DOI: 10.5604/20830157.1201311

SWIRL FLOW ANALYSIS BASED ON ELECTRICAL CAPACITANCE TOMOGRAPHY

Ayoub Saoud, Volodymyr Mosorov, Krzysztof Grudzien
Lodz University of Technology, Institute of Applied Computer Science

Abstract. *This paper describes an application of dual-plane Electrical Capacitance Tomography (ECT) system for gas-solid swirl flow measuremetns. The angular component of the velocity in the pipes cross section was calculated. The angular velocity was determined based on tomographic data sets obtained from the physical model and also simulated data sets of the swirl flow phenomena. Analysis of material concentration changes in time, with the aid of sequences of 2D reconstruction images, allowed to swirling flow, angular velocity vectors to be successfully evaluated.*

Keywords: electrical capacitance tomography, swirl flow, flow velocity

ANALIZA PRZYPŁYWU WIROWEGO Z ZASTOSOWANIEM ELEKTRYCZNEJ TOMOGRAFII POJEMNOŚCIOWEJ

Streszczenie. *W artykule opisano zastosowanie dwupłaszczyznowego systemu elektrycznej tomografii pojemnościowej (ECT) do pomiaru przepływów wirowych materiałów sypkich. W artykule zaprezentowano metodę wyznaczania składowej kątowej prędkości przepływu. Algorytm opiera się na analizie obrazów tomograficznych. Analiza zmian koncentracji materiału sypkiego w czasie, otrzymana przy pomocy sekwencji 2D obrazów tomograficznych, pozwoliła na ocenę przepływu wirowego poprzez wyznaczenie wektora prędkości kątowej przepływu. Weryfikację metody przeprowadzono na podstawie danych uzyskanych za pomocą przygotowanego modelu fizycznego i zbioru danych pomiarowych symulowanego przepływu wirowego.*

Słowa kluczowe: elektryczna tomografia pojemnościowa, przepływ wirowy, prędkość przepływu

Introduction

Flow measurement is essential in all industrial applications. The high accuracy of the flow metring is extremely important in order to precisely control and drug formation processes [3, 9, 13]. In the other hand, errors in metring can cause a huge cost losses and inefficiency repercussions. Accurate of flow measurements and control mainly depends on the correct determination of flow velocity. The main problem in flow velocity measurement rises when the flow behaviour significantly deviating from the laminar profile.

Properly designed control system should apply flow measurements technique, providing information about parameters of the process with high precision and independent on flow regime. The swirl flow requires the analyse of these two velocity components to determine swirl angle and explain the mechanism of the swirl phenomena [9, 17]. In order to measure the swirl flow with high accuracy is necessary to take into account the dynamic changes of the flow patterns in both temporal and spatial coordinates. Significant of the swirl flow measurement confirm very broad industrial types of the flow phenomena, where the knowledge about the axial and angular velocity components increase the efficiency of the control system: gas-solid [7], gas-oil [17], combustion chambers [14], cylindrical separators [5] and mixing by agitation [10] are frequently encountered swirl flow phenomena in many industrial applications. Usually, the swirl effects are extensively seen as either the desire result of design or unavoidable possibility unforeseen and side effects of the flow material propagation inside pipes, vessels.

Flow characterisation and metering include phase distribution and velocity components are required in order to fully describe the process. Any measurement technique applied to the flow expected to measure the parameters with the same fidelity of the cross-sectional distribution of the flow profile. Therefore, Electrical Tomography (ET) is a typical non-instructive technique for measuring the flow inside pipes, vessels. Electrical Capacitance tomography (ECT) technique has been widely used for flow measuring, visualisation and investigation [1, 4], and ECT became an area in which is of a practical value in the determination of the dielectric properties (permittivity) and further generate a cross-sectional view.

