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Application Study on Bubble Detection in a Metallic Bubble Column Using Electrical Resistance Tomography

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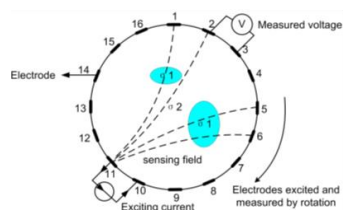
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Abstract

Electrical resistance tomography (ERT) has been chosen as the field of study because of its advantages of being low cost, suitable for various kinds and sizes of pipes and vessels, having no radiation hazard, and being non-intrusive. In the development of ERT systems for metallic bubble column, prior knowledge of the fundamental process of the ERT system whilst improving the design and operation of the process equipment is essential. The fabricated electrodes need to be electrically insulated from the metal wall. Besides that, conducting boundary strategy is implemented to overcome the grounding effect of the metallic vessel.

Keywords: Bubble columns; gas holdup; conducting boundary; electrical resistance tomography

■1.0 INTRODUCTION

Bubble columns have been widely used in industrial applications, mainly in the chemical and pharmaceutical industries, due to their simplicity and efficiency. The applications require gas-liquid and gas-liquid-solid contact with the advantages of ease of operation, absence of moving parts, low energy consumption and minimal space requirement. They are being widely employed in catalyst reactions, coal treatment, absorption, hydrogenation, fermentation, alkylation, carboxylation, bio-reactions and wastewater treatment processes for their advantages of simple structure, low cost, high efficiency, etc.[1, 2]. Knowledge of the various properties of the bubbles such as bubble velocity distribution, bubble size distribution, local gas holdup, and specific interfacial area, is of considerable importance in the development of a fundamental understanding of bubble columns' dynamics and for their proper design and operation [3].

Gas holdup is a very important parameter for mass transfer operation in bubble columns. The average gas holdup is a global parameter and it is important in deciding the size of the reactor. The radial gas holdup distributions will give local gas concentration, and help to understand the flow pattern. The development and the application of a non-intrusive and non-invasive measuring technique capable of investigating gas holdup distributions will greatly facilitate current efforts to predict and improve reactor performance. Neal and Bankoff [4] first made measurements of radial gas holdup distribution in two-phase flow using an electrical resistivity probe. Since then, many measurements using different techniques have been reported. Various conventional measuring techniques such as the hot wire probe, electro-resistivity probe, optical fibre probe as well as pressure tap and shutter plate, have been devised. However, these are not suitable because the measurements themselves interfere with the motion of the bubbles, and consequently vary the hydrodynamics of the system [5].

In recent years, the applications of tomographic techniques as a robust non-invasive tool for direct analysis of the characteristics of multiphase flows have increased. The application of process tomography for investigating gas holdup distributions in a bubble column is the major subject of much research [2, 5-14]. Tomography offers a unique opportunity to reveal the complexities

of the internal structure of an object without the need to invade it. One of the most extensive modalities of tomography is Electrical Resistance Tomography (ERT). ERT is an accepted diagnostic technique for imaging the interior of opaque systems. It is relatively safe and inexpensive to operate and is relatively fast, thus enabling real-time monitoring of processes. This technique has found applications in many areas, including medical imaging, environmental monitoring, and industrial processes. Recent research conducted on ERT is summarized in Table 1. There are many examples of ERT used to qualitatively image the material distributions of multiphase processes within electrically insulating (non-conducting) walls. However, only a few studies deploying ERT within electrically conducting vessels have been reported, and these have provided primarily qualitative results for the purpose of process monitoring [15]. Thus a measurement system using ERT techniques to monitor the gas volume fraction for the application of conducting a bubble column reactor is proposed in this research.

■2.0 ELECTRICAL RESISTANCE TOMOGRAPHY

One of the most extensive modalities of tomography, which has greatly evolved since it was invented in the 1980s, is electrical resistance tomography (ERT), a particular case of electrical impedance tomography (EIT). ERT has become a promising technique in monitoring and analysing various industrial flows due to its diverse advantages, such as high speed, low cost, suitability for various sizes of pipes and vessels, having no radiation hazard, and being non-intrusive [16-21]. It has the potential of providing both qualitative analysis by providing the data required for measurement of some flow parameters, such as velocity distribution, and flow regime identification [22]. As a non-intrusive, fast visualization tool, close attention has been paid to ERT in multiphase flow research. Recent research on ERT is summarized in Table 1. Compared with conventional measurements, ERT can provide real-time cross-sectional images of conductivity distribution within its sensing region. Other parameters, for example local and global gas hold-ups and radial velocity maps, can be extracted from the reconstructed images [1].

