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METHODS FOR MONITORING GRAVITATIONAL FLOW IN SILOS USING TOMOGRAPHY IMAGE PROCESSING

Krzysztof Grudzień, Dominik Sankowski
Lodz University of Technology, Institute of Applied Computer Science

Abstract. *The article presents the methods of monitoring of the process of gravitational silo discharging with aid of tomography techniques. The described methods apply to funnel and mass flow measurement. The core unit of the presented monitoring system is an image-processing module, while the images are obtained with aid of the electrical capacitance tomography. For the funnel type of flow, the outputs of image processing are parameters describing the process flow, location and material concentration in funnel area. In the case of the mass flow regime the presented method provides information about the parameters of shear zones arising by the wall region of the silo that influence the interaction between the bulk and silo construction during silo discharging.*

Keywords: *electrical capacitance tomography, tomography image processing, gravitational flow, granular material*

METODY MONITOROWANIA PRZEPŁYWU GRAWITACYJNEGO W SILOSACH Z ZASTOSOWANIEM PRZETWARZANIA OBRAZÓW TOMOGRAFICZNYCH

Streszczenie. *Artykuł przedstawia metody monitorowania procesu grawitacyjnego opróżniania silosu z materiałów sypkich z zastosowaniem technik tomograficznych. Opisane metody dotyczą pomiaru przepływu kominowego oraz masowego. Głównym elementem systemu monitorowania jest moduł przetwarzania obrazów uzyskanych przy pomocy elektrycznej tomografii pojemnościowej. Wynikiem przetwarzania obrazów są parametry procesu, opisujące lokalizację komina przepływu i koncentracji materiału w jego obszarze dla przepływu kominowego. W przypadku przepływu masowego przedstawiona metoda dostarcza informacji o obszarze strefy ścinania, występującej w obszarze przyściennym silosu, mającą wpływ na wynik interakcji materiału sypkiego i konstrukcji silosu podczas jego rozładunku.*

Słowa kluczowe: elektryczna tomografia pojemnościowa, przetwarzanie obrazów tomograficznych, przepływ grawitacyjny, materiał sypki

Introduction

The range of process tomography applications is very wide. Depending on the objectives of particular application different aspect of applied technique can be considered [7, 20, 24]. In order to choose the best option it is necessary to analyse needs of the speed of measurement acquisition system, image resolution, robustness and cost of the tomography system. Of course these aspects are connected with the process, which have to be measured. The level of dynamic changes of process states and the physic-chemical properties of process components (e.g. conductive or non-conductive materials) should be analysed [19, 21]. Besides these aspects it should be decided what is main function of applied measurement system: investigation works or real-time control. The use of tomography system in laboratory environment allows to be more flexible and easier to apply than in industrial application. However both fields of exploration can be used for other purposes. In order to elaborate better methods for flow monitoring of process, the process has to be investigated and physicochemical phenomena taking place during running process understanding. Such gained knowledge is necessary to prepare effective process control module with implemented algorithm of measurement data processing.

This paper demonstrates application of two different tomography modalities for gravitational flow optimization process from different point of view. The used electrical capacitance tomography systems allow monitoring the state of silo flow in real time. While the X-ray tomography system allows to investigate granular particle distribution in 2D radiography as well as 3D tomography in much higher resolution then in case of ECT, however in much smaller scale. Time resolution in the case of X-ray system is not so important as for the real-time monitoring system.

1. Gravitational flow in silo

Gravitational (gravity) flow is one of types of transport mechanism. Such type of flow is often used in installations of granular material transport system [2, 3, 19, 21]. In industrial installations, depending on purpose of installation, size and shape of silos can be different as well as the material of construction. These elements have significant influence on particle behaviour during flow. Additional factors having impact on the flow consist in the determination of the time variant factors (humidity, temperature conditions, etc.). Usually it is not easy to forecast such dependences during design stage of the container. Some of the characteristic features of the bulk solids flow are dynamic volume changes during processes of receptacle unloading [2, 3, 4, 14, 19]. These changes depend on many factors, such as initial density of the granular material, stress level, mean grain diameter, specimen size and direction of the deformation rate. These parameters can perturb silo flow. On Figure 1 is presented typical material distribution in silo. Depending on the material properties and silo geometry different flow types can occur.

