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OPTICAL TOMOGRAPHY: CONCENTRATION MEASUREMENT IN A PNEUMATIC CONVEYOR

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Abstract. This paper describes an investigation into the use of optical fibre sensors in a tomographic measurement system designed to measure the flow of dry solids in gravity drop and pneumatic conveyors. A simple model of the system is provided and used to predict the response of individual sensors and the full system. Results are provided which show the model is acceptable.

1.0 INTRODUCTION

Tomography Process involves the use of instruments which provide cross-sectional profile of the distribution of materials in a process vessel or pipeline. By analysing two suitably spaced images it is also feasible to measure the vector velocity profile [1,2]. Hence from this knowledge of material distributions and movement, internal models of the process can be derived and used as an aid to optimising the design of the process. This promises a substantial advance on present empiri methods of process design, often based on input/output measurements, with only a limited amou o information about the detailed internal behaviour of the process [3].

2.0 COMPARISON OF THE SENSING TECHNIQUES

A number of sensing methods are available to provide imaging systems of which some will be outlined in this section.

2.1 Optical Sensors (Visible and Infra-red)

Optical systems can be used where the conveying fluid is transparent to the incident optical radiation. The received signals are modulated by the relative attenuation factors of the components in the flow. The optical system can be designed using a pair of optical transducers. The transducer pair consists of an infra-red emitting diode (LED) and a sensing photodiode [4]. Pulses of infra-red light are generated by the emitter and optically configured to form a collimated beam through the fluid in the pipe. The voltage generated by the sensor is related to the amount of attenuation in the path of the beam, caused by the flow regime. The analogue signals from an array of multiplexed transducers, covering a cross-section of a pipe, are converted into digital form and passed into an image reconstruction system. Data acquired in this way can form the basis for a number of reconstruction algorithm enabling an image of the cross-section of the flow regime to be created.

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This optical system has a high data capture rate. Its major problem is due to the physical size of the transmitter and receiver which limit the resolution which can be obtained. Smaller optical devices will improve the resolution and enable optical systems to be applied to pneumatic conveying systems. These smaller devices can be based on optical fibres.

2.2 Positron Emission Tomography (PET)

The characteristic of this method of imaging is that it pinpoints the positions of individual particles in the medium, and not bulk masses as in X-ray tomography. Safety problems arise from the use of the radioactive isotopes required to produce the positron emissions. Also the isotopes have to be injected into the flow. This limits its present applications to laboratory studies or processes where injection and mixing are easy to arrange.

2.3 X-ray

The equipment needed for this is large and bulky, and a high element of danger is involved due to the presence of ionising radiation - so this would not be the best suited tomographic tool for flow imaging in an industrial setting.

2.4 Nuclear Magnetic Resonance (NMR)

This is a very expensive way of imaging suitable for laboratory investigations but not viable for imaging flows in large process vessels.

2.5 Ultrasound

The equipment in the ultrasound measurements include an ultrasonic generator, a transducer to transmit and receive ultrasonic waves and some kind of computerised image processing system.

Ultrasound is now being applied to flow imaging in pipes, and research is being undertaken to develop a tomographic system for flow imaging with ultrasound. However, ultrasound has several specific problems which may limit its application to pneumatic conveyors where transport velocities are generally high for medium to light solids loading. The speed of sound in gas limits the data acquisition rate and particle impact on the flow pipe may produce very high levels of noise at the transducer.

2.6 Electrical Impedance Tomography (EIT)

This technique is being applied to industrial measurement where the process uses a conducting fluid to carry immiscible fluids and solids which possess different bulk conductivities. It cannot be used for pneumatic conveying.

2.7 Electrical Capacitance Tomography (ECT)

Electrical capacitance tomography (ECT) systems are suitable for imaging industrial multi-component processes involving non-conducting fluids [5]. An ECT system basically consists of three sub-system, the primary sensor with multiple electrodes, the capacitance data acquisition electronics and the computer system for image reconstruction and process data interpretation.

Capacitance systems are suitable for medium to high solid loading in the conveyor process. However, as the solid loading decreases the systems fail to produce meaningful images because of the relatively low signal to noise ratio of the capacitance to voltage transducer and non-uniform sensing fields.

