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# Tomographic imaging of industrial process equipment: techniques and applications

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*Indexing term: Tomographic imaging*

**Abstract:** Opportunities for the use of non-invasive tomographic sensor technology are described and reviewed critically. Imaging instruments based on electrical sensing methods are discussed with respect to a number of process applications, including measurement of component concentration profiles, phase boundaries, component velocities and component mass flow rate. The use of low-noise electronic devices for process image sensing and the computationally intensive digital signal processing systems for image reconstruction are discussed. Limitations of current electronic techniques, particularly for future ultra high speed image reconstruction are revealed and directions for future progress are elucidated.

## 1 Introduction

Process tomography provides real-time cross-sectional images of the distribution of materials in a process. By analysing two suitably spaced images it will be possible to measure the direction and speed of material movement. Hence from this knowledge of material distribution and movement, internal modes of the process can be derived and used as an aid to optimising the design of the process. In Section 5 we will describe how this promises a substantial advance on present methods of process design which are based on input/output measurements, with only a limited amount of empirical or analytical information about the internal behaviour of the process.

The process industry uses high capital cost plant which is 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 based on average parameters (temperature, mean flow velocity, chemical composition etc). In some cases it has been possible to use the micro-scale data (instantaneous temperature, velocity, composition etc) at specific points in the process. However, complex experimental approaches (e.g. laser anemometry) involving sensing of microscale data are not economically feasible for many process design and operation needs, and for these latter cases the 'process tomography' approach using simple external sensors has much to offer.

Diagnosis of macroscopic phenomena based on intermittent microscopic data has occurred analogously in medical practice. For many decades diagnosis was dependent on external observations and measurements (palpation, blood pressure, body temperature etc). More recently we have seen spectacular advances made possible by computer aided tomographic scanning. In many ways the need for the study of process tomography is similar to that which existed in the past for medical tomography.

A range of applications to process vessels is possible, with interrogation of mixing and separation processes being prime candidates. Gravity and centrifugally assisted separators (e.g. cyclones) are probably the most widely used industrial separation processes. Therefore cost-effective design and operation can yield substantial capital and operational savings. Measurements in these process vessels have been extremely difficult because of the aggressive nature of the mixtures handled (e.g. dense aqueous particulate suspensions). Therefore exact models for design and operation are not available for opaque and fast moving dispersions because the basic in-process measurements cannot be made using optical instrumentation (opacity limitation) or higher energy radiation methods (photon count/speed limitation). By tomographically imaging the density and velocity distribution of the vessel contents, a more structured approach to modelling, design, and operation should be possible.

Tomographic imaging can also be applied to transport pipelines. Early work has been concerned with measuring two-phase flow in industrial pipelines, especially oil/gas and oil/water flows from offshore oil wells. Similar

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methods could also be used for improving the measurement of dry solids, where existing flow and concentration metering devices are affected by changes in upstream flow conditions that can often lead to significant measurement errors due to changes in flow regime. Imaging would be of direct use in monitoring these changes, and making accurate concentration measurements would be a significant improvement on current practice.

This paper will set out the range of sensing options, the structure of tomographic systems and image reconstruction, applications to process equipment, applications to flow measurement, the background to electronic design of process tomography equipment and the requirement for future electronic device development for some applications. The overall aim is to help the reader to understand the systems and electronic techniques needed to realise the exciting future potential for noninvasive tomographic imaging of process equipment.

## 2 Tomography: from medicine to processes

Tomographic imaging techniques were first used to diagnose lung disorders in the early 1930s. Since then the medical technique has advanced to meet increasing demands for better resolution and extended measurement periods. Modern computer-assisted tomography (CAT) scanners are used routinely for investigating human physiological functions and have been used in engineering laboratories for a number of process applications. A high-energy radiation source is often used, in which species within the mixture are labelled or an externally applied radiation source is employed. The use of such radiation-based methods is undesirable on the grounds of safety and expense. Furthermore, since radiological techniques rely on counting photons arriving at a detector, they are not generally suited to monitoring the performance of fast-moving mixtures unless very intense radiation sources are employed.

Safer sensing techniques include ultrasound and electrical impedance (resistance, capacitance and inductance) methods. Some of these methods have been applied in medical science but are less developed for process engineering requirements. Table 1 presents a summary of some better known tomographic techniques that may find application in chemical and biological processing.

## 3 Basic elements of a process tomography system

A process tomography system can be subdivided into three basic blocks: the sensor, the sensor electronics and

the image reconstruction, interpretation and display (Fig. 1). As with all measurement systems the sensor is probably the most critical part. The manner in which the

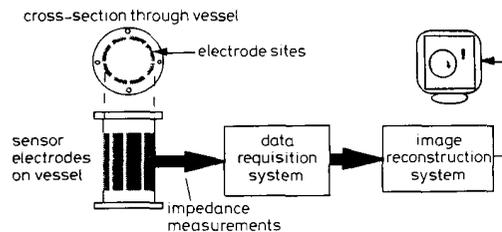


Fig. 1 Process tomography system

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, noninvasive, require minimum maintenance or calibration and, in many cases also be intrinsically safe.

Sensing techniques include electrical, ultrasound, nucleonic and optical (Table 2). Most sensors can be categorised as either hard or soft field. With hard field sensors, such as nucleonic, the sensor field sensitivity is not influenced by the nature of the flow being imaged. However, with soft field sensors, such as capacitance and conductivity, the sensing field is altered by the phase distribution and physical properties of the mixture being imaged. This limits the resolution (Section 8) compared with hard field sensors, nevertheless the electronic sensing methods are preferred for most process applications because of their low cost and safety.

Process images are usually required in real-time, therefore the dynamic response of the sensors is important. With electrical sensors this is not a significant problem, however with nucleonic sensors the photon noise means that rather long averaging times have to be used. The emphasis of this paper will be on electrical sensing.

