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Rectangular Electrode Characteristic in Electrodynamic Solid Particle Measurement.

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Abstract- **Electrodynamic sensor was used in process industry because of lower price and robust designed. It is also used to increase the efficiency of energy and raw materials usage and to improve product quality and process efficiency. Three types of electrode are available in particular application such as pin shape, quarter ring shape and ring shape. This paper focused on the investigation of the pin shape structure and the characteristic of the rectangular shape by using different structure sizes of various lengths and with fixed width. Non-instrusive method was applied to the design of rectangular electrode. The characteristic based on sensitivity of electrode and the spatial filtering effect of sensor will be investigated by using different size of electrodes.Then, the model will be proposed and compared with experimental result.**

Keywords- electrostatic; electrodynamic; rectangular; mass flow; non intrusive; sensitivity; spatial filtering effect.

I. INTRODUCTION

The process of transfer solid particle in pipeline generates an electrostatic charge between particle and the metal pipe. Electrostatics charge can be detected using sensing device or called as electrode and convert into voltage by associated electronic or known as electrodynamics transducer. The electrodynamic measurement is based on charge detected by the sensor as the charged particles flow past in the pipeline. Sensors of electrode generally consist of metal or electrode insulated from the walls of the conveyor or pipeline. Three shape of electrode commonly used in this process measurement such as pin, quarter ring and ring shape. The ring electrodes are widely used in process measurement and have been thoroughly investigated [3, 4].

Electrostatic transducer which consists of associated electronic are robust and low cost implementation in measurement, so it has high potential to be applied in process tomography. In process tomography, [5] several identical transducers are positioned around the vessel being interrogated to provide measurements which are used to reconstruct dynamic images of the movement of the material being monitored. The application of large numbers of sensors used ring electrode shape is no longer applicable and small sensors as pin electrode consisting of either circular or rectangular section are more appropriate to be applied.

In applications where the process is varying rapidly, for example pneumatically conveyed of solid particles, the measurement of the system parameters should be known. This paper investigates the relationships between sensor size of rectangular electrode in characteristic of sensor sensitivity and the frequency bandwidth as termed spatial filtering effect [6] of the transduced signals.

The principle of measurement techniques are based on electrostatic phenomena in pneumatics pipelines which is contains information of velocity and mass flow rate of particles. The information of particle that depends on large particle will carry higher charge on its surface than a smaller one [1]. This charge level will be detected by using electrostatic sensor and convert it to voltage signal. The charge level can be represented by:

$$V(t) = \alpha \sum q(t) \tag{1}$$

Where,

q =amount of electrostatic charge carried on each particle
α = constant depending on design of the charge amplifier circuit.
V (t) = the resulting voltage signal

As mentioned before, the friction and collisions of solid particle in pipeline are entirely random. So, the value of V(t) is the result voltage of undeterministic signal captured by electrostatic transducer and change it to discrete times sequence, V(n) at suitable sampling frequency where n= 0,1, 2 and so on. In the electrostatic sensor design, the different term are used to describe the electrostatic sensing technology such as tri bioelectric, electrodynamics and electrostatic.

II. MEASUREMENT THEORY

A. The Sensitivity of Electrode

The sensitivity of electrode is a change of average voltage detected by electrostatic transducer due to a change in the mass flow rate pneumatic conveyor process of solid particle transfer. Mass flow rate of the pneumatic conveying process can be calculated by experimental result on calibration curve of control flow particle through the pipeline. Mass flow rate is measured manually by the collection of flowing material over a recorded time of 10 seconds and then the average of mass in 1 second will be calculated. Unit mass flow rate is (g/s). The sensitivity of electrode can be calculated by a linear trend line fitted from measured values of average voltage versus flow rate. The gradient of this line provides the sensor sensitivity of sensor and the unit of sensitivity is volt/gram/second (V/g/s).

