Review

Tomography for Improving the Design and Control of Particulate Processing Systems†

F.J. Dickin, T. Dyakowski, S.L. McKee, R.A. Williams, R.C. Waterfall, C.G. Xie and M.S. Beck

Process Tomography Group, UMIST*

Abstract

The ability to interrogate the dynamic internal characteristics of processing plants by using conventional instrumentation is severely limited for most practical conditions. The results of recent work, employing non-intrusive electrical sensors to obtain 2-dimensional images of component concentration profiles in cross-sections through process equipment, is making industry aware of new prospects for improving the design and control of many processes.

The range and status of sensing techniques and other enabling technology for the new subject of "Process Tomography" is outlined in this paper. This is followed by a discussion of the applications and future technical challenges which must be considered if process tomographic techniques are to find widespread application, with a particular emphasis on electrically-based sensor technology.

1. Introduction

Process tomography involves the use of instruments which provide cross-sectional profiles 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. Hence from this knowledge of material distribution 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 empirical methods of process design, often based on input/output measurements, with only a limited amount of information about the detailed internal behaviour of the process.

The process industry uses high-capital-cost plants which are often designed and operated on the basis of past experience and on models which usually assume time and space averaged parameters (e.g. 'well-mixed' reactors, 'completely' fluidised beds, etc.). The measurements made in such systems are also usually based on average parameters (temperature, mean flow velocity, chemical composition, etc). In some cases it has been possible to obtain microscale data (instantaneous temperature, velocity, composition, etc) at specific points in the process. However, complex experimental approaches (e.g. laser techniques involving sensing of microscale information) are not economically or practically feasible for many process design and operation needs. For these latter cases the 'process tomography' approach using simple external sensors has much to offer.

A process tomography system can be subdivided into three sub-systems: the sensor, the data acquisition system, and the image reconstruction and display (Fig. 1). As with all measurement systems the sensor is probably the

* P.O. Box 88, Manchester M60 1QD, UNITED KINGDOM
† Received May 13, 1992
most critical part. The manner in which the sensor interrogates the process, and the quality of information obtained as a result of this, has a profound effect on the reliability and accuracy of the complete system. Practical considerations place a number of constraints on the sensor. Ideally it should be compact, non-intrusive, require minimum maintenance or calibration, and in many cases also be intrinsically safe.

Sensing techniques include electrical, ultrasound, nucleonic, and optical: a brief review of sensors appropriate to powder systems has been given elsewhere. Most sensors can be categorised as having either a hard or a soft field. With 'hard-field' sensors, such as nucleonic, the sensor field sensitivity is not influenced by the distribution of materials in the process being imaged. However, with 'soft-field' sensors, such as capacitance and conductivity, the sensing field is altered by the component distribution and physical properties of the mixture being imaged. Although this limits the resolution compared with hard-field sensors, nevertheless the electronic sensing methods are often preferred for on-site process applications because of their low cost, safety, and speed.

2. Applications

Potential applications for process tomography embrace the three basic stages encountered in process engineering development:

**Stage 1** Development of new process routes involving fundamentals of chemical process design (reaction kinetics, hydrodynamics etc.).

**Stage 2** Implementation of the required process route by designing efficient industrial-scale equipment.

**Stage 3** Routine process control, flow measurement and mass balancing functions, to enable operation under optimal conditions and to allow operational flexibility. Other applications exist for environmental monitoring of aqueous-based and gas-based mixtures.

At all three stages in the overall design of a process it is necessary to devise models (often based on a computational fluid dynamics approach) for the phenomena concerned, equipment characteristics and, ultimately, to simulate the entire process preferably in a dynamic sense. It is in this context that the use of tomographic techniques may offer a step-change in technology by enabling models to be verified with reference to tomographically measured internal process parameters. This is of some importance in the design of particulate processes.

