PARTICLES MASS FLOW RATE AND CONCENTRATION MEASUREMENT USING ELECTROSTATIC SENSOR

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Abstract- In many industries where flow parameters measurement is essential to control manufacturing process, the use of a reliable, cost effective and high accuracy instrument is an important issue. Appropriate measurement method and design leads to improvement of pneumatic conveyors operation and process efficiency. This paper present an instrumentation design based on passive charge detection using a single electrostatic sensor. Two different sensor electrodes are applied to show the flexibility of electrostatic sensor application. A time domain signal processing algorithm is developed to measurement of mass flow rate and concentration profile from acquired electrical charge signal. The findings is led to a low cost and high accuracy design, the experimental test results of the design shows less than $\pm 5\%$ error between measured parameters and reference reading acquired from the manual weighing.

Index terms: pneumatic conveyors; passive charge; electrostatic sensor, mass indicator.

I.   INTRODUCTION

Mass flow rate and concentration measurement are an important factors in many industries such as coal fired power plants, pharmaceutical, chemical and food stuff production process. Control of flow parameters effectively improves productivity, product quality and process efficiency in such industries [1, 2]. Mass flow measurement methods are categorized in two groups, inferential measurement method and direct or true measurement method. In inferential measurement, particles mass flow rate is obtained by measuring and multiplying of instantaneous velocity and concentration [3]. Inferential method is mostly favorable when in addition of mass flow rate measurement the measurement of velocity and concentration are required to control of the flow process. In direct method, sensing element reacts directly to the mass flow rate variation.

Many type of non-restrictive flow sensors are developed in last decade based on inferential and direct methods which most of them followed the inferential method [4-6]. Installing the proper measurement system depend on nature of particles flow in conveyors, material type and particles size, velocity, moisture and homogeneity profile. This paper presents a direct measurement method utilizing a single electrostatic sensor which offers a high accuracy, inexpensive and reliable measurement of solid particles flow rates and concentration.

II.   ACTIVE AND PASSIVE CHARGE DETECTION METHOD

Particles flow sensors based on electrical charge detection are developed in two methods. In first method ('active mode'), external voltage source is applied to charge the moving particles in a pipeline [7]. Passing charged particles through a charge detecting chamber produces an electrical current (I_0) which is directly proportion to the solid particles mass flow rate [7] :

$$M_s = cI_0 \tag{1}$$

where c is a constant and determined by calibrating the instrument with the particles martial. In second method natural charge on particle is detected ('passive mode'). Solid particles movement into a pipeline is a source of electrostatic charge generation. This charge is the result of particles collision to each other, particles impact to the pipe wall and friction between particles and air flow. The magnitude of generated electrostatic charge depends on material types, particles size

and concentration. The quantity of this charge is not predictable. Electrostatic charge density in solid particles pneumatic pipelines is between $10^{-7} - 10^{-3} C/kg$ [8]. Based on Coulomb's law for interacting point charge, *E* field generated due to a single charge in the space is given by:

$$E = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \hat{r}$$

(2)

Where *q* is a single charge of a particle, *r* is the distance between charge *q* and sensor, $\hat{r}$ is the unit vector, point from charge *q* to sensor and ε_0 is the electric constant. Perturbation of electrical field inside the pipe, generated by solid particle passage, can be detected by installing appropriate electrostatic sensor (passive mode).

III.   ELECTROSTATIC SENSOR DESIGN

An electrostatic sensor consists of two main parts, sensing electrode and signal conditioning circuit. Electrostatic sensor electrodes can be made in different shapes such as rod, quarter ring, ring and netted ring shape. Selecting the correct electrode shape for the flow meter depends on pipe diameter, martial type, particles velocity and size, and homogeneity of particles flow. To illustrate, a quarter ring shape electrode in an inhomogeneous mass flow regime won't be enough reliable, or a netted ring shape electrode is obstructive or susceptible to suffer by wear or abrasion. In this study, pin and ring shape electrostatic electrode are separately utilized to detect the electrical charge. As it depicted in Figure 1, electrostatic electrodes are installed to an earthed chamber while they are absolutely isolated from chamber body.

