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Optical Tomography Imaging in Pneumatic Conveyor

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Abstract: This paper describes the development of a tomographic system by employing optical sensors using low cost approach. The final aim of this project is achieving real-time monitoring of solid particles having low concentration flow when conveyed in vertical pneumatic conveyor. The developed tomography system consists of 32 pairs of Light Emitting Diode (LED) and silicon PIN photodiode. These sensors are used to monitor the emitted radiation for fluctuations caused by particles interfering with the beam when passing through it. A good design of sensor fixture may increase the collimating of light beam from a light source that passes through a flow regime. The obtained information from sensors provided the cross-sectional material distribution in conveyor. By using this information, the relationships between particle distribution and light attenuation effects are investigated by using computer programming to reconstruct the image. The results obtained from this investigation shows that the low cost optical sensors are suitable for monitoring low and medium concentration flowing materials. Optical sensors provide an opportunity to design sensors with a very wide bandwidth, thus enabling the measurement of high speed flowing particles or droplets. *Copyright © 2008 IFSA.*

Keywords: Optical tomography, Image reconstruction

1. Introduction

Pneumatic conveying is defined as the transport of various granular solids and dry powders using an air (or other inert gas) stream as a transportation media. Material handling by pneumatic conveying is increasingly becoming routine in industrial businesses. 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 [1]. Pneumatic conveying offers many advantages over other methods of granular solids transport, factors such as low routine maintenance and manpower costs, dust free transportation and flexible routing. The main disadvantage is the reliance upon empirical procedures for conveyer design, which in effect limits the design to a specific solid material. Relatively minor changes in pipeline layout or operating conditions can often result in unpredicted blockage problems. In addition, power consumption, wear rate, product degradation and particle size separation can be major problems [2].

Process tomography provides several real-time methods to obtain the cross-section parameter in process plant related to the material distribution. These methods involve taking numerous measurements from sensors placed around the vessel of the investigated process plant. The measured data are then fed into a computer program to obtain the internal behaviour of the conveyor. An important advantage in the application of tomography is the ability to explore the spatial distribution of the contents of a process vessel in an intrinsically safe manner and non-invasively. Optical tomography is an attractive method since it may prove to be less expensive, have a better dynamic response, and be more portable for routine use in process plant compared to other radiation-based tomography techniques such as positron emission, nuclear magnetic resonance, gamma photon emission and x-ray tomography [3].

The ability of process tomography in obtaining the internal behaviour of process plant is applied to pneumatic conveyor for a better control of processes, reduced costs and waste. The developed variable density flow meter using electrical capacitance tomography method to measure mass flow rate in pneumatic conveyor was proved to be able to improve process measurement in Montell UK Ltd [4]. An initial work was conducted by applying optical fiber sensor into pneumatic conveyor shows the potential of concentration measurement [5] [7]. The employment optical sensor used the direct analysis method for internal characteristic of process plants has proved the ability to improve the process design and operation of equipment.

2. Optical Sensor Design

2.1. Measurement Metrology

The basic idea of the system involves the projection of a narrow beam from one boundary point and measuring received light at another boundary point. In pneumatic conveyor system, the optical transmitters and receivers are installed around the vessel of conveyor within the same axes. The light from transmitter is projected into the conveyor and detected by the opposite receiver in conveyor. An electronic circuit is used to measure the received light level. The proper use of electronic circuit is able to measure at least two physical parameter of flowing object in conveyor. One of the measurements is the intensity of received light that is related to the distribution of flowing object, while the other measuring is differential of light signal that is related to particle flow rate [9].

For intensity measurement, the voltage generated by the sensors is proportional to the level of received light. It is related to the amount of attenuation in the path of the beam caused by the flow regime. To minimize the error and simplify the calibration process, the ratio of sensor's output signal to a set of reference voltage measured with the level achieved with no obstructions in the light path are used to construct the concentration profile. It is assumed that the relationship between the number of particles passing through a beam and the corresponding sensor output voltage is linear. This measurement performs well in low concentration conveying system. For differential of light signal measurement, an AC coupling technique is used to remove the DC source of output signal from receiver. The obtained measurement depends on the particle flow rate and individual path length of sensor within the conveyor [5]. In other words the more particles that intersect a light beam the greater the output signal.

