Jurnal Teknologi, 41(D) Dis. 2004: 91–104

ELECTROSTATIC SENSOR FOR REAL-TIME MASS FLOW RATE MEASUREMENT OF PARTICLE CONVEYING IN PNEUMATIC PIPELINE

MOHD. FUA'AD BIN HJ RAHMAT[1] DAN YAW WEE LEE[2]

Abstract. This paper discussed the electrostatic sensors that have been constructed for real-time mass flow rate measurement of particle conveying in a pneumatic pipeline. Many industrial processes require continuous, smooth, and consistent delivery of solids materials with a high accuracy of controlled flow rate. This requirement can only be achieved by installing a proper measurement system. Electrostatic sensor offers the most inexpensive and simplest means of measuring solids flows in pipes.

Keywords: Electrostatic sensor, cross-correlation, peripheral velocity

1.0 INTRODUCTION

In order to increase the efficiency of energy and raw materials usage and to improve product quality and process efficiency, the demand of continuous monitoring of the flow rate of solids in pneumatic pipelines is rising in many industrial areas. According to Arko [1], applications of pneumatic conveying systems can be found in many industries dealing with food processing, plastic product manufacturing, textile, paper, power generation, solids waste treatments, and many others. Many processes require continuous, smooth, consistent delivery of solids materials with high accuracy of controlled flow rate. This requirement can only be achieved by installing a proper measurement system. Electrostatic sensor offers the most inexpensive and simplest means of measuring solids flows in pipes. As electrostatic sensors respond only to moving solids in the pipe, the measured data enjoy a large degree of immunity from the effects of solids accretion which adversely affect other technologies [2].

Applications of electrostatic sensors include process tomography [3], aerospace and soil properties determination [4]. Other terms such as electrodynamic and triboelectric have also been used in the literature to describe this sensing technology. 'Electrodynamic' refers to the fact that the charge arose from the movement of particles. 'Triboelectric' emphasized that the particles are charged due to the friction or direct

---

[1] Control & Instrumentation Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor. E-mail: drfuaad@fke.utm.my

[2] Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor. E-mail: quark_yaw@yahoo.com

contact between the particles and the electrode. 'Electrostatic' implies the electrostatic nature of the sensing principle of the sensor. It can be used to replace the other terms because it is the most appropriate word to describe the fundamental sensing principle of the sensor. The major advantage of utilizing an electrostatic sensor is its high sensitivity for concentration metering. In fact, the combination of this technique with cross-correlation signal processing algorithms provides the most economical methods of measuring the velocity of solids in pipelines. By accurate metering of the material in industrial processes, the ultimate target is to achieve efficient resource usage, in terms of material, energy, operating cost, maintenance, and investment. A 5% saving of these resources within one year would be very significant on a national scale. It is also imperative to create safe working environment and to meet stringent government regulations.

2.0 ELECTRICAL CHARGING PHENOMENON

Electrostatic charge can be generated from the movement of powder or particulate materials in pipelines of the industrial plant. The electrification of solids can occur due to the collisions between particles, impacts between particles and pipe wall and friction between particles and air stream [5]. The quantity of charge carried on particles is normally unpredictable. According to Yang [2], particles in pneumatic pipelines possess charge densities in the range of $10^{-7} - 10^{-3}$ C kg^{-1}. There are several factors that can affect the magnitude of electrostatic charge. For examples, condition of the surfaces, state of electrostatic charge prior to contact, particle size and shape, force of contact, and environmental conditions such as pressure, atmospheric composition, and humidity [6]. However, meaningful signals from the perturbations in the electric field caused by the passage of charged particles can be detected by electrostatic charge sensor. If the electrode of the sensor has no direct contact with the particles in pipe, the sensing method is merely electrostatic induction. On the other hand, direct charge transfer will occur if the electrode is exposed directly to particles. Nonetheless, if the ratio of axial dimension of the electrode to pipe size is small, electrostatic induction will be the dominant factor [7]. Basically, the induction model for a single charged particle, q, can be derived from the following Equation [8]:

$$E = \frac{q}{4\pi\varepsilon_0 R^2}, \tag{1}$$

where E is the electric field, ε_0 is the permittivity of free space (8.854×10^{-12} F/m), and R is the distance between the charged particle and a particular point.

3.0 ELECTROSTATIC SENSOR

In order to understand the sensing mechanism of the electrostatic sensor, a suitable mathematical model is inevitable. The corresponding models have been discussed in detail by researchers such as Yan *et. al* [5] and Rahmat [8].

Assume that a particle *p*, carrying a charge *q,* traveling in uniform velocity, *V*, along a path which is perpendicular to the vertical axis of the electrode. The illustration is shown in Figure 1. The electric field, *E*, due to the charged particle at distance *R* is given by Equation (1). The component of the field normal to the sensor, *E*-, is:

$$E\perp=\frac{q}{4\pi\varepsilon_0 R^2}\sin\theta \tag{2}$$

The induction charge in a small element of the electrode area, *δA* is given by [5]

$$dQ=-\varepsilon_0 E_\perp \delta A \tag{3}$$

In addition, we can obtain the following equations:

$$\delta A = w\Delta a \tag{4}$$

$$\sin\theta=\frac{x}{R} \tag{5}$$

and

$$R^2=(y-a)^2+x^3 \tag{6}$$

Hence,

$$dQ=-\frac{qxw}{4\pi}\frac{\Delta a}{[(y-a)^2+x^2]^{1.5}} \tag{7}$$

From Equations (4) – (7), it can be shown that the total charge induced into the sensor is given by:

$$Q=-\frac{qxw}{4\pi}\int_{1/2}^{1/2}\frac{1}{[(y-a)^2+x^2]}dv \tag{8}$$

Maple is used to calculate the integration and the equation becomes:

$$Q=\frac{1}{4}\frac{qw\left(-\frac{\left(y+\frac{1}{2}L\right)}{\left(y^2+yL+\frac{1}{4}L^2+x^2\right)^{.5}}-\frac{\left(y-\frac{1}{2}L\right)}{\left(y^2-yL+\frac{1}{4}L^2+x^2\right)^{.5}}\right)}{x\pi} \tag{9}$$

where *L* is the size of the sensing electrode, *x* is the horizontal distance between the charged particle and the center of electrode, and *y* is the vertical distance between the charged particle and the center of electrode. Then, the current, *I* is given by:

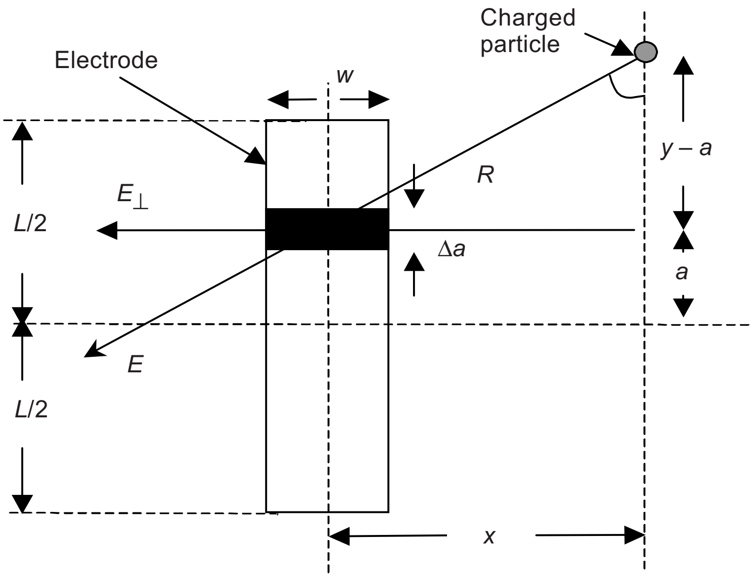


Figure 1 Mathematical model of elenc signal

$$I = \frac{dQ}{dt} \tag{10}$$

and

$$t = \frac{y}{V} \tag{11}$$

Using Maple to do the calculation, the equation is shown as below:

$$I = \frac{1}{4}\frac{qw}{x\pi}\left(-\frac{y^2}{V\left(y^2+yL+\frac{1}{4}L^2+x^2\right)^{0.5}} + \frac{0.5\left(y+\frac{1}{2}L\right)\left(2\frac{y^3}{V}+\frac{y^2L}{V}\right)}{\left(y^2+yL+\frac{1}{4}L^2+x^2\right)^{1.5}} + \frac{y^2}{V\left(y^2-yL+\frac{1}{4}L^2+x^2\right)^{0.5}} + \frac{0.5\left(y-\frac{1}{2}L\right)\left(-2\frac{y^3}{V}+\frac{y^2L}{V}\right)}{\left(y^2-yL+\frac{1}{4}L^2+x^2\right)^{1.5}} \right) \tag{12}$$

The signal from the charged particle has been drawn based on the aforementioned equations by utilizing powerful numerical analysis software, MATLAB, as shown in

Figure 2. These curves are for $q = 1$ C, $x = 10$ mm, $w = 10$ mm, $L = 20$ mm and $V = 5000$ mm/s. The figure shows a typical example of the induced charge in electrode and corresponding sensor current.

