# Charge Distribution Reconstruction in a Bubbling Fluidized Bed Using a Wire-Mesh Electrostatic Sensor

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***Abstract*—The presence of electrostatic charge in a bubbling fluidized bed influences the operation of the bed. In order to maintain an effective operation, the electrostatic charges in different positions of the bed should be monitored. In this paper a wire-mesh electrostatic sensor is introduced to reconstruct the charge distribution in a bubbling fluidized bed. The wire-mesh sensor is fabricated by two mutually perpendicular strands of insulated wires. A Finite Element Model is built to analyze the sensing characteristics of the sensor. The sensitivity distributions of each wire electrode and the whole sensor are obtained from the model, which proves that wire-mesh electrostatic sensor has a higher and more uniform sensitivity distribution than single wire sensors. Experiments were conducted in a gravity drop test rig to validate the reconstruction method. Experimental results show that the charge distribution can be reconstructed when sand particles pass through the cross section of the sensor.**

***Keywords*—charge distribution; reconstruction; wire-mesh electrostatic sensor; sensor characterization; sensitivity distribution**

## I. INTRODUCTION

Due to the contact and frictions between the particles and between the particles and wall, electrification is inevitable in a fluidized bed. The presence of electrostatic charges in the bed affects the operation of the bed. The hydrodynamics in the bed, such as bubble size and shape and solids mixing rate, changes with the level of electrostatic change in the bed. If the charge on the particles exceeds a critical value, the particles in the bed may adhere to the wall and even cause discharges and explosion [1]. In order to maintain an effective operation of the fluidized bed, the electrostatic charges in the bed should be continuously monitored. However, there are few sensors that are available for reliable, accurate and low-cost charge density measurement at present.

As an off-line measurement tool, Faraday cups were used to directly measure the charge density in the bed [2, 3]. However, charge generation and dispassion during the sampling process would influence the measurement result and Faraday cups were susceptible to variations in environmental factors. Apart from Faraday cups, electrostatic probes were developed to measure the electrostatic charges in fluidized beds. A theoretical model was developed by Chen *et al.* to explain the electrical current signals due to the passage of isolated gas bubbles in a fluidized bed [5, 6]. Based on this model, a collision probe was built to measure the particle charge-to-mass ratios in a 2D bubbling fluidized bed. An induction probe, which was mounted flush with the outside wall of the bed, was also developed by Chen *et al.*. They applied a number of induction probes to measure the induced charge signals due to the passage of bubbles and the charge distribution around the bubbles was reconstructed with different algorithms [7-9]. He *et al.* [10, 11] developed a dual-tip electrostatic probe for the measurements of particle charge density and bubble properties in a bubbling fluidized bed. The estimated particle charge density and bubble rise velocity were in reasonable agreement with those obtained using a Faraday cup and video imaging. However, electrostatic probes can only provide localized charge distribution information near the electrode. In order to maintain an effective operation of the fluidized bed, the electrostatic charge distribution in the whole cross section of the bed should be monitored.

As a noninvasive tomography method, electrostatic tomography (EST) was applied to visualize the flow pattern and reconstruct the charge distribution in the pneumatic conveying pipeline [12-15]. A 16-electrode system was applied by Green *et al.* to reconstruct the concentration profile in a gravity conveyer [12]. Machida *et al.* combined a back projection algorithm with the least squares method to reconstruct the electrostatic charges carried by particles [13]. Zhou *et al.* used the permittivity distribution acquired from an electrical capacitance tomography (ECT) system to improve the charge sensitivity field of an EST system and to reduce the uncertainty relating to the charge distribution reconstruction [14]. However, the sensitivity distribution of the sensor used for the EST system is not uniform, which may result in reconstruction errors, especially in the central area of the pipe.

For the first time, a wire-mesh electrostatic sensor is introduced in this paper to reconstruct the electrostatic charge distribution in a bubble fluidized bed. In comparison with ring-shaped and arc-shaped electrodes, the wire-mesh electrode has higher and more uniform spatial sensitivity especially in a large diameter fluidized bed. The drawback of the electrode is that the wire-mesh can obstruct the flow of particles in the bed and hence suffer from wear problems. However, the degree of obstruction depends on the diameter of the wire and the spacing between them and a wear resistant material can be used to prevent the abrasion of the wire. A wire-mesh electrostatic sensor was applied to measure the mean size of pneumatically conveyed particles [16].