Then, for a given uniformed flow rate, the output signal from each sensor will be directly proportional to its optical path length. The optical path length is defined as the distance travelled by the beam in conveyor.

2.2. System Design

For the investigation purpose, a conveying pipe with 58 mm (2 inch) internal diameter is used. The designed system consists of 3 major paths. First is a sensor fixture used to fabricate the sensors around the wall of the conveying pipe. Second is the sensor system that consists of 32 pairs of 3 mm super bright LED and 3 mm Silicon PIN photodiode. The LED used provides a narrow view angle of light emission with 635 nm wavelength while the photodiode consists of a narrow reception angle and width spectral respond. The sensor system also includes 32 sets of electronic pre-amp system to convert the generated current from photodiode to voltage. The third path consists of 32 sets of adjustable gain amplifier circuit to provide a signal conformity level to interface with computer data acquisition system.

In this project, parallel projection is employed. Those sensors are arranged in two arrays with sixteen sensors each and placed along orthogonal projections to one another. The arrangement was built around a cross-section of the pipe by using the designed fixture. Figs. 1(a) and 1(b) show the side view and top view of the investigated conveying pipe. The light source is directly transmitted to photodiodes instead of through the usage of fiber optics as transmitters such as the initial system designed by R. Abdul Rahim [5]. The advantages of the present system are the simplification of the sensors fabricating technique, direct applied the narrow view angle of LEDs instead of using lenses (for light collimate purpose), adjustable of light source's intensity, ability to driving LEDs with different types of signals instead of DC source, low cost and low maintain for designed system. Fig. 1(c) shows the 2 arrays of 16 pairs of sensors arranged in orthogonal projection.

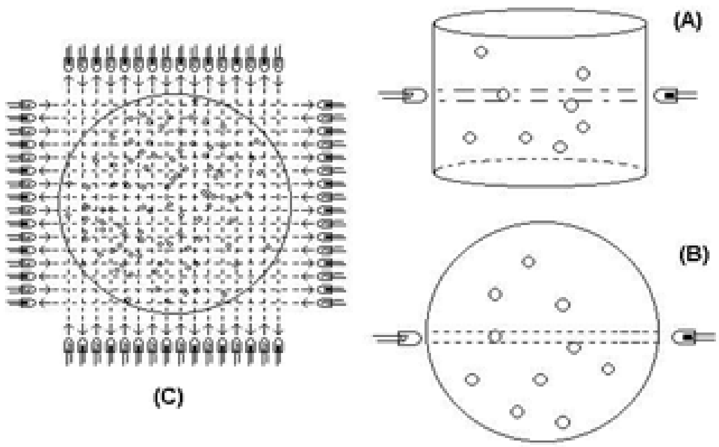

Fig. 1. Sensors Configuration.

Since this system is designed for orthogonal projection, thus each and every sensor is not related to each other. For high accuracy and precision measurement, the diverted light from emitter to other receiver is not allowed. To collimate the light, the narrow view LED plays an important role. In addition, a light stopper with a diameter of 1mm is placed in front of the LED to cut off some unexpected diverged light and all the transmitters and receiver pairs are arranged in an alternate arrangement as shown in Fig. 1(c). By using those methods, the width of light delivery at receiver is around 2 mm. However, due to imperfect sensors fabrication, a small amount of diverged light still occurs in the system. Those effects of light diffraction and scattering are ignored in this project, because the primary effect is attenuation of optical energy by particles intercepting the beam. Thus each sensor takes only a sample measurement of the particles flowing in the pipe. However, it is assumed that each receiver produces reading which represents a realistic sample of the solids passing through the space at each side of the transmitter.