## 4 Tomographic image reconstruction

Fig. 2 shows a system for electrical impedance tomography based on capacitance measurements using 8 electrodes [14]. The sensor is constructed by mounting eight electrodes on the outer surface of an insulating-pipe

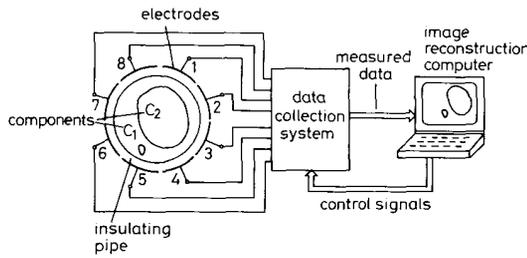
Table 1: Selection of tomographic techniques applied to process engineering

| Process                               | Sensing method                    | Reference                   |
|---------------------------------------|-----------------------------------|-----------------------------|
| Fluidised bed studies                 | $\gamma$ -radiation               | Seville <i>et al.</i> [1]   |
|                                       | X-Ray                             | Banholzer <i>et al.</i> [2] |
|                                       | Positron emission (PET)           | Bemrose <i>et al.</i> [3]   |
|                                       | Capacitance*                      | Halow <i>et al.</i> [4]     |
| Encapsulation and ceramics processing | X-Ray (CT)                        | Ioka and Yoda [5]           |
|                                       | X-Ray (CT)                        | Sawicka and Palmer [6]      |
|                                       | X-Ray                             | Eberhard <i>et al.</i> [7]  |
| Atmospheric pollution monitoring      | Laser absorption                  | Wolfe and Byer [8]          |
| Flame reactor                         | Interferometry*                   | Hertz [9]                   |
| thermometry                           | Infra-red emission*               | Uchiyami [10]               |
| Bioreactors and foaming               | Optical*                          | Hartley <i>et al.</i> [11]  |
|                                       | Nuclear magnetic Resonance (NMR)* | Heath <i>et al.</i> [12]    |
|                                       | NMR*                              | McCarthy [13]               |

\* Indicates that the method uses a nonhazardous sensing principle

**Table 2: Features of sensing techniques used for process tomography**

| Principle  | Practical realisation  | Typical applications  | General remarks  | Comments on reconstruction algorithms  |
|--|--|---|--|--|
| Modulation of beam of electromagnetic radiation by the dispersed components in the flowing fluid | Optical techniques   | Many two-component systems where the carrier phase is transparent to the radiation used | Conceptually simple, high definition possible, fibre optic light guides can simplify optical arrangements. Images of central region poor if second phase concentration is high, owing to absorption near walls | Similar algorithms well established for medical CT   |
|  | Ionising radiation x-ray and $\gamma$ -ray.  | Systems where there is a substantial density difference between the components          | 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)  |  |
| Reflection of external radiation   | Ultrasonic pulse echo systems  | Two-component systems where reflections occur at boundaries, e.g. liquid/gas flows      | Ultrasound 1 MHz pass through metal/liquid interface so a 'clip-on' system is feasible. 'Ringing' of transmitter may cause difficulty in imaging discontinuities close to the vessel walls                     | Similar to some NDT and medical applications   |
| Instantaneous measurement of electrical properties of the flowing fluid                          | Electrical capacitance plates on walls of pipe detect the presence of the second component | Oil/gas, oil/water, gas/solids etc  | Inexpensive, fast and rugged. High definition not possible. Loss of definition near centre of vessel   | Sensor field is affected by distribution of second phase so algorithms must allow for this |
|  | Conductivity sensing electrodes near wall of pipe  | Water/oil, water/gas, water/solids etc  | Similar to capacitance but electrode polarisation greasy deposits etc. may be a problem  | Similar to capacitance, similar methods used for some medical applications                 |
|  | Inductive sensors  | Ferrous and nonferrous materials  | Noncontact electrodes  | Not yet fully developed  |



**Fig. 2** Capacitance tomography system

section. The data collection system measures the capacitance between any two of the eight electrodes in all possible combinations given by  $N(N - 1)/2$  where  $N$  is the number of electrodes, being 28 for an eight-electrode system. The transducer uses stray-immune charge-transfer techniques and measurements are made in parallel to reduce data capture time.

Typically capacitances of the order of 1 pF can be measured to an accuracy of 1% FS in the presence of 50 pF stray capacitance. Under computer control the data capture time using this technique for all 28 measurements is 2.5 ms at present [15]. An accompanying paper describes a more sensitive capacitance sensor using 12 electrodes to give improved resolution [16].

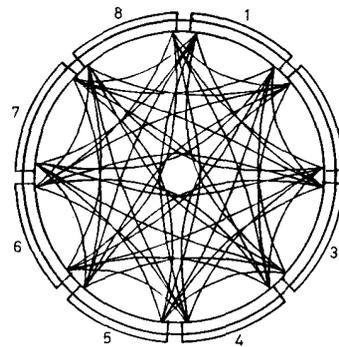
The field pattern for the 28 combinations (or projections) obtained with an eight-electrode system is shown in Fig. 3 (drawn using finite element analysis [17]).

Given the field pattern of the projections, there are many image reconstruction algorithms described in papers. Back projection is the simplest of these and although the other techniques are claimed to give more accurate images (Section 7.3), the increased computational intensity has led workers to concentrate on the

back projection algorithm for electrical impedance tomography, applied to both process engineering and medicine [18].

The simplicity of back projection is illustrated in Fig. 4. An arrangement using only three pairs of electrodes in the X and Y direction is shown. The shaded areas represent a fluid or solid in the vessel which is electrically different from the material around it. If, as in cases 1 and 2, we look at the X and Y directions, it is obvious where the areas of material are, because of the X and Y overlap. But, in the third case, the method throws up an inconsistency. This is why it is necessary to look at a system in more than two directions (e.g. the 28 directions shown in Fig. 3) otherwise the results can be misleading.

