

Electrical Tomography: a review of Configurations and Applications to Particulate Processes[†]

M. G. Rasteiro^{1*}, R. Silva¹, F. A. P. Garcia¹ and P. Faia²

Department of Chemical Engineering, Faculty of Sciences and Technology, University of Coimbra¹

Department of Electric and Computers Engineering, Faculty of Sciences and Technology, University of Coimbra²

Abstract

Despite decades of research, the study of suspension flows still continues to be a subject of great scientific interest. In the development of accurate models for suspension-related processes, prior knowledge of several flow characteristics is essential, such as spatial distribution of phases, flow regimen, relative velocity between phases, etc. Several non-invasive techniques of flow characterisation can be found in the literature, however, electrical tomography offers a vast field of possibilities due to its low cost, portability and, above all, safety of handling. In this paper, a review of the use of electrical tomography for industrial/process monitoring purposes will be presented, giving information about the evolution throughout the years and about the limitations and advantages of the different configurations. Moreover, the signal de-convolution strategies, to obtain the images of the process, will also be discussed. The most recent advances in both fields will be presented. Additionally, information about the strategy adopted by the authors to produce a portable EIT system will be described. Finally, the future challenges for electrical tomography will be addressed.

Keywords: Electrical tomography, ECT, EIT, ERT, disperse systems

1. Introduction

Despite decades of research, the study of suspension flows still continues to be a subject of great scientific interest. In the development of accurate models for suspension-related processes, prior knowledge of several flow characteristics is essential, such as spatial distribution of phases, flow regimen, relative velocity between phases, including transient dynamic changes in multiphase processes, among others. Several non-invasive techniques of flow characterisation can be found in the literature¹, however, electrical tomography offers a vast field of possibilities due to its low cost, portability and, above all, safety of handling, since there is no need to use radiation which requires special handling and leads to dangerous waste.

Tomography offers a unique opportunity to reveal the complexities of the internal structure of an object

without the need to invade it. The concept of tomography was first published by a Norwegian physicist, Abel², for an object with axi-symmetrical geometry. Nearly 100 years later, an Austrian mathematician, Radon³, extended Abel's idea for objects with arbitrary shapes. The root of the word tomography is derived from the Greek words “tomos” meaning “to slice” and “graph” meaning “image”. Advances on the use of the tomography technique, namely computerised tomography (CT) and computerised axial tomography (CAT), were presented by Godfrey Hounsfield of Great Britain and Allen Cormack of the United States during the 1970s⁴. Since then it has become widely used as a medical diagnostic technique. In this case, a narrow beam of X-rays sweeps across an area of the body and is recorded with a radiation detector as a pattern of electrical impulses. Data from many sweeps are integrated by a computer, which uses the radiation absorption figures to assess the density of the tissues at thousands of points. The densities are used to produce a detailed cross-sectional image of the internal structure under scrutiny.

Later, the concept of tomography and its non-invasive way of imaging was extended to beyond

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¹ 3030-790 Coimbra, Portugal

² 3030-290 Coimbra, Portugal

* Corresponding author

E-mail: mgr@eq.uc.pt

TEL: (+ 351)239798700 FAX: (+ 351)239798703

the medical field. Tomography has been developed over the last decade into a reliable tool for imaging numerous industrial applications⁵⁻⁷. Currently, there are a number of tomographic techniques other than the electrical methods discussed in this paper available for studying complex multiphase phenomena. These include, for example, X-ray, γ -ray and positron emission tomography systems⁸, magnetic resonance imaging⁹, ultrasonic systems¹⁰, optical^{11, 12} and infrared¹³ tomography. Each of these techniques has its advantages, disadvantages and limitations. The choice of a particular technique is usually dictated by many, very often contradictory factors, depending on the application envisaged, including the characteristics of the medium, the objective of the measurement, the dimensions of the equipment, etc.

Electrical tomography is one of the available methods. It is relatively fast and simple to operate, has a rugged construction and is sufficiently robust to cope with most industrial environments. The apparent drawback of electrical tomography is its relatively low spatial resolution — typically 3-10% of the pipe diameter¹⁴. This, however, should be viewed in the context of the practical industrial applications. Moreover, more sophisticated inversion algorithms can improve the sensitivity of this technique. Electrical tomography is used to obtain both qualitative and quantitative data needed in modelling multiphase systems. Tomographic data can provide, in a non-invasive way, cross-sectional profiles of the distribution of materials or velocities in a process vessel or pipeline, or supply information about transient phenomena in the process. Results obtained from tomographic measurements can then be applied for process design or process control. Electrical tomography is, in certain cases, the most attractive method for real-time imaging of industrial processes, because of its inherent simplicity and low cost.

Electrical tomography can be further divided into two methodologies: electrical capacitance tomography (ECT) and electrical impedance tomography (EIT). Electrical resistance tomography (ERT) is a particular case of electrical impedance tomography. ECT and EIT produce images based upon variations in permittivity and conductivity, respectively. Recently, Yu et al¹⁵ have introduced another electrical technique, the electromagnetic tomography (EMT). Of these methodologies, ERT is the most widely and easily implemented, ideally for purely resistive mediums¹⁶.