Signal conditioning circuit is the second part and main part of electrostatic sensor, depicted in Figure 2. It converts and amplifies electrostatic raw signals to AC voltage signals. The applied electrostatic sensor has three outputs, Output 1 provides non-inverting amplified signal and two other outputs give rectified and average voltage of non-inverting amplified signal respectively [9]. The passage of particles in pipe induces electrical charge to the electrode. The current flow through the input resistor generates the voltage, which provides the input to the IC TL084 that functioned as non-inverting voltage follower; the output of this stage is used as guard voltage for the input circuit to minimize stray capacitance of the circuitry and is the AC coupled to the input of the non-inverting voltage amplifier which is the output *V (t)*.
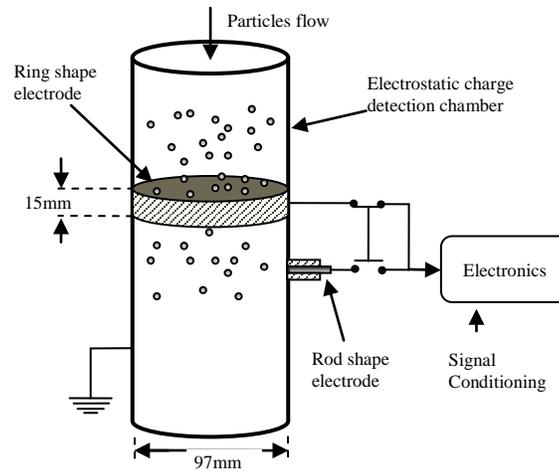
Figure 1. Electrostatic sensing chamber and installed sensing electrodes
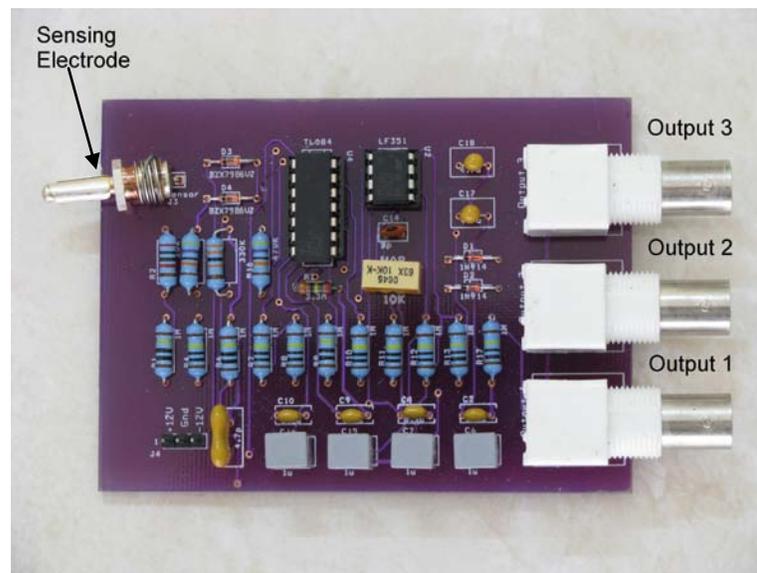

