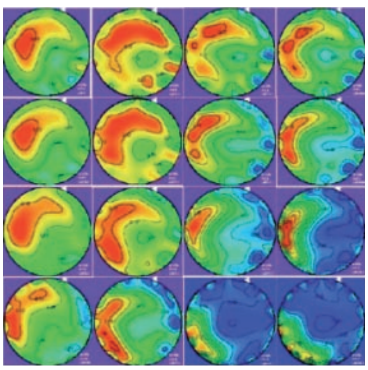
Seeing is believing

Steven Stanley, Gary Bolton, Les Bolton and **Paul Featonby** give a close insight into visualising and understanding live processes

CHEMICAL engineers could be forgiven for envying Superman. With his x-ray vision, he could easily see through clothes, walls or whatever, allowing him to foil his foes before they could do any harm. On a chemical plant with a process that isn't performing as it should, the ability to see through pipes and reactor vessels would come in handy, too. A multitude of sensors is on the market, of course, but they can't always be used, be it because they can't penetrate the vessel in which the reaction is taking place because they wouldn't function in conditions in or around the reactor, or simply because the place of interest is physically inaccessible. Fortunately, chemical engineers have tools that allow them to be just like Superman – well at least a little bit. The tool in question is process tomography.

Process tomography (also known as industrial tomography) involves taking samples from across multiple points across an area and displaying them as two or three-dimensional graphics, in real time. The samples can be taken with a variety of non-invasive methods, such as electrical impedance, electrical resistance, ultrasound, x-rays or Terahertz energies. A computer then analyses the data and visualises it in real time. The technique makes it possible to measure processes where conventional intrusive techniques fail, either because they cannot penetrate or because of harsh conditions. Results are displayed as real-time 3D graphics, allowing better understanding of the process.



Typical planar data of activity within a pipeline, from which 3D imaging is generated

Tomography allows chemical process users to estimate the spatial distribution of phases and chemicals inside their processing vessels or pipelines, giving instant feedback on reaction processes, or efficiency of transport. This can be particularly useful in the production of pharmaceuticals and fine chemicals, and in the food industry, where tomography offers great insights into the structural transformations found in colloids and gels. In mineral engineering, tomography can monitor separation and transport operations continuously, helping ensure maximum production.

In many other process industries, tomography helps characterise particulate and structural systems, and hybrid situations involving gasses, liquids and solids. It has long been used in medical body-scanning through the use of ultrasound and magnetic-resonance imaging.

The UK is at the forefront of developing and applying tomography to industrial processes. Since 1996, the Virtual Centre of Industrial Process Tomography (VCIPT) – set up as a collaboration between the Universities of Leeds and Manchester – helps interested companies work with a multi-disciplinary research group comprising 30 university staff. VCIPT researchers come from a broad range of backgrounds, spanning computing, electronics, mathematics, physics, process engineering, and particle science. Participating companies cover an equally wide spread, including food, minerals, pharmaceuticals, and petrochemicals, as the following examples illustrate.

instrument development

Industrial Tomography Systems (ITS) was one of the pioneers in electrical tomographic measurements. The company, founded in 1997, first developed the P1000 electrical resistance tomography (ERT) system, based on instrumentation developed at UMIST. ERT measures electrically-conducting systems such as aqueous solutions. In 2000, ITS launched a considerably upgraded version (the P2000), which has recently been validated for use in regulated industries such as life sciences.

In 2002 it licensed the world's first dual-modality electrical capacitance tomography (ECT) and ERT system from the Universities of Leeds and Manchester: the M3000. ECT can visualise non-conducting systems by measuring variances in the electrical permittivity of the materials. A dual-mode ERT and ECT system is well suited for obtaining data from systems that can change from electrically non-conducting to conducting. More recently, an ultrasound tomography (UST) module has been developed for the M3000, making triple-mode tomography a distinct possibility.

