FLOW REGIME IDENTIFICATION IN PNEUMATIC CONVEYOR USING ELECTRODYNAMIC TRANSDUCER AND FUZZY LOGIC METHOD

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Abstract- Electrodynamic sensor, which can also be called as tribo-electric sensor, senses the electrostatic charge carried by the particle. The tomography system using electrodynamic sensor is called as tribo-electric tomography system. Source of the signal induced on the electrodynamic sensor is brought by the object to be measured and no excitation circuit is necessary. Measuring concentration distribution of the solid particles is essential because it contains useful information about potential problems and further more improve efficiency in the manufacturing or chemical processes. This study proposes to use electrodynamic transducer to measure electrical charge within pneumatic pipeline and utilize the fuzzy logic technique to identify the pattern of flow regimes through pneumatic pipeline. Promising results are obtained through experimental studies.

Index terms: Pneumatic conveyor, electrical charge, image reconstruction, concentration profile, fuzzy logic, flow regimes.

I. INTRODUCTION

Mass flow measurement of particulate solids in pneumatic pipeline plays a significant role to achieve improved product quality, process efficiency and increased productivity. These requirements can be accomplished by installing suitable measurement system. The electrostatic sensing approach has created a main attention in the flow measurement society in recent years. An electrodynamic transducer or electrostatic transducer or also known as electrical charge tomography offers inexpensive and simplest means to measure flow whilst data collected from this method can provide information to determine crucial parameters such as mass flow rate and volumetric flow velocity within multiphase flows and processes. Electrodynamic transducer or electrical charge tomography has been studied and reported within past few decades by many researchers. Among new researchers who also investigate the used of electrodynamic transducer in terms of hardware, software systems and algorithms were Ma et al [1], Rahmat et al [2], Yan et al [3], Xu et al [4] and many more. Green et al [5] developed an electrodynamic tomography system by utilizing upstream and downstream arrays of sensors to measure concentration profiles and velocity profiles of particles at gravity conveyor. In order to construct tomogram images of solid particles flow they applied linear back projection (LBP) and filter back projection (FBP) methods. Combination between concentration profiles and velocity profiles they successfully determined mass flow rate through the measurement section. Yan et al [6] carried out experimental studies on pneumatic conveyor circulating pulverized coal and cement using an electrodynamic sensor and a radiometric densitometer. Investigations were carried out to quantify the accumulated solids and to identify the relationship between the deposition and plant operational parameter including solids type, particle size, mass flow rate and conveying air velocity. Machida et al [7] applied two methods images reconstruction algorithms namely back projection (BP) method and least-squares method to electrodynamic tomography system. The reconstructed images were compared with original image. The results show that BP method is accurate in detecting the position of the electrostatic charge and is capable of detecting the size of the object but disadvantage of this method is it could not distinguish two charges at separate points in the sensing zone. On the other hand the least-squares method able to differentiate two point of charges but the reconstructed images were poor quality due to the large pixel size. Finally, by combining these two methods images reconstructed produced better results. Xu et al

[8] proposed a method to measure the mean velocity of solid particles based on spatial filtering effect of the electrostatic sensor. They successfully derived a general formula by analyzing quantitatively the spatial filtering characteristic of the electrostatic sensor along with the accepted assumptions in order to determine the relationship between the spatial frequency characteristics of the sensor and solid particle velocity. Experiment was performed on the bench-scale gravity-fed particle flow experimental rig to test the performance of the velocity measurement system. The off-line experimental results show that the repeatability is within ±5% over the velocity range of 2-6ms^{-1} for concentrations of solid particles in the range of 0.5-0.6%.

This paper describes the basic principle of electrodynamic sensor and investigates the use of electrodynamic sensor to determine particles concentration measurement within cross-sections through a process namely pneumatic conveyor. Nevertheless baffles of different shapes are slot in to the pipeline to form different flow regimes hence fuzzy logic method has been used to identify each type of these flow regimes furthermore produced improve concentration profiles.

II. THE ELECTRODYNAMIC SENSOR

a. Response on a moving particle

The movement of solid particles in pneumatic pipeline generates a certain amount of electrostatic charge. This expected phenomenon in most dry particulate system referred as the electrification of particles, emerged due to continuous and frequent collision and friction between the solid materials being transported and the walls of conveying pipes, impact between particles and friction between particles and air stream with charge densities in the range 10^{-7}-10^{-3} C kg^{-1} [9]. The present of charges carried by particles can be detected by electrodynamic sensor. Sequentially to examine the interaction between the charged particles and the sensor, mathematical modeling is essential.

The approximate mathematical model for electrodynamic transducer is derived and discussed comprehensively by Yan et al [3]. Yan et al [3] point out that the physical geometry of the electrode should be included in the modeling therefore more realistic model is developed by assuming the electrode perfectly conductive ring with its outer surface earthed, existing in the electrostatic field of a point charge +q. On top of that the axial length (W) and diameter of the electrode (D) are considered, nevertheless the radial thickness is ignored. Several assumptions are made to model the sensor. Firstly it is assumed that the vertically downwards movement of a single particle, p is carrying a charge, q with a constant velocity, V. Secondly, this particle travels along a path which is perpendicular to the vertical axis of the electrode [11].

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

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

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 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 induce charge q' and current from the sensor have been plotted using a prominent numerical analysis software called Matlab as illustrate graphically in figures 1 and 2 respectively. These figures are for D= 88mm, q= 10 Coulomb, x=65mm, W=10mm, and V=2.5ms^{-1}. Figures 1 and 2 show typical curves for induce charge q' and current output of the sensor.

