Development of Electrical Capacitance Tomography for Solids Mass Flow Measurement and Control of Pneumatic Conveying Systems

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Abstract *– This paper describes a novel development of a solid mass flow meter incorporating a combination of a twin-plane Electrical Capacitance Tomography (ECT) System and a DSP-based multi-channel direct cross correlator. In addition to flow imaging, the ECT system is able to measure the concentration and velocity of the solids moving in the conveying pipe. By using inferential measurement, it is possible to get the mass flow rate by combining the concentration and velocity measurements. Industrial evaluation of the measuring system was undertaken and results and challenges are presented.*

Keywords: ECT, mass flow, cross correlation, pneumatic conveying

1. INTRODUCTION

1.1. The need for solid flow metering

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.

From a number of conveying parameters, one parameter of particular interest relates to the amount of material conveyed per unit time i.e. the mass flow rate, expressed in kg/second or ton/hour. By accurate metering of the material in industrial processes, the ultimate target is to achieve efficient resource usage, in terms such as material, energy, operating cost, maintenance and investment. A 5% saving of these resources within one year would be very significant on a national scale. It is also imperative to create safe working environment and to meet stringent government regulations.

1.2. Research in solid flow metering

Research in multi-phase flow metering has gained a lot of attention from universities and manufacturers during the last two decades, as seen from the large number of publications in this area [1,2,3]. Despite that, there is still a serious lack of accurate and reliable flow meters for solid/gas phase systems. This is what drives our investigation to develop such a measuring instrument using a novel approach, and apply it to pneumatic conveying systems.

Several factors motivate our project to developing solid/gas flow meter based on an ECT system:

- Growing need for accurate solid flowmeters to be used in pneumatic conveying systems.
- Instrumentation based on the unique ability of **multi-sensor capacitance and electrodynamic charge** measurements to

accurately measure the rapidly varying solids concentration and velocity profiles in **dense phase pneumatic conveyors** (5-200 kg solids/kg air, 1-30m/s)

- No obstruction to flow and highly resistant to abrasion
- Application of tomographic and cross correlation techniques

2. A NEW APPROACH TO SOLID FLOW MEASUREMENT

2.1. A systematic approach

Figure 1 below illustrates a novel approach to solid/gas flow metering, which incorporates a combination of a twin-plane Electrical Capacitance Tomography (ECT) System and a DSP-based multi-channel direct cross-correlator. Other than just for flow imaging, the choice of a twin-plane ECT offers a unique ability to measure the concentration and velocity of the solids moving in a conveying pipe. Meanwhile, a DSP-based multi-channel cross-correlator, specifically developed for this project, provides an independent measurement of velocity [4]. Its inputs come from four pairs of electrodynamic charge sensing electrodes. Inferential measurement permits the mass flow rate to be calculated by combining these concentration and velocity measurements.

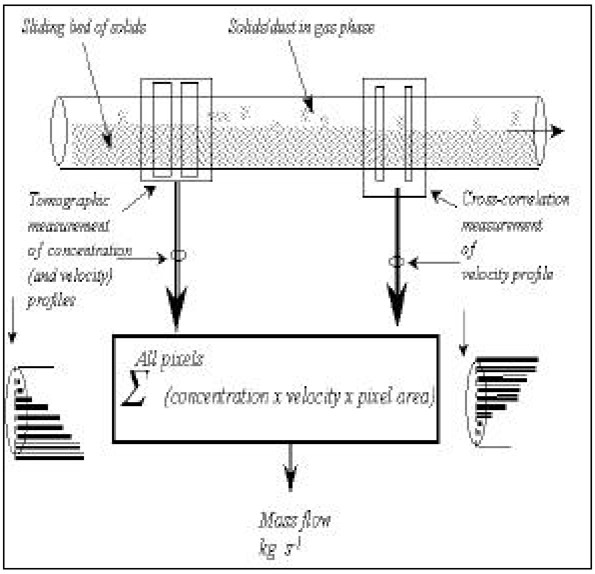

Figure 1. Schematic arrangement of mass flow measurement

2.2. Sensing electrode design

A special assessment of electrode design for the twin-plane ECT sensor has been done to obtain the optimal sensing area. A study by Hammer and Green [6] about the spatial filtering effect of capacitive sensor for flow measurement reveals, that an electrode length of between one and two internal pipe diameters gives an electrode length coefficient of one. Here, electrode length coefficient is defined as the ratio of effective electrode length and its actual length. As the internal pipe diameter of our pipeline is 50 mm, the electrode length is chosen to be 75mm. Figure 2 depicts an axial cut of the ECT sensor, showing the electrodes, spacer, shielding and the pipe wall.