Developing of the velocity measurements methods is conducted for many years. Each progress provides better quality information about the process. Currently, a lot of works can be found in the literature concerning the velocity measurement [4, 6, 12]. However, the problem of the velocity measurements in a case of the swirl flow is still open. Therefore, the authors propose a method for calculating the velocity components based on a modified cross-correlation technique. Contrary to known methods for instance [17], which use the “best pixel correlation” technique, it utilises the time-spatial cross-correlation technique on tomographic images from an ECT system, taking into account the spatial and the temporal relationship in data. The angular component was determined to the tomographic data sets obtained from the using of the physical model (Fig. 3) in simulating the swirl flow phenomena. Analysis of the material changes within the reconstructed tomographic images, allowed the angular velocity to be successfully evaluated.

1. Electrical Capacitance tomography – measurement principles

The Electrical Capacitance Tomography is a non-invasive visualization technique based on sensing the differences in the dielectric properties (electric permittivity) of two phases appearing in flowing medium (e.g. gas and solid). ECT allows to visualize in the form of an image a material distribution inside sensor [5, 9, 13, 15]. For solid-gas flow, e.g. during pneumatic conveying, the gas and the solid phase characterize different permittivity value, the reconstructed image provides information about solid concentration distribution inside sensor space. A typical 2D ECT sensor consists of a number of electrodes located around of pipe. On Fig. 1 is presented a schematic of a one plane 2D ECT sensor [15]. A single image of the spatial distribution of a mixture volume of two materials is reconstructed based on a single set of capacitance measurements – between each pair of electrodes, taken at one time point. These measurements constitute the so-called measurement frame. All the inter-electrode capacitances are measured by application of high accuracy (typically 0.1fF) and high-speed (typically 200 frames per second for 8-elecotrdes sensor) acquisition units. The methods of electrical capacitance measurement are depended on the techniques applied in acquisition unit.

The main advantages of ECT systems are non-invasive measurements; there is no direct contact between the object under inspection and the sensors and there is no change in the characteristics of the explored object, and enough high speed of acquisition system to control dynamic industrial process in real-time. These two aspects are very often taken into account during developing new algorithms for monitoring and controlling units of industrial processes [3, 11, 13].

For the objective of the swirl phenomena analysis considered in this paper, sequences of reconstructed images were used as input data. Reconstruction procedure in this work was based on iterative back projections algorithm [16]. Authors are aware, that it is not the best algorithm for reconstruction in terms of image quality, however the time of reconstruction is enough short for the real-time controlling system. More details about laboratory set-up are given later.

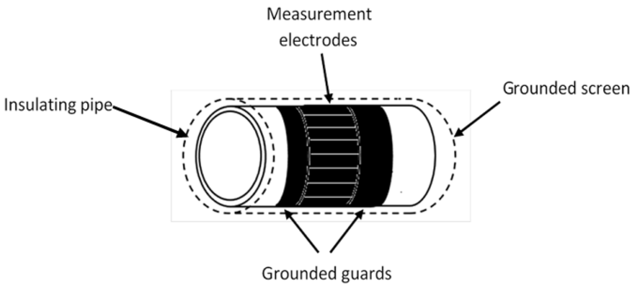

Fig. 1. Structure of a typical ECT sensor

2. Flow swirl characterisation

Swirl flow in a pipe can be introduced as a combination of the vortex and axial motions [16], with helical streamlines (Fig. 2). In industry application in order to generate the swirl phenomena, the flow should be passed through two consecutive out of plane bends [13, 16]. Swirl generators (Swirlers) are mainly used to intensify the mixing or to enhance the convective heat transfer between the fluid and the pipe wall. The swirl flow phenomena can also occur in industry installations without additional swirl ones. Regarding the specific application considered in this paper the gas-solid flow in a cyclone separator can be a direct recipient of the proposed method for velocity analysis as the extremely need for control and visualisation [2, 8].