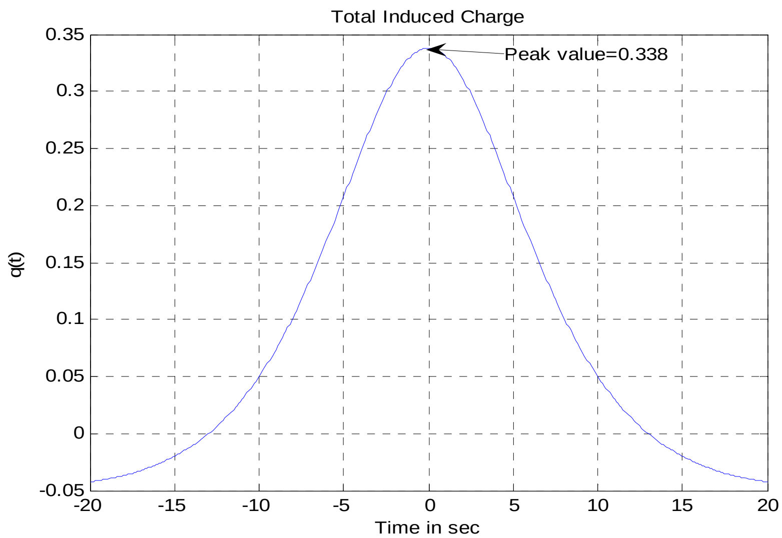

Figure 1. A typical curve of induced charge for electrodynamic sensor

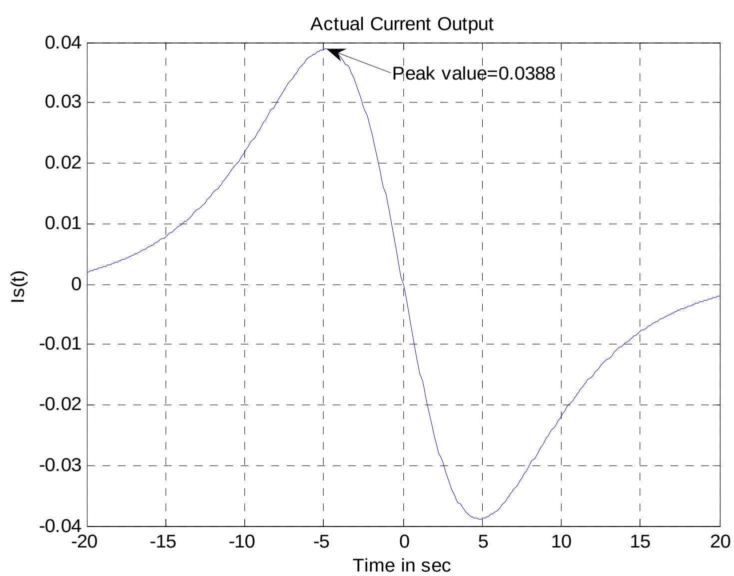

Figure 2. A typical curve of current for electrodynamic sensor

b. Sensor design

Fundamentally electrodynamic sensor is charge to voltage converter which the principle is based on the concept of Coulomb's theory of charge as stated in equation 4.

$$Q = CV \tag{4}$$

Where Q is the quantity of charge in coulombs, C is a capacitance in farads and V is voltage in volts. An electrodynamic transducer composed of two basic elements namely the electrode and the associated electronic circuit which act as sensing device and signal conditioning circuit respectively. The electrode is a metal conductor which is electrically insulated from the metallic conveyor and forms a capacitance to earth. The signal conditioning circuit has several stages such a non inverting voltage follower, a precision rectifier and a low pass filter. Figure 3 shows a block diagram of electrodynamic transducer.

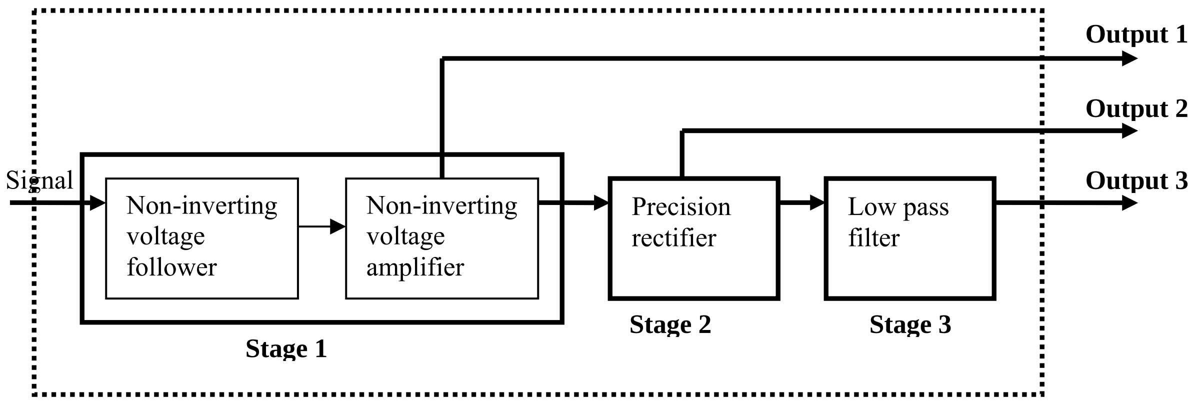

Figure 3. A block diagram of electrodynamic transducer

At stage 1, a capacitor is placed between input and ground consecutively to made measurement similar with capacitance formed from the electrode so that the capacitance has an approximate value of 5.5 to 5.7 pF. Charge, Q is induced in the electrode due to the movement of charging particles whilst resulting voltage V_i. The input resistor provides a path current to flow into and out of the capacitance is connected between electrode and ground. The current flows through the input resistor generate voltage simultaneously supply the input to the integrated circuit amplifier TL084N (IC1) which acts as non-inverting voltage follower. The output of this follower is used as a guard voltage for the input which functioned to minimize stray capacitance of the input circuitry, besides it is ac coupled to the input of non-inverting voltage amplifier (IC2). The output of this stage is called output 1 which is suitable for cross correlation measurement and acts as an input to the next stage.

The second stage is precision rectifier comprise of two operational amplifiers (IC3 and IC4) that ac coupled to the previous amplifier. The function of this ac coupling is to remove any long term drift in amplifier IC2. The rectifier provides the nominal gain of 1. The output of this stage is rectified voltage and known as output 2 which can be used for spatial filtering test. The spatial filtering effect is defined as the relationship between sensor size and the frequency bandwidth of the transducer determined from the frequency response obtained during a pulse which corresponds to a detectable particle. The output 2 is directly coupled input to IC5 at next stage.
At stage 3, amplifier IC5 is low pass filter circuit has an upper cut off frequency of 0.167 Hz which provides smoothing for the prior stage. Output of this stage is averaged output namely output 3. A constructed circuit of an electrodynamic transducer is show in figure 4.

Figure 4. A constructed circuit of electrodynamic transducer

III. MEASUREMENT SYSTEM OF ELECTRODYNAMIC TRANSDUCER

The experimental set-up in the present study is shown in figure 5. The gravity test flow rig has been used to facilitate the measurement of concentration profiles of the solid particles in a vertical pneumatic conveying pipeline. An array of 16 electrodynamic transducers mounted around circumference of pneumatic pipeline. An automatic vacuum loader is used to convey solid materials from storage tank to the hopper through a material feed vane. The distance between the feeder and the transducer is 1.4m. The conveyed solid materials are plastic beads where each has mean size of 3mm. The plastic beads fed down from the hopper into pipeline passing through measurement section. These plastic beads accelerate under the force of gravity. The flow rate of the solid material is controlled by the rotary valve and its speed rotation is set by the control unit