For heterogeneous systems comprising materials with different electrical properties, ECT and EIT

can monitor dynamic processes such as: mixing; cyclones; fluidised beds; pneumatic, hydraulic and belt-conveyed transportation; etc. ECT and EIT are low-cost, but, in general, low-resolution, imaging methods. The rate at which images can be produced varies, depending on the data acquisition system, the measurement protocol, and the method of image reconstruction. Increasing the measurement speed permits faster dynamic processes to be captured, although this can increase the noise level, which in turn reduces the image quality. Tomography can be applied off-line or on-line. For off-line measurements, the capture time can be set fast relative to the dynamic changes in the process and the data processing time can be slow. The spatial resolution is normally high in this case. For on-line measurements, both the data capture time and the processing time have to be fast relative to the control time. This usually leads to poorer spatial resolution. Other factors that affect image quality are the physical nature of the measurements, and the method of image reconstruction used. In process applications, the interest is often in some average quantity, such as void fraction, throughput, mean velocity, etc. For model validation, higher resolution of the images is required.

In this paper, a review of the use of electrical tomography for industrial/process monitoring purposes will be presented, giving information about the evolution along the years and about the limitations and advantages of the different configurations. Moreover, the signal de-convolution strategies and reconstruction techniques used to obtain the images of the process will also be discussed. The most recent advances in both fields will be presented. Additionally, several applications of the different electrical tomography configurations will be addressed. Finally, a brief description of the strategy adopted by the authors to produce a portable EIT system with high resolution will be presented, discussing the approach implemented for signal injection, which allows us to deal with more conductive media, as can usually be found at the industrial level, and also the reconstruction approach, which allows us to obtain sharper images. Results obtained with this new system in a pilot rig conveying solid/liquid suspensions will be presented. To finalise, the future challenges for electrical tomography will be addressed, namely the possibility to use it for control purposes and also to deal with complex suspensions, with a disperse phase with non-isometric objects.

2. Fundamentals of Electrical Tomography

The theoretical model connecting the dielectric permittivity (or electrical conductivity) of a two-phase mixture to the volume fraction of one material dispersed within another was first presented by Maxwell¹⁷⁾. In his calculations, Maxwell assumed that small spheres of one material are uniformly distributed in the continuous phase of another material and that a homogeneous electrical field is disturbed by their presence. The spheres are assumed to be of equal diameter and small compared to the distance between them. The distribution of electrical properties inside a pipe, corresponding to the particle distribution, is obtained from measurements of electrical quantities, such as capacitance or conductance, between pairs of sensors located around the pipe's wall, and by applying an appropriate reconstruction algorithm which mathematically links the measured values with that distribution.

The concept of describing the composition of a multiphase system based on the above principles has been used for many years to monitor gas-solid, gas-liquid or liquid-solid systems. Small capacitance probes have been used repeatedly to measure the local solids concentration in gas-solid flows^{18,19)}. These probes have also been used in the oil and gas industry²⁰⁾.

Normally, excitation sources (voltage or current) for use with electrical tomography are of low frequency (below 5 MHz). Thus, these systems are mainly described by the equations governing the electrostatic field. When the flux (or current) lines meet an interface of different permittivity or conductivity, they deflect. Typically, the electrodes are installed at equal intervals around the periphery of the process vessel or pipe, in order to extract the maximum information. Capacitance-sensing electrodes are usually installed in a non-invasive way (outside the pipe made of dielectric material). Their area has to be large enough to give a sufficient capacitance change. Resistivity-sensing electrodes can be very small. They are usually placed flush with the inner surface of the pipe, in contact with the media, but they are still considered non-intrusive.

3. Capacitance Tomography

The objective of ECT is to reconstruct the dielectric properties of an object from the measurement of electrical capacitance taken between all possible pairs of electrodes. **Fig. 1** shows a cross-sectional view of

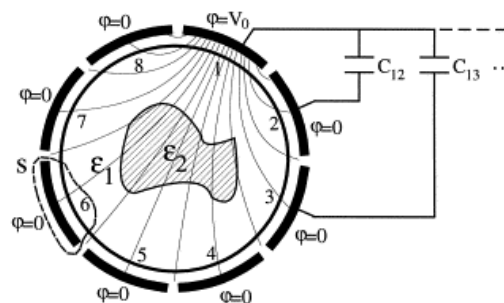


Fig. 1 Schematic representation of the measurement principle of an ECT system (adapted from²¹⁾).

an ECT sensor equipped with eight electrodes.

The electrodes can be either external or internal. External electrodes are used if the pipe is made of an insulating material, and internal ones have to be used if the pipe is made of a conducting material. External electrodes are easier to design and to maintain. They remain unaltered for a long time because they are not subjected to extreme temperatures, pressure or turbulence. So, they do not become contaminated by the materials flowing in the pipe. The main inconvenience of these electrodes is the non-linearity in the characteristics. Proper correction factors have to be used in order to make the characteristics linear. Internal electrodes are more complex to design, because they may have to withstand extreme conditions, and may even be subjected to corrosion. However, the change in capacitance can be assumed directly proportional to the change in permittivity inside the vessel.