Now, considering the system shown in Fig. 2, the measured capacitance values, whose amplitude depends on the dielectric distribution in the pipe, are fed to a computer for image reconstruction using a linear back-



**Fig. 3** Image pixels formed by the boundaries of the 28 positive sensing areas

projection algorithm. A data processing system based on an array of INMOS transputers has been used for this operation.

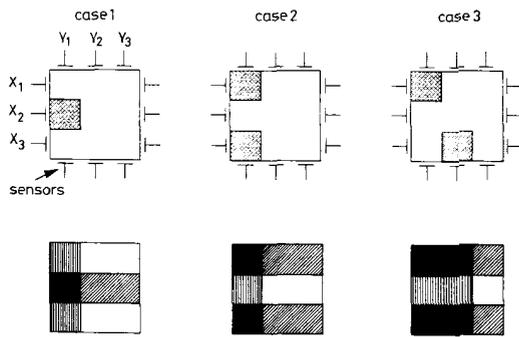


Fig. 4 Back projection method

Horizontal view of sensors  
Vertical view of sensors

The linear backprojection algorithm consists of a matrix multiplication

$$[G] = [R][M]$$

where  $G$  is the grey-level array (i.e. the reconstructed image),  $R$  is the reconstruction coefficient matrix, (obtained from the field data illustrated in Fig. 3), and  $M$  is the measurement array (from the measured capacitance signals in Fig. 2).

The program structure consists of processes for data input, calibration, reconstruction, display and interpretation, together with an overall control/monitor process. Of these, reconstruction is computationally the most intensive task, occupying over 50% of the processor's time.

The reconstruction process for the 8 electrode system consists of around 5,000 arithmetic operations and takes 24 ms to execute in one T400 series transputer processor. The use of multiprocessor networks that reduce the reconstruction time is described in accompanying paper [19].

## 5 Process applications for tomographic imaging

The need for process imaging is analogous to that of medical imaging — it enables noninvasive interrogation of the internal behaviour and location of contained matter. However, for processes the prospective applications are numerous and wide ranging, since the technique need not be limited to routine diagnosis of existing bodies (or plant). It is a fact that modern methods of process modelling and control have not been applied as widely to systems which handle suspensions of solids or fluids as to those which handle exclusively liquids. The basic reason for this is the restriction of the sensors which are available to measure even elementary material and process parameters. The most important parameters are phase flow-rate, phase concentration and particle-size distribution. Given the availability of suitable imaging equipment to measure these parameters, the technique can be employed at the three basic levels encountered in process engineering development:

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

*Stage 2:* Implementation of the required process route by designing efficient industrial-scale equipment (Section 5.1).

*Stage 3:* Routine process control, flow measurement and mass balancing functions, to enable operation under optimal conditions and to allow operational flexibility (section 6).

At all three stages in the overall design of a process it is necessary to devise models 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, for example, to facilitate the development of realistic process models. These have, hitherto, relied on theoretical computational fluid dynamics simulations run under conditions that are far removed from the real process conditions, or cannot be validated experimentally. For instance, the design of separation equipment handling 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 multibody 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 tend to be 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 protocol of process equipment, with accompanying savings in capital equipment, and higher productivity. Once a plant has been installed there are some obvious benefits in having the means to 'look inside' to investigate suspected malfunctions. More importantly, possibilities exist to perform accurate velocity, mass and component measurements (Section 6.1). Such information could form part of a process control strategy.

At present the development of tomographic systems is being directed to produce instruments for stage 1 and 2 type applications. Process monitoring and control applications will involve using simplified versions of the systems required for detailed interrogation of, for example, reactor hydrodynamics and reaction kinetics. The application of process tomography seems almost boundless, but by way of example some possible applications are listed below.

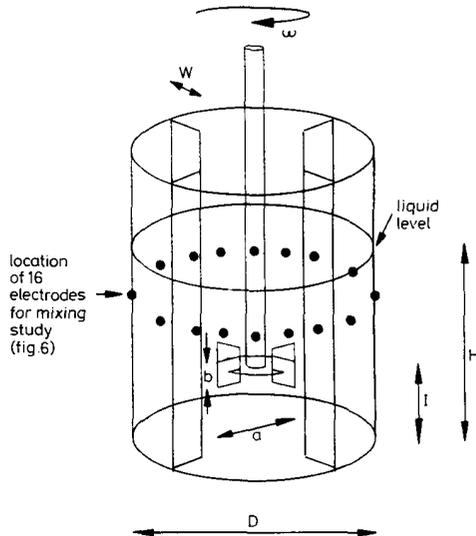
(a) *Stirred tank reactors, polymerisers etc:* Design and operation of these processes would be improved by having continual tomographically derived measurements including enhanced information on the effective mixing zones and polymer generation patterns (Section 5.1 and Fig. 6).

(b) *Separation processes:* Gravity and centrifugally assisted (e.g. cyclone) separators are probably the most widely used industrial separation processes. More cost-effective design and operation could yield substantial capital and operational savings.

(c) *Biochemical and fluidised bed reactors:* Processes growing biological materials may require the gas phase (air) to be uniformly dispersed to maximise oxygen contact area. Imperfections in design and operation can lead to dead mixing zones which can reduce process efficiency. It will be possible to detect the air pockets by

tomographic means, thus leading to improved process design and operation. Similarly the concentration profiles and recirculation patterns within fluidised beds (e.g. catalyst beds, granulation processes) could be elucidated.