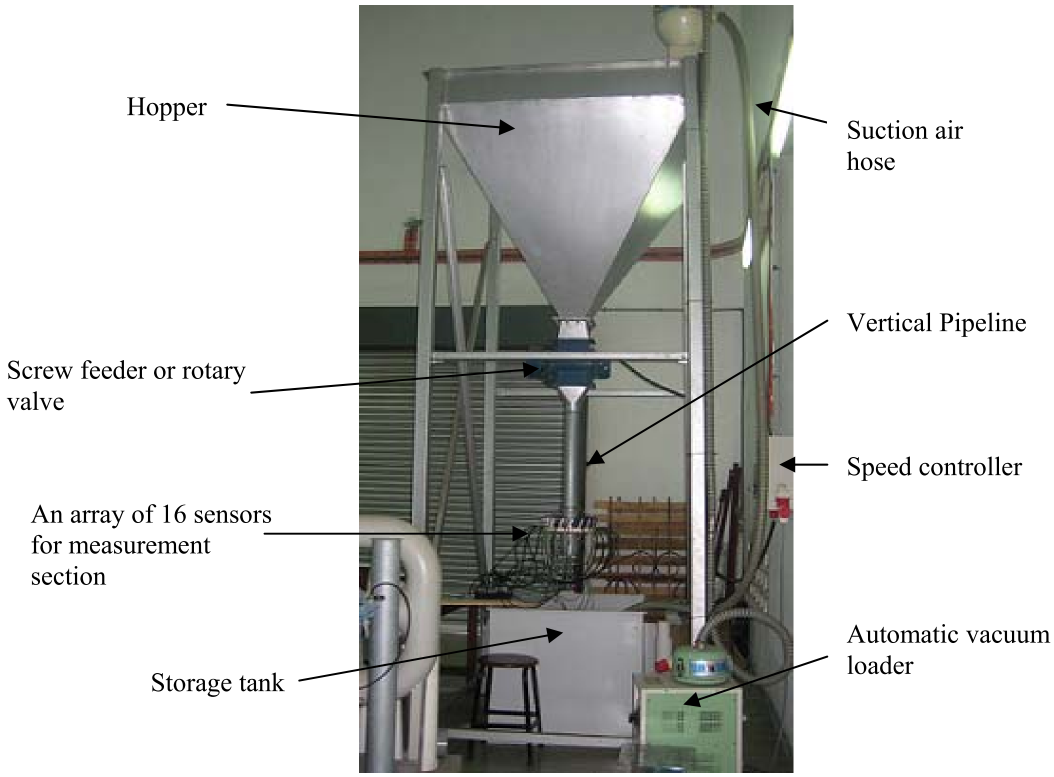

Figure 5. Measurement system of gravity flow rig

The data received from an array of 16 transducers is captured by data acquisition card Keithley KUSB-3116 and stored for image reconstruction process. This data acquisition card functions as an interface between the sensors and the computer. The responses of output 1 and output 2 from the sensor are then plotted and shown in figure 6 and 7 respectively.

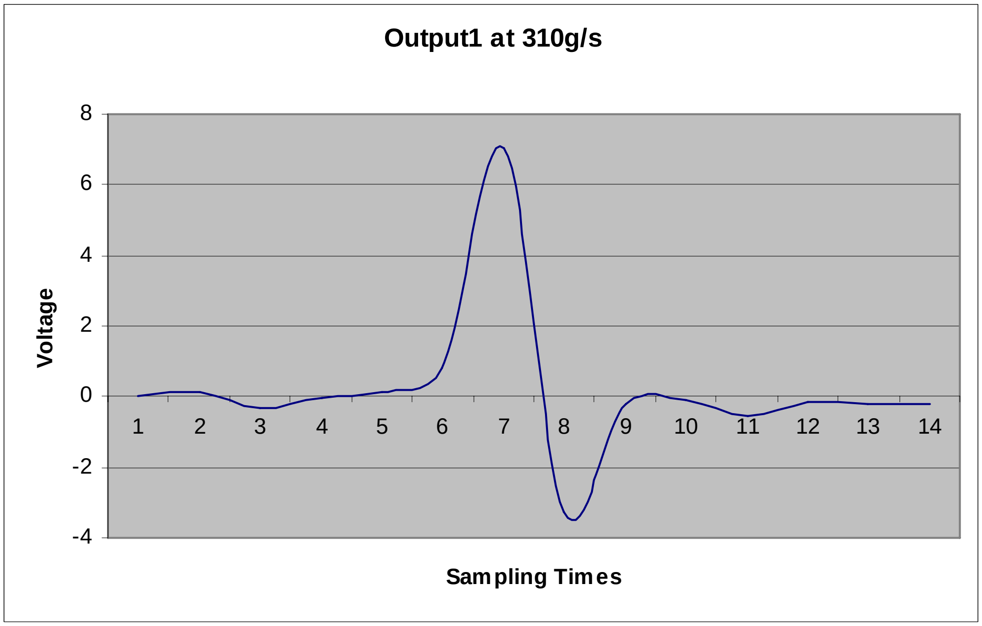

Figure 6. Response of output 1 from electrodynamic transducer

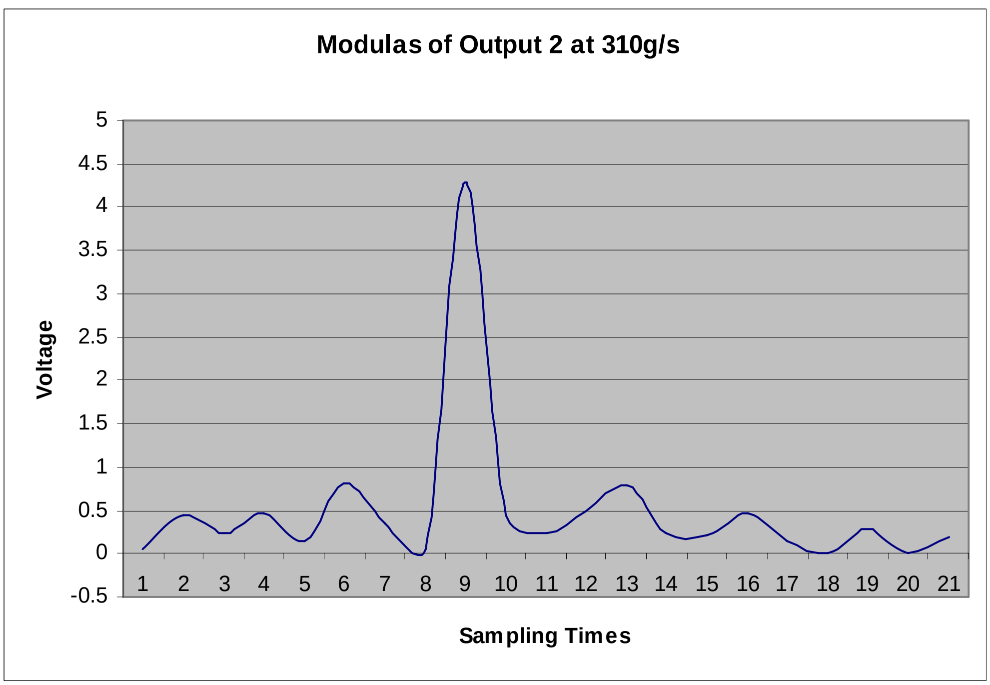

Figure 7. Response of output 2 from electrodynamic transducer

Figure 8 also shows the responses of output 1 and 2 from the sensor which captured through digital storage oscilloscope Tektronix (Model TDS 2024B) for authentication purpose.