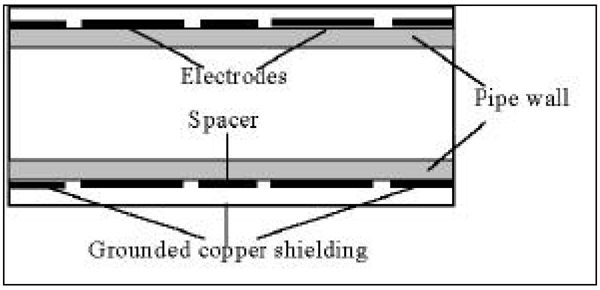

Figure 2. Schematic of twin-plane ECT sensors

To investigate the effect of solids fraction in the pipe and spacing between sensor planes to the sensing fields, a further numerical simulation was undertaken [7]. As a result, a grounded band of 50 mm between the planes was used to minimise interference between planes.

2.3. Mass flow rate determination

The mass flow rate can be determined in the following way. Using the tomographic images, the solids concentration measurement is readily at hand, as each pixel value in the cross sectional images gives the solids concentration at the corresponding position in the pipe. Two independent methods of solids velocity measurement are employed. The first method is by cross-correlation of two sequences of ECT images from the first and second planes to get axial vector velocity at each pixel position in the pipe cross section; very similar to the pixel-wise concentration measurement. This method allows velocity measurement up to, say, 3 m/s due to the limited current frame rate of the ECT of around 100 frames per second. As it will be clear from the ECT data analysis later, special features of intermittent flow give a possibility for simple velocity calculation.

For velocity higher than 3 m/s, ECT will not be able to determine velocity properly as it is limited by its capture rate. An electrodynamic charge sensing technique offers a solution. Here, the results from the DSP-based charge cross correlator must be used to give both the instantaneous and averaged velocity. Velocity of up to 30 m/s can be measured readily by this last method. On the other hand, solids density measurement can be performed off-line before running the flow rig. The solids density is assumed constant during the operation. If online density and moisture measurements are required, microwave or radioactive methods might offer a solution [5]. Multi-modality measurements are now emerging to tackle a variety of problems.

When the instantaneous solids concentration, velocity, density and the pipe cross sectional area are already known, the instantaneous mass flow rate is calculated by integrating the product of individual pixel concentration, velocity and density over the whole pipe cross sectional area. Sometimes it is necessary to have both instantaneous and time-averaged concentration, velocity and mass flow rate for monitoring and control purposes.

2.4. Mass flow rate for intermittent flow

Image cross correlation works well for continuous flows with enough variations which act as tagging signals. Unfortunately, this method performs poorly when the flows are intermittent, i.e. the flows stop and go randomly in the pipe during conveying. During our tests, we observed that dense phase conveying tends to appear as a type of intermittent slug flow or dune flow.

The formation of such a discontinuous flow presents difficulty in the calculation of the actual concentration and velocity of the conveyed solids. The ECT will capture data whether or not solids move. When the solids are in the rest state, the calculation of solids fraction would erroneously give the same values for a number of frames. The pixel cross correlation to obtain velocity would fail especially when the lower part of a horizontal pipeline is always contained with solids. The plots of global solid fractions from two ECT planes over time fortunately show very similar patterns. The individual slug velocity is thus easily calculated by counting the number of frame shift between planes as illustated in Figure 3 below.