(d) *General aspects of process safety and reliability:* There are many instances where quantities of an



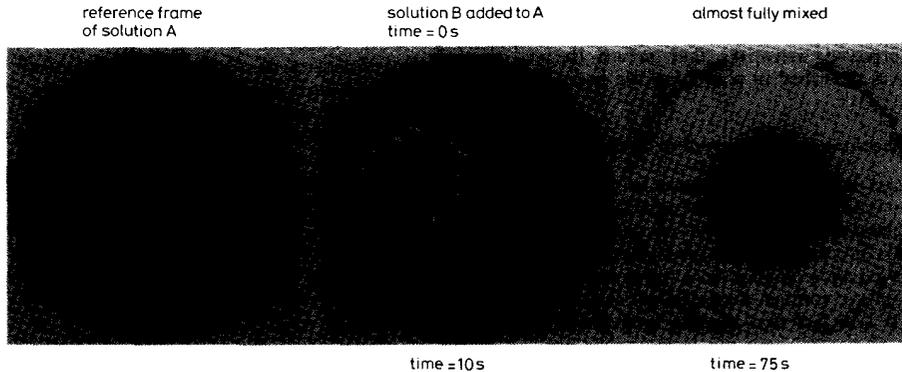
**Fig. 5** Standard mixing tank configuration also showing approximate location of imaging plane for results given in Fig. 6

$$D = H$$

$$l/D = a/D = 1/3$$

$$b/a = 1/5$$

$$W/D = 1/10$$



**Fig. 6** Time sequence of images showing mixing of fluid B (1% NaCl) in fluid A (0.1% NaCl) in a stirred vessel

unwanted component can cause maloperation. Examples include gas in boiler feed water and agglomeration of solids in vessels causing pipe blockages. The measurement systems for process tomography could be produced, possibly in a simplified form, to detect the build-up of new phases of components which lead to such maloperation.

### 5.1 Imaging of process reactors

The task of imaging the concentration profiles within a stirred vessel will now be considered as an example of the use of process tomography in chemical process design. This corresponds to a 'stage 2' type application, according to the classification given in Section 5.

Mixing vessels are commonly used to produce a homogeneous mixture of several components (or phases) sometimes in the presence of a simultaneous chemical reaction. Consequently, the hydrodynamic flow patterns and the distribution of residence times of fluid elements within the reactor are of importance. Most mixing vessels conform to a standard geometry (Fig. 5) in which the relative dimensions of the tank diameter, baffle width, impeller size etc. are fixed thus allowing comparison between different tanks and scale-up from laboratory to industrial size units. Before the advent of fast process tomographic techniques the behaviour within such vessels could only be elucidated from laboratory trials by optical inspection (using a pure fluid contained in a transparent mixing vessel and coloured dyes), radiative tracers, or by placing invasive sensors (e.g. conductivity cells) within the reactor. All of these methods had severe limitations being either invasive (thus perturbing the fluid flow), time consuming (i.e. requiring repetitious experimentation) and sometimes potentially hazardous. More importantly, some of these techniques could not be used if the mixture under examination was optically opaque, or contained a high percentage of solids. Electrical sensing methods do not exhibit these constraints and are, therefore, extremely attractive to the process engineer. Furthermore, noninvasive tomography allows inspection of the process in its normal environment thus allowing validation of theoretical models, based on computational fluid dynamics.

Fig. 6 shows an example of the time sequence of images delineating the mixing of two liquids obtained at one image plane within a batch vessel using an electrical impedance instrument [20]. The shading corresponds to different values of electrical conductivity and demonstrates how EIT can be used to abstract the concentration gradients within the reactor, in this case, from a

knowledge of the initial conductivities of the components liquids (Fig. 7). Such information can be acquired at different image planes (and ultimately in 3-D) for different process conditions (stirrer speeds, rates of addition of reactants etc.) and is likely to be an invaluable tool to the process engineer.

### 6 Tomographic imaging for multicomponent flow measurements

Multicomponent flow measurement is a situation where tomographic systems could be used to obtain a precise measurement, with the facility to crosscheck the performance with laboratory scale flow plants. This area has

been intensively developed during the past few years, largely because of oil industry requirements [21]. Therefore the theoretical and practical development of systems

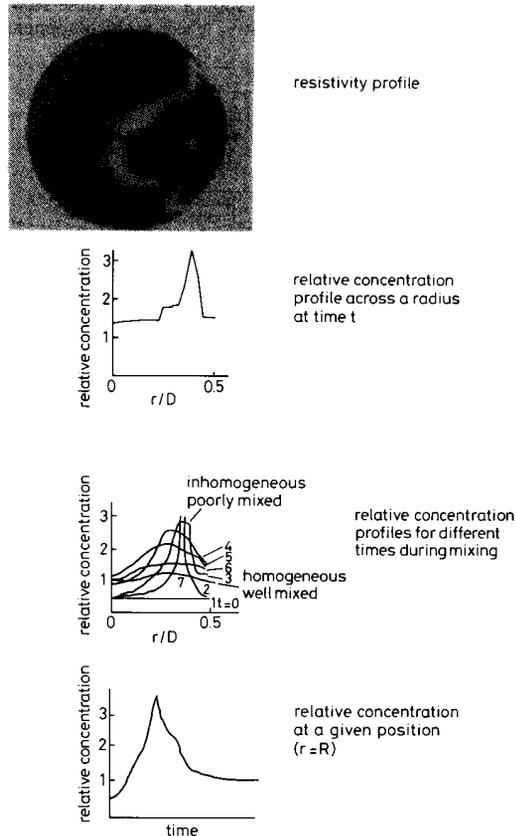


Fig. 7 Concentration gradients in reactor

for 'flow imaging' is at a more advanced stage than other process applications, and so, as a case study, flow imaging will be described in some detail.

Until recently, most flowmeters have been used to measure single-component materials (petrol, gas, water etc) at point of use in production plants. However, the increasing need to use resources more efficiently and build processing plants that can be operated cost-effectively, while minimising pollution, has led to an increasing demand for multi-component flowmeters.