The electrode sensitivity was modeled based on circular electrode by considering the effect of a single charged particle, q, as it moves vertically downwards at the constant velocity, v. The assumptions is the point charge has travelling in an axial direction parallel to the axis of the pipe, the particle has a constant, finite amount of charge which is not dissipated during the time when it travels through the sensing volume. The surface area of the pin electrode is small compared to the radius of the pipe flow. The charge acts as a point source and the electrode not conducting with the pipe. Single charged particle was assumed to be a point charge of value q, which is the field, is uniformly radial [10].

$$E=\frac{q}{4\pi r_i^2 \varepsilon_0} \qquad (2)$$

The point charges can induce a potential onto the small surface of the flat electrode. The flat electrode was used to sense the changing of potential at the non-conducting or dielectric pipe wall. It was assumed, no other interacting fields on the electrode if no surface charges on the pipe wall. Surface area πr_e^2 showed in Figure 1 which is considered normal to the flux on particular designed. The proportion of the flux passing through the sensor due to the charged particle at the distance i [10], is;

$$\frac{\pi r_e^2}{4\pi r_i^2} \qquad (3)$$

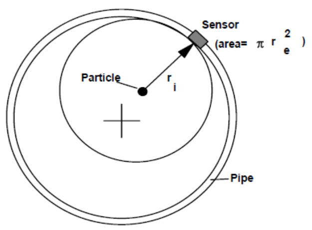

Figure 1. Relationship between particle and sensor

Charge induced onto the electrostatic sensor is proportional to q. Hence,

$$Q_e=\frac{kqr_e^2}{r_i^2} \qquad (4)$$

Equation 4 show the amount of charge induced onto the electrode and depends upon the radius of the electrode squared or the area of the electrode. The charge was stored at the capacitor and provides a voltage V_e given by

$$Q_e=CV_e \qquad (5)$$

The voltage was amplified, rectified, smoothed and the average voltage was calculated. The sensitivity of the sensor is defined as:

$$\frac{Q_e}{q_i} \qquad (6)$$

This value of sensitivity is difficult to determine because the level of the conveyed charge, q_i, cannot be controlled. In this paper, a series of sensor diameters was compared simultaneously as a resulted the same q_i was detected. The voltage also was amplified, rectified and average voltage was calculated.

B. *The spatial filtering effect*

The spatial filtering effect is a relationship between sensor size and the frequency bandwidth of transducer that was determined from frequency response obtained during corresponding to a detectable particle. The spatial filtering effect investigation arising from capacitance electrodes was described by Hammer and Green [6]. This investigation also related to the velocity of flowing discontinuous material to the frequency bandwidth of the sensed signal [8]. The process of tomography using electrodynamic sensors generally use pin type of electrode which is circular or hemispherical electrodes. However, some applications maybe required rectangular electrodes [7]. The results from the rectangular electrodes can be compared with the measurements obtained using capacitance electrodes [6].

The rectangular electrode are much longer than the circular electrode ones and the recordings of the voltage from the sensor, that was taken while investigating the spatial filtering effect, are slightly different from those flat ended, circular electrodes. The above analyses need to be modified in order to determine the spatial filtering characteristic of long rectangular sensors. In the rectangular electrode of experiment verification analysis, the long electrodes are curved approximately to the same radius as the charged bead moves along to ensure the bead electrode gap remains constant as it passes. In this case the charged bead is passing the electrode for a longer period than for the circular sensor. The charge and discharge currents are noticeably spaced in time, as are the corresponding rectified voltages as shows in Figure 6. The spatial filtering effect for this system is calculated by considering the system as consisting of two impulses with a time delay separating them. If the pulse duration's are short compared with a/v they may be regarded as two Dirac pulses:

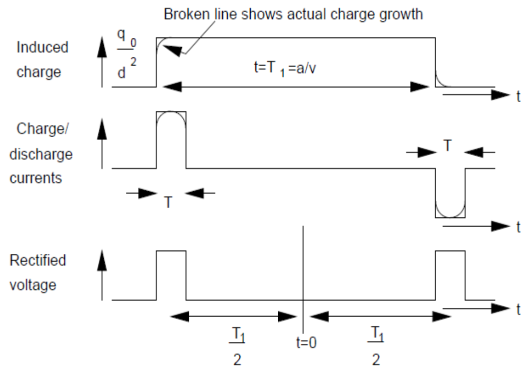

Figure 2. Idealised induced charge and corresponding voltages for the rectangular electrode.

