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REAL TIME TOMOGRAPHIC IMAGING USING AN ARRAY OF ELECTRODYNAMIC SENSOR

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Abstract. The main purpose of this paper is to investigate the feasibility of developing a computer program for real time generation of concentration profiles of a pipe in process tomography. The main feature of the computer program is to interface between tomographic measurement system and computer using Data Acquisition System. An array of 16 electrodynamic sensor have been used in this process tomography. The sensitivity maps for the individual sensor are generated in the forward problem. In the inverse problem, the concentration profile will be calculated from measured sensor values by basic back-projection algorithm. Then the major limitation of the basic back-projection algorithm will be solved by filtered back-projection algorithm. The Visual Basic programming language is used to develop the computer program. The program is able to do on-line monitoring of concentration profile. Besides that, the program also displays the measured sensor values and bar graph of the normalised sensor values.

1.0 INTRODUCTION

The word tomography derives from Greek *tomes* section. Tomography is an interdisciplinary field concerned with obtaining cross-sectional images of three-dimensional objects. Process tomography can be defined as a process of obtaining plane section images through an object [1]. Its feature ability to unravel the complexities of a structure without the need to invade the object, makes the tomography system widely used in medical field. The development of medical tomography has led to the widespread utilisation of body scanner in medical field, such as computed tomography (CT), also known as CT scans, developed in the early 1970s. This imaging method X-rays the brain from many different angles, feeding the information into a computer that produces a series of cross-sectional images. CT is particularly useful for diagnosing blood clots and brain tumors [2]. Another widely used body scanner in medical field is positron emission tomography scan (PET scan). PET scan is a diagnostic imaging technique that uses a sophisticated camera and computer to produce images of

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how a person's body is functioning. A PET scans shows the difference between the abnormal and healthy functioning tissues.

In early 90's, tomography system was implemented in industry field. Process tomography is the analogy of medical tomography, where the aim is to visualize the internals within an industrial process such as the transportation activity in a pneumatic pipe. Knowledge of fluid flow behaviour is critical to the design of numerous devices such as engines, valves, boilers and turbo machines. Flow visualisation is often the first step in experimental analysis of these flows, since qualitative (and sometimes quantitative) information about the flow can be obtained quickly and at minimal cost [3]. This makes the tomographic measurement become more important in today's industrial processes. From the engineering point of view, process tomography is not only to obtain a good quality computed image, but also to obtain quantitative (numerical) interpretation of an image that can be further processed to provide flow information such as particle sizing. A basic process tomography can be established by installing a number of sensors around the pipe or vessel to be imaged. Data that is measured by the sensors will be sent to a computer. This data will be processed to reconstruct a tomographic image of the cross section being sensed by the sensors. The tomographic image can provide information on concentration, velocity and mass flow rate profile of the flows.

2.0 BASIC STRUCTURE OF PROCESS TOMOGRAPHY SYSTEM

Although the detailed design of a process tomography system will depend on the process with which it is to be used and the output information required, all system can be divided into three basic subsystems as shown in Figure 1.

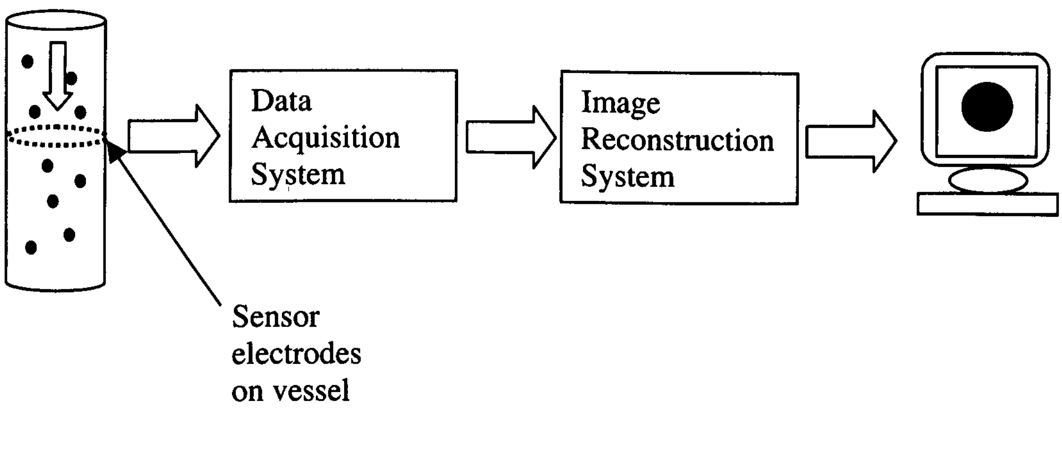

Figure 1 Schematic block diagram of a flow imaging system

Although they can be divided into smaller subsystems, the function of each subsystem and the interactions between them need to be considered early in the design phase. The three subsystems of process tomography system are:

(i) Sensor
(ii) Data acquisition system
(iii) Image reconstruction system and display

In the measurement systems above, the sensor is probably the most crucial part of a flow imaging system. Sensing techniques currently under consideration for use in flow imaging systems include electrical, ultrasound, nucleonic and optical [3]. The sensor that is selected in this tomographic measurement system should be compact, non-intrusive, reliable, and require minimum maintenance. Another criterion for sensor selection is the content of the cross section under interrogation [4]. For example, an inductance sensor may be suitable for conducting flowing material but not for non-conducting flowing material. The signal that is received by the sensors is a very small current signal, normally in unit nanoamperes. It needs to be amplified, conditioned and converted into a standard analogue voltage signal for further processing. A standard electronic circuit is required for the process of amplifying, conditioning and converting. This is also known as electrodynamic tomography sensor. In the tomographic measurement system, electrodynamic sensors are used to measure the electrostatic charges generated by friction of the moving dry solid against the conveyor wall. There are some advantages of electrodynamic tomography sensor. It is a passive type of sensor, therefore requires no additional excitation system. Moreover, electrodynamic sensors are small in size, robust and low cost. They are very useful in tomographic measurement system with a high sensitivity to low flow rates of dry solid material. The electrodynamic sensor has a high spatial filtering bandwidth. This makes it very suitable for measuring of concentration, velocity and volume flow rates in a tomographic system.

Data acquisition refers to collection of information. This subsystem functions as an interface between the real world of physical parameters with the world of computers. The circuitry in this system permits us to acquire analog data from one or more sources and converts them into an equivalent digital signal recognisable to a computer [5]. The output of the sensor is in analog form and it cannot be directly forwarded to the computer for further processing. So, a subsystem that is able to convert the analog signal into digital form is required. The major task of this subsystem is to convert the analog output signal of the sensors into digital form. This digital signal is suitable for statistical analysis of the process or for conveying system design purposes.

The third subsystem refers to the software or programming part of the system. The image reconstruction algorithm will be implemented into the software. Received data is processed based on the image reconstruction algorithm to produce the tomographic image. The tomographic image can be displayed in two basic formats: a colour format or numerical format. The success of image reconstruction may depend upon adequate data pre-processing to remove the effects of discontinuities or noise, in the measured data [3].

3.0 TOMOGRAPHIC MEASUREMENT SYSTEM

The measurement system consists of an array of 16, equally spaced, circular sensors mounted around on an 81 mm diameter steel pipe. The measurement system is based on the charge that is generated by the solid particles when they are moving through the pipe. The charge will be induced in the sensor. The induced charge will then be converted to voltages and amplified to a level that is suitable for data acquisition system to process on-line. Electrodynamic sensors are robust, low cost and suitable to be used in the measurement system of the process tomography. It is used to sense the electrostatic charge, which is carried by dry solid particles. The position of the electrodynamic sensor at the cross section through a pipe at the measurement section is as shown in Figure 2.

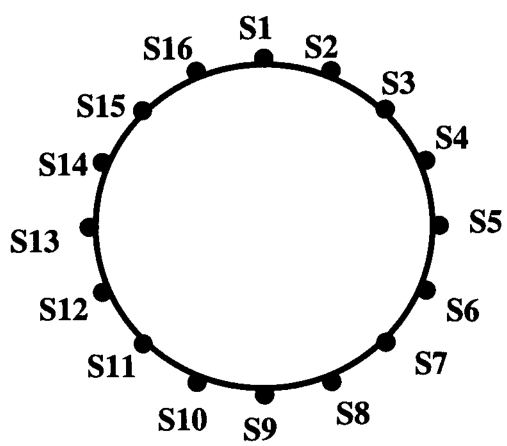

Figure 2 The position of transducers at the measurement section

As dry solid particles are moving through a conveyor, an electrostatic charge accumulates on the particles. The magnitude of the charges depends on many factors, such as physical properties of the particle, including the type, shape, humidity and size of materials. However, in many manufacturing systems, the process control provides repeatable conditions, resulting in repeatable levels of charge on the particles [2]. The electrostatic charge is detected using electrodes and converted into a voltage signal by the electrodynamic transducer.