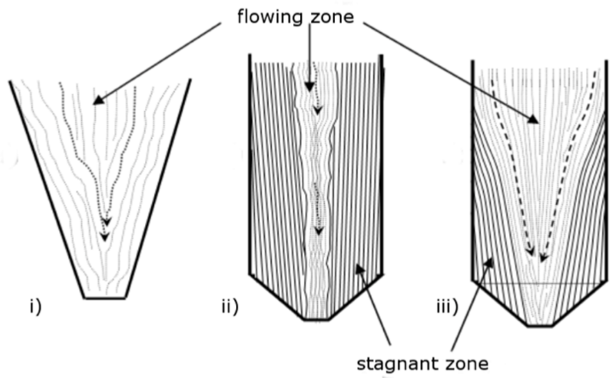

Fig. 1. Principal discharge hopper powder flow, (a) flow regime (mass flow (i), funnel flow (ii), semi-mass flow (iii))

In the case of mass flow material is moving almost at the same velocity in each part of silo [19, 21]. For this type of flow very important phenomena are taking place on boundary the material and silo wall and are manifested in form of dynamic effects. From the diagnosis point of view especially the sand behaviour along the silo wall (at various heights above the outlet) is very important due to these dynamic effects, which can lead to vibrations, serious malfunction or even to construction devastation.

During funnel flow two main regions are observed, e.g. the so-called stagnant zone (located by the walls of container) and funnel flow (usually present in the centre), [19, 21]. Material is flowing only in funnel area, while in the stagnant area is expected to maintain its packing density fraction. The material in the dynamic region is less densely packed due to the flow forced by discharging process.

The visualisation of material concentration changes and tracking of the process state is very interesting from monitoring and control point of view, when the visualisation and data processing after generate control signal in real-time. Accurate description of the bulk solid concentration (not only during the silo filling, but also during emptying) demands measurement methods of a non-invasive character with possibility of visualization of opaque container. Electrical capacitance tomography (ECT) meets this requirement and allows to monitor and diagnose process of the silo discharging by the observation of the concentration changes of the bulk solid inside the silo cross section in real time [20, 7, 8, 24]. Xray tomography system provides much better quality images, however they are more time consuming to obtain and cost of such system is much higher [10].

2. Electrical Capacitance Tomography

The common approach to tomographic measurement data analysis is their processing in order to obtain reconstructed image of the distribution of required property in the examined cross section area. In the electrical capacitance tomography (ECT) case it will be the dielectric permittivity distribution ε, which is obtained from a vector of independent measurements of capacitances $\boldsymbol{C}$ (Fig. 1). The reconstructed image is typically presented in form of matrix consisted from 32x32 pixels. Each pixel represents relative permittivity value as normalized value, value 1 corresponding to full sensor space for initial particle packing state (particle and air voids mixture) and 0 corresponding to empty sensor (air only). Thus permittivity distribution ε could be directly related to solid material concentration in sensor space. The procedure of constructing the tomographic image is called image reconstruction, which results in inverse problem solution [11, 25]. The image on Figure 2 shows an example of the reconstructed material concentration distribution inside sensor space based on vector of normalized measurement capacitances $\boldsymbol{C}$ taken from 8-electrodes capacitance sensor ($\boldsymbol{C}=[C_{1\text{-}2}, C_{1\text{-}3}, \ldots, C_{7\text{-}8}]_{1x28}$). The main difficulty in image reconstruction for ECT comes from non-linear relationship between the capacitance and permittivity distribution and under-determined nature of the inverse problem [5, 17, 23].

The obtained reconstructed image or image sequence can be further processed and analysed in order to acquire important information about the industrial process. There are applied and widely developed image information analysis and processing methods for image defined in such way [12, 20]. The extraction of industrial process characteristic parameters gives possibility of predicting unwanted incidents and feasibility of the in-depth exploration of dynamic spatial and temporal phenomena occurring during industrial process. Moreover, information derived from tomograms can be used as a signal for monitoring or control of the given process [3, 9].

