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CENTRAL AND ECCENTRIC GRANULAR MATERIAL FLOWS IN BINS/HOPPERS REGISTERED BY DPIV OPTICAL TECHNIQUE*

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A b s t r a c t. Application of a new optical technique – Digital Particle Image Velocimetry in investigation of inherently transient processes of granular material flows in a plane model of silo built of Plexiglas is presented. The transparent walls of the model allow for flow visualisation and PIV measurements of velocity fields or local stresses in the material. The outlet in the model was located in three changed positions. Flax-seed as a granular material was used in the experiments. This material develops negligible static electricity when flowing and sliding over Plexiglas. The experimental setup consists of high resolution camera (SensiCam) permitting to acquire about 200 pairs of 1280x1024 pixel images with frequency of 3.75 Hz. Evaluation of grain displacement (and velocity) is performed for each pair of images, taken at the interval 0.267 s. A sequence of digital images of moving material in the model is analyzed with PIV. The zones where the material is in motion and the stagnant zones are characterized. The change of local velocity with time is demonstrated with this method providing an insight into the dynamic behaviour of the granular material. The fluctuations of material motion lead to changes of the wall stresses.

K e y w o r d s: flax-seed, DPIV, eccentric and central flow

INTRODUCTION

The first papers of Jenike [15, 16] described mass and funnel flows from hoppers. Watson and Rotter [35] classified funnel flow as a semi-mass flow and internal or pipe flow. The issue of investigating the flow zone boundary and

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velocities in flowing materials plays an important role in research works. Predicted by Jenike, the radial velocity field (RVF) was verified in practice by many, and their works were aimed at investigating the type of flow and ranges of the stagnant boundaries [9,13,32-35]. Velocities, stagnant boundaries, evolution of flow zones in cohesionless granular materials can be predicted introducing theoretical models into the analysis: the rigid perfect plastic model and a kinematic model [12,19,23,24,34], or the revised kinematic material model [11]. Weir [36] presented a new "softening" variable-density plastic flow model and applied it to the steady radial flow of a cohesionless granular material from steep-walled wedge and conical hopper.

The behaviour of flowing material and measuring of flow patterns was registered by researches using different techniques. Kvapil [18] used two different colours of material and the flow was observed through the transparent walls of the model. Optical techniques such as the X-ray technique were applied by Blair-Fish and Bransby [5], Drescher *et al.* [10] to obtain information from deeper flow layers. The latest measurement technique, PIV, allows to obtain velocity fields, velocity magnitude contours or stresses in the flowing material [20,26 30-32].

PARTICLE IMAGE VELOCIMETRY

Particle Image Velocimetry technique is a well established experimental method in fluid mechanics, allowing for quantitative measurement of two-dimensional flow structure. It enables the measurement of the instantaneous in-plane velocity vector field within a planar section of the flow field and allows to calculate spatial gradients, dissipation of turbulent energy, spatial correlations, and the like. In the classical PIV technique, images are recorded on photographic film, and the flow field is obtained via the computation of the spatial correlation into small regions. To process large numbers of such images appeared to be a very laborious task. Therefore, an alternative approach – referred to as Digital Particle Image Velocimetry – was introduced. The application of DPIV allows for a simple realization of the cross–correlation technique for pairs of two separate images. The typical DPIV evaluation procedure is based on the analysis of two successive images of the flow. This paper is our effort to apply the optical flow technique based on DPIV in granular material flows to measure flow boundaries and velocity fields in bins/hoppers. In Quenot *et al*. [27], an Optical Flow technique DPIV based on the use of Dynamic Programming is described in detail and one can find the detailed description of the DPIV method and the history of its development, possibilities and application. Digital images are recorded directly with a CCD camera and frame-grabber. A velocity vector is obtained for every pixel of the image. Calibration carried out for synthetic sequences of images shows that the accuracy of measured displacement is about 0.5 pixel/frame for tested two–image sequences and 0.2 pixel/frame for four-image sequences. The aim of the present investigation is to explore the possibility of using the optical flow technique based on PIV to measure velocities in a granular flow, especially for eccentric flows.