Table 1: Summary of recent research and applications employing ERT [23]

Reference	Application
Zhang and Chen [14,15]	Two-phase flow regime identification
Yang et al. [12]	Void fraction/ Gas holdup measurement
Sharifi and Young [11,16]	Flow monitoring, velocity distribution and flow rate measurement of various milk solutions
Jin et al. [17]	Gas holdup measurement
Dong et al. [18]	Visualization of multiphase flow
Tan et al. [19]	Visualization of multiphase flow
Zhang et al. [20]	Visualization of multiphase flow
Yenjaichon et al. [21]	Mixing of a pulp suspension and chlorine dioxide
Xu et al. [22]	Flow monitoring
Tahvildarian et al. [23]	Solid-liquid mixing in a slurry reactor
Kourunen et al. [24]	Gas holdup measurement in a laboratory flotation (separation process) cell
Jin et al. [6]	Gas holdup profile and flow regime identification
Jin et al. [25]	Bubble rise velocity and bubble size estimation

Reference	Application
Jin et al. [26]	Gas holdup profile measurement in a concurrent bubble column
Williams et al. [27]	Gas holdup measurement in flotation process
Toye et al. [28]	Gas holdup in hydro-dynamics of bubble columns
Fransolet et al. [29]	Gas holdup measurement
Meng et al. [30, 31]	Flow measurement
Kowalski et al. [32]	Early onset detection of ageing in formulated products.
Karhunen et al. and Seppanen et al. [33-37]	Concrete imaging
Jin et al. [38]	Gas and solid holdups distribution
Hosseini et al. [39]	Solid–liquid mixing
Cui et al. [40]	Flow regime monitoring and gas holdup computation
Chao Tan and Feng Dong [41]	Cross-correlation velocity of oil–water two-phase flow in a horizontal pipe
Cao et al. [42]	Flow monitoring
Chao Tan and Feng Dong [43]	Flow regime identification
Xu et al. [7]	Flow measurement
Razzak et al. [44]	Solids and velocity holdup distributions
Razzak et al. [45]	Gas and solid holdups distribution, Velocity distribution
Razzak et al. [46]	Gas and solid holdups distribution, Velocity distribution
Park et al.. [47]	Monitoring of a radioactive waste separation process
Pakzad et al. [48]	Investigation of mixing process
Tan et al. [49]	Flow monitoring
Lee and Bennington [50]	Flow velocity
Ruzinsky and Bennington [51]	Liquor flow measurement
Kim et al. [52]	Flow monitoring
Cutrupi et al. [53]	Biomedical application
Chen et al. [54]	Flow regime identification
Wang et al. [55]	Velocity distribution and gas holdup in swirling flow
Kim et al. [56]	Mixing
Jin et al. [57]	Gas holdups and velocity distribution
Henningsson et al. [58]	Velocity profile
Dyakowski et al. [10] (Review Paper)	Gas–solids and liquid–solids systems monitoring
Sharifi and Young [59] (Review paper)	Paper review on applications to chemical engineering

The basic idea of ERT is that the conductivity of different media is distinct in each case. Thus, the medium distribution of the measured area can be identified if the conductivity or resistance distribution of the sensing field is obtained [24, 25]. The operation mode of an ERT system is to provide the sensing field with exciting current (or voltage) and measure the potential difference (or current) via electrodes mounted on the boundary of the domain [26,

27]. Usually, the operating principle of the ERT system is current exciting and voltage measurement. The exciting current is applied into the measurement section through a pair of electrodes and excites the sensing field. When the conductivity distribution varies, the sensing field varies with it and results in a change in the electric potential distribution. Likewise, the boundary voltage of the sensing field changes accordingly. The measured voltage contains information on the conductivity in the sensing field, and the internal flow status can be obtained from further information processing [25]. This is shown in Figure 1. In the case of the conducting pipes or vessels, the electrodes need to be insulated from the conducting wall [28].
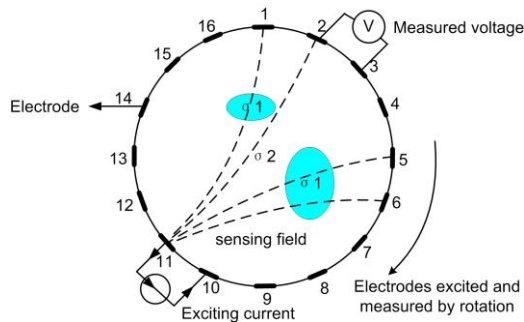