The electrodes are excited one by one and the capacitance values between the excited electrode and the remaining ones are measured. It can be easily shown that for N electrodes there are $L=N(N-1)/2$ independent measurements. This is because capacitances $C_{i,j}=C_{j,i}$ and $C_{i,i}$, i.e. self-capacitance, is not measured. The measurement protocol, as described, can be imagined as a rotation of the electrical field around the pipe cross-section in discrete steps, by an angle $\alpha=360^\circ/N$. This is analogous to the source-detector movement in computerised tomography used in medical imaging.

The relationship between the spatial distribution of the permittivity and the measured capacitances can be derived from Maxwell's equation. For an ECT system, only one electrode is excited at one time, the others are always at virtual earth potential. Thus, the total electric flux, calculated over all the electrode surfaces, equals zero. The data acquired is used to construct the permittivity distribution images. The magnitude of the inter-electrode capacitance is usu-

ally very small. Therefore, the measurements can be easily influenced by exterior earth capacitances, larger than the measured signals. To eliminate these effects the electrodes have to be externally shielded. The choice of the number of electrodes is the result of a balance between the spatial resolution required and the image acquisition rate. Speeds of 100 frames per second are frequently used in ECT.

The frequency of the electrical signal imposed is usually of the order of 1 MHz. Thus, the corresponding wavelength of the electromagnetic radiation is of the order of hundreds of meters, exceeding the sensor size by several orders of magnitude. The electrical potential distribution inside the measuring volume can then be described by the electrostatic field theory.

ECT requires, as has been described, a more complex sensor array than ERT, and difficulties arise when dealing with conductive materials^{22, 23}. Thus, it is suitable for processes dealing with insulating mixtures of different permittivities. ECT is a fairly low-resolution imaging technique, but possesses a good overall accuracy for volume fraction estimation in flows of disperse systems²⁴. The images can be used in deciding on the adequate control actions to be taken. Moreover, using dual plane sensors, the technique can, additionally, supply information on the particle velocity via cross-correlation of the cross-sectional averaged time series²⁴.

4. Resistivity Tomography

In true electrical impedance tomography, the complex impedance of a mixture is used. It is based on a phase-sensitive measurement, where the resistive component is detected by the in-phase measurement

and the capacitive component by the quadrature phase measurement¹⁴. In this case the differences in both the real and imaginary parts of the impedance are measured²⁵⁻²⁷. The invention of electrical impedance tomography is attributed to John G. Webster in a publication from 1978²⁸; however, the first practical application of EIT occurred in 1984²⁹ through the work of Barber and Brown. Both EIT and ERT (a particular case of EIT) can be used to investigate processes where the continuous phase is electrically conducting. ERT is used for purely resistive media¹⁶.

In EIT, an electrical current is injected through a set of electrodes placed in the boundary of the domain under study, thereby resulting in an electrical field that is conditioned by the material distribution within the domain³⁰. The resulting electrical potentials at the domain perimeter can be measured using the remaining electrodes, and those values are fed to an inverse algorithm to attain the previously unknown conductivity/resistivity distribution. The procedure is only complete when all electrodes are used for injection or projection, so the cycle has as many projections as the number of electrodes (see **Fig. 2**). A characterisation of the distribution of the electrical field is used to deduce the material distribution within the domain. In the case of ERT, which is easier to implement^{27, 32, 33}, the aim is to reconstruct the distribution of electrical conductivity within a system. Similar to true EIT, in an ERT system the electrical current flow is induced between one pair of neighbouring electrodes, whereas differential potentials between all remaining pairs of adjacent electrodes are measured.

This procedure is repeated for all pairs of neighbouring electrodes until a full rotation of the electrical field is obtained. It can easily be shown that the

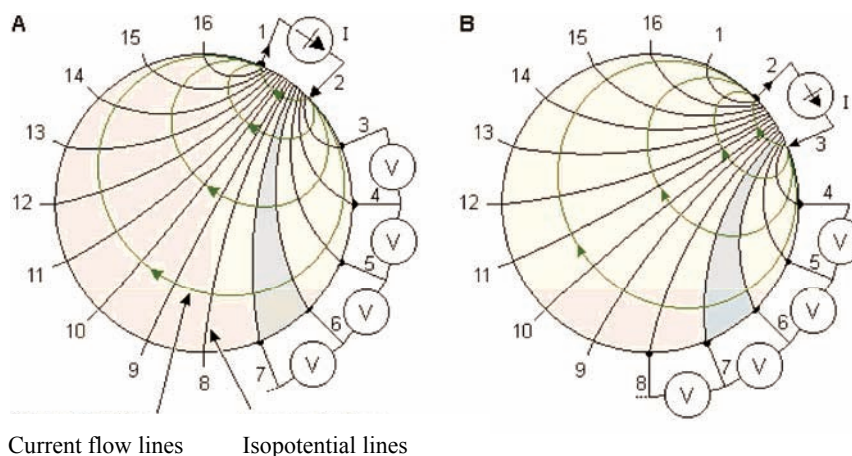


Fig. 2 EIT adjacent injection and measurement protocol for the first (A) and second (B) projections (adapted from³¹).

number of independent differential voltage measurements for an N -electrode system is $L=N(N-3)/2$, for the adjacent injection and measuring protocols, the electrode pair used for exciting the domain is excluded from the measurements. The frequency of alternating current in an ERT system is typically 20-150 kHz, so the quasi-static conditions can be justified. The current varies synchronically in the measurement volume and Ohm's law can be applied.

