

Research on plug-in electrostatic sensor applied in gas-solid two-phase flow measurement

Jie Liu

Guangxi Vocational and Technical Institute of Industry, Nanning, Guangxi, China

Email: 20271795@qq.com

Abstract- A plug-in electrostatic sensor simulative model was built through COMSOL Multiphysics simulation software. The sensitivity distribution on the center section of a plug-in electrostatic sensor was simulated and investigated. Through comparing different sensitivity distribution under the conditions of different electrode insert depths and of different electrode diameters, the influences of these factors on the sensitivity of electrostatic sensor were analyzed and discussed.

Keywords- gas-solid two phase flow; plug-in electrostatic sensor; COMSOL Simulation; sensitivity analysis

I. INTRODUCTION

The flow velocity of particles is a very important parameter in the gas-solid two phase flow [1]. In accordance with different types of sensors, measurements of solid particle velocity could be classified into the followings, capacitance method, optical method, ultrasonic method, microwave method, ray method, electrostatic method and so on[2,3]. In the electrostatic method, electrostatic sensor is widely researched by domestic and foreign scholars for its simple structure, high sensitivity and good repeatability.

One of the key points of electrostatic measurement system lies in the sensor's design. The accuracy and stabilization of the measurements directly depend on the sensor's frequency response characteristics and output property.

In this paper, a model of a plug-in electrostatic sensor measurement was built by using of COSMOL simulation software. Besides, sensitivity distribution on the radial section of the electrostatic sensor was researched based on the simulation results. In addition, based on comparing different sensitivity distribution under the conditions of different electrode insert depths and of different electrode diameters, the influences of these factors on the sensitivity of electrostatic sensor were analyzed and discussed.

II. BASIC PRINCIPLE

Sensitivity is an important parameter reflecting the performance of an electrostatic sensor. In measuring the average concentration of the gas-solid two phase flow, it is very necessary to design a sensor with even sensitivity distribution in order to reduce the influence of flow pattern.

The space sensitivity of electrostatic sensor is defined as, the absolute value of induced electric quantity on the electrode under the effects of a point charge at a certain position in the inducing range. Based on the finite-element analysis model of the electrostatic sensor, when a point

charge is at a certain position in the inducing range, the induced electric quantity on the electrode relates to the coordinates(x, y, z) of the point charge. The space sensitivity of electrostatic sensor could be expressed as the following equation[4]:

$$S(x, y, z) = \left| \frac{Q}{q} \right| \quad (1)$$

where, Q represents the induced electricity quantity on the electrode when the electric quantity of the point charge is q. Therefore, by changing positions of the point charge, the space sensitivity distribution can be worked out through a finite-element model analysis[5].

III. MODELING AND SIMULATION OF ELECTROSTATIC SENSOR

The sensor model was set up in the simulation environment produced by COMSOL Multiphysics software. First, physical environment was created. Second, the geometric model was built based on the settings of pipeline's axial direction as Z axis, radial direction as X axis, and tangential direction as Y axis. According to experimental requirement, a freely-moved point charge was placed in the pipeline' interface. The geometric model was shown in Figure 1.

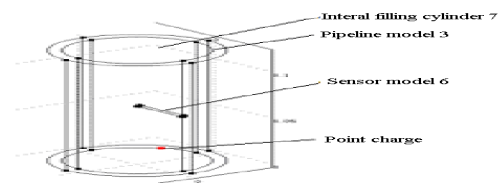


Figure1 Geometric Model of Electrostatic Sensor

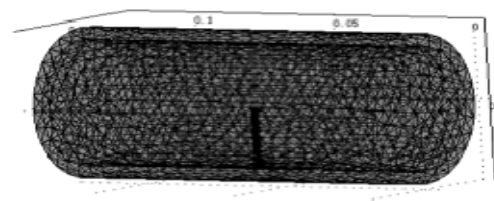


Figure2 Free Mesh Dissection Schematic of Electrostatic Sensor Velocity Measurement Model

Third, physical quantities in the solving domain were set, and the point charge was set as -1C. Then the field was divided into several small triangles to realize mesh

generation, shown in Figure 2. After that, the simulation of the sensor's space sensitivity distribution could be performed.