The electrodynamic transducer normally consists of two basic elements, electrode or sensor and associated electronics. The sensor generally consists of a conductor structure, insulated from the walls of the pipe. The sensor is placed 0.5mm outside the wall of the pipe to minimise boundary problems [6]. There are two types of sensors used in particular application of electrodynamic transducers, ring electrodes and pin electrodes. The pin electrodes will give the same result as ring electrodes if the flow is axis symmetric. In process measurements, the ring electrodes are widely used and have been thoroughly investigated [7].

4.0 IMAGE RECONSTRUCTION SYSTEM

Tomographic image is derived from the measurements using a filter back-projection algorithm. In order to derive this algorithm, the forward problem must be solved. In this work, the forward problem is used to model the individual sensors and then produce sensitivity map for each sensor [8]. These maps are then used to solve the inverse problem, and derive the linear back projection and filtered back projection algorithms. The solution of the inverse problem aims to provide an image of the charge concentration distribution within the conveyor. The image reconstruction algorithm will be implemented in software discussed in Section 5.

4.1 The Forward Problem

The forward problem determines the theoretical output of each of the sensors when the sensing area is considered to be two-dimensional and contains a uniformly distributed charge of σ coulombs per square meter [5]. To calculate the sensitivity model for each sensor, the cross section of the pipe is mapped onto a rectangular array. The rectangular array is a nine by nine rectangular array that consists of 81 pixels as shown in Figure 3.

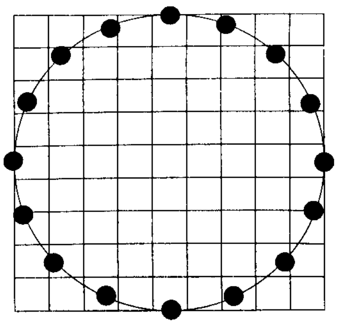

Figure 3 A 9 × 9 rectangular array of 81 pixels

The effect of each sensor on each pixel due to the uniform surface charge, σCm^{-2} is determined separately. Each pixel is considered in turn. The sensitivity map is generated by calculating the charge of a chosen pixel that would be induced into the sensor. In the sensitivity map, each pixel is identified numerically. The first number represents the column and the second number represents the row. Figure 4 shows the numerical identity of each pixel.

11	21	31	41	51	61	71	81	91
12	22	32	42	52	62	72	82	92
13	23	33	43	53	63	73	83	93
14	24	34	44	54	64	74	84	94
15	25	35	45	55	65	75	85	95
16	26	36	46	56	66	76	86	96
17	27	37	47	57	67	77	87	97
18	28	38	48	58	68	78	88	98
19	29	39	49	59	69	79	89	99

Figure 4 Numerical identity of each pixel

4.1.2 Calculation of Sensitivity Map for Sensor 1

The diameter of the pipe is 81 mm. Each pixel of the rectangular array is 9 × 9 mm. The center of the pipe is defined as coordinate (0, 0, 0) as shown in Figure 5.

For the model of sensor 1, the general sensitivity equation is

$$I_1 = \iiint \frac{\sigma}{r^2} dV \int_x dx \int_y dy \int_z \frac{\sigma}{x^2 + (41-y)^2 + z^2} dz$$

where (x, y, z) is the coordinate of the part of the pixel contributing to the sensor output, r is the distance of the charge to the sensor and the inverse square law is obeyed. The total induced charge for sensor 1 when σ is assumed to be 1 Cm^{-2} is

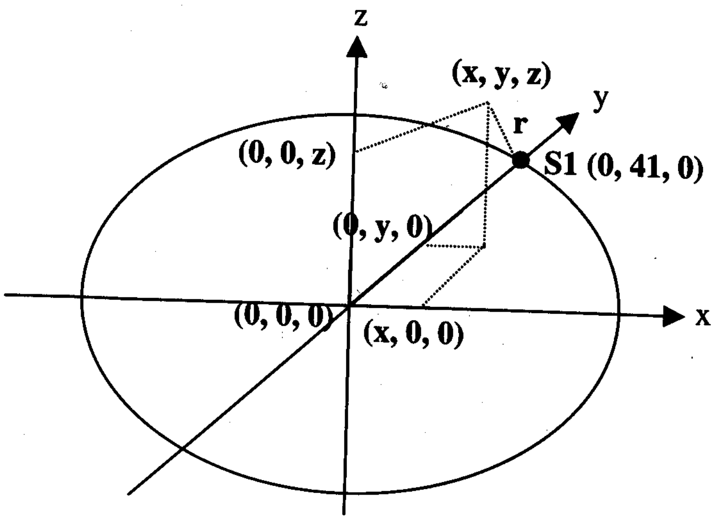

Figure 5 The sensitivity model for sensor 1

$$I_1 = \int_{-40.5}^{40.5} \int_{-\sqrt{40.5^2-x^2}}^{\sqrt{40.5^2-x^2}} \int_{-81}^{81} \frac{1}{x^2+(41-y)^2+z^2} dzdydx = 376.28 \text{ coulombs}$$

