VOL. 20, NO. 2-3, 2021, 121-126
www.elektrika.utm.my
ISSN 0128-4428

ELEKTRIKA
Journal of Electrical Engineering

Development of an Electrical Charge Sensing Prototype for Pneumatic Conveying Imaging System

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Abstract: In the view of heterogeneous flow characteristics of solid particles in pneumatic pipeline system, electrostatic signals of an array 16 electrical charge sensors were developed. The distribution solid particle properties of the electrostatic signals in handling of vertical pneumatic conveying system under different flow conditions were monitored and experimental verification was conducted. The results show that the energy distribution of an array electrostatic signals can be used to determine the distribution of solids inside the pipe. Regardless of the differences in mass flow rate, the pattern of experimental outputs was identical which demonstrates that mass flow rate disparity has no impact on the structure of voltage output. This result also indicates that the electrical charge sensor able to quantify the dissemination of solid particles in pneumatic conveying stably and accurately.

Keywords: Electrostatic signal, filter back propagation, linear back propagation, pneumatic conveyor, solid particle.

Article History: received 25 May 2021; accepted 12 June 2021; published 15 October 2021.

1. INTRODUCTION

Over recent decades there are enormous demand for the use of pneumatic conveying system from diverse industries likes energy, chemical, food manufacturing, medication, ceramics, rubber and plastic [1]. Some of the key factors which lead to increase recognition of pneumatic conveyor across various end-use industries for instance are high reliability, low operational and maintenance costs, reduced risk of material spillage, and low energy consumption.

Monitoring the flow performance in pneumatic conveying pipeline is vital when the stable flow transmute towards temporal flow due to the gas velocity and transporting air is not enough. This phenomenon would trigger stern pipeline blockage. Consequently, one of the most auspicious methods used to measure the solid-gas two-flow in pneumatic conveying pipeline is the electrostatic technique due to the advantages of stable performance, non-invasive structure, and low cost [2]

Considering the sensitivity of measurement, electrostatic sensor has a drawback of limited sensitivity, as a result, only particles proximate to electrode can be efficaciously sensed. Therefore, electrostatic monitoring system composed of single sensor has poor accuracy for the application of gas-solid flow density monitoring or particle size monitoring [3]. With the intention of improved the accuracy and reliability monitoring system, positioning multiple electrostatic sensors around the circumference of pipe have become trend among researchers [4-6].

Kumar et al. analysed the real-time monitoring system for unstable and stable flow condition by adopting the Fast Fourier Transform and Hilbert-Huang Transform techniques. They constructed a circular of six electrostatic sensors array with used of arc-sharped type electrode at two different section of a pilot pneumatic conveying pipeline [7]. Nonetheless, the factors influence the sensing characteristics such as material and geometric shape of electrode used were also analysed [8-10]. Zhang et al. proposed data fusion algorithms and cross-correlation technique to present the dynamic characteristics of the particles flow by using strip-shaped electrodes and square-loop shaped electrodes of the sensing head embedded in a vertical square-shaped pipe with different flow conditions [11]. Thuku et al. investigated the circular electrostatic sensor arrays constituted from rod-shaped electrode to establish the sensing model and formulated the relationship between sixteen and four sensors [12]. Furthermore, a new improved model for ring-shaped sensing head for electrostatic sensor based on point charged was presented and analysed using finite element method [13] which suitable for circular electrostatic sensor arrays. Other issues influence the interest of researchers for the solid-gas two-phase flow in the context of high-velocity pneumatic conveying were the impact of electrifying particle collisions and mechanical processes which frequently resulted to particles deterioration, electrostatic type flow measurements and flow characteristics performance [14-15].

The major purpose of this work is to develop a prototype electrical charge sensor which used as measuring tool to monitor the concentration profile of solid-gas two-flow in the pneumatic pipeline for different flow conditions. The sensing unit were electrical charge type of sensor or better known as electrostatic sensor. Two algorithms were used namely linear back propagation and filtered back propagation algorithms to determine the tomographic images. Experiments were carried out in a laboratory scale test rig vertical pipe pneumatic conveyor.