Recent advances have been directed both to the sensor design and to the acquisition system. The use of discrete electrodes is limited to aqueous-based fluids that present continuous admittance²⁶⁾. When large bubbles are present, some electrodes may lose contact with the conductive fluid and the results become inconsistent. In this case, conductive ring electrodes present a good possibility to overcome that problem²⁶⁾. Additionally, flush-mounted electrodes, as is required by resistivity tomography, can introduce another problem since the surface of the electrodes can be easily altered with time. Particular attention has to be paid to this aspect when dealing with extreme process conditions. In particular, the effect of temperature can dramatically change the conductivity of the fluid. Thus, temperature compensation has to be applied to the current or voltage measurements, when it changes a lot in the process over time.

Regarding the data acquisition system, new developments allow acquisition speeds of 1000 frames/s²⁶⁾. The current injection strategy is also important to guarantee better acquisition times and better sensitivity. Using a voltage-controlled current source together with an equal width pulse synthesizer to produce synthetic wave forms for electric field excitation and demodulation leads to less noisy data²⁶⁾. The voltage source must have low output impedance. When using a voltage source, the current supplied to the system increases as the fluid conductivity increases. This is particularly important in the case of a highly conductive medium (conductivities above 2 S/m) which is quite frequent in real industrial processes^{27,34)}.

Other parameters that have to be carefully considered when using EIT or ERT, besides the shape and size of the electrodes as mentioned above, is the separation distance between electrodes and the frequency of excitation of the electrical current. These parameters condition the current density distribution between electrodes and determine the true effective measuring volume³⁵⁾. The effect of the size of the electrodes can be substantially reduced through calibration³⁶⁾. As with ECT, EIT can also be used to measure the disperse phase velocity by using

dual plane sensors and applying a cross-correlation algorithm^{37, 38)}. A minimum acquisition speed of 100 frames per second is necessary to obtain accurate estimates of the velocity distribution³⁷⁾.

5. Image Reconstruction

In electrical tomography techniques, the measurements are sensitive within a 3D region (i.e. a volume); the sensitivity varies across the nominal sensing zone, and the sensitivity for a particular position within this zone also depends on the spatial variation of the physical parameter being imaged within the entire sensing zone. This non-linear behaviour makes image reconstruction difficult. Both capacitance and resistivity tomography are governed by a similar set of partial differential equations, and the reconstruction algorithms have many similarities. Reconstructing an image from the measurements (capacitances in ECT, potential differences in EIT) is called the inverse problem, whilst calculating the measurements from a known image is called the forward problem. In this case, the problem is one of mapping a set of theoretical parameters into a set of experimentally measured values. In the case of ECT, this would mean calculating the capacitance values for a given distribution of dielectric permittivity inside the system. This problem has a unique solution. The inverse problem, however, in addition to the difficulties caused by non-linearity, is also usually ill-posed and ill-conditioned. Mathematically, we are faced with a matrix inversion problem. In the case of ECT, the inverse problem is equivalent to finding the material distribution inside the system based on a set of capacitance values. This is what we usually call a reconstruction problem. The aim is to obtain the reciprocal of operator F which gives the original distribution of dielectric properties $\varepsilon = \varepsilon(\gamma)$ from the measured values of capacitance C^o :

$$\varepsilon(\gamma) = F^{-1} [C^o] \quad (1)$$

There is no analytical solution to this problem, mainly because of its non-linearity. The number of unknowns is much higher than the available data. So, there is an infinite number of solutions which match the capacitance measurements. The only possibility is to construct a permittivity distribution that best fits the measurements.

For EIT, a similar approach has to be followed. The forward problem calculates the electrical potentials in the boundary using an initial estimation of the conductivity/resistivity distribution, while the inverse

problem reconstructs the conductivity/resistivity distribution based on the electrical potentials measured in the boundary, through the use of an adequate mathematical procedure. The distribution of the electrical field in the domain can be modelled in the forward problem using Maxwell laws³⁹. The problem of finding the solution for the inverse problem is tackled by solving first the forward problem, which is used as an effective calibration. The boundary voltages or capacitances are usually calculated using finite element methods (FEM) for a known distribution of permittivity or conductivity. The sensitivity matrix is obtained from the measured values (voltage or capacitance). This solution is then supplied to the reconstruction technique to obtain the values of permittivity or conductivity in the system nodes from the measured capacitance or voltage/current values. The sensitivity matrix and the measured boundary values are used to interpret the changes (permittivity/conductivity) in the system nodes.

