Chemical and Process Engineering 2014, 35 (4), 397-408
DOI: 10.2478/cpe-2014-0030

APPLICATIONS OF ELECTRICAL CAPACITANCE TOMOGRAPHY FOR RESEARCH ON PHENOMENA OCCURRING IN THE FLUIDISED BED REACTORS

Jan Porzuczek*

Cracow University of Technology, Institute of Thermal Engineering and Air Quality Protection,
Warszawska 24, 31-155 Kraków, Poland

The paper presents a review of current achievements in the Electrical Capacitance Tomography (ECT) in relation to its possible applications in the study of phenomena occurring in fluidised bed reactors. Reactors of that kind are being increasingly used in chemical engineering, energetics (fluidised bed boilers) or industrial dryers. However, not all phenomena in the fluidised bed have been thoroughly understood. This results in the need to explore and develop new research methods. Various aspects of ECT operation and data processing are described with their applicability in scientific research. The idea for investigation of temperature distribution in the fluidised bed, using multimodal tomography, is also introduced. Metrological requirements of process tomography such as sensitivity, resolution, and speed of data acquiring are noted.

Keywords: Electrical Capacitance Tomography (ECT), fluidisation, hydrodynamics, temperature distribution, application review

1. INTRODUCTION

The term ‘tomography’ is common for all measurement and visualisation methods that provide the information about spatial distribution of certain properties within examined object, using measurements performed at the border of this object (Tapp et al., 2003). As a result of the measurement, the graphical representation of properties distribution, which is a set of measurements in the sensor cross-section, can be achieved. That explains the etymology of the word ‘tomography’ (from Greek: τομη – cut, divide). Originally this technique was only used in medicine for imaging of tissue lesions, using ionising radiation as the information carrier. The interest in the utilisation of the electrical phenomena in tomography that was noted in the 1980s contributed to the advent of electrical tomography which was relatively inexpensive in the application. In the early 1990s electrical tomography was used in research, and then for monitoring and control of industrial processes (Xie et al., 1995). The first practical applications of process tomography were carried out in the petrochemical industry (Ismail et al., 2005), but nowadays these methods are also widely applied in many other areas of science and technology (Dyakowski et al., 2000; Tapp et al., 2003; Yang, 2007).

Depending on the electrical and magnetic properties of the examined object, different measurement methods are possible to be applied:

- Electrical Impedance Tomography (EIT) – the distribution of electrical conductivity is determined within the examined object thus it must conduct electricity. The most typical

---

*Corresponding author, e-mail: porzuk@pk.edu.pl applications of EIT include monitoring of multiphase flow (George et al., 2001) and mixing processes (Kourunen et al., 2008), also with chemical reactions during mixing (Stanley, 2006). This method is likewise applicable to the study of combustion (Yan et al., 2012).

- Electrical Capacitance Tomography (ECT) – allows to determine the permittivity distribution in an area filled with dielectric (Yang, 2007). Like EIT, capacitance tomography is mainly used to monitor multiphase processes, such as mixing processes or separation of substances (Tapp et al., 2003). ECT tomography is also used in the petrochemical industry (Ismail et al. 2005), drying technology (Rimpilainen et al., 2012; Wang et al., 2009) or pharmaceutical industry (Burggraeve et al., 2013). In the monitoring of multiphase flow, ECT devices may also be applied as flowmeters (Pradeep et al., 2012).
- Electromagnetic Tomography (EMT) or Magnetic Induction Tomography (MIT) – is mainly used to determine the permeability distribution in the examined object (Peyton et al., 1996). Typical applications of EMT comprise: geological exploration, biomedical research, material inspection and separation processes (Liu et al., 2005; Peyton et al., 1999).

In addition to electrical tomography, ultrasonic and optical tomography are also widely applied in the industry (Filipowicz, 2011). The combination of process tomography modalities such as ECT and EIT may also be noted (Cui et al., 2009; Li and Soleimani, 2013; Marashdeh et al., 2007; Qiu et al. 2007). This approach is the example of a multimodal tomography (also known as hybrid tomography), enabling to gain extensive data about the monitored process.

Fluidisation phenomenon has been known since the 1920s (Basu, 2006), when it was discovered by Fritz Winkler and used to build the first fluidised bed gasifier. This phenomenon is defined as the operation through which fine solids are transformed into a fluid-like state through contact with gas or liquid. With variations in gas velocity the bed changes its state, so-called "fluidisation regime", from packed bed, through bubbling bed, slugging bed (only in reactors of small diameter), turbulent bed, fast bed, up to pneumatic transport of solids (arranged in order of increasing velocity). Contemporary fluidised bed reactors are used mainly in power generation as the basic elements of fluidised bed boilers and gasifiers (Basu, 2006; Porzuczek, 2012). Excellent mixing of the phases, resulting in a large contact area of reactants, allows the use of fluidised bed reactors in chemical technology processes such as catalytic, adsorption and thermal regeneration of selected substances (Żukowski et al., 2011). The phenomenon is also commonly used in fluidised bed dryers (Rimpilainen et al., 2012; Yang, 2007). Despite numerous applications of fluidisation, as well as nearly a hundred years of research, not all phenomena occurring in the fluidised bed have been thoroughly explained. Modern measurement techniques that provide information about spatial distribution of the parameters such as temperature, density of the bed, or properties and concentrations of the reactants play a key role in research on fluidisation. In the related literature, eg. (Werther, 1999) one can find descriptions of innovative measurement methods and their possible applications in the studies of fluidisation. Much attention is given to methods of determination of local velocity (Doppler laser anemometry), bubble formation (Yang et al., 2007) and the most important in fluidised beds: solid concentration (X-ray and gamma-ray tomography, capacitance tomography) (Wiesendorf and Werther, 2000). Tomographic methods were also used in measurements of bed height as well as determination of the minimum fluidisation velocity (Escudero and Heindel, 2011).