This paper is organized as follows. The sensor design of the wire-mesh electrostatic sensor is introduced at first. Then the characteristics of the sensor are analyzed by establishing a finite element model (FEM). Finally, the charge distribution reconstruction of the sensor is verified by experiments conducted using a gravity drop test rig.

## II. SENSOR DESIGN AND CHARACTERIZATION

In the bubbling fluidized bed, with the movement of bubbles, electrostatic charge is generated due to the interactions between particles, the frictions between particles and walls of the bed and the relative motion of the particles with air. Based on the electrostatic induction, a wire-mesh electrostatic sensor is built to measure the charge distribution in different parts of the bed. The wire-mesh electrostatic sensor and its installation on a bubbling fluidized bed are shown in Fig. 1. The electrode of wire mesh electrostatic sensor is made up from two mutually perpendicular strands of insulated wires with a diameter of 1.5 mm. In each strand, there are 8 wires with an even spacing of 20 mm. The wires in the sensor are made from steel with a diameter of 1 mm. Shrinkable plastic tubes, with thickness of 0.25 mm, are fitted outside the wires to prevent the direct charge transfer between the charged particles and the wires. When the charged particles pass through the mesh, charges are induced on different wires of the sensor. By measuring the induced charges from the wires of the sensor, the charge distribution in the cross section of the bed can be reconstructed. In the present sensor design, approximately 14% of the bed is blocked by the wires. With relatively less number of wires and larger spacing between them, the effect of the blockage by the wires can be reduced. Due to the intrusiveness of the wire-mesh sensor, direct impact of particles with the electrode introduces spike in the electrostatic signal. However, this effect is minimized in signal conditioning electronics of the measurement system.

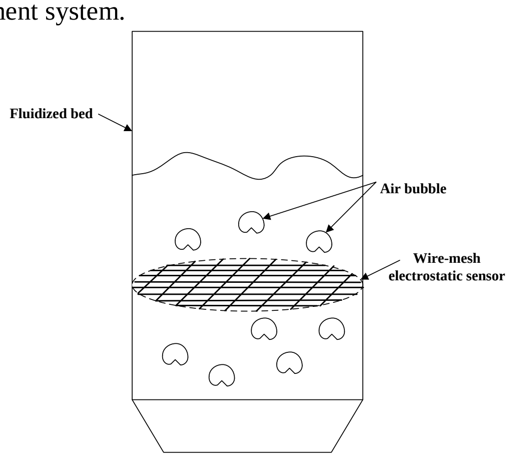



Fig. 1 Wire-mesh electrostatic sensor on a bubbling fluidized bed

In order to improve the performance of the wire-mesh electrostatic sensor, the sensing characteristics of the sensor should be analyzed. The electrostatic field due to the charged particles in the bed is governed by the following equation:

$$\nabla^2\varphi = -\frac{\rho}{\varepsilon_0\varepsilon_r} \quad (1)$$

where $\varphi$ is the electrical potential, $\varepsilon_0$ is the permittivity of free space, $\varepsilon_r$ is the relative permittivity of the material and $\rho$ is charge density in the bed. After solving the electrical potential, the surface charge density $\sigma$ can be found from the relation:

$$\sigma = \varepsilon_0\varepsilon_r E = -\varepsilon_0\varepsilon_r\nabla\varphi \quad (2)$$

The quantity of induced charge $q_i$ on the surface of the wire is calculated from:

$$q_i = \int_s \sigma ds \quad (3)$$

In view of the wire-mesh structure of the electrostatic sensor (Fig. 1), it is impractical to find an analytical solution to the above equations. However, it is possible to build a FEM model to analyze the characteristics of the sensor. An FEM model of the wire-mesh electrostatic sensor is built using COMSOL, as shown in Fig. 2. A cylinder with the same diameter of the bed (180 mm) is set to be the model domain. A set of 16 cylinders with a diameter of 1.5 mm is used to model the wire-mesh. Because the thickness of the insulated material is only 0.25 mm, it will have less effect on the sensing characteristics. As a result, the effect of the insulated material is not considered in the FEM modeling. A sphere with a radius of 1 mm is applied to model the charged particle. The materials of the wires and the model domain are set to steel and air respectively. The relative permittivity of the particle is set to 2.5 and the charge on the particle is set to 1 μC. The boundary condition is set to ground for the electrodes and zero charge for the outer surface of the model domain. Tetrahedral quadratic Lagrange elements are used in the mesh mode of the FEM model. The wire electrodes are meshed much finer than other subdomains so as to reflect the charge distribution in the electrode explicitly. In order to obtain the sensitivity distribution of the sensor, the cross section of the bed is divided into a 9 × 9 grid. During the simulation, the charged particle is placed in the center of different grids of the cross section and the induced charges on each electrode of the sensor are calculated according to equations (1)-(3).

