Development of a Variable Density Flowmeter for an Industrial Application

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Abstract *- Montell Carrington Limited produces polyethylene and polypropylene nibs, which are sold in bulk form to companies who use them to make products for the consumer market.*

Work has been undertaken at the Manchester Metropolitan University, in collaboration with Montell, to develop a Variable Density Flowmeter using Process Tomography that will enable the mass flow of nibs to be measured with an accuracy of ±2%. The nibs are stored in 30 storage bunkers, each with a capacity of 500 tonnes. The external distribution of nibs is achieved using 40 tonne road tankers that are filled from each of the bunkers using a gravity feed. The flowmeter was situated between bunker discharge outlet valve and the tanker. Measurement of the density distribution across the pipe, using Process Tomography, enabled the mass flow into the road tankers to be determined.

Keywords: Tomography, Massflow, Capacitance, Sensor

1. INTRODUCTION

The development of the Variable Density Flowmeter consisted of three main stages. The first was the design of an electrical capacitance tomographic (ECT) imaging system based on an AC bridge capacitance measuring circuit -the PT1 system- capable of measuring capacitance levels in the order of femto Farads [1]. Prior to this development, the capacitance measuring systems used in ECT imaging systems was the charge - discharge circuit [2]. Pickup showed that the AC bridge circuit was not stray immune [1],[3] but could be used to produce tomographic images. The PT1 was an eight electrode, serial capacitance sensing system (applied to a 100mm diameter pipe) and used primarily for imaging static images and real time images up to 2-3 frames per second. It had a sinusoidal signal source of 1 MHz and the capacitive detection circuit had a sensitivity of 8.85v/pF [3].

To increase the imaging speed a second stage of development was undertaken and a parallel measuring system developed- PT 2. Analysis of the parallel capacitance measuring system showed that a “mutual” capacitance exists between two adjacent electrodes that affects the capacitance measurements and hence the tomographic image. The AC Bridge capacitance circuit was modified to include an inductor in the feedback path to limit the effects of the “mutual” capacitance. The PT2 system consisted of an eight electrode parallel sensing system, using a low frequency (8kHz) software generated sinusoidal signal source and AC amplifier detector circuit mounted on the pipe adjacent to the sensing electrodes. The use of a low frequency signal source made the capacitance detector circuit stray immune and less sensitive to high frequency noise. A PC based Texas C40 parallel processing system was used to process the data and provide the tomographic images. Two TMS C40 processors housed in a QPC/C40B Loughborough Sound Images motherboard were used in the image formation. The task of the first processor was to control the detector electronics and pass capacitance measurements values to the second processor. This then performed an image reconstruction algorithm and transferred the image grey levels to the PC. The host program resident in the PC maintained overall control of the system and displayed the image on the VDU. A closed loop control system based on the PT2 system was designed to control the flow of nibs in a pneumatic flow rig (100 mm pipe diameter). The imaging system was used to detect the occurrence of saltation and a Proportional - Integral control algorithm, using the tomographic image, was developed to remove the saltation dune.

The final stage, the development of the Variable Density Flowmeter -the Montell Process Tomography (MPT) system -was based, in part, on the PT2 system. The operating frequency of the MPT system was increased to improve the sensitivity and the speed of imaging and additional design features incorporated.

2. MONTELL REQUIREMENTS

One of the requirements for any instrument placed in-line on an industrial plant is that is does not interfere with plant production. Montell required a non-intrusive method of measuring the mass-flow of nibs flowing out of the bunkers. The accuracy produced by the operators was 4%, about 1000 kg in a 24 Tonne load. The instrument was required to improve on that accuracy and improve on repeatability of the tanker loadings so that it would be possible to predict the delivery costs of the product more accurately. The measurement electronics also had to be reliable as access to them would be difficult once the instrument was installed. The data acquisition rate had to be fast enough to measure the average concentration of the product flowing through a section of pipe and had to be able to store all the results for later analysis.