Of particular interest might be the use of capacitance tomography owing to its dynamic properties that give the possibility to study rapid processes such as combustion, explosions (Yan et al., 2012) or bubble formation and evolution (Yang et al., 2007). The possibility of obtaining high-speed data acquisition allows the use of ECT also in research on fluidisation regimes (Makkawi and Wright, 2002a). Although twenty years have passed since the publication of the first papers describing the application of ECT tomography to study fluidisation (Wang et al., 1995), the potential of this method does not seem to have been fully exploited. Therefore, the purpose of this paper, beside describing state-of-the-art of ECT is to widespread the potential of capacitance tomography.

2. ELECTRICAL CAPACITANCE TOMOGRAPHY

Electrical Capacitance Tomography (ECT) is a non-invasive method of measurement and visualisation which allows determination of the spatial distribution of permittivity within the space surrounded by the sensor. If there are known interdependencies between the permittivity and temperature, humidity, etc., it is also possible to infer about the process inside the reactor.

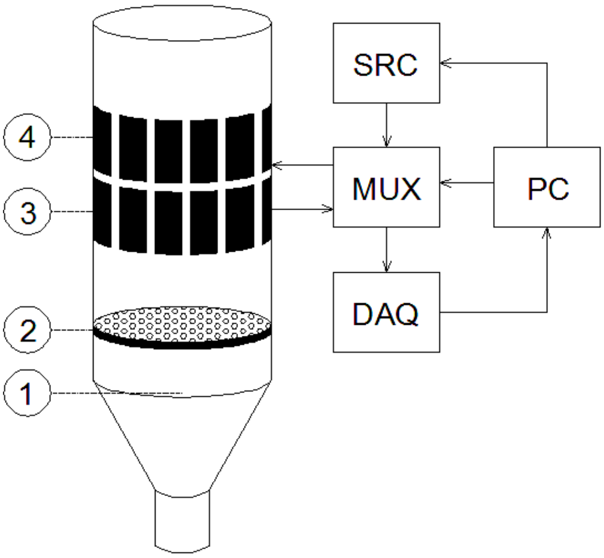

Fig. 1. A test stand used to carry out experiments on ECT measurements with fluidised bed reactor; 1 – windbox, 2 – air distributor, 3 and 4 – planes of ECT sensor, PC – controller/computer, SRC – voltage source, MUX – multiplexer or matrix switch, DAQ – data acquisition device

The sensor consists of one (2D tomography) or several (3D tomography and ECT-based flowmeters) sets (‘planes’) of n electrodes placed on the side surface of the examined area. The measurement set is a sequence of energising (with DC or AC voltage source) consecutive electrodes of the sensor and measuring the capacitance between the source electrode and the other. Hence, the total number of independent capacitance measurements depends on the number of electrodes n; for a single-plane sensor it is expressed by Equation (1):

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

For example: for a typical 12-electrode ECT sensor, the number of independent capacitance measurements is 66. As may be seen, this significantly limits the measurement resolution (radial). It is known that improvement of geometric resolution is possible by increasing the number of electrodes in a sensor. However, this is associated with the reduction of area of each electrode and thus diminution of capacitance that has to be measured. On the other hand, enhancement of the electrode area can be achieved by increasing its length; unfortunately, it reduces the axial resolution of the device. It may be stated that the number of electrodes, their size and number of the planes must be adjusted closely to destination of the ECT sensor. Capacitance between two selected electrodes can be determined by Equation (2) (Wang et al., 2009):

$$C = \varepsilon_0 \varepsilon_r \Phi \tag{2}$$

According to Filipowicz (2011), capacitance between adjacent electrodes is in the range of 0.2 - 0.5 pF, while for the opposite electrodes reaches only 10 - 20 fF. Measurement of such small capacitance requires highly sensitive instrumentation, typical requirement is the ability to detect changes in the capacitance of about 0.1 fF or even smaller (Yang, 2007).

Determination of the permittivity distribution in the cross-section of a sensor, based on the measured capacitance, requires a two-step process. The aim of the first stage is to solve the forward problem, leading to designation of the sensitivity matrix of the measurement system. This step is based on the Laplace equation which defines the distribution of electrical potential φ in the studied area (Eq. 3):

$$div(\varepsilon \, grad \, \varphi) = 0 \tag{3}$$

The solution of Equation (3) for a given measurement system is usually carried out with numerical methods. It leads to the designation of the sensitivity matrix S, satisfying the relation (4):

$$C = S \cdot \varepsilon \tag{4}$$

Reconstruction of the permittivity image ε is the second stage of the analysis of acquired data. The image is constructed by solving the inverse problem defined by Equation (5).

$$\varepsilon = S^{-1} \cdot C \tag{5}$$

However, the S matrix is not the square one, thus the S^{-1} does not exist. It is therefore not possible to use conventional methods of determining the inverse matrix. This problem has resulted in a number of algorithms for image reconstruction (Filipowicz, 2011; Rimpilainen et al., 2012), approximating the solution of the inverse problem.

3. CURRENT APPLICATIONS OF ECT TOMOGRAPHY FOR RESEARCH ON FLUIDISED BED REACTORS

Currently, the development of ECT tomography is associated with new designs of sensors, high-resolution capacitance transducers and modern image reconstruction algorithms, including so-called ‘soft computing’ methods (eg. neural networks). Although rarely, some examples of new applications of this technique in scientific research and industrial applications can be found.