To achieve a precise tomography system, the sensing area should be fully covered by sensors in order to obtain high resolution. The number of sensors should be the more the better. However, for a low cost approach used in this system fiber optics is not used as transmitter, it is impossible to achieve both requirements due to the physical size of sensors. The total area interrogated by the system depends on 2 factors, the beam width and the distance between two beams. To obtain high resolution, both parameters should provide small numbers. The total area covered by the sensor can be determined by the sum of the multiplication of each optical path length within the conveyor with the beam's width. From Figs 1c, it is obvious that individual path lengths are a function of the sensor position within the measurement section. The path length for half of a cross-section can be determined with the following equation,

$$L_n = 2\sqrt{r(n+\frac{1}{2})j) - (n+\frac{1}{2})^2 j^2}, \quad (1)$$

where L_n is the path length of n-th sensor within single axes arranged from the top to centre, r is the radius of pipe and j is the distance between two sensors. The total cross section area covered by a single projection is

$$\begin{aligned} &= 8d\sum_{n=1}^{8}\sqrt{r^2-(r-(n-\frac{1}{2})j)^2} \\ &= 1464.703\text{mm}^2 \end{aligned}, \quad (2)$$

where d is equal to 2 mm (beam width), r is equal to 29mm and j is equal to 3.625 mm. The designed system employed two projections hence the total areas covered can be calculated by multiplying the above result with two and minus the repetition of cross section area between two projections. The result is obtained as below

$$\begin{aligned} &= 2929.4 - \frac{\pi r^2}{D\times D}\times N_x \times N_y \quad \times d^2 \\ &= 2125.2\text{mm}^2 \end{aligned}, \quad (3)$$

where D is the pipe diameter and Nx, Ny is the number of sensors for each projection. N_x and N_y both equal to 16. The total cross section area in conveyor is 2642 mm^2, hence approximately 80% of the pipe cross-section area is monitored.

3. Experimental Configuration

A pilot plant scale gravity flow rig has been designed and constructed to allow conveying particulate object with controllable flow rate. A schematic of this conveyor is shown in Fig. 2.

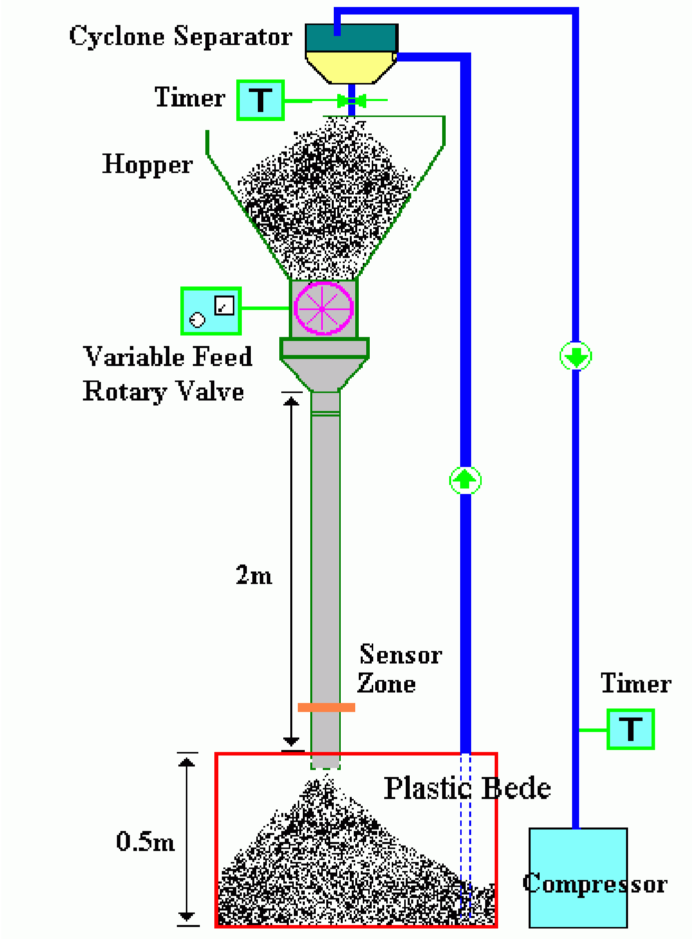

Fig. 2. Pneumatic Conveyor Experiment Rig.