Let us consider an example from the petroleum industry, concerning the problem of two-component measurement. In a typical offshore production facility, fluid from each well is pumped to the production platform where it undergoes preliminary processing before being shipped or piped to shore. The crude oil produced by an offshore reservoir usually contains both gas and water components. The flow pattern of the resulting mixture varies with the flow's conditions and is generally not predictable. It is important for the operator of a production platform to know which types of fluid a well is producing. The current method of solving this problem is to separate the fluids first, and then monitor each, using conventional single-component flowmeters (e.g. orifice plate for gas, turbine meter for oil). With the space on a production platform becoming more expensive and the

development of subsea production systems increasing, the use of conventional offshore separators is becoming less desirable.

Therefore a particularly interesting but difficult flow measurement problem arises; i.e., how the component fractions of an oil/gas or oil/water mixture can be reliably monitored without separation in a hostile environment. The qualities required for such a measurement system are that it should be:

- (a) nonintrusive, to avoid sensor erosion and pressure drop
- (b) a real-time measurement, to provide instantaneous feedback to the production operator
- (c) inline to avoid the problem of sample representivity
- (d) reliable, because maintenance will be costly, and perhaps impossible in the short-term
- (e) easily calibrated for use subsea.

Measurement systems based on tomographic imaging, where electrical capacitance sensors are the choice for nonconducting oil-based mixtures (Sections 3 and 4) satisfy the above criteria. The sensor electronics is robust and requires no adjustment onsite. All setting up and routine sensitivity checking is controlled by the image reconstruction computer which can be located in a non-aggressive environment with an optical fibre link to the sensor.

### 6.1 Basic principle of the flow tomography method

In medical imaging, the sensing system must be moved axially along the body to obtain a 'multislice' cross-section; however, in flow imaging the flow field moves along the pipe so that a single image plane is sufficient to characterise the flow. In addition, the axial velocity of each of the components over the cross-section of the pipe must be measured, and this may be done by cross-correlation of information from two image planes spaced along the pipe axis.

Fig. 8 shows the basic principle of the flow imaging method of two-component flow measurement. A two-

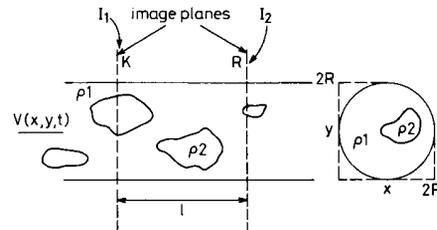


Fig. 8 Flow imaging for measurement of nonhomogenous flow

component flow is moving axially between the two image planes  $I_1$  and  $I_2$ , which are spaced sufficiently close together for there to be only a small change of the flow field between the planes.

Consider a small element  $\delta x \delta y$  in the cross-section of the flow, located at position  $x, y$  in image plane 1. The element may consist of either component 1 or component 2 and, by letting the element mass flow rate at time  $t$  be  $M_1$  or  $M_2$  (depending on whether it is component 1 or 2) we can write

$$M_1(\delta x, \delta y, t) = \delta x \delta y \rho(x, y, t) v(x, y, t) w_1(x, y, t) \quad (1)$$

and

$$M_2(\delta x, \delta y, t) = \delta x \delta y \rho(x, y, t) v(x, y, t) w_2(x, y, t) \quad (2)$$

where  $\rho(x, y, t)$  is the density,  $v$  is the velocity, and  $w_1, w_2$  are binary weighting functions to denote whether the element is composed of component 1 or component 2, i.e.

$$w_1(x, y, t) = 1$$

and

$$w_2(x, y, t) = 0 \quad \text{if } \rho(x, y, t) = \rho_1 \quad (3)$$

and

$$w_1(x, y, t) = 0$$

and

$$w_2(x, y, t) = 1 \quad \text{if } \rho(x, y, t) = \rho_2 \quad (4)$$

the average mass flow rates of the two components over the whole cross-section of the pipe are obtained by integrating the small element flow rates in eqns. 1 and 2 over space and time. The result is

$$M_1 = \frac{1}{T} \int_{t=0}^T \int_{x=0}^{2R} \int_{y=0}^{2R} \rho(x, y, t) v(x, y, t) \times w_1(x, y, t) dx dy dt \quad (5)$$

and

$$M_2 = \frac{1}{T} \int_{t=0}^T \int_{x=0}^{2R} \int_{y=0}^{2R} \rho(x, y, t) v(x, y, t) \times w_2(x, y, t) dx dy dt \quad (6)$$

Eqns. 5 and 6 represent a complete solution to the two-component flow measurement problem. This solution requires measurement of the cross-sectional density profile  $\rho(x, y, t)$  which is obtained by a tomographic imaging system [14, 16].

In addition, the cross-sectional velocity profile  $v(x, y, t)$  is needed, this being obtained by crosscorrelating the density information between the two image planes  $I_1$  and  $I_2$  in Fig. 8 to give the crosscorrelation function

$$R_{I_1 I_2}(x, y, \tau) = \frac{1}{T} \int_0^T \rho(I_2, x, y, t) \rho(I_1, x, y, (t - \tau)) dt \quad (7)$$

From eqn. 7 we compute the time delay  $\tau^*(x, y, t)$  of the maximum value of the function  $R_{I_1 I_2}(x, y, \tau)$ .

The velocity profile is therefore given by

$$v(x, y, t) = \frac{l}{\tau^*(x, y, t)} \quad (8)$$

where  $l$  is the spacing between  $I_1$  and  $I_2$ .

Further details of the basic principles of cross-correlation velocity measurement are given elsewhere [22].