Figure 1 Operating principle of ERT [25]

2.1 Developments of ERT/EIT on Conducting Vessel

Extracting information from industrial pipelines is important in observing the process to ensure it meets certain standards or requirements. Tomography seems to be one of the great applications to accommodate this environment. Most of the vessels and pipelines in industry are made from conducting material. However, most of the research on tomography has used vessels made from non-conducting materials. This section will present the previous research on ERT which was conducted on metal or conducting vessel walls. The motivation behind the research of ERT/EIT on conducting vessel walls was initiated by Wang *et al*. [29, 30]. By using an excitation and measurement strategy and adapting the proposed sensitivity coefficient method, useful images of resistivity distribution are obtained from the metal vessel with insulated electrodes using existing ERT systems. Yuen *et al*. [31] presented a paper on ERT imaging of a metal-walled solid–liquid filter. Correspondingly, Grieve [15] set up an online EIT within pressure filtration for industrial batch processing. The wall was fabricated from an electrically-conducting alloy. Finite element modelling (FEM) was adopted for the system and then it was integrated with a modified version of the electrical impedance tomography and diffuse optical tomography reconstruction software (EIDORS) 3D algorithms to provide a three-dimensional image within the metallic vessel using the complete electrode model.

A novel EIT diagnostic system has been developed and used by Liter *et al*. [32] to quantitatively measure material distributions in opaque multiphase within electrically-conducting (i.e. industrially relevant or metal) vessels. The system applied seven equally spaced ring electrodes to a thin non-conducting rod that was inserted into the vessel. In this work, Sandia's steel pilot-scale bubble column reactor (SBCR) was used as the plant. Only resistive EIT is the ERT considered for the purpose of this work. The invasiveness of the electrode used in the system created a non-axisymmetric flow-field disturbance that introduced a bias in the current flow paths. The disturbance was not modelled in the FEM

simulations used to reconstruct the electrical conductivity distributions and thus presented a source of possible significant error.

York *et al*. [33] have progressively published their work on the EIT system within metal-walled industrial production pressure filters for a number of years. The metal wall strategy is employed in the intrinsically safe instrument developed. Sensor architecture has been implemented that is compliant with the process such that it is not detrimental to the efficiency or the integrity of the associated vessel structure. MATLAB-based EIDORS 3D software has been employed to yield images from simulated data.

A 3D image reconstruction using real EIT measurements obtained from a metal-walled (stainless steel) laboratory test platform has been investigated by Davidson [34]. It is considered to be comparable to a large-scale industrial filtration unit. Two image reconstruction techniques have been applied via relatively sophisticated FEM modelling. A generalized Tikhonov regularization method is compared to the linear back projection (LBP) technique. It is observed that the regularized technique is far less sensitive to the modelled geometry compared to LBP. In addition, the regularized technique is more successful in accurately reconstructing multiple inhomogeneities within an aqueous system. A further experiment has shown similar sensitivity in a wetted powder-based system. It is concluded that EIT via a regularization method has significant potential for detecting 3D malformations and non-uniformities in industrial pressure filtration systems.

Industrial tomography systems (ITSs) have developed a linear ERT sensor integrated onto a glass-lined finger baffle for use in glass-lined stainless steel vessels which are commonly used in the pharmaceutical sector [35].

2.2 ERT Measurement Strategy for Conducting Vessel

Measurement strategy is necessary, especially in ERT, to define the experiment which involves a metal or conducting vessel. In ERT, quantitative data which describes the state of the conductivity distribution inside the vessel is obtained. Good data collection strategies are very important because generally misleading images can be rebuilt if a full set of independent measurements is not collected [36, 37]. To all intents and purposes, selecting the strategy that has a good distinguishing ability and high sensitivity to conductivity changes in the process is necessary in ERT. There are four main strategies in ERT: the adjacent strategy, conducting boundary strategy, opposite strategy and diagonal strategy.

The first application of ERT only considered electrode arrangements operating within vessels having insulating walls and applied the adjacent measurement strategy which is the most common one. This strategy is as illustrated in Figure 1. In this strategy, current is injected between an adjacent pair of electrodes and voltage is measured from successive pairs of neighbouring electrodes. The injection pair is switched through the next electrode pair until all independent combinations of measurements have been completed. However, the majority of the process vessels in industry have conducting walls and therefore provide an additional current sink during the measurement process. This gives rise to both reduced sensitivity in the bulk of the material and increased difficulty in obtaining stable measurements referenced to the injected currents [34].