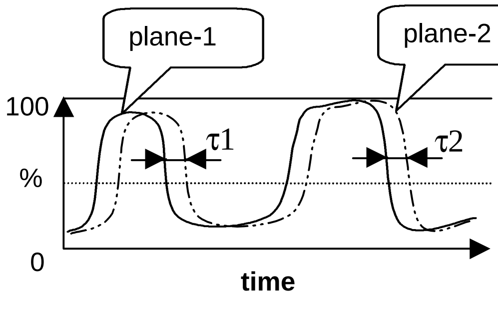

Figure 3. Concentration and delay time of an intermittent slug flow

Here, we introduce a term '*intermittency factor.*' This factor is to account for the 'stop and go' of the intermittent slug flow under investigation which otherwise would give a too high mass flow rate. From our experiments, it is found that this factor needs to be calculated only once for the first time.

The straight forward way of deriving the intermittency factor is to divide a reference MFR by calculated MFR for the very first measurement. For further calculation of MFR based on ECT data, the same intermittency factor is included to correct the outputs.

Finally, a meter factor is then calculated to test how accurate is the MFR measurement by ECT and by reference load cells. Ideally, the meter factor should be very close to a value 1.0. Any deviation from 1.0 means an error relative to the reference. Load cell measurements act as the independent reference mass flow rate to justify the mass flow rate measured using this new arrangement.

3. INDUSTRIAL EXPERIMENTS OF FLOW MEASUREMENT

An industrial evaluation has been carried out to show that this new arrangement can produce mass flow rate measurement in addition to the flow visualisation obtained by the tomographic system. For this purpose, the Neu Engineering's Neuphase conveying system has been used to generate dense phase flows of plastic beads. In this experiment, the sensors were located close to the exit of a blow tank to measure the solids discharge rate. Discontinuous slug and dune flows were observed through a transparent pipe section.

3.1. Experimental set-up

A simplified schematic of the pneumatic flow loop for an industrial testing is drawn in Figure 4.

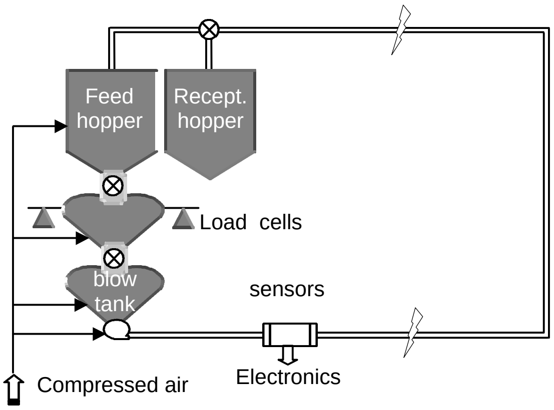

Figure 4. Simplified schematic of pneumatic flow rig

Starting from the feed hopper, solids flow through a valve to the blow tanks. Pressure by compressed air in the lower blow tank forces the solids to enter the pipeline. In the pipeline, solids travel around 80m long and loop back to the feed or reception hopper.

Figure 5 below shows an on-site photograph of the experimental set-up.

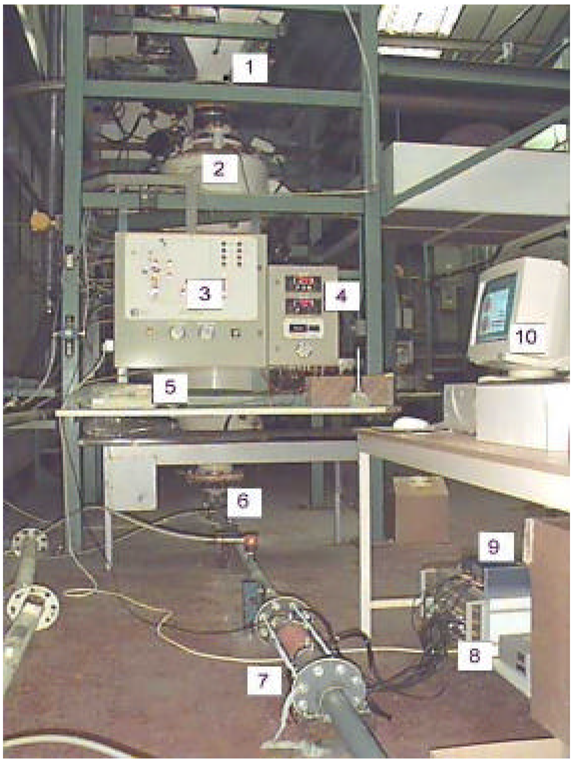

Figure 5. Measurement system installed in a full scale pneumatic conveying system