Many process models have, hitherto, relied on theoretical computational fluid dynamics simulations whose model parameters are unquantifiably removed from the real process conditions, or whose predictions cannot always be adequately validated experimentally. For instance, the design of separation equipment holding concentrated solid/liquid dispersions that are optically opaque is often approached by estimating unit behaviour based on the (non-opaque) liquid phase only. The presence of multi-body particle-particle interactions often inhibits accurate prediction of the actual behaviour of the concentrated dispersion. Similarly, the modelling of process equipment frequently has to be based on empirical mass and population balance models derived from sampling the input and output streams to a given process (or so-called 'black-box' modelling). Such methods can be effective, but rely upon the availability of an adequate operational data-base to describe the behaviour of similar pieces of equipment handling similar components. As a consequence, such methods tend to be very system specific and rarely assist in providing any understanding of the fundamental mechanisms occurring within the process equipment. The net result is that considerable caution has to be exercised in scaling-up equipment design from the laboratory or pilot plant to full industrial scale. Potentially, the use of tomography would result in a more rigorous and confident design basis for process equipment. In some cases a modified equipment design would promote: safety, cost savings in capital equipment, floor space or overall productivity. Once a plant has been installed there are some obvious benefits in having the means to 'look inside' to investigate suspected malfunctions, wall wear, or poor performance. However, and more importantly, possibilities exist to perform accurate velocity, mass and component measurements. Such information could form part of the process control strategy.
3. Enabling Technology

The availability of efficient and low-cost integrated circuit components and digital signal processing systems has provided a foundation for rapid development of new tomographic imaging systems in the late 1980s and early 1990s. A brief resumé of the historical development of the enabling technology will be described.

Significant projects have been carried out in UK universities, in Norway, Germany and the USA, with emergent projects in two Chinese universities and by a Polish instrument manufacturer. Related technologies associated with electrical sensors were developed for geophysical applications in the early 1980s.

3.1 Strategy for Sensor Design

Various sensing methods are needed for process tomography applications (Table 1). In the UK, a UMIST group has concentrated mainly on capacitive (section 3.1.1) and resistive (section 3.1.2) impedance sensing and on a new method of inductive sensing (section 3.1.3). Work on ultrasound sensing has been carried out at UMIST and Leeds University in the UK in association with Tianjin University in China and at Karlsruhe University in Germany (section 3.1.4). Optical sensing systems have been investigated at Bolton Institute of Higher Education in the UK, Hannover University in Germany and Micromath International in Poland (section 3.1.5). UK work on process imaging using gamma-ray tomography is featured at Surrey University. Positron-based imaging is carried out at Birmingham University. Extensive work on magnetic resonance imaging (MRI) using modified nuclear magnetic resonance (NMR) systems is being performed at Cambridge University and in the US.

A group of UK higher education establishments is collaborating on process tomography and is involved in instrumentation system modelling for solving the forward problem of field analysis, on which image reconstruction is based. It is becoming clear that process tomography instrument design could be aided by CAD packages for optimising the spatial sensitivity of the electrodes and for simulating the complete system, so that its performance can be assessed before commitment to detailed design.

3.1.1 Capacitive impedance tomography

A capacitive tomography system for imaging pipelines containing insulating mixtures (such as solids/gas and liquid/gas) is already delivering valuable images of powder/air and kerosene/nitrogen flows. It uses a charge-transfer capacitance transducer working at 15 volts with a noise level as low as 0.08 fF r.m.s. and a 6" pipeline twelve-electrode system. It enables void fraction and the flow regime to be determined and is the first key stage in developing a non-invasive two-component mass flow meter. The oil industry is supporting early research; future work will be on gas/solids systems.

The Department of Energy in the USA is investigating the use of capacitance tomography for fluidised bed visualisation. They use a 16-electrode system, with the electrodes energised at 500 volts to generate views of the dielectric constant of the bed.