Over the past three years ITS has worked with BP, BHR Group and University of Leeds on the measurement and modelling of fluid flows in multiphase chemical reactors, using a new high-speed electrical impedance tomography (EIT) system, the Z8000, based on research at Leeds.

Chemical engineers have used ERT early on to measure flow patterns and material distribution in stirred vessels. The P2000 has been used world-wide in applications such as mixing, flow, and separation processes. A typical sensor comprises 16 electrodes which are mounted on the periphery of a pipeline or process vessel. The standard geometry is circular, although many other configurations are possible. This is made from stainless steel pipe with a polymer liner through which the electrodes are fixed so that they make contact with the process fluids but do not disturb the flow pattern.

The M3000 is mainly used to measure multi-phase flow containing oil, water (and gas and solids) as the system can obtain useful and meaningful data over the entire composition spectrum.

The Z8000 offers almost a two-order of magnitude increase in data capture rates compared to the P2000 and M3000 systems. Early work at Leeds shows it has promise in multi-phase flow characterisation and velocity measurement of fast-flowing systems in both tanks and pipelines.

nuclear

The UK's National Nuclear Laboratory NNL (formerly known as Nexia Solutions) provides experts and technologies for the UK's nuclear industries, and is an active member of VCIPT.

Because of the nature of the material handled within the nuclear industry, gathering information on what's going on inside a process, storage vessel, or container without having to gain physical access is often safer and cheaper. Therefore, process tomography is used in many applications including the internal imaging of process units, storage vessels, waste containers as well as active samples.

Recently, NNL has researched a cosmic ray muon-imaging system for imaging large and dense objects; employed non-intrusive gamma rays to determine fluid levels inside process vessels; worked on x-ray enabled post irradiation examination (PIE) of mock-up fuel pins; used ERT to visualise fluid mixing and solid suspensions; and carried out high resolution 3D micro-tomography of graphite samples.

Previously, NNL used ERT to examine the position of a mechanically-induced vortex inside a crystallisation reactor that is part of a nuclear reprocessing facility. The presence and depth of the vortex provides valuable information on the overall performance of the reactor, and NNL regularly uses ERT to remotely measure the depth of the vortex.

The ERT sensor, which is in contact with the tank contents, has been designed to withstand the extreme combined conditions of high chemical reactivity, radiation, and abrasion caused by the strongly acidic circulating flow. It works hand-in-hand with a data acquisition system that has been specifically designed to cope with the demanding conditions caused by the high conductivity of the liquor and the need to have a long cable between the system and the sensor. A software user interface displays the current vortex image and a historical trend of vortex depth. Images of the vortex are obtained using an image reconstruction algorithm based on linear back projection. The images are processed further to measure vortex depth; should it exceed parameters either at the low or the high end, an alarm is triggered.

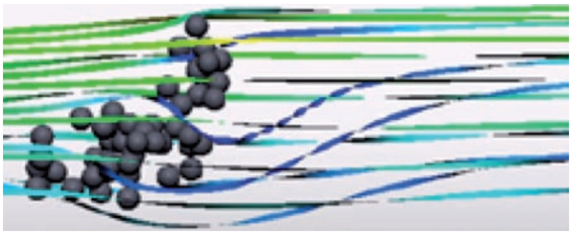
oil and gas

Petrochemical and oil refining uses many multi-phase chemical reactors. In many cases, the phases are mobile – for example, in fluidised beds used for processes such as the manufacture of polyolefins and acrylonitrile, and in slurry reactors used for a range of hydrogenation reactions.

The precise hydrodynamic behaviour of these reactors can be extremely important for design and operation, since poorly-mixed regions can make the reaction less selective, or the rapid flow of large bubbles through the reactor can hurt conversion rates.

However, it can be very difficult to establish the hydrodynamic behaviour of mobile phases. Historically, it has been studied with 'cold flow' modelling, using air and water in transparent equipment at ambient conditions. However, this can be misleading, as the behaviour of the organic fluids and gases at high pressure and temperature can be quite different to the cold fluids used in the model.