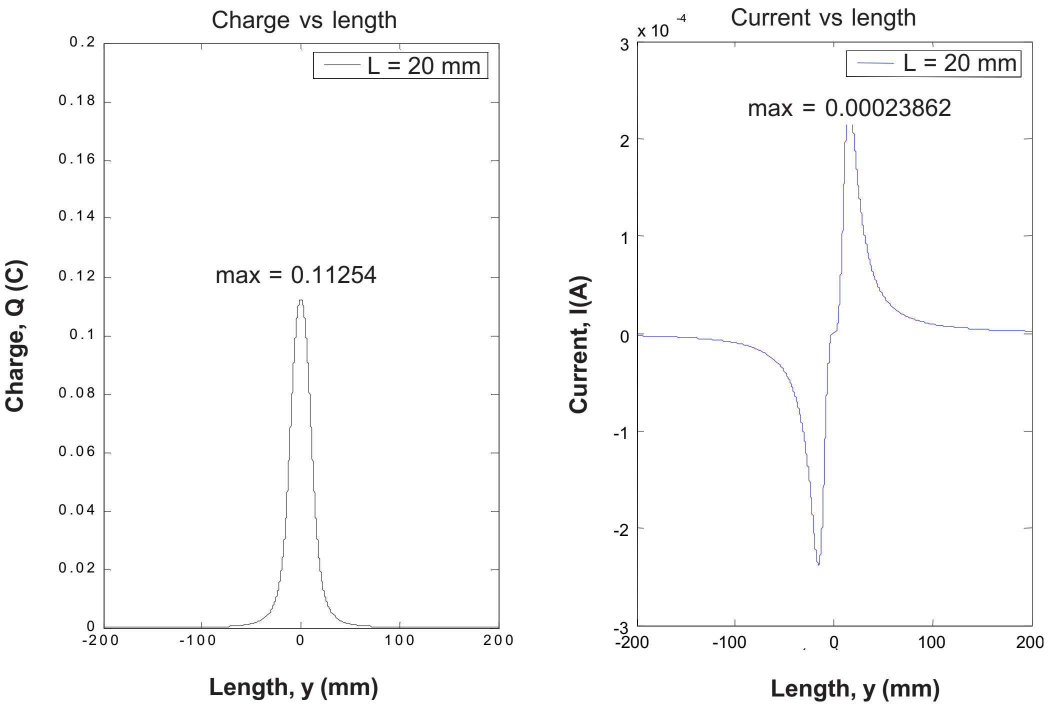


Figure 2 Induced charge and sensor current signal generated using MATLAB

The pneumatic pipeline is assumed to be a perfectly conductive metal with its external surface grounded, as shown in Figure 3. Hence, the interior space of the pipeline is free from the interference of external electric field. The electrode is treated as a perfectly conducted rod connected to the signal conditioning electronic with input resistance *R*. The operation of the measurement system begins when the electrostatic sensors detect an electrostatic charge. The analog signal magnitude from each sensor depends on its position in the array. The induced charge in the electrode will be converted to a voltage signal by a signal conversion circuit. Then, the voltage signal will be transferred to succeeding signal conditioning circuit in order to generate various outputs such as AC voltage, rectified voltage, and average voltage. The outputs will be sent to a computer for data processing via a data acquisition system. Information such as peripheral velocity, concentration profile, velocity profile, and mass flow rate can be obtained by proper software such as an offline program written by Azrita [3].

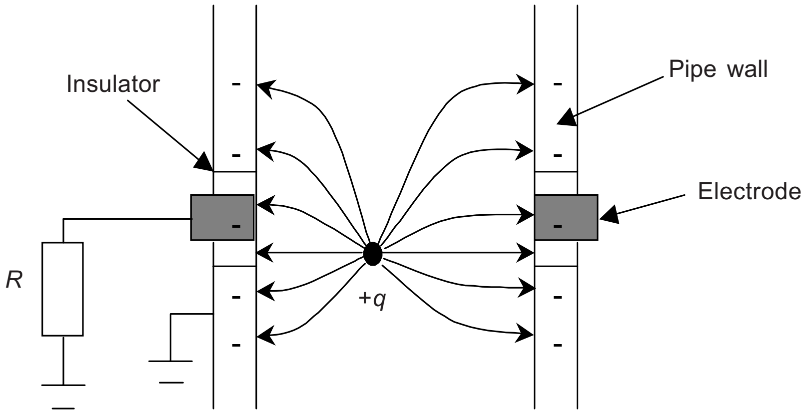


Figure 3 Electric field lines of a single charged particle

4.0 ELECTROSTATIC SENSOR ELECTRONIC

The electrostatic sensor consists of several parts such as an electrode, a noninverting voltage follower, a precision rectifier, and a low pass filter. Figure 4 illustrates the block diagram of an electrostatic sensor. The transducer consists of two basic elements, the electrode and associated electronics [9]. As discussed by Rahmat [8] and Shackleton [9], the electrode is a metal conductor which is electrically insulated from the metallic conveyor, and forms a capacitance to earth. A capacitor is connected between input and earth so that measurements are made with a similar capacitance, which has a value of 5.5 to 5.7 pF. Charge Q is induced in the electrode due to the passage of charging particles.

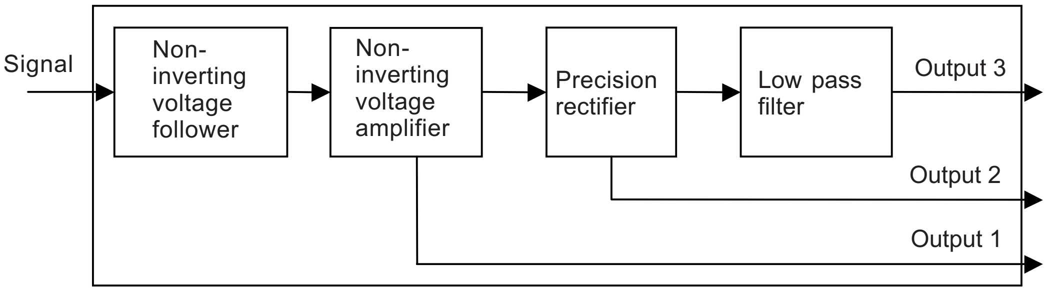


Figure 4 A block diagram of an electrostatic sensor

The input resistor will provide a path for current to flow into and out of the capacitance formed between electrode and earth. The current flow through the input resistor generates the voltage, which provides the input to IC TL084 that functioned as non-inverting voltage follower. The output of this stage is used as a guard voltage for the input circuit to minimize stray capacitance of the input circuitry and is AC coupled to the input of the non-inverting voltage amplifier.