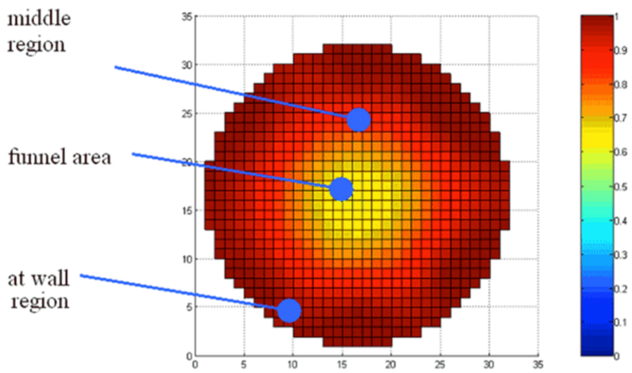

Fig. 2. Tomographic image reconstructed for hopper flow with characteristic funnel flow areas indicated

3. Shear zones analysis during mass flow

The movement of all particles characterizes the mass flow that occurs after opening the silo outlet. One of most important aspects from monitoring point of view are changes in material distribution during silo discharging. The concentration changes in granular materials during silo flow are complex due to appearing localization of the deformation in the form of narrow zones of intense shearing [2, 3, 13, 19, 21]. The shear zones occur along silo walls and also inside of the flowing, initially dense, granular material in the bin section with rough walls and in the hopper part of silo, independently of the wall roughness. The shear zones appearing on the border between silo wall and moving particles, in the case of mass flow, are especially significant from dynamics effect monitoring aspect. These effects are caused by interaction between the silo construction and the flowing granular material. The effects are noticeable as vibrations or pulsations of the silo [13]. On Figure 3 changes of material constriction in time based on sequence of reconstructed images are presented. Reduced concentration, comparing to initial packing density level, records at silo wall and higher in centre of silo is visible. This result was obtained for initially loose packing density and rough silo wall.

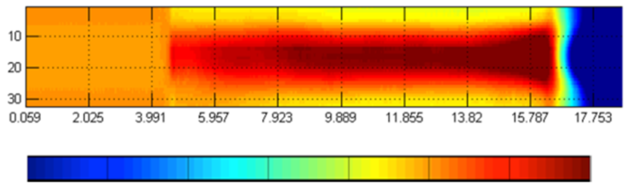

Fig. 3. Visualisation of ECT tomography images in form of topogram [9]

Next figure (Fig. 4) shows changes of material concentration in chosen position of pixels, for two ECT sensor located at different height above silo outlet (1.0m and 1.5m).

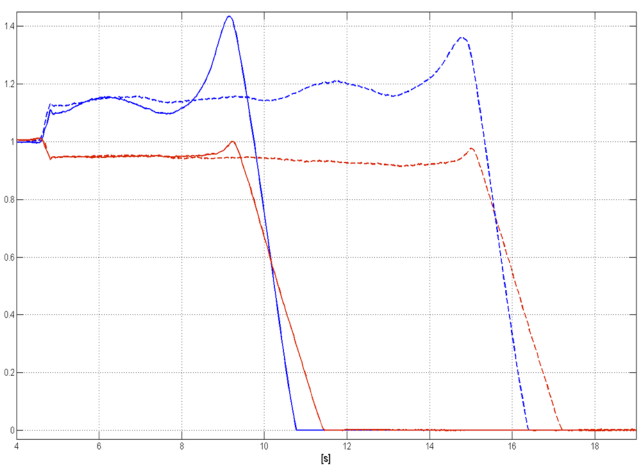

Fig. 4. Material concentration changes for initially loose packing sand and rough silo walls in different area of silo cross-section. Continuous lines represents changes wall-adjacent pixel p(1,15) for reconstruction based-plot. Centre plot (for pixel p(15,15)) – dashed line [9]

The material concentration distribution is validated with use of applied X-ray system. On Figure 5 2D radiography images after processing (normalization) are presented. The shape of silo was rectangular in order to better analyse influence of silo wall on the flow behaviour. At silo wall is visible the shear zone; lower level of material concentration.