The basis of knowledge about fluidisation is fluidised bed hydrodynamics. Of particular importance is the spatial distribution of solid particle concentration and its dynamics. This is associated with determination of fluidisation regime as well as formation and evolution of bubbles. Application of a visualisation method for distribution of the solid phase can contribute to optimise the design of reactors, parameters of their operation, as well as lead to improved knowledge of the fluidisation phenomenon. Hydrodynamics of the fluidised bed has been widely presented in the literature (Basu, 2006; Escudero and Heindel, 2011; Yang et al. 2007).

It is thought, that the applicability of ECT tomography to study the regime of fluidisation, determining the local concentration of the solid phase and the dynamics of bubble formation is already well verified. As stated above, fluidised bed hydrodynamic issues are essential knowledge in the scope of fluidisation. However, from the perspective of the considered measurement method they are also the easiest to investigate. The use of dependence of permittivity on the concentration of the solid phase allows the imaging of the spatial distribution of solids. Moreover, high rate of data acquisition, typical for ECT, allows obtaining reliable information about the dynamics of changes in the distribution of solid particles. The very first research, conducted in the 1990s, was related to these phenomena. For example, Wang et al. (1995) applied the eight-electrode capacitance tomograph to analyse solid particle concentration and its variation in different fluidisation regimes (bubbling, slugging and turbulent). The size of bubbles and analysis of their shape was also investigated. Research on this matter was conducted subsequently by many teams. Most experiments were conducted in cylindrical reactors. However, Liu et al. (2001) proposed the use of ECT tomograph to study the fluidisation regime in a reactor of square cross section. The authors noted that the lack of rotational symmetry of the sensor increased the complexity of data analysis. Dyakowski et al. (2000) gave a detailed review of applications of ECT in fluidisation studies and two-phase flows in the first period of the development of this visualisation method. The use of multi-plane sensors, as proposed for example in (Makkawi and Wright, 2002a; Warsito and Fan, 2005), allowed the visualisation of three-dimensional distribution of concentration of the solid phase which was a significant step in the development of ECT. Nowadays, the term Electrical Capacitance Volume Tomography (ECVT) is often used (Rimpilainen et al., 2012; Wang et al., 2010a) for such systems. Taking into account very high speed of data acquisition, currently more than 200 frames per second (fps), the dynamics of bubble evolution and their motion may be examined with good accuracy. It is noteworthy that the latest achievements in ECT have improved speed of data acquisition up to 1000 fps (Yang et al. 2014). The accuracy of determining the position of a moving object was analysed by Wang et al. (2010a). The authors compared the results obtained with a triple-plane ECT system with the position of a falling object captured with a fast video camera and CFD (Computational Fluid Dynamics) simulation of the process - obtaining a high consistency of results. High quality of ECVT imaging was also confirmed by Weber and Mei (2013). The authors studied the distribution of the solid phase and the size and frequency of bubbles. It is worth mentioning that the sensor they used had 24 electrodes arranged into six planes which also shows the scale of progress in the field of ECT devices.

Recently, a lot of attention has been given given to improve imaging quality as well as to expand the measurement abilities of ECT tomographs, utilising additional analysis of acquired data sets. Makkawi and Ocone (2007) proposed a combination of ECT measurements of solid concentration together with numerical modeling of fluidised bed hydrodynamics. Additionally, the pressure drop across the bed was measured. The aim of the research was to develop a tool to predict the hydrodynamics of a fluidised bed (profiles of particle and gas velocity). A twin-plane tomograph, 8 electrodes in each plane was applied for this purpose. The authors stated good consistency of obtained results with theoretical predictions. Nevertheless, it was also found that for a large amount of bubbles the numerical model was unstable. It required correction to study important fluidisation regime such as bubbling bed. Another approach for analysis of imaging data was shown by Rautenbach et al. (2013). ECT measurements were combined with statistical analysis of acquired data to determine the quality of fluidisation. The research was conducted using a twin-plane tomograph with 12 electrodes in each plane. It was stated that the reliable measure of quality and uniformity of fluidisation might be skewness and kurtosis of ECT measurements of the distribution of solid particle concentration. The attempts of merging ECT measurements with CFD modeling for improvement of particle distribution imaging (Jiang et al., 2014; Zhao, 2010) also might be noteworthy.

Calibration of the sensor is an essential issue in a study of the spatial distribution of particle concentration using ECT. A typical solution of this problem, commonly used by most researchers (Makkawi and Ocone, 2007; Wang et al. 1995), is based on the calibration of the instrument in the two extreme points of the range. At first, calibration is performed with the empty sensor ($\varepsilon_r \cong 1$) then with a sensor filled with a solid material for approximation of maximum permittivity. However, the problem of interpolation between two extreme points needs more attention. Wiesendorf and Werther (2000) compared most commonly used interpolation methods, showing significant differences between them. The same authors also highlighted the significant effect of temperature on relative permittivity, pointing to the need to compensate its impact in the study of fluidised bed hydrodynamics. Further discussion of these issues might be also found in paper by Asami (2002).

Analysing the usefulness and reliability of the considered measurement method it is necessary to draw attention to validation methods. Imaging of solid particle concentration might be verified using capacitance probes (Wiesendorf and Werther, 2000) but the use of such an invasive method can significantly disturb the measured quantity. Non-invasive methods such as fibre optic probes (Pugsley et al., 2003) are free from this disadvantage. Studies on the formation of bubbles in a fluidised bed often use a bubble model (phantom) - a ping-pong ball (with additional filling) entered into the bed (Weber and Mei, 2013). Rautenbach et al. (2013a) showed that the error of the phantom diameter measurement using ECVT reached 6.5%. In recent years the results of comparative studies on imaging of phenomena occurring in the fluidised bed were published. For example, Holland et al. (2009) showed a comparison between ECT tomography and Magnetic Resonance Imaging (MRI). Similarly, Rautenbach et al. (2013b) provided a comparison of two tomographic methods: ECT and X-ray tomography. Acceptable consistency of obtained results increases the reliability of capacitance tomography.