A system has recently been reported for obtaining the velocity profile using ultrasonic transducers located on a single plane, this method of 'vector tomography' implies back-projection image reconstruction of flow-velocity dependent ultrasonic signals to produce a velocity image directly [23]. Although attractive in principle, the effect of ultrasound scattering and attenuation caused by large gas bubbles remains to be fully investigated and it is thought that this may limit the range of applications.

### 6.2 Potential applications of flow imaging

The tomographic flow imaging method provides cross-sectional images of the component distribution in the flow. These could be used in two ways; first as a diagnostic, where the images are updated to provide a real-time 'picture' of the flow and secondly for measurement purposes. For measuring the component mass flow rate of

two-component mixtures, two imaging systems would be required. Fig. 9 shows the algorithmic blocks required to calculate the component mass flow rate from eqns. 5 and 6. Some important potential applications of these techniques can be found in industry, where multicomponent

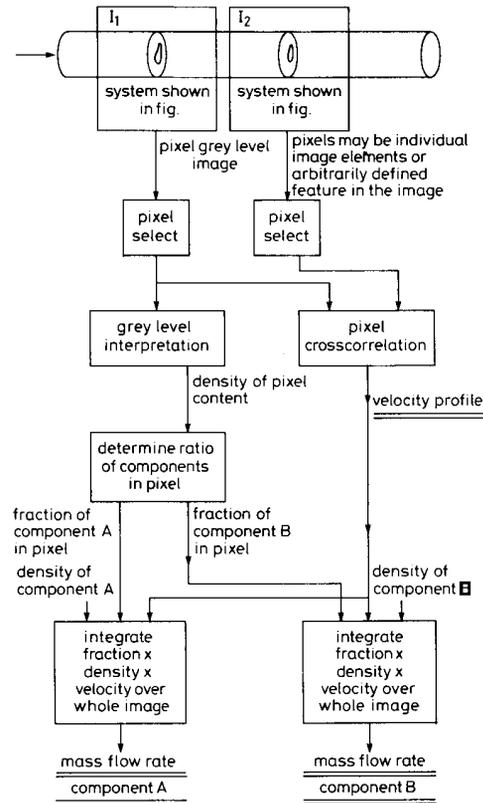


Fig. 9 Measurement of velocity profile and component mass flow

flow measurement has been highlighted as one of the highest priority areas of development. The oil industry examples given below are meant to be illustrative. Pipeline flows in industry may be multicomponent and similar applications to those listed abound.

(a) *Petroleum production systems and well testing*: To perform production tests on individual wells, the particular line must be disconnected, attached to a test separator, and the individual component flow rates (of oil/gas/water) then measured. This is an expensive and time-consuming process and does not allow real-time monitoring of the system performance. The flow imaging system will enable real-time multicomponent flow rate information to be gathered, thus leading to optimised production and increased recovery. Even simple flow imaging instruments for flow regime identification will provide early warning of the development of large gas slugs which can overload separation plant, damage subsea pump bearings and sometimes cause safety problems.

(b) *Future subsea and remote collection systems*: Flow imaging could enable continual monitoring of individual wellheads, which are connected to subsea collection manifolds. The imaging system would provide useful diagnostic information as the well flow changes with time, and

the method of flow rate measurement (described in Section 6.1) would give a measurement of the oil and gas component flow rates without any need for separation.

(c) *Oil custody transfer*: This involves sampling oil/water mixtures to determine the oil content. The sampling is accurate provided that the mixture is homogeneous, but sometimes changes in flow regime can cause inhomogeneous flow and result in large sampling errors. A flow imaging system could be used to detect inhomogeneous flow so that appropriate action could be taken to reduce the custody transfer error.

## 7 Electronic and signal processing systems

The electronic system of a tomographic imaging unit is a complex mix of both analogue and digital hardware interfaced with a computer system running specially written software. The parts of a basic system can be seen in Fig. 2, which shows the sensor array at the front end, connecting into the data acquisition system, which in turn is interfaced to the host computer. The analogue variations sensed by the front-end transducers are digitised and transferred to the computer by the data acquisition unit. The received data are then processed in the image reconstruction system to reveal the information sensed by the transducers.

The primary sensing system is arguably the most critical part and needs to match the process requirements. A wide range of methods was introduced in Section 3, however we will now consider the electrical techniques of capacitive and resistive impedance, and magnetic properties. These are all well suited to process applications (Table 2) because of their fast response, robustness and low cost.

### 7.1 Electrical sensors for process tomography

**7.1.1 Capacitance sensors:** The system in Fig. 2 shows capacitance sensors as the front-end transducers [14, 16]. A pair of electrodes is selected, under programme control, via two pairs of electronic switches. The capacitance between the ten selected electrodes is represented by  $C_x$  in Fig. 10.

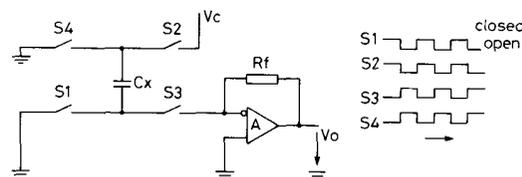


Fig. 10 Capacitance measuring circuit

$C_x$  depends on the effective permittivity of the material between the two selected plates. One plate, called the 'active plate' is charged and discharged cyclically between  $V_c$  and ground by opening and closing switches S2 and S4 in antiphase. The second electrode of  $C_x$ , called the 'detecting electrode' is connected to ground via S1, when the active electrode is switched to  $V_c$ . Thus,  $C_x$  is charged up to  $V_c$  across its plate. When S1 and S2 open, S3 and S4 close. The active plate is discharged to ground and the detecting plate is pulled down towards  $-V_c$ . However, the operational amplifier tries to maintain its input at virtual earth, and so produces an output voltage  $V_o$  to drive current through  $R_f$  to charge up the detecting electrode. The output voltage  $V_o$  is directly proportional to the unknown capacitance value  $C_x$ .