3.1.2 Resistive impedance tomography

Resistive methods are suited to imaging aqueous systems including slurry conveyors, crystallisers, reactors, mixers, separators, and various kinds of porous media. Resistive tomography systems for medical use have been developed during the last few years, with major contributions by the Sheffield University Hospital group. A tomography system designed for process use has recently been constructed at UMIST (up to 64 electrodes, frequency 75 Hz—150 kHz, excitation current up to 30 mA), and is being evaluated experimentally on process vessels, with particular attention being paid to metal-walled vessels to investigate any errors due to the conductivity of the walls. There are significant differences from the medical system because the human body is never in a steady state, so the medical systems are designed on a 'difference imaging' basis to examine relative changes over a short time scale, whereas proc-
<table>
<thead>
<tr>
<th>PRINCIPLE</th>
<th>PRACTICAL REALISATION</th>
<th>TYPICAL APPLICATIONS</th>
<th>GENERAL REMARKS</th>
<th>REMARKS ON RECONSTRUCTION ALGORITHMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation of beam of electromagnetic radiation by the dispersed components in the flowing fluid.</td>
<td>Optical techniques.</td>
<td>Many 2-component flows where the carrier phase is transparent to the radiation used.</td>
<td>Conceptually simple, high definition possible, fibre optic light guides can simplify optical arrangements. Images of central region poor if second phase concentration is high, due to absorption near walls. Heavy shielding may be required to collimate beams and for safety. Photon statistical noise limits response time (only low-speed flows unless large sources are used).</td>
<td>Similar algorithms well established for medical CAT.</td>
</tr>
<tr>
<td>Reflection of external radiation.</td>
<td>Ultrasonic pulse echo systems.</td>
<td>2-component flows where reflections occur at boundaries e.g. liquid/gas flows.</td>
<td>Ultrasound, say 1 MHz pass through metal/liquid interface so a 'clip-on' system may be feasible for liquid flow. 'Ringing' of transmitter may cause difficulty in imaging discontinuities close to the pipe walls.</td>
<td>Similar to some NDT and medical applications.</td>
</tr>
<tr>
<td>Instantaneous measurement of electrical properties of the flowing fluid.</td>
<td>Electrical capacitance plates on walls of pipe detect the presence of the second component.</td>
<td>Oil/gas, oil/water, gas/solids flows etc.</td>
<td>Inexpensive and rugged. High definition not possible, but good for slug and annular flow, water separation measurements, dune and spiral flow patterns in pneumatic conveyors. Loss of definition near centre of pipe. Similar to capacitance, but electrode polarization, greasy deposits, etc. may need to be considered.</td>
<td>Sensor field is affected by distribution of second phase, so algorithms must allow for this.</td>
</tr>
<tr>
<td></td>
<td>Conductivity sensing electrodes near wall of pipe.</td>
<td>Water/oil, water/gas, water/solid flows.</td>
<td></td>
<td>Similar to capacitance, similar methods used for some medical applications.</td>
</tr>
</tbody>
</table>
ess tomography systems must give results from absolute measurements of impedance which requires more precise instrumentation and image reconstruction algorithms. A number of process applications (mixing, separator design etc) are being investigated by UMIST\textsuperscript{15,16}. Rensselaer Polytechnic Institute in the USA is also making noteworthy advances in resistive impedance tomography\textsuperscript{17,18}, using adaptive current excitation principles.

### 3.1.3 Electro-magnetic tomography

This method of imaging uses a sensor system with directional sensing coils for imaging materials which affect inductive fields projected over the cross-section of a process. It should enable the specific imaging of metals in the presence of substantial amounts of non-metallic materials, which is of interest in minerals processing and material recycling\textsuperscript{19}.

### 3.1.4 Ultrasonic tomography

Ultrasonic tomography has been extensively developed for medical applications. However, these systems require operator interpretation of results and are generally not suitable for high-speed process tomography. Designs for a system more suitable for process application, using specially developed wide-angle transmitters with transputers for image reconstruction have been suggested\textsuperscript{20,21,22}. The wide-angle transmitters are combined with multiple receivers, and enable the image to be obtained with a small number of transmitters being “fired” in sequence, thus speeding-up the image frame-rate compared with systems where many narrow-angle transducers need to be fired in sequence. Work at Karlsruhe University has been concerned with vector tomography for velocity profile measurement\textsuperscript{23}, they have demonstrated the system on bubble columns. A large number of transmitters are used which enable good images to be obtained, but the frame rate is limited for the reasons given above.

### 3.1.5 Optical tomography

An optical tomography system using arrays of light-emitting diodes and photo-detectors for each projection has been constructed at Bolton Institute of Higher Education\textsuperscript{24}. Optical systems for investigating mixing phenomena have been developed at Hannover University\textsuperscript{25}. Future applications will employ optical techniques for calibration of other process tomography systems, and in some processes it is anticipated that optical access may be possible, thus enabling higher resolution than would be achieved using conventional electrical tomography.

Optical tomography is a useful way of teaching the basic principles of tomographic image reconstruction, a demonstration system using a simple optical bench has been made in Poland\textsuperscript{26}.

### 3.1.6 Tomography using ionising radiation

Gamma-ray tomography is very appropriate for imaging particulate systems\textsuperscript{6}, and since it is a ‘hard’ radiation, the image resolution can be better than it is when using electrical methods of tomography. However, the imaging speed is relatively slow because of the long averaging times required to reduce to acceptable levels the image flicker caused by the count rate limitations of gamma photon detection.