There are several methods for reconstructing EIT and ECT images which can be broadly divided into three classes: linear (single-step and iterative methods); non-linear iterative methods; and heuristic multivariate methods.

Linear methods

Linear methods are fast, as images are generated by simply multiplying the measurements by a single, pre-calculated matrix. Linear back-projection (LBP) is the most widely used linear method. In LBP, the matrix is the transposal of an estimated solution to the forward problem, based upon either field gradients or more commonly, sensitivity maps (the area in the measuring volume is divided into sensitivity areas)⁴⁰. In the first case, we speak about non-iterative linear methods. An iterative back-projection algorithm was proposed by Yang⁴¹ which is much more accurate. LBP tends to produce, in general, poor, heavily smoothed images because the transposed solution from the forward problem is, in fact, a poor estimate of the solution to the inverse problem that is actually required. It is assumed that the electrical field is not distorted by changes in permittivity/conductivity, similar to what happens in X-ray or γ -ray tomography. Mathematically, this approach is correct when the dielectric properties of the phase components are close to one another. However, LBP methods can provide a fast on-line qualitative view of the process. The linear methods have been improved by including approaches based upon ridge-regression or eigenanalysis⁴². In practice, LBP has been used successfully for gas-

solids or gas-oil systems²¹.

Non-linear methods

Non-linear methods use numerical forward solvers to predict measurements and use sensitivity maps associated with an estimate of the image to calculate measurement residuals. The estimated image is then updated via a non-linear iterative scheme such as the modified Newton Raphson (NR)⁴³ or adaptive mesh regenerating techniques⁴⁴. NR can introduce significant artificial errors in the solution. Regularisation methods such as the Marquard and the Tikhonov methods have to be applied to obtain a better approximation at each step²⁶. The regularisation can, nevertheless, introduce further noise in the final image²⁶. In direct inverse solution algorithms such as the sensitivity conjugate gradients method (SCG), the algorithm searches for the minimised residual vector, and leads to images with improved accuracy²⁶. These methods are generally called multi step inverse solution algorithms (STM) and normally provide a better description of the dynamic nature of the process³⁸. Adopting non-linear iterative methods offers more flexibility in the measurement protocol that can be used. However, the considerable computational load makes them much slower than linear or heuristic methods. Non-linear iterative methods are currently too slow for real-time image reconstruction, although this may change through a combination of efficient algorithms⁴⁵ and the continued fall in computing costs. Cho et al.⁴⁶ applied an adaptive mesh grouping method based on fuzzy genetic algorithm to decrease image reconstruction time. Mesh optimisation is also an important step towards higher resolution images³⁴. So far, this type of method is most suited for off-line image reconstruction.

Heuristic methods

Heuristic methods can be linear or non-linear. The relationship between training (or calibration) sets of images and measurements is modelled empirically. The training set can be calculated (numerically or analytically), or obtained experimentally. Linear heuristic models include multiple linear regression⁴⁷. Non-linear methods include self-organised maps and artificial neural networks⁴⁸. For process applications, image reconstruction is often an intermediate step towards calculating other variables so heuristic models can, in principle, relate the measurements directly to the variable of interest⁴⁹.

6. Applications

ECT and EIT have been used to study a wide range of different systems. The bulk of the work has used ECT and EIT as research tools, in which model systems are studied on small-scale rigs or in pilot plants. The transferral from the research environment to real-life process monitoring has been slow, although some examples have been reported.

Some up-to-date electrical tomography applications

In a work by Larachi et al., the hydrodynamics of gas-liquid packed beds was studied experimentally using twin-plane electrical capacitance tomography⁵⁰. The distribution of solids concentration in different processes plays a key role in the process industry, thus several examples of the use of electrical tomography are in the field of solids distribution visualisation. Experimental studies were carried out to measure the solids concentration in a cyclone separator using ECT⁵¹. ECT and EIT were also used to monitor the flow regimes during hydraulic (solid-liquid) and pneumatic (solid-gas) transport. An ECT test system has been used to monitor the pneumatic transport of rape seeds⁵². Others, Sundaresan et al.⁵³, have addressed the problem of pneumatic conveying of granular solids in vertical and inclined risers using electrical capacitance tomography. Recently, pneumatic conveying (a model system of plastic pellets) has been studied using dual-plane ECT and an electrodynamic sensor⁵⁴. Paste extrusion has also been studied using EIT, in a work of William et al.⁵⁵. An ERT system was used to visualise swirling flows in a conveying pipe³⁰. The internal flow structure within fluidised beds of different sizes has been studied using ECT⁵⁶ in order to better understand the hydrodynamics of these systems⁵⁷. Capacitance computed tomography techniques were also used to visualise particle movement in the draft tube of a spouted fluidised bed for the coating process of drug production⁵⁸. ERT has been used as well to enhance the performance of a differential pressure flowmeter (Venturi type) in two-phase flow measurements⁵⁹.

Foams are also an important issue in a variety of industrial processes including mineral production processes such as froth flotation. Applying electrical capacitance tomography to low water fraction foams (<0.05) was addressed by William et al.⁶⁰. Kourunen et al. used electrical impedance tomography to image the mixing of two miscible liquids in a turbulent flow, using the trump-jet mixing system of papermaking chemicals and additives⁶¹.

