IMAGE RECONSTRUCTION TECHNIQUES FOR ELECTRICAL IMPEDANCE TOMOGRAPHY – A BRIEF REVIEW

Gonzales, Raul, rgonzales@usp.br
Queiroz, Jorge Luiz Lima, kairos@joinville.udesc.br
Departamento de Engenharia Mecânica, Universidade de São Paulo; Departamento de Química, Universidade de Santa Catarina

Graf, Jean Carlos, grafjean@gmail.com
Departamento de Engenharia Eletrica, Universidade de Santa Catarina

Abstract. *The electrical impedance tomography has been applied to a broad range of research in medical and engineering processes. This method is applied to obtain images of internal conductive volumes which are used as a research subject. Conductivities that generate the image pixels are reconstructed using a Generic Iterative Algorithm (GIA). However, as this is a non linear and ill-conditioning problem, which makes it particularly difficult in order to solve the problem of electrical impedance tomography, it is required a detailed knowledge for its application. This work considers the properties of the estimation methods for reducing noise in generated images EIT process, like Tikhonov and Levenberg-Marquardt method regularization, and evaluates the simplicity and reduced computational time of Newton-Raphson algorithm up to convergence. This study also raises questions regarding the characteristics to be observed during application of the technique, such as the standardization of the current, regulation, convergence and evaluation of the image, and their contributions for a better quality.*

Keywords*: Electrical Impedance Tomography, Newton-Raphson Method, Image Analyses Finite, Element method.*

1. INTRODUCTION

The techniques **of** electrical impedance tomography (EIT) generate images of cross section from the spatial variation of conductivity generated by sets of voltages measured at the border. Since the impedance is not directly measured from the voltages measured at the border it is obtained using the equations of electric potential and the finite element method. The voltages measured at the border are functions of impedance and current are applied to the scanner TIE. Using different sequences of patterns of current and voltages injected into an approximation of the spatial distribution of impedance changes inside the object is reconstructed. TIE has numerous applications that can be categorized into three main fields: 1. Industrial. This application includes the image of fluid flow in lines of ducts, measures of distribution of fluid flow in vessels of mixtures, and non-destructive testing such as the detention of cracks (Cheney et al, 1999; Dickin et al, 1996). 2. Geophysics. These applications include geophysical prospecting, measured through holes and surfaces (Polydorides & Lionheart, 2002**).** 3. Medicine. EIT is used to monitoring pulmonary and cardiac functions, cerebral function measurements (Barber 1984, Barber and Brawn 1989), detection of hemorrhage, digestive system measurement, detection and classification of tumors in the breast tissue and functional imaging of the thorax (Eyugoblu et al,, 1989 Harris et al, 1992).

EIT has severe limitations that may prevent its adoption in routine medical diagnostics. Its biggest limitation is its low spatial resolution, susceptibility to noise and errors of the electrodes. In medical applications, there is a wide diversity of characteristic of images. EIT is not suitable for anatomical images in the same way that the magnetic resonance imaging (MRI) or computed tomography (CT). However, the EIT seems to be promising as a diagnostic tool for clinicians. It has the advantage of being relatively inexpensive when compared with modalities such as MRI, CT, and Positron Emission Tomography (PET). Besides, EIT equipment is not evasive, safe, and as it's small, lightweight and easy to transport can be easily moved and left for extended periods of time, with low energy cost and maintenance. Its use can be viable in continuous monitoring at the bedside in diseases such as pulmonary edema, where it is necessary to monitor the amount of air into the lungs while avoiding risks to the patient, also in brain hemorrhage and gastric lavage. Besides, it is able to produce a high number of images per second which encourages the use of functional research body in contrast to the anatomical image. The application of functional images that can be considered an intermediate step to a technique that determines the change in volume flow of air entering the lungs while avoiding harm to the patient.

2. INDUSTRIAL TOMOGRAPHY PROCESS

The term "industrial tomography process" (ITP) refers to a whole wide range of non-invasive visualization techniques, which are relatively new (since the late 1980s) and still under development. The goal of ITP is to obtain images of the cross section of the dynamics of industrial processes (Adler, 1996 and Adler, 2004; Asfaw and Adler, 2005). Tomography techniques provide a new way of viewing of internal behavior of the industrial processes. The cross-sectional images produced by tomography provide valuable process information that can be used for visualization, monitoring, mathematical modeling, verification and possible intelligent controls. There are many types of tomography system such as electrical, ultrasound, radiation, nuclear magnetic resonance (NMR), microwave and optical.