A typical operating frequency is 1 MHz, which can be achieved by readily-available CMOS switches. While measuring the capacitance between the two plates, the remaining electrodes are earthed, acting as 'guardrings' to the selected plates.

As will be appreciated, to make this measurement method yield high accuracy results, with good resolution in the presence of significant stray capacitance, requires design and engineering of the highest calibre [16].

**7.1.2 Resistive impedance sensors:** When using resistive impedance sensors, the electrodes are a ring of points penetrating the vessel wall (Fig. 1). A specified AC current is injected between two electrodes and the resulting voltages generated at the vessel wall are measured between the remaining electrodes. Currently, only the real component of the impedance is measured, i.e. the electrical conductivity (or resistivity) of the medium in the observation space (Fig. 11). Obviously, this method is appropriate for use on conducting, e.g. aqueous fluids. Whereas with capacitive sensors, the size of the plates must be relatively large to detect a significant capacitance, this is not a limitation with the 'point' electrodes used for current injection and voltage measurement. Physically 16, 24 or 32 electrodes can be accommodated in a ring, compared with 8 or 12 capacitive plates. Increasing the number of electrodes from 8 to 32 yields an increase of more than 20 times the number of pixels. However, the effective resolution in the reconstructed image will improve by a much smaller factor owing to the field distortion effects discussed in Section 8. On the other hand, the computational analysis load increases steeply with the number of electrodes.

The most critical electronic requirements in an impedance tomography system are

(a) the current source, which must provide a constant drive current irrespective of variations of process fluid conductivity and electrode surface conditions [24]

(b) the voltage measurement amplifier, which should have a high input impedance to avoid errors due to electrode contact impedance, a high common mode rejection to avoid errors due to circulating earth currents and be insensitive to connecting cable length (e.g. by using triaxial cable connectors as described by Dickin *et al.* [20]).

**7.1.3 Inductive sensors:** An alternative method of electrical tomography is to use inductance sensing. The placement of a metal within a magnetic field will obviously distort that field and this effect can be detected by search coils placed around the vessel. The technique would appear to have significant potential for certain application areas, e.g. metal ore separation processes.

### 7.2 Data acquisition system (DAS)

The basic system for data collection from an impedance system (see 7.1.2) is shown in Fig. 11. At the front end of the system, the signals from the transducers (voltages in this case) are buffered before being passed to the multiplexer, which selects signals under programme control. Because of the wide range of sensitivities relating to the different combinations of electrodes, a programmable-gain-amplifier is employed to ensure the best use of the analogue-to-digital converter's (ADC) dynamic range. The amplified signal is filtered, with varying degrees of sophistication, but at least to remove frequencies above half the sampling frequency, before being digitised in the ADC. This information is now in digital form and is passed from the DAS to the host computer for image reconstruction.

### 7.3 Image reconstruction

The data presented to the computer are an array of numbers relating to electrical measurements taken

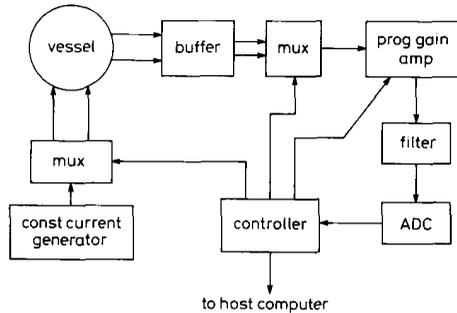


Fig. 11 Components of an EIT data acquisition system (DAS)

between two points. As can be seen from Fig. 3, we do not have a regular array of pixels as would arise from a raster-scan T.V. picture, but an irregularly shaped and sized array of pixels. Even to derive the arrangement shown in Fig. 3 requires a significant amount of computer time. There are basically two methods of image reconstruction currently under consideration.

(a) modified fast-filtered back projection [24].

(b) finite-element methods using Newton-Raphson matrix minimisation [25].

Of these methods, only the first, back projection, has been commercially developed (Section 4), the computational overhead being considered too great, using currently available hardware, for the Newton-Raphson method. Various alternative techniques are being investigated to relieve the load on the host computer. Fig. 12

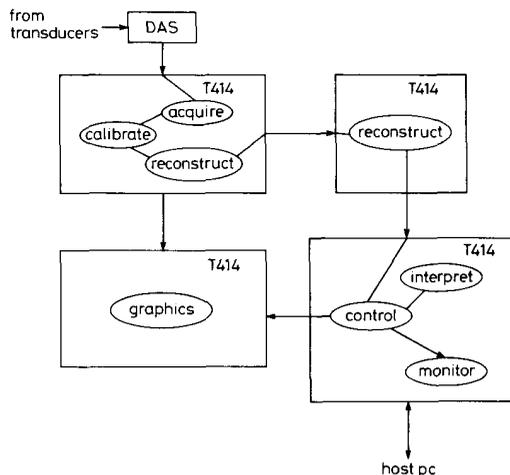


Fig. 12 Front-end ring of transputers

shows a ring of four transputers acting as a front-end processor and using this system: image reconstruction, using back projection, has been achieved up to 70 frames per second [15]. Transputers are individually fairly powerful processing nodes, however, many of the operations required for image reconstruction are directly based on the simple operations of AND, OR, exOR,

NOT and shift. Arrays of simple gates in two- or three-dimensions can be configured into cellular automata to perform the required tasks, for example, comparing the numerical value assigned to a pixel with its nearest neighbours. Such large scale arrays can be implemented in full-custom VLSI circuits or alternatively semicustom application-specific integrated circuits (ASICs). Programmable ASICs are available where the interconnection lattice for the individual cells of the ASIC is held in random-access memory (RAM). These are known as electrically reconfigurable arrays (ERA) or field programmable logic devices (FPLDs). Not only would such a system allow changes in algorithm to be implemented, but this could be done dynamically, so in a 'pipeline' structure the same physical ASIC could perform two or more separate functions at different times [26].