Electrical capacitance tomography has been adapted to characterise combustion phenomena in a scaled model of an internal combustion engine by Vilar et al.⁶²; it was thus possible to locate flame position, measure flame size and to monitor the effect of varied air/fuel ratio. Electrical resistance tomography was applied for the study of three-dimensional imaging of concrete⁶³. ERT has also been used recently for multivariate process control of a sunflower oil/water emulsion process⁶⁴. In a similar way, the applicability of electrical resistance tomography to pharmaceutical chemicals development has been considered: vessel/stirrer configurations designed to mimic typical plant reactor geometries were investigated in connection with multiphase processes typical of the pharmaceuticals industry⁶⁵. Electrical impedance tomography was also adapted to monitor drug release three-dimensionally as a function of time⁶⁶. EIT was also used for imaging the electrical conductivity distribution within a two-dimensional cell culture, in a work by Morgan et al.⁶⁷.

Two-phase flow tomography by EIT: current developments

The authors have also been working on the improvement of EIT applied to image acquisition of two-phase flows (solid/liquid) with the aim of CFD model validation³⁴. The EIT system developed by them measures the differences in both the real and imaginary parts of the impedance, so no data is lost. This EIT system is a portable one, to be transported easily to any location where an electrode ring is present and can be used for 16-electrode or 32-electrode rings. To circumvent difficulties and costs of designing a current source, a choice was made to depart from traditional EIT systems, and instead a voltage source was designed. It has been demonstrated that using a voltage source for stimulating the domain instead of a current source allows surpassing the limitations found when studying more conductive media²⁷. This EIT system has already been described elsewhere³⁴; however, for the sake of a better understanding, a brief description is given here. A series of USB-type devices is used for purposes of interfacing between the EIT system and the PC (DAQ boards). The devices are used to read the electrical potentials by means of the analogue input channels. The EIT system designed has an image acquisition frame rate that can achieve up to 4000 frames per second and 1000 frames per second for the 16- and 32-electrode measurement rings, respectively. A programmable frequency voltage waveform generator with an output frequency up to 25 MHz was implemented. Two ad-

ditional signals, both with unitary magnitude, one in phase and the other 90 degrees out of phase with the excitation signal, are generated simultaneously. Then the electrical potential voltages read at the electrodes are multiplied by these two unitary signals. The signals resulting from the multiplications go through low-pass filters: this allows isolation of the constant terms needed to determine the impedance of the domain. The routing of the excitation signal and of the electrode potentials to the multipliers is done using analogue multiplexers: the addressing of the multiplexers is accomplished through the digital outputs of the DAQ boards.

Tomographic images of solid-liquid suspensions

The experiments were conducted in a pilot rig described elsewhere^{34, 68}. In short, the test section consisted of a horizontal PVC tube, 7.5m in length and 100 mm in internal diameter. The flow rate was measured by an electromagnetic flowmeter and the pressure drop was measured by a differential pressure transducer whose pressure taps were 4 metres apart. Appropriate lengths were inserted before and after the test section to account for entrance and exit effects. The electrodes were mounted equally spaced around the circumference of Perspex tubes, and the tubes were inserted in the test section between the pressure taps. For the tests depicted here, an adjacent injection strategy was adopted with the 16-electrode system, with a frame acquisition rate of 4000 frames per second, while the voltage source was configured to produce a sinusoidal waveform of 2 kHz frequency and 1.5 V of amplitude. With this set-up, a 90 μ A current amplitude was applied to the domain. The tests were performed using solid/liquid suspensions of spherical glass beads in a diluted aqueous solution of NaCl (conductivity of 663 μ S/cm) flowing in the system. The bead sizes ranged from 400 to 600 μ m in diameter. For image reconstruction, the open source software EIDORS³⁹, under consideration of direct differential measured voltages, was used (two meshes were tested: mesh 1 with 2304 linear elements and 1201 nodes, a structured mesh, and mesh 2 which is a non-structured one with 415 linear elements and 241 nodes). This software implements a non-linear back-projection method using a regularised algorithm (Tikhonov regularisation). To solve the forward problem, the Complete Electrode model (CEM)⁶⁹ was chosen: this model incorporates the shunt effect and the contact impedance in the electrode/domain interface³⁹. Tests were performed at different flow rates, from 0 up to 52 m³/h. At very

low flow rates, the particles were not moving and remained as a fixed bed sedimented on the bottom of the tube. But once the flow was increased enough to fluidise the bed, the particles started moving, and as the flow rate continued to increase, the amount of sedimented particles decreased and these became more and more dispersed in the conveying medium until a quasi-uniform distribution was reached. This is evident in **Fig. 3** where each row refers to a value of the flow rate: 0, 13, 33 and 52 m³/h; the first column shows photographs of the conveying suspension inside the tube, the second and third columns show the reconstructed images using mesh 1 and mesh 2, respectively, once again considering direct differential measured voltages. For all images depicted in the middle and right columns of **Fig. 3**, dark blue identifies a higher impedance state and dark red a lower impedance state (in a linear transition scale).