Three examples of the sensitivity calculation are shown as below.

$$Pixel32 = \int_{-22.5}^{-13.5} \int_{22.5}^{13.5} \int_{-81}^{81} \frac{1}{x^2+(41-y)^2+z^2} dzdydx = 9.287 \text{ coulombs}$$

$$Pixel51 = \int_{-4.5}^{4.5} \int_{31.5}^{40.5} \int_{-81}^{81} \frac{1}{x^2+(41-y)^2+z^2} dzdydx = 55.282 \text{ coulombs}$$

$$Pixel83 = \int_{22.5}^{31.5} \int_{13.5}^{22.5} \int_{-81}^{81} \frac{1}{x^2+(41-y)^2+z^2} dzdydx = 5.31 \text{ coulombs}$$

The calculation is repeated for all pixels. A software program, named Mathcad, can do this kind of calculation. Complete and parts of pixels outside the pipe have zero induced charge to the sensor. So, pixel 11, 12, 18, 19, 21, 29, 81, 89, 91, 92, 98 and 99 has a sensitivity value of zero. The generated sensitivity map for sensor 1 is shown in numerical format in Figure 6 and colour format in Figure 7.

0	0	6.17	20.75	55.28	20.75	6.17	0	0
0	5.2	9.29	13.52	16.5	13.52	9.29	5.2	0
2.22	5.31	6.83	8.42	9.19	8.42	6.83	5.31	2.22
3.08	4.24	5.07	5.78	6.07	5.78	5.07	4.24	3.08
2.91	3.39	3.87	4.23	4.37	4.23	3.87	3.39	2.91
2.14	2.74	3.02	3.23	3.31	3.23	3.02	2.74	2.14
1.09	2.24	2.42	2.54	2.59	2.54	2.42	2.24	1.09
0	1.49	1.97	2.05	2.08	2.05	1.97	1.49	0
0	0	0.88	1.5	1.71	1.5	0.88	0	0

Figure 6 Numerical sensitivity map for sensor 1

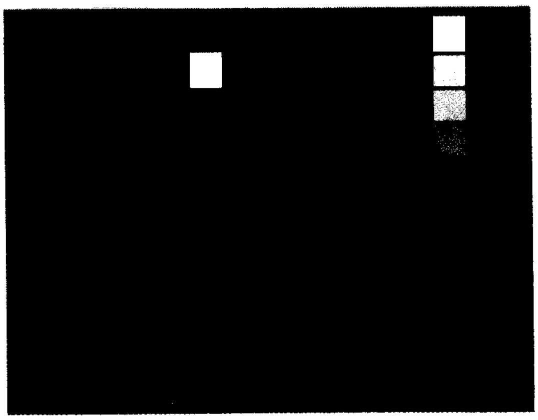

Figure 7 Colour sensitivity map for sensor 1

4.2 The Inverse Problem

The sensitivity maps in section 4.2 will be used to solve the inverse problem. Solution of the inverse problem aims to provide an image of the charge concentration distribution within the conveyor, which would result in the measured sensor outputs [6]. The produced image is based on two algorithms, basic back projection and filtered back projection.

4.2.1 *Basic Back Projection Algorithm*

The basic back projection algorithm generates a charge concentration map within the pipe. The procedure is to multiply each sensor voltage reading with its sensitivity map respectively. This multiplication step produces sixteen, 9 × 9 matrices. The corresponding individual elements from the 16 matrices are then summed up to produce a single matrix, namely the concentration matrix.

A concentration profile has been calculated assuming that all the sensors reading are 1V. This profile is named as theoretical concentration profile. The theoretical concentration profile in numerical format is shown in Figure 8, with the relative position of the pipe mapped onto in. Figure 9 displays the result as a colour tomogram, where the colour relates to the charge concentration.