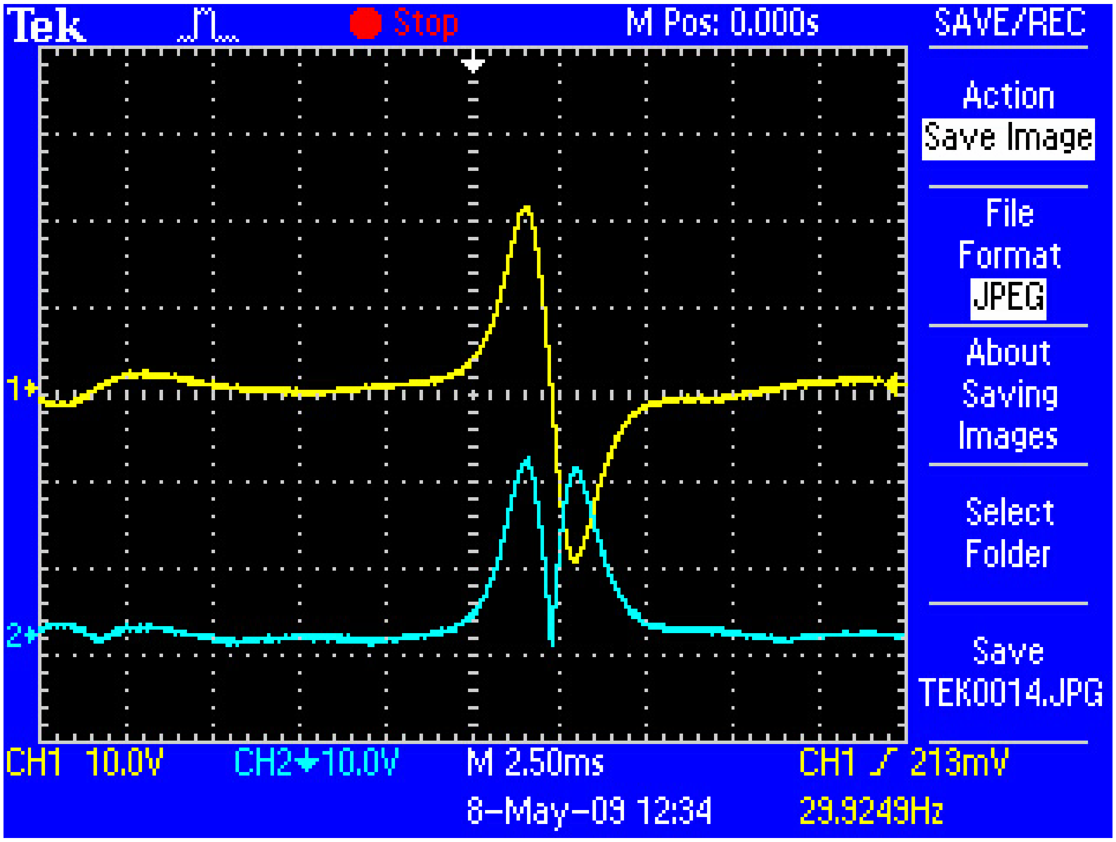

Figure 8. Response of outputs 1 and 2 from electrodynamic transducer

IV. IMAGE RECONSTRUCTION

The main objective of image reconstruction is to attain a better image by exploiting the measured output sensor with a suitable algorithm. In this work, Linear Back Projection (LBP) and Filter Back Projection (FBP) algorithms have been used to obtain concentration profile. Firstly, forward problem should be solved in order to obtain theoretical output of each sensor by assuming charges of σ coulombs per square meter are uniformly distributed on the sensing area [10]. The cross sectional area of pipe is mapped onto 11 x 11 rectangular array consisting of 121 pixel as shown in figure 9.

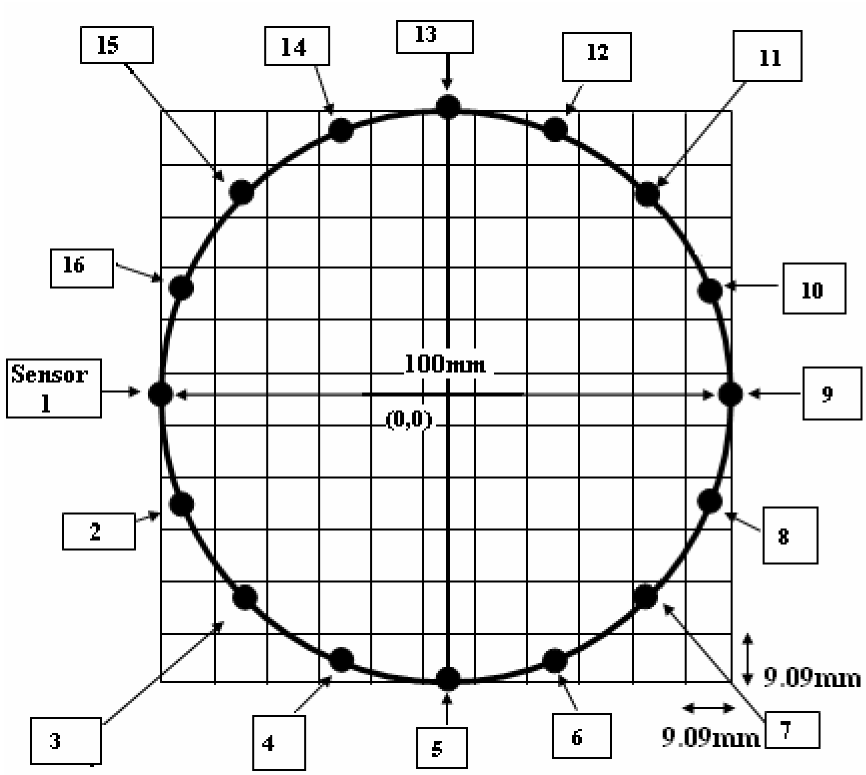

Figure 9. Sensor arrangement for 11x11 rectangular array maps on cross section pipe

The sensitivity of each sensor is generated by calculating the charge that the chosen pixel will induce into sensor using equation 5 where the centre of pipe has rectangular coordinate of (0,0) with pipe diameter 100mm and each pixel has dimension of 9.09mm x 9.09mm.