CENTRAL AND ECCENTRIC FLOW INVESTIGATIONS

J.W. Carson stated [8] that "Silos and bins fail with a frequency which is much higher than almost any other industrial equipment." Different are silo failures which can be divided into four groups: those due to design errors, due to construction errors, due to usage or due to improper maintenance. Different flow patterns in the material may be formed and may be caused by different reasons. One of them is the method of filling and discharge. Considering a central filling and discharge flow, Jenike presented in [15,16] mass flow and funnel flow. Watson and Rotter [35] determined the funnel flow as semi-mass flow and internal or pipe flow. The flowing zone predicted by Jenike's radial velocity field occurred to be far narrower than that observed in practice [9]. In these investigations the hopper geometry, height of packed materials, the size of particles, material density, material-wall interface friction were considered as parameters having an influence on the shape of flow patterns [13,25,33-35].

During discharge from a densely packed hopper, a plug flow zone forms in the material and it extends upward to the upper surface. In central discharge, this zone widens in time and quickly reaches the hopper walls. In eccentric discharge, one may notice a different behaviour of the flowing zone. This paper presents registration of the boundaries of the flowing zones in eccentric filling and discharge by DPIV technique. After opening the outlet, we observe the forming plug flow zone in the material and its boundaries are vertical or concave suitably to the kind of the flow. In the initial phase of the flow, quite different velocity distributions form in the vicinity of the outlet and near the upper surface. In the advanced phase of the flow, the flow zone widens and the boundaries become more or less curved.

Different than expected are flow patterns obtained during non-symmetrical filling and discharge. The load distribution, velocity distributions, velocity profiles may also be radically changed if the outlet is placed not in the symmetry axis of the bin. In practice one can meet a non-controlled method of filling and discharge that results in dynamic loads which may even collapse the bin. Presented here are some cases of central and eccentric discharge which illustrate the dynamic behaviour of the material. During the flow, both central or eccentric, arches and ratholes can form in the material. In fact we cannot predict the behaviour of the material in spite of our efforts to have the bin filled in a special way [34]. So far only axial symmetric states of stresses are recommended in international standards, among others in ASAE Standards [3], ENV 1991-4 [12]. If the flow is eccentric to the silo axis, the discharge flow patterns are much more complicated. A few approaches have been developed for the design of bins under eccentric discharge [17,29,37]. Code committees even avoid defining discharge pressures and flow patterns in standards because of continuing uncertainties and the many serious failures involving eccentric discharge. Moreover, they discourage the use of eccentric discharge which may be very dangerous for the structure. Some attempts have been recently made at investigating eccentric filling and discharge in hoppers trying to indicate many additional problems which occur during eccentric discharge, i.e. non-symmetrical bin wall loads which may lead to quite different work of the structure. Codes and guides include eccentric discharge but they treat it very differently [1,2,28]. These additional, unexpected problems occurring during eccentric filling and discharge are found to be a major cause of hopper failures. Recently a group of researches tried to investigate the problems mentioned above.

In recent years, silo designers have been trying to complete research works to codify rules for eccentric filling and discharge. Some experiments and investigations on silo wall pressures have been recently completed [4,6,7,14,21]. Blight found [6] that near the eccentric outlet the Jenike theory of pressures is also valid for the case of eccentric emptying. Ayuga *et al.* [4] investigated pressure distribution in discharge process in a silo with central and eccentric outlets and described the influence of outlet eccentricity. Molenda *et al.* [21] investigated bin loads induced by eccentric filling and discharge of grains. It was found that eccentric discharge induced dynamic moments much higher than static moments on the bin wall.

EXPARIMENTAL SETUP

This paper presents the application of DPIV (Digital Particle Image Velo-cimetry) technique in measurements of evolution of granular material flows in plane hoppers with central and eccentric filling and discharge. The behaviour of the material in these processes, the evolution of central and eccentric flows, velocity magnitude contours, velocity vector fields, and velocity distributions at certain levels in the model are presented in the analysis. To obtain data on the evolution of plug flow in a plane model made of Plexiglas, eccentric filled with flax-seed, a series of experiments was conducted and selected results of those are presented in this paper.

The experimental setup consisted of a Plexiglas box, a set of illumination lamps, and a high resolution CCD camera (PCO SensiCam). The 12-bit flow images with resolution of 1280 pixels x 1024 pixels and maximum frequency of 3.75 Hz were acquired by Pentium 4-based personal computer. Long sequences of

100-400 images were taken at variable time intervals for subsequent evaluation of the velocity fields. The velocity field was evaluated for triplets of images using optical flow PIV technique. Dense velocity fields with vectors for each pixel of the image were obtained and used for further evaluation of the velocity profiles and velocity contours. Intrinsic resolution of the PIV technique is limited by the size of the area of interest that is used in the application of the cross correlation algorithm between subsequent images and this is generally one order of magnitude larger than a single pixel.

