DUAL MODALITY TOMOGRAPHY SYSTEM USING OPTICAL AND ELECTRODYNAMIC SENSORS FOR TOMOGRAPHIC IMAGING SOLID FLOW

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***Abstract-** Process tomography is a technique to realize flow imaging in a process vessel or pipeline by using the sensor system. This technique involves the use of tomographic imaging methods to manipulate data from sensors in order to collect sufficient information about the flow in the pipeline. The overall aim of this paper is to investigate the benefits of dual modality (optical and electrodynamic) tomography system for the measurement of tomographic images of solids flow. This research will investigate the distribution of conveying plastic beads in a conveying pipe by placing optical and electrodynamic sensors around the pipe without interrupting the flow inside the pipe.*

Keywords: Dual modality, tomography, solid flow, optical sensors, electrodynamic sensors.

I. INTRODUCTION

The field of process tomography is growing rapidly. Tomographic imaging offers a unique opportunity to discover the complexities of structure without the need to invade the object [1]. It is an expansion from the early research involving x-ray tomography, which focused on how to obtain 2-D cross-section images of animals, human, and non-living things.

The application of process tomography is analogous to the application of medical tomographic scanners for investigating the human body, but applied to an industrial process as there is a widespread need for the direct analysis of the internal characteristics of process plants in order to improve the design and operation of equipment [2]. Process tomography can be applied to many types of processes and unit operations, including pipelines, stirred reactors, fluidized beds, mixers, and separators. Depending on the sensing mechanism used, it is non-invasive, inert, and, non-ionizing. It is therefore applicable in the processing of raw materials: in large scale and intermediate chemical production; and in the food biotechnology areas [3].

In tomography, a variety of sensing methods can be used based on very often contradictory factors. While most devices employ a single type of sensor, there are a number of opportunities for multi mode systems using two or more different principles [4]. In principal, there is no single sensing method capable of detecting all suspended solids flow or explore all important flow characteristics. Taking these limitations into account, it is vital to combine the technologies of optical sensors and electrodynamic sensors to produce a single measurement system. The concept of combining both sensing mechanisms provides the opportunity to obtain and compare each other that can be used to improve the accuracy of concentration profiles [5].

II. OPTICAL SENSOR MODELING

In optical tomography, the cross section of an object is scanned by a parallel projection (Figure 1). When light passed through the object along the straight line AB in the sensing zone from the light source to the photodiode, light is attenuated as shown in Equation 1.

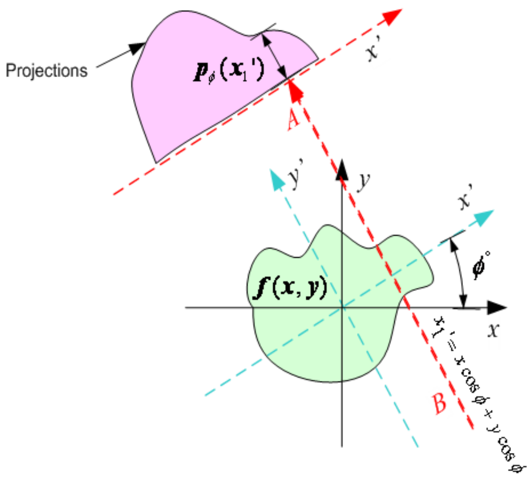

Figure 1: An object $f(x,y)$, and its projection $P_\phi(x_1')$, shown for angle $\phi°$.

$$I = I_o \exp(-\mu d) \quad (1)$$

where: I_o = original intensity of the light source, I = measured intensity, μ = linear attenuation coefficient, and d = thickness of object.

The coordinate systems illustrated in Figure 1 are used to describe line integrals and projections. The object is represented by a two-dimensional function f(x, y) and each line integral is represented by the projection angle ϕ and a detector position x' parameters [6]. The Equation of AB in Figure 1 is shown in Equation 2.

$$x\cos\emptyset + y\sin\emptyset = x' \quad (2)$$

where:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\emptyset & \sin\emptyset \\ -\sin\emptyset & \cos\emptyset \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (3)$$

In addition, this resulted in the line integral $p_\emptyset(x')$

$$p_\emptyset(x') = \int_{(\emptyset,x)\text{line}} f(x,y)\,ds \quad \mathbf{(4)}$$

By using delta function, this can be rewritten as:

$$p_\emptyset(x') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\,\partial(x\cos\emptyset + y\sin[\emptyset - x')\,dxdy] \quad (5)$$

For the discrete implementation, Equation 4 can be rewritten as:

$$p_\emptyset(x') = \sum_{M_i=0}^{M_i-1}\left[\sum_{N_i=0}^{N_i-1} f(x,y)\,\partial(x\cos\emptyset + y\sin[\emptyset)\,\Delta x]\right]\Delta y \quad (6)$$

where: N_i=total number of horizontal cell/pixel, M_i=total number of vertical cell/pixel.