Figure 2. Electrostatic sensor with an installed pin electrode

IV.   EXPERIMENTAL SET-UP

To verify the presented method a series of particles mass flow rate measurements has been conducted using a gravity test rig. However this method is applicable in pneumatic particles conveyors in known velocity and size profile. Figure 3 shows a picture of applied test rig; it is consist of a particles bunker in the top, rotary feeder to control mass flow rate in the pipe and a vacuum loader which refills the bunker.
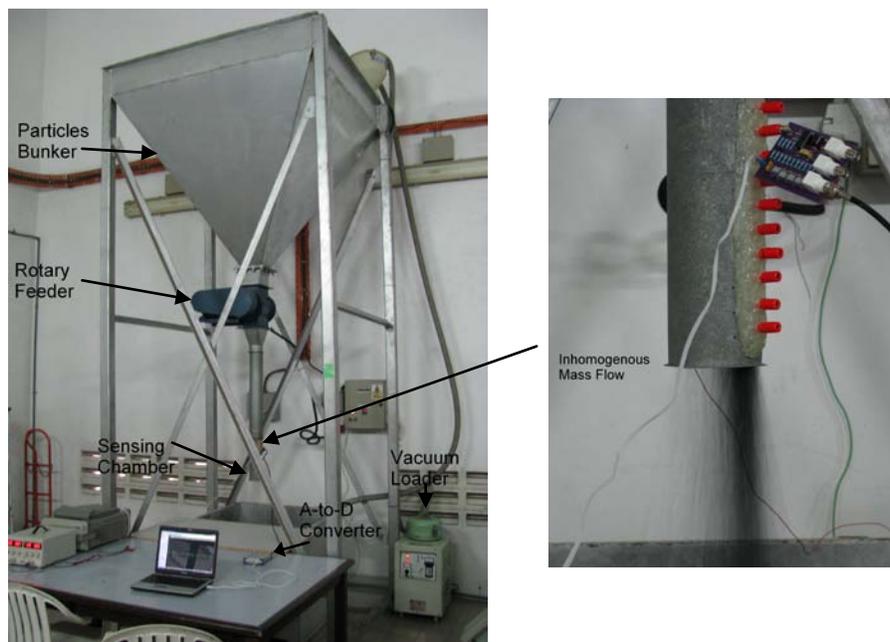
Figure 3. Flow metering test rig for data capturing

Plastic beads with material density of 950 kg/m^3 and median size of 3mm are used as test materials; particles fall with zero initial speed and pass the electrode with constant speed 4.3 m/sec. Pipe diameter is 3.75 inch, mass flow rate measurement varies between a range of 73.84 and 643g/sec and mass flow regime as it depicted in Figure 3 has an inhomogeneous flow profile. The operation of measurement system begins when electrical charges are detected by electrostatic sensor. Electrostatic sensor converts the detected signal to an AC voltage with the gain 500 and then this signal is sampled by 1 kHz sampling frequency using an A-to-D signal converter. And converted signal is applied in computer software to extract mass flow rate and concentration profile.

V.   MEASUREMENT PRINCIPLES

Amount of electrostatic charge on moving solid particles in a pipe affected mainly by variations in particles median size, velocity, mass flow rate and concentration. If two first factors are known parameters, mass flow rate and particles flow concentration could be obtained through the analysis of the variation in magnitude of detected electrostatic charge on particles. This method

is suitable especially in gravity flow rigs; however in pneumatic particle conveyors which particles size and velocity remain constant this method could be used as a most simple, cost effective and reliable method.

Using the appropriate transducer the physical signal from charge carried by particle can be converting to measureable signal such as voltage form. The magnitude of detected charge in transducer output can be represented as [10]:

$$V(t) = \alpha \sum q(t) \qquad (3)$$

Where q is amount of charge carried by moving particles, α is a constant and depend on amplification of sensor electronics and $V(t)$ is resulted voltage. The charging of the particles in the pipeline is result of random particles to particles collision and particles impact to the wall, so the resulted voltage $V(t)$ is a stochastic signal. Statically, with high probability the higher solid particles mass flow rate carry a higher amount of electrical charge in moving particles, which results in higher magnitude of resulted voltage $V(t)$. This phenomenon can be used as basis for particles mass flow rate and concentration measurement. A number of signal processing algorithms include autocorrelation, power spectrum analysis and wavelet transform could be applied to derive particles flow parameters information from acquired signal. In this study a simple time domain method presented by Zhang et al [10] that they applied it to derive particles size profile in their experiment is developed to derive mass flow rate information from detected electrostatic signal in this paper. From measured mass flow rate and other known parameters of particles flow, the concentration profile $\beta(t)$ can be given as follows [7]:

$$\beta_s(t) = \frac{M_s(t)}{\rho A V_s(t)} \qquad (4)$$

In equation 4, ρ and A are material density and cross section of pipe respectively and $V_s(t)$ is particles velocity in flow conveyor.