Practically, the ERT instrument consists of a series of electrodes located around a process unit. The equipotential lines arising from the potential gradient generated by an alternating current source connected between two adjacent electrodes are represented in Figure 2. For a homogeneous process matrix, a symmetrical array of equipotential contours will be created which may be interrogated by monitoring the phase and amplitude of the potential difference pairs of the remaining electrodes, using a high

impedance measuring device. If an object is placed at the centre of a conducting body and adjacent strategy is applied, the equipotential lines around this point appear to radiate from the centre of the body, creating a distortion in the electric field which may be detected at the measurement electrodes. This is shown in Figure 3. The opposite case would be true for an object in the insulating body, as in Figure 4 [15].
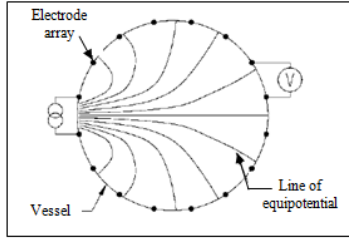

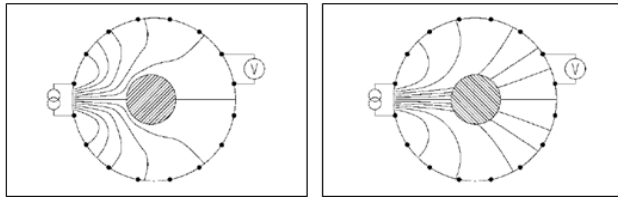**Figure 2** Equipotential lines for a homogeneous ERT [15]

Figure 3 Conducting body [15]   **Figure 4** Insulating body [15]

Before applying ERT to an electrically-conducting vessel, an electrical path passing through the vessel wall must be taken into consideration. The adjacent strategy is unsuitable for application to the conducting vessel since much of the electrical current from the injection electrode will travel to ground through the wall material rather than through the multiphase mixture, greatly reducing sensitivity. This is called the grounding effect of the vessel. One possible method of accounting for the conducting vessel wall is to use the wall itself as the ground electrode [32].
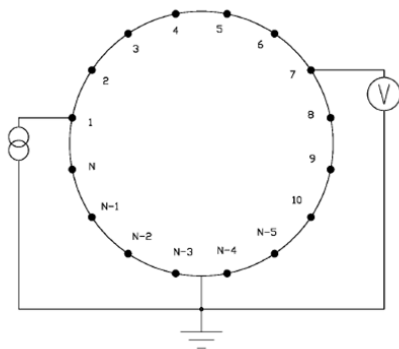

Figure 5 Conducting boundary strategy [15]

Conducting boundary strategy, as in Figure 5, has been proposed and developed by [29] for the conducting vessel wall to overcome the grounding effect. The strategy considers each electrode acting sequentially as a current source, whilst the whole of the metallic vessel behaves as a grounded current sink. In this strategy, all voltage measurements are referenced to the same earth potential of the conducting boundary. The number of unique

measurements, N, in the conducting boundary or 'metal wall' strategy can be defined as follows:

$$N = \frac{n(n-1)}{2} \tag{1}$$

where n is the total number of electrodes [34].

2.3 Mathematical Modelling for ERT

ERT belongs to a class of diffuse tomography modalities since the paths of electric currents are not straight lines. Current diffuses all over the target, and the current distribution in the material depends on the internal conductivity distribution $\sigma = \sigma(r)$. Adapting the boundary voltage measurements in reconstructing the conducting distribution is an *ill-posed inverse problem*. Accurate modelling of the measurements and prior information on the target distribution is required in solving the inverse problem [38].

The *forward model* will be used later to solve the inverse problem which is the reconstruction problem in ERT. The model relates the dependency between the conductivity distribution and the boundary voltages. The most accurate model for ERT measurements so far is the *complete electrode model* introduced by Cheng *et al.* [39]. The complete electrode model consists of the following partial differential equation and the boundary conditions

$$\nabla.(\sigma\nabla u) = 0, r \in \Omega \tag{2}$$

$$\int_{e_l} \sigma\frac{\partial u}{\partial n}dS = I_l, r \in e_l. l = 1, ..., L \tag{3}$$

$$\sigma\frac{\partial u}{\partial n} = 0, r \in \partial\Omega \setminus \cup_{l-1}^{L} e_l \tag{4}$$

$$u + z_l \sigma\frac{\partial u}{\partial n} = U_l, \quad r \in e_l, l = 1, ..., L \tag{5}$$

where:
Ω = computational domain
$\sigma = \sigma(r)$ = conductivity distribution
$u = u(r)$ = electric potential inside Ω
U_l = potential on lth electrode
I_l = current on lth electrode
z_l = contact impedance between the lth electrode and the object
n = outward unit normal