The methods of tomography are still under development, some challenges remain to be focused: improving the sensitivity of the spatial resolution of the measures, development of more accurate methods of image reconstruction, improve the efficiency of data processing, mechanical and electronic hardware design appropriate for the safe and reliable use in harsh industrial environments (not only in the laboratory).

EIT is an ill-conditioning problem and to find stable results on the solution incorporates some form of baseline knowledge on problem behavior. In this sense, much more needs to be done for the precision of retrieval of images and for the direct generation of models that describe more accurately the trajectories made by photons in tissues and inverse models to recover precisely the images of the optical properties of tissues (Klose, 2003). The use of Newton optimization schemes, through the Jacobian (which relates to measures of data in outline the optical properties), these algorithms have been widely used because they are easy to implement and can be easily generalized to both bases of image reconstruction simple and complex (Dehghani et al, 2003, Yalavarthy, 2007). Other alternative methods for reducing the number of parameters include the use of basic reconstruction (Paulsen 1996) and also the use of mixtures of algorithms adapted to the specific environment of interest being refined for greater numerical accuracy.

2.1. Multiphase Fluid

ITP applications in fluids are common to find in different phases, called multiphase fluids in the same region. These fluids in different states are detected by the concentration of each phase which is computed based on knowledge of the electrical conductivity of each phase, generating the tomography of the electrical conductivity of each phase. In this case using electrical resistance tomography (ERT) that can be applied to various processes involving conductive fluids in the continuous phase. Typical applications are the ERT views of multiphase fluids in pipelines and tanks in agitation, for which commercial devices available for a wide range of size and type of material. Recent applications can be seen in Table 1 (Gigu `ere, R., et al., 2008).

Table 1. IET Applications para pesquisa de fluidos

Applications	Phases	References
Flow in pipes	Solid - Liquid	Steverson et al, 2006; Dai, 2004; Norman et al, 2005; Pullum et al, 2006.
	Gas - Liquid	Dong et al, 2006; Wang et al, 2006.
	Liquid - Liquid	Henningsson et al, 2006; Henningsson et al, 2007.
Stirred tank	Liquid - Liquid	Ricard et al, 2005; Kim et al, 2006.
	Gas - Liquid	Ricard et al, 2005.
	Gas - Liquid	Stanley et al, 2005.
Compact bed reactor	Solid - Liquid	Bolton et al, 2004.
Solid - Liquid	Solid - Liquid	Vijayan et al, 2007; Fransolet et al, 2001; Toye et al, 2005. Fransolet et al, 2005;

3.MODELS

3.1. Direct Problem

If Ω is an area subjected to the presence of an electric field (Cheney et al., 1999) thereby generating a distribution of electric potential, Maxwell's equation,

$$\Delta\gamma(x,\omega)\Delta u=0 \tag{1}$$

where x is a point within Ω, u is the electric potential and γ is adimitivitie , if electric currents are injected into the boundary surface δΩ then we have the electric density J as

$$\gamma\delta u/\delta\upsilon \; = \text{J em } \delta\Omega \tag{2}$$

Equations (1) and (2) along with the condition $\int \delta\Omega$ J = 0, u $\int \delta\Omega = 0$, and $\int \delta\Omega$ u = 0, (reference voltage), constitute a pattern of electrodes which is known as Continuum Model**.** The total flow of current through the electrode is equal to the integral of current density, ie:

$$\int_{\varepsilon 1} \gamma \delta u/\delta \upsilon \, ds = C_l \qquad l = 1, 2, .. L \tag{3}$$

The matrix of local conductivity for each element of the mesh is obtained from equation (Vanegas, 2002):

$$[\, y_c \,] = \iiint_V \frac{1}{4A^2}[B]^t[D][B]dV \quad = \frac{tA}{4A^2}[B]^t[D][B] = \frac{t}{4A}[B]^t[D][B] \tag{4}$$

where yc = local conductivity matrix, T: thickness; B: geometric matrix, D: matrix properties, A: area of each triangular element. To calculate the voltages is used the term,

$$[Y]*[V_i] = [C_i] \tag{5}$$

where **[Y]** is the global conductivity matrix, and **[V i]=** is the vector of voltages at points of the element mesh finites. And, [C i]: is the pattern of voltages applied to the electrodes. Then there is the equation

$$[V_i] = [Y^{-1}]*[C_j] \tag{6}$$

Where $[Y^{-1}]$ is the inverse of the matrix conductivity overall.