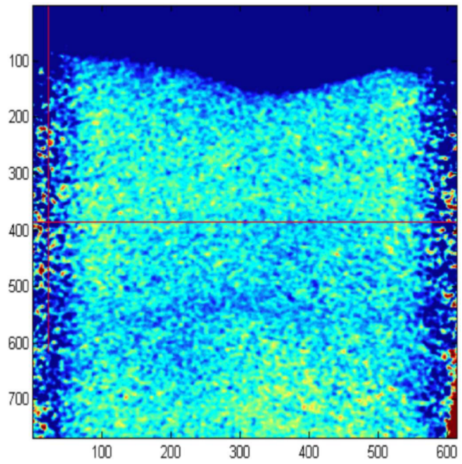

Fig. 5. 2D processed radiography image visualisation of shear zone phenomena [10]

The X-ray visualisation allows investigating silo flow, however utilization of this tomography modality in industrial environment can be unreasonable from real time measurement and cost of system point of view. In order to monitoring shear zones phenomena image processing module based on ECT data was applied, which allows to localize shear zone thickness along silo walls. In case of rough walls, shear zone occurred in wall-adjacent region, and dilatancy reached ~5-8% of initial state (Fig. 6b). The thickness of shear zone, determined with simplified approximation of pixel number (approximation method is described further below), was ~20mm, for silo model 200mm in diameter. Shear zone can be met also, with smaller effect, for smooth wall (Fig. 6a). The previous work showed, the initial packing density rise results in shear zone decrease [2, 4].

In order to determine the shear zone parameters (e.g. material concentration and size), processing method of reconstructed images was applied. Details of this image processing algorithm can be find in [6].The main point of algorithm is image segmentation which allows to determine the indices of all the pixels belonging to shear zone, according to the following formula (eq. 1):

$$\varepsilon(i) = \begin{cases} 2, & \varepsilon(i) \geq (1-\lambda * \bar{C}) * \bar{\varepsilon} \\ \varepsilon(i), & \varepsilon(i) < (1-\lambda * \bar{C}) * \bar{\varepsilon} \end{cases}, \text{ i=\{1,\ldots,M\}} \qquad (1)$$

where $\bar{C}$ is a mean of normalized capacitance records, $\bar{\varepsilon}$ is mean of normalized image pixel values, $\varepsilon(i)$ is a consecutive pixel, M is a total number of reconstructed image pixels, and λ is an experimentally chosen value.

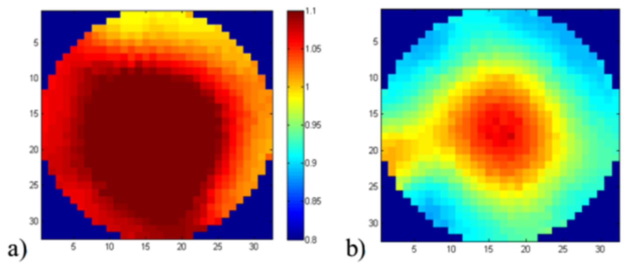

Fig.6. Tomographic visualization (in form of tomogram – full reconstructed cross-section image) of concentration changes – loose sand, at sensor height h=1.0 m, time 7 s of silo discharging a) smooth wall, b) rough wall

After processing (eq. 1) all pixels with value 2 are considered as the non-shear zone area. In the next step of algorithm are determined pixels, which belong to boundary between shear zone area (pixels without modification value ε) and rest of pixels (with value 2). The pixels that belong to shear zone and have at least one neighbourhood pixel from rest of images are marked as boundary pixels. The average distance between boundary pixels and centre of images allows estimating thickness of shear zone. The material concentration in shear zone is calculated as average value for all pixels cover the estimated shear zone. On Figure 7 is presented the characteristic of parameters changes of shear zones.