$$S = \iint \frac{C}{r^2} dA = \int_x dx \int_y \frac{C}{x^2 + \left(50.5 - y^2\right)} dy \tag{5}$$

Where r is point charge to sensor distance, A is pipe cross sectional area.
The total induced charge of sensor can be calculated using equation 6 if C is assumed to be 1cm^{-1}.

$$S1 = \int_{-50.5}^{50.5} dx \int_{-\sqrt{\left(50.5^2 - x^2\right)}}^{\sqrt{\left(50.5^2 - x^2\right)}} \frac{1}{x^2 + \left(50.5 - y^2\right)} dy \tag{6}$$

With this method, the sensitivity map of each sensor is calculated and data reading from each sensor is to be multiplied by its sensitivity map to provide 16 matrices of size 11x11. The corresponding individual elements from the 16 matrices are summed to produce LBP projection concentration profile. While for theoretical LBP concentration profiles it can be obtained by assuming each sensor read is 1V. However result obtained from the theoretical LBP concentration profile shows that LBP has low estimation of solids at the centre of conveyor due to non linear sensing mechanism of electrodynamic transducer. Consequently to overcome LBP limitation the filter back projection algorithm is established. Filter mask is generated by taking the highest pixel value of LBP concentration profile and dividing it by each pixels value within pipe mapping. However this filter mask is only applicable for full flow regime thus different filter mask must be calculated for different flow regimes. Prior applying these filter mask, information on different flow regimes must be identified.

V. IDENTIFICATION OF FLOW REGIMES USING FUZZY LOGIC

The efficiency of process is closely related to accurate measurement and control of hydrodynamic parameters such as flow regime, flow rate, etc. Measurement of flow regime will be beneficial to modification or improvement of the operational strategies resulting in increased process efficiency, production and hence, profits. In this work four type of flow regimes namely full flow, three quarter flow, half flow and quarter flow are created by placing various baffles shape in the path of the incoming plastic beads inside the pipeline. The problem of identification different type of flow regime is solved by employing fuzzy logic technique. Fuzzy logic is based on natural language. The advantages of fuzzy logic are allowing the use of expert knowledge as linguistic statement such as “if” which enable to search for optimal solution.

In general, in designing a fuzzy model application there are several steps to follow as stated below.

(1) Identify the input and output variables by considering convenience linguistic subsets such as very high, high, medium, low, very low, big, very big, small, very small, etc.
(2) Formation of fuzzy rules based on the expert knowledge or experience and/or on the available theory. The rules relate the combined linguistic subsets of input variable to the convenience linguistic output subset. Fuzzy rule includes statement “IF-THEN”.
(3) Define fuzzy inference system. It is necessary to defuzzify the output set for arriving to a crisp value that will be required by the final user.
(4) Evaluate the system

Matlab's Fuzzy Logic Toolbox has been used in solving problem of flow regime identification since it's capability to provides a number of interactive tool that allow accessing many of the functions through a graphical user interface (GUI).

Based on the result of experiment conducted previously two input and four output variables amongst membership functions for each feature have been defined. The output voltage of the sensor and angle of the sensor were chosen as input variables whilst the four types of flow regimes were chosen as output variables. There are two membership functions for the voltage and four for sensor angle. Membership functions used for the input and output are trapezoidal membership function as stated in equation 7.

$$\Pi\ (u;\alpha,\beta,\gamma,\delta)= \begin{cases} 0 & \text{For } u<\alpha \\ \dfrac{(u-\alpha)}{(\beta-\alpha)} & \text{For } \alpha\le u<\beta \\ 1 & \text{For } \beta\le u\le\gamma \\ \dfrac{(\delta-u)}{(\delta-\lambda)} & \text{For } \gamma<u\le\delta \\ 0 & \text{For } u>\delta \end{cases} \qquad (7)$$

Figure 10 show the structure of fuzzy control as shown in Matlab's Fuzzy Inference System (FIS) Editor.

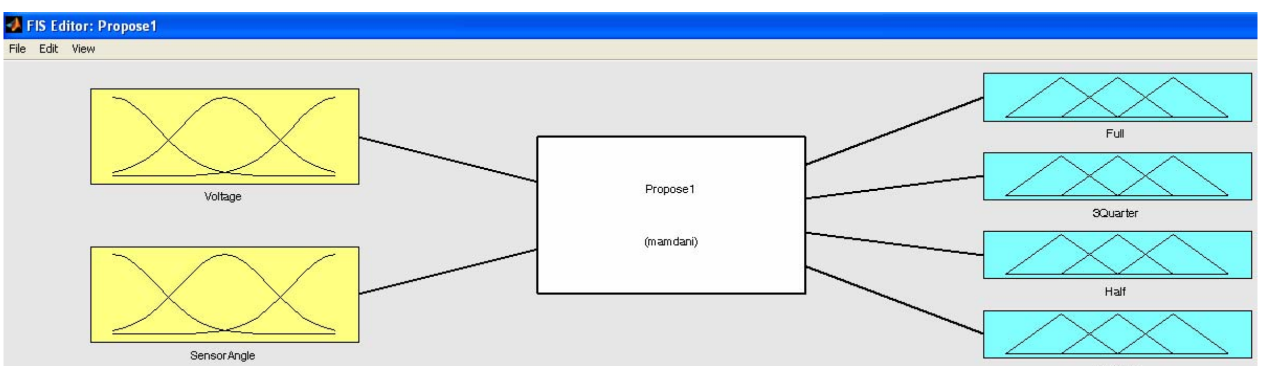

Figure 10. Structure of fuzzy controller

After the features are extracted, the identification process which involved the fuzzy rules and inference process can be applied. For the problem presented in this paper, a set of suitable linguistic information could be organized by identifying a set of directive codifying suitable resolution strategies as a function of typical identification requirement. This task can be solved by defining a knowledge base structured on a set of fuzzy rules that codify the heuristic resolution methodology defined by the following example set of linguistic directives:

Quarter flow regime is recognized only when:

- The output voltage is sufficiently high
- The summation angle of sensor location is 90^o

Using these linguistic directives based on the experimental results makes it easy to obtain set of fuzzy rules. Rules for flow regimes identification procedure in verbose format as follows:

If (Voltage is High) and (SensorAngle is A1) then (Full is null)(3Quarter is null)(Half is null)(Quarter is Quarter)(1)

If (Voltage is High) and (SensorAngle is A2) then (Full is null)(3Quarter is null)(Half is Half)(Quarter is null)(1)

If (Voltage is High) and (SensorAngle is A3) then (Full is null)(3Quarter is 3Quarter)(Half is null)(Quarter is null)(1)

If (Voltage is High) and (SensorAngle is A4) then (Full is Full)(3Quarter is null)(Half is null)(Quarter is null)(1)

If (Voltage is Low) and (SensorAngle is A1) then (Full is null)(3Quarter is null)(Half is null)(Quarter is null)(1)

At this point the fuzzy inference system has been completely defined, in that the variables, membership functions and the rules necessary to calculate classes are in place. The fuzzy logic controller for classifier is based on Mamdani fuzzy classifier with the following parameters.