Shown in the photograph are: *(1)* feed hopper, *(2)* blow tank, *(3)* control panel, *(4)* display of solids weight, *(5)* chart recorder, *(6)* joining of the blow tank to the pipeline, *(7)* tomographic and electrodynamic charge sensors, *(8)* twin-plane ECT data acquisition system, *(9)* DSP-based cross correlator and *(10)* PC and display monitor. Not visible in the photograph is the load cells supporting to the blow tank. Each ECT plane has 8 electrodes of 75mm length. The distance between two nearest ends of the electrodes from first plane to the second plane is 50mm. In addition, 4 pairs of 5mm width electrodynamic sensors for the DSP-based correlator are employed, axially spaced at 20mm. The solids used for this evaluation are plastic beads of 3-5 mm average diameter.

3.2. Experimental procedure

The main steps involved with field trials are summarised below.

Sensors installation: Since we are interested in the measurement of the mass flow rate of the solids leaving the blow tanks, the sensors should be mounted as close to the lower blow tank exit as possible. However, we need to allow the flow to develop fully. The sensors, which are already pre-fitted around a piece of clear perspex pipe, of 69 cm long, are therefore installed in the pipe line at a distance of 270 cm away from the lower blow tank exit. This distance is 54 times the internal pipe diameter (5 cm)

Calibration of load cells: Since the solids flow rate derived from the load cell measurements will be used to calibrate the measurements performed by the ECT system, the load cells must first be calibrated properly. The measurement range of the load cells was set to 0 kg (for empty blow tanks) and 228kg (for full blow tanks).

Calibration of ECT system: Although the ECT system had been calibrated just before the perspex pipe containing the sensors was installed in the conveyor pipeline, it was found that in-situ recalibration was necessary. This was thought to be caused by the twisting/movement of the cabling and shielding relative to the sensing electrodes during the installation of the perspex pipe into the pipeline.

Density measurement of conveyed solids: The density of solids being conveyed needs to be known in advance, in order to calculate the mass flow rate. For most processes the density measurement can be carried out once only, as it will not change significantly during the transport.

ECT data collection and load cell chart recording: After the ECT system and load cells were successfully calibrated, two tasks had to be carried out simultaneously. These tasks were measurement / data collection by the twin-plane ECT, and continuous recording of the total solids weight in the blow tank by a chart recorder. Each ECT measurement result had to be accompanied by its corresponding chart of the solids weight in the blow tank for a certain period. This allows calculation and comparison of the solids mass flow rate based on two independent measurement systems: ECT system and load cell system.

3.3. Technical problems arising

There were some technical problems identified during the experiments, which constitute an obstacle to using ECT system in an industrial environment.

First, as already indicated earlier (see section 3.2), there was a need for recalibration of the ECT system. Although it was easy to calibrate the ECT sensors prior to installation, this seemingly simple task was found to be exceedingly tedious with the sensors in-situ. Clearly, the method of empty-full calibration [8] is unacceptable for industrial processes, since the on-going process has to be halted during calibration.

Second, a problem of electrostatic charge accumulation and spark is commonly found in a pneumatic conveying system. This problem becomes obvious when dry materials such as plastic beads are being conveyed. Attention must be paid to eliminate or reduce the chance of excessive charge build-up and sparks, which could otherwise be hazardous to the operators, the electronic instruments and the entire system.

During our tests, the measuring electronics failed each time sparks occurred. So the first step was to protect the electronics. Back to back fast, signal diodes were used to limit the input levels and give a low impedance path to ground to speed up charge decay. This measure worked well and the electronics withstand sparks that still occurred sometimes. In addition to placing diodes, massive grounding was adopted for the pipes, sensors and electronics. Usage of a glass tube instead of perspex pipe should reduce the charge induction and accumulation around the sensors. Another less practical way was the use of anti-static spray around the sensors to make a fast path to ground. However, this was not done since it could cause short circuits to the sensors.

4. EXPERIMENTAL RESULTS

The results of this preliminary study in industrial environment are presented below. The concentration and velocity profiles of the flowing solids are described first. The mass flow rates are the last.