The optical model is based on the length of the optical sensing beam within the conveyer. The voltage of each individual path length sensor increases with increased plastic beads flow rate [7]. It is assumed that the relationship between the number of plastic beads passing through a beam and the corresponding sensor output voltage is linear [8]. For a given uniform flow rate the output voltage from each sensor will be directly proportional to its optical path length.

The forward problem provides the theoretical output of each sensor under no-flow and flow conditions when the sensing area is considered two-dimensional. The cross section of the circular pipe is mapped onto a 16 x 16 rectangular arrays of 256 pixels as shown in Figure 2 in order to solve the forward problem.

The diameter of the pipe for this project is 80mm, so the dimension of each pixel can calculated as 5mm x 5mm (80mm/16 sensors). The fiber optic (with an outer diameter of

2.3mm) was placed at the centre of each pixel. S_{O_0} represents the first optical sensor and T_{O_0} represents the first light transmitter.

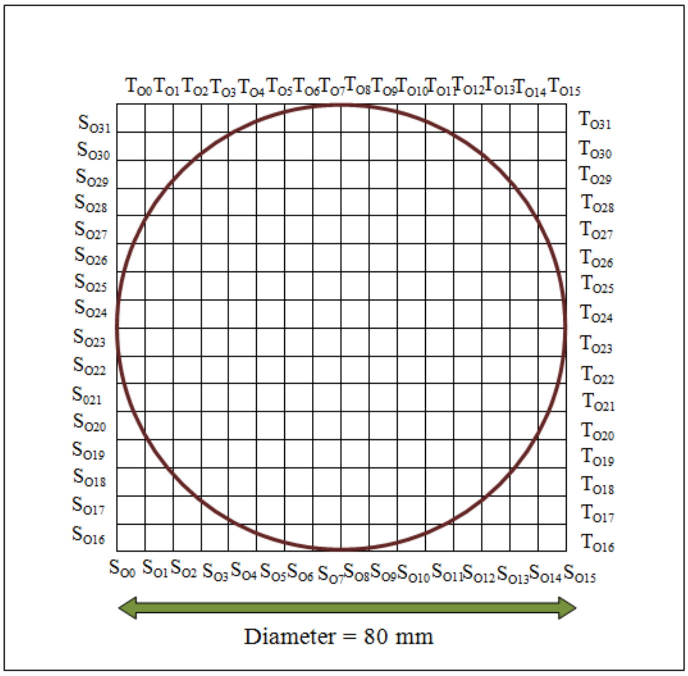

Figure 2: A 16 x 16 rectangular array of 256 pixels with optical sensors position.

The sensitivity matrix for each sensor is formed by calculating the ratio of the area of the light beam in each pixel to the area of the corresponding pixel. Each pixel is evaluated separately and the contribution from each pixel forms the sensitivity map [9]. The Linear Back Projection Algorithm (LBPA) is chosen in order to develop the concentration profile. It is obtained by combining the projection data from each sensor with its computed sensitivity map. Each sensitivity matrix is multiplied by its corresponding sensor reading to obtain the image reconstruction.

III. ELECTRODYNAMIC SENSOR MODELING

The induction of voltage on the sensors electrode by charged particles as they flow past the sensors mounted on the conveying wall forms the basic working principle of electrodynamic sensors [10]. It has been established that the magnitude of the charge acquired by solids depends upon the moisture content of the atmosphere, the particle size distribution and the velocity with which the particle moves and/or impinges onto surfaces [11]. The forward problem determines the theoretical output of each electrodynamic sensor when the sensing area is considered two-dimensional and contains a uniformly distributed charged of σ coulombs per square meter [12]. To solve the forward problem, the theoretical output of each sensor due to placing a certain surface charge σ at all the possible locations in the pipe cross section has to be calculated. Similar to the optical system, the pipe cross section for electrodynamic system is mapped onto (16 x 16) rectangular arrays of 256 pixels as shown in Figure 3.