Over/under weight tankers lose money and improving tanker content accuracy could save about £240,000 pa on the one plant. There are 30 bunkers, which would require flowmeters to be installed. If the developed MPT flowmeter were to cost £7,500 and an installation /cabling cost of £5,000 the total cost would be £375,000 giving a payback of 18 months

Future developments will require velocity as well as bulk capacitance measurements for variable flow systems and for the analysis of flow patterns of the nibs and powders.

3 SYSTEM OVERVIEW

Montell's requirement for an industrial tomography system presented new design issues. The application and operating environment of the system was very different from the PT1 and PT2 systems.

The PT1 and PT2 systems had been designed for the pneumatic test rig that had a pipe diameter of 100 mm and all of the development had been based around those dimensions. The pneumatic pipe work at Montell was based around 260mm - 300mm diameter piping, which meant a new design of sensor array.

The MPT system had to be built around the larger pipe diameter, operate outdoors, be robust and need little or no maintenance once installed. The main application of this system was to image the flow of nibs discharged from 500 Tonne storage bunker into road tankers. As the flow rate of the nibs was expected to be fairly slow (4-7 m/s as opposed to 25m/s for dilute phase pneumatic flow) a frame rate of 3 frames/sec was considered adequate for the application.

The Montell Process Tomography system was designed with the following elements:

- Twelve electrodes with driven axial shield
- An hardware generated sinusoidal signal source
- An AC bridge capacitance detector working at a frequency of 100kHz
- Hardware demodulation

The overall schematic of the MPT system is given in Figure 1 below. It can be seen that, like the PT2 system, the MPT used local capacitance detectors. The two systems also used the same hardware DSP configuration. However the number and configuration of the electrodes were changed and a new signal generation and demodulation section was developed for the MPT system.

The software the MPT system was designed to be more readable and maintainable using object-oriented methods. This also allowed the file formats produced by Process Tomography Ltd to be easily incorporated into the software system. The classes are grouped into 5 categories: Capacitance Data, Reconstruction, Storage, Communication and Graphics.

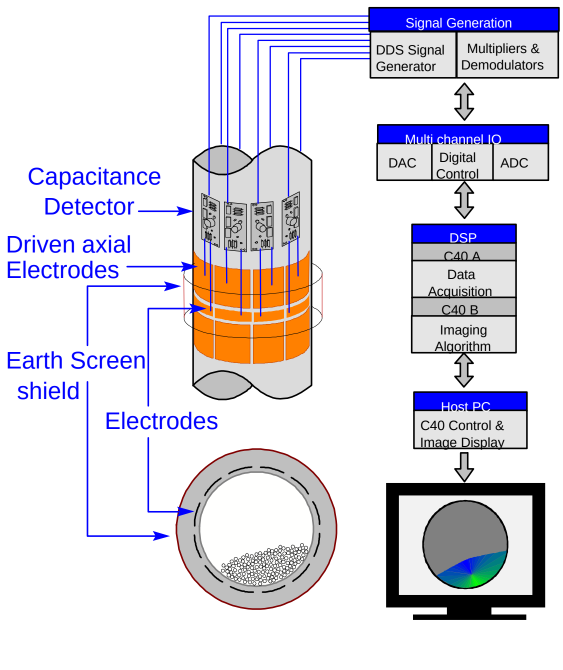

Figure 1 Overall Schematic of the Montell Process Tomography System

4 DESIGN OF THE SENSOR ARRAY

The design of the array was undertaken as a joint venture between MMU and Montell. The main limitation with any sensor array for capacitance tomography is that the pipe the array is built around must be non-conducting. A design was developed of a non-conducting insert to fit inside a normal piece of conveying pipe. A diagram of the insert is shown in Figure 2 below.