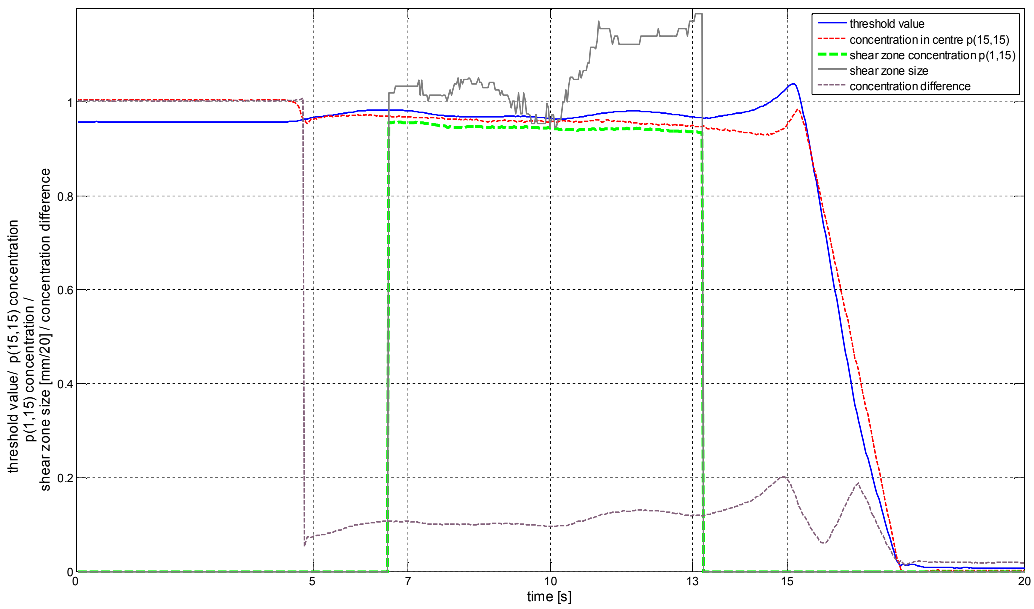

Fig.7. Characteristic plot of shear zone parameters change during silo discharging bulk solid flow [6]

4. Funnel flow, blocked, movement of centre of gravity

The main problems in this type of gravitational flow are blockage, or partially blockage (e.g. arching, ratholing), and slowdown of material flow. During production such situation causes poor product or stopping production and elimination of problems. The proposed method of funnel flow monitoring is based on tracking of area and position of funnel flow in cross-section of silo at height of ECT sensor. Output of algorithm consists in set of funnel parameters: position of centre of gravity funnel area, shape of funnel area and concentration of material in funnel area.

On Figure 8a 3D Xray tomography images of funnel are presented while Figure 8b shows radiography images. X-ray images (radiography and tomography) show material concentration distribution with details over height of silo. In the case of ECT system, the reconstructed image shows concentration at sensor height above silo outlet and as average value from length of electrodes. The 2D ECT image provides cross-section of silo (Fig. 7).