Currently, advanced studies on fluidisation hydrodynamics already treat process tomography as a reliable tool. The example of such experiments is a study on the interaction between fluidised bed and the gas stream, injected into the bed perpendicularly to the axis of the reactor (Wang F. et al., 2010b). The authors presented a visualisation of the gas jet propagation obtained with a 3D ECT system. The measurement method used in that experiment has also enabled the determination of the gas velocity profile. Another example of the use of ECT in an advanced study is the paper (Cai et al., 2013) where the tracing of the motion of a large object in a fluidised bed was depicted.

Spatial distribution of permittivity in the fluidised bed depends on several factors including: kind and concentration of substances, humidity, temperature, and pressure. The research on fluidised bed hydrodynamics, which has been analyzed above, was typically conducted at ambient temperature with bed material that did not change its properties during the experiment (eg. quartz sand). Temperature gradients or changing the properties of the bed material lead to significant complications in reaching unambiguous interpretation of the determined distributions of permittivity. Examples of process tomography applications in such conditions can be found in drying technology. Fluidised bed dryers are currently produced in both laboratory and industrial scale (Yang, 2007). Control of the drying process, especially with the optimisation of energy consumption in relation to product quality, requires on-line measurement of moisture content in a dried material. These issues were analysed by e.g. Wang et al. (2009). The paper presented the possibility of using a single-plane 8-electrode ECT tomograph as the non-invasive system to measure the moisture content in a dried material. The authors proposed and experimentally verified the model for mapping the permittivity distribution into the moisture content. As during the drying process the average temperature in the reactor varied between 20-60 °C, an algorithm to compensate these changes had to be applied. The second aspect analysed in that study was the practical application of ECT in the automatic control system to control the laboratory fluidised bed dryer Sherwood M501. Another example of tomographic monitoring of the drying process was shown by Rimpilainen et al. (2012). The paper is distinguished by the use of a conical reactor (cylindrical reactors are used more often) as well as the multi-plane sensor, which allowed visualisation of the spatial (3D) distribution of moisture content. During experiments the temperature was stabilised thus there was no need to compensate its changes. In order to verify the proposed method of measurement, dried material was sampled during the experiment and then its moisture content was measured using a different method (moisture analyser). Several methods for estimating moisture content of a dried material from the measured distribution of permittivity, using approximating polynomials, were proposed. Obtained results were encouraging - the observed differences between ECT and moisture analyser were about 7-11%. The authors noted the possibility for improvement of the results by taking into account the correction of air velocity. It is interesting to note the recent dissemination of the term "tomometrics" for process tomography applications in measurement systems, such as humidity, flow, etc., (Pradeep et al., 2012). The importance of this issue was acknowledged as tomometrics was the subject of a separate section on the Conference ‘7th World Congress on Industrial Process Tomography’ in 2013.

As shown above, lots of expectations are associated nowadays with three-dimensional (3D) tomography. Because of the need to reduce the height of sensor electrodes in 3D tomograph, the measured capacitance is also reduced. This implies the necessity to search for the most favorable geometric layout and the number of electrodes (Wang F. et al. 2010a), often using optimisation methods. The need for simulation studies leading to optimise sensors was already noticed (Yan et al.

1999), but currently it is the basis for design of modern ECT systems (Alme and Mylvaganam, 2006). Makkawi and Wright (2002b) indicated the important impact of dynamic properties (eg. data acquisition rate) of a measuring system as well as its optimisation on obtained quality of imaging of phenomena taking place in a fluidised bed.

The quality of image reconstruction of permittivity is highly dependent on the applied numerical algorithm (Filipowicz, 2011; Yang, 2007). In most studies, eg. (Liu et al., 2001) Linear Back Projection (LBP) algorithm was applied. This algorithm is considered to be the easiest to implement but obtained images are generally of low quality (Tapp et al., 2003). Better results can be achieved using iterative algorithms such as Landweber, as selected papers have comparatively shown (Makkawi and Wright, 2004; Wang et al., 2009; Warsito and Fan, 2001). Shape reconstruction method (Soleimani et al., 2006) or algorithms based on artificial neural networks (Warsito and Fan, 2005) are examples of modern approaches. The fuzzy-logic classification, used by Banasiak et al. (2014) for the analysis of two-phase flow, is another example of such an approach. Wang et al. (2012) provides a comparison of imaging quality obtained with different image reconstruction algorithms: LBP, Landweber, Tikhonov regularisation as well as their own algorithm – 'Dynamic Reconstruction Method'. The reconstruction of an image, especially when algorithms more complex than LBP are employed, is resource-intensive computing. Recent advances in parallel computing using multiprocessor systems, and even the graphics processing unit (GPU) may contribute to increased use of complex algorithms.

4. POSSIBILITIES OF TEMPERATURE DISTRIBUTION ANALYSIS USING ECT

It is commonly thought that fluidised bed reactors are characterised by equalised temperature in the volume of the bed. This is concluded upon the fact of intense mixing occurring in this area as well as a large heat capacity of solid phase. This property is only confined to the area of the emulsion phase. High-temperature reactors, such as furnaces of power boilers, are known to have the temperature gradient observed in the bubbles up to several hundred Kelvin (Basu, 2006; Żukowski et al., 2009). A significant gradient of temperature field also occurs in the area of rapid reaction such as ignition of fuel grain. The knowledge about the temperature distribution in the fluidised bed is fundamental for the analysis of processes occurring in such conditions. It may be noted that the typical temperature measurement, performed with thermocouples, provides only information about the average value of this quantity (Porzuczek, 2012). The most common solution to this problem (Werther, 1999) is to insert a group of spatially arranged thermoelectric sensors of small dimensions into the bed to estimate the temperature distribution. Unfortunately, this approach also disturbs the temperature field. There are also non-invasive measurements, based on an analysis of visible light emission recorded with a digital camera (Żukowski et al., 2009; Smart et al., 2010). The advantage of this method is high speed data recording, which allows the identification of even short-term changes in bed temperature. However, the uncertainty of measurements obtained in this way is not fully known.

