;
Q2data1(1)=0;
for k=2:length(t1)
    UP1(k)=UB*(rB/(L+UB*t1(k)))^2;
    Cc(k)=UP1(k)^2/(Pdensity*(1-0.402));
    I2data1(k)=A*UP1(k)^(8/5)*Pdensity*exp(-Cc(k)*Pdensity/UP1(k));
    Q2data1(k)=(I2data1(k)+I2data1(k-l))/2*stept+Q2data1(k-l);
    I2data(k)=I2data1(k);
    Q2data(k)=Q2data1(k);
end
I2data2(1)=I2data1(length(t1));
Q2data2(1)=Q2data1(length(t1));
Q2data(length(t1)+1)=Q2data2(1);
I2data(length(t1)+1)=I2data2(1);

for m=2:length(t2)
    I2data2(m)=0;
    Q2data2(m)=(I2data2(m)+I2data2(m-1))/2*stept+Q2data2(m-1);
    Q2data(length(t1)+m)=Q2data2(m);
    I2data(length(t1)+m)=I2data2(m);
end
I2data3(1)=I2data2(length(t2));
Q2data3(1)=Q2data2(length(t2));
Q2data(length(t1)+length(t2)+1)=Q2data3(1);
I2data(length(t1)+length(t2)+1)=I2data3(1);

for n=2:length(t3)
    I2data3(n)=0;
    Q2data3(n)=(I2data3(n)+I2data3(n-1))/2*stept+Q2data3(n-1);
end
Q2data(length(t1)+length(t2)+n)=Q2data3(n);
I2data(length(t1)+length(t2)+n)=I2data3(n);
end
I2data4(1)=I2data1(length(t1));
Q2data4(1)=Q2data3(length(t3));
Q2data(length(t1)+length(t2)+length(t3)+1)=Q2data4(1);
I2data(length(t1)+length(t2)+length(t3)+1)=I2data4(1);

for q=2:length(t4)
    UP2(q)=UB*((rB/(L+UB*t4(q))))^2);
    Cc(q)=UP2(q)/2/(Pdensity*(1-0.402));
    I2data4(q)=A*UP2(q)^2/(Pdensity*exp(-Cc(q)*Pdensity/UP2(q)));
    Q2data4(q)=-(I2data4(q)+I2data4(q-1))/2*stept+Q2data4(q-1);
    Q2data(length(t1)+length(t2)+length(t3)+q)=Q2data4(q);
    I2data(length(t1)+length(t2)+length(t3)+q)=I2data4(q);
end

% Calculate the amount of charge remained on the bubble surface
for h=1:length(Q2data)
    QB(h)=QBi-Q2data(h);
end

% Calculate the induced charge
while t < (-(rB+L)/UB)
    j=j+1
    tdata(j)=t;
    Q=0;
    theta=0;

    % integration over the probe surface to obtain the total induced current
    while theta<=pi
        theta=theta+steptheta;
        SCDptotal=0;% SCDp = Surface Charge Density while r1 is positive
        thetaB=-pi/2+gapB;
        while thetaB<=pi/2-gapB
            thetaB=thetaB+steptheta;
            x=rB*(cos(thetaB));
            y=L+UB*t+rB*(sin(thetaB));
            d=(x^2+y^2)^0.5;
            c=-rP/d;
        end
    end
end

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r1=((rP)^2+d^2-2*rP*d*(cos(theta)))^0.5;

SCDp=-QB(j)*rP*(1+1/c^2)/(er1*8*pi^2*r1^3);
SCDptotal=SCDptotal+SCDp*steptheta;
end

SCDtotal=2*SCDptotal;
Q=Q+SCDtotal*2*(2*pi*((rP)^2)*(abs(sin(theta)))*steptheta);
end

Qdata(j)=Q;
Idata(j)=-(Qdata(j)-Qdata(j-1))/stept;

t=t+stept;
end

while t <= ((rB-L)/UB)
  j=j+1
  tdata(j)=t;
  Q=0;
  theta=0;

  % integration over the probe surface to obtain the total induced current
  while theta<=pi
    theta=theta+steptheta;
    SCDptotal=0;% SCDp = Surface Charge Density while r1 is positive
    thetaB=-pi/2+gapB;
    % integration over the bubble surface to obtain the total surface charge density
    while thetaB<=pi/2-gapB
      thetaB=thetaB+steptheta;
      x=rB*(cos(thetaB));
      y=L+UB*t+rB*(sin(thetaB));
      d=(x^2+y^2)^0.5;
      c=-rP/d;
      r1=((rP)^2+d^2-2*rP*d*(cos(theta)))^0.5;
      SCDp=-QB(j)*rP*(1+1/c^2)/(er2*8*pi^2*r1^3);
    end
  end
end

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% integration over the probe surface to obtain the total induced current
while theta<=pi
    theta=theta+steptheta;
    SCDptotal=0;% SCDp = Surface Charge Density while r1 is positive
    thetaB=-pi/2+gapB;
    % integration over the bubble surface to obtain the total surface charge density
    while thetaB<=pi/2-gapB
        thetaB=thetaB+steptheta;
        x=rB*(cos(thetaB));
        y=L+UB*t+rB*(sin(thetaB));
        d=(x^2+y^2)^0.5;
        c=-rP/d;
        rl=((rP)^2+d^2-2*rP*d*(cos(theta)))^0.5;
        SCDp=QB(j)*rP*(1+1/c^2)/(er1*8*pi^2*r1^3);
        SCDptotal=SCDptotal+SCDp*steptheta;
    end
    SCDtotal=2*SCDptotal;
    Q=Q+SCDtotal*2*(2*pi*((rP)^2)*(abs(sin(theta)))*steptheta);
end
Qdata(j)=Q;
Idata(j)=-(Qdata(j)-Qdata(j-1))/stept;
t=t+stept;
end

while t <= tf
    j=j+1
    tdata(j)=t;
    Q=0;
    theta=0;
    SCDptotal=SCDptotal+SCDp*steptheta;
end

while t <= tf
    j=j+1
    tdata(j)=t;
    Q=0;
    theta=0;
    SCDptotal=SCDptotal+SCDp*steptheta;
end
Qdata(j)=Q;
Idata(j)=-(Qdata(j)-Qdata(j-1))/stept;

t=t+stept;
end

% save the data onto a file

Qtotal=Qdata+Q2data;
Itotal=Idata+I2data;

Itotal2(1)=0;
for r=2:length(Qtotal)
    Itotal2(r)=-(Qtotal(r)-Qtotal(r-1))/stept;
end

timedata=tdata';
Currentdata=Itotal';
Chargedata=Qtotal';

save IdataE0 Currentdata -ascii
save QdataE0 Chargedata -ascii

% Plot the graphs for charge inducement without direct charge transfer

subplot(2,1,1)
plot(tdata,Itotal,tdata,Itotal2)
xlabel('Time [s]')
ylabel('Current [A]')
title('(a)')

subplot(2,1,2)
plot(tdata,Qtotal)
xlabel('Time [s]')
ylabel('Cumulative Charge [C]')
title('(b)')