Then the transducer response may be written

$$v_i(\omega) = \int_{-\frac{T_1}{2}-\frac{T}{2}}^{-\frac{T_1}{2}+\frac{T}{2}} k\frac{q_0}{d^2}e^{j\omega t}dt + \int_{\frac{T_1}{2}-\frac{T}{2}}^{\frac{T_1}{2}+\frac{T}{2}} k\frac{q_0}{d^2}e^{j\omega t}dt \qquad (7)$$

Where T is the time taken to charge and discharge the electrode. After integration and expansion equation (7) gives

$$\frac{V_i}{q_0} = \frac{4k}{d^2\omega}\cos\frac{\omega T_1}{2}\sin\frac{\omega T}{2} \qquad (8)$$

This may be written in the frequency domain.
The modulus of equation (8) is given by,

$$\left|\frac{V_i}{q_0}\right| = \frac{2k}{d^2}\left|\cos\frac{\omega a}{2v}\right|\left|\frac{\sin\left(\frac{\omega T}{2}\right)}{\frac{\omega}{2}}\right| \qquad (9)$$

and the effect of a and v on the modulus shown the 'sinc' and 'cos' function.

III. METHODOLOGY

The process of measurement the static charge by electrostatic sensor consist the design of the electrode or sensing device in rectangular electrode shape. The several sizes of area were implemented or assembled to pneumatic conveying plant of plastic bead. The electrical charge was detected from electrode then converts to voltage by electrodynamics transducer or associated electronic. The calibration curve of gravity flow rig is important for calibration of pneumatic conveying plant to measure the mass flow rate of the plastic beads at solid loading. Further process can be preceding after find the flow rate.

The experiment of measurement using non-intrusive electrode rectangular designed will be read and converted by electrodynamics transducer. The system was interfaced by data acquisition system (DAS). Further analyses were carried out using computer software.

A. Electrodynamic sensor

The diagram of the electrodynamic sensor (Figure 3) consists of a plain metal rod called as electrode. The designed was isolated from the metal conveying pipe walls by the insulator such as glass or plastic. This electrode has a capacitance to earth. The value is very small (fraction of a pico Farad) but the values is different due to manufacturing tolerances. A low value of capasitor (several pico farad) was connected in parallel to minimise the effect of capacitance. The resistor was connected in parallel with the capacitors to provide a charge/discharge path [10]. The charged particles in the pipe will flow the electrode and produces inducing charge into the process. The current flow through the resistor due to the induce charge cause varying voltage. The voltage then was buffered by a unity gain of non inverting amplifier. The output provides a driven guard for the input circuitry and was amplified and conditioned by others circuitry.

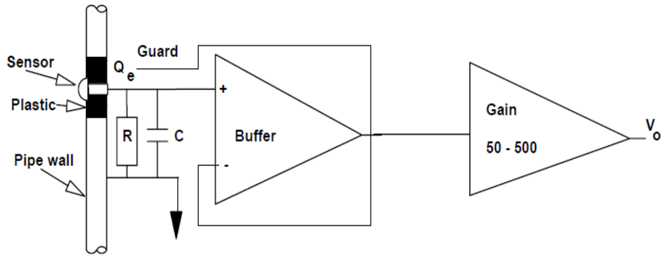

Figure 3. The transducer circuit

IV. RESULT AND DISCUSSION

The sensitivity can be determined by using different size of sensor. The solid particle flows passing each of the rectangular electrodes and the level of charge on the flowing solid particle is very difficult to quantify, however since the sensors are evaluated in the same time, their outputs may be compared directly. The different area of rectangular electrode were implemented which is ranging length from 20 mm to 300 mm and the wide is fix to 10 mm. The arrangement of rectangular electrode in pipeline with different size area is shown in Figure 4.

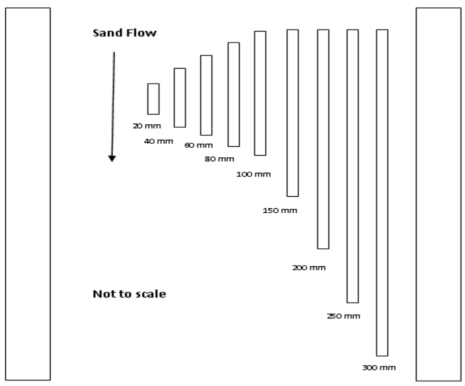

Figure 4. Arrangement of rectangular electrodes for sensitivity measurements

A series of different particle flow rates was applied to the rectangular electrodes and the output was determined. Results for the sensor sensitivity of rectangular electrode were collected and the result of several electrode area shown in Figure 5 to Figure 7. A linear regression line is fitted to the measured values. The gradient of this line provides the overall sensitivity of the sensor (V/gm/s) and summarized in Table 1 and Figure 8.