The velocity of the flow usually provides significant knowledge about the flow state for controlling and monitoring the flow process. However, the velocity calculation can be very challenging, especially when the velocity profile for the radial and axial component is dramatically changing. Spatial-temporal changes of the flow characteristics are dependent on the conditions such as flowing material properties, flow rate and the geometry of the pipe. Therefore, the flow regime should be taken in consideration in order to obtain high accurately of flow measurement system. The determination of the current flow regimes in pipes is not a trivial task. The independent method for flow pattern permitting the flow velocity to be calculated with high robustness is not invented yet. It is a well-known problem of calculating the velocity values when the flows are not laminar, such as swirl flow and turbulent flow.

One of the methods used in the flow velocity calculation is the correlation technique. This technique used to determine the delay time of the measurement signals between the located sensors [11, 13]. This delay is used basically to determine the flow velocity. A measurement system such as ECT system can provide rich information about the spatial-temporal changes of the flow should be considered in the detailed analysis of the flow process character. The sequences of images attained from the planes of sensors give the possibility of obtaining the velocity profile, as-well as the velocity components of the swirl flow.

The phase fraction distribution and the velocity components may provide a clear imaging of the evolution of the flow. The calculation of the velocity components in case of the swirl flow is a very important task, hence the methods for axial, and the radial component calculation has been developed [4, 14, 15]. In this study, a spatial cross-correlation method enables the focus on the angular component of the velocity to be successfully calculated.

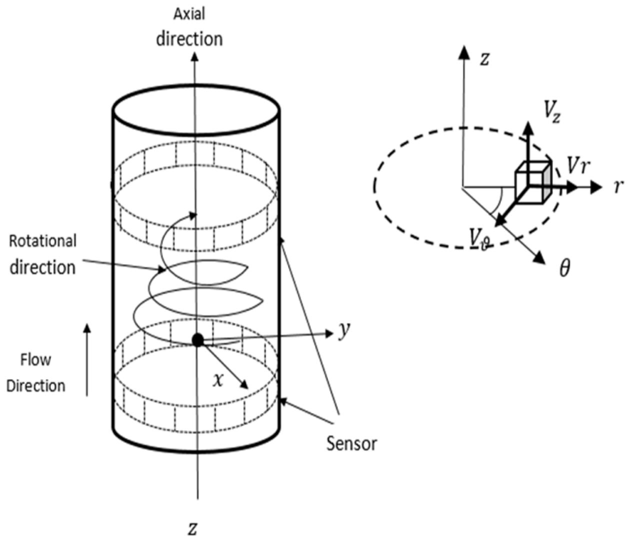

Fig. 2. Twin-plane ECT system for flow characterisation

In case, of the swirl flow, the material changes along the axial direction of the pipe from plane X to plane Y can be considered as a rotational process (Fig. 3). Let $X_{[n,m]}(iT)$, $Y_{[n,m]}(iT)$ $[n,m]$ is the pixel coordinate, two separated series of images from planes X, Y respectively, with frame rate resolution T. The hypotheses can be introduced by proposing that the image from the first plane is high correlated with some rotated image from the second plane. Therefore, the spatial cross-correlation technique can be applied by calculating the spatial-time correlation between an image from plane X and a rotated image from plane Y for all possible angles. The high correlated pair of images determines the spatial difference in angle between the two images.

A straightforward application of the spatial cross-correlation function for a chosen time iT can be as follows (eq. 1):

$$\mathrm{R}_{\mathrm{X}_{[n,m]}\mathrm{Y}_{[n,m]}}(\theta,\mathrm{kT}) = \sum_{n=0}^{N-1}\sum_{m=0}^{N-1}\mathrm{X}_{[n,m]}(\mathrm{iT})\,\mathrm{Y}_{[n,m],\theta}((\mathrm{i}-\mathrm{k})\mathrm{T}), \tag{1}$$

where θ is the angle of rotation ($\theta = 0,1,\ldots,359°$) applied on the image $Y_{[n,m]}(iT)$, τ is the delay time of the material propagation between the planes and is calculated directly as $\tau = k \cdot T$, $k = 1,2,\ldots,K$. The angular velocity V_θ is given by (eq. 2):

$$\mathrm{V}_\theta = \frac{\Delta\theta}{\tau} \tag{2}$$

The angular displacement $\Delta\theta$ can be calculated as the difference in angle between images from plane Y for different time instants (kT) when $K = 1,2,\ldots K$.