The flow loop consists of a 3.5 meters long and 45mm diameter plastic bend tube to suck the plastic bade from the storage tank to hopper. A timer provided by compressor (vacuum pump) is used to control the release of high-pressurised air from cyclone separator and at the same time feeding the plastic bade into the hopper. The flow loop is completed by feeding the plastic bade back to the tank using the pulling effect from the gravity through an adjustable rotary valve feeder and a two-meter long down pipe. The pipe was designed with an ability to change into different diameters with a maximum of 100 mm. An available control panel with digital indicator is used to control the speed of rotary feeder which propagates to mass flow rate. Due to the feeder in conveyor is a rotary valve, the resulting flow has been un-uniformed. An initial attempt to calibrate the plastic bade flow rate versus digital indicator number was done by taking the average measurement of the weight of dropped plastic bade within a fix duration. Fig. 3 shows the calibration result of mass flow rate versus indicator on control panel.

The calibration curve provided a linear relationship between flow indicators with mass flow rate, the function of the mass flow rate can be determined and expressed as the following equation.

$$f(x) = 22 \times x, \qquad (4)$$

where $f(x)$ is the mass flow rate of plastic bade for x indicator.

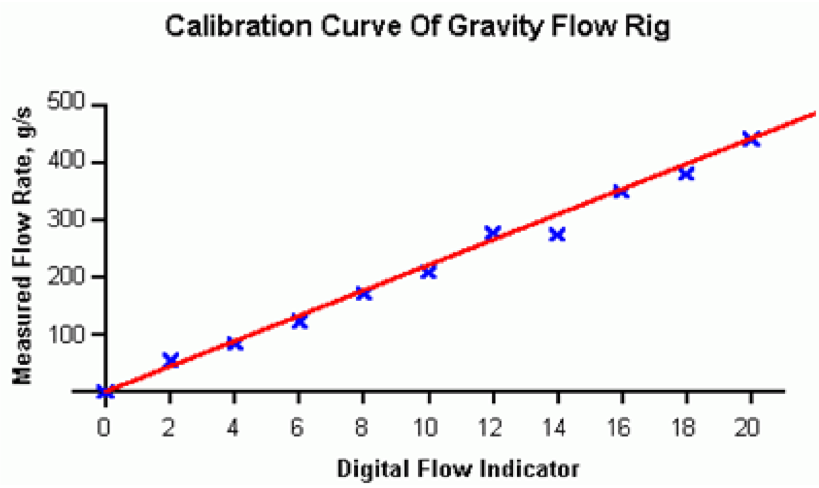

Fig. 3. Mass Flow Rate Calibration Curve.

3.1. Concentration Profile

The measurement technique applied in the project was based on intensity measurement. The aim of the project described in this paper is to generate tomographic images of the conveyor by using these measurements. To model a 32 sensors system, 32 sensitivity maps consisting of a rectangular array of 32x32 pixels is used. Each sensor corresponds to one sensitivity map. Pixels outside the pipe will not contribute to the measurement so the sensitivity value is zero. If the beam of the sensor being considered passes through a pixel within the pipe the pixel has a sensitivity of one, otherwise zero. To obtain each pixel value of each sensitivity map, the simple back projection algorithm is used. Based on this algorithm, the sensor voltage V_i is multiplied with its sensitivity matrix. To obtain the concentration profile, the same element of 32 sensitivity maps is summed. In practice, there are only two sensor's voltages that will contribute to the final individual pixels' values. These correspond to the pixel at the intersection of the X and Y sensor beams.