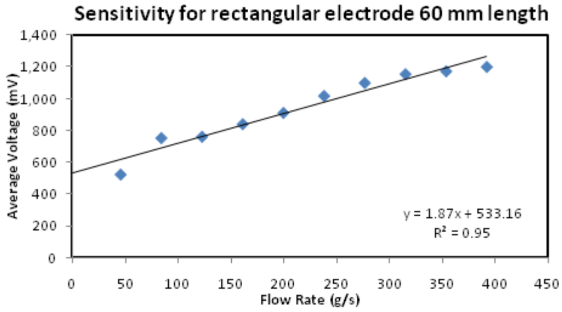

Figure 5. Average voltage versus mass flow rate of 60 mm length.

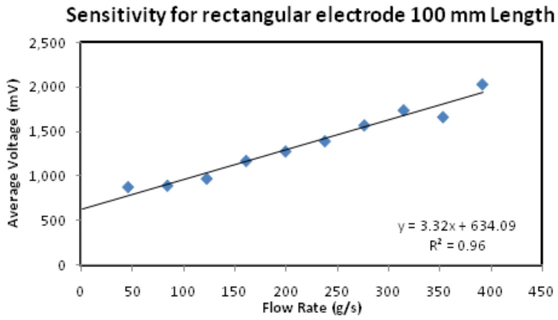

Figure 6. Average voltage versus mass flow rate of 100 mm length

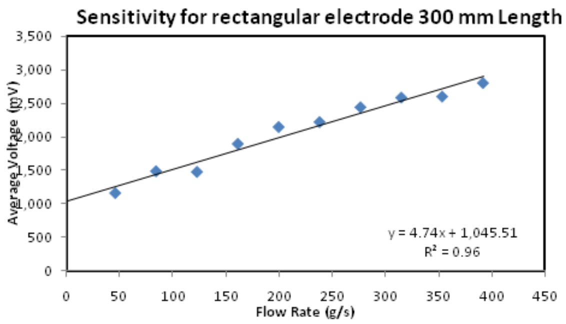

Figure 7. Average voltage versus mass flow rate of 300 mm length

Analyses were carried out on the results and all the test are summarised in Table 2 and graphically shown in Figure14.

TABLE 2. ELECTRODE SENSITIVITY OF RECTANGULAR ELECTRODE

Length electrode (mm)	Area electrode $(mm)^2$	Transducer sensitivity (mV/g/s)	Electronic gain	Electrode sensitivity (mV/g/s)
20	200	0.98	150	0.0065
40	400	1.65	150	0.0110
60	600	1.74	150	0.0116
80	800	2.33	150	0.0155
100	1000	3.32	150	0.0221
150	1500	3.96	150	0.0264
200	2000	4.44	150	0.0296
250	2500	4.61	150	0.0307
300	3000	4.74	150	0.0316

From the result Figure 8 shows that the non-linear relation between electrode sensitivity and area of rectangular electrodes. The best fit or coefficient line is 95.97 percent and the result show for the long length of rectangular electrode, sensitivity is asymptotically increases to 0.03179 mV/g/s. so, the increasing of lengths rectangular electrode have certain limit with the sensor sensitivity. In this case of width 10 mm the highest length for higher sensitivity is about 250 mm to 300 mm, more than that will produce same sensitivity at 0.03179 mV/g/s.

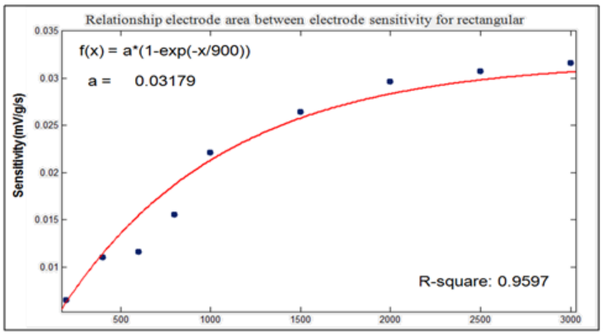

Figure 8. Overall sensitivity versus area of electrode (rectangular sensors).