2. METHODOLOGY

2.1 Sensing Mechanism

The electrostatic charges are produced due to movement of solid particles in a pneumatic pipeline. At any point when particle encounters another surface like pipe wall the electrification of solid particles might possibly predicted.

Ma et al. classified two main factors determine the quantity of charge on the moving particles in the pipeline such as chemical and physical properties of particles and the surrounding environment. Particle size and shape, velocity, volume resistivity, dielectric permittivity, chemical compositions are under physical and chemical properties. Besides, temperature, humidity and pipeline roughness are considered under surrounding environment properties [16].

The oscillations of electric field owing to the charged particles path would gain a signal can be identified by sensing head associated with suitable signal conditioning circuit. The sensing interaction is attained solely by electrostatic induction from the charging solid particles provided the sensing head is implanted within the pipeline, therefore there is no direct connection between the sensing head and the solid particles. Contrary if the sensing head is disclosed directly to the moving solid particles inside the pipeline therefore the charge will transmit immediately to the signal conditioning circuit. Nonetheless, electrostatic induction becoming major interaction if diameter of the exposed sensing head is smaller than pipe diameter. [17]. Figure 1 displays a theoretical framework model for electrostatic sensing system.

2.2 Electrical Charging Phenomenon

Understanding the physical mechanism behind the electrical charging phenomena would lead to better insight of particle property. As explained previously in section 2.1, the existent of electrostatic charge in pneumatic pipeline due to collision among moving solid particles and friction between particles and the pipe wall would produce a triboelectric effect. Electrical charge sensor can be used to examine this triboelectric effect which involve the sensing principle through the movement of a charged particle. With the purpose of investigating the correlation between the charged particles and the sensing head of electrical charge sensor apprehending the mathematical modeling is crucial.

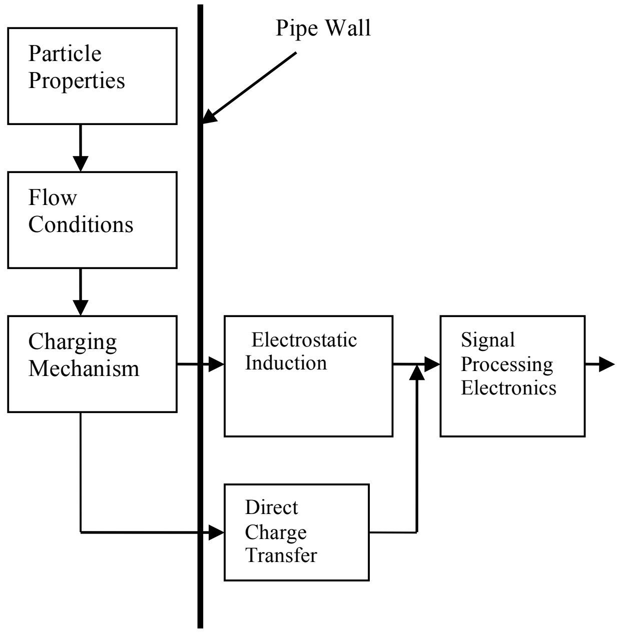

Figure 1. Model of Electrostatic Sensing System

The identical mathematic model of electrical charge sensor has been derived comprehensively by many researchers [18-21]. The pragmatic model is developed by considering the physical geometry of the sensing head is conductive ring with outer surface earthed, the diameter of the sensing head (D), the axial length (W) and subsisting in the electrostatic field of a point charge +q. The radial thickness of sensing head is disregarded. This model studies the single point charge, q which moves at a constant velocity, v. Figure 2 shows the coordinate system modelling of electrical charge sensor with respect to the point particle charged.