3. Laboratory set-up

In order to simulate the swirl flow phenomena within the sensing volume, a physical model was created and is consisted of a cylindrical object (cylinder) made from Plexiglas (permittivity 3.2) with diameter of 142 mm and length of 500 mm, a wrap long elastic plastic tube (sheaths) with diameter of 20 mm and length of 1000 mm, rolled on hollow roll of paper, the rolled procedure made 4 loops on the hollow roll, the distance between two loops is 210 mm (see Fig. 3c).

The ECT system used in the study has specifically designed sensors. The ECT sensor used comprises a cylindrical profile made from a PMMA material (Polymethyl Methacrylate), which has a relative dielectric permittivity of 0.85, outer diameter / inner profile sensor 150/142 mm, and the wall thickness is 4 mm. The ECT sensor consists of 32 measuring electrodes, organized in 4 layers by 8 electrodes (Fig. 3b). The electrodes made of copper with a thickness of 0.2 mm, width of 50 mm for each, a height of 70 mm for 1 and 4 layers, 30 mm for the 2 and 3 layers. The electrodes were mounted on the outer wall. During the investigation only the plane 1 and 4 were used.

The external screen is made of copper sheet with thickness of 0.5 mm connected to the grounding measurement system; insulation of the external screen is made of polyurethane foam dielectric with permittivity of 1.6, and two internal screens boundary made of copper tape with thickness of 0.2 mm, and height of 25 mm each (Fig. 3a).