Dependence of dielectric permittivity on its temperature can be obtained from model calculations or measurements (Chełkowski, 1993). This gives the potential to adopt this feature to determine the temperature field using ECT tomography. This possibility was noticed for example in (Tapp et al., 2003) but without a broader analysis of the problem. It is noteworthy that simple mapping of determined permittivity of the substance into the corresponding temperature is only possible in homogeneous environment (Yang et al., 2008). Although it excludes the possibility of determining the temperature field in the fluidised bed using ECT tomography in its basic form; this may be the basis for its modification.

In most papers, the sensor of ECT tomograph is treated as a perfect capacitor with a capacitance determined by Equation (2) that was introduced above. Real capacitors are not able to keep the charge infinitely long because of energy dissipation resulting from non-ideal dielectric. Considering an AC powered capacitor, it can be seen that in such a system, in addition to charging current which phase shifting the voltage of angle $\pi/2$, the loss current flows in-phase with the applied voltage. Permittivity should therefore be considered in the space of complex numbers (complex permittivity) (Chełkowski, 1993):

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{6}$$

The real part (ε') represents capacitor's ability for energy storage, while the imaginary part (ε'') is the ability to dissipate energy; j stands for the imaginary unit. A real capacitor can be described in simplified terms as the substitute circuit of capacitance C and resistance R connected in parallel. Introducing the term of loss tangent (Eq. 7) which is well known in electrical engineering:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{1}{\omega RC} \tag{7}$$

one can state the dependence of dielectric properties on the applied voltage frequency. In fact, both ε' and ε'' of the dielectric at a given temperature are dependent on frequency. Therefore, the method for determining the temperature field based on the analysis of frequency characteristics can be proposed. Dependency of both ε' and ε'' of the bed material on temperature is known for many substances (Chełkowski, 1993; Yang et al., 2008) but can also be obtained experimentally (Thorp et al., 1987). Measurement of dielectric characteristic as a function of frequency of the applied voltage is known as dielectric spectroscopy (Asami, 2002). This method is known e.g. in physics of polymers; however, so far it has found no appreciable part in process tomography. This technique can be used to determine simultaneously the frequency characteristics of the properties of both accumulation and dissipation of energy by the dielectric, thus creating a kind of multimodal tomography. Although this substantially increases the complexity of the measurement system itself as well as analysing the data, it incomparably enhances the ability to identify phenomena occurring inside the reactor.

In recent years multimodal tomography has been the subject of much research. Marashdeh et al. (2007) investigated the possibility to apply multimodal tomography (capacitance – impedance), using a typical ECT sensor. The aim of the research was the study of detection of the location of substances differing in permittivity and conductivity. For this purpose phantoms with known electrical properties were placed inside a sensor. The authors found significant improvement in object location, which shows a valid potential of multimodal tomography, yet unused on a wider scale. The emergence of the first commercially manufactured multimodal ECT/ERT tomographs, e.g. M3000 by Industrial Tomography System Ltd. (Qiu et al., 2007) may be noted. There is increasing attention to the development of new design of ECT/ERT sensors for multimodal tomography (Cui et al., 2009). The need to analyse the interaction between modalities (e.g. the effect of particle charging) that may adversely affect image quality was also indicated (Gao et al., 2012).

The use of multimodal process tomography to study the temperature field in fluidised bed seems to be realistic but will require modification of currently available ECT equipment. This is connected with the necessity to measure two parameters which can determine the sought distributions ε' and ε'' instead of one - capacitance. For this purpose the above-cited paper (Marashdeh et al., 2007) presents measurements of capacitance and power, dissipated by a resistive component. It seems that the measuring of current amplitude and phase shifting is more practical to determine the frequency characteristics of the examined object. There are examples of such solutions in tomography: e.g. Wang M. et al. (2013) applied multimodal tomography with spectrometric analysis to measure the absorption of carbon dioxide in a bubble column (using the above-mentioned M3000 tomograph). The measurement was performed in a wide range of excitation frequency (1Hz – 32MHz). A similar solution was applied by Li and Soleimani (2013) for flow imaging of dielectric/conductive mixtures, for example gas/water/oil mixture. The general requirement when applying dielectric spectroscopy is the use of AC tomograph (Yang, 2007) with a programmable signal source such as DDS (Direct Digital Synthesis) generator. Determination of the spatial, three-dimensional distribution of temperature requires a multi-plane (3D) sensor. As previously noted, such sensors are characterised by very small capacitance between their electrodes, so a typical capacitance measurement resolution of 0.1 fF may be insufficient, because it considerably limits the resolution of the temperature measurement. Commercially available ECT tomographs have already achieved the resolution of 0.01 fF in measurement range of 0-2000 fF, but their cost is very high. Temperature field is subject to change over time thus, placing a requirement of its measurement, it is necessary to use an appliance with a proper data acquiring speed. Detailed requirements for a ECT measurement system can be determined only by numerical simulations which will form the basis for further research together with indispensable experimental validation.