For spatial filtering effect analysis of rectangular electrode shape, rectified voltage signal measured by electrodynamics transducer will be inversed and converted into frequency domain using Fourier transform analysis. The result for rectangular electrode on the frequency spectrum is combination of 'sinc' and 'cos' function that follows the theory calculated on (Equation 9). The frequency spectrum can be observed in term of cut off frequency [6]. The result of frequency spectrum for rectangular electrodes with different area was shown in Figure 9 until 11 with mass flow rate is fix to 45.85 g/s. At the right of the figure show the signal on time domain which is non-inverting voltage and rectified voltage signal. The left signal is frequency domain signal which is frequency spectrum of rectified voltage.

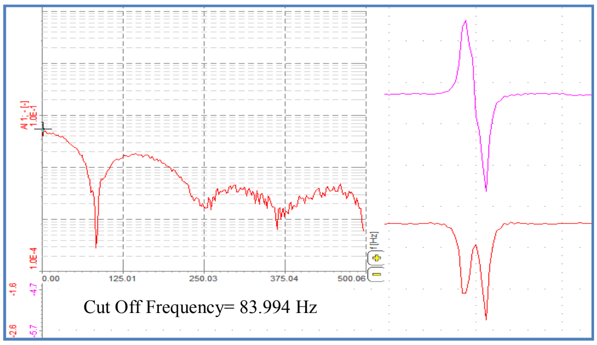

Figure 9. Rectified voltage on time and frequency domain for length 20 mm.

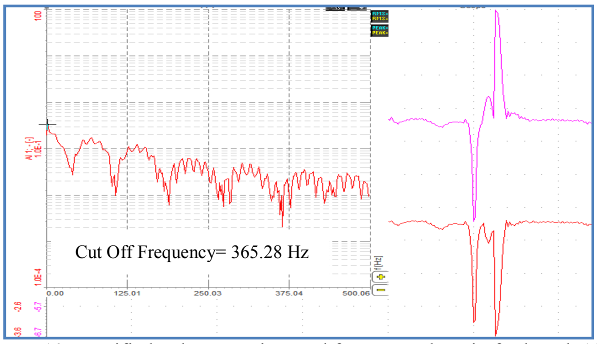

Figure 10. Rectified voltage on time and frequency domain for length 100 mm.

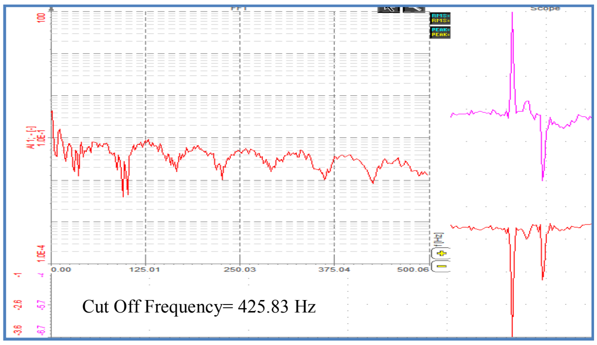

Figure 11 Rectified voltage on time and frequency domain for length 300 mm.

The result for rectangular electrode on frequency spectrum shows the combination of ‘sinc’ and ‘cos’ function that follows the theory. This frequency spectrum can be observed in term of cut off frequency acquired. The sensor characteristic of spatial filtering effect will continue with the relationship between cut off frequency and electrode area of rectangular electrodes and the result shown in Figure 12. From observation, increasing of length rectangular electrode will asymptotically increase the cut off frequency to 428.8 Hz.

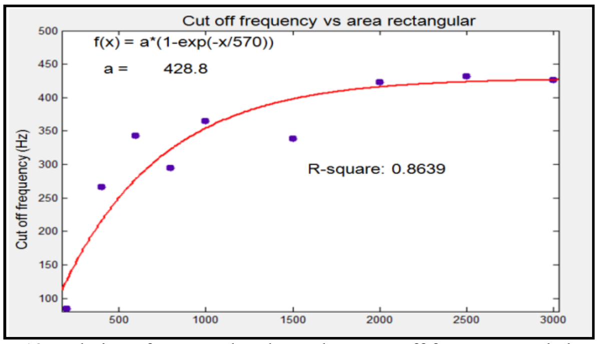

Figure 12. Relation of rectangular electrode on cut off frequency and electrode area.

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