- And method: min
- Or method: max
- Implication: min
- Aggregation: max
- Defuzzification: centroid

A simulation was developed with the use of Simulink sequentially to review the effectiveness of the designed controller whilst the performance of the system can be justified. Figure 11 show the Simulink block diagram for identification of flow regimes.

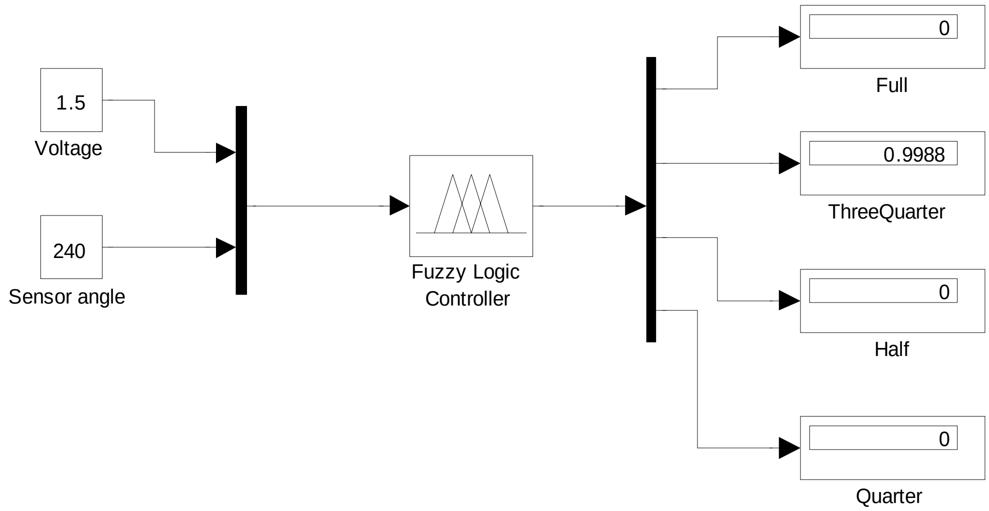

Figure 11. Simulink block diagram

VI. RESULTS AND DISCUSSION

a. Flow regimes

The output of electrodynamic sensors consists of several data regarding the information related with the flow regimes or flow patterns and the flow rate of the particles. Figures 12, 13 and 14 show the output of electrodynamic sensors for different type of flow regimes and also the dataset were taken at three different flow rates.