Positron emission tomography\textsuperscript{7} is attractive because particular species of particles can be radio-labelled and their transit through a process can be imaged in 3 dimensions. However, the technique is inherently slow if a large number of particle trajectories has to be individually monitored, since only a small number of radio-labelled particles can be separately resolved at one time.

4. The Use of Tomographic Technology for Fluid-based Conveying Processes

Hydraulic and pneumatic conveying can be employed to transport solids over long distances, sometimes several hundred kilometres, which may offer a less expensive method than conventional transportation by road or rail. Design and modelling of these processes is of considerable importance, and this is a prime candidate for tomographic interrogation.

Considering the case of solid/liquid transportation, a range of flow regimes can occur, subject to process parameters such as phase volume fraction of solids, flow velocity, hydraulic pressure gradient and the physical properties of both the solid and the suspending liquid. The particle size of solids also has a significant effect upon the resultant flow regime produced.
Generally, a slurry is identified as being either homogeneous or heterogeneous. In the former, a high concentration of fine solids is suspended, while the latter is characterised by an asymmetric distribution of solids in the suspending liquid, with particles readily demonstrating a tendency to settle and form either a moving or a stationary bed of particles on the base of a horizontal pipeline. The velocity at which such a situation can arise is referred to as the critical deposition velocity, and represents a fundamental parameter in the design of slurry pipelines. Another phenomenon characteristic of a heterogeneous slurry is saltation, in which the suspension of particles due to turbulence is surpassed by gravitational force, and particles are subsequently suspended and deposited periodically on the surface of a moving or stationary bed.

In horizontal pneumatic conveying, the flow regimes encountered are largely dependent upon the suspending gas velocity. As the velocity is reduced, the trend is for the distribution of solid particles to become progressively less uniform. Eventually, a moving bed of particles can form coupled with a saltation effect similar to that described above. At sufficiently low velocity, the particle bed can build up to result in a blockage of the conveying line. Clearly, the flow velocity is significant and, as in the design of pipelines for hydraulic conveying, both the flow velocity and pipeline pressure drop represent essential design parameters. Fig. 2 illustrates the change in pressure drop with superficial gas velocity, defined as the volumetric gas flowrate divided by the cross-sectional area of the pipe. The diagram also suggests a suitable range for the loading factor, LF, defined as the ratio of the mass flow of particles to the mass flow of gas. Fig. 3 shows images obtained using a capacitance tomography instrument for different flow behaviours encountered in horizontal pneumatic conveying. These images illustrate the way that tomographic methods can be used to visualise process behaviour, to enable flow regimes to be identified, and for quantification of void fraction.

In vertical pneumatic conveying, it is found that as the LF decreases and the suspending gas velocity increases, the tendency is to encounter a uniform distribution of particles. In contrast, the choking velocity represents a gas velocity so low that a series of 'slugs' result. Generally, as the superficial gas velocity is decreased, a transition from dilute-phase to dense-phase will be observed. Pneumatic transport with low air velocity allows pressure drop to be minimized and as a consequence to reduce the amount of energy provided to the compressor. For vertical pneumatic transport, the relationship between pressure drop and superficial gas velocity is illustrated in Fig. 4: it clearly shows an optimum velocity for minimizing the pressure drop; this velocity depends on the flow regime which can be measured tomographically (Fig. 3).

A prime advantage in the application of process tomography to such systems is the ability to explore the spatial distribution of the contents of a vessel in an intrinsically safe manner, i.e. non-invasively. Further, electrical
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 than radiation-based tomographic techniques such as positron emission, nuclear magnetic resonance, gamma photon emission, and X-ray tomography. Practical constraints such as the diameter of a large process vessel will render the direct application of radiation-based techniques difficult, and in this instance, electrical tomography would prove more advantageous.

Other process applications for tomography lie in the area of process control, in the detection of blockages in either full-scale pipelines or those of a pilot plant - to identify possible production difficulties would greatly enhance the efficiency of operation. The flow regimes discussed previously could be identified with ease and so further act as an aid to process control. In the case where flow velocity is below critical deposition velocity and a moving or stationary bed results, access to real-time images would allow a rapid response to be taken, thereby allowing the operation to continue without being further impaired.