In COMSOL electrostatic field, it was not allowed to directly set up the moving speed of the point charge. As a result, "COMSOL with Matlab" was applied in order to realize continuous moving of the point charge. The initial position of the point charge was set at (0.005, 0, 0.01) and motion vector was set as (0, 0, 0.001). After cycling for eleven times, the point charge reached (0.005, 0, 0.012). The induced electric quantity at each different position was recorded by Matlab program.

IV. MATHEMATICAL MODEL OF POINT CHARGE

The mathematical model of the point charge is shown in Figure 3, where, L represents the length of the electrode; X represents the maximum measurement range of the electrode; and R represents the electrode radius.

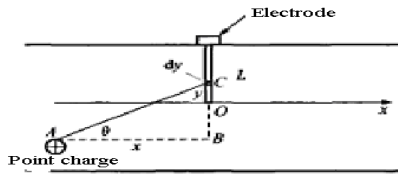


Figure3 Mathematical Model of Point Charge

The derivation process is shown as follows. Electric field intensity of Point C is:

$$E = \frac{q_1}{4\pi\epsilon_0 [(y-a)^2 + x^2]} \quad (2)$$

Facet ds expressed by vector:

$$ds = \pi R dy \quad (3)$$

Charge q calculated through Gauss Formula:

$$ds = -\epsilon_0 E ds = -\epsilon_0 E ds \cos \theta = -\frac{x q_1 dy}{4 [(y-a)^2 + x^2]^{1.5}} \quad (4)$$

Integrate (4) with y , it is gained as:

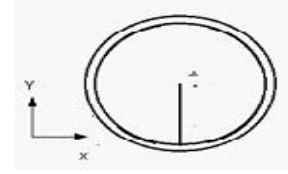
$$q = \int_0^L \frac{x q_1 R dy}{4 [(y-a)^2 + x^2]^{1.5}} = \frac{R q_1}{4x} \left\{ \frac{L-a}{[(L-a)^2 + x^2]^{0.5}} + \frac{a}{(a^2 + x^2)^{0.5}} \right\} \quad (5)$$

4.1 ELECTRIC QUANTITY CORRESPONDING TO DIFFERENT POSITIONS OF SINGLE POINT CHARGE

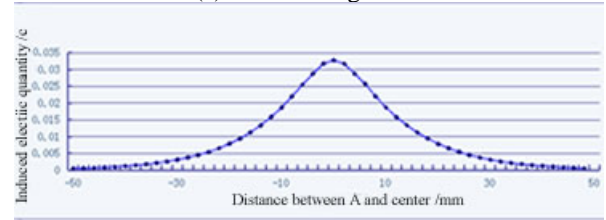
Equation (5) makes a good explanation about how the position of a solid particle in gas-solid two-phase flow exerts influence on the induced charge, and it also helps to obtain records of space sensitivity distribution of the electrode. When a point charge with a unit of electric quantity is put at a position inside the pipeline, the absolute value of the induced electric quantity on the sensor can reflect the sensor's sensitivity to this specific position.

The following arrangements were made for the convenience of calculation: the electric quantity of Point A $q_1 = -1C$; transmission range inside the pipeline (10 mm-110 mm); the initial position of Point A (0.005, 0, 0.01) (as

shown in Figure 4 (a)). Then Point A moved along Z axis toward positive direction with a step length of 0.002 m. The electric quantity induced by the electrode at each position was recorded as shown in Figure 4 (b).



(a) Point Charge A



(b) Axial Sensitivity Distribution Corresponding to Different Positions of Point A

Figure 4 Different Positions of A Single Point Charge and Its Corresponding Axial Sensitivity

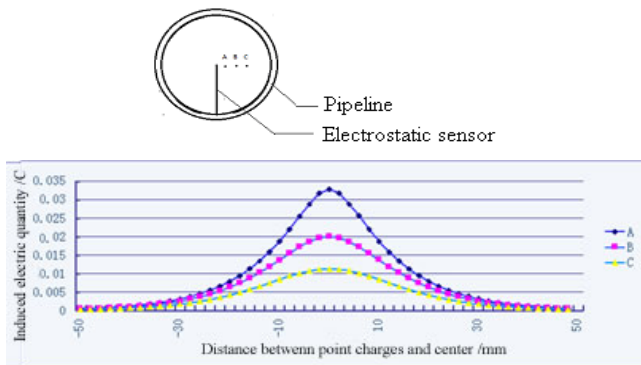
From Figure 4(b), it is concluded that, the closer the single point charge is moving to the electrode, the larger electric quantity will be induced on the sensor electrode. When the point charge moves onto the same plane with the electrode, the induced electric quantity achieves maximum. The curve of the induced electric quantity appears to be a normal distribution. The abscissa of the curve's peak stays at 0, which means the point charge is on the same plane with the sensor electrode.