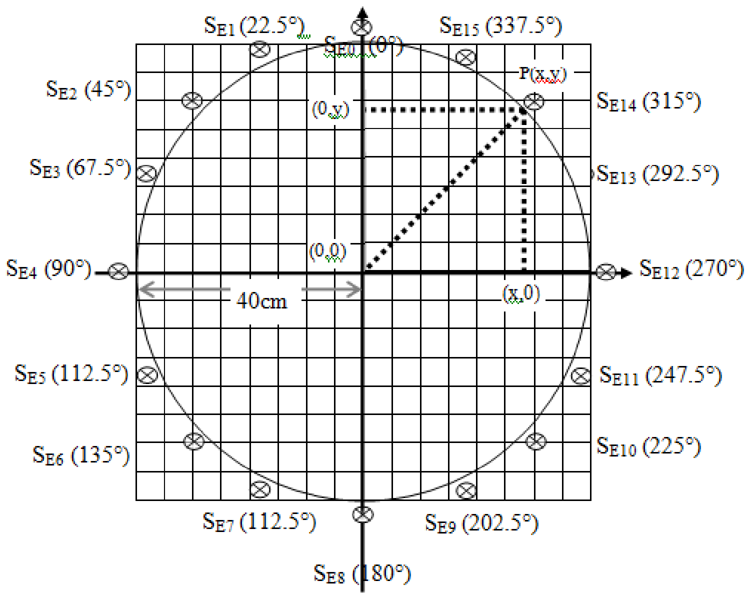

Figure 3: A 16 x 16 rectangular array of 256 pixels with electrodynamic sensors position.

The center of the electrodynamic pipe is chosen as the origin i.e. (0,0) rectangular coordinate value [13]. The coordinate is determined to calculate the contribution of each pixel to the electrodynamic sensors.

The solution to the forward problems needs to define models and calculating the sensitivity map of each sensor. Assume that a uniform surface charge of σ C m^{-2} is present at each pixel and hence each pixel would induce a certain amount of charge on the array of sensors.

All electrodynamic sensors are placed 0.5mm outside the pipe boundary in order to minimize boundary problems. As an example, the general sensitivity equation for first electrodynamic sensor is defined as in Equation 7;

$$S_{E_0} = \iint \frac{\sigma}{r^2} dA = \int_y dx \int_x \frac{\sigma}{x^2 + (40.5 - y)^2} dy \qquad (7)$$

Where (x, y) is the coordinate of the part of the pixel contributing to the sensor output, r is the distance of the charge from the first electrodynamic sensor S_{E_0}, and A is the cross sectional area of the pipe.

The linear back projection algorithm is generated when the sensitivity map of each sensor is multiplied by its corresponding sensor reading and the value of similar pixels from all the 16 matrices is summed up to produce the concentration map of 16x16 matrix.

IV. MEASUREMENT CONFIGURATION

In this project, the projection employs dual modality sensors consisting of optical and electrodynamic position, equally placed outside a pipe with 82 mm outer diameter and 80mm inner diameter. The optical sensor has 32 BPX65 photodiode sensors acting as receivers arranged in orthogonal projection and two halogen bulbs acting as light transmitters. meanwhile, the electrodynamic system has 16 electrodes positioned equidistantly around the periphery of the pipe wall and separated from the optical system at a distance of 10cm. Hence, for the dual modality, the total number of sensors used is 48.

The 32 photodiodes are labeled S_{O_0} to $S_{O_{31}}$ for the optical sensors, and the 16 electrodes are labeled as S_{E_0} to $S_{E_{15}}$ arranged around the circumference of the pipe wall. Suitable signal conditioning circuits process outputs from the sensors before entering a data acquisition system (DAS). The DAS card KPCI-1802HC with 64 channels and 333 k sample per second was used to capture the data. The DAS can only read 64 readings at a time. An outline of the dual modality measurement in tomography system is shown in Figure 4, where plane S_O represents optical sensors and plane S_E represents electrodes.