3.0 VOLUME OF MEASUREMENT SECTION INTERROGATED BY THE OPTICAL FIBRE SENSOR

This section investigates the volume of the measurement volume actually interrogated. The fibres are mounted into slots machined into the measurement section in an invasive but non-intrusive (i.e. the flow pattern is not affected by their presence) manner. In order to investigate the feasibility of the proposed system, two arrays of sixteen transducers each are placed along orthogonal projections (Figure 1). This choice of sixteen per projection is a compromise between high resolution (more sensors) and the limited financial budget available for the project.

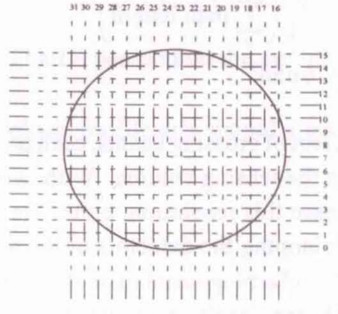


Figure 1 Arrangement of two orthogonal 16 transducer projections

Figure 2 shows the beam width and spacing inside the pipe for one array.

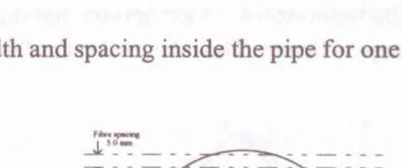


Figure 2 Dimensions of 16 transducer projection

The pipe in which the sensors are mounted has a nominal bore of 81 mm with a sensor spacing of 5 mm. This spacing means that with an optical fibre diameter of 1 mm, approximately one fifth of the cross-section is directly interrogated and the remaining four fifths are not being in a direct path between a source and its receiver, although there may be some output due to the beam spreading out from the transmitter fibre due to its optical aperture and light scattering by the particles. The effects of diffraction and scattering are ignored, because the primary effect is attenuation of optical energy by particles intercepting the beam. Thus each fibre is taking only a sample measurement of the particles flowing in the pipe. However, it is assumed that each fibre produces readings which represent a realistic sample of the solids passing through the space at each side of the fibre.

Although the transmitted beam diameter expands to a maximum of 4 mm, the width of the detected beam is only 1 mm, the diameter of the optical fibre. Then the total volume of the measurement section,

V_T being interrogated is

$$V_T = \pi \frac{d^2 l}{4}$$
$$= 5.15 \times 10^3 \, MM^3$$

where d = 81 mm, l = 1 mm is the width of the fibre.
The volume being monitored by each projection of sixteen views, V_{16} is

$$V_{16} = \pi \frac{l^2}{4} \left(\sum_0^{15} \text{path length} \right)$$
$$= 76 \, mm^3$$

This means that, neglecting the effect of crossing beams, each projection provides a statistical sample consisting of 15.4% of the flow in the sensing volume. With two projections, approximately 30% of the volume is sampled. To increase this resolution, either the sensors could be spaced at 2.5 mm without the expanded beams overlapping the detectors or the transmitters could be interspersed by receivers. This would enable a 32 × 32 arrangement to be attained, and the volume sampled to be 60%. Signal processing of the received beams results in a voltage which increases with increased solid flow rate, i.e. the more particles that intersect a beam the greater the voltage. The assumption made in this paper is that the relationship between solid concentration passing through a beam and the corresponding sensor output voltage is linear. Thus the total mass flow rate is given by equation 1.

$$V_{total} = \sum_{j=0}^{31} V_i = k \dot{m} \sum_{j=0}^{31} P_i \tag{1}$$

Where k is a constant proportionality, is a mass feed rate and P is a path length of ith beam and Vi, is the output of the ith transmitter receiver pair.

Continuing with this assumption, for a given uniform flow rate the output voltage from each sensor will be directly proportional to its optical path length. The theoretically predicted sensor outputs for a uniformly distributed solid flow are shown in Figure 3.