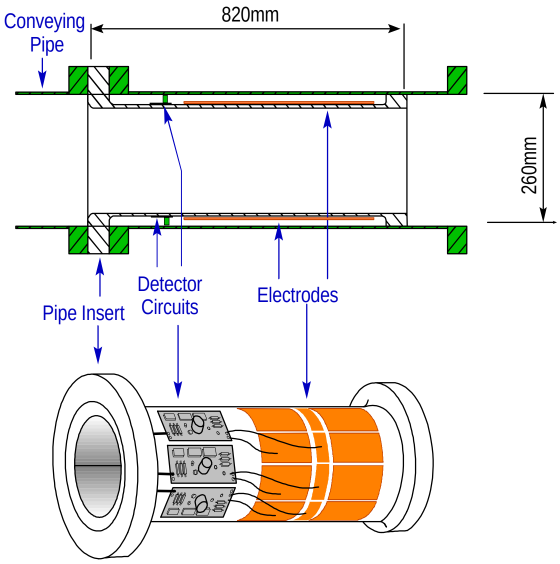

Figure 2 The Pipe insert with detectors and electrodes

The insert was made of polypropylene so that there were no contaminants in the pipe stream. As some of the Montell pipe work had different diameters, using the insert design technique had the advantage that it allowed the same design to be used in different diameter pipes.

5 SYSTEM PERFORMANCE

5.1 Capacitance Detector

The capacitance detector design followed on from the design for the PT2 system of using local capacitance detectors but differed in some key areas. The PT2 capacitance detector had an operating frequency of 8kHz and used software digital signal generation and sampling, followed by software demodulation to obtain the capacitance measurements.

The MPT capacitance detector(Figure 3) used a hardware 100kHz sinusoidal signal generator and hardware demodulator to obtain the capacitance measurements. The d.c. driving and back off signals were provided from the DSP IO card and were mixed with the a.c. driving using multipliers. The back off signal was in anti-phase to the driving signal and was adjusted to eliminate the standing capacitance between the two electrodes. This arrangement allowed the detector to respond only to the change in unknown capacitance.

PSpice was used to simulate the MPT detector voltage output to small capacitance (~fF) changes. By extrapolating the simulation results, the voltage output was estimated to be 1.91V/pF. This figure is lower than PT1 sensitivity achieved by Pickup [3] at 1MHz - 8.85V/pF, but is in the same order as that achieved by Yang et al [4] for a detector working at 500kHz - 2.36V/pF.