4. Results

4.1. Concentration Measurements

The starting mass flow rate of plastic bade was set to 20 gm/s. The analogue output from the sensors system was fed into a PC through Keithley DAS1802HC data acquisition plug in board that provided 12-bit resolution. The sampling rate is set at 200 samples per channel per second and all the channel's gain are set to 5 Volt. One minute of signal from sensors system were captured and stored in PC directly using count value provided by DAS with maximum of 4095 (12 bit resolution). A total of 12000 data per sensor is obtained and the mean of each sensor and mean of all sensors is determined by using the computer program. The measurements were repeated for a range of flow rates up to 400 gm/s. Before started each measurement, the feeder is switched off and a set of sensors reference voltages is measured. Then the ratio of mean of all sensors for each flow rate is calculated. As the result, a negative linearly relationship between signals lost ratio and plastic bade flow rate is obtained and shown in Fig. 4.

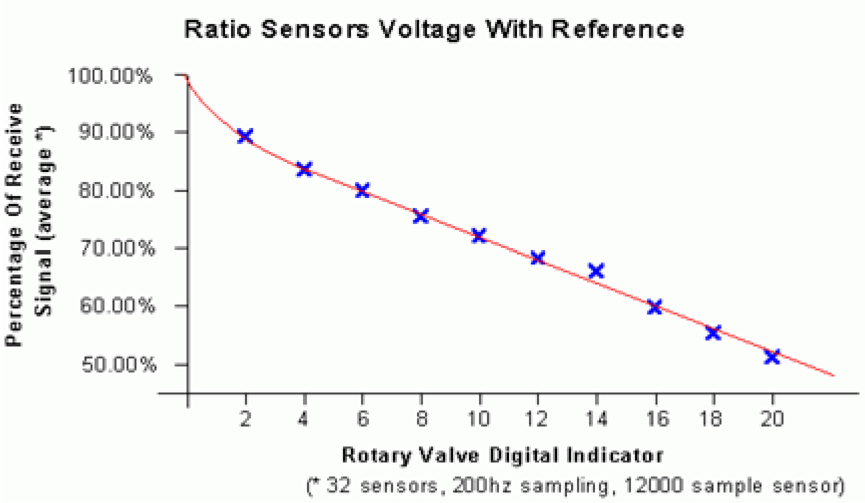

Fig. 4. Relationship between plastic bade mass flow rate with ratio of received voltage.

Based on the curves obtained from Fig. 3 and Fig. 4, an expression of mathematical model for function of mass flow to ratio of received signal can be expressed as the following equation

$$M = 1000 - 11 \times S, \tag{5}$$

where M is the mass flow rate for plastic bade regarding the percentage of ratio of received signal, S. This mathematical model is an efficient estimate for measured percentage of ratio less than 90% due to un-linearly curve above 90%.

4.2. Image Reconstruction

To obtain the reconstructed image of cross-section pipe, the concentration profile described above is used. Each pixel of concentration profile has a maximum value of 8190 by summing the corresponding x and y values. The final concentration profile is obtained by determining the percentage of each pixel of concentration profile to reference profile. A gradient of colours is used to represent those percentages of ratio for cross-section image reconstruction. Fig. 5 shows the ratio (percentage) of gradient of colours representation.

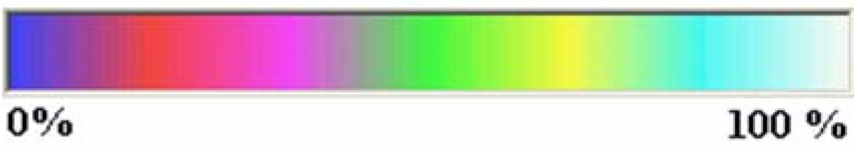

Fig. 5. The colours of percentage of ratio of the received signal representation.

To minimize the effect of the uncovered zone and smoothen the pixels effect on the tomographic image, the resolution of the sensitivity map can be increased by estimating the value between two sensors. This can be performed by using linear interpolation function. This method provides the value between the 2 values through calculation. The mathematical model for linear interpolation is shown as below

$$S(x) = S(x_0) + \frac{S(x_1) - S(x_0)}{x_1 - x_0}(x - x_0), \quad (6)$$

where s(x) is the calculated value between 2 sensors at position x from x_0, x_0 and x_1 are position of two dissepiments sensor while s(x_0) a s(x_1) are their value. Fig. 6 shows the reconstructed cross-section images by applying linear interpolation function into the concentration profile obtained and representing it by using the gradient of colours.