The variations in conductivity are functions of the current, which are functions of voltage and thus to know these changes that will generate the image, is necessary to solve an inverse problem. In the solution process is supposed a distribution of initial conductivity, and are calculated the voltages, and then it´s verified if this happens conductivities new approach of the previous ones, within a specified tolerance.

3.2. Inverse Problem

The goal of image contrast is to reconstruct the changes in impedance or conductivity that occurs in a chosen time interval. However, it does not know the impedance change, that´s why it is an inverse problem. To solve it, it is supposed a value for the solution and based on measurements and theoretical formulation, it is calculated the other value and verifies that the difference between the calculated and the supposed value is less than the tolerance. Otherwise, it is made new interaction form. The method is commonly used for applications in images that change over time, such as change of impedance during respiration (Adler et al 1996, Adler 2004). The refinement of the contrast of the image is widely applied to improve the reconstruction and ensure image stability when facing problems such as unknown contact impedance, inappropriate position of the electrodes, contour insufficiently known, nonlinearity and the use of approximations of the electric field 3D by 2D (Barber1989; Harris et al, 1992).

The calculation of changes in conductivity is accomplished by using a linear approximation to the operator. When faces a non-linear problem solution is interactive with the operator linearized being updated and reapplied every iteration. However most applications that use the image contrast implies that the variation of conductivity during the time interval is small for a single step of the linear operator is sufficient solution to a "good enough". In this way, it must seek an algorithm of good convergence, the method of Newton-Raphson is chosen for its simplicity and high capacity of convergence. The linear operator is known as Jacobian or sensitivity matrix. In a model with elements E and M measures of the contour, the Jacobian, also called sensitivity matrix is a matrix M × E. The Jacobian matrix is calculated column by column with the i_{th} column describing the effect of the change in conductivity of the i_{th} signal of the element measured between pairs of electrodes.

The sensitivity matrix is defined as $H_j(\sigma_0)$;

$$H_{j,i}(\sigma_0) = Y^{-1}\frac{\partial Y}{\partial \sigma_i}Y^{-1}c_j \tag{7}$$

Where

c_j: represents the excitement standard; Y^{-1} is the inverse of the matrix conductivity.

$H_{j,i}(\sigma_0)$: is the matrix of sensitivity depending on the conductivity of the elements σ_i, with i patterns of voltages.

$\frac{\partial Y}{\partial \sigma_i}$: partial derivative matrix of conductivity with respect to the conductivity of the elements, with i = 1, a n_e (is the element number) Then Equation (7) is calculated with respect to each element:

$$H_{j,i}(\sigma_0) = Y^{-1}\frac{\partial Y}{\partial \sigma_1}Y^{-1}c_j - Y^{-1}\frac{\partial Y}{\partial \sigma_2}Y^{-1}c_j \ldots - Y^{-1}\frac{\partial Y}{\partial \sigma_{ne}}Y^{-1}c_j \tag{8}$$

In the classical formulation of the Newton-Raphson method in EIT, we try to find the distribution of conductivity σ * that minimizes the differences between the voltages calculated using the finite element method and voltages measured (or taken from other methods):

$$\{e\} = \{V_e\} - \{V_m\} \tag{9}$$

Where $\{V_e\}$ and $\{V_m\}$ are calculated voltages and the voltages measured, respectively. The formulation of global finite element model,

$$[Y] \times [V_c] = [C] \tag{10}$$

So the difference between voltages

$$\{e\} = [T] \times [\, Y(\sigma)]^{-1} \times \{C\} - \{V_m\} \tag{11}$$

where T is the transformation matrix to make the equations dimensionally consistent, which means, the dimension (Vm) is equal to the number of electrodes on the border, while the size of (Ve) is equal to the number of degrees of freedom finite element model in the direct formulation. However, the voltages are calculated in positions corresponding to points of measurement, the electrodes that are in the real model,