In addition, Kirchoff's current law

$$\sum_{l=1}^{l} I_l = 0 \tag{6}$$

must be fulfilled, and the potential reference level has to be fixed, for example by writing

$$\sum_{l=1}^{l} U_l = 0 \tag{7}$$

The solution of the ERT forward problem is by computing electrode potentials U_l given the conductivity distribution, and the electrode currents I_l are obtained by solving the partial differential equation (2) with conditions (3)–(7). The system (2)–(7) has a unique solution which can be approximated by using the finite element method (FEM) [38]. The FE approximation of the model results in the following form:

$$V = R(\sigma, z) + v \tag{8}$$

where:

V = voltage observations (differences between electrode potential U_l)
$R(\sigma, z)$ = mapping from the conductivity distribution σ and the contact impedance z to the electrode voltages
v = measurement noise vector

3.0 RESEARCH METHODOLOGY

In this research, the gas volume fraction in a bubble conducting vessel will be monitored using Electrical Resistance Tomography (ERT). The type of flow regime that will be used is bubbly flow. The system will be separated into two parts which are the front-end system (hardware) and the software development. The overall ERT system includes the design and implementation of the current excitation circuit, conducting bubble column, signal conditioning circuit, data acquisition system and serial communication with a host computer for image reconstruction and analysis. This is as shown in Figure 6.

The front-end part consists of the electrode array and associated electronic hardware to acquire data needed to produce a meaningful image. In this research, 16 equally spaced electrodes are fabricated inside the periphery of the conducting pipe. The research will apply a pipe with 100mm inner diameter. To achieve reliable measurements, the electrode must be more conductive than the fluid [40]. Note that the metal electrodes for electrically-conducting (metallic) process vessels differ slightly from the non-conducting (plastic) vessels in which the electrodes need to be insulated from the conducting vessel.
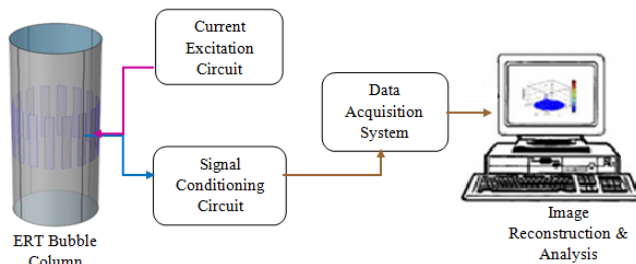

Figure 6 Block diagram of ERT system

Commonly, an alternating current at a magnitude of tens of mA is applied in ERT. The minimum current applied by [21] was 0 mA, in which the amplitude current was adjusted with an amplitude range of 0-10 mA. The maximum injection current utilized in ERT to date is 75 mA, used by [41] to measure the distribution of gas holdup in a multistage bubble column. In this study, a constant current is injected to the electrode. The current is converted from the square wave voltage source using an AD817 op amp which acts as a voltage to current source (VCCS). Square waveforms are selected since they are easier to process than sinusoidal waveforms, which require the demodulation circuit and low pass filter at the data acquisition part. This not only complicates the structure but will also weaken the real-time performance [21]. Typically, the frequency of alternating current in an ERT system is 20-150 kHz. Conducting boundary strategy has been applied where the metal wall itself behaves as the ground electrode. The current source is injected sequentially into each electrode whilst the pipe acts as the grounded current sink. A bubble is a form of gas which is an excellent insulator and has very low conductivity. Conductivity measures a material's ability to conduct an electric current. Electric current will be produced when a conductive medium is injected with the external electric field. When flux or current lines pass through a purely conductive

medium, the lines will be evenly distributed. But when they meet an interface or different conductivity medium, they will deflect [42].

The output voltage is then amplified and measured across each electrode sequentially. All voltage measurements are referenced to the same earth potential of the conducting boundary. They are then fed to the data acquisition system (DAS) for further processing. All signals will be synchronized to make sure that the measurements are taken correctly and captured into the display unit by the data acquisition system (DAS) card. The received data is interfaced to the digital computer for image reconstruction.