4.1. Concentration profile

Figure 6 is a screen shot of an online measurement by a twin plane ECT system. Two circles are images of cross sectional 'view' or concentration profiles of the solids in the pipeline at two different places. Here, the measured concentrations are 81% and 99%, respectively. The top image is the concentration profile at the first plane with a small air fraction at the upper part. The bottom image indicate that at second plane the pipe is full of solids.

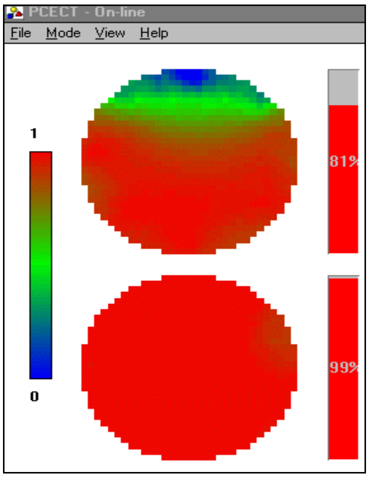

Figure 6. Online tomographic images of twin-plane ECT show solids concentration profiles at their respective planes

The upper graph of Figure 7 below is a plot of global concentrations calculated from 2 series of 1000 images. The black solid line is concentrations at plane-1 and the blue dotted line is that of the plane-2. Two points are important to note regarding this plot. First, the size and spacing of slugs are randomly distributed. The production of random sized slugs is probably due to the absent of rotating valve in the joining between the blow tank and pipeline. Second, the trend of solids fraction exhibited by first and second planes is very similar. It shows that the measurements are highly correlateable.

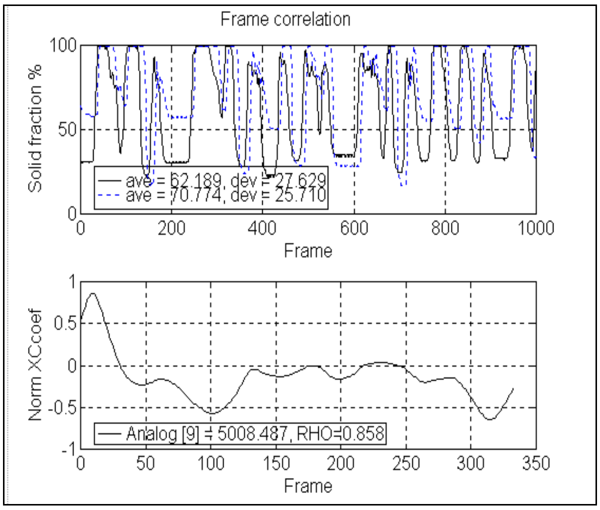

Figure 7. Plots of solids fractions of 1000 frames (TOP), and their cross correlation (BOTTOM)

Also shown in lower part of Figure 7 is the cross correlation of both concentrations to give a delay of 9 images and NCC of 85%. It tells us that the solids travel from plane-1 to plane-2 in 9 frame time. Since the distance between planes is known, the average plug velocity can be calculated.

4.2. Velocity profile

By cross correlating two arrays of cross sectional images, the velocity profiles can be calculated. The next two pictures are the velocity profile and its Normalised Cross correlation Coefficients (NCC). The velocity at the upper part of a horizontal pipe is higher than that of lower part, as shown in Figure 8 below. The layers of different velocities across the pipe cross section agree with the expected profile for dense slug flow. The NCC profile is included here in Figure 9, to show that velocities at the upper part can be determined confidently (indicated by high NCC). At the lower part of the pipe, however, the solid velocities are very low or even zero and thus does not contribute significanlty to the mass flow rate.

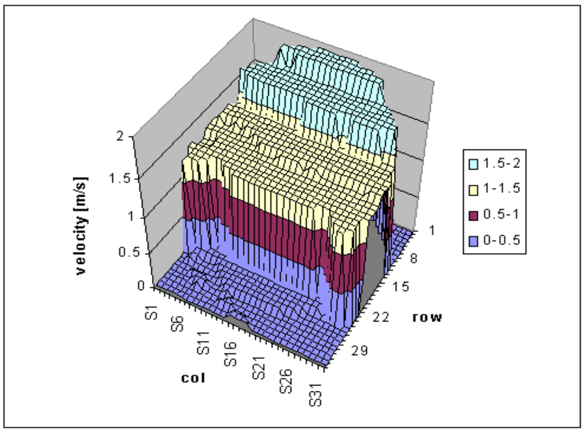

Figure 8. The velocity profile shows that the velocity at the upper part of a horizontal pipe is higher than that of lower part