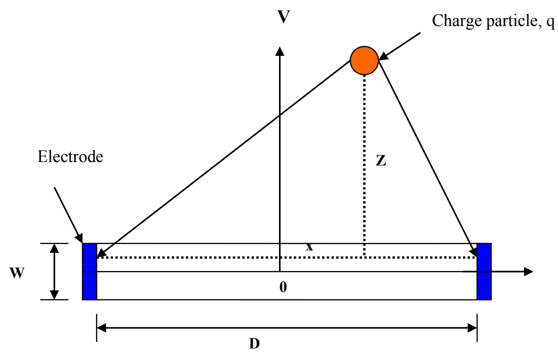

Figure 2. Coordinate Modelling of Electrical Charge Sensor

The total induced charge q' on the inner surface of the sensing head is given by equation 1.

$$q' = -\frac{Dq}{4\pi}\int_0^{\pi} \frac{0.5D - x\cos\theta}{F^2(x,\theta)} \times \left(\frac{z+0.5W}{\left[(z+0.5W)^2 + F^2(x,\theta)\right]^{1/2}} - \left[\frac{z-0.5W}{(z-0.5W)^2 + F^2(x,\theta)^{1/2}}\right] \right) d\theta \quad (1)$$

Where F(x,θ) is a function of x and θ

$$F(x,\theta) = |QN| = \left[(0.5D)^2 + x^2 - Dx\cos\theta\right]^{\frac{1}{2}} \qquad (2)$$

The actual current output of the sensor due to the movement of the point charge, q is given by equation 3.

$$Is(t) = \frac{dq'}{dt} = -\frac{DqVs}{4\pi} \times \int_0^{\pi} \left(\frac{0.5D - x\cos\theta}{\left[(V_s t + 0.5W)^2 + F^2(x,\theta)\right]^{3/2}} - \frac{0.5D - x\cos\theta}{\left[(V_s t - 0.5W)^2 + F^2(x,\theta)\right]^{3/2}} \right) d\theta \qquad (3)$$

Based on equations 1 and 3 the signals of induced charge q' and current from the electrical charge sensor have been plotted and shown in figures 3 and 4, respectively.

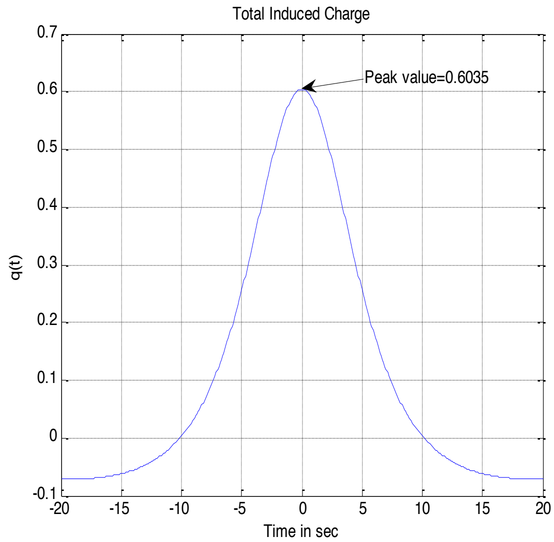

Figure3. Induced Charge Signal

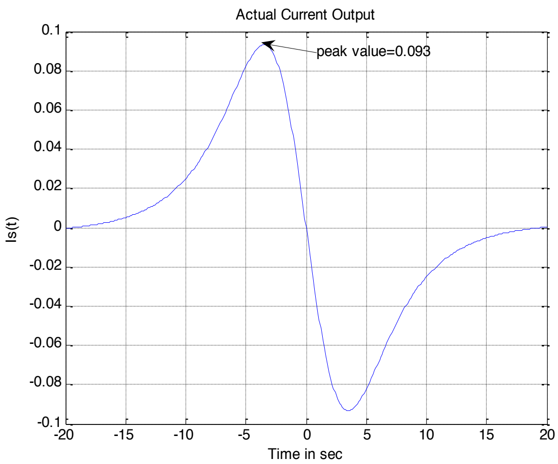

Figure 4. Current Signal

2.3 Electrical Charge Sensor

The fundamental concept of an electrical charge sensor is charged to voltage converter contingent on the principle of Coulomb's theory of charge as stated in equation 4.

$$Q = CV \qquad (4)$$

Where Q is the quantity of charge in coulombs, C is a capacitance in farads and V is voltage in volts. Figure 5 shows the circuit diagram of the electrical charge sensor.