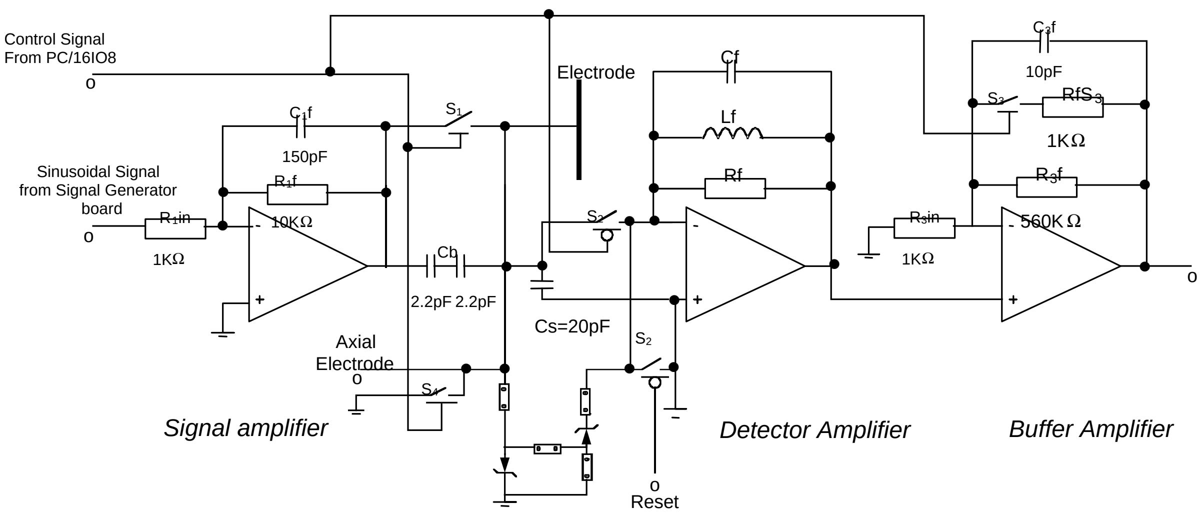

Figure 3 MPT drive/detect board

Once the system was built, measurements were made of the standing capacitance between electrodes and the results are summarised in Table 1. The values found are comparable to those reported by Yang et al[4]

Electrode No	2	3	4	5	6	7	8	9	10	11	12
Capacitance (fF)	484	27	10	5	3	2	3	5	10	27	480

Table 1 Measured air capacitance values of each electrode for the MPT capacitance detector

5.2 Static Image Tests

A number different flow regimes were simulated on the MPT system using a combination of a rod and sieve assembly that allowed up to 139 rods to be placed in predefined places within the pipe. The SNR for the a single rod at the centre of the pipe was 4.32. This was the smallest phantom available and represented 4.5% of the imaging diameter or 0.2% of the imaging area. Allowing for the variance of the SNR results taken the ISR, using the criteria defined by Xie et al [5], was calculated to be < 0.2% of the imaging area.

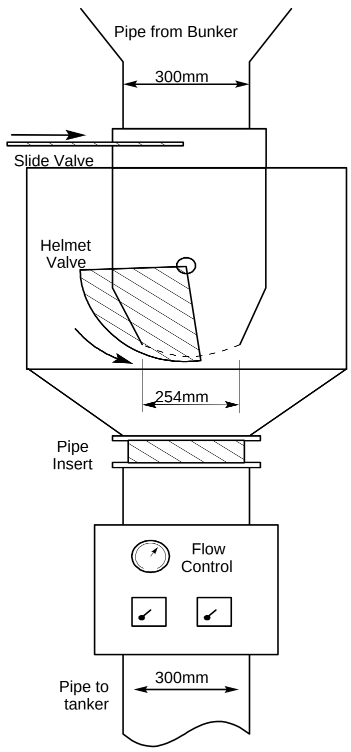

Figure 4 Bunker outlet and flow control valves

6 PPLICATION TO THE MONTELL POLYPROPYLENE PLANT

The MPT system was installed in the outlet of one bunker (Figure 4) for the duration of the testing. A total of 11 profiles were analysed to investigate the possible correlation between average measured capacitance and mass-flow rate. Previous work by Edgar [6], using a simulated bunker and commercial mass flow cross correlation measuring system, showed that the nibs reached terminal velocity within 0.5m of the outlet of the bunker.

Two sets of results were obtained from the experiments: a profile of the average measured capacitance of the product in the pipe and a set of corresponding tomograms (pictures of the flow regimes). A typical set of results is shown in Figure 5 and Figure 6 below. Figure 6 shows four rectangular pulses (labelled a-d) with each pulse representing a load of product being deposited into a filling point on the tanker.

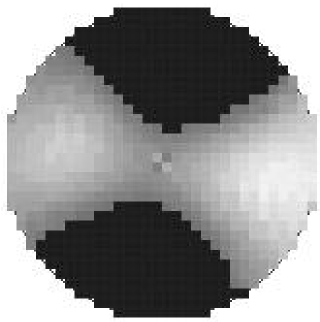

Figure 5 A tomogram for T=240s

6.1 Flow regime analysis

Figure 6 shows some trends that were common to all the flow profiles generated. The tankers were filled at three or four separate points, these can be seen as the one small rectangle (time 30s - 100s) followed by three distinct rectangles (time 120s-450s, 540s-720s and 780s-1000s). Each rectangle is preceded by a small spike where the operator opens the two valves (helmet valve followed by the slide valve) and the product begins to flow down the side of the pipe. This initial flow gives the peak in the graph.