As it discussed, electrostatic signal is a random signal and random process can be described by its combination samples. $V(t)$ the output of sensor, is sampled as random discrete sequence $V(n)$, $(n = 0, 1, 2, ...)$ using a suitable sampling frequency. In this method in order to get mass flow rate information a parameter called *Mass Indicator* is introduced. Using empirical rule we divide the sequence $V(n)$, into two subsequences in a way that the first subsequence includes N_1 samples

fall in $(\bar{V} - k\sigma, \bar{V} + k\sigma)$ region and second subsequence includes N_2 samples fall beyond of first region. Where $\bar{V}$ and σ are average value and standard deviation of $V(n)$ respectively and k is a constant equal to 1.2 in this study. Following this, average power of first and second subsequence of $V(n)$, P_1 and P_2 are calculated as [10]:

$$P_1 = \frac{1}{N_1} \sum_{n1} V^2(n) \tag{5}$$

$$P_2 = \frac{1}{N_2} \sum_{n2} V^2(n) \tag{6}$$

The Mass Indicator (M) can be given as:

$$M = 10\log\frac{P_2}{P_1} \tag{7}$$

M is an independent value which is the ratio of P_2 and P_1 which derived from a signal generated by the same particles flow. The initial charge on particle is assumed to be negligible otherwise it can affect Mass Indicator (M). To reduction of the initial charge, the mass flow rig and the particles bunker must effectively earthed. M is a dimensionless variable that changes in a proportionality with magnitude of output voltage $V(t)$. Finding the relation between Mass indicator M and mass flow rate M_s and between Mass indicator M and concentration profile β for both pin and ring electrode will be the measurement procedure in this paper.

VI.   EXPERIMENTAL RESULTS

Using equation 7, M for a number of different mass flow rates is calculated and at the same time manual weighing of the particles is recorded to have the reference measurement. The reference measurement is used to compare real and measured mass flow rate data. To distinction, M_r is represents Mass Indicator using ring-shape electrode and M_p represents Mass Indicator using pin-shape electrode. Table 1 shows the M_r, M_p of mass flow rates obtained by manual weighing. To find the relation between mass flow rate and calculated M_r or M_p it is required to have an equation in a way that any M represent a measured mass flow rate with best fit approximation. In ten different mass flow rates M_r and M_p are calculated, the graphs in Figure 4 and Figure 6

indicate a logical relation between M_r, M_p and desired (manually) measured mass flow rates (plotted in blue spots).

Table 1. Mass Indicator of different mass flow rates using electrostatic sensor

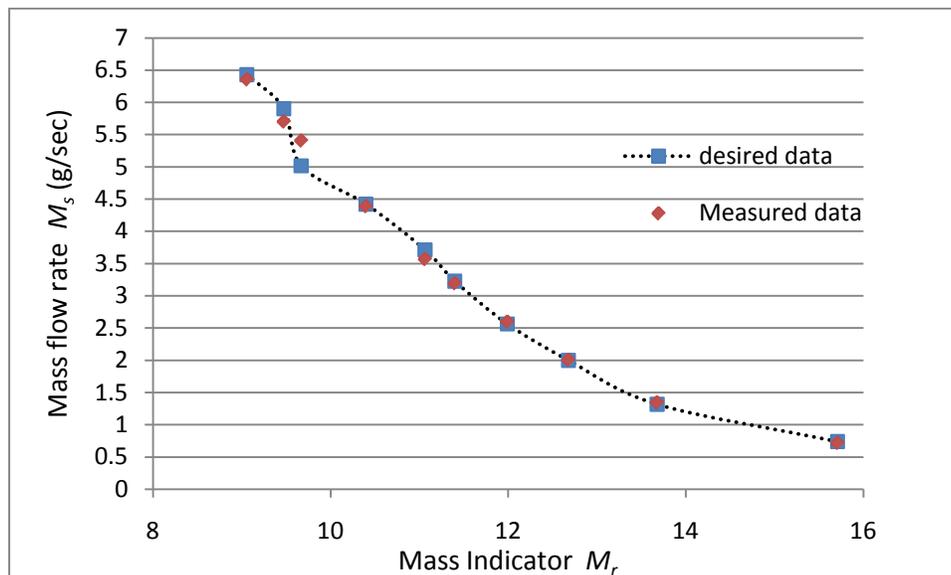| No.	Mass flow rate (g/sec)	M_r	M_p
1	73.84	15.7088	22.9028
2	131.7	13.6761	20.57
3	200	12.678	19.8067
4	256.4	11.9894	18.607
5	322.8	11.3972	17.9434
6	371.4	11.062	17.2623
7	442.1	10.3967	16.8372
8	501.6	9.6675	16.3435
9	590.3	9.4714	15.8938
10	643	9.0561	15.5923