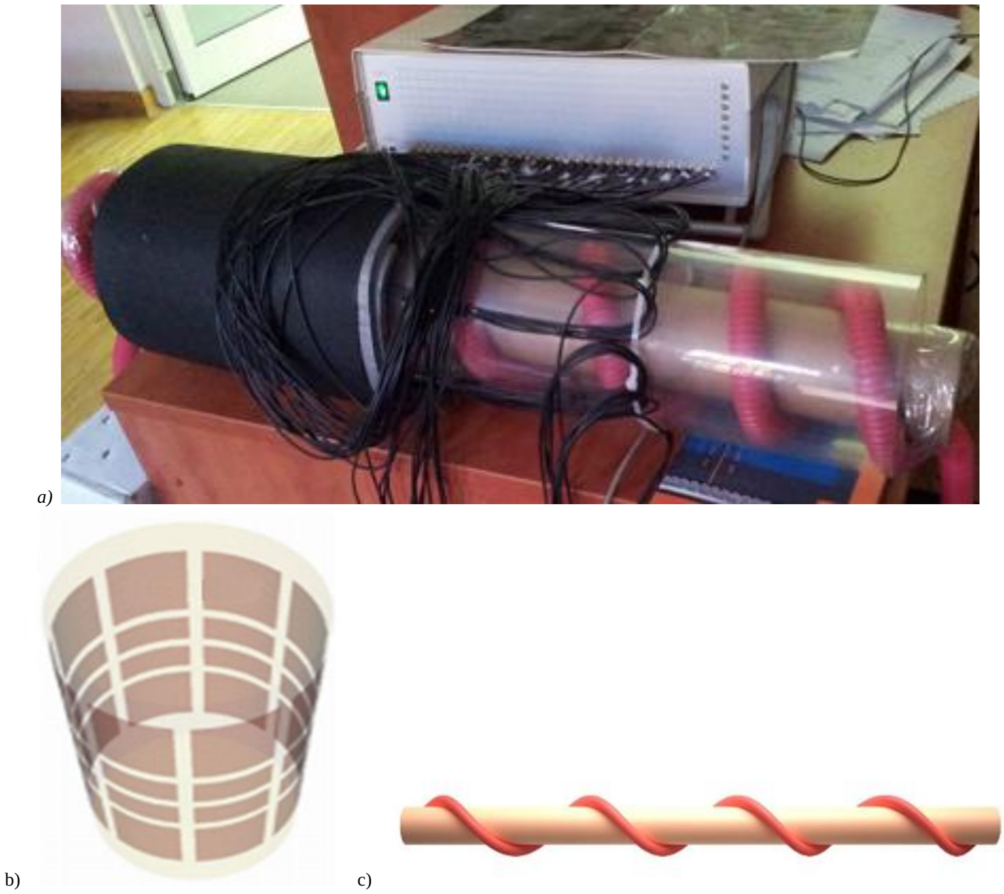

Fig. 3. ECT measurement unit and the physical model used in the experiment, a) measurement unit, b) scheme of ECT sensors, c) physical model

4. Experimental procedure

The first step was the calibration of ECT system, to obtain the best gain for measurement channels based on measurement range between empty and full sensor space. A series of tests of our physical model were performed to simulate the swirl flow ECT unit measurement, each of the two separate measurement planes where operated as a flow visualisation module. During the measurement, the phantom (long elastic plastic tube wrapped on a roll of paper) was shifted to the sensors space (Fig. 3). The data was collected with enough acquisition speed (11 frames/sec). An iterative back-projection algorithm was used for the 2D image reconstruction [1]. For each plane was prepared 500 images (32 × 32 pixels), represent the material changes and concentrations. Figure 4 shows the ECT normalised tomograms for chosen time moments. The reconstructed images demonstrate the rotation of the material inside the sensor space as it takes a place in the case of the swirl flow.

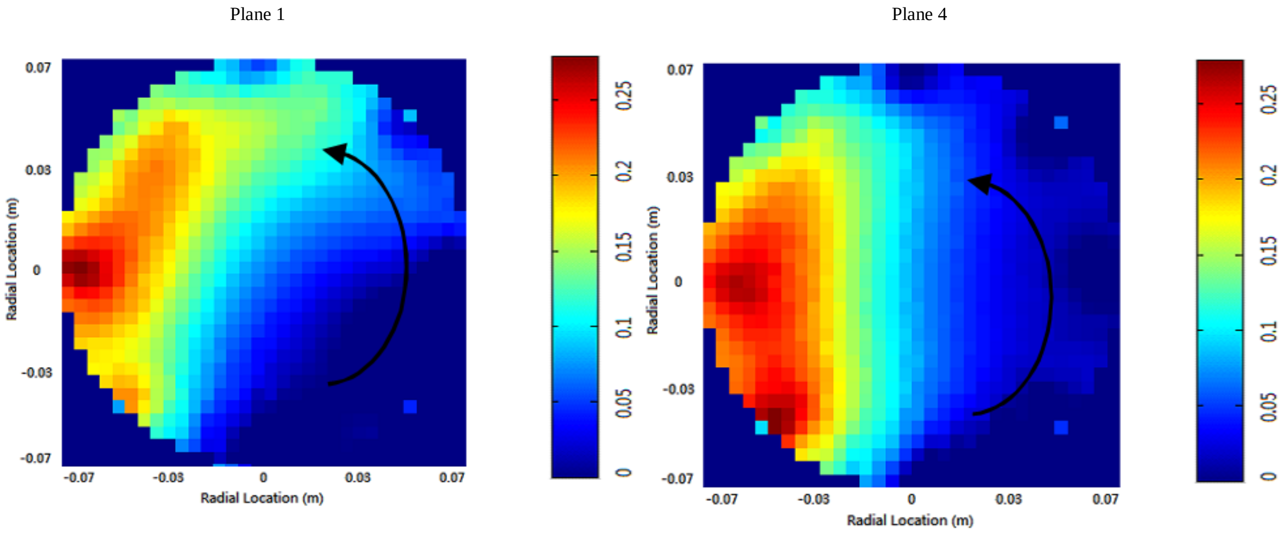

Fig. 4. ECT normalised concentration tomograms for a chosen time instant (frame 148). The colour bar represents the solid concentration against the air