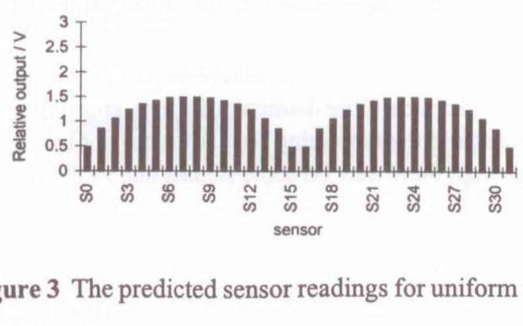


Figure 3 The predicted sensor readings for uniform flow

If the effective path length is reduced, say by a baffle as shown in Figure 4, the method described above may be used to predict the expected sensor output voltages.

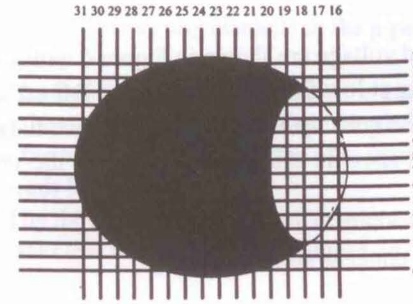


Figure 4 The effect of baffle position on the predicted optical path length

These calculations determine the voltage profile that should arise from sensors arranged around the circumference of the conveyor.

4.0 RESULTS

4.1 Test on scattering effect

To test the interaction between adjacent receivers, a single transmitter fibre was energised and the outputs from all the receivers monitored for a range of sand feed rates. The results are shown in Figure 5.

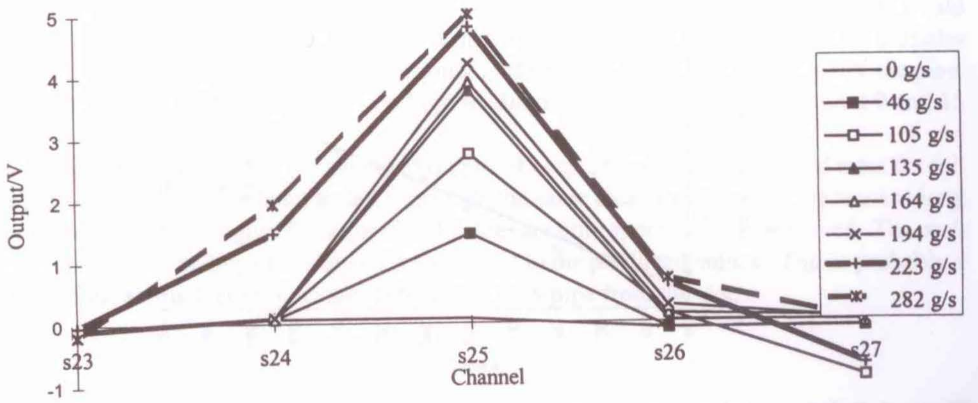


Figure 5 Scattering effect

At low feed rates (46 to 194 gm/s) no interaction was detected. Flow rates of 223 gm/s and above one adjacent receiver indicated approximately 1.5V (equivalent to 46 gm/s) and the other produced a small contribution towards the total concentration measurement.

4.2 Results of concentration measurements using sand

The sand flow was set to provide a flow rate of 40 gm/s. The output of the optical fibre sensor was monitored for several seconds and the mean voltage determined. The measurements were repeated for a range of feed rates up to 520 gm/s. The measurements were limited to maximum feed rates of 320 gm/s due to the data capture time of thirty two seconds and the amount of sand available in the hopper.

Results for the time averaged voltage are shown in Figure 6 with a linear regression line fitted to the results. The negative reading at low flow rates is due to a DC offset voltage in the amplifier. A gravity drop conveyor is used, the velocity at a given length down the pipe is mainly the function of gravity and so is constant at a specific cross-section. Since the velocity is constant and mass feedrate $\dot{m}$,

$$\dot{m} \propto \text{concentration} \times \text{velocity} \tag{2}$$

then, for the conditions of the tests presented here, concentration is directly proportional to .

4.2.1 Analysis of results and discussion

The equation of the straight line graph shown in Figure 5 is:

$$V_o = 0.005\ \dot{m} - 0.008 \tag{3}$$

The average number of particles in the measurement volume should increase directly as a linear function of the solid flow rate. This linear relationship demonstrates the suitability of the optical sensor for concentration measurement for lightly loaded uniformly distributed flows (up to approximately 2% solids by volume in the test) and providing the ends of the fibre to be kept free of dust during the measurement procedure. In a practical system this could be achieved by placing an air purge upstream of the optical fibre.

