Further Investigation into Spatial Sensitivity of Electrostatic Sensors

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Abstract. In gas-solids flow measurement, non-uniform spatial sensitivity of sensors has been a fundamental issue as the even distribution of solids cannot be guaranteed. In this paper, the focus is on the circular electrostatic sensors. By far, the investigation of the spatial sensitivity of electrostatic sensors has been mainly based on the response to a single charged particle at different locations, which forms a basic mathematic model, or the spatial sensitivity of an electrostatic sensor; accordingly the spatial sensing volume can be outline. However, as the above defined “spatial sensitivity” varies with the location of a particle, the spatial sensing volume with regard to a single particle is not a good indicator of the spatial characteristics. In this paper, it is proposed to express the spatial sensitivity as the response of a sensor to a flow stream. Any particle flow can be regarded as a sum of a series of “roping” flow streams either the particles are evenly or un-evenly dispersed. Hence this model can be used to deal with complex flow profiles in applications. The spatial sensitivity of a ring-shaped electrostatic sensor is theoretically analyzed in this paper, which is supported with the experimental results, and also validated through simulations.

Introduction

In gas-solids pneumatic conveyance, solids are transported using gas, usually air. The accurate measurement of such flow is very important. For example, in iron making, the control of mass flow rate, velocity, and concentration of pulverized coal are essential for combustion efficiency and greenhouse gas reduction. Pipe blockage, wear of conveyors and conveying efficiency are vital for the safety and cost of solids transportation even there is no combustion is involved.

One of the problems for measuring pneumatically conveyed solids is that the flow profile varies with conditions of particle size, conveying velocity, air to solids ratio, solids density, routing of pipe and pressure of conveying gas [1,2]. Over past twenty years, various methods have been developed including several tomographic techniques. Different tomographic techniques such as electrical capacitance, electrical impedance and electrostatic tomography have a common ground [3,4,5,6], which is to weight signals based on the spatial location, so that the image of flow or concentration profile can be reconstructed. For other tomographic techniques, one of problems for lean phase (diluted) flow is so called “diminish return”, i.e., in order to achieve high spatial resolution, the number of electrodes has to be greater, which requires smaller size of each electrodes. Yet a small electrode produces a diminished signal. This is the main reason, in tomography, quite often, several electrodes are clustered to form a large one [7] or long electrodes are constructed [8].

Different from tomographic techniques, the circular electrostatic sensor has its simple configuration. However such configuration has inherent non-uniform spatial sensitivity. In order to overcome this problem, complex signal processing is required. In this paper the spatial sensitivity of the circular sensor is studied. Different from the previous publications, the spatial characteristics close to the pipe wall is revealed, and the response to flow streams is investigated and experimentally verified.
**Spatial Sensitivity of Electrostatic Sensor**

To the authors’ knowledge, there is no official definition of the “spatial sensitivity” for gas-solids flow measurement. As early as in 1982, Massen[9] studied the sensing length of an electrostatic sensor, and he defined the “aperture” of the sensor as the width of the electrode along the axial direction, it is an early version of “sensing zone”. Similarly, Hammer [10] called the above “Aperture” “Equivalent Field Length”. Gajewski realized that the aperture is actually much larger than the width of a given circular electrostatic sensor in his early publications [11]. Cheng’s model [12] for the induced charge on the electrode of a circular sensor to a single charged particle inside the pipe has been used as spatial sensitivity. The simulation and experimental results used in this paper can still be explained using this model, although a double exponential model provides better accuracy [13].

As shown in Figure 1, for a given configuration, the property of insulator, the initial and boundary conditions, the total induced charge on a circular sensor electrode can be expressed as a function of location, assuming a point charge (particle) is carried by a particle located in the “vicinity” of the sensor. Figure 2 shows the mesh set-up for simulations using Finite element method. The mathematical model, i.e. the induced charge on the electrode due to a single charged particle is given by [12],

\[ Q = A(r, x)e^{k(r, x)x^2} \]  

where \( Q \) is the induced charge on the ring-shaped electrode, \( A(r, x) \) and \( k(r, x) \) are functions of radial coordinate \( r \) and longitudinal coordinate \( x \). Due to symmetrical construction, \( Q \) doesn’t depend on the angular variable \( \theta \)

![Figure 1. View of Sensor: Longitudinal (a) and Cross Sectional (b).](image1)

![Figure 2. Response to a single charged particle moving along longitudinal axis at r=R/2.](image2)

In Figure 2, the response of the sensor to a charged particle moving along pipe central line is shown. The graph in Figure 3 represents the response to the same charged particle when it moves in longitudinal direction at different radial position \( r \), where \( R \) is the inner radius, \( W \) the width of the sensor. It is clear that for the same charged particle, the induced charge on a given circular electrode increases. When the particle approaches the pipe wall, and the induced signal becomes weaker when the charged particle moves away from the pipe wall. Figure 3 also indicates that the sensing length in longitudinal direction is shorter when the charged particle moves near the pipe wall.
According to the results represented in Figure 2 and Figure 3, one can imagine the sensing volume to a single charged particle has an oval shape. With more simulation results, and the definition of boundary of sensing zone is as 1% of the maximum induced charged when the single charged particle is allocated closed to the pipe wall on the central cross section, the sensing volume is illustrated in Figure 4. Only when the particle appears within the sensing zone, the electrode can effectively detect it.