The second part of this research is the software development part which explains the application program for generation of concentration profiles. The application program will be developed by using appropriate software and routines, and will be used to generate the concentration profile for the corresponding liquid-gas flow in the conducting bubble column. The application program main flowchart is shown in Figure 7.
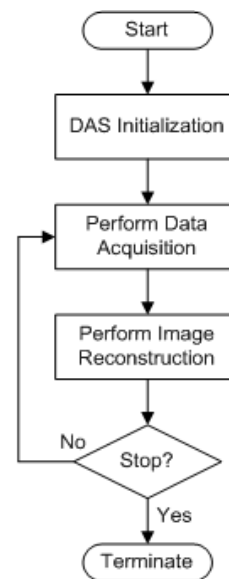

Figure 7 The application program main flowchart

4.0 RESULTS AND DISCUSSION

The superiority of the conducting boundary strategy over the adjacent protocol for a metallic vessel is confirmed in an experiment conducted by [15]. The clarity attained is illustrated in Figure 8 and Figure 9, where the typical tomograms for a phantom placed near the centre of a homogeneous medium are provided.
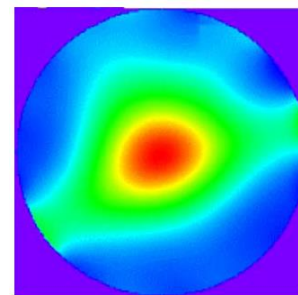

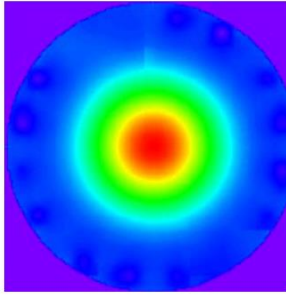**Figure 8** Metal wall and adjacent strategy [15]

Figure 9 Metal wall and conducting Strategy [15]

From the results, the theory mentioned earlier has been proven where the pipe wall itself needs to be grounded when using a metal wall. Thus, when applying ERT on a metallic bubble column, the conducting boundary approach needs to be implemented. The adjacent strategy on a metal pipe will cause the equipotential lines around the centred object to radiate from the centre of the pipe.

■5.0 CONCLUSIONS

Industrial process pipelines are mostly known to be constructed from metal which is a conducting material. It is proven that ERT can be applied successfully on the conducting vessel wall and pipelines both for laboratory and industrial application. As for the current excitation strategy, a conducting boundary protocol has to be applied when it comes to metallic vessels to overcome the grounding effect. Conversely, from the literature, not much work has been undertaken on ERT deploying the conducting vessel. It is believed that further exploration of this topic can deliver valuable information to give new insights and benefits to relevant areas and industry. Further potential improvements to the current design and image reconstruction of the ERT system are possible so that it can be applied effectively and successfully with the conducting vessel.

Acknowledgement

References

[1]   C. Yang, H. Wang, and Z. Cui. 2012. Application of Electrical Resistance Tomography in Bubble Columns for Volume Fraction Measurement. In 2012 IEEE International Instrumentation and Measurement Technology Conference, I2MTC 2012, May 13, 2012 - May 16, 2012, Graz, Austria. 1199–1203.

[2]   H. Jin, Y. Lian, Y. Qin, S. Yang, and G. He. 2012. Distribution Characteristics of Holdups in a Multi-stage Bubble Column Using Electrical Resistance Tomography.

[3]   J. Xue, M. Al-Dahhan, M. P. Dudukovic, and R. F. Mudde. 2008. Four-point Optical Probe for Measurement of Bubble Dynamics: Validation of the Technique. *Flow Measurement and Instrumentation.* 19: 293–300.

[4]   L. G. Neal and S. G. Bankoff. 1964. A High Resolution Resistivity Probe for Determination of Local Void Properties in Gas–liquid Flow. 490–494.

[5]   M. D. Supardan, Y. Masuda, A. Maezawa, and S. Uchida. 2007. The Investigation of Gas Holdup Distribution in a Two-phase Bubble Column Using Ultrasonic Computed Tomography. *Chemical Engineering Journa.* 30: 125–133.

[6]   M. Fransolet, P. Crine, P. Marchot, and D. Toye. 2005. Analysis of Gas Holdup in Bubble Columns with Non-Newtonian Fluid Using Electrical Resistance Tomography and Dynamic Gas Disengagement Technique. *Chemical Engineering Science.* 6118–6123.

[7]   M. Hamidipour and F. Larachi. 2010.Characterizing the Liquid Dynamics in Cocurrent Gas-liquid Flows in Porous Media Using Twin-plane Electrical Capacitance Tomography. *Chemical Engineering Journal.* 165: 310–323.