The output of the non-inverting voltage amplifier is amplified voltage (output 1), which is used for cross correlation measurement. It is also used as the input to the following stage. The subsequent stage is precision rectifier which consists of two operational amplifiers that AC coupled to the preceding amplifier. The rectifier provides the nominal gain of 1. The output of this stage is rectified voltage (output 2) that can be used for spatial filtering tests. Basically, any flow sensor exhibits some form of spatial filter effect on the original flow signal due to the finite physical size and geometrical shape of the sensing volume [2]. The spatial filtering effect can be defined as the relationship between the sensor size and the frequency bandwidth of the transducer, determined from the frequency response obtained during a pulse, which corresponds to a detectable particle [8]. This is also used as directly coupled input to the low pass filter circuit. This stage provides filtering and smoothing for the previous stage to produce the averaged output (output 3).

A double layers PCB for electrostatic sensor had been designed using Protel 99SE. Simulation had been done to investigate the response of the sensor. There are four main components in an electrostatic measurement system. The components are sensing part, signal conditioning system, data acquisition system, and computer that is used for signal processing. Figure 5 illustrates the block diagram of the electrostatic measurement system.

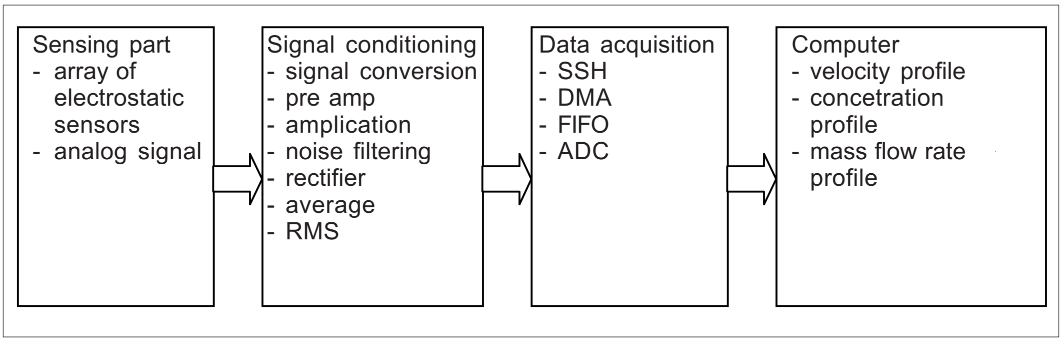


Figure 5 Block diagram of an electrostatic measurement system

5.0 CROSS-CORRELATION TECHNIQUE

One of the methods to verify the constructed electrostatic sensors is the determination of peripheral velocity by cross-correlating signals from the upstream and downstream sensors. It is also known that cross-correlation velocity measurement provides a means better than the Doppler approach. In fact, the electrostatic cross-correlation solids velocimeter is superior to virtually all other types of known cross-correlation flow instruments [2]. Two set of identical sensors will be installed with a chosen axial distance apart from each other, as shown in Figure 6. The distance between the upstream and downstream sensors is crucial because a low separation produces a higher correlation coefficient, but high speed data acquisition and processing is needed, whereas larger separation results in a lower correlation coefficient [10]. The separation between, the upstream and downstream sensor was set to 5 cm, which was half of the pipe diameter [8]. However, a smaller value can be used for a high speed data acquisition card. The transit time taken by the particles moving from the upstream sensor to the downstream sensor was measured by cross-correlating the two signals using a signal processor or computer software such as MATLAB.

The magnitude of the charge depends on the physical properties of the particles, such as size, conductivity, shape, humidity and composition, as well as on the pipe wall roughness, pipe diameter, and pipe length traversed by the particles. Solid velocity and concentration are also major factors contributing to the magnitude of the charge. However, the cross-correlation process is independent of the signal magnitude so that the factors are not important, provided the signals are substantially greater than any internal amplifier noise [11]. The peripheral velocity (or sensor-to-sensor velocity) is then calculated from a simple formula,

$$v = L/\tau \tag{13}$$

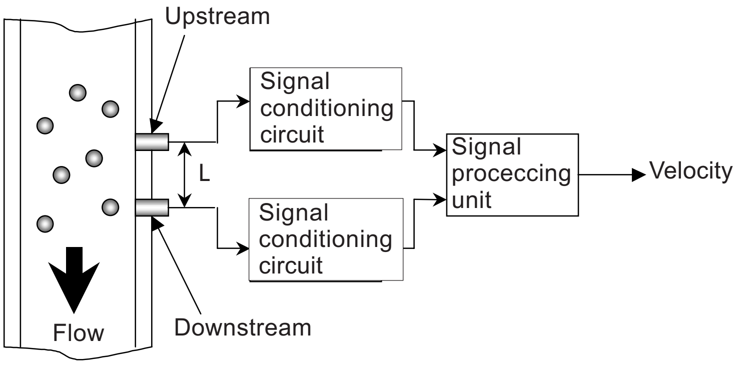


Figure 6 Block diagram of velocity measurement by cross-correlation technique

where v is the flow velocity, L is the axial distance between two sensors, and τ is the transit time.