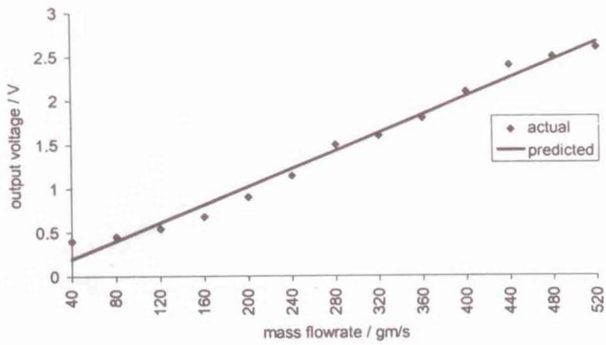


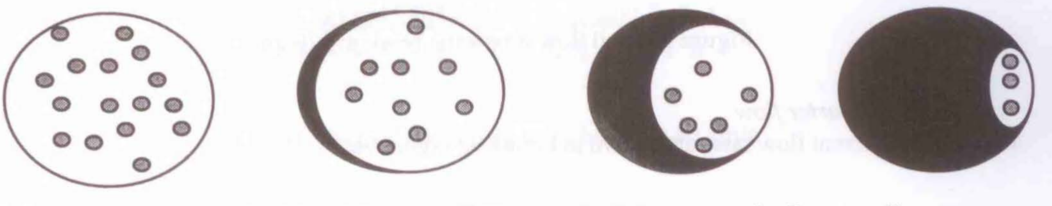
Figure 6 Relationship between mass flow rate and optical sensor output voltage for optical fibre receiver number twenty five

4.3 Concentration measurement with thirty-two sensors

The aim of this section is to investigate the use of the optical array for concentration measurement across the pipe. Measurements were made by energising all 32 transmitters and monitoring the output at a solid flow rate of 40 gm/s using the data acquisition system to obtain 312 samples, with a sampling frequency of 10 Hz per channel for 32 seconds, for each flow measurement. The measurements were repeated for a range of solid mass flow rates from 40 to 120 gm/s using the plastic beads. The tests were repeated for a range of artificially created flow regimes.

The regimes created and tested are:

1. Full flow : This is generated by not putting any obstacle in the pipe so that a full, continuous flow is obtained (Figure 7a).
2. Three quarter flow : This is created by the baffle blocking a quarter of the pipe diameter and leaving the other three quarters clear for plastic beads (Figure 7b)
3. Half flow : This is created by the baffle blocking half the pipe diameter and leaving the other half clear for plastic beads (Figure 7c).
4. Quarter flow : This is created by the baffle blocking three quarters of the pipe diameter and leaving the other quarter clear for plastic beads (Figure 7d)



a. **Full flow** b. **Three-quarter flow** c. **Half flow** d. **Quarter flow**

Figure 7 Diagram of baffle configurations for generating flow regimes

4.3.1 Results with plastic beads flow

4.3.1.1 Full flow

No obstruction is used upstream of the sensor array so that, under ideal conditions, the solids would be uniformly distributed within the flow section. With a uniform distribution, the number of particles passing through a given beam should be proportional to the path length of that beam inside the pipe, i.e. sensors numbered 7 and 8 should provide high readings relative to sensors numbered 0 and 15 (Figure 1).

Figure 8a and Figure 8b shows the averaged output of each sensor at different feed rates for full flow. The predicted values have been scaled to provide the same mean flow rate and are shown along side for comparison. In both Figure 8, the predicted values are only approximately achieved. The peak values for the measured readings are skewed with respect to the predicted values. This is probably a characteristic of the screw feeder, because it enters the flow pipe from the side.

