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# Application of Capacitance Electrical Tomography for On–Line and Off-line Analysis of Flow Patterns in a Horizontal Pipeline of a Pneumatic Conveyer

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***Abstract*** *– Investigation and control of flow phenomena in the pneumatic conveying of solids requires a detailed knowledge on the flow regimes and a number of phase flow properties. Electrical capacitance tomography (ECT) is shown here to be a robust tool for this purpose, particularly when dense phase plug flow is to be monitored. The application of ECT to dense phase powder conveying in an experimental vacuum system is demonstrated and described, including the visualisation of slug size, shape and velocity. Measured gas and solid flow rates were also analysed in an attempt to ultimately provide a basis for comprehensive on–line analysis. A number of statistical estimators were selected and used in data processing, in order to distinguish between particular types of dense flow. The results show the potential for use of the method for the on–line control of dense phase pneumatic conveyors.*

## 1. INTRODUCTION

Pneumatic conveying offers many advantages over other methods of granular solids transport involving 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 often result in an unnecessarily high or variable wear rate and power consumption. In addition, product degradation and particle size separation can be major problems.

Slug flow regime, when it occurs in the system, has the advantage of a low air requirement and hence energy demand, low pipeline erosion and low product degradation. However, the *control* requirements of such a transportation system are clearly far more acute in respect to the maintenance of flow regime and the prevention of blockage [1].

This contribution presents a continuation of the authors investigations in using electrical capacitance tomography to monitoring and control such a system [1,2,3]. Details on measurement procedure and the method of data processing are given in [4]. In this analysis we restrict our consideration to statistical parameters such as perturbations of the average in pipe cross–section normalised dielectric constant $<\varepsilon>$.

## 2. EXPERIMENTAL SET–UP

The experimental vacuum conveying system is shown in Figure 1. The system was designed to enable different types of powder flows to be generated in a controlled manner. It is a closed loop for solids and an as open system for air. In order to facilitate visual observations of the flow regime the horizontal test section, 3 m long, was made from transparent pipe, 52 mm inner diameter. Solids sucked from solid tank are transferred through an standpipe 11m in length and stored in the vacuum conveyor. Induced air is pushed through filter and removed by the vacuum pump to atmosphere. The vacuum conveying system parameters are sufficient to generate a wide range of flow patterns, from dense slug flow up to dilute, fast flow with low solid concentration. A detailed description of the system is given in [4,5].

The material conveyed were nylon plastic pellets having a bulk density of 750 kg $m^{-3}$, solid density of 1120 kg $m^{-3}$, length 2–3 mm with an aspect ratio between 1–2. For this medium, the maximum mass transferred during a single run was *ca*. 25 kg, these being determined by the volume of the solids hopper.

Design of the ECT sensor used for monitoring the flow patterns in the test section was based on the solution of the electrostatic field in the sensing region described by Ostrowski *et al* [6]. Twelve sensing electrodes 100 mm long were supported by two assemblies of guard electrodes. Since the distance required to develop a particular perturbation typical for the tested flow regime was unknown *a priori*, the sensor was movable along test section i.e. its position vs. the inlet section was adjustable.

Images from the ECT systems were reconstructed using a conventional linear back projection, as in the work reported above. These data were used in the statistical and stochastic analysis.

## 3. RESULTS

In the work reported here, reconstructed images can be time-gated to enable quantitative analysis by time-stacking sequential images. The typical information that can be obtained is as follow:

- the average volume occupied by solids
- the height of the solid/gas interface (if present)

and then the sequences of images may used to extract [4]:

- slug length and distribution of slug lengths[1]
- slug velocity and velocity distribution[1]
- slug frequency and distribution
- correlation analysis of the above parameters.

As mentioned above in present analysis we concentrated on the perturbations of the averaged cross–section normalised dielectric constant <ε> obtained as the arithmetic mean value for all pixels (the standard number is 814 for the ECT system). Such analysis is sufficient to estimate the flow pattern and so provide the necessary information for the control procedure.

Within the range of dense flow regime some sub–regimes may be recognised and defined. Even if air inlet conditions are constant is possible to distinguish between *slow* and *fast* (or *dense* and *less dense*) slug flows. The boundary between these two sub–regimes is necessarily artificial. There is however an important point that the fast slug flow has a general tendency to transform into the dilute flow while the slow slug flow demonstrated the trend to block the pipeline.

Additionally, keeping inlet conditions constant and closing and opening periodically an other injection valve (in this case valve 5 in Figure 1) it is possible to obtained a very regular slug structure (called here as *injected* flow).

Examples of <ε> plotted versus time (in seconds) for the three slug structures mentioned above are shown in Figures 2–4. For comparison, the bottom diagram in Figure 4 shows a typical signal for the dilute flow. Table 1 presents a set of basic statistical parameters for each signal. A summary of flow condition for the fast and slow slug flows is given in Table 2.

Differences between particular slug patterns are clearly visible. The slow slug flow is more regular then the fast slug flow (generally, the fast slug flow represents the more *disordered* structure compared with the slow slug flow). The two top diagrams in Figure 4 shows the trend to blockage typical for this structure. Is also characteristic that the bottom level of solids for all signals is not constant but rather a random variable.