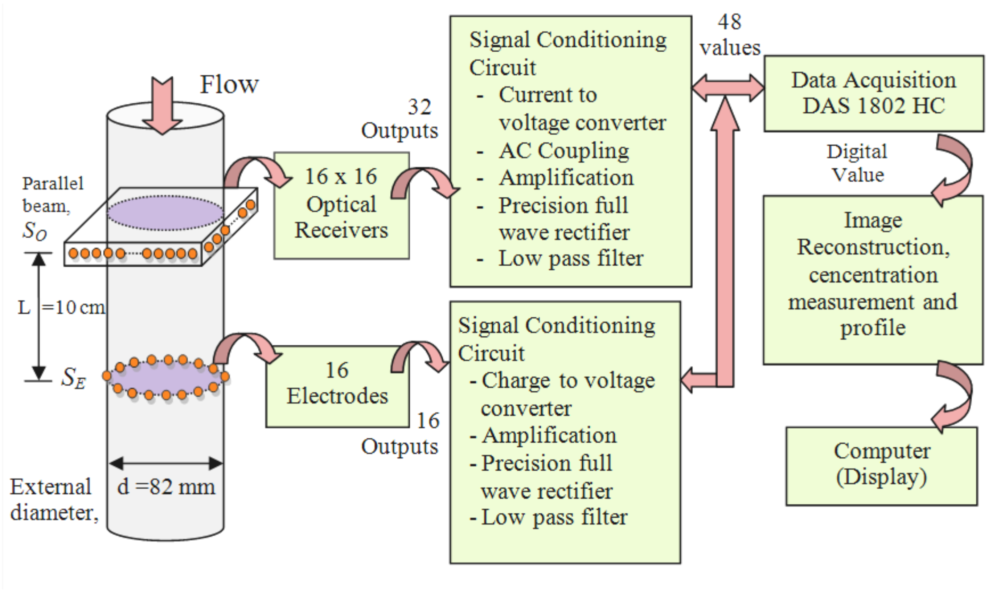

Figure 4: A block diagram of the dual modality tomography system

V. PROCESS RIG

Figure 5 shows the main source of data in this project, which is the gravity flow rig. The rig was used to control the flow of material and enable repeated solid concentration and distributions to be monitored. The conveyed material used in this measurement is the plastic beads of mean size 3mm.

Several parts formed the flow rig. First is the storage hopper. When the vacuum loader is switched, the plastic beads will move to the hopper before it goes through the measurement systems. Another part is the screw feeder. The mass flow rate of the plastic beads is controlled by adjusting the rotational speed of the screw feeder. The screw feeder was positioned at the bottom of the hopper as shown in the Figure 5. The speed of rotation was set to a suitable value needed by a control unit.

The measurement section containing the optical sensors is mounted on a vertical pipe at a distance of 1.20m below the outlet of the screw feeder. In reality, both sets of transducers should be positioned close to each other to reduce the possibility of an image offset when the data sets are combined. On the other hand, the smaller the distance, the better the similarity of signals obtaining from the two planes [14]. In this research, the separation between the optical and electrodynamic sensors is set, as a compromise to 10cm so that each sensor outputs can be compared adequately. The plastic beads were fed from the hopper into the pipe via a suitable speed screw feeder at a controlled rate.