Figure 4. Expected and measured mass flow rates using ring electrode

A regression analysis is applied to find the relation between M_r and mass flow rate (M_s) and the result equation is obtained as:

$$M_s = 0.17M_r^2 - 3.74M_r + 30.63 \qquad (8)$$

The calibration equation 8 gives mathematical relation between mass flow rate (M_s) and Mass Indicator (M_r). Using equation 8 and (M_r) from Table 1, the measured mass flow rate can be

determined; it denoted as measured data in Figure 4. As it discussed after measurement of mass flow rate, the concentration profile can be calculated using equation 4 while the velocity of particles flow is known. Figure 5 shows the relation between concentration profile β and Mass Indicator (M_r). The resulted mathematical relation between concentration profile β and Mass Indicator (M_r) is determined using regression analysis as follow:

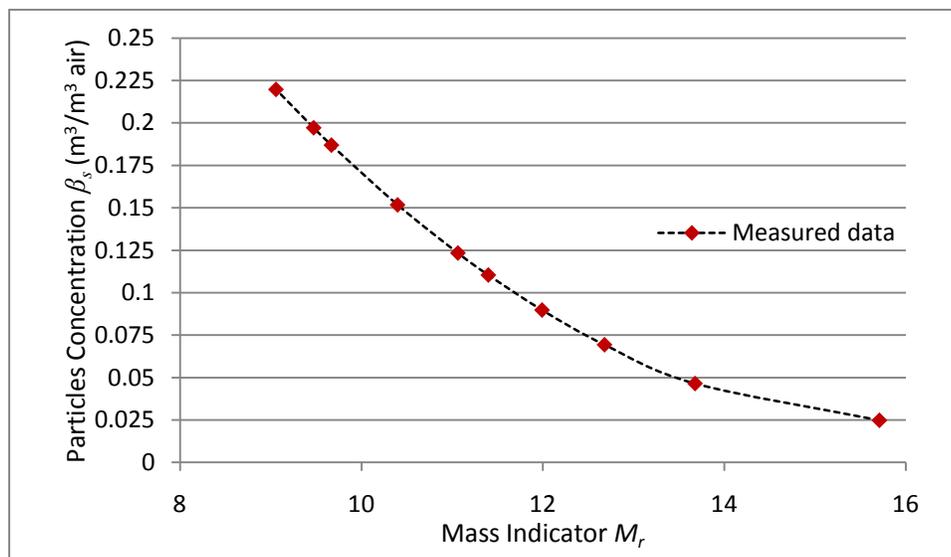$$\beta_s = 0.004M_r^2 - 0.13M_r + 1.06 \qquad (9)$$

Figure 5. Concentration profile using ring electrode

To measurement mass flow rate and concentration using pin electrode, the same procedure can be utilize to find the resulted equation between mass flow rate (M_s) and Mass Indicator (M_p) as follow:

$$M_s = 0.19M_p^2 - 4.92M_p + 56.6 \qquad (10)$$

Using equation 10 and (M_p) from Table 1, the measured mass flow rate can be determined; it denoted as measured data in Figure 6.