The analog signals from sensors will be converted to discrete signals by data acquisition card. Hence, the signals sent to the computer are discrete time sequences. In order to obtain transit time, τ, a discrete time version of cross-correlation function is needed. The cross-correlation function for two discrete time sequences is given by [12]

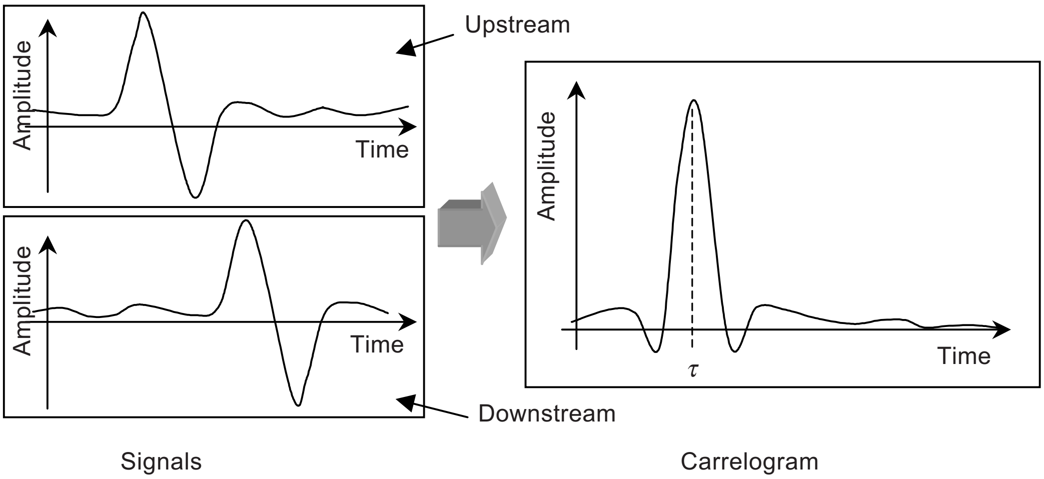


Figure 7 Cross-correlation of upstream and downstream signals

$$R_{xy}[\tau] = \sum_{n=-\infty}^{\infty} x[n]y[n-\tau] \quad \tau = 0, \pm 1, \pm 2, \pm 3, \ldots, \tag{14}$$

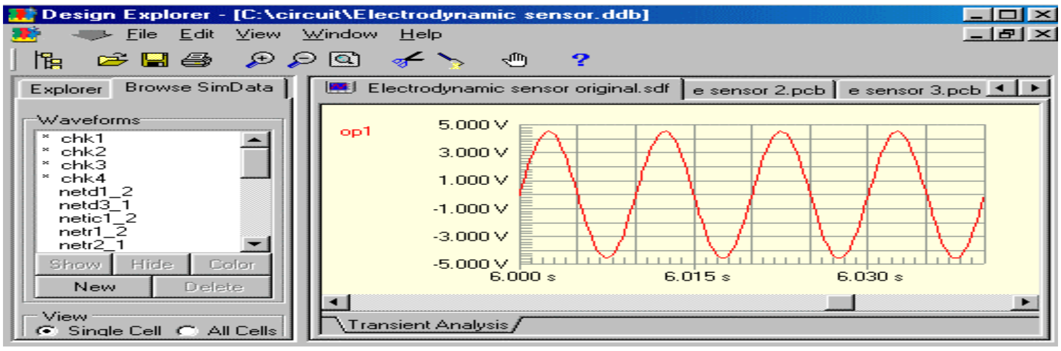
where τ is the time shift parameter or transit time, $x[n]$ is the reference sequence which remains fixed in time, and $y[n]$ is the time sequence that is shifted with respect to $x[n]$. In this paper, $x[n]$ corresponds to upstream signal, whereas $y[n]$ corresponds to downstream signal.

6.0 PRELIMINARY RESULTS AND DISCUSSION

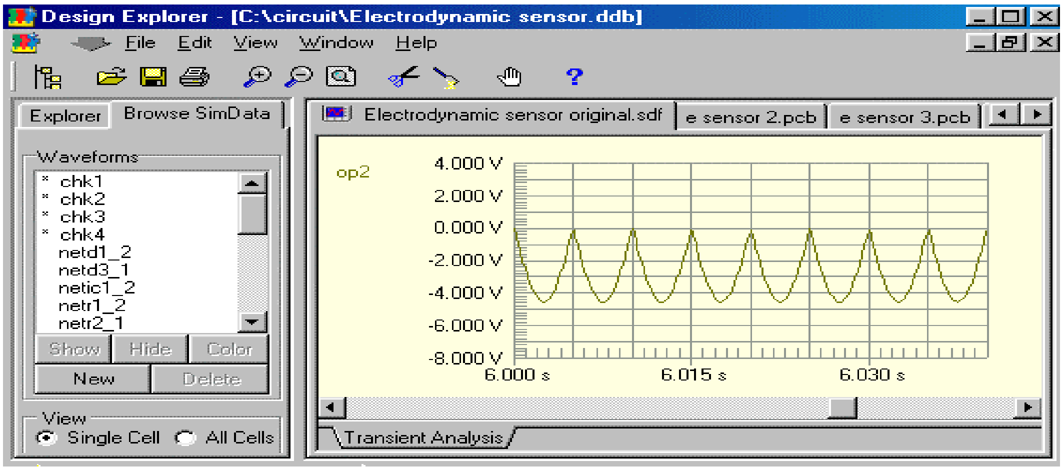
The constructed electrostatic sensors had been tested using sine wave from signal generator and digital storage oscilloscope Yokogawa (DL1520). Outputs of the testing were similar to simulated results that were carried out by using Protel 99SE, as shown in Figures 8 and 9. Output 1 was amplified AC voltage signal, output 2 was rectified voltage signal and output 3 was averaged voltage signal.

There was no obvious signals distortion, as shown in figures above. The circuit functioned as predicted by simulation using computer software. However, the simulated results and real results did not exactly match due to several factors. For example, the physical condition for connection between the electronic components and wire may vary depending on the soldering. In addition, interference and influence from various sources in a real testing environment are different from the simulated environment.