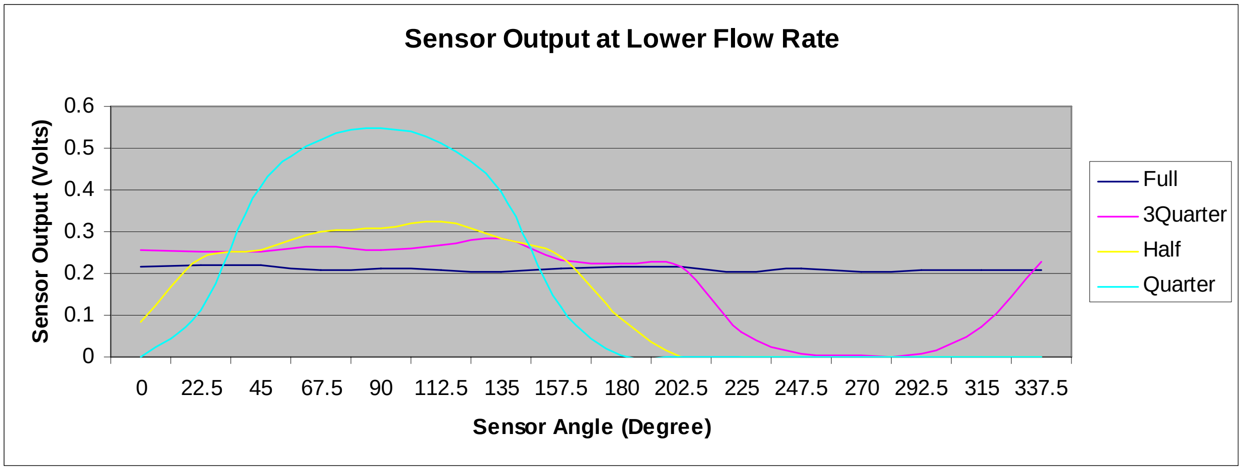

Figure 12. Sample of sensor output at lower flow rate

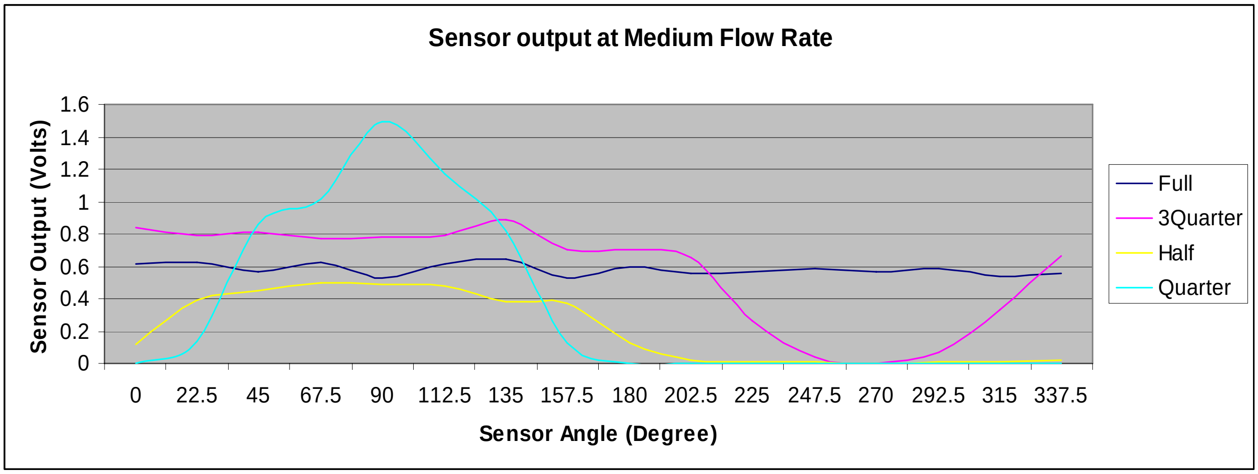

Figure 13. Sample of sensor output at medium flow rate

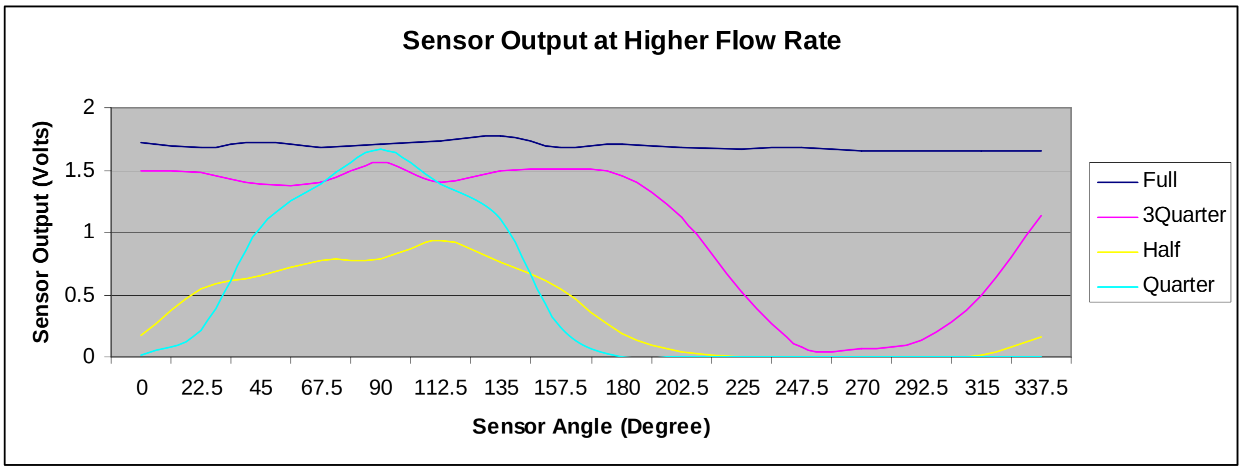

Figure 14. Sample of sensor output at higher flow rate

It is clearly shown from figures 12 to 14 that the patterns are almost consistent for each type of flow regime no matter what the flow rate of particles could be. From these set of data we can deduce that the identification process can be accomplished without considered the flow rate of particles. A series of ten set of data for each flow regimes are used to evaluate the performance of fuzzy logic technique in identifying different types of flow regimes. Table 1 shows the success of fuzzy logic technique in identifying the different types of flow regimes.

Table 1: Successful identification of flow regimes

No	Types of flow regime	Data test	Accomplish	Correct identification %
1	Full	10	10	100
2	Three quarter	10	10	100
3	Half	10	10	100
4	Quarter	10	10	100

b. Concentration profile

The concentration profiles of plastic beads at various flow regimes were obtained from the average output of electrodynamic transducers. Concentration profiles for both linear back projection (LBP) and filter back projection (FBP) are developed using Matlab program. Figures 15, 16, 17 and 18 show the concentration profiles for full flow, three quarter flow, half flow and quarter flow with the used of LBP and FBP at flow rate 210g/s respectively.