The accurate determination of flow velocity, used in basic design equations for the design of both pipelines and pump power requirements, will enable a process engineer to refine the design of such equipment cost-effectively. Process tomography should also enhance an understanding of particle dynamics for both steady and unsteady flow and further, assist in the validation of fundamental design equations through accurate determination of parameters such as phase mass flowrate and flow velocity. The spatial variation of solids concentration and velocity should be readily determined, along with concentration profiles as a function of concentration, particle size distribution and flow velocity.

5. Current Developments and Future Challenges in Tomographic Instrumentation Using Electrical Sensors

Electrical field methods are emerging as robust, safe and relatively low-cost techniques for obtaining tomographic images of the contents of industrial equipment. Other sensor systems are available (e.g. gamma-ray and positron emission, section 3.1.6) which can produce higher resolution images than the electrical methods, but at the expense of ease of operation, speed and cost.

A medium-speed (ca. 100 frames per second) capacitive impedance tomography system is now ready for further development leading to industrial use (section 3.1.1), the application being mainly to the non-conducting fluids used in the oil industry. Although the existing instrument is suitable for oil well riser applications, there is a need to improve the sensitivity and speed for applications such as measuring flame front propagation. This most demanding requirement involves capacitively imaging flame fronts in a cylinder head. For engines running up to 6000 rpm this would involve increasing the image speed to 36,000 frames per second and using very small electrodes. A method of improving transducer sensitivity using replacement of existing charge transfer techniques by stray-free capacitance bridge measurements incorporating digital signal processing is being investigated\(^\text{21}\). A research group in Norway is investigating the use of dedicated silicon technology to make capacitance sensors of optimal design. Much of this technology is directly applicable to interrogation of dry powder processing.

The resistive impedance tomography method is suitable for use with electrically conducting systems (most chemical process applications). It forms the basis for model verification aimed to improve the design of industrial equipment. The use of impedance spectroscopy may in future provide a method for imaging specific components in a multi-component mixture, and is
likely to be of interest for performing measurements in powder slurry systems.

Combined capacitive and resistive impedance transducers will have to be designed for applications where the measurement zone can change between being dominated by dielectric effects or by conductivity effects. The research challenges will be to identify the fluid transition, develop electrodes and electronics suitable for conducting and non-conducting fluids, and to design reconstruction algorithms suitable for imaging spaces where there are two different fluid states existing in the measurement zone.

There are a number of specific and rather fundamental challenges in process tomography which should be highlighted because their solution will need a considerable amount of research. One aspect is to define procedures for quantifying the performance of tomographic imaging systems; so far very few reports on this have been written\(^{10,28}\). This leads us into considering the following challenges:

a) Resolution. The attainable resolution is dependent on the correct placement, sizing and shielding of impedance electrodes and energising fields. This involves solving the forward problem as part of the design method using proprietary finite element design packages, and is particularly important in making cost-effective tomography installations. "Empirical" approaches to electrode sizing and placement relative to guards, interfering metalwork etc. are a costly and time-consuming process.

The image resolution (and fidelity) is also influenced by the type of algorithm used to solve the inverse problem of image reconstruction. Most work so far has involved using relatively straightforward backprojection and filtered backprojection methods. However, it is postulated that variations in the position of the field equipotentials due to the spatial distribution of material in the process could be compensated for by more advanced reconstruction techniques. Investigations have started on the use of iterative reconstruction algorithms such as a modified Newton–Raphson algorithm for quantitative impedance tomography\(^{19}\).

Imaging industrial equipment with non-circular geometry will involve special challenges with electrode placement and with image reconstruction. Typical cases include plate separators and stirred tank reactors\(^{29}\).

b) Speed. Data capture rates (aperture times) of 100 frames per second have already been achieved with electrical tomography systems where the measurement frequency is high (ca. 1 MHz for capacitive and inductive sensors and ca. 50 kHz for resistive sensors). Speed increases of up to, say 1000 frames per second should be attainable by parallel operation of sensing and signal processing systems, but will involve careful attention to the signal-to-noise ratio of the sensor electronics and elimination of cross-coupling by multifrequency methods. Operation at even higher speeds will probably require major developments in sensor electronics.