5. CONCLUSIONS

Electrical Capacitance Tomography is fast evolving measurement technology that has already gained the well-established position of a reliable research tool. As indicated in this paper, owing to non-invasive and high speed measurement, ECT is readily applicable to study the phenomenon of fluidisation. The main area of application of ECT tomography is research on fluidised bed hydrodynamics: the fluidisation regime, distribution of solid concentration and dynamics of bubble formation. Attention is also drawn to the possible use of three-dimensional (3D) tomography that provides, for example, the ability to visualise the interaction between the bed and the gas stream introduced into the bed. Another aspect of the application of ECT tomography is research on bed material properties and their variability. Attempting to determine the moisture content in the bed material in a fluidised bed dryer is an example of such applications. In this paper the potential possibility of determining temperature distribution in the fluidised bed is also highlighted. The proposed concept is based on the complex permittivity dependence on material temperature and frequency of applied voltage. It is stated that detailed requirements for an ECT measurement system can be determined only by numerical simulations. The idea of temperature distribution imaging is not proved yet and it still requires to be validated, which will form the basis for further research.

SYMBOLS

C	capacitance, F
j	imaginary unit, -
L	number of independent capacitance measurement, -
n	number of sensor electrodes, -
R	resistance, Ω
S	sensitivity matrix, -

Greek symbols

δ	loss angle of capacitor, rad
ε	permittivity of dielectric, F/m
ε_0	vacuum permittivity, F/m
ε_r	relative permittivity of dielectric, -
φ	electrical potential, V
Φ	geometric factor of the sensor, m
ω	angular frequency, rad/s

REFERENCES

Alme K.J., Mylvaganam S., 2006. Electrical Capacitance Tomography – sensor models, design, simulations and experimental verification. *IEEE Sensors J.*, 6, 1256-1266. DOI: 10.1109/JSEN.2006.881409.

Asami K., 2002. Characterization of heterogeneous systems by dielectric spectroscopy. *Prog. Poly. Sci.*, 27, 1617-1659. DOI: 10.1016/S0079-6700(02)00015-1.

Banasiak R., Wajman R., Jaworski T., Fiderek P., Fidos H., Nowakowski J., Sankowski D., 2014. Study on two-phase flow regime visualization and identification using 3D electrical capacitance tomography and fuzzy-logic classification. *Int. J. Multiphas. Flow*, 58, 1-14. DOI: 10.1016/j.ijmultiphaseflow.2013.07.003.

Basu P., 2006. *Combustion and gasification in fluidized bed*. CRC Press.

Burggraeve A., Monteyne T., Vervaet Ch., Remon J.P., De Beer T., 2013. Process analytical tools for monitoring, understanding and control of pharmaceutical fluidized bed granulation: A review. *Eur. J. Pharm. Biopharm.*, 83, 1-15. DOI: 10.1016/j.ejpb.2012.09.008.

Cai R., Zhang Y., Li Q., Meng A., 2013. Tracing the motion of a large object in a fluidized bed using electrical capacitance tomography. *Flow Meas. Instrum.*, 33, 1-9. DOI: 10.1016/j.flowmeasinst.2013.04.009.

Chełkowski A., 2009. *Physics of dielectrics*. PWN (in Polish).

Cui Z., Wang H., Xu Y., Zhang L., Yan Y., 2009. An integrated ECT/ERT dual modality sensor. *International Instrumentation and Measurement Technology Conference*, Singapore, 5-7 May 2009.

Dyakowski T., Jeanmeure L.F.C., Jaworski A.J., 2000. Applications of electrical tomography for gas-solids and liquid-solids flows – A review. *Powder Technol.*, 112, 174-192. DOI: 10.1016/S0032-5910(00)00292-8.

Escudero D., Heindel T., 2011. Bed height and material density effects on fluidized bed hydrodynamics. *Chem. Eng. Sci.*, 66, 3648-3655. DOI: 10.1016/j.ces.2011.04.036.

Filipowicz S.F., 2011. *Modern methods and algorithms of process tomography*. BEL Studio Sp.z o.o. (in Polish).

Gao H., Xu Ch., Fu F., Wang S., 2012. Effects of particle charging on electrical capacitance tomography system. *Measurement*, 45, 375-383. DOI: 10.1016/j.measurement.2011.11.007.

George D.L, Shollenberger K.A., Torczynski J.R., O'Hern T.J., Ceccio S.L., 2001. Three-phase material distribution measurements in a vertical flow using gamma-densitometry tomography and electrical-impedance tomography. *Int. J. Multiphase Flow*, 27, 1903-1930. DOI: 10.1016/S0301-9322(01)00042-8.

Holland D.J., Marashdeh Q., Müller C.R., Wang F., Dennis J.S., Fan L.S., Gladden L.F., 2009. Comparison of ECVT and MR measurements of voidage in a gas-fluidized bed. *Ind. Eng. Chem. Res.*, 48, 172–181. DOI: 10.1021/ie8002073.

Ismail I., Gamio J.C., Bukhari S.F.A., Yang W.Q., 2005. Tomography for multi-phase measurement in the oil industry. *Flow Meas. Instrum.* 16, 145-155. DOI:10.1016/jflowmeasinst.2005.02.017.

Jiang Y., Qiu G., Wang H., 2014. Modelling and experimental investigation of the full-loop gas–solid flow in a circulating fluidized bed with six cyclone separators. *Chem. Eng. Sci.* 109, 85-97. DOI: 10.1016/j.ces.2014.01.029.

Kourunen J., Kayhko R., Matula J., Kayhko J., Vauhkonen M., Heikkinen L., 2008. Imaging of mixing of two miscible liquids using electrical impedance tomography and linear impedance sensor. *Flow Meas. Instrum.*, 19, 391-396. DOI: 10.1016/j.flowmeasinst.2008.07.002.