5. Results and discussions

In Figure 4, the cross-sectional phase fractions provide valuable information about the gas-solid distribution. Figure 5 shows, an example of calculating the spatial difference of the flow structure using the spatial cross-correlation technique. The angular component of the velocity was calculated based on the spatial cross-correlation function. Figure 5 shows an example of calculating the spatial correlation between frame #125 from plane 4 and two frames #125, #126 from plane 1, respectively. The correlation function allows to determine the angular displacement equal to 20°. Figure 6 presents the angular component of the velocity during the flow propagation in the pipeline. The characteristics were estimated based on tomography data sets coming from two planes (plane 4 and 1) show that the variation of the angular velocity component is between 0 and 7.5 rad/s for one time period (*T*) and between 0 and 5.5 rad/s for two times period (2*T*), we can notice the similarity between the two variations. However, there are some unlikely peaks due to the push procedure of our phantom into the sensors space.

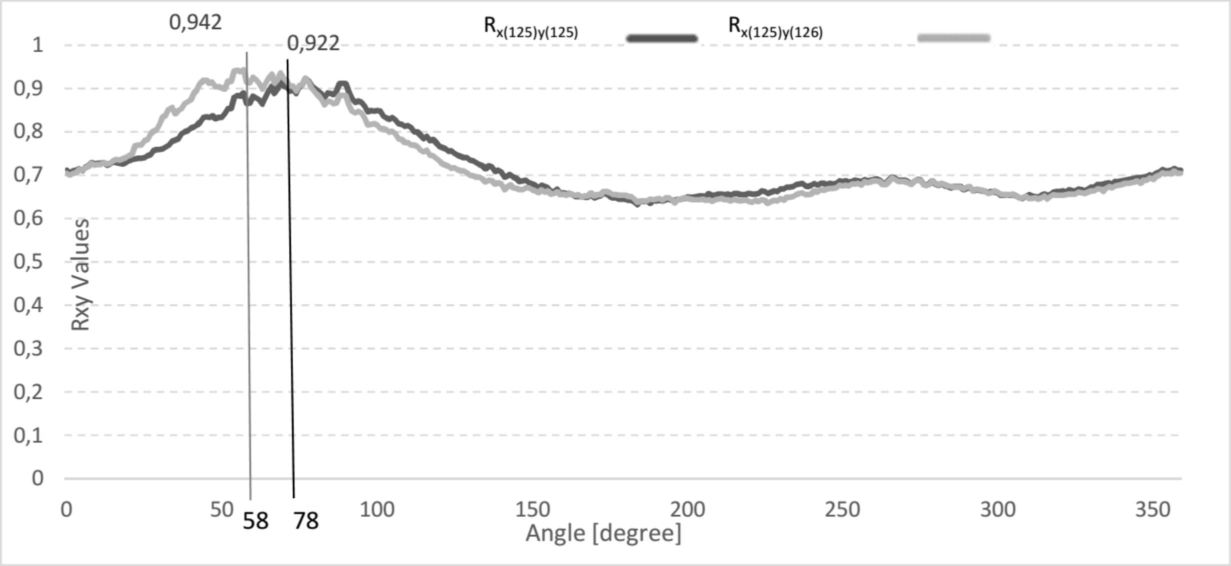

Fig. 5. Example of the spatial difference of flow structures using the spatial cross-correlation technique for image X (#125) plane 4 and two images Y (#125), Y(#125,#126) plane 1