0	0	71.7	98.75	124.9	98.75	71.7	0	0
0	104.7	96.80	88.2	85.6	88.2	96.8	104.7	0
71.7	96.8	83.3	77.3	75.6	77.3	83.3	96.8	71.7
100.1	88.2	77.3	72.5	71.1	72.5	77.3	88.2	100.1
124.9	85.6	75.6	71.1	69.8	71.1	75.6	85.6	124.9
100.1	88.2	77.3	72.5	71.1	72.5	77.3	88.2	100.1
71.7	96.8	83.3	77.3	75.6	77.3	83.3	96.8	71.7
0	104.7	96.8	88.2	85.6	88.2	96.8	104.7	0
0	0	71.7	98.7	124.9	98.7	71.7	0	0

Figure 8 The theoretical numerical concentration profile

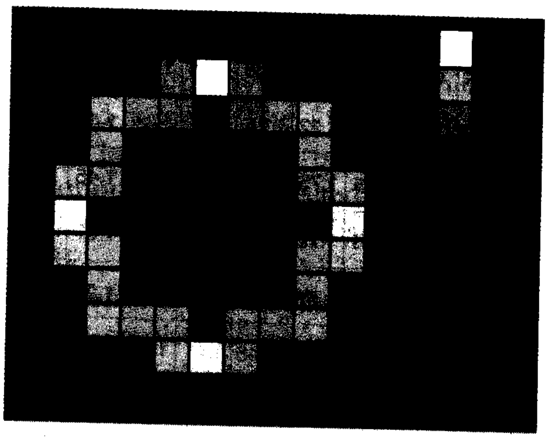

Figure 9 The theoretical colour concentration profile

The limitation of the basic back projection algorithm, that is the low estimation of solids at the center of the conveyor, can be identified from the Figure 8 and Figure 9. Filtered back projection algorithm is used to reduce this limitation.

4.2.2 *Filtered Back Projection Algorithm*

The major limitation of the basic back projection algorithm arises due to the nonlinear sensing mechanism of the electrical charge transducer [7]. Theoretically, when a uniformly distributed solid flow in the conveyor, the concentration matrix should be uniform at 124.91 units per pixel. However, from the calculation of the basic back projection algorithm, it shows lower values at the center of pipe, compared with the edge of pipe.

To overcome this problem, a filtered mask need to be determined, which will be combined with the basic back projection algorithm, to provide a filtered back projection algorithm. This filtered mask provides weighting to individual pixels to provide a uniform concentration profile [6].

Assuming that all the sensors have an output of 1 V, the concentration matrix will be calculated as described in the forward problem. The filter matrix can be obtained by taking the maximum value of 124.91 units per pixel, which is then divided, by each pixel value within the pipe mapping. The calculated filtered mask is shown in Figure 10. Figure 11 displays the colour of filtered mask. This filter matrix is only applicable for full flow applications. Similar filters should be calculated for different flow patterns.

0	0	1.74	1.265	1	1.265	1.74	0	0
0	1.193	1.29	1.41	1.45	1.41	1.29	1.193	0
1.74	1.29	1.50	1.63	1.65	1.63	1.50	1.29	1.74
1.247	1.41	1.61	1.72	1.75	1.72	1.61	1.41	1.247
1	1.45	1.65	1.75	1.78	1.75	1.65	1.45	1
1.247	1.41	1.61	1.72	1.75	1.72	1.61	1.41	1.247
1.74	1.29	1.50	1.63	1.65	1.63	1.50	1.29	1.74
0	1.193	1.29	1.41	1.45	1.41	1.29	1.193	0
0	0	1.74	1.26	1	1.26	1.74	0	0

Figure 10 The numerical filtered mask

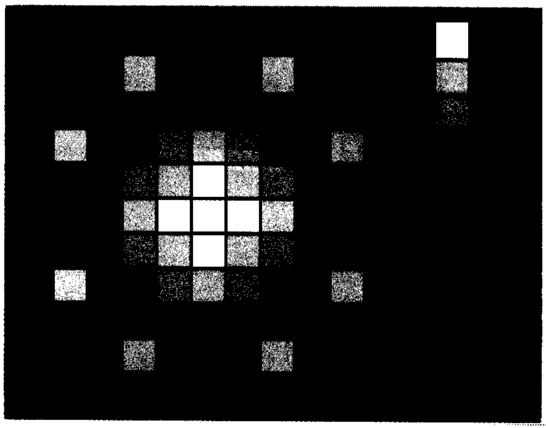

Figure 11 The colour filtered mask

5.0 SOFTWARE OVERVIEW

Collecting large amount of data from instruments is a tedious job. Therefore, it is essential to develop an application program to reduce time consumption for data collection as well as increasing the accuracy of the result. In this project, an application program is developed to serve this purpose. This project requires an application program to perform data collection automatically from the electrodynamic transducers. First and foremost, this application program must be user friendly, Window-based by which everyone will find no difficulty using. The application program will communicate with the electrodynamic transducers via an AX5412, 16 channels interface card, to read data from 16 sensors. Users will expect the application program to help them retrieve data from the tomographic masurement system. The application program will run by itself in a user-defined period. The application program will have the capability of collecting large amount of data from the electrodynamic transducers. It will manipulate the collected data and with also be able to come out with particular graph. Microsoft Visual Basic is chosen to develop the application program [9].