Li Y., Soleimani M., 2013. Imaging conductive materials with high frequency electrical capacitance tomography. *Measurement*, 46, 3355-3361. DOI: 10.1016/j.measurement.2013.05.020.

Liu S., Yang W.Q., Wang H., Yan G., Pan Z., 2001. Flow pattern identification of fluidized beds using ECT. *J. Therm. Sci.*, 10, 176-181. DOI: 10.1007/s11630-001-0062-1.

Liu Z., He M., Xiong H., 2005. Simulation study of the sensing field in electromagnetic tomography for two-phase flow measurement. *Flow Meas. Instrum.*, 16, 199-204. DOI: 10.1016/j.flowmeasinst,2005.02.008.

Makkawi Y.T., Wright P.C., 2002. Fluidization regimes in a conventional fluidized bed characterized by means of electrical capacitance tomography. *Chem. Eng. Sci.* 57, 2411-2437. DOI: 10.1016/S0009-2509(02)00138-0.

Makkawi Y.T., Wright P.C., 2002. Optimization of experiment span and data acquisition rate for reliable electrical capacitance tomography measurement in fluidization studies – a case study. *Meas. Sci. Technol.* 13, 1831-1841. DOI: 10.1088/0957-0233/13/12/305.

Makkawi Y.T., Wright P.C., 2004. Electrical capacitance tomography for conventional fluidized bed measurements – remarks on the measuring technique. *Powder Technol.* 148, 142-157. DOI: 10.1016/j.powtec.2004.09.006.

Makkawi Y.T., Ocone R., 2007. Integration of ECT measurements with hydrodynamic modelling of conventional gas-solid bubbling bed. *Chem. Eng. Sci.*, 62, 4304-4315. DOI: 10.1016/j.ces.2006.11.048.

Marashdeh Q., Warsito W., Fan L.-S., Teixeira F., 2007. A multimodal tomography system based on ECT sensors. *IEEE Sensors J.*, 7, 426-432. DOI: 10.1109/JSEN.2006.890149.

Peyton A.J., Yu Z.Z., Lyon G., Al-Zeibak S., Ferreira J., Velez J., Linhares F., Borges A.R., Xiong H.L., Saunders N.H., Beck M.S., 1996. Overview of electromagnetic inductance tomography: description of three different systems. *Meas. Sci. Technol.*, 73, 261-271. DOI: 10.1088/0957-0233/7/3/006.

Peyton A.J., Beck M.S., Borges A.R., de Oliveira J.E., Lyon G.M., Yu Z.Z., Brown M.W., Ferrerra J., 1999. Develpment of electromagnetic tomography for industrial applications. Part 1: Sensor design and instrumentation. *1st World Congress on Industrial Process Tomography*, Buxton, 14-17 April 1999.

Porzuczek J., 2012. *Optimization of the fluidized bed boilers operation in nonstationary states*. Monograph, Environmental Engineering Series, Cracow University of Technology, Krakow (in Polish).

Pradeep Ch., Ru Y., Mylvaganam S., 2012. Reverse flow alarm activation using electrical capacitance tomometric (ECTm) correlation. *Sensors Applications Symposium (SAS), 2012 IEEE*. 7-9 February 2012, 1-5. DOI: 10.1109/SAS.2012.6166311.

Pugsley T., Tanfara H., Malcus S., Cui H., Chaouki J., Winters C., 2003. Verification of fluidized bed electrical capacitance tomography measurements with a fibre optic probe. *Chem. Eng. Sci.*, 58, 3923-3934. DOI: 10.1016/S0009-2509(03)00288-4.

Qiu C., Hoyle B.S., Podd F.J.W., 2007. Engineering and application of a dual modality process tomography system. *Flow Meas. Instrum.*, 18, 247-254. DOI: 10.1016/j.flowmeasinst.2007.07.008.

Rautenbach Ch., Melaaen M.C., Halvorsen B.M., 2013. Statistical diagnosis of a gas-solid fluidized bed using Electrical Capacitance Tomography. *Int. J. Multiphase Flow*, 49, 70-77. DOI: 10.1016/j.ijmultiphaseflow.2012.10.002.

Rautenbach Ch., Mudde R.F., Yang X., Melaaen M.C., Halvorsen B.M., 2013. A comparative study between electrical capacitance tomography and time-resolved X-ray tomography. *Flow Meas. Instrum.*, 30, 34-44. DOI: 10.1016/j.flowmeasinstrum.2012.11.005.

Rimpilainen V., Heikinnen L., Vauhkonen M., 2012. Moisture distribution and hydrodynamics of wet granules during fluidized-bed drying with volumetric electrical capacitance tomography. *Chem. Eng. Sci.*, 75, 220-234. DOI: 10.1016/j.ces.2012.03028.

Smart J., Yan Y., Riley G., 2010. Characterisation of an oxy-coal flame through digital imaging. *Combust. Flame*, 157, 1132-1139. DOI: 10.1016/j.combustflame.2009.10.017.

Soleimani M., Lionheart W.R.B., Dorn O., 2006. Level set reconstruction of conductivity and permittivity from boundary electrical measurements using experimental data. *Inverse Probl. Sci. En.*, 14, 193-210. DOI: 10.1080/17415970500264152.

Stanley S.J., 2006. Tomographic imaging during reactive precipitation in a stirred vessel: Mixing with chemical reaction. *Chem. Eng. Sci.*, 61, 7850-7863. DOI: 10.1016/j.ces.2006.09.029.

Tapp H.S., Peyton A.J., Kemsley E.K., Wilson R.H., 2003. Chemical engineering applications of electrical process tomography. *Sensor. Actuator. B-Chem.*, 92, 17-24. DOI: 10.1016/S0925-4005(03)00126-6.