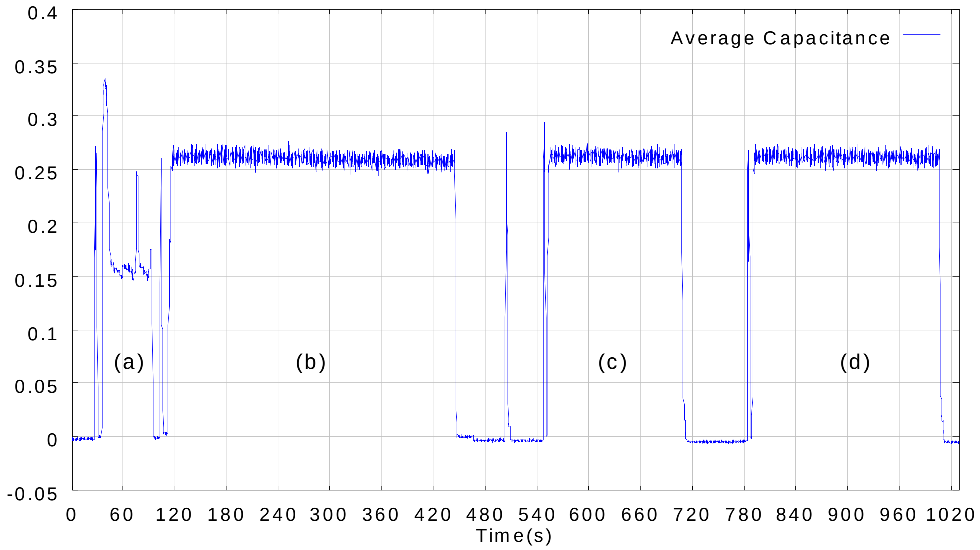

Figure 6 A typical flow profile of a tanker loading

6.2 Main Flow

Figure 7 with the corresponding tomograms in Figure 8 and Figure 9 show the flow of the product for section (b) of Figure 6. The initial spike, shown in Figure 7, corresponds to the product forming on the side of the pipe as shown in Figure 8 and quickly splitting into two sections before being curtailed by the operator. The main section of flow, shown in Figure 7, corresponds to the flow building on both sides and establishing a regular pattern as shown in Figure 9.

6.3 Flow profile measurements

Two methods were used to calculate the average capacitance: averaging of all 66 electrode measurements and averaging of all but the 12 adjacent electrodes measurements, resulting in an average of 54 measurements. Averaging of the 54 measurements has proved to be less sensitive to noise [5], and both methods were used to produce a flow profile so that they could be compared. The two different profiles are shown in Figure 10.

Figure 10 shows that the average of the 54 measurements follows the same trend as the average of 66 but is of a lower value and has less noise. This feature produces more consistent results in the overall profiles.

6.4 Mass-flow analysis

Given that the average capacitance measurements shown in Figure 10 are all proportional to the flowing density (*r*) of the product in the pipe (i.e. $kg.m^{-3}$) then, the mass-flow, *W*, can be determined by:

$$W = r \cdot v \cdot A \text{ , kg.s}^{-1} \qquad (1)$$

Where: *v* - the flowing velocity $m\ sec^{-1}$, which is assumed to be constant for the run [6] and *A* - Area of the pipe m^2.

The mass flow is directly proportional to the flowing density of the product. The average capacitance measurements taken from the flow profile were accumulated over the entire profile giving the total of the average capacitance's. To obtain the average of each of the totals each total was divided by the number of frames for that run.

The actual mass-flow was calculated by taking the weighbridge mass and dividing it by the time taken to deliver the product into the tanker.