Figure 12 is the screen shot of the application program that was written in Visual Basic software. It consists of two forms. The upper form is named *Concentration Profile*. It shows the concentration profile in a pipe and measured sensor voltages. The sensitivity map is built up by 81 pixels that show the concentration profile in a pipe. The colour bar is a reference point to the concentration profile. In the colour bar, the lightest colour represents the

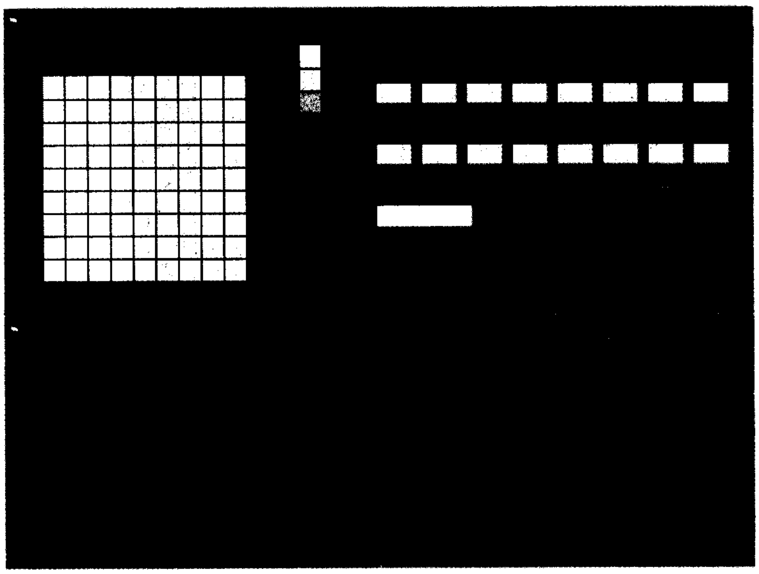

Figure 12 Concentration profile application program

highest concentration value while the darkest colour represents the lowest concentration value. The 16 text boxes are used to show the 16 measured sensor voltages. User can select the format of concentration profile in the *Tomography Form* combo box. The concentration profile can be shown in colour format, numerical format or both combination of colour and numerical format. The button named *Setting* is used to initialise the device driver. The *Start* and *Stop* button is used to instruct the application program to start or stop collecting data. User can exit this application program by clicking the *Exit* button. The lower form, named *Normalised Sensor Voltages* is used to show the 16 normalised sensor voltages. The sensor voltages are shown in bar graph in this form.

6.0 RESULTS AND DISCUSSION

For the measurement system, the data is collected from the averaged sensor output. Tomographic images of the concentration distributions at sensor measurement section is calculated using the linear back projection algorithm and the filtered back projection algorithm. Results from the measurements can be obtained from the application program. Measurement is based on the charge carried by the plastic rod that is being induced in the sensors. Several experiments have been carried out to test the reliability of this real time system.

6.1 Experimental Result Using Single Sensor

An experiment had been carried out for the system in the laboratory. A plastic rod that carried charge had been moved near the electrode of sensor 7. The results of this experiment are shown in 3 formats as Figure 13, 14 and 15. These 3 figures have the same result. The only difference among these 3 figures is the display format of the concentration profile. The results of the charge concentration profile in Figure 13 and 14 are shown in colour and numerical format respectively. In Figure 15, the charge concentration profile is shown in