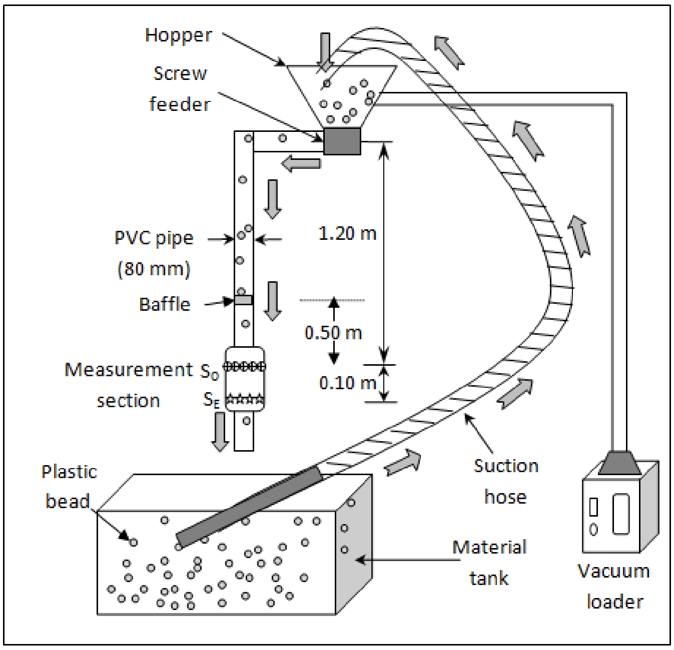

Figure 5: gravity flow rig diagram

VI. RESULTS

Concentration profiles of the plastic beads flowing in the gravity flow rig are produced using Linear Back Projection(LBP) algorithm for optical and electrodynamic tomographic systems. Figures 6 (a) and (b) show the concentration profile for optical sensor for half flow, whereas Figures 7 (a) and (b) show the concentration profile for electrodynamic sensor for the same flow.

The concentration profile in Figures 6 (a) and (b) clearly show that half of the pipe has much lower concentration compared to the rest of the pipe. Meanwhile Figures 7 (a) and (b) show that the area of flowing plastic beads has higher voltage when the flow occurs compared to the blocking area. Sensors sixth, S_{E5} to twelfth, S_{E11} have more concentration compared to other sensors.

Lower concentration values are observed at the center of the profile. Moreover, several values are observed at the peripheral of the pipe, which means there is a high concentration of plastic beads at those pixels.

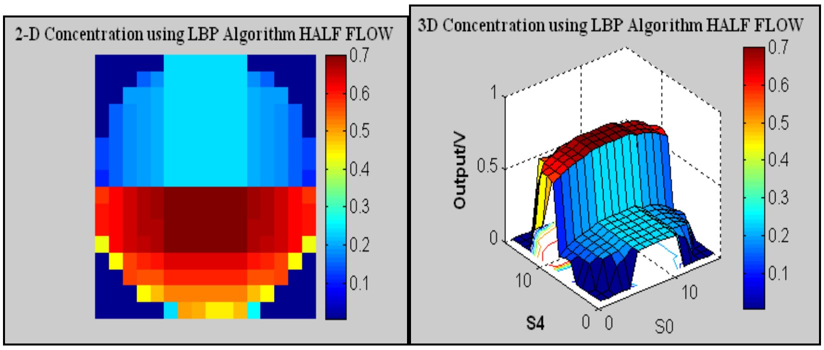

Figure 6: Concentration profile for optical sensor for a half flow condition (a) Two dimension (b) Three dimension.

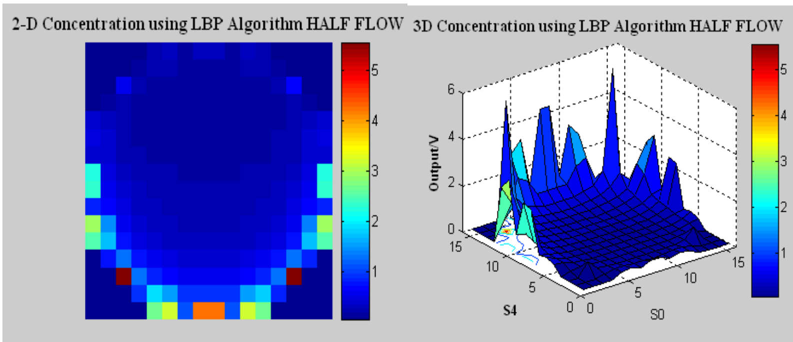

Figure7: Concentration profile for electrodynamic sensor for half flow condition

(a) Two dimension (b) Three dimension

DISCUSSION AND CONCLUSION

A dual modality tomographic system is described for the concentration profile of the plastic beads for optical and electrodynamic tomographic images with the same pattern flow using the same material. The concentration profile for electrodynamic shows that the response of the material flowing near the pipe wall is better compared to the middle of the pipe. In other words, the detection of the material near the sensing zone is higher compared to the area far away to sensors. The electrodynamic is insensitive to permittivity changes at the center of the sensor, which is located far from the electrodes. On the other hand, the images produced by the optical measurement system are shown to be uniform when detecting the materials flow in the pipeline. It is most sensitive at the center of the pipe. Therefore, in many cases, the application of only one tomographic modality is not sufficient to explore all important flow characteristics. Further work should be carried out to fuse these images so that an accurate representation of the actual concentration profile can be obtained.

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