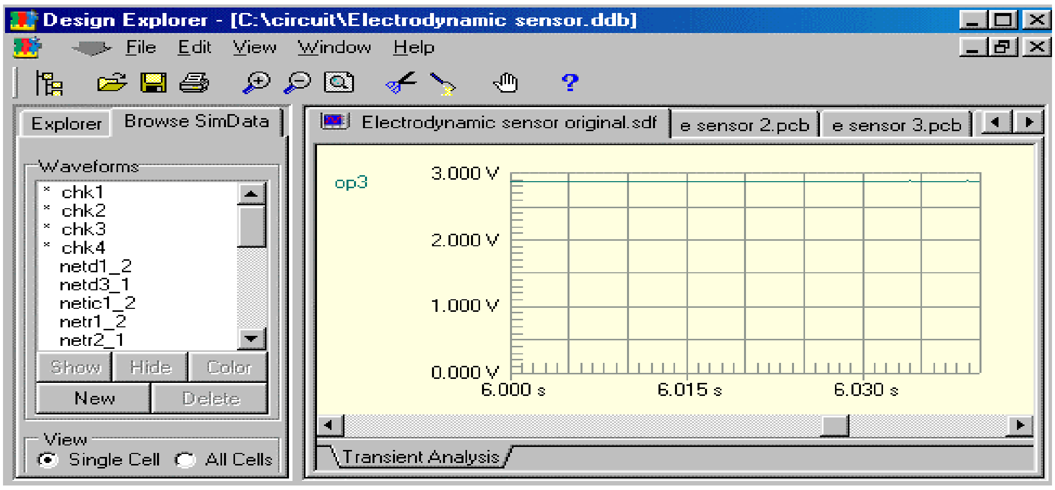
The sensors were also tested using gravity flow rig for peripheral velocity measurement. The results are shown in Figure 10. This was done using the data acquisition system to obtain 1000 samples from the sensors. The measurements were performed by sampling sensor output at a frequency of 1 kHz. Mass flow rate was set