The alternative approach to reducing the image reconstruction task to basic logical operations is to use ever more powerful computing nodes. A range of digital signal processing (DSP) chip-sets is now available and these would obviously be suitable for use in matrix manipulation. The superpipeline employed in the floating point unit of high performance RISC processors, such as the Intel i860 (rated at 80 Mflops peak) enable it to achieve performances comparable to the Cray 2 super computer at a fraction of the cost [27].

### 7.4 Developments in the electronics system

The front end of an electrical process tomography system is limited by the fundamental laws of physics. Electrode design and orientation will be improved, as with shielding and noise reduction, but these improvements will be, by and large, incremental.

The electronics of the data acquisition system will be improved; increased resolution, accuracy, stability, signal-to-noise ratio, higher (or lower) operating frequencies, will be needed to match the wide variety of process materials to be imaged. With semicustom integrated circuits including analogue capability, it will become possible to mount much of the electronics of the DAS right up at the transducer head.

However, it is in image reconstruction that great strides are predicted. While high definition images cannot be expected, the improved algorithms being developed will be made, with the aid of parallel processing techniques, to run in real time. Using reasonable cost components, good quality quantitative image reconstruction at 200 frames per second can be expected in the next few years.

## 8 Discussion

The feasibility of high speed tomographic imaging for measuring the component distribution in multi-component processes has been demonstrated by several case studies. Probably the earliest description of an electrical impedance tomography system based on capacitance sensors was in 1989 by Huang *et al.* [14] who described an 8-electrode slow reconstruction speed system (reconstruction by PC) which gave images of sand/air mixtures in a cross-section of a pipe. An application of the 8-electrode system to flow regime identification was described by Xie *et al.* [17]. A much faster version of this system, based on transputers for image reconstruction was described by Salkeld *et al.* [28] and in a PhD thesis by Salkeld [15]. In the United States work was carried out during the late 1980s on multi-electrode capacitance tomographic system for measuring the void

distribution in cold-models of fluidised beds of coal, described in a paper by Halow *et al.* [4].

Work on electrical impedance tomography using low frequency resistive impedance sensors, for applications to processes containing electrically conducting fluids, followed the earlier work on capacitive sensors and is described in a paper by Dickin *et al.* [20]. However, many papers were published in the late 1980s on the application of electrical impedance tomography to medicine and these are summarised in a recent textbook by Webster [24].

Ultrasonic systems could find application in cases where it is appropriate to image the density differences between materials. Developments in sensor technology are described by Gai *et al.* [29], image reconstruction aspects are described by Weigand and Hoyle [30], a novel method for obtaining the velocity profile is described in the paper on vector tomography by Hauck [23].

Based on these case studies we believe that Table 3 represents a realistic assessment of the performance that is now attainable using electrical sensing methods.

**Table 3: Outline specification for some aspects of typical process tomography systems**

|   |   |
|---|---|
| Sensing principle   | Electrical capacitance (nonconducting fluids) electrical impedance (conducting fluids)  |
| Sensing electrodes  | Say, 8 to 16 capacitance plates or impedance electrodes   |
| Image resolution (target)   | 1 in 20 of projection distance (diameter of process vessel) 1 in 400 of projected area (cross-sectional area of process vessel)                   |
| Minimum size of phase boundary/particles that can be resolved   | Equal to the imaging resolution above   |
| Measurement of phases or particle too small to be resolved  | Ratio of phases is measured within an imaged element even though individual particles cannot be resolved  |
| Discrimination between concentration of components of the same phase within multicomponent mixtures (e.g. multiminerals mixtures) | Possibly by complex impedance measurements; currently being investigated  |
| Speed   | Target of about 1000 frames per second  |
| Image reconstruction  | Real-time may use INMOS transputer-based architectures, optimised vector-processor architectures (Intel i860), or cellular automata architectures |

We note that by using all-electronic measurements systems, image rates of well over 100 frames per second are technically feasible. This is much faster than previously used x-ray and  $\gamma$ -ray methods which are limited to much lower speeds because of safety/photon count considerations. Ultrasound methods of imaging are also slow owing to the sonic velocities being quite low, although, by using recently developed wide-angle transmitters, speeds of 400 frames per second in a 100 mm diameter vessel using 12 interrogating transducers are possible [29].

The spatial resolution of electrical field sensing systems is limited by field spreading, but we feel that a spatial resolution of 1 in 20 along the projection distance could be obtained in many applications (corresponding

to one part in four hundred over the projection area). Fortunately the electrical properties of each image boundary are functionally related to the image grey-level, so that the component ratio of a two-component mixture within a boundary can be measured, although individual particles cannot be imaged.

A most significant need is the indepth study and development of the coherent body of knowledge required to establish a sound practical and theoretical design framework for the emerging science of process tomography systems. Specific future investigations could include:

(a) fundamental limitations in spatial and temporal resolution of various sensor configurations (capacitance, impedance, ultrasonic, optical and radiation)

(b) the spatial and temporal resolution needed for particular applications

(c) grey scale requirements, particularly for binary and ternary mixtures where pixel elements are incompletely filled by one component

(d) correction of the image distortion caused by the electrical field equipotentials changing with the varying electrical properties of the material in the image space.

We believe that process tomographic techniques will have a number of exciting and innovative future applications for process engineers offering opportunities to visualise the internal characteristics of hitherto inaccessible particulate processes, mixing, reactor, and transportation systems.

To realise the full potential of process tomography, the present generation of electronic systems will need to be significantly improved (Section 7). The future here is bright, with current developments in semisystem analogue and digital integrated circuits. DSP chip-sets, vector processors and reconfigurable logic arrays becoming available to facilitate rapid progress.

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