This sensor consists of two main parts i.e., sensing head and suitable electronic conditioning circuit. The sensing head is segregated from the pipe wall by a nylon plug. The moving charged particles pass through the pipe will be detected by the sensing head made from silver steel conductor rod.

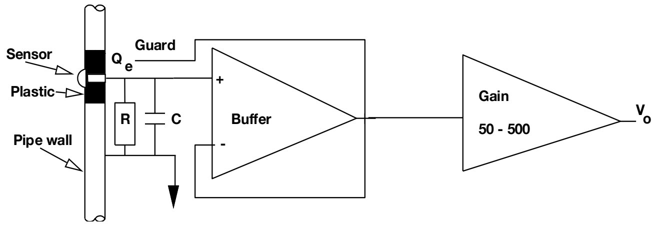

Figure 5. Electrical Charge Sensor Circuit Diagram

The electronic circuit used for conditioning the signal received from the moving charged particles has three major phases which are analogue front end, voltage gain and noise mitigation. These three phases are performed by pre-amplifier, secondary amplifier, and low pass filter. The main function of this part of sensor is to convert the detected charge signal to voltage signal and amplifies the electrostatic signal considering the detected charge signal received by sensing head is very weak. Then this signal will transform into three types of outputs. The first output used to acquire the velocity is an ac voltage signal. The second output can be used for spatial filtering test is a rectified voltage signal. The third output used for concentration profile is an averaged voltage signal. The electrical charge sensor is shown in Figure 6.

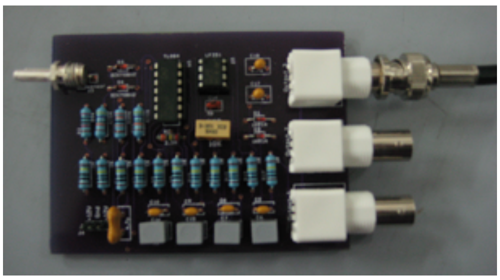

Figure 6. Electrical Charge Sensor

2.4 Experimental Scheme

The experimental test rig was designed to obtain the data for this project. The test bench comprises of a reservoir, a bunker, material feeder vane, vertical pipe and 16 electrical charge sensors. These 16 electrical charge sensors were installed equally around the circumference of pipe with a height of 1.4m from the feeder. Solid particles, made from plastic material with a size of 3mm cubes each are fed down through the pipe of 100mm diameter via the variable speed screw feeder at controlled rates. Figure 7 shows the 16 electrical charge sensors installed around the pipe wall.

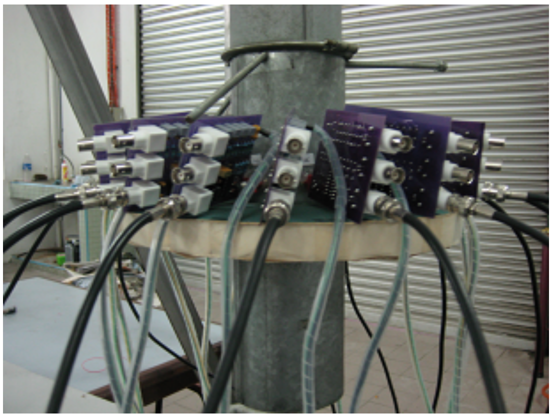

Figure 7. Sixteen Electrical Charge Sensors Mounted Around the Pipe

The measurement was performed by connecting all 16 sensors to a data acquisition system. The Keithley KUSB-3116 data acquisition card with sampling frequency of 1 kHz was used to capture the signal data. This data acquisition card communicated the signal between the electrical charge sensor and the computer for storage and processing purposes. The responses from each sensor in time domain were then plotted and shown in Figures 8 and 9.