4.2 ELECTRIC QUANTITIES CORRESPONDING TO DIFFERENT POSITIONS OF MULTIPLE POINT CHARGES

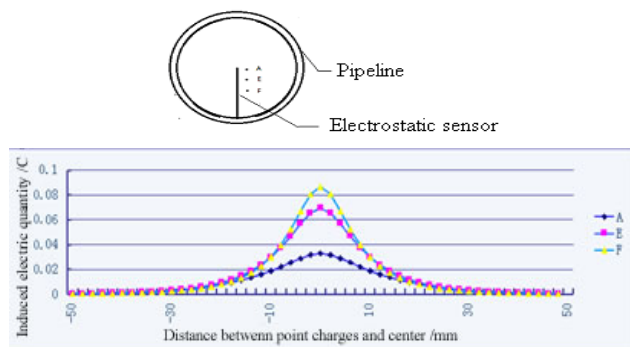
In order to research the sensitivity changes of the electrostatic sensor in the whole inducing range inside the pipeline, the sensitivity distributions of point charges in different positions were studied. Five point charges, namely A, B, C, E, F, were selected on the radial section of the device as studying objectives.

The X and Y coordinates of the five point charges were respectively set as follows: A (0.005, 0), B (0.010, 0), C (0.015, 0), E (0.005, -0.005), F (0.005, -0.010). All the five point charges moved along Z axis from $Z=0.010$ toward positive direction with step length of 0.002 mm. The sensitivity distribution of each point was recorded as shown in Figure 5.

From Figure 5, we can see that with moving of the point charges, the closer the charges are to the electrode, the larger electric quantities will be induced. When the point charges move onto the same plane with the electrode, the induced electric quantities achieve maximum. All curves of the induced electric quantities appear to be normal distribution. The corresponding abscissa of each curve peak stays at 0, which means each point charge is on the same plane with the sensor electrode.



(a) Sensitivity Distribution of Different Point Charges in Horizontal Position at the End of Electrode



(b) Sensitivity Distribution of Different Charges in Parallel Direction with Electrode

Figure 5 Induced Electric Quantities Responding to Point Charges of Different Positions

Comparing the three curves of A, B, C, it is concluded that for the points of same Z coordinate, the closer their X coordinates are to the sensor, the larger the induced electric quantities will be. Also, from the three curves of A, E, F, it is concluded that with moving of different point charges along with the direction in which the sensor is inserted, the closer the charges are to the sensor, the larger the induced electric quantities will be.

Therefore, under the condition of charges carrying the same amount of electricity, the induced electric quantities on the electrode relate to the distances between the charges and the electrode. The relation between the induced electric quantity and the distance (from charges to electrode) is inversely proportional, i.e., the shorter the distance is, the greater the amount of induced electric quantity will be.

V. ANALYSIS ON ELECTRODE DIAMETER AND INSERT DEPTH

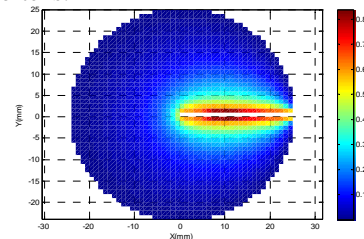
The influences of the electrode diameter and the electrode insert depth on the sensitivity of the sensor were analyzed based on the simulation results.

4.1 EFFECTS OF ELECTRODE DIAMETER

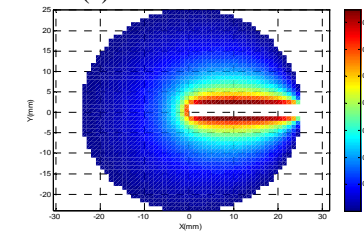
Three electrodes were selected in order to study the effects of different electrode diameters (S1: length 25 mm, diameter 1 mm; S2: length 25 mm, diameter 2 mm; S3: length 25 mm, diameter 3 mm). In the simulation process,

only half of the points on the central section were researched as both the section and the distribution of induced electric quantities were symmetrical. The upper section was divided into 25 lines. During its moving, the induced electric quantity of each point in each line was recorded. All the data were put in the form of matrix. The free place of matrix was recorded as zero. After that, the sensitivity distribution of the electrostatic sensor was drawn by Matlab, as shown in Figure 6.