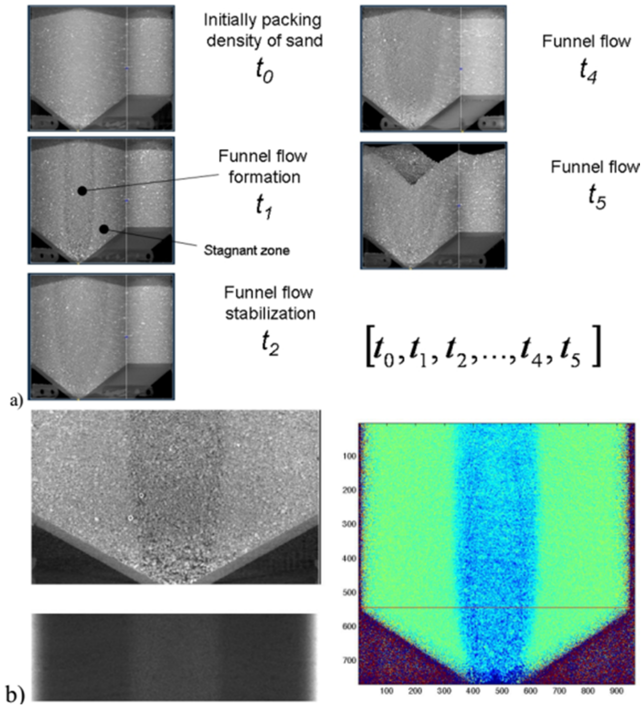

Fig. 8. Xray visualisation of material distribution during funnel flow, a) sequence of 3D reconstructed images, b) zooming of funnel area visualisation with aid of 3D tomography image and 2D radiography image after processing [10]

Stack of ECT reconstructed images gathered during funnel flow is presented on Figure 9. There are visible the concentric areas of cross –section of silo (for the same height) with different level of concentration.

In order to estimate the funnel parameters the spatial segmentation algorithms for tomography image were developed. After the reconstruction and binarization of image (pixels are splited into 2 groups – funnel area and rest of sensor area, based on eq. 1 with other value of λ) pixels belonging to the funnel area are determined. Based on centre of gravity of boundary pixels (boundary between funnel area and stagnant zone) cloud of points around the funnel is constructed. The ellipse axes are determined by applying the least-squares analysis and linear regression methods for these points. Based on centre of ellipse and proportion of ellipse axes (ratio of the major and minor ellipse axes) it is possible to track position of funnel (x_0,y_0), size and shape of funnel area. This information allows to monitor proper discharging process. The main steps of this algorithm are presented on Figure 8.

The presented analysis of tomographic image can be carried out for the sequence of images, which are obtained during silo gravity discharging process, what allow to track state of process. On Figure 11 and 12 results for silo flow without blockage and with partial blockage of silo are presented.

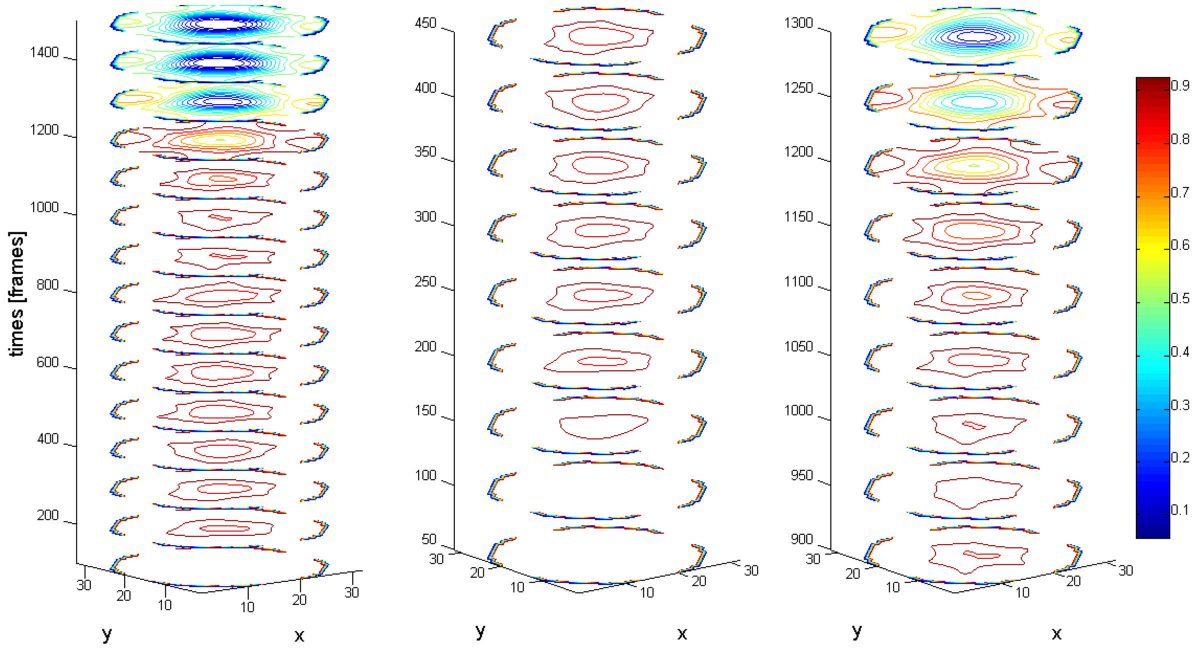

Fig. 9. Stack patterns of combined 2D image sequence reconstructed for fixed sensor location and different funnel size. 1 frame corresponds to 20ms [16]