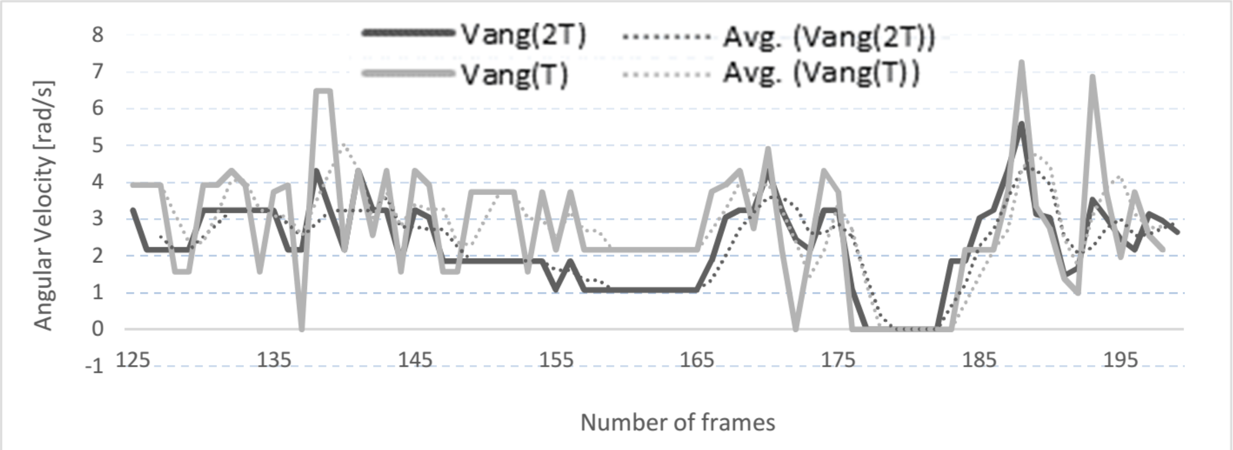

Fig. 6. Angular component of the velocity for one time period T and 2T

6. Conclusion

This study is an application of a twin-plane Electrical capacitance tomography system for swirl flow characterisation. A physical model was created and successfully simulated the swirl flow phenomena. This allows verifying the proposed approach for test cases as well as conducting comparison between obtained results with the aid of proposed methods of swirl flow velocity estimation versus known values of velocity of modelled swirl flow components. The Velocity component (angular) of the swirl flow was successfully calculated based on the spatial cross-correlation technique. Results provide a good consistency with the known flow parameters and show that the angular velocity is almost constant in the experience. The results demonstrate also the potential capability of the electrical capacitance tomography for measurement flow distribution in a pipeline.

Acknowledgement

Work funded by the European Commission under the Erasmus Mundus GreenIT project (GreenIT for the benefit of civil society. 3772227-1-2012-ES-ERA MUNDUS-EMA21; Grant Agreement nº 2012-2625/001-001-EMA2).

Bibliography

[1] Giguerre R., Fradette L., Mignon D., Tanguy P.A.: Analysis of slurry flow regimes downstream of a pipe bend. Chemical engeneering Research & Design, 87(7A)/2009, 943–950.

[2] Gutmark E.J., Li G., Grinstein F.F.: Characterization of Multiswirling Flow, in: Engineering Turbulence Modelling and Experiments 5, (eds. W. Rodi, N. Fueyo), 873–884.

[3] Hammer E.A., Johansen G.A., Dyakowski T., Roberts E.P.L., Cullivans J.C., Williams R.A., Hassan Y.A., Claiborn C.S.: Advanced experimental techniques, in: Multiphase Flow Handbook, CRC/Taylor and Francis, Boca Raton 2006.

[4] Hristov H., Mann R., Lossev L., Vlaev S.D., Seichter P.: A 3-D Analysis of Gas-Liquid Mixing, Mass Transfer and Bioreaction. Food and Bioproducts Processing.79 (4)/2001, 232–241.

[5] Huang Z., Wang B., Li H.: Application of capacitance tomography to the void fraction measurement of two phase flow. IEEE transaction on Instrumentation and measurement, 52(1)/2003, 7–12.