The flow parameters (i.e. air and solid flow rates and their superficial velocities) shown in Table 2 do not provide clear information for distinguishing a particular slug pattern and are insufficient for the system control purposes. Such information however is provided by the statistical parameters, namely, the normalised mean dielectric constant, its standard deviation and mean. Standard deviation of the signal yields clear differentiation between any slug flow and the dilute flow (or blockage). Median calculation is a convenient tool to differentiate between slow and fast slug flow patterns. Thus, the on–line control procedure can be based on these two estimators only.

| No. | Flow regime | mean value of <ε> | median of <ε> | st.dev. of <ε> |
|---|---|---|---|---|
| 1 | slow slug | 0.70 | 0.77 | 0.16 |
| 2 | slow slug | 0.66 | 0.72 | 0.20 |
| 3 | slow slug | 0.53 | 0.59 | 0.25 |
| 4 | slow slug | 0.51 | 0.38 | 0.22 |
| 5 | slow slug | 0.51 | 0.44 | 0.24 |
| 6 | fast slug | 0.17 | 0.08 | 0.24 |
| 7 | fast slug | 0.16 | 0.08 | 0.23 |
| 8 | fast slug | 0.13 | 0.04 | 0.21 |
| 9 | fast slug | 0.12 | 0.04 | 0.21 |
| 10 | fast slug | 0.10 | 0.04 | 0.19 |
| 11 | injected | 0.30 | 0.20 | 0.26 |
| 12 | injected | 0.11 | 0.04 | 0.21 |
| 13 | injected | 0.10 | 0.04 | 0.19 |
| 14 | injected | 0.08 | 0.04 | 0.16 |
| 15 | dilute | 0.11 | 0.11 | 0.09 |

**Table 1: Flow regimes corresponding with the signals <ε> (t) shown in figures and associated statistical parameters of these signals.**

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[1] In combination with additional data e.g. video images.

| No. | Air flow rate* [$m^3$ $s^{-1}$] $\times10^3$ | Air superficial velocity [m $s^{-1}$] | Solid flow rate [kg $h^{-1}$] | Solid superf. velocity [m $s^{-1}$] |
|---|---|---|---|---|
| 1 | 0.89 | 0.42 | 1370 | 0.16 |
| 2 | 0.48 | 0.23 | 1210 | 0.14 |
| 3 | 0.70 | 0.33 | 1320 | 0.15 |
| 4 | 0.79 | 0.37 | 1370 | 0.16 |
| 6 | 0.87 | 0.41 | 1410 | 0.16 |
| 7 | 0.89 | 0.42 | 1440 | 0.17 |
| 8 | 0.93 | 0.44 | 1480 | 0.17 |

**Table 2: Air and solid flow rates and the superficial velocities for selected number of the fast and slow slug flows listed in Table 1.**

If the off–line analysis is possible it is reasonable to complete more comprehensive estimation including auto-correlations, power spectra and histograms of the signals. Examples of these are shown in Figures 5 and 6.

Figure 6a–f shows examples of auto-correlation functions (top) and power spectra (bottom) calculated for all types of flow. It is clear that the *macroscales* as well as *microscales* are larger for slow slug flow by about one order of magnitude. The injected flow is characterised by relatively high repeatability of the signal (Figure 5e). Thus, calculation of auto-correlation is a simple, effective and robust tool to distinguish between particular dense flow patterns. If the slug frequencies are to be considered, it is more suitable to calculate the power spectral density of the signal. Since spectral *leakage* is generally present it is therefore common practice to *taper* the original signal ($<\varepsilon>$) before transformation, reducing any discontinuities at its edges, as discussed elsewhere [4]. The presented power spectra were calculated using data tapering and then a Fast Fourier Transform. The slow slug flow is characterised by small power spread with distinctive strong peak at about 0.3 Hz. The frequency component above 1 Hz may be neglected. The fast slug flow represents the wider spread, up to 3 Hz, with a few maximas. All power spectral densities calculated for this flow regime (not shown here) are similar to each other and there is no clear dependence of their shape on the phases flow rates within their ranges tested in present experiment. The power spectra of the injected flow are generally close to that obtained for the slow slug flow.

Examples of the histograms for flow regimes being tested are shown in Figure 6. The range of $<\varepsilon>$ equal to <0, 1> was subdivided into one hundred quantization levels. These estimators are also different. For the slow slug flow distribution of probability is more symmetrical, however the random character of the solid levels is clearly visible. Also, the $<\varepsilon>$ distributions are close to *bimodal* (i.e. representing the minimum and maximum solid levels) as plotted in histogram form in figure 6a. It is seen that the slow flow represents a more symmetrical distribution than the fast flow. For the former the maximum probability occurs from relatively high values of $<\varepsilon_N>$, while from the latter low solid levels are more probable.

The injected flow represents a mixed structure for which both distributions are possible depending on the mode of valve operation. The histogram for the dilute flow shows significant non-uniformity resulting from the gravity force.

It would of course be possible to extend the number of estimators and include e.g. higher order moments: *skewness* and *kurtosis* as the additional tests. However, we found that none of these provides a clearer method of flow pattern recognition.

The work and principles, that have been described, now are extended for on-line control of conveyors with special regards to the flow regime prompt identification and the quantitative estimation of statistical parameters for particular flow patterns.

## 4. CONCLUSIONS

The work described here demonstrates the preliminary application of *ECT* to some industrial scale problems. The use of *ECT* for modelling of complex powder flow in dense phase powder flow is potentially a fruitful area. The use of the methodology for on-line control is also promising and industrial examples seem likely to emerge in near future. This will require further and integrated development of the sensor systems and process control systems using model-based reconstruction algorithms where possible and fusion of tomographic data with other conventional multi-sensor data.

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