$$\{V\}_N \Rightarrow T \Rightarrow [V_c]_L \tag{12}$$

Thus, the equation can be expressed {e} = 0 for each standard injected voltages. To find the set of equations using the Newton-Raphson, it is used the Taylor series expanded, ie

$$f_{(i)}(\sigma + \partial\sigma) = f_{(i)}(\sigma) + \Sigma \frac{\partial f_{(i)}(\omega)}{\partial \sigma_j} \partial\partial\sigma_j + O\left(\partial\sigma^2\right) \tag{13}$$

The terms $\partial\sigma^2$ and higher order do not contribute significantly in the calculations, and doing, fi (σ + ∂ σ) = 0, we have a system of linear equations in ∂ σ, which directs every function of the solution to zero simultaneously,

$$\sum_{j=1}^{N} J_{ij}\partial\sigma_j = -f_{(i)}(\sigma), \tag{14}$$

Where

$$J_{ij} = \frac{\partial f_{(i)}(\sigma)}{\partial \sigma_j} \tag{15}$$

Equation (14) defines an iterative process to calculate the homogeneous conductivity σ * for every element, every iteration k, and the conductivity supposed σ k, is solved Equation (15) and allows the update σ * (Yorkey et al.1987 a, b)

$$\sigma_i^{k+1} = \sigma_i^k + \partial\sigma_i, \quad i = 1,...E \tag{16}$$

And we have the homogeneous conductivity for each element of the finite element mesh. When the iteration produces a change of σ * less than the tolerance, the method converges.

3.3. Distributions of Current

Several protocols for injection of current and collection of measures have been proposed over the years. With some exceptions, the protocols can be categorized as directed to each pair or multiple pairs of electrodes (Borsic, 2002). Scanner of pairs directed has a single source of current source where the terminals are sequentially connected to driving of pairs of electrodes and voltage is measured between electrode pairs remaining. The current source is then transferred to another pair of electrodes and the measurement process repeated until the voltage source to pass through all electrodes collecting a full set of measures. Systems of several unities are more complex and expensive, but have the ability to conduct current in more than two electrodes at the same moment, while the obvious advantage of a drive system of a single pair, which needs only one current source is measured in successive most common procedure. The current is applied and injected through two adjacent electrodes and the resulting strains pairs of adjacent electrodes. Or, the current is applied through the next couple of electrodes and the voltage measurements are repeated. The procedure is repeated until every possible pair of electrodes adjacent was used to inject current. The strategy of adjacent injection requires a minimum of hardware to implement, it is directed mainly to the outer region of the object photographed. Current density is more high injection between the electrodes and decreases rapidly as a function of the distance. The method is therefore very sensitive to the contrasts of conductivity near the border and insensitive to central contrasts. It is also sensitive to disturbances in outline form of the object, the placement of the electrode is very sensitive to measurement errors and noise (Dicken, 1996). However, these problems can be minimized through techniques such as regularization.

3.4. Regularization

The method of regularization consists in determining the approximate solution smoother and consistent with the data under observation for some level of noise. The search for the smoothest solution is an additional information, which changes the ill-conditioning problem (which is the case treated in the present work) in a well-posed problem. The regularization methods are present in large varieties often is formally defined as a inversion method depending on a single real parameter $\alpha \geq 0$, which produces a family of approximate solutions (Karl, 2000). Regularization techniques are the methods of Tikhonov regularization, try to reduce the effects solving a system ill-conditioning (Cohen-Bacrie et al., 1997), restoring the continuity of the solution on data (Cheney et al, 1990). The most widely referenced method is the method of Tikhonov regularization or Tikhonov-Phillips method. With Tikhonov regularization of information about the solution, commonly referred to as prior information is incorporated into the solution as an additional term in the minimization of least squares. It minimizes the expression of form:

$$\min \phi_2\left(\vec{\sigma}\right) = \frac{1}{2}(\overrightarrow{V_m} - \overrightarrow{V_c}(\vec{\sigma}))^t(\overrightarrow{V_m} - \vec{V}_c(\sigma)) + \alpha\left(H^t H \vec{\sigma}\right) = 0 \tag{17}$$