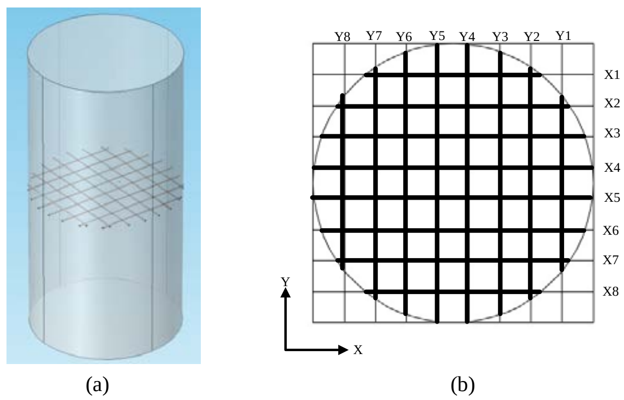
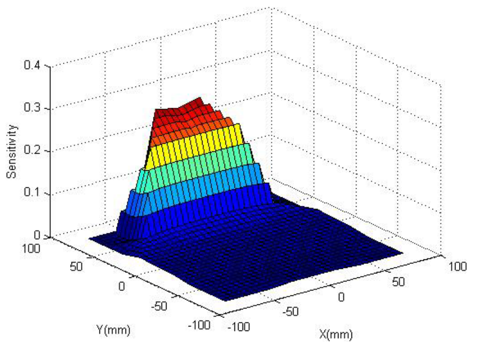



Fig. 2 FEM model of the wire-mesh electrostatic sensor (a) and the cross section of the model (b)

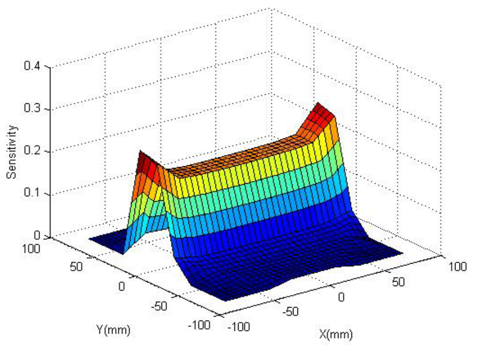
The sensitivity $S_i$ $(x, y)$ of the $i$th electrode of the wire-mesh sensor when the charged particle is placed in the position $(x, y)$ of the cross section is calculated by

$$S_i(x, y) = q_i / q_s \quad (4)$$

where $q_i$ is the induced charge on the $i$th electrode and $q_s$ is the charge on the particle. By placing the charged particle in different positions of the cross section, the sensitivity profile of each electrode of the sensor can be obtained. The sensitivity distribution of the wire-mesh sensor is shown in Fig. 3. It can be concluded from the sensitivity profiles of wires X1 and X4 that each electrode is more sensitive to the charged particle near the wire. The sensitivity distribution of the whole sensor is obtained by summing up the sensitivity profiles of all the electrodes, as shown in Fig. 3(c). The average sensitivity of the sensor is 0.985. The relative deviation of the sensitivity at each point from the average value is shown in Fig. 3 (d). It is evident that the wire-mesh sensor has a higher and more uniform sensitivity distribution than other forms of electrostatic sensor[12].




(a)

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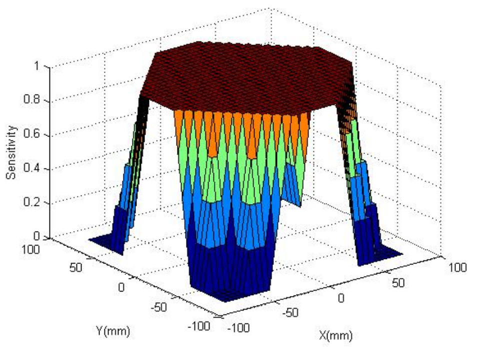
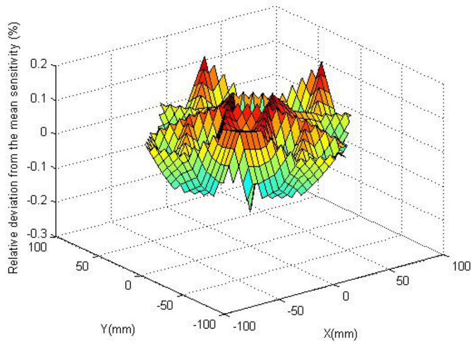