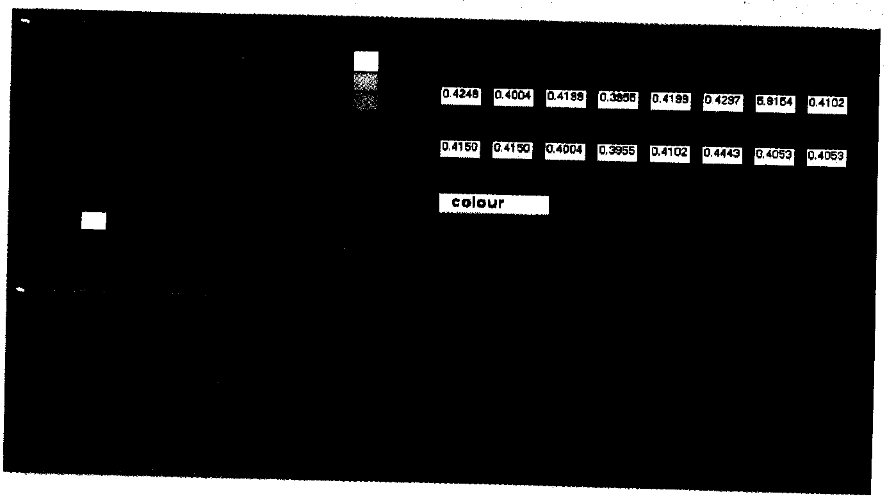

Figure 13 Colour concentration profile for plastic rod at sensor 7

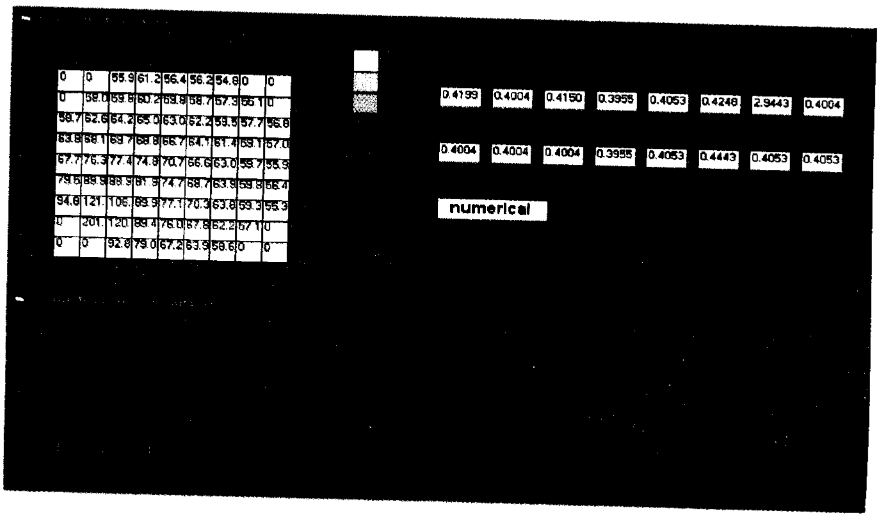

Figure 14 Numerical concentration profile for plastic rod at sensor 7

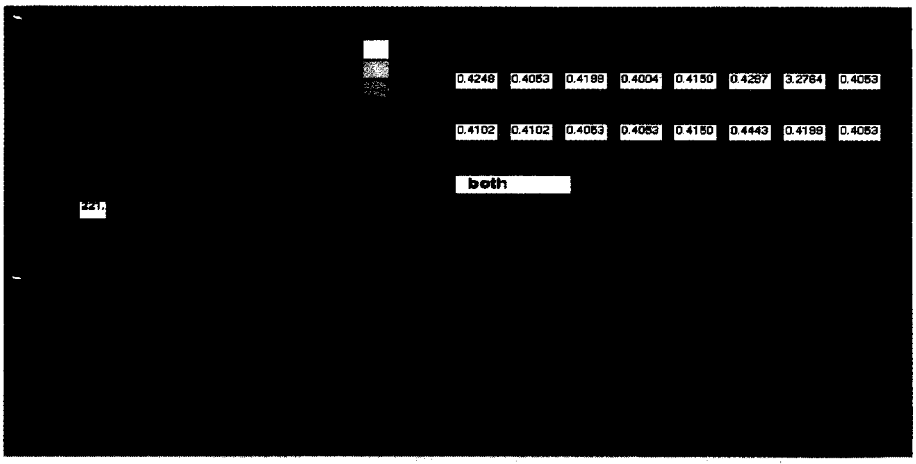

Figure 15 Colour and numerical concentration profile for plastic rod at sensor 7

both combinations of colour and numerical format. Due to the presence of the charge that is carried by the plastic rod, sensor 7 has a high value of average DC output, 2.9443 V. It is more evident the bar graph. It shows sensor 7 as having the highest value among the sixteen sensors. The pixel with a white colour proves that charge is concentrated around sensor 7 at the measurement cross section of the pipe.

6.2 Experimental Result Using Several Sensors

Experiments were also carried out using several sensors. The plastic rod that carried charge is moved around the surface of several sensors in the pipe. The results of the experiments are shown in Figure 16 and Figure 17. In one experiment, the plastic rod is moved around the internal surface of the pipe, from sensor 11 to sensor 15. The result of the experiment is shown in Figure 16. As shown in the bar graph, the average DC outputs of sensor 11 to sensor 15 are higher compared with other sensor outputs. The pixels around sensor 12 and sensor 13 have a lighter colour. It shows that a large amount of charge has been concentrated around sensor 12 and sensor 13.