Data processing systems for reconstructing high-speed images fall into two general categories. For research applications it will often be sufficient to store the data and reprocess it at a lower speed. For real-time imaging concerned with some process monitoring, control and measurement applications, Transputer systems are already proving successful. Alternative configurations such as cellular array processors and the use of dedicated digital signal processing devices merit careful consideration.

c) Subject contrast. This term is used to denote the ratio in the process cross-section of the maximum to minimum density (for X-rays) or specific impedance (for electrical impedance tomography), and is an attempt to measure the 'sensitivity' of the tomographic instrument. In order to form a tomographic image, the sensor radiation or the field lines from the sensors must pass through all components of the object. With a penetrating radiation such as X-rays this is not usually a problem. (However, radiation methods are often unsuitable for process tomography because of the requirements for radiation containment, high cost and slow response.) Electri-
cal field methods are relatively straightforward for insulating mixtures (e.g. gas/oil) where the dielectric constant ratio is low, so that electrical capacitance tomography is used, and for electrically conducting mixtures (e.g. most processes based on aqueous fluids and absorbent solids) where the specific conductivity ratio is low, so that low-frequency electrical impedance tomography is successful.

Although electrical methods are suitable for very many applications, there are cases where the presently available high-frequency capacitive impedance (1 MHz) and low-frequency (50 kHz) resistive impedance methods may not be fully suitable. Examples include imaging of flame structure and flame front propagation in internal combustion engines, where the flame is highly ionized and electrically conducting, whereas the zone in advance of the flame front is electrically insulating. Similarly, in oil industry separation process imaging, the oil–water mixture inversion means that combined capacitive and resistive impedance measurements are required. To cater for such a wide range of measurement conditions there is a need to develop multi-frequency sensor systems, measuring both resistive and reactive components.

d) Vector velocity. A full understanding of process behaviour requires a knowledge of the direction of material movement as well as its distribution. The velocities can be measured by cross-correlation of the image data. This is a computer-intensive operation; especially if the direction of the velocity vector is not known. Transputers with additional digital signal processors can be used for velocity imaging. Cellular array computers and electrically reconfigurable logic arrays should enable a higher data throughput than Transputer-based systems.

An alternative method for obtaining the velocity profiles is known as ‘vector tomography’. This uses ultrasonic sensors to measure velocity data, from which the velocity profile is obtained by tomographic reconstruction. The potential of vector tomography is being investigated at Karl-sruhe University (section 3.1.4).

e) Process control using tomographic image data. A tomographic image can provide the measurements at selected locations of internal process parameters which are critical to the optimal control of a process. Numerous opportunities for process control of plants exist and remain to be developed. For example, component control in pipelines, control of solids distribution in crystallisers, homogeneity of mixing processes, solids flow in bunkers. Thus, state variables directly associated with optimal operation could be used for process control, the state being actually measured rather than estimated from other measured parameters. Such measurements for process control would be based on localised information, so simplified tomographic measurement systems could be used.

f) Scale-up. Early applications of process tomography are to research and pilot scale plants of modest dimensions. An advantage of electrical field methods for tomographic imaging is that they are intrinsically able to be scaled-up (and down). Indeed, electrical conductivity imaging has been used on a terrestrial scale. Optical and ionising radiation methods are also amenable to scale-up. Ultrasonic methods may be more problematic because the relatively low velocity of sound results in image frame-speed limitations (section 3.1.4).

6. Conclusions

Some process tomography systems (resistive and capacitive impedance) are available for immediate application to two-phase processes where the resolution and speed requirements are modest (say 1 in 20 of projection distance and 100 frames per second, respectively). For more stringent applications, sensors with improved signal-to-noise ratios need to be developed and more accurate image reconstruction algorithms need to be implemented. This work demands using the latest methods for sensor design and construction, and for interpreting the extensive range of mathematical techniques for image reconstruction into effective signal processing algorithms.
The techniques of process tomography are advancing rapidly in the early 1990s, and the subject is showing signs of providing a mature method suitable for low-cost visualisation of process behaviour. The application of process tomography will, no doubt, be 'user demand led' and the authors hope that this paper will assist teams of instrument and process engineers in exploring new applications to particulate processes.

References


11) Xie C.G., Huang S.M., Hoyle B.S., Thorn R., Lenn C., Snowden D., and Beck M.S.: Electrical capacitance tomography for flow imaging: system model for development of image reconstruction algorithms and design of primary sensors, IEE Proc.-G, 139 (1992), 89-97


18) Isaacson D.: Distinguishability of conductivities by electric current computed tomography, IEEE Trans. Medical Imaging, MI-5 (1986), 91-95