(a) Output 1 of simulation

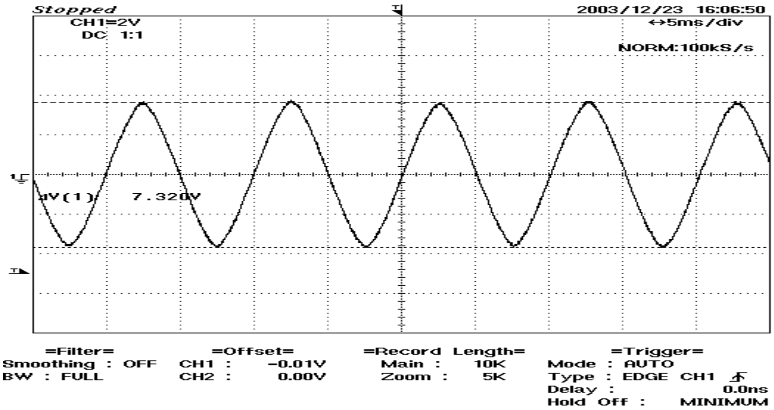


(b) Output 2 of simulation

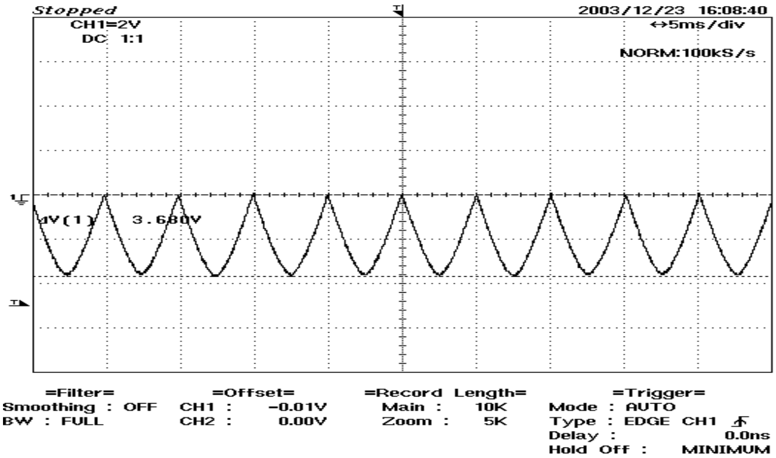


(c) Output 3 of simulation

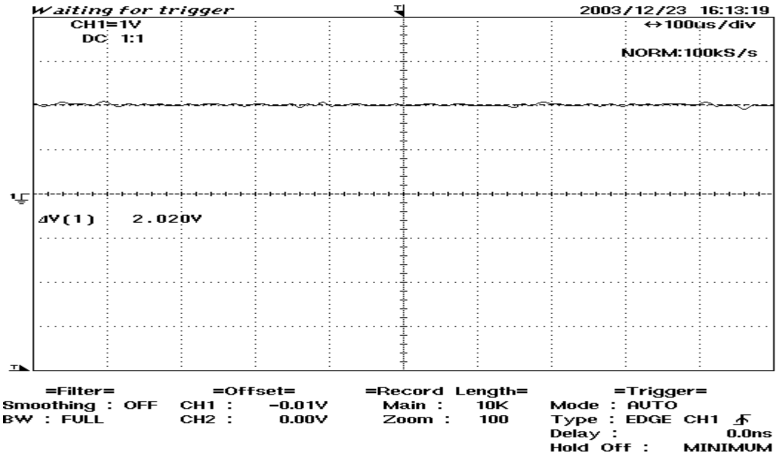
Figure 8 Simulated results



(a) Output 1 of the electrostatic sensor



(b) Output 2 of the electrostatic sensor



(c) Output 3 of the electrostatic sensor

Figure 9 Real testing results

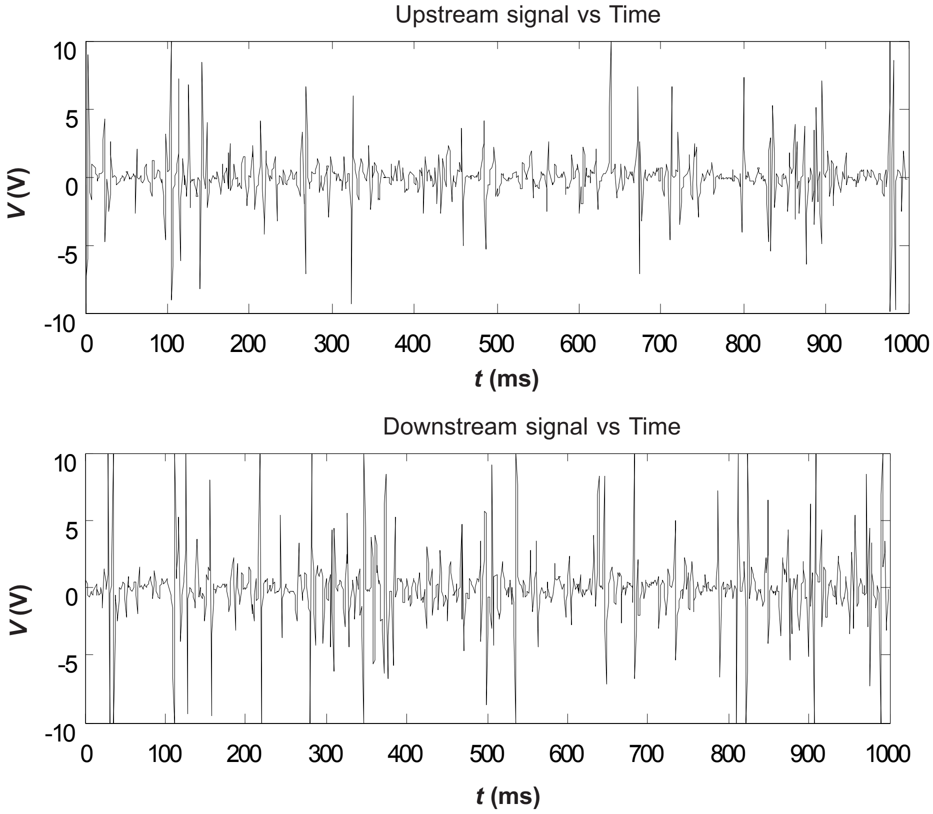


Figure 10 Signals from the upstream and downstream sensors

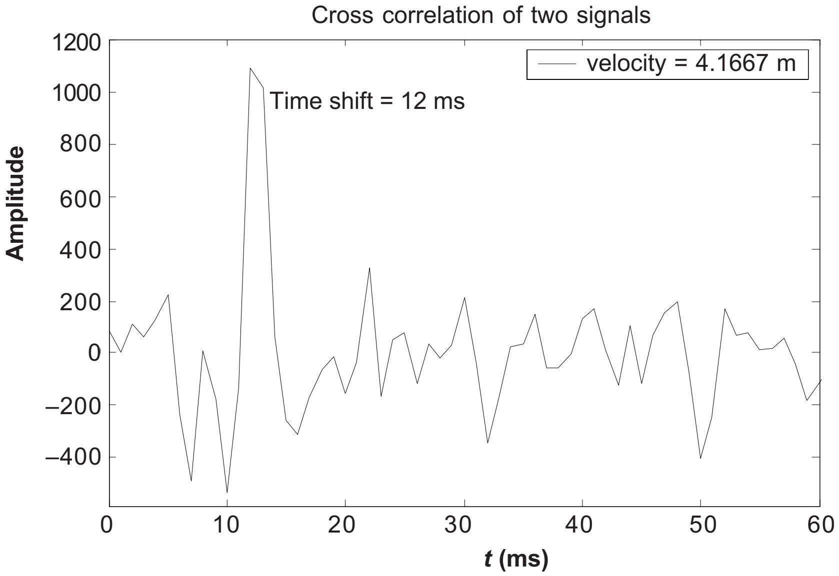


Figure 11 A correlogram of upstream and downstream signals generated by MATLAB

to 83 g/s. Figure 10 shows the signals from the upstream and downstream sensor. Cross-correlation of the upstream and downstream signals is performed offline using a program written in MATLAB. Transit time was 12 ms and peripheral velocity was 4.2 m/s, as shown in Figure 11.

The effect of aluminium foil as the shield of sensor was also investigated. Two sensors were placed in a gravity flow rig. Sensor 1 is the upstream sensor and sensor 2 is the downstream sensor. Sensor 2 was shielded using aluminium foil (earthed), whereas sensor 1 was not shielded by aluminium foil. Figure 12 shows the experimental results of this test. It can be seen that output of sensor 2 was smoother and less noisier than the output of sensor 1. Hence signal-to-noise ratio can be increased by introducing aluminium foil as the cover of sensor.