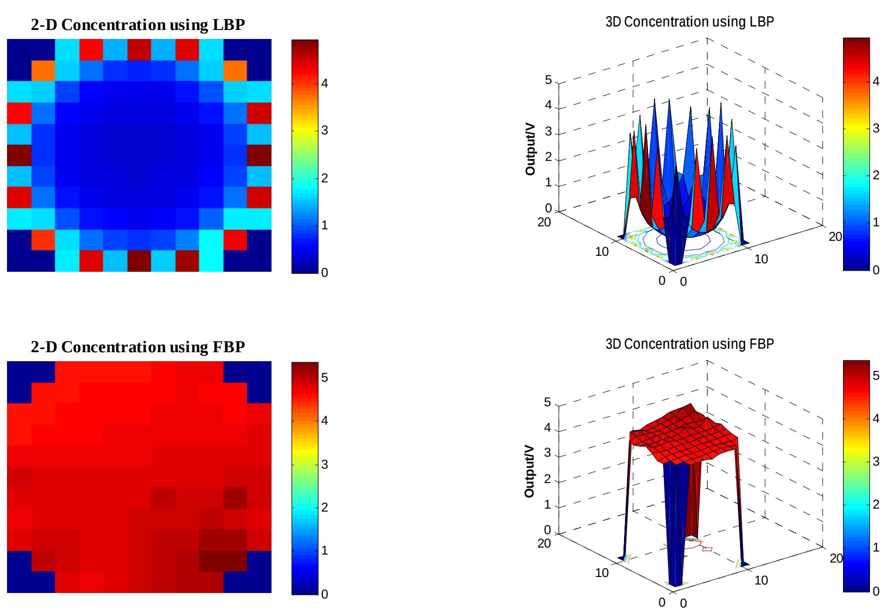

Figure 15. Concentration profile for full flow using LBP and FBP

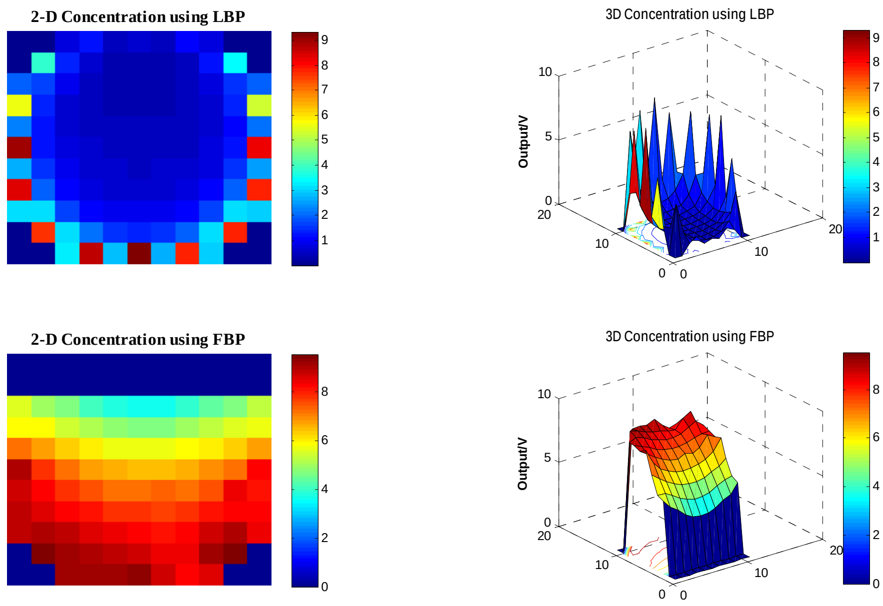

Figure 16. Concentration profile for three quarter flow using LBP and FBP

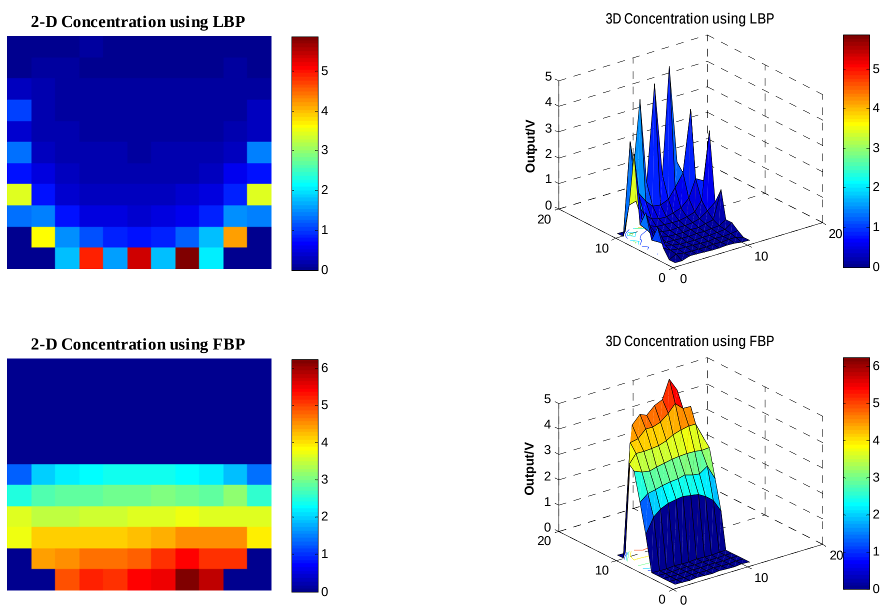

Figure 17. Concentration profile for half flow using LBP and FBP

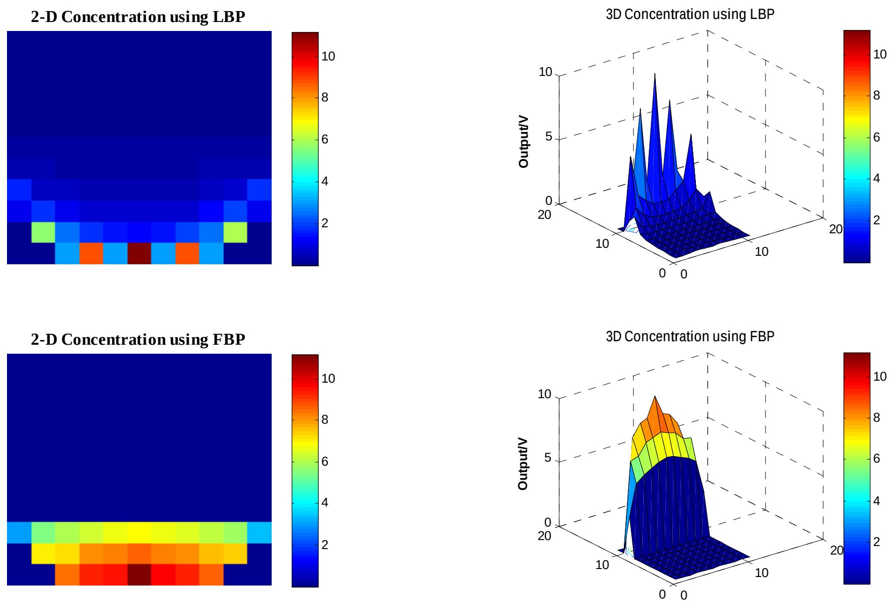

Figure 18. Concentration profile for quarter flow using LBP and FBP

The concentration profiles of figures 15 to 18 show the distribution of plastic bead particles at a cross-section of the pipe conveyor. By looking at the tomographic images plotted based on LBP algorithm it is clearly shows that the images have low estimation of solid concentration at the center of image while on the other hand for the those images plotted using FBP algorithm there were no lower concentration exist at the centre of images which make the images look very similar with the actual situation at the pipeline.

VII. CONCLUSIONS

In this paper the feasibility of using fuzzy logic method for the identification of four different types of flow regimes based on measurement made by electrodynamic transducer were examined. Experiment were performed in a metal vertical column 100mm in inner diameter and 1.4m tall, with flow of mixed between air and plastic beads diameter of 3mm each. At test section wall, an array of 16 electrodynamic transducers escalated around the column and the data were captured at the rate of 1 kHz. A total of 40 data records covering full, three quarter, half and quarter flow regimes were obtained.

The designed electrodynamic transducer is capable of giving measurements on the concentration profiles of moving solid particles in the pipe. The designed fuzzy logic controller to identify four different types of flow pattern is worked very well. It was concluded that fuzzy logic technique is one of the precise tool for solving identification problems. It was proved after success in identifying the four different types of flow regimes using fuzzy logic technique the more accurate concentration profile of solid particles were obtained with applying the filter back projection algorithm.

REFERENCES

[1] J.Ma and Y.Yan, "Design and evaluation of electrostatic sensors for the measurement of velocity of pneumatically conveyed solids", Flow Meas. Instrum. 11, 2000, pp. 195-204.

[2] M.F.Rahmat and H.A.Sabit, "Application of neural network technique and electrodynamic sensors in identification of solid flow regimes", Jurnal Teknologi 46(D), June 2007, pp. 77-92.

[3] Y.Yan, B.Byrne, S.Woodhead, and J.Coulthard, "Velocity measurement of pneumatically conveyed solids using electrodynamic sensors", Meas. Sci. Technol Journal. 6, 1995, pp. 515-537.

[4] C.L.Xu and S.M.Wang, "Solid particle velocity measurement based on spatial filtering effect of electrodynamic sensor", Chin. J. Chem. Ind. Eng. 58, 2007, pp. 67-74.

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

[6] Y.Yan, and B.Byrne, "Measurement of solids deposition in pneumatic conveying", Powder Technology Journal. 9, 1997, pp. 131-139.

[7] M.Machida, and B.Scarlett, "Process tomography system by electrostatic charge carried by particles", IEEE Sensor Journal, Vol. 5 No. 2, April 2005, pp. 251-259.

[8] C.Xu, B.Zhou, D.Yang, G.Tang, and S.Wang, "Velocity measurement of pneumatically conveyed solid particles using an electrostatic sensor", Meas. Sci. Technol. Journal.19, 2008 24005.1-24005.9.

[9] J.A.Cross, "Electrodynamics Principles, Problems and Applications", Bristol: Adam Hilger, 1987.

[10] R.G.Green, M.F.Rahmat, K.Dutton, K.Evan, A.Goude, and M.Henry,"Velocity and mass flow rate profiles of dry powder in a gravity drop conveyor using electrodynamic tomography system", Meas. Sci. Technol Journal. 8, 1997, pp. 429-436.

[11] M.F Rahmat and N.S Kamarudin, An electrodynamic sensor for electrostatic charge measurement, International Journal on Smart Sensing and Intelligent System, Vol. 2 No. 2 June 2009, page 200-212