[8]   H. Jin, M. Wang, and R. A. Williams. 2007. Analysis of Bubble Behaviors in Bubble Columns Using Electrical Resistance Tomography. *Chemical Engineering Journal.* 130: 179–185.

[9]   H. Jin, S. Yang, M. Wang, and R. A. Williams. 2007. Measurement of Gas Holdup Profiles in a Gas Liquid Cocurrent Bubble Column Using Electrical Resistance Tomography. *Flow Measurement and Instrumentation.* 18: 191–196.

[10] M. A.-D. Junli Xue, M. P. Dudukovic, R. F. Mudde. 2007. Bubble Velocity, Size, and Interfacial Area Measurements in a Bubble Column by Four-point Optical Probe.*Wiley online, AICHE.*

[11] J. Kourunen, T. Niitti, and L. M. Heikkinen. 2011. Application of Three-Dimensional Electrical Resistance Tomography to Characterize Gas Holdup Distribution in Laboratory Flotation Cell. *Minerals Engineering.* 24: 1677–1686.

[12] A. Shaikh and M. Al-Dahhan. 2005. Characterization of the Hydrodynamic Flow Regime in Bubble Columns via Computed Tomography. *Flow Measurement and Instrumentation.* 16: 91–98.

[13] V. P. Chilekar1, M. J. F. Warnier1, J. van der Schaaf1, B. F. M. Kuster1, J. C. Schouten, J. R. van Ommen. 2005. Bubble Size Estimation in Slurry Bubble Columns from Pressure Fluctuations. *Wiley online, AICHE,* May.

[14] M. R. Widyanto, M. B. Utomo, K. Kawamoto, B. Kusumoputro, and K. Hirota. 2006. Local Gas Holdup Measurement of a Bubble Column Using SONIA-Ultrasonic Non-Invasive Method. *Sensors and Actuators A: Physical.* 126: 447–454.

[15] B. D. Grieve. 2002. On-line Electrical Impedance Tomography for Industrial Batch Processing. Degree of Doctor of Philosophy, Department of Chemical Engineering, UMIST Manchester, UK.

[16] Z. Cao and L. Xu. 2012. Direct image reconstruction for 3D electrical resistance tomography by using the factorization method. In 2012 IEEE International Instrumentation and Measurement Technology Conference, I2MTC 2012, May 13, 2012 - May 16, 2012, Graz, Austria. 1919–1922.

[17] J. K. L M Heikkinen , T Savolainen , P J Vauhkonen , J P Kaipio and M Vauhkonen. 2006. Real Time Three-dimensional Electrical Impedance Tomography Applied in Multiphase Flow Imaging. *Measurement Science and Technology.* 17.

[18] H. Jin, S. Yang, G. He, M. Wang, and R. A. Williams. 2010. The Effect of Gas-liquid Counter-current Operation on Gas Hold-up in Bubble Columns Using Electrical Resistance Tomography. *Journal of Chemical Technology and Biotechnology.* 85: 1278–1283.

[19] Y. Xu, H. Wang, Z. Cui, and F. Dong. 2009. Application of Electrical Resistance Tomography for Slug Flow Measurement in Gas/Liquid Flow Of Horizontal Pipe. In 2009 IEEE International Workshop on Imaging Systems and Techniques, IST 2009, May 11, 2009 - May 12, 2009, Hong Kong, China. 319–323.

[20] F. Dong, E.-P. Li, and B.-B. Wang. 2007. Optimization Design of Electrical Resistance Tomography Data Acquisition System. In 6th International Conference on Machine Learning and Cybernetics, *ICMLC 2007, August 19, 2007 - August 22, 2007*, Hong Kong, China. 1454–1458.

[21] F. Dong, C. Tan, J. Liu, Y. Xu, and H. Wang. 2006. Development of Single Drive Electrode Electrical Resistance Tomography System. *IEEE Transactions on Instrumentation and Measurement.* 55: 1208–1214.

[22] M. Sharifi and B. Young. 2012. Qualitative Visualization and Quantitative Analysis of Milk Flow Using Electrical Resistance Tomography. *Journal of Food Engineering.* 112: 227–242.

[23] S. R. Aw, R. A. Rahim, M. H. F. Rahiman, F. R. M. Yunus, and C. L. Goh. 2014. Electrical Resistance Tomography: A Review of the Application of Conducting Vessel Walls. *Powder Technology.* 254: 256–264.