The relation between concentration profile β and Mass Indicator (M_p) is graphed in Figure 7. The resulted mathematical relation between concentration profile β and Mass Indicator (M_r) using regression analysis is given as:

$$\beta_s = 0.004M_p^2 - 0.17M_p + 1.96 \qquad (11)$$

Two electrostatic sensor electrodes provide M_s and β with two different equations, reveals that pin electrode and ring electrode have different sensitivity characteristics from each others. Ring-

shape electrode surround all around the moving particles so it detect higher power of electrostatic charge than pin-shape electrode and it results M_r is smaller than M_p. Furthermore detected charge by ring-shape electrode is independent value from type of mass flow regime, while further investigation shows pin electrode is susceptible to error during an inhomogeneous particles flow regime.
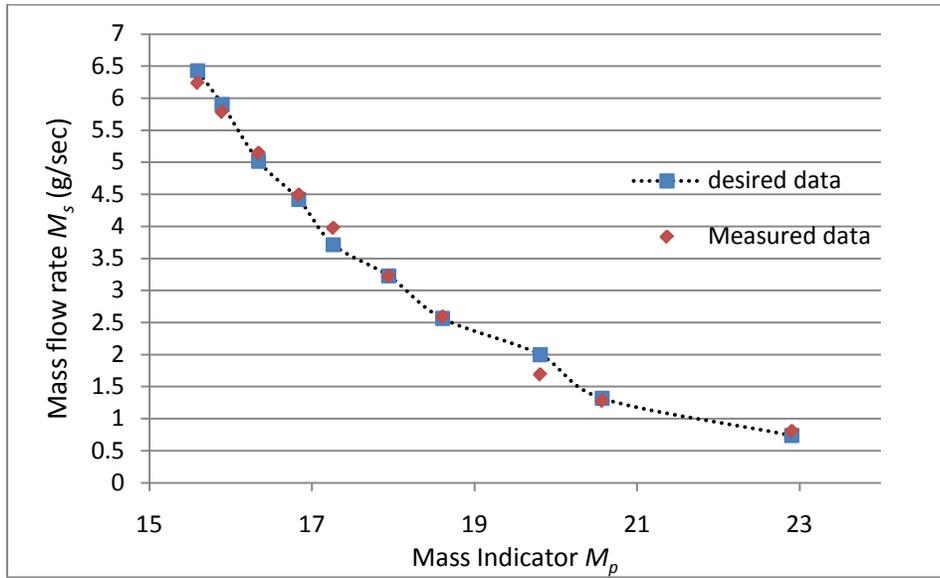
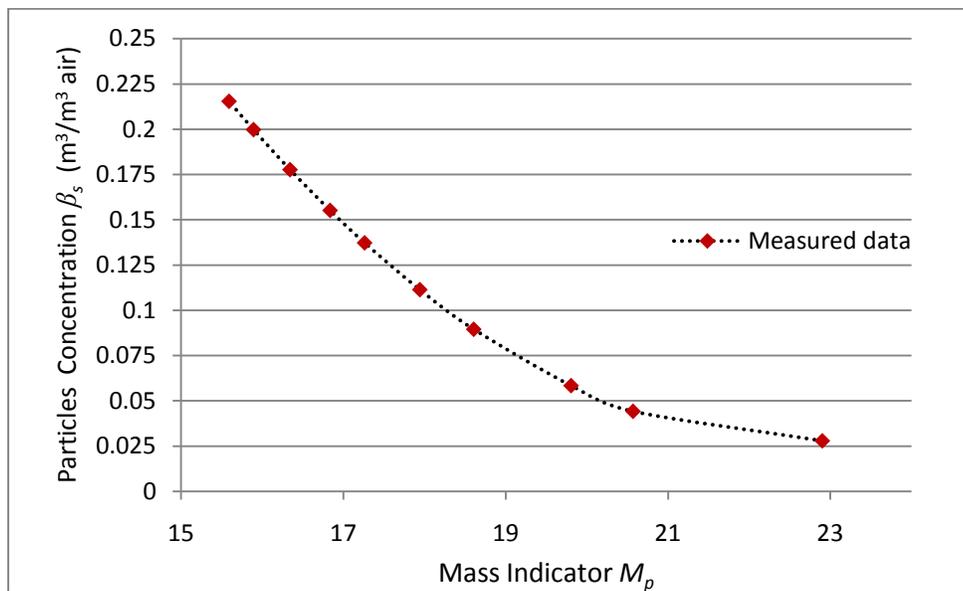Figure 6. Expected and measured mass flow rates using pin electrode