where Vm is the measured voltage vector and σ is the initial value of conductivity and Vc is the operator that simulates the distribution of voltage with the initial conductivities. Then the solution is the desired reconstruction that minimizes the distribution of conductivities. Assuming that σ_k distribution initially supposed, this idea was evaluated by Vauhkonen et al (2001), the distribution conductivity was approximated as a linear combination of some basis functions that pre-selected that were constructed from initial information of the structure and conductivity (Miranda, 2000).
The modeling of the impedance of contact at the interface of electrode and the medium has been used by various authors in order to obtain a more representative of the electrical behavior at the border of the middle and get a more accurate estimate of the conductivity. In this sense, it was implemented the model proposed by Hua et al (1993),besides, also represents the distribution of electric field at contact interface, it is considered the dominant effects of impedance contact to the electrode, such as discrimination, contact impedance effect shunt and edge. The effects resulting from these procedures are observed in the following topics.

3.5. Results of Numerical Analysis

In the curves of convergence presented for tests, it was used as a parameter the rule Euclidiana of the differences between the voltages measured and calculated, and the increment of conductivity at each iteration (Vanegas Molina, 2002), which means:

$$\left\|\overrightarrow{V_m} - \overrightarrow{V_c}\right\|_1 = \left|\left(\overrightarrow{V_m} - \overrightarrow{V_c}\right)^t\left(\overrightarrow{V_m} - \overrightarrow{V_c}\right)\right|^{\frac{1}{2}} \tag{18}$$

$$\left\|\delta\vec{\sigma}\right\|_2 = \left[\delta\vec{\sigma}^t\delta\vec{\sigma}\right]^{\frac{1}{2}} \tag{19}$$

For achievement of the theoretical data was used a finite element mesh containing 32 nodes and 44 elements. The conductivity distribution was used 2.5 $(\Omega m)^{-1}$ and in other regions was used 8.78 $(\Omega m)^{-1}$ the thickness of elements was 0.1. 10-3m. The model was excited through the patterns diametric current injection, and the value current applied to 16 points on the border with a value of 5 mA.

Based on the analysis of experimental data is seen that the classical method of Newton-Raphson presents a good performance converging with few iterations (Vanegas Molina, 2002). Its solution has two parts the direct solution (linear) and other part non-linear, the inverse problem the association of these two solutions makes the measured and calculated voltages fluctuate around the path to the appropriate solution, as per Figure 1 (a).The curves of the classic process of convergence of Newton-Raphson are shown in Figure (1a) and (1b).

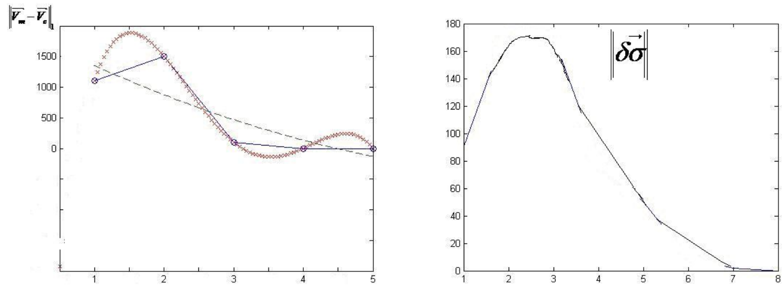

Figure 1. Convergence of Newton-Raphson algorithm with theoretical data: a) square error of the voltages $\left\|\vec{V}_m - \vec{V}_c\right\|_1$ *and* b) in relation the conductivities $\left\|\delta\vec{\sigma}\right\|$ according to iterations.(Adapted from Miranda, 2000).

The Fig. 1(a) and (b) show the advantage of using the method to process experimental data, and application of Tikhonov regularization that penalizes solutions with large variations in elements near the mesh. This methodology has been shown appropriate in surveys of TIE allowing the generation of images.

3.5. Evaluation of Images

From a set of image with with ideals data is possible to compare the generic algorithms of reconstruction of image. Figure 2 represents the tomography reconstructed using generic Iterative Algorithms (GIA). A dimensional finite element model was used to reconstruct the images (Gigu `ere, R., et Al, 2008).