The Plexiglas silo model had a height of 80 cm, a depth of 10 cm, and a width of 26 cm. The model was placed on a stand and granular material was supplied through a pipe suspended above the model. The width of the outlet was 1 cm and placed in three different positions as was mentioned above. The material shows certain static electricity when flowing and sliding over Plexiglas. Properties of the material used in the experiments are the following: wall friction against Plexiglas ϕ_w = 26^o, angle of internal friction $\phi_e = 25^o$, granular material density deposited through a pipe with zero free-fall: – ρ_b kg m^{-3}, in two cases 746 kg m^{-3} at 1 kPa and 747 kg m^{-3} at 8 kPa.

Uniform and repeatable packing of the material with no particle segregation was obtained. The model was filled with a 78 cm high column of flax-seed. Flax-seed has the shape of a flattened rotational ellipse of 4mm x 2mm, of brown colour, and a plain brilliant surface.

SELECTED RESULTS

In the literature we can find few experimental measurements of the stagnant zone boundary in bins/hoppers with eccentric filling and discharge. More approaches are concerned with central filling and discharge in silos. That is why it seems to be a valuable task to undertake this challenge and try to investigate material behaviour in these complicated phenomena. In this paper we present some results obtained in the DPIV analysis. Figures 1a, b, c show the evolution of the plug flow zone during gravitational discharge. Figure 1 presents the velocity contours for the flowing seed when the model is filled eccentric from the left side and the outlet is located in three different positions.

The total time of flow for flax-seed was 123 s in case a), 142 s in case b) and 146 s in case c). Velocity fields and velocity magnitude contours of the flowing flax-seed were obtained from the sequence of 315 images taken at the intervals of 0,2666 s. The development of a high velocity region (red colour contour) at the outlet is clearly visible. The stagnant zones are indicated by the blue colour on the velocity contour map. Figure 1a presents the discharge when the filling was on the opposite side to the outlet, and a plug flow zone in the flow region developed near the wall of the model and propagated upward and then widened a little, and we can say that it slids on the wall. It looks like a half candlelight growing in the advanced phase of the flow after 100 s. The flow region becomes concave and the material gradually slides on the stagnant region surface.

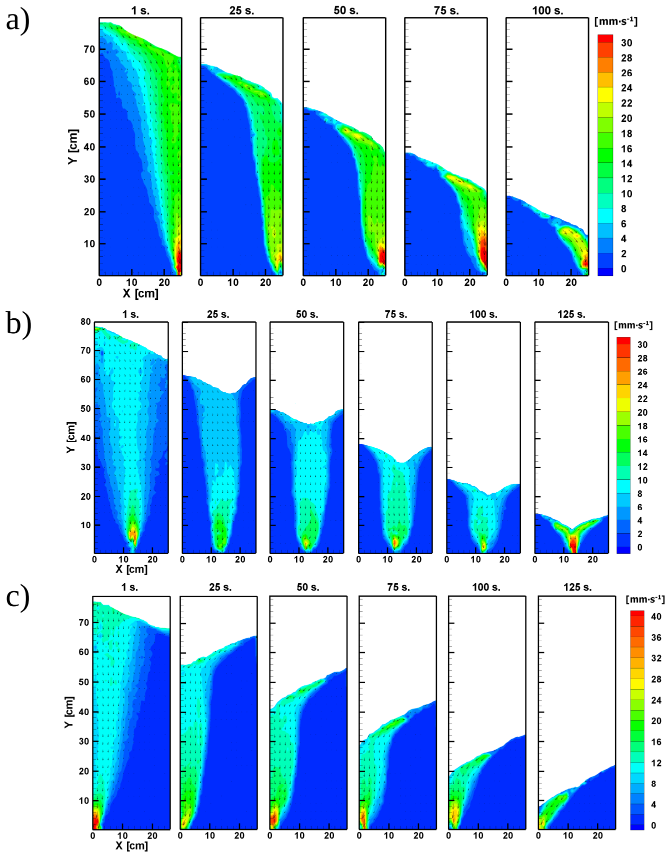