Figure 7. Concentration profile using pin electrode

The equations 8-11 need to be calibrated again if any parameter of the particles flow profile includes particles type, velocity and median size changes. A computer program is applied to derive M_s and β from calculated M_r and M_p. The comparison between measured mass flow rate from equations 8 and 10 and reference readings acquired by manual weighing shows 2.4% and 4.5% error using ring-shape and pin-shape electrodes respectively.

VII.   CONCLUSION

The presented method is based on passive electrostatic charge detection that uses two common electrostatic sensing electrodes to achieve solid particles mass flow rate and concentration profile. A developed simple time domain signal processing algorithm is applied to get information from acquired data. The method involves quite simple and cost effective instrument design but the technique is applicable when mass flow rate is the only variable in particles flow regime. In addition using two different electrodes in this experiment confirm the flexibility of applying this sensor in different installations. The initial charge on particles affects the output reading but this disadvantage could be declined effectively by connecting the particles bunker to the earth. Applying this technique didn't show the related error greater than ±5% .In sum up the advantages of the method are dominant than its drawbacks so it could be effectively applicable in industrial particles flow rigs.

REFERENCES

[1]   Barratt, I. R.; Yan, Y.; Byrne, B.; Bradley, M. S. A., "Mass flow measurement of pneumatically conveyed solids using radiometric sensors," *Flow Measurement and Instrumentation,* vol. 11, pp. 223-235, 2000.

[2]   Xu, L.; Cater, R, M.; Yan, Y., "Mass flow measurement of fine particles in a pneumatic suspension using electrostatic sensing and neural network technique," *IMTC 2005- Instrumentation and Measurement,* vol. 1, pp. 17-19, 2005.

[3]   Beck, M.S.; Green, R. G.; Thorn, R., "Non-Intrusive measurement of solids mass flow in pneumatic conveying," *J. Phys. E: Sci. Insrtum,* vol. 20, pp. 835-840, 1987.

[4]   Green, R. G.; Rahmat, M. F.; Evans, K.; Goude, A.;Henry, M.; Stone, J. A. R., "Concentration profiles of dry powders in a gravity conveyor using an electrodynamic tomography system," *Meas. Sci. Technol,* vol. 8, pp. 192-197, 1997.

[5]   Isa, M.D.; Rahmat, M. F.; Jusoff, K.; Hussin, T. A. R., "Validation process for electrical charge tomography system using digital image technique," *Applied Physics Research,* vol. 1, pp. 11-18, 2009.

[6]   Rahmat, M. F.; Sabit, H. A. , "Flow regime identification using neural network based electrodynamic tomography system," *Jurnal Teknologi,* pp. 109-118, 2004.

[7]   Yan, Y., "Mass flow measurement of bulk solids in pneumatic pipelines," *Measurement Science and Technology,* vol. 7, pp. 1687-1706, 1996.

[8]   Rahmat, M.F.; Kamaruddin,N.S., "An electrodynamic sensor for electrostatic charge measurement," *International Journal on Smart Sensing and Intelligent Systems,* vol. 2, pp. 200-212, 2009.

[9]   Rahmat, M. F.; Kamaruddin, N. S.; Isa, M. D., "Flow regime identification in pneumatic conveyor using electrodynamic transducer and fuzzy logic method," *International Journal on Smart Sensing and Intelligent Systems,* vol. 2, pp. 396-416, 2009.

[10]   Zhang, J. Q.; Yan, Y., "On-line continuous measurement of particle size using electrostatic sensor," *Powder Technology,* pp. 164-168, 2003.