7.0 CONCLUSIONS

From the preliminary results, the electrostatic sensors for real-time mass flow rate measurement functioned as expected from simulation. Electrostatic sensors provide a cost effective way for sensor-to-sensor velocity measurement. Further experiment needs to be carried out using 32 sensors to obtain concentration profile, velocity profile, and

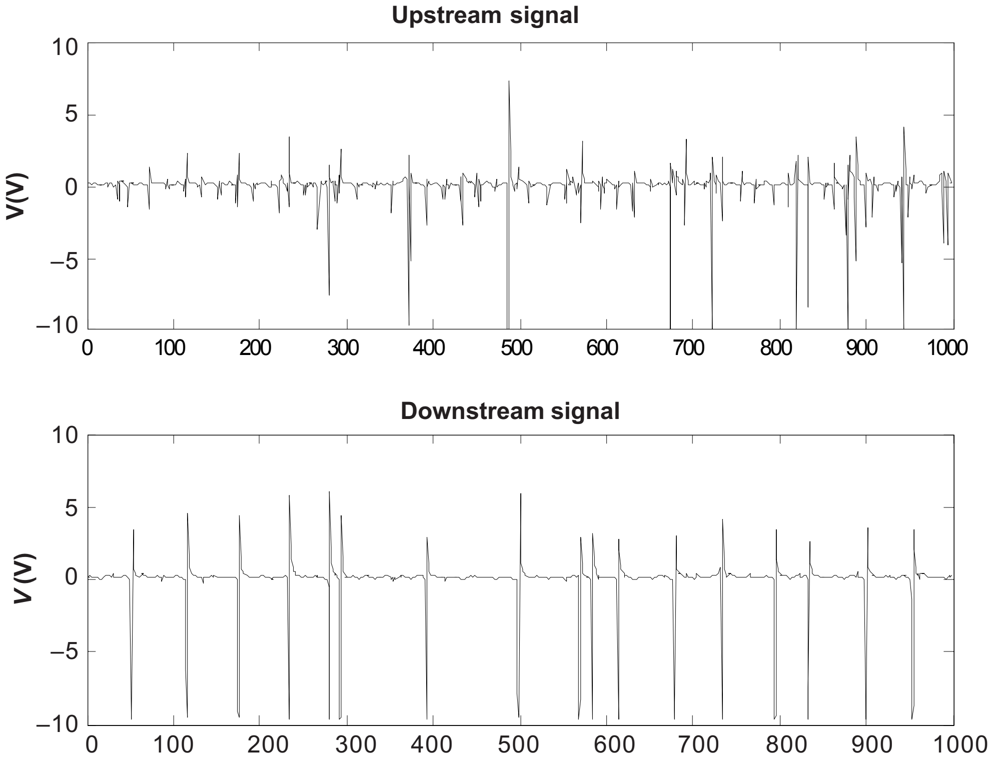


Figure 12 Effect of aluminium foil as the electric shield

mass flow rate profile. In addition, programming language such as Visual C++ should used for a real-time software development.

REFERENCES

[1] Arko, A., R. C. Waterfall, M. S. Beck, and T. Dyakowski. 1999. Development of Electrical Capacitance Tomography for Solids Mass Flow Measurement and Control of Pneumatic Conveying Systems. *1st World Congress on Industrial Process Tomography*: 14-17.

[2] Yan, Y. 1996. Mass Flow Measurement of Bulk Solids in Pneumatic Pipelines. *Meas. Sci. Technol*. 7: 1687-1706.

[3] Azrita, A. 2002. *Mass Flow Visualization of Solid Particles in Pneumatic Pipelines using Electrodynamic Tomography System*. M. Eng. Thesis, Universiti Teknologi Malaysia.

[4] Calle, C. I. et al. 2003. Embedded Electrostatic Sensors for Mars Exploration Missions. *Proceedings of the ESA-IEEE Joint Meeting on Electrostatics 2003*: 90-103.

[5] Yan, Y., B. Byrnet, S. Woodhead, and J. Coulthard. 1995. Velocity Measurement of Pneumatically Conyed solids Using Electrodynamic Sensors. *Meas. Sci. Technol*. 6: 525-537.

[6] Guardiola, J., V. Rojo, and G. Ramos. 1996. Influence of Particle Size, Fluidization Velocity, and Relative Humidity on Fluidized Bed Electrostatics. *Journal of Electrostatics.* 37: 1-20.

[7] Institute of Measurement and Control. 2001. *Guide to Flow Measurement of Particulate Solids in Pipelines*. U.K.: Institute of Measurement and Control.

[8] Rahmat, M. F. 1996. *Instrumentation of Particle Conveying Using Electrical Charge Tomography*. PhD Thesis, Sheffield Hallam University.

[9] Shackleton, M. E. 1982. *Electrodynamic Transducer for Gas/Solids Flow Measurement*. M. Phil Thesis, University of Bradford.

[10] Beck, M. S., and A. B. Plaskowski. 1987. Cross Correlation Flowmeter: Their Application and Design, Adam Hilger, Bristol.

[11] Xie, C. G., A. L. Stott, S. M. Huang, A. Plaskowski, and M. S. Beck. 1989. Mass-flow Measurement of Solids Using Electrodynamic and Capacitance Transducers. *J. Phys. E: Sci. Instrum*. 22: 712-719.

[12] Mitra, S. K. 2001. *Digital Signal Processing*. Singapore: McGraw Hill.