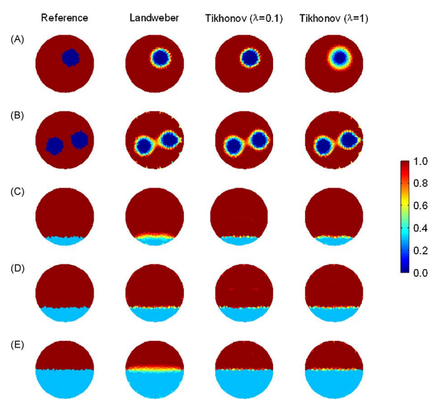

Figure 2. Image reconstruction using Generic Iterative Algorithms.

The method Tikhonov requires the selection of constant that is found heuristically. During the selection the researcher compares the images with reference images, Fig 2 and selects the value of constant from the images found. The Fig. 2 shows this selection based on figures of references to compare the quality of the reconstructed images. Wheeler et al (2002) revised several figures of reference for the IET, which have been proposed in the literature and serve as benchmarks. One way to compare is to use the known capacitances and compare the images obtained with the figures of merit to find the best value (Adler, 1996; Adler, 2004). This method uses the Tikhonov regularization parameter, adjustable that controls the trade-off between the noise performance and the image resolution. In Fig. 3, obtained in this

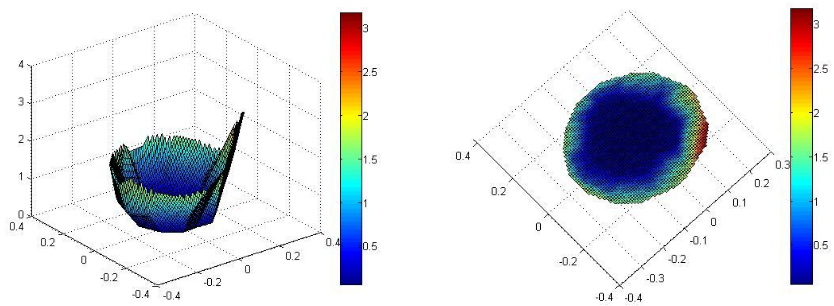

Figure 3. Distribution of Impedance in a saline environment

work with the Newton-Raphson method were used to compare the capacitances obtained to ensure that it was accomplished a good reconstruction of the original image. Intuitively, the selection should produce solutions that preserve maximum data as far as possible, applying the least amount of prior information needed to obtain an useful reconstruction. This approach allows a theoretical interpretation of the image reconstruction algorithm that takes into account natural way the various sources of prior information: the magnitude of equipment noise electronics and the maximum spatial resolution obtained for the number of electrodes used.

4. CONCLUSION

The aim of this study was to revise the techniques of electrical impedance tomography by emphasizing the relevant topics for the search of fluids, characterizing the iterative algorithm to be used and adjust to the conditions of industrial processes. The industries need tools that provide fast answers in any process that requires management. The iterative algorithm that best fits the setting with rapid response is the method of Newton-Raphson and that solves the nonlinear system, associated to the square error minimizing provided by the differences between the voltages measured and calculated efficiently.

Based on tests with data from numerical simulation it was found that the method of Newton-Raphson in its classical numerical formulation shows well performance and converges with a low number of iterations. This encourages the further development of tools that monitor the flow of fluids in tough environments, as petroleum exploration and research within metallurgical furnaces. Currently applications also arise in the food industry to monitor the process of automated manufacturing of food to ensure efficiency with better use of raw materials and waste reduction.
The convergence time is a great attraction for research into industrial products. Figure (3), shows that using the Newton-Raphson (MNR) has good performance, obtaining images with high rates of gradient conductivity. This behavior shows the potential of MNR for research of multiphase fluids, as are most fluids found in industrial processes.

4. REFERENCES

Adler A, Guardo R, 1996 “Electrical impedance tomography: regularized imaging and contrast detection”, IEEE Trans Med Imaging, vol 15 170-9

Adler A, 2004 “Accounting for erroneous electrode data in electrical impedance tomography”, Physiol Meas, 227-238

Asfaw Y, Adler A, 2005 Automatic Detection of detached and erroneous electrodes in electrical impedance tomography, Physiol Meas, 26 S175-S183.