(c)




(d)

Fig. 3 Sensitivity distribution of the wire-mesh electrostatic sensor: (a) sensitivity distribution of wire X1, (b) sensitivity distribution of wire X4, (c) sensitivity distribution of the whole sensor, (d) relative deviation from the mean sensitivity

## III. CHARGE DISTRIBUTION RECONSTRUCTION

Given the sensitivity distribution of the wire-mesh sensor, if the charge distribution in the bed is known, the induced charge on each electrode of the sensor is calculated. Inversely, if the induced charge on each electrode of the sensor is available, the charge distribution in the bed can be reconstructed. The charge distribution reconstruction method is explained by the following equation:

$$q_{rec}(x,y)=\frac{1}{16}\sum_{i=1}^{16}q_i\,/\,S_i(x,y) \qquad (5)$$

where $q_{rec}$ $(x, y)$ is the reconstructed charge in the position $(x, y)$, $q_i$ is the induced charge on the $i$th electrode of the sensor and $S_i$ $(x, y)$ is the sensitivity of the $i$th electrode in the position $(x, y)$. According to equation (4), the charge on particle $q_s$ in the position $(x, y)$ can be obtained by dividing the induced charge $q_i$ on the $i$th electrode with the sensitivity $S_i$ $(x, y)$ of the $i$th electrode. The reconstructed charge in the position $(x, y)$ is the average of the contribution from all the electrodes of the sensor. By calculating the reconstructed charge in different positions of the cross section of the bed, a $9 \times 9$ matrix of the charge distribution is obtained. Finally, the reconstructed charge distribution is calculated by the triangle-based linear interpolation from the $9 \times 9$ matrix.

## IV. EXPERIMENTAL SETUP

In order to validate the charge distribution reconstruction method of the wire-mesh electrostatic sensor, experiments were conducted in a gravity drop test rig. The diagram of the test rig is given in Fig. 4. Sand particles were dropped from a funnel to the cross section of the sensor. The average diameter of the sands used in the experiments was 175 μm. The diameter of the outlet of the funnel was 12 mm and the distance between the outlet of the funnel and the sensor's cross section is less than 10 mm. As a result, the sand particles were concentrated to a small region of the cross section when they passed through the wire-mesh sensor. A holder was used to fix the funnel and the radial position of the funnel could be adjusted. The picture of the wire-mesh electrostatic sensor is shown in Fig. 5. With the fluctuation of electrostatic charges on the particles and the movement of the particles, a minute change in electric current is detected on the electrode. The current signal is converted to a voltage signal through an amplifier. The signal is then fed into a second-order low-pass filter with a bandwidth of 2000 Hz. Finally the signal is further amplified through a gain adjustable amplifier. The amplified signals from the circuit are sampled using a NI USB data acquisition card. The electrostatic signals from all electrodes of the wire-mesh sensor were sampled simultaneously with a sampling frequency of 5 kHz and a sampling time of 30 seconds.