When the system was stationary (the pump was switched off) the particles were sedimented in the lower region of the pipe and the gradient of conductivity was high (first row); when the flow rate was 13 m³/h, the particles were already moving but generally were dragged by the water into the lower region of the pipe which clearly looks like a deposit at the bottom where the conductivity gradient is high (second row). For the highest flow rate, 52 m³/h, the particles were almost completely distributed all over the entire cross-section of the pipe, therefore a very small gradient of conductivity exists, the image corresponding to the red colour, with some slightly higher concentration near the bottom, as is evident in the 4th row of **Fig. 3**.

7. Future Trends

Electrical tomography has been evolving over the years, becoming more accurate, retrieving images with better resolution, becoming faster and acquiring new functionalities. These upgrades result either from new sensor configurations, new injection strategies, upgrading of the acquisition system, better and/or faster reconstruction algorithms, etc.

The ring electrodes developed for bubbly systems represent a step forward in the use of electrical tomography for such systems, including processes involving foams²⁶. Linear sensors, constructed from printed circuit boards (PCBs) are also now being used to better visualise non-circular vessels or ducts⁷⁰. Additionally, a recently added feature to electrical tomography is the data acquisition feature using a dual-electrode device, in order to obtain in-

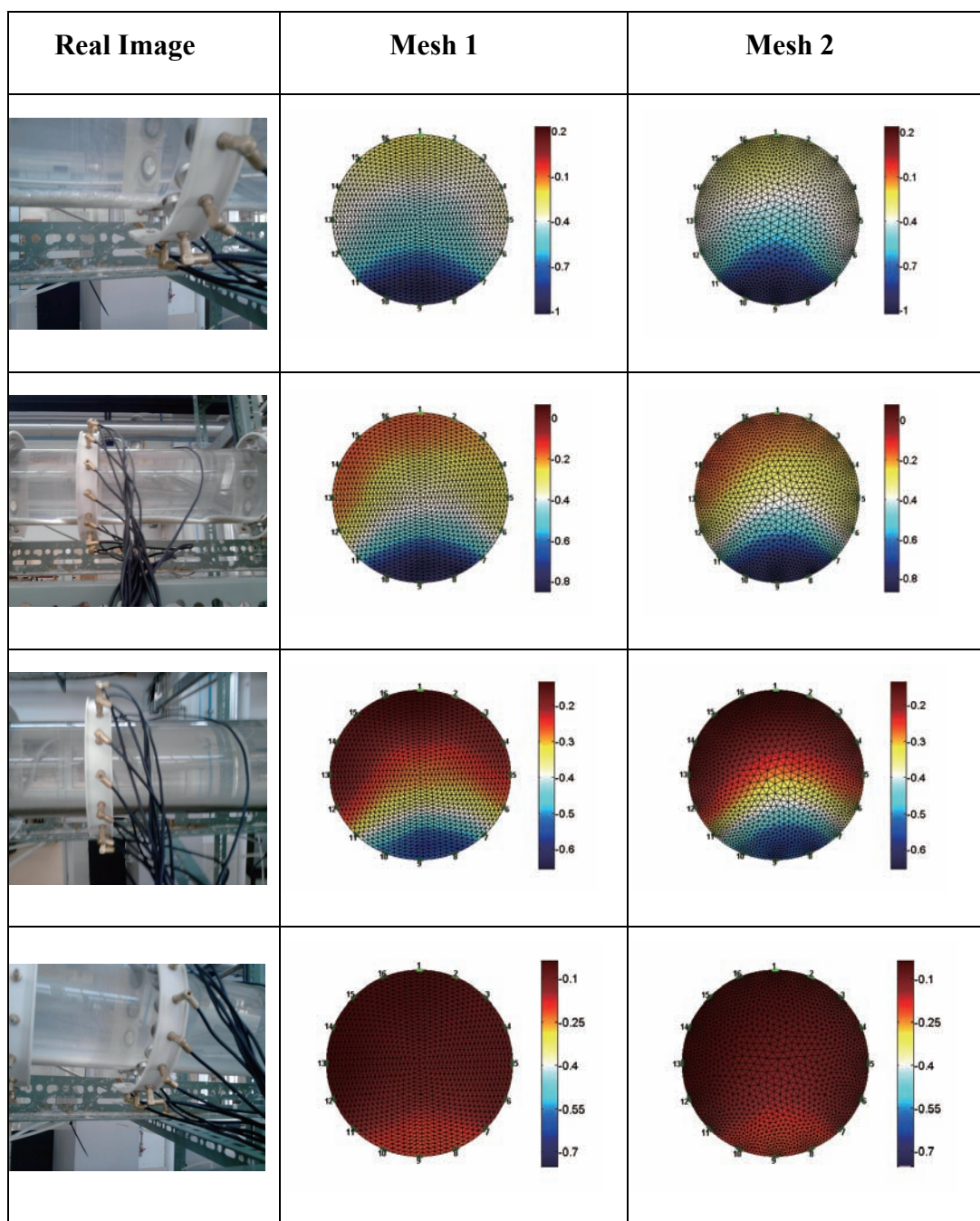


Fig. 3 Solid-liquid suspension tests carried out with an average particle concentration of 3.9 g/l for flow rates of 0, 12, 33 and 52 m³/h, respectively, from top to bottom (left column contains pictures of the section under study, middle column images obtained using mesh 1 and the right column images obtained using mesh 2) (reproduced from³⁴).

formation about the velocity profile in the process through cross-correlation of the signals acquired^{26, 30}. This functionality is expected to be further developed in the future. In this case, ERT can be used coupled with other measuring techniques to improve the accuracy of traditional flowmeters used for multiphase systems⁵⁹.