Tomographic imaging methods such as x-ray and gamma-ray imaging have been used to map the density in fluidised beds, but they can suffer from limited temporal resolution, which may be important in understanding bubble behaviour. They can also be difficult to apply to large thick-walled reactors. Positron-emitting particle tracking (PEPT) has been used to trace the paths of particles in reactors, but is constrained by access to suitable emitters. Electrical tomography complements these other approaches, and is particularly useful at providing high-speed images, albeit with relatively low spatial resolution. In addition, the combined use of



High-speed electrical resistance tomography gives the potential for detailed flow analysis in complex systems

Array of eight detectors on the underside of a 15 cm pipe

capacitance, resistance, and inductance can, in many cases, make it possible to distinguish between different materials of similar density (eg liquids and solids, or different liquid phases), which cannot be resolved any other way.

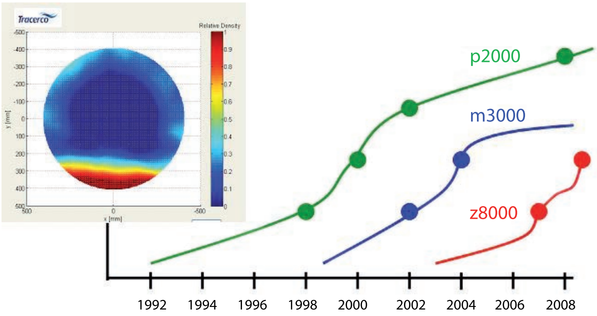
However, each of these measurement approaches provides only a part of the picture. VCIPT's now broadened focus on multi-modality, particularly the intent to integrate analysis of the raw data rather than the final image, promises to deliver more process information than the sum of the parts and provide both high temporal and spatial resolution of the contents of processes.

specialty chemicals

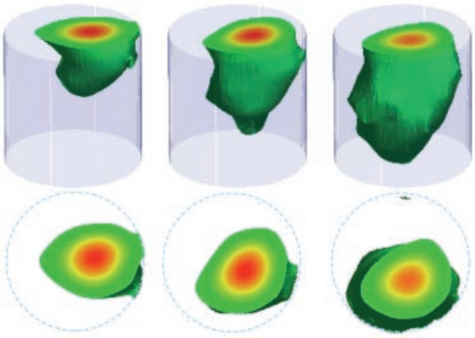
Tracerco, part of the Johnson Matthey group, provides instrumentation and diagnostics services to industry. Much of Tracerco's technology is based on gamma radiation, allowing through-wall measurements to be made, avoiding process shutdowns and minimising inconvenience. Its gamma-ray tomography is used for the non-intrusive examination of the contents of pipelines and vessels across a wide range of process industries. The process vessel can be a packed distillation column or a fluidised catalyst riser or standpipe where flow distribution of the process fluids is vital to performance.

The basic principle of this nucleonic technique is simple: the amount of radiation absorbed by the material that it passes through is a function of its density. By measuring the radiation reaching a detector, we can measure the density of the material through which it passes.

Sealed gamma radiation sources such as cobalt 60 or caesium 137 provide high-energy gamma rays capable of penetrating steel pipes or vessels. These are typically used with scintillation crystal detectors,



Typical results showing build-up in the bottom of a pipe



Mixing studies: ERT-derived images following the injection of a conducting tracer into a stirred vessel

coupled to photomultiplier tubes.

By arranging a single source with an array of detectors around a vessel, multiple density measurements can be obtained across different paths through the vessel. A two-dimensional tomographic image of the vessel contents is reconstructed.

The hazards of using such techniques are often misunderstood. The amount of radiation used is small and engineers who perform these measurements at overseas sites generally receive more radiation during the flight than they do while making the measurement!

The versatility of such a tomography system is essential. It must be completely portable and adaptable to a wide range of pipe and vessel sizes, corresponding to varying processes, with diameters in the range 15 cm to 10 m.