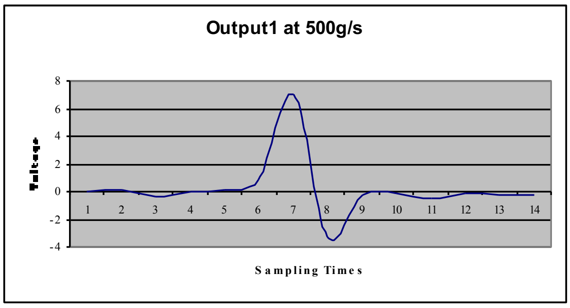

Figure 8. Charge Signal of Output 1

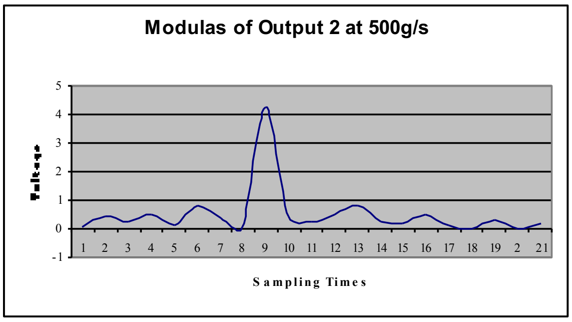

Figure 9. Current Signal of Output 1

3.3 RESULTS AND DISCUSSIONS

3.1 Average Output of the Sensors

A few sets of data at various flow rates within 110 g/s to 500 g/s of the averaged voltage output are captured through data acquisition Keithley KUSB-3116 for each electrical charge sensors to investigate the concentration profiles. Figure 10 shows the graph of the averaged voltage at flow rate 350g/s.

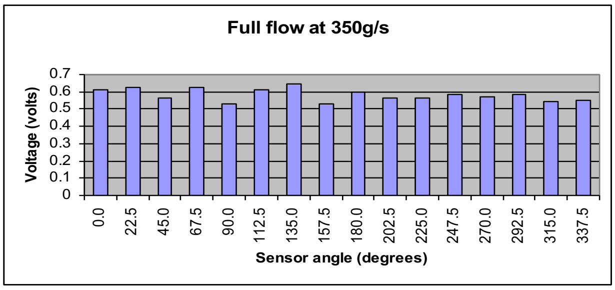

Figure 10. Average output at flow rate of 350 g/s

From the observation, it clearly shows that distributions of net charge carried by particles are not concentrated uniformly over the measurement section. This non-uniform particle distribution happened due to non-constant particles flow rate generated by the rotary valve used in this experiment.

3.2 Measured and Predicted Outputs

The calculation of predicted voltage for the output of sensor is derived by determine a scaling factor prior to calculate the predicted voltage of the sensor output. Considered that the solid particles distributed uniformly within the measurement section, the scaling factor, S_T for predicted output is calculated by following equation.

$$S_T = \sum_{i=1}^{16} S_i = 224.43 \tag{5}$$

The total voltage reading from sensors, U_T.

$$U_T = \sum_{i=1}^{16} U_i \tag{6}$$

The scaling factor, K_U.

$$K_U = \frac{U_T}{S_T} \tag{7}$$

Predicted voltage output Pi = Sensitivity * K_U.

$$P_i = S_i \times K_U \tag{8}$$

The total sensitivity of sensors, S_T is given by the summation of sensitivity map. The calculation of scaling factor was done to measure mass flow rate from 110 g/s to 500 g/s. Figure 11 shows comparison between measured output and predicted output for flow rate at 350g/s.

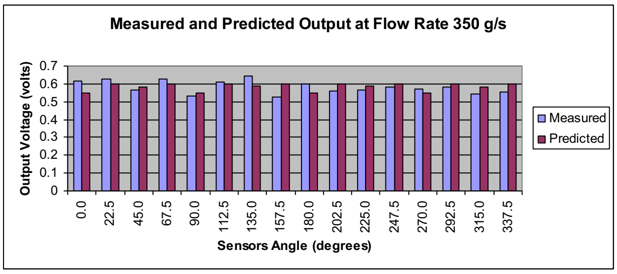

Figure 11. Experimental sensor output and predicted sensor output for full flow regime at flow rate of 350 g/s.

Generally, the experimental output voltages measured from the sensors are nearly identical to the predicted output voltage. However, further observation shows that some of the experimental outputs are higher than predicted output otherwise some of the experimental outputs are lower than predicted voltage.