[24] M. S. B. A Plaskowski, R Thorn and T Dyakowski. 1995. *Imaging Industrial Flow.* London: IOP Publishing Ltd.

[25] C. Tan and F. Dong. 2009. Gas-Water Two-Phase Flow Regime Identification with Feature Fusion from an ERT System and a VCone Meter. *IEEE.* 2: 218–222.

[26] S. Hosseini, D. Patel, F. Ein-Mozaffari, and M. Mehrvar. 2010. Study of Solid-liquid Mixing in Agitated Tanks Through Electrical Resistance Tomography. *Chemical Engineering Science.* 65: 1374–1384.

[27] C. Tan, F. Dong, and M. Wu. 2007. Identification of Gas/Liquid Two-Phase Flow Regime Through ERT-Based Measurement and Feature Extraction. *Flow Measurement and Instrumentation.* 18: 255–261.

[28] S. J. Stanley and G. T. Bolton. 2008. A Review of Recent Electrical Resistance Tomography (ERT) Applications for Wet Particulate Processing. *Particle and Particle Systems Characterization.* 25: 207–215.

[29] M. Wang, F. J. Dickin, and R. A. Williams. 1994. Electrical Resistance Tomography of Metal Walled Vessels and Pipelines. *Electronics Letters.* 30: 771–773.

[30] M. Wang, F. J. Dickin, and R. A. Williams, 1995. Modelling and Analysis of Electrically Conducting Vessels and Pipelines in Electrical Resistance Process Tomography. *IEE Proceedings: Science, Measurement and Technology.* 142: 313–322.

[31] E. L. Yuen, R. Mann, T. A. York, and B. D. Grieve. 2001. Electrical Resistance Tomography (ERT) Imaging of a Metal-Walled Solid-Liquid FilterE. Presented at the 2nd world Congress on Industrial Process Tomography, Hannover, Germant.

[32] S. G. Liter, J. R. Torczynski, K. A. Shollenberger, and S. L. Ceccio. 2002. Electrical-Impedance Tomography for Opaque Multiphase Flows in Metallic (Electrically-Conducting) Vessels. Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US).

[33] T. A. York, J. L. Davidson, L. Mazurkiewich, R. Mann, and B. D. Grieve. 2005. Towards Process Tomography for Monitoring Pressure Filtration. *Sensors Journal, IEEE.* 5: 139–152.

[34] J. L. Davidson, 2004. Three-dimensional Electrical Impedance Tomography Applied to a Metal-walled Filtration Test Platform. *Measurement Science and Technology.* 15: 2263–2274.

[35] (July 18th). *Electrical Resistance Tomography.* Available: http://www.itoms.com/solutions/electrical-resistance-tomography.

[36] M. Kaminoyama, K. Nishi, R. Misumi, and A. Tagawa. 2007. Presented at the 5th World Congress on Industrial Process Tomography, Bergen, Norway.

[37] L. Pakzad, F. Ein-Mozaffari, and P. Chan. 2008. Measuring Mixing Time in the Agitation of Non-Newtonian Fluids Through Electrical Resistance Tomography. *Chemical Engineering and Technology.* 31: 1838–1845.

[38] A. Seppanen, K. Karhunen, A. Lehikoinen, J. P. Kaipio, and P. J. M. Monteiro. 2009. Electrical Resistance Tomography Imaging of Concrete. in 2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR 2008, November 24, 2008 - November 26, 2008, Cape Town, South Africa. 231–232.

[39] K. S. Cheng, D. Isaacson, J. C. Newell, and D. G. Gisser. 1989. Electrode Models for Electric Current Computed Tomography. *IEEE Transactions on Biomedical Engineering.* 36: 918–924.

[40] P. Tahvildarian, H. Ng, M. D'Amato, S. Drappel, F. Ein-Mozaffari, and S. R. Upreti. 2011. Using Electrical Resistance Tomography Images to Characterize the Mixing of Micron-sized Polymeric Particles in a Slurry Reactor. *Chemical Engineering Journal.* 172: 517–525.

[41] H. Jin, Y. Lian, Y. Qin, S. Yang, and G. He. 2013. Distribution Characteristics of Holdups in a Multi-stage Bubble Column Using Electrical Resistance Tomography. *Particuology.* 225–231.

[42] M. G. Rasteiro, R. Silva, F. A. P. Garcia, and P. Faia. 2011. Electrical Tomography: A Review of Configurations and Applications to Particulate Processes. *KONA Powder and Particle Journal.* 29: 67–80.