Barber, D. C.; Brawn, B.N. 1984 “Applied Potential Tomography”, J. Phys. E. Sci. Instrum., vol. 17, pp 723-733.

Barber, D.C. 1989 “a review of image reconstruction techniques for electrical impedance tomography” Med. Phys. 16 (2), Mar/Apr p.162-9.

Bolton, G.T. Hooper, C.W. Mann, R. Stitt, E.H. 2004 “Flow distribution and velocity measurement in a radial flow fixed bed reactor using electrical resistance tomography, Chem. Eng. Sci. 59 1989–1997.

Borsic A, 2002 “Regularisation Methods for Imaging from Electrical Measurements”, PhD Thesis, Oxford Brooks Universit.

Cheney, M., Isaacson, D. Nevell, J.C. 1999 “*Eletrical Impedance tomography*”, SIAM J. Applied Math. Review . pp. 85-101.

Cheney M, Isaacson D, Newell JC, Simske S, Goble JC, NOSER, 1990 “An algorithm for solving the inverse conductivity problem Internet”, J Imaging Systems & Technol, 2, 66-75.

Cohen-Bacrie C, Goussard Y, Guardo R, 1997 “Regularized reconstruction in electrical impedance tomography using a variance uniformization constraint”, IEEE Trans. Medical Imaging, 1997, 16, 562-571.

Dehghani, H. Pogue, B. W. Jiang, S. Brooksby, B. and Paulsen, K. D., 2003. "Three dimensional optical tomography: resolution in small object imaging," Appl. Opt. **42**, 3117-3128.

Dai, Y. Pachowko, A.D. Wang, M. 2004 "The control of polymer addition to raw waste sludge using electrical resistance tomography—a preliminary study", Part. Part. Syst. Charact. 21, 228–233.

Dickin F, Wang M, 1996 "Electrical resistance tomography for process tomography", Meas Sci Tech, 1996 7 247-260.

Eyuboglu BM, Brown BH, Barber DC, 1989 "In vivo imaging of cardiac related impedance changes", IEEE Eng Med Biol Mag, 8, 3945.

Fransolet, E. Crine, M. L'Homme, G. Toye, D. Marchot, P. 2001 "Analysis of electrical resistance tomography measurements obtained on a bubble column", Meas. Sci. Technol. 12 1055–1060.

Fransolet, E. Crine, M. Marchot, P. Toye, D. 2005 "Analysis of gas holdup in bubble columns with non-Newtonian fluid using electrical resistance tomography and dynamic gas disengagement technique", Chem. Eng. Sci. 60 6118–6123.

Gigu`ere, R. Fradette, L., Mignon, D. Tanguy, P.A. 2008 "ERT algorithms for quantitative concentration" Measurement of multiphase flows Chemical Engineering Journal 141 305–317

Harris ND, Brown BH, Barber DC, 1992 Continuous monitoring of lung ventilation with electrical impedance tomography, Med Biol Soc, 1754-1755.

Henningsson, M. Ostergren, K. Dejmek, P. 2006 "Plug flow of yoghurt in piping as determined by cross-correlated dual-plane electrical resistance tomography, J. Food Eng. 76 163–168.

Henningsson, M. Regner, M. Ostergren, K. Tragardh, C. Dejmek, P. 1997 "CFD simulation and ERT visualization of the displacement of yoghurt by water on industrial scale, J. Food Eng. 80 166–175.

Hua, P.J. Woo, J. G. Webster & Tompkins, 2001 "Finite Element Modeling of Electrode Skin Contact Impedance in electrical Impedance Tomography" IEEE trans. Biomed. 40(4) 335-343.

Karl WC, 2000 "Regularization in image restoration and reconstruction, in Handbook of Image and Video Processing", Bovik A, Ed, chapter 3, 141-161. Academic Press, 2000.

Klose, A. D. and A. H. Hielscher, 2003 "Quasi Newton methods in optical Tomography image reconstruction," Inverse Probl. 19, 387-409.