Then the regression graph was plotted for full flow regimes at various flow rates within 110g/s to 500g/s to determine the relationship between sensors output and measured flow rates as shown in Figure 12.

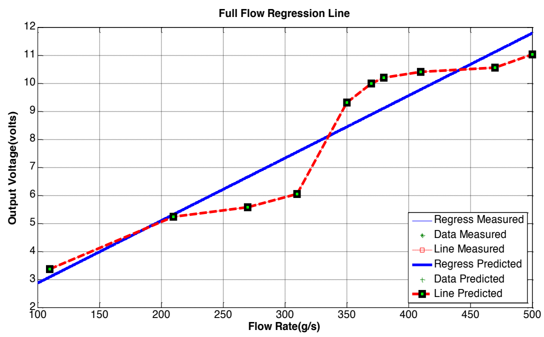

Figure 12. The sum measured output and predicted output with regression lines.

The graph shows a positive linear relationship between the transducer output and the measured flow rate. The correlation coefficient of both measured and predicted output is 1.000 and the gradient of the linear regression line is 0.022. Therefore, the two regression lines for both measured and predicted outputs are overlap as clearly shown in Figure 12. The following equation is obtained by applying linear fit regression for both measured and predicted output regression lines.

$$V(output) = 0.022 \times flowrate + 0.6357 \quad (9)$$

3.3 Concentration profiles

The averaged output produced by output number three of electrical charge sensor is used to generate the concentration profiles of flow regimes at different flow rates. Two types of image reconstruction algorithms namely linear back projection (LBP) algorithm and filtered back projection (FBP) algorithm have been chosen to present the tomographic images of the concentration profile for plastic bead particles over the measurement section in the pneumatic pipeline. Figures 13 and 14 show the tomogram of concentration profile for full flow at measured flow rates of 350 g/s using LBP and FBP algorithms, respectively.

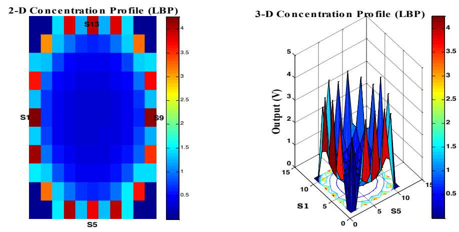

Figure 13. Concentration profiles for full flow at 350 g/s using LBP algorithm.

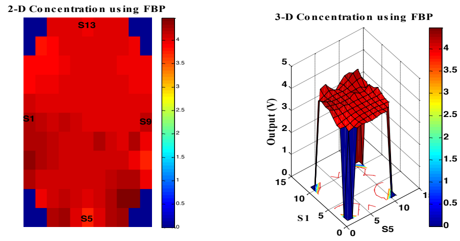

Figure 14. Concentration profiles for full flow at 350 g/s using FBP algorithm.

Figures 13 and 14 graphically visualize the tomographic images for dissemination of concentration profile across a measured sectional view of pneumatic pipe. For linear back projection profiles show that electrical charge sensors detected the existence of charge adjacent to the sensing region and the amount of charge proximate to the pipe wall are greater compared than charge at the center of pipeline. As for the filter back projection algorithm the concentration profiles almost uniformly distributed at any region across a measured pipeline.

4. CONCLUSION

Electrical charge sensor is one of the efficacious instruments for imaging dissemination of solid particles in pneumatic pipeline system. The method and technique have been developed effectively is emerged that electrical charge sensor is applicable for measuring equipment to be used in laboratory and industry.

The electrical charge sensor is greatly responsive to sense charge proximate to sensing region based on the proved results deduced from theoretical and experimental data. Positioning an array of 16 electrical charge sensors around the circumference of pipe and the application of linear back projection algorithm and filtered back projection algorithm are effective measurement technique for solid-gas flow in pneumatic conveyor system.

ACKNOWLEDGMENT

This research work is supported by Universiti Teknologi Malaysia Transdiciplin Research Grant number VOT 06G80.

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