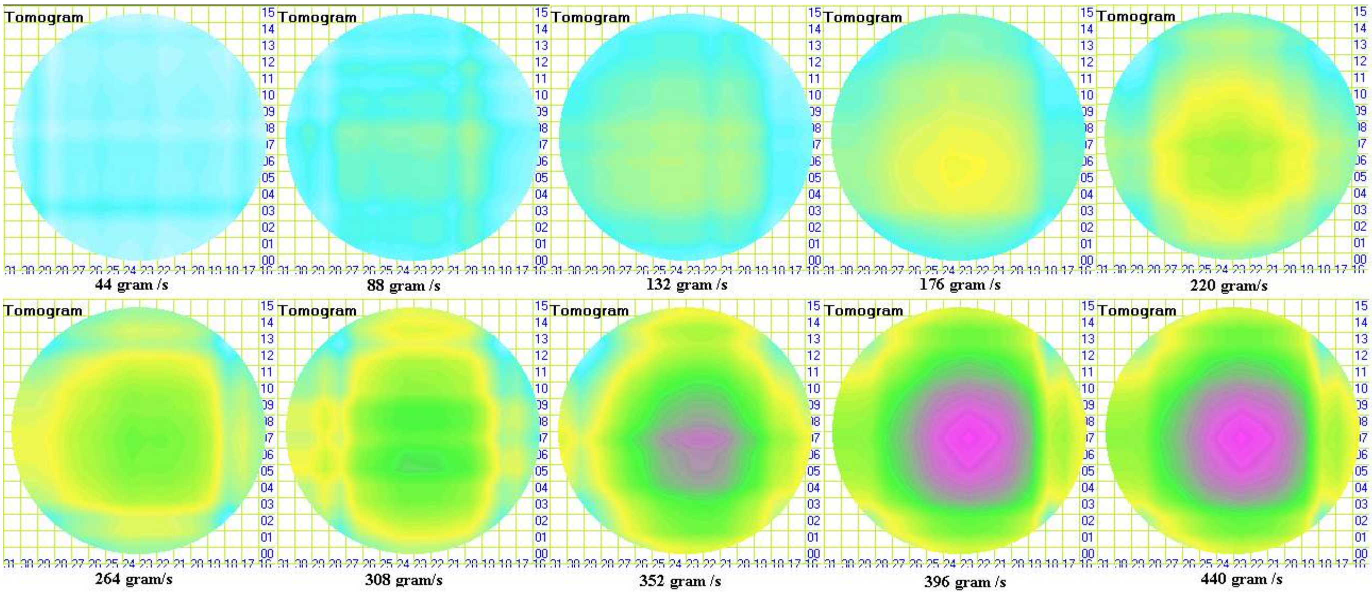

Fig. 6. Cross Section Image Reconstruction For Difference Flow Rate of Plastic Bade.

5. Conclusions

The Eq. 6 of a linear expression shows that the average mass flow rate of particles in the measurement volume increases directly as an inverse linear function to the percentage of ratio of received light. This linear relationship demonstrates the suitability of the optical sensor to perform concentration measurement for uniformed and un-uniformed flows. However, due to the ability of flow rig control, this result is valid for low (40 gram/s) to medium (440 gram/s) distribution flow. Some modification to the capacity of flow rig should be conducted to provide tests for heavy distribution flow.

For flow imaging, the reconstructed cross-section image shows the particles distributions concentrates at the centre of the pipe. This is due the fact that rotary feeder cannot provide a uniformed flow. Resulting in that the use of interpolation function is able to smooth reconstructed image.

The overall accuracy of the measurement can be improved by adding fiber optic as the light transmitter to increase the number of optical sensors so that more information from the conveyor can be interrogated.

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