[6] Jawarneh A.M., Tlihan H., Al-Ahyyab A., Ababneh A.: Strongly flows in a cylindrical separator. Mineral Engineering, 2008, 366–372.

[7] Li H., Tomita Y.: Characterization of pressure fluctuation in swirling flow gas-solid two-phase flow in horizontal pipe. Advanced Powder Technology, 12 (2)/2001, 169–185.

[8] Liu S., Chen Q., Wang H.G., Jiang F., Ismail I., Yang W.Q.: Electrical capacitance tomography for gas–solids flow measurement for circulating fluidized beds, Flow Measurement and Instrumentation, 16(2-3)/2005, 135–144.

[9] McCann H., Scott D.M.: Process Imaging For Automatic Control, Boca Raton, FL: CRC Press, 2005.

[10] Mosorov V., Sankowski D., Mazurkiewicz L., Dyakowski T.: The "best-correlated pixels" method for solid mass flow measurements using electrical capacitance tomography. Measurement Science and Technology, 13/2002, 1810–1814.

[11] Mosorow V.: A method of transit time measurement using twin-plane electrical tomography, Measurement Science and Technology, 17(4)/2006.

[12] Orbay R.C.: Swirling turbulent flows in a combustion chamber with and without heat release. 10th Japan/China Symposium on Coal and C1 Chemistry, 104/2013, 133–146.

[13] Plaskowski A., Beck M.S., Thorn R., Dyakowski T.: Imaging Industrial Flows – Applications of Electrical Process Tomography, IOP Publishing, Bristol., 1995.

[14] Rammohan A.B.: Flow swirl and flow profile measurement in multiphase flow, 31st International North Sea Flow 2013.

[15] Yang W.Q., Liu S.: Role of tomography in gas/solids flow measurement, Flow Measurement and Instrumentation, 11/2000, 237–244.

[16] Yang W.Q., Peng L.H.: Image reconstruction algorithms for electrical capacitance tomography, Measurement Science and Technology, 14(1)/2003.

[17] Yi L., Wuqiang Y., Xie C. et al.: Gas/oil/water flow measurement by electrical capacitance tomography. Measurement science and technology, 24/2013.

M.Sc. Eng Ayoub Saoud
e-mail asaoud@kis.p.lodz.pl

Graduated from the Faculty of Science and Technology, University Bachir Ibrahimi BBA, Algeria.
Ph.D. student in Electrical Engeneering, University of Bejaia, Algeria.
Ph.D. student in the Technical University of Lodz, Institute of Applied Computer Science, Poland.

D.Sc. Eng. Volodymyr Mosorov
e-mail: volodymyr.mosorov@p.lodz.pl

Volodymyr Mosorov received his Ph.D. in 1998 from the State University of Lviv, Ukraine. V. Mosorov was awarded the title of Doctor of Science from AGH University of Science and Technology Krakow Poland in 2009. He is now an associate professor at the Institute of Applied Computer Science of Lodz University of Technology, Poland. His research interests include process tomography systems and its industrial applications. He has been involved in these areas for more than 15 years. Member of the International Society for Industrial Process Tomography. He has published more than 80 technical articles.

Ph.D. Eng. Krzysztof Grudzień
e-mail: kgrudzi@iis.p.lodz.pl

Assistant Professor of Applied Computer Science at Lodz University of Technology. Member of Polish Information Processing Society and ACM Lodz Chapter. He obtained Ph.D. in 2007 in the field of Computer Science, Process Tomography specialty. His research interests include applications of non-invasive imaging techniques and identification of dynamic industrial processes parameters, development of algorithms for image processing and analysis with particular reference to the analysis of sequences of 2D tomography images gathered from the ECT and X-rays tomography systems.

otrzymano/received: 17.02.2016 *przyjęto do druku/accepted: 31.03.2016*