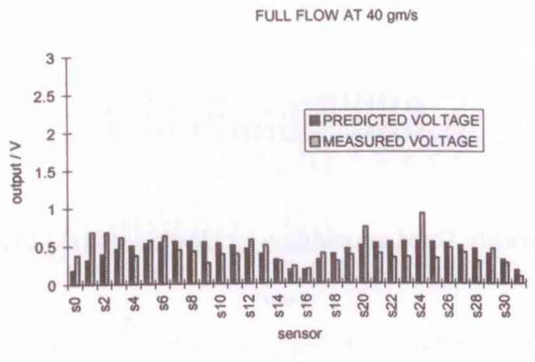


Figure 8a Full flow for plastic beads at 40 gm/s

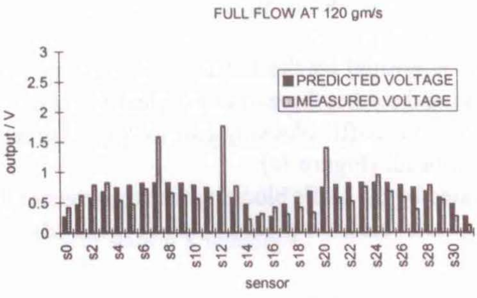


Figure 8b Full flow for plastic beads at 120 gm/s

4.3.1.2 Three quarter flow

Results for different flow rates are shown in Figure 9a Figure 9b.

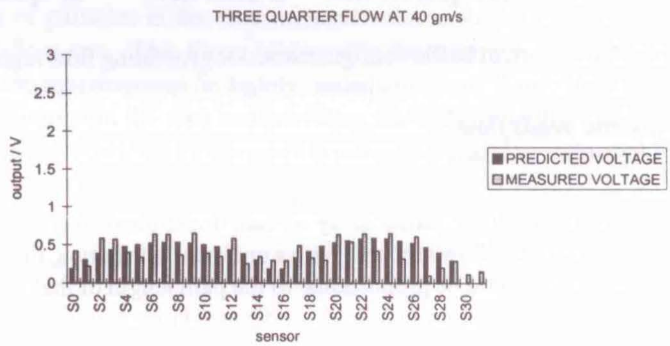


Figure 9a Three quarter flow for plastic beads at 40 gm/s

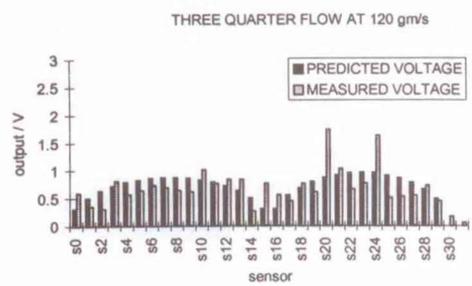


Figure 9b Three quarter flow for plastic beads at 120 gm/s

4.3.1.3 Half flow

This is created by the baffle blocking half the pipe diameter so that the other half will be clear for plastic beads flow (Figure 7c).

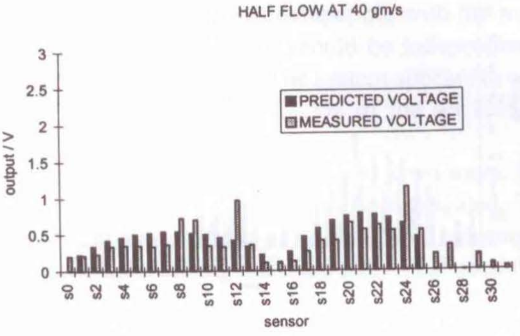


Figure 10a Half flow for plastic beads at 40 gm/s

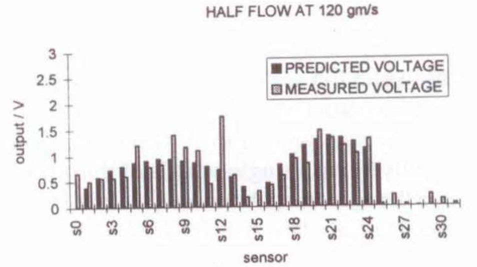


Figure 10b Half flow for plastic beads at 120 gm/s

4.3.1.4 Quarter flow

This is created by the baffle blocking three quarters of the pipe diameter so that only a quarter is clear for plastic beads to flow (Figure 7d).