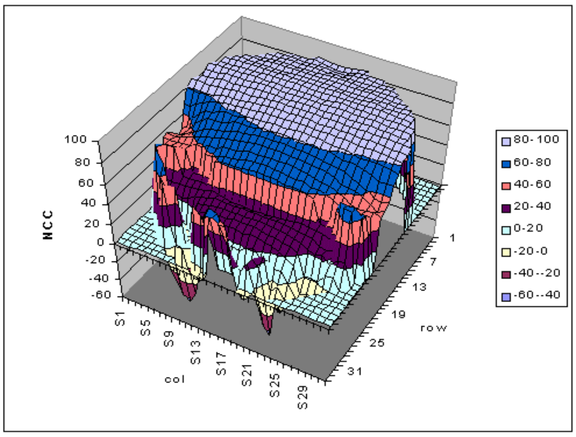

Figure 9. The NCC profile of velocity profile shown in Figure 8.

4.3. Mass flow rate

Table 1 and Figure 10 summarise the mass flow rates obtained by the ECT system and by a chart recorder connected to load cells. An intermittency factor is calculated to correct the very first ECT measurement. Both mass flow rates are very close.

Table 1. MFR measurement results

Exp. No	Measured MFR (ton/hour)	LC MFR (ton/hour)	Meter Factor	Error (%)
1	1.9345	1.9006	1.0178	1.78
2	1.9536	2.0207	0.9668	-3.32
3	2.0951	2.0290	1.0326	3.26
4	1.8496	1.8703	0.9889	-1.11
5	1.8496	1.9280	0.9593	-4.07
6	2.2137	2.0681	1.0704	7.04
7	1.8289	1.8623	0.9821	-1.79
8	2.1955	2.0949	1.0480	4.80
9	1.9510	1.9937	0.9786	-2.14
10	2.0986	2.0187	1.0396	3.96
11	2.1439	2.0776	1.0319	3.19
12	2.1962	2.1982	0.9991	-0.09
13	2.0821	2.0412	1.0201	2.01
14	2.2857	2.0687	1.1049	10.49
15	1.9757	2.0153	0.9803	-1.97

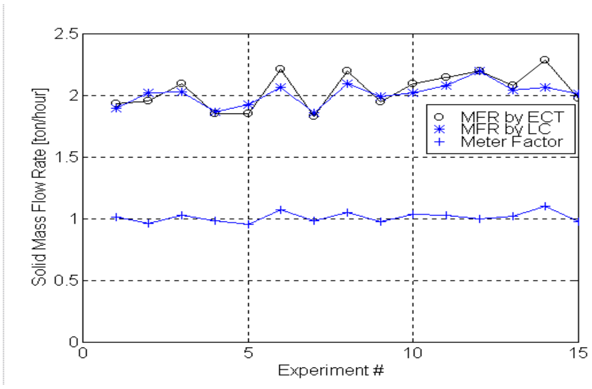

Figure 10. Plot of MFR measured by ECT and Load Cell and the corresponding meter factor

Figure 10 above plots the mass flow rates and meter factor from Table 1 for ease of comparison. The trends are similar for both mass flow rates and the meter factor line is close to a straight line of 1. Most errors are within 5% and the average error is 1.4%. These errors might be attributed to the calibration of ECT, load cells and the chart recorder.

5. DISCUSSION

Industrial evaluation of the proposed new approach of flow measurement has been carried out and produced very promising results. Flow parameters of interest such as velocity, solids fraction and mass flow rate were readily obtainable by this measurement. With concentrated effort, it should be possible to exploit the proposed approach to make a cost effective and reliable flow meter for non-intrusive online use.

Since the mass flow measurement performed here is of inferential approach, concentration and velocity are also available. By utilising on-line reading of these three parameters and the availability of ECT images, better operational control of the pneumatic conveying system could be achieved. Better control can result in less material breakdown, less pipe wear, lower power consumption and a higher safety standard.

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