On the other hand, the injection strategy can be an

important parameter to be controlled when applying electrical tomography to real industrial processes. Voltage sources have proved to be a better option in the case of highly conductive fluids^{27, 34}. Temperature compensation of the reference profiles is also a good strategy when dealing with conductive fluids³⁰.

Finally, and regarding the hardware of electrical tomography, modularity has become an important

characteristic, mainly when industrial application is envisaged⁷¹. Moreover, multi-modal process tomography, exploiting multiple sensors and allowing the integration of their data⁷², will be pursued in the future.

Another domain where a lot of work is being done is image reconstruction algorithms. In fact, improving this step can contribute a lot to the better resolution of the final images and, additionally, faster reconstruction algorithms are needed if on-line applications are targeted. Work is being done in order to minimise the influence of small perturbations in the measured data, on the inverse solution. This is, for instance, the case of the standard Tikhonov regularisation (STR), which is now being applied for on-line reconstruction⁷³ included in a semi-parametric model reconstruction algorithm. Further coupling of STR with maximum entropy regularisation (MER) can additionally reduce the artefacts of the reconstructed images⁷⁴. This technique is particularly well suited for 3D reconstructions. Heuristic methods are another route for on-line reconstruction⁴⁹.

Regarding the applications, besides its use for model validation in particulate processes, nowadays in connection with sophisticated CFD models⁴⁴, the application of electrical tomography for the on-line control of the process is now being pursued. Traditionally, electrical tomography was used in the industrial process to inspect abnormalities in the equipment. Recent studies show that it is now possible to use ERT for multivariate statistical process control, where it is used to predict the probability of the process monitored being in a normal or abnormal operational state⁶⁴. Another important vector which has been pursued for years, but still needs further development, is the conversion of the reconstructed permittivity/conductivity images to adequate physical values for each particular application³⁶.

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Author's short biography



M. G. Rasteiro

Maria da Graça Rasteiro graduated in Chemical Engineering at the University of Coimbra, did post graduate studies in Loughborough University, UK, and obtained a PhD in Chemical Engineering/Multiphase Processes, in 1988, in the same university, under the co-supervision of Professor Brian Scarlett. She is presently an Associate Professor in the Chemical Engineering Department of the University of Coimbra in Portugal. She was a member of the working group on Particle Characterization of the European Federation of Chemical Engineering, and is presently a member of the Portuguese Engineers Association and a founding member of the Portuguese Society for Engineering Education (SPEE). Her research interests have always been in the field of Particle Technology and she started the first Portuguese laboratory on particle characterization. Presently, she has got research interests in the field of particle aggregation, rheology of particle suspensions, solid/liquid flow modelling including fibre flow modelling, and on experimental techniques for flow visualization including tomographic techniques.



R. Silvae

Rui César Costa da Silva received his degree in Chemical Engineering from the University of Porto in 2006, In 2009, received his Master Degree in Chemical Engineering from the University of Coimbra. He is presently a Ph.D. student at the research group of Particle Technology and Multi-Phase Systems in the University of Coimbra. His research interests are in Multiphase Systems, Process Tomography and Computational Fluid Dynamics.



F. A. P. Garcia

Fernando A. P. Garcia was graduated as a chemical engineer in the Instituto Superior Técnico of the Technical University of Lisbon. He obtained a Master degree in Biological Engineering in Chemical Engineering and then a PhD degree in Chemical Engineering in the University of Birmingham, UK. He started his academic career in the University of Coimbra, first as an assistant demonstrator in the areas of fluid dynamics and transport phenomena. After his doctorate he became an assistant professor and latter an associate professor. Apart from the transport phenomena, his main interests are in the area of biocatalysis and downstream operations of fermentation processes and in treatment of industrial effluents. He is a member of several scientific institutions. He served as secretary of the ESAB, the European Section Applied Biocatalysis of the European Federation of Biotechnology and more recently as a member of the Executive Board, remaining as member of the Scientific Board.



P. M. Faia

Pedro M. Faia received is degree in Electrical Engineering (1990), is M.S. in Automation (1994) and is Ph.D in Electronic Materials (2003) from the University of Coimbra. He is an Auxiliary Professor at the Department of Electrical Engineering and Computers of the University of Coimbra where is research interests concern the research and development of solid state chemical sensors, sensor integration techniques, Electrochemical sensor and biosensors, Impedance Spectroscopy technique and applications. He is a member of the Portuguese Materials Society.