Figure 17 is the result of another experiment. The plastic rod is moved around at sensor 1, sensor 2 and sensor 16. As shown in the figure, pixels around sensor 1, sensor 2 and sensor 16 have lighter colours.

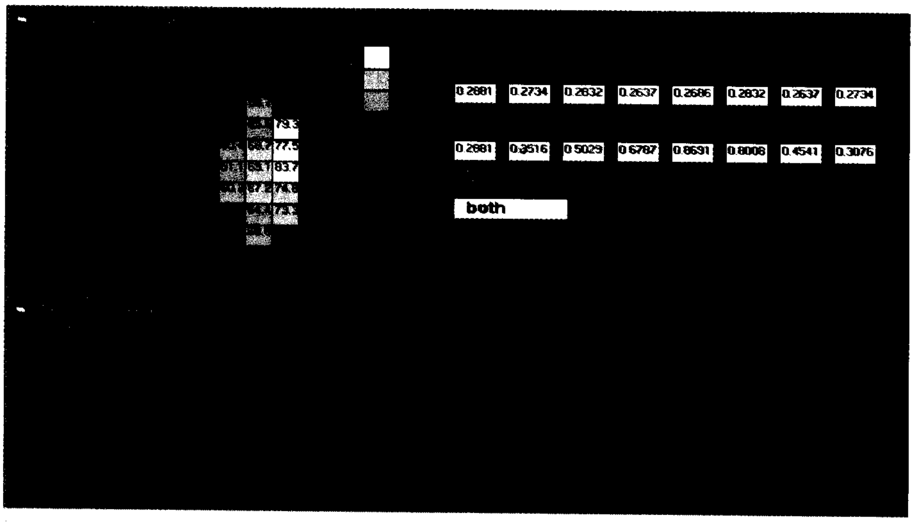

Figure 16 Charge concentration profile for plastic rod at sensor 11 to sensor 15

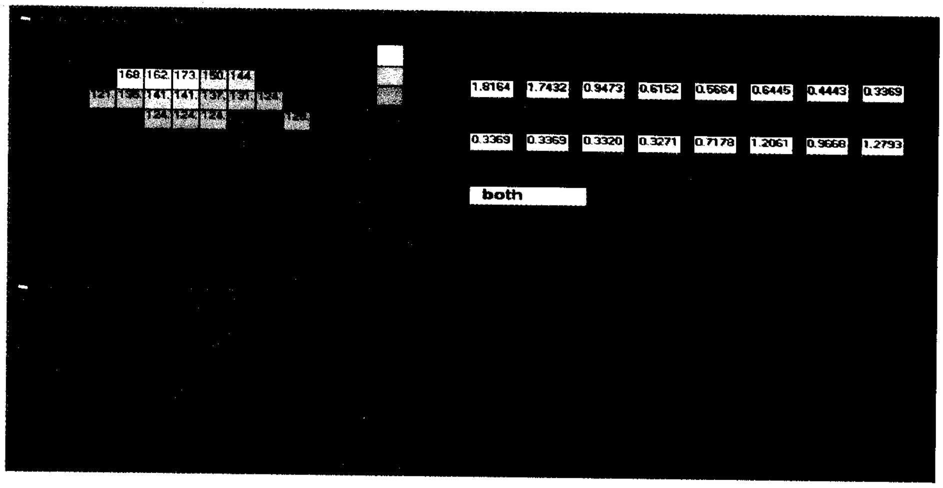

Figure 17 Charge concentration profile for plastic rod at sensor 1 and sensor 2

6.3 Discussion

The results in Figure 13 to 17 show that the application program is able to display the charge concentration profile in a pipe in real time. Colour of the pixels clearly shows the charge distribution in a pipe. Information about the amount of charge distributed in a pipe can be obtained from the numerical format of concentration profile. In the experiment, the sensors showed a low output although the plastic rod was not placed in the pipe. This offset value may be caused by noise generated in the amplifier circuit in the electrodynamic sensor. The measured value therefore will not be precise since it includes the offset value. Further work is required to enhance the precision of the system.

7.0 CONCLUSIONS

In this project, a real time system has been designed and developed for process tomography to obtain flow information in a pipe. The main feature of this project is the computation of the concentration profile of solid particle conveyed over a cross section of a pipe. The interfacing technique used to interface between electrodynamic sensors and computer is the key point of this project. Output from the sensor is sent to the application program through Axiom AX5412 data acquisition system card. From the analysis of the experimental result, this system is able to compute the concentration profile of solid particle conveyed in a pipe.

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