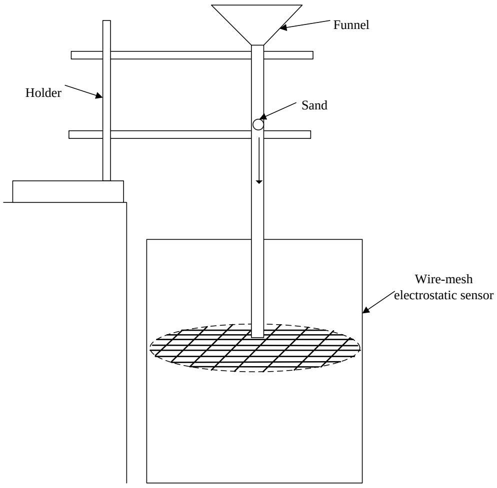



Fig. 4 Gravity drop test rig

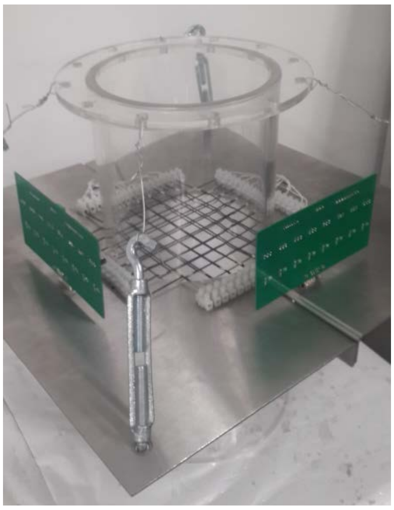


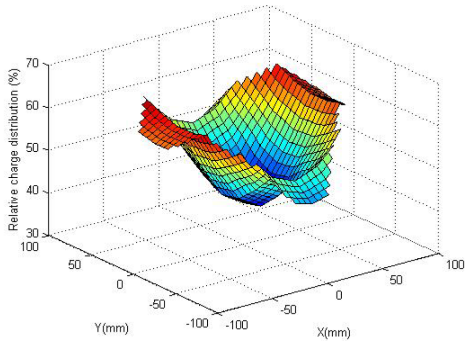
Fig. 5 Picture of the wire-mesh electrostatic sensor

## V. RESULTS AND DISCUSSION

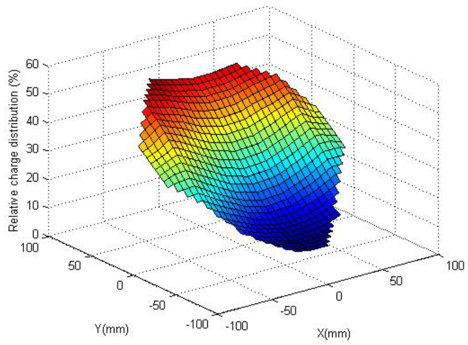
According to equation (5), the induced charge on each electrode of the sensor should be measured in order to reconstruct the charge distribution. However, it is difficult to directly measure the induced charge on each electrode of the wire-mesh electrostatic sensor. The electrostatic signal is generated due to the fluctuation of induced charge on the electrode, which is related to the charges on the particles in the sensitivity volume of the electrode. In this paper, Root Mean Square (RMS) value of the electrostatic signal is calculated to reflect the quantity of the induced charge on the electrode. Based on the RMS value of the electrostatic signal, equation (5) is reformulated as

$$q_{rlc}(x,y) = \frac{1}{16}\sum_{i=1}^{16}\left(\frac{RMS_i - RMSN_i}{RMSN_i}\right) / S_i(x,y) \qquad (6)$$

where $q_{rlc}$ $(x, y)$ represents the relative level of charge in the position $(x, y)$, $S_i$ $(x, y)$ is the sensitivity of the $i$th electrode in the position $(x, y)$, $RMS_i$ is the RMS value of the $i$th electrode when particles passed and $RMSN_i$ is the RMS value of the $i$th electrode when no particles are present. By calculating the relative difference of the RMS values when sand particles pass the sensor and when no particle flow, the influence of the noise on the reconstruction result is reduced. By calculating the relative level of charge in the whole cross section of the bed, the relative charge distribution is obtained. During the experiments, the funnel was placed in the center and near the wall of the bed, respectively. The charge distributions under the two conditions are reconstructed, which are shown in Fig. 6. The valley of the distribution can reproduce the dropping positions of sand particles. Since the induced charge on the electrode has an opposite sign with the charge on the particle, the distribution from the RMS value of the signal is opposite to the real distribution, which can qualitatively represent the charge distribution.




(a)




(b)

Fig. 6 Relative charge distributions when sand particles passed through the wire-mesh sensor in the center (a) and near the wall (b)

## VI. CONCLUSIONS

In this paper, a wire-mesh electrostatic sensor is introduced to reconstruct the charge distribution in the bubbling fluidized bed. A FEM model of the sensor is built to investigate to sensing characteristics of the sensor. It is found that by combing the sensitivity of all the electrodes, a higher and more uniform sensitivity distribution of the sensor can be obtained. The charge distribution reconstruction method is validated by the experiments conducted using a gravity drop test rig. The RMS values of the electrostatic signals on each electrode are calculated and the relative charge distribution in the bed can be reconstructed using the wire-mesh sensor, which proves that the wire-mesh electrostatic sensor can be used to reconstruct the charge distribution in the bed. Although present work only gives qualitative result of the charge distribution, quantitative evaluation of the sensor will be our future work. In order to evaluate the performance of the sensor, a charge calibration process will be conducted. The relationship between the RMS values of the signals from different electrodes of the senor and the charge on the particles can be established. As a result, quantitative comparison between the results from a Faraday cup and the sensor will be obtained.

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