Response to a Stream of Flow (Rope)

Assume a stream of particles with the same polarity and the same amount of charge spread along pipe axis at a given radial location, the collective response of the sensor to these particles can be calculated based on the superposition theorem.

\[
Q = \sum_{i=1}^{n} A(x_i, r) e^{k(x_i, r)x_i^2}
\]  

This concept is shown in Figure 5, and expressed in Eq (3) where the length L should equal or greater than the length of sensing zone in the longitudinal direction. The gap between particles should be dependent on the applications. For example, it should reflect concentration and particle size.

\[
Q = \int_{-L/2}^{L/2} D(x, r) A(x, r) e^{k(x, r)x^2} dx
\]

where \( D(x, r) \) stands for the density function of charged particles in the region \( x \sim x + dx \) to the total charged particles in the entire sensing volume at a given radial position \( r \).
Considering the results presented in Figure 3 and Figure 4, one can imagine that for a stream of particle flow, when it in the centre or close to the pipe wall, the total induced charge will be lower. At the centre axis, although the sensing zone is larger, the sensitivity to each particle is lower; whilst when the stream is close to the wall, the size of sensing zone is reduced, and the number of particles making effective contribution to the total induced charge is smaller. This can be clearly seen for a flow stream at different radial position in Figure 4.

**Simulation Results: Sensitivity to a Roping Particle Stream**

The simulation was conducted as illustrated in Figure 5, the charge induced on the electrode with a width of 1/5 of the radius was obtained as the stream was located in different radial locations. The normalized induced charge is used as a sensitivity of the sensor to the flow stream as depicted in Figure 6.

![Figure 6. Sensitivity to particle stream.](image)

It is clear that the sensitivity is not uniform, nor monotonic with radius position of the stream. This is caused by the combination of the magnitude of sensitivity to a charged particle as shown in Figure 2 and Figure 3, and the effective sensing volume as depicted in Figure 4. The simulation results are similar to the experimental results obtained in a large scale pneumatic conveying rig during 2001-2005. The experimental results were not fully understood at the time [14].

**Experimental Results to “Roping” Flow**

It is not easy to validate the response of the sensor to a single charged particle. However the response to a roping flow stream can be performed so long as a roping flow stream can be created. The sensitivity defined as the response to roping flow has its practical meaning. The experiments were conducted in a large scale pneumatic conveying facility, with “Roping flow stream” created with a one inch diameter jet. The flow rate was kept constant during the experiments. The jet radial position was adjusted continuously across the pipe radial direction. The diameter of the pipe and the sensor was 14 inches. The velocity was kept at about 25m/s, and the mass flow rate of the pulverized coal was 260kg/s. Figure 7 provides the test results of response to the above “roping” flow stream.
Analysis of Response to Roping Flow Stream

If treating the flow coming out of the jet in the above experiments as a flow stream, the response in Figure 7 actually represents spatial sensitivity, which can be compared with the simulation graph in Figure 6. When a particle stream as shown in Figure 4 and Figure 5 passes the sensing zone close to the pipe wall, the contribution of the particles near the sensor cross section is higher. However most of particles in this stream have little contribution as they are out of the sensing zone. As the particle stream move away from the inner wall, the numbers of particle making contribution increases, but the sensitivity of to each particle decreases. The combination of the above two effects results in a turning point near pipe wall in the response to a “roping” flow stream in a circular sensor. In a column coordinator system, the turning points form a hollow cylinder, representing a “stationary” surface.

Compared the experimental results to that from simulation, it seems that the non-uniformity of the actual sensor is severer when the “roping” flow stream moves radially around the pipe centre. The difference may be caused by the characteristics of the conditioning circuit, and the abundant frequency components in the real flow stream. Besides any movement of particles in radial direction would have made contribution to the overall signal, whilst in the simulation, such effect was not included. However both simulation and the experimental results showed turning points when the particle stream or “roping” flow moves from the central location to the pipe wall. It is this stationary surface of spatial sensitivity that complicates the compensation of non-uniform spatial sensitivity.

Conclusions and Future Work

From the investigation presented in this paper, it can be concluded that the response of a circular electrostatic sensor to a flow stream is more complicated than it was thought. The sensitivity is not monotonic with radius r, which is due to the combined effect of the spatial sensitivity and the sensing volume to a charged particle.

To deal with uneven particle distribution, the uniformity of spatial sensitivity to a flow stream needs to be achieved. The current research work is on two directions: on one hand the effort is on realizing improved spatial sensitivity through signal processing, mainly by weighting frequency components of the signal; on the other hand, the focus is on optimization of configuration. Through changing the design of sensor’s shape, diameter and insulation structure to achieve a uniform spatial sensitivity. The signal processing method is preferred as it offers simple design, low cost and robust structure. With the research proceeds, the outcomes will be reported accordingly.
References