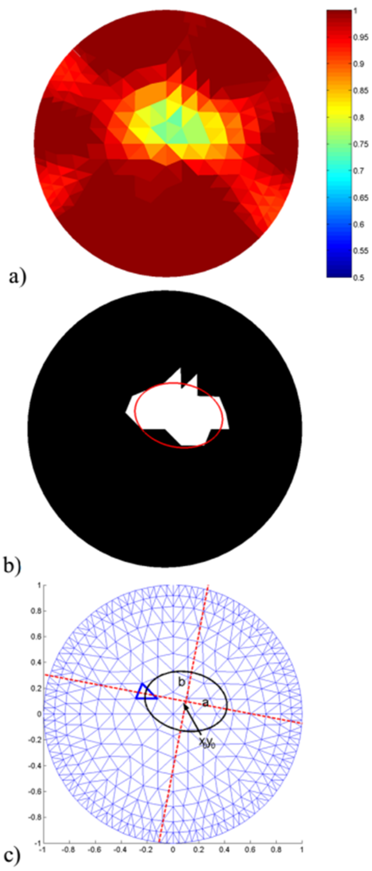

Fig. 10. The main steps in defining the hopper flow parameters. a) reconstruction image, b) image thresholding, c) determined ellipse parameters

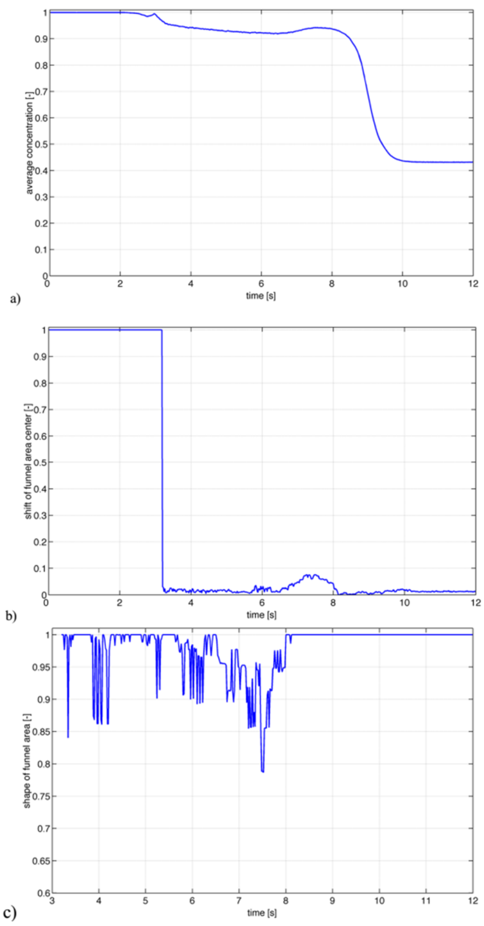

Fig. 11. Funnel parameter for flow without blockage, a) average concentration changes in time, b) position of centre of funnel gravity, c) changes of shape funnel ratio