The results were then plotted against the calculated mass flow to determine if there was a relationship. The results are shown in Figure 11. The dashed lines show that all the average total capacitance measurements were linear with respect to mass-flow. Further analysis showed the average 54 measurements had the closest correlation to mass-flow.

6.5 Mass analysis

The total mass of product delivered the into tanker can be calculated by multiplying the mass-flow by time t (secs), such that the total mass of product, *M*, is given by:

$$M = r \cdot t \cdot v \cdot A \text{ , kg} \qquad (2)$$

The value obtained from the Mass-flow analysis was multiplied by the corresponding time for the run, giving mass from the average capacitance data. The results of both the Mass Flow analysis and Mass analysis are summarised in Table 2 below.

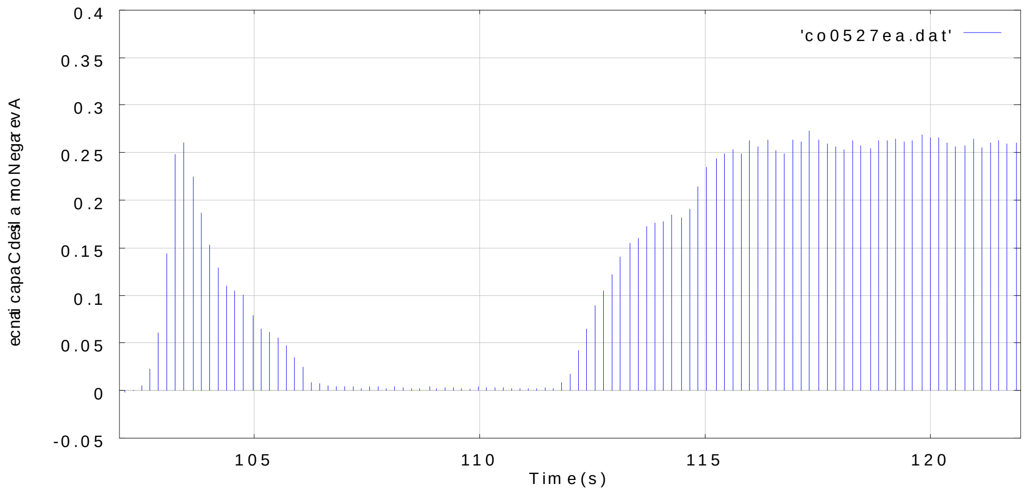

Figure 7 Expanded flow profile, showing data for 102 to 122 seconds

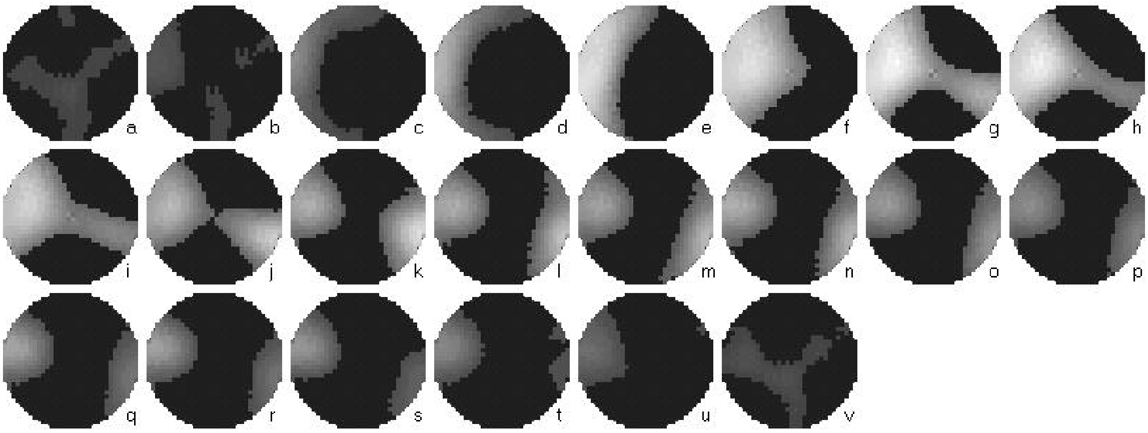

Figure 8 Flow tomograms for time 102s to 107s

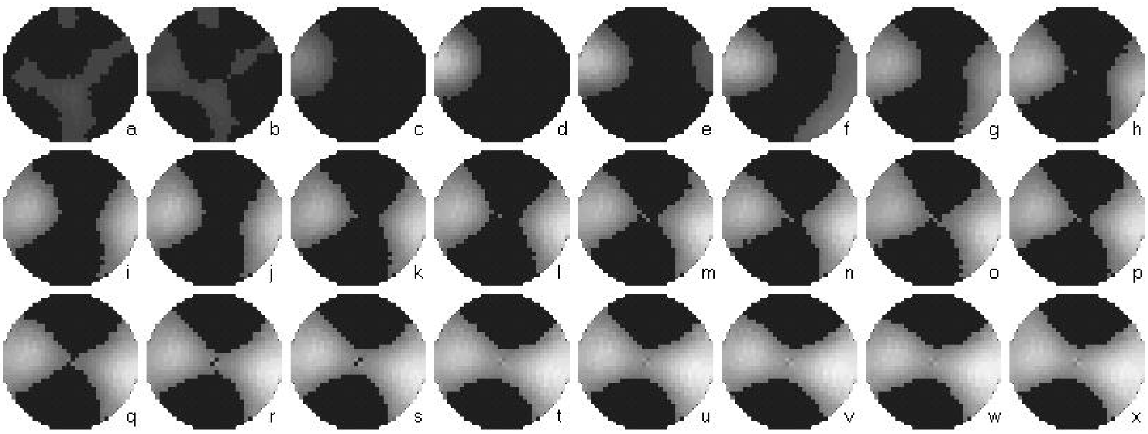

Figure 9 Flow tomograms for time 112s to 117s

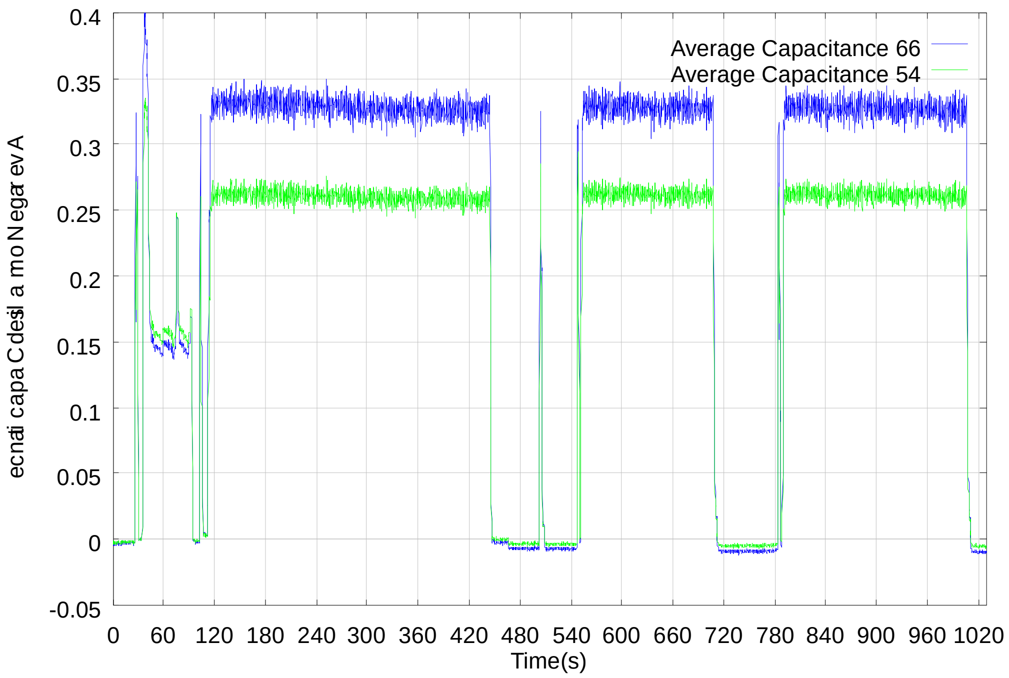

Figure 10 Typical flow profile, using averages of 54 and 66 electrode measurements