The Tracerco tomography technology has proven to be a practical tool for investigating flow distributions of vapour/liquid and vapour/solid systems inside process vessels. It has been used in packed bed applications, on fluidised catalyst risers, and on pipelines with a wide range of diameters.

pharmaceuticals

GlaxoSmithKline (GSK) uses process tomography to improve its understanding of the fundamental processes found within the pharmaceutical sector. One such process is the measurement of concentrations, especially for control of reactivity and reaction rates. Using a few single-point measurements gives only poor understanding of this, especially when concentration fields vary in both space and time. To build up a full picture, measurements have to be taken at multiple points in a fast and non-intrusive, non-invasive way. On top of this, to find use in industry, any instrumentation must also be inexpensive. The technology developed by VCIPT satisfies all these requirements, especially as computing speed and power continue to advance.

Previous largely-conservative design and scale-up policies, coupled with regulations which in the past required that process steps be precisely replicated during scale-up, have left the pharmaceutical industries apparently trailing behind more modern-looking industrial sectors like electronics. Hence, many manufacturing facilities look like simple geometric scaled-up copies of common laboratory equipment like beakers and filters. What is needed to improve manufacturing is a framework to encourage innovation in the process technology, which is soundly based upon clear understanding of the underlying process fundamentals.

In 2003 GlaxoSmithKline pioneered direct application of ERT into pharmaceutical R&D. ERT was ideally suited for evaluation on a typical glass vessel widely encountered in pharmaceutical manufacturing. A cylindrical vessel equipped with a Pfaudler retreat-blade impeller was fitted with a 4x16 sensor array, which fitted flush into the glass walls, and hence were completely non-intrusive and did not interfere with the flow and mixing generated by the rotating impeller. Initially ERT was used to capture tomographic images following the injection of a brine tracer (high conductivity) in tap water (low conductivity) which allowed the dynamics associated with the fluid mixing to be clearly discerned as the tracer mixes in three dimensions. Moreover, the tangential swirling and the axial-radial convection of the conducting tracer were captured in space and time. In this case, the dense information obtained via ERT gave a more profound basis for validating the CFD. These evaluations will enhance understanding of the complexities of fluid mixing and their role in determining the performance of stirred vessel reactors when used in pharmaceutical manufacturing.

Imaging of fluids in the interior of process units will undoubtedly make a growing contribution within the pharmaceutical sector. In the future, improved process imaging will result from combining more than a single modality, for example ERT combined with x-rays, t-rays, optics, acoustics, or MRI.

conclusions

To date, process tomography has been used to study spatial component distribution in challenging and high value industrial processes. Typical and contrasting application examples are in pipeline flows and pharmaceutical crystallisers, which feature multiple components in complex states. Commercial industrial process tomography products are now available that allow speedy evaluation and application of the technology. Today's processes are capable of major improvement giving productivity gains, and reduced waste/energy usage and emissions. Just as tomographic non-invasive imaging has revolutionised medical diagnosis, the acquisition of multi-dimensional process data is the key to major design and operational benefits.

Process tomography has been shown to offer key information for improved process design and operation, but has been limited by ill-posed data and system limitations. New developments in multi-modal and high-speed systems promise major advances and further benefits for process engineering. **tce**

For information regarding membership and up-and-coming promotional events please contact the VCIPT administrator Phillip Ronson at philip@vcipt.org.uk or visit www.vcipt.org

Alternatively, come and see us at the international symposium: *What, where, when: multi-dimensional advances for industrial process monitoring*, to be held at Leeds University, UK, on 23 June.

(clockwise from top left): Steven Stanley (sjs20@nnl.co.uk) is a technology manager at the National Nuclear Laboratory; Gary Bolton (gary.bolton@itoms.com) is an applications specialist at Industrial Tomography Systems; Les Bolton (leslie.bolton@uk.bp.com) is the reaction engineering advisor for BP's global aromatics and acetyls businesses; Paul Featonby (Paul.Featonby@matthey.com) is a technology manager at Tracerco