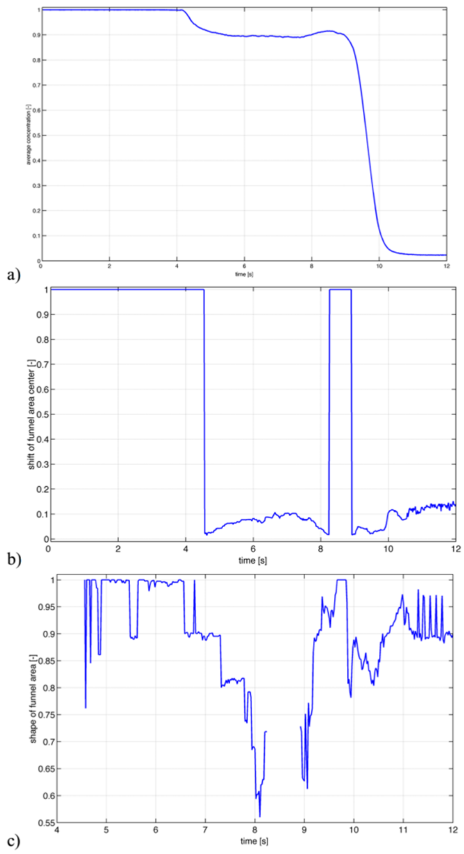

Fig. 12. Funnel parameter for flow with partially blockage, a) average concentration changes in time, b) position of centre of funnel gravity, c) changes of shape funnel ratio

The analysis of presented characteristics show that shape of funnel area is, in case of properly discharging process, different from value 1 (the silo cross-section) up to 0.79 (fig. 11c). For the flow with partial blockage of silo this difference is up to 0.56 (fig. 11c). The main important time range of silo discharging process is until 8 second for blockage silo and until 7 for flow without blockage. This is time between opening the silo outlet and appearing of the upper surface of material at sensor position. The increasing of average concentration changes (8 second for blockage and 7 second for non-blockage flow; fig. 11a, 12a) is caused by measurements attribute of ECT unit, where is observed increasing of capacitance measurements where upper level of material is near the edge of electrodes. For these time windows the difference for both cases is more visible. The blockage of silo flow was prepared in form of bulk particles stuck to silo wall, causing first of all shift of funnel are to non-blocked site of silo. So the different in case of funnel shape, for blocking and non-blocking flow, is not so visible as for value of the shift of funnel centre (fig. 11b, 12b). The shift of centre of funnel area is more visible for blockage flow, where this parameter increased to 0.1 (fig. 12b).

5. Conclusions

The investigations of the silo flow monitoring methods conducted with aid of tomography techniques are fruitful. Their main advantage is the possibility to see inner material distribution without introduction any disturbance into the process. Two main aspects, which can be considered in context of silo flow visualisation are understanding of flow behaviour and monitoring in real-time state of process. Both aspects are presented in paper. ECT systems are suitable to apply in control system, while the X-ray tomography is useful for in-depth analysis of granular flow.

The described methods of mass and funnel flow are based on tomography image processing and analysis. Information, which is analysed, is used gathered from single image, so only spatial information about material distribution is considered. In this case the quality of image has significant impact on results. The reconstructed algorithm for ECT technique was not discussed in paper. The set of the determined parameters in single time point cannot be as useful as the changes in time of these characteristic parameters of flow. It is necessary to analyse not only values of parameters but also changes of these values over time.

Other aspect, which is necessary to be discussed for tomography visualisation of silo flow, is that stopping the flow by silo operator causes similar measurement and reconstructed image as for non-stopping flow. This feature could be eliminated by temporal analysis of obtained results and have to be solved in the future.

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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 PhD 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.

Prof. Dominik Sankowski
e-mail: dsan@iis.p.lodz.pl

Head of the Institute of Applied Computer Science, at the Lodz University of Technology.
He achieved a PhD with distinction (1979), DSc (habilitated doctor - 1989), and granted the title of professor (1998). Since 2001 he has held the position of full Professor. Member of: IEEE Computer Society, Electro-thermal Section of the Polish Academy of Sciences, Group of Experts in the Computer Science specialisation of National Accreditation Committee (PKA). Communication Director of International Society of Process Tomography (ISIPT).
His research interests include Image Processing and Analysis, Pattern Recognition, Artificial Intelligence, Software Engineering, Data Processing, Real-Time Systems, IT Systems in Management, On-line Identification of Industrial Objects, Automation of the Thermal Processes.

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