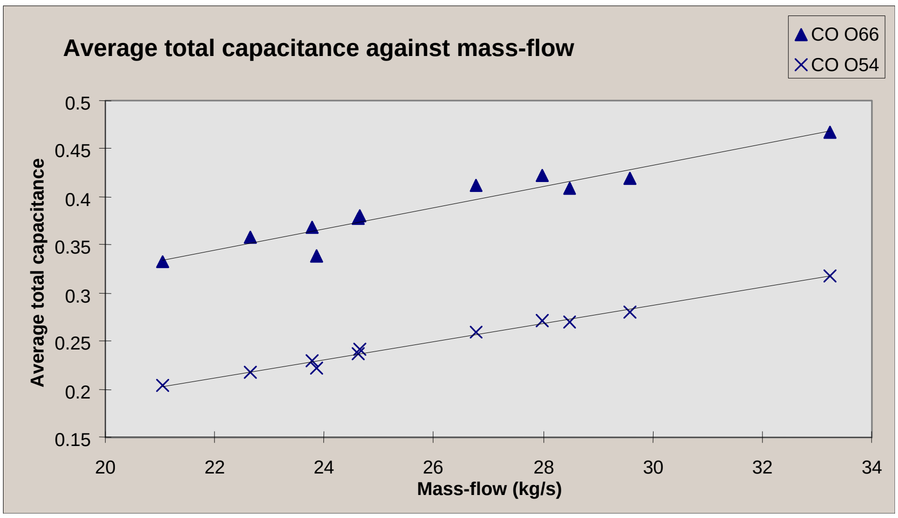

Figure 11 Average total capacitance against mass-flow for average total capacitance data

7. RESULTS SUMMARY

The error results shown in Table 2 were calculated using MS-Excel least square analysis. The table shows the maximum positive and negative errors produced by each measurement technique. The standard deviation of the results gives a good indicator of how widely spread the results were. To measure mass-flow using only the time, yielded a maximum error of 6.74%. Edgar [6], using a commercial mass flow measuring system, achieved better results with a maximum error of 3.89%. The MPT system however showed the smallest maximum error of 2.29%. The standard deviation of the results also followed the pattern, with the MPT system again yielding a lower error than either time or the measuring system used by Edgar.

The mass results are even more indicative of the performance of the MPT system. The time data produced a maximum error of 17% and a standard deviation of 10.19%. The MPT showed an order of magnitude increase in performance with a maximum error of 1.64% and a standard deviation of 1.09%, indicating that all the results were very close to the true value. There were no results for mass from the Edgar trials.

Mass Flow	Time	MPT	Edgar results
Max positive	6.74%	2.29%	3.89%
Max negative	-2.17%	-1.41%	-3.54%
Std Dev	2.55%	1.07%	2.46%
Mass	Time	MPT	
Max positive	17.68%	1.64%	
Max negative	-14.10%	-1.44%	
Std Dev	10.19%	1.09%	

Table 2 Results summary

8. CONCLUSION

The average capacitance measurements made by the MPT system are shown to be proportional to the mass flow-rate of the material down loaded from the storage bunkers. The MPT system could predict the mass flow of the product to within $\pm$2.29% and the mass of the product delivered to the tanker to within $\pm$1.64%. The system could reduce the number of overloaded tankers and improve the mean mass of product delivered by the tankers to customers, resulting in a substantial financial saving to Montell UK Ltd.

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