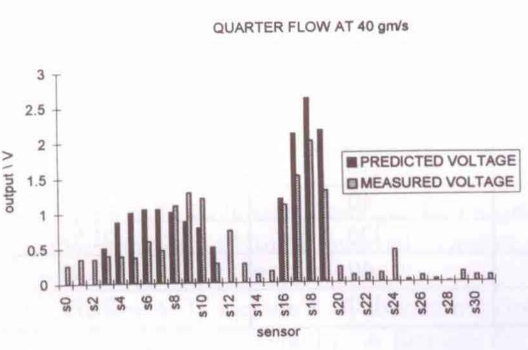


Figure 11a Quarter flow for plastic beads at 40 gm/s

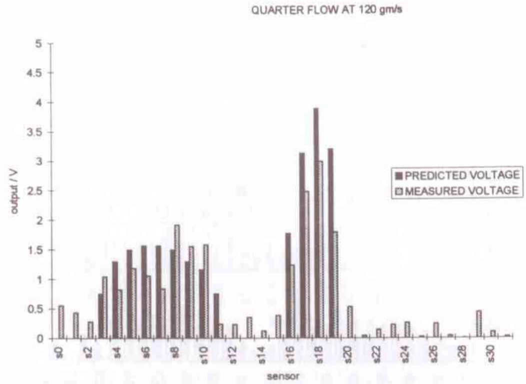


Figure 11b Quarter flow for plastic beads at 120 gm/s

4.4 Discussion of results from different types of flow

The results obtained by comparing the measured and predicted flow rates show some general agreement. However there are two noticeable discrepancies. Firstly, under half and quarter flows the predictions show several sensors with zero output. This is not achieved, though these sensors actually only show low levels of solids passing them. This result is due to inter particle collisions and particle wall collisions occurring while the solids travel between the baffle and the measurement section. Secondly, the voltage profile is different to the predicted profile. This is due to a combination of two factors; the fact that the screw feeder fails to provide a uniform distribution across the pipe inlet and the measured voltage profile only being a single sample of thirty-two seconds duration (a longer measurement period may improve the agreement between theory and practice).

The total measured output for the thirty two sensors is summed for all the measurements. The values obtained for three quarter, half and quarter flow are compared with the total measured output for full flow at each mass flowrate to obtain an estimate of the error of the system. Ideally, the measurement should be independent of the flow regime, so that the system can be used to measure the mass flowrates.

Table 1 shows the error for each flow measurement for plastic bead flow.

Table 1 Error for each flow measurement for plastic beads flow

Profile	Mass flow rate (gm/s)	Total output voltage for 32 sensors (V)	Error (%)
Full flow	40	13.91	
	120	20.63	
Three quarter flow	40	13.12	5.68
	120	21.60	4.70
Half flow	40	13.28	4.53
	120	21.57	4.56
Quarter flow	40	13.10	5.82
	120	21.72	5.28

The statistical parameters for the error have been calculated and show a mean of 5.43% and standard deviation of 0.21%.

6 CONCLUSIONS AND FUTURE WORK

Tests on linearity showed straight line relationships between sensor output and mass flow rate, with no sign of saturation over the range of flows used: up to 4% vol./vol. The model based on the optical path length of each transmitter receiver pair seems compatible with the measured accuracy of the system. For flow measurement, the system results should be independent of how the solids are distributed in the flow cross-section (flow profile). The system appears to achieve this requirement, because all the measured flow rates were within 11.3% of the set feeder rate for all the flow distributions investigated.

The overall accuracy of the measurement can be improved in two ways. Firstly, by increasing the number of optical fibre sensors so that more of the conveyor is interrogated. The number of fibres can easily be doubled, increasing the sampled volume to 62%. Secondly, by using a longer averaging time constant to reduce the rapid fluctuations arising from the individual particles, which could be provided either in hardwares or softwares.

Optical tomography systems have been relatively neglected. This paper, however, demonstrates that they work in the laboratory. They have several advantages over other sensing systems. They are linear in their response to increases in concentration and the optical beams travel in straight lines. This simplifies the reconstruction of tomograms, which should also be provided at high speed. The high resolution (better than 2%) and frequency bandwidth associated with these sensors should enable velocity profiles to be obtained. The major problem is in keeping the optics clean. However, many industrial processes make use of air purge systems and this may be a suitable case.

The effect of scattering and diffraction of light due to the particles has been neglected. Further work to determine their importance in the flow measurement is required. The information, presently being neglected, may have relevance to particle size distribution.

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