Thorp J.S., Bushell T.G., Evans D., Rad N.E., 1987. The temperature and frequency dependencies of permittivity and dielectric loss in reaction bonded silicon nitride. *J. Mater. Sci.*, 22, 2641-2644. DOI: 10.1007/BF01082157.

Wang F., Marashdeh Q., Fan L.-S., Warsito W., 2010. Electrical capacitance volume tomography: Design and applications. *Sensors*, 10, 1890-1917. DOI: 10.3390/s100301890.

Wang F., Yu Z., Marashdeh Q., Fan L.-S., 2010. Horizontal gas and gas/solid jet penetration in gas-solid fluidized bed. *Chem. Eng. Sci.*, 65, 3394-3408. DOI: 10.1016/j.ces.2010.02.036.

Wang H.G., Senior P.R., Mann R., Yang W.Q., 2009. Online measurement and control of solids moisture in fluidised bed dryers. *Chem. Eng. Sci.*, 64, 2893-2902. DOI: 10.1016/j.ces.2009.03.014.

Wang S.J., Dyakowski T., Xie C.G.,Williams R.A., Beck M.S., 1995. Real time capacitance imaging of bubble formation at the distributor of a fluidized bed. *Chem. Eng. J.,* 56, 95-100. DOI: 10.1016/0923-0467(94)02916-4.

Wang M., Ramskill N.P., Barns S., Raynel G., Qiu Ch., Rayner Ch., 2013. A feasible process tomography and spectroscopy measurement system to determine carbon dioxide absorption. *Flow Meas. Instrum.* 31, 77-85. DOI 10.1016/ j.flowmeasinst.2012.09.005.

Wang Z., Chen Q., Qang X., Li Z., Han Z., 2012. Dynamic visualization approach of the multiphase flow using electrical capacitance tomography. *Chinese J. Chem. Eng.*, 20, 380-388. DOI: 10.1016/S1004-9541(12)60401-7.

Warsito W., Fan L.-S., 2001. Measurement of real-time flow structures in gas-liquid and gas-liquid-solid flow systems using electrical capacitance tomography (ECT). *Chem. Eng. Sci.* 56, 6455-6462. DOI: 10.1016/S0009-2509(01)00234-2.

Warsito W., Fan L.-S., 2005. Dynamics of spiral bubble plume motion in the entrance region of bubble columns and three-phase fluidized beds using 3D ECT. *Chem. Eng. Sci.* 60, 6073-6084. DOI: 10.1016/j.ces.2005.01.033.

Weber J.M., Mei J.S., 2013. Bubbling fluidized bed characterization using Electrical Capacitance Volume Tomography (ECVT). *Powder Technol.* 242, 40-50. DOI: 10.1016/j.powtec.2013.01.044.

Werther J., 1999. Measurement techniques in fluidized bed. *Powder Technol.*, 102, 15-36. DOI: 10.1016/S0032-5910(98)00202-2.

Wiesendorf V., Werther J., 2000. Capacitance probes for solid concentration and velocity measurements in industrial fluidized bed reactors. *Powder Technol.*, 110, 143-157. DOI: 10.1016/S0032-5910(99)00276-4.

Xie C.G., Reinecke N., Beck M.S., Mewes D., Williams R.A., 1995. Electrical tomography techniques for process engineering applications. *Chem. Eng. J.*, 56, 127-133. DOI: 10.1016/0923-0467(94)02907-5.

Yang Ch., Cui Z., Xue Q., Wang H., Zhang D., Geng Y., 2014. Application of a high speed ECT system to online monitoring of pneumatic conveying process. *Measurement*, 48, 29-42. DOI: 10.1016/j.measurement.2013.10.024.

Yang G.Q., Du B., Fan L.-S., 2007. Bubble formation and dynamics in gas-liquid-solid fluidization – A review. *Chem. Eng. Sci.*, 62, 2-27. DOI: 10.1016/j.ces.2006.08.021.

Yang W., 2007. Tomographic imaging based on capacitance measurement and industrial applications. *I. W. Imag. Syst. Techni. IST 2007*., 1-6. DOI: 10.1109/IST.2007.379587.

Yang Y., Yang W., Zhong H., 2008. Temperature distribution measurement and control of extrusion process by tomography. *I. W. Imag. Syst. Techni. IST 2008*, 170-174. DOI: 10.1109/IST.2008.4659963.

Yan Y., Qiu T., Lu G., Hossain M.M., Gilabert G., Liu S., 2012. Recent advances in flame tomography. *Chin. J. Chem. Eng.*, 20, 389-399. DOI: 10.1016/S1004-9541(12)60402-9.

Yan H., Shao F., Wang S., 1999. Simulation study of capacitance tomography sensors. *1st World Congress on Industrial Process Tomography*. Buxton, 14-17 April 1999.

Zhao T., Takei M., Doh D., 2010. ECT measurement and CFD-DEM simulation of particle distribution in a down-flow fluidized bed. *Flow Meas. Instrum.*, 21, 212-218. DOI: 10.1016/j.flowmeasinst.2009.12.008.

Żukowski W., Baron J., Bulewicz M.B., Kowarska B., 2009. An optical method of measuring the temperature in a fluidised bed combustor. *Combust. Flame*, 156, 1445-1452. DOI: 10.1016/j.combustflame.2009.03.004.

Żukowski W., Baron J., Kowarska B., Olek M., Zabagło J., 2011. Thermal regeneration of bleaching earth in a fluidized bed reactor. *Przemysł Chemiczny*, 90, 1107-1112 (in Polish).

Received 01 August 2012
Received in revised form 14 April 2014
Accepted 17 June 2014