Kim, S. Nkaya, A. N. Dyakowski, T. 2006 "Measurement of mixing of two miscible liquids in a stirred vessel with electrical resistance tomography, Int. Commun. Heat Mass Transfer" 33 1088–1095.

Miranda, D.A.A. 2000 "Algoritmo da Tomografia por Impedância Elétrica Baseada em Newton Raphson" São Paulo.

Norman, J.T. Bonnecaze, R.T. 2005 "Measurement of solids distribution in suspension flows using electrical resistance tomography" Can. J. Chem. Eng. 83 24–36.

Paulsen K. D. e Jiang, H. 1996 "Enhanced frequency-domain optical image reconstruction in tissues through total-variation minimization" Appl. Opt. **35**, 3447-3458.

Polydorides N, Lionheart WRB, 2002 "A MATLAB based toolkit for three-dimensional Electrical Impedance Tomography: A contribution to the EIDORS project, Measurement Science and Technology, 13, 1871-1883.

Pullum, L. Graham, L. Rudman, M. Hamilton, R. 2006 "High concentration suspension pumping", Miner. Eng. 19 471–477.

Ricard, F. Brechtelsbauer, C. Xu, Y. Lawrence, C. Thompson, D. 2005 "Development of an electrical resistance tomography reactor for pharmaceutical processes", Can. J. Chem. Eng. 83 11–18.

Soleimani, M., G´omez-Laberge, C.and Adler, A. 2006 "Imaging of conductivity changes and electrode movement in EIT" Physiol. Meas. **27** S103–S113.

Stanley, S.J. Mann, R. Primrose, K. "Interrogation of a precipitation reaction by electrical resistance tomography" (ERT), AICHE J. 51 (2005) 607–614.

Stevenson, R. Harrison, S.T.L. Miles, N. Cilliers, J.J. 2006 "Examination of swirling flow using electrical resistance tomography", Powder Technol. 162 157–165.

Toye, D. Fransolet, E. Simon, D. Crine, M. L'Homme, P. Marchot, G. 2005 "Possibilities and limits of application of electrical resistance tomography in hydrodynamics of bubble columns" Can. J. Chem. Eng. 83 4–10.

Vanegas Molina, N.A, 2002, 2002 "Redução do Erro Numérico do Filtro Extendido de Kalman Aplicado a Tomografia de Impedância Elétrica", São Paulo, 108p.

Vauhkonen M, 1997 "Electrical Impedance Tomography and Prior Information", PhD thesis, Department of Applied Physics, Kuopio University.

Vauhkonen M, Lionheart WRB, Heikkinen LM, Vauhkonen PJ and Kaipio JP, 2001 "A Matlab Package for the EIDORS project to reconstruct two-dimensional EIT images", Physiol Meas, 2001, 22 107-111.

Vijayan, M. Schlaberg, H.I. Wang, M. 2007 "Effects of Sparger geometry on the mechanism of flow pattern transition in a bubble column" Chem. Eng. J. 130 171–178.

Wheeler J, Wang W, Tang M, A comparison of methods for measurement of spatial resolution in two dimensional circular EIT images, Physiol Meas, 2002, 23, 169-76.

Yalavarthy, P. K. Pogue, B. W. Dehghani, H. and Paulsen, K. D. 2007 "Weight-matrix structured regularization provides optimal generalized least-squares estimate in diffuse optical tomography," Med. Phys. **34**, 2085-2098.

Yorkey, T.J., Webster, J.G. and W.J. Tomkins, 1987, ”Comparison of Impedance Tomography Reconstruction Algorithms”. Clin. Phis. Phys. Physiol, Meas.8 (Suppl. A.), 55-62.

Yorkey TJ, Webster JG, Tompkins WJ, 1987b, “An improved perturbation technique for electrical impedance imaging with some criticisms”, IEEE Trans Biomed Eng, BME-34, 898-901.

Wang, M. Lucas, G. Dai, Y. Panayotopoulos, N. Williams, R.A. 2006 “Visualisation of bubbly velocity distribution in a swirling flow using electrical resistance tomography”, Part. Part. Syst. Charact. 23 321–329.

Woo EJ, Hua P,Webster JG, TompkinsWJ, 1992 “Measuring lung resistivity using electrical impedance tomography”, IEEE Trans Biomed Eng, 39, 756-60.