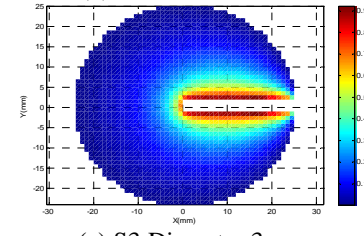
From Figure 6, it is clear that the space sensitivity of the plug-in electrode distributes unevenly on the center section. It could be roughly seen that with lengthening of the diameter, the space sensitivity of the plug-in electrode increases gradually. Besides, the scope of sensitivity increase turns to be larger when the distance to the plug-in electrode shortens.



(a) S1:Diameter 1mm



(b) S2:Diameter 2mm



(c) S3:Diameter 3mm

Figure 6 Sensitivity Distribution of Sensors of Different Diameters

In addition, the average sensitivity values and sensitivity mean-square deviations of sensors of different radii were calculated, and the results were shown in Figure 7.

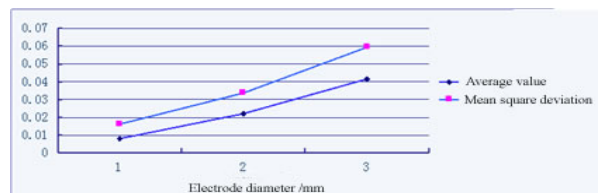


Figure 7 Distribution of Average Sensitivity Values and Mean-square Sensitivity Deviations

It is found that the sensor's average sensitivity is under the influence of the electrode diameter. As the electrode diameter elongates, the average induced electric quantity increases. In addition, from Figure 7, it is also seen that as the electrode diameter elongates, the mean-square deviation of sensitivity increases. That is to say, the sensitivity distribution inside the sensor becomes uneven as the diameter become longer, which goes against the accurate measurement of the gas-solid two phase flow.

4.2 EFFECTS OF INSERT DEPTH

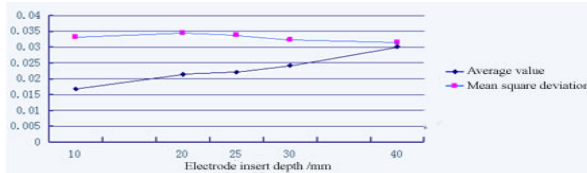


Figure 8 Average Sensitivities and Sensitivity Mean-Square Deviations Corresponding to Different Insert Depths

Other than the diameter, the insert depth of the electrode also influences the sensitivity of the central section. Five electrodes were selected to study the effects of different electrode insert depths (P1: insert depth 10 mm, diameter 2 mm; P2: insert depth 20 mm, diameter 2 mm; P3: insert depth 25 mm, diameter 2 mm; P4: insert depth 35 mm, diameter 2 mm; P5: insert depth 40 mm, diameter 2 mm).

The average sensitivity values and sensitivity mean-square deviations of sensors of different insert depths were calculated, as shown in Figure 8.

From Figure 8, it could be seen that the sensor's average sensitivity enlarges gradually with deepening of the electrode insert depth, approximately to a linear distribution. No significant change happens to the mean-square deviation of the sensor's sensitivity with changing of the electrode insert depth. Under the condition of the electrode inserted deeply, along with deepening of the depth, the sensitivity mean-square deviation turns to be smaller due to enlargement of the sensitive scope. Therefore, it comes to the conclusion that the sensor's sensitivity scope enlarges with the deepening of the electrode's insert depth, but the influence is insignificant.

VI. CONCLUSION

In this paper, the plug-in electrostatic sensor was simulated and studied through COMSOL software.

A mathematical model of the point charge was established. Both sensitivities of a single point charge and multiple point charges were simulated and analyzed. It comes to the conclusion that with moving of the point charge, the induced electric quantity on the electrode relates to the distance between the charge and the electrode. The relation between the induced electric quantity and the distance is inversely proportional, i.e., the shorter the distance is, the greater the amount of induced electric quantity will be.

(2) The influences of the electrode diameter and the electrode insert depth were simulated and analyzed. It comes to the conclusion that as the electrode diameter elongates, the sensor's average sensitivity increases while the sensitivity distribution inside the sensor becomes uneven. In addition, the sensor's sensitivity scope enlarges with the deepening of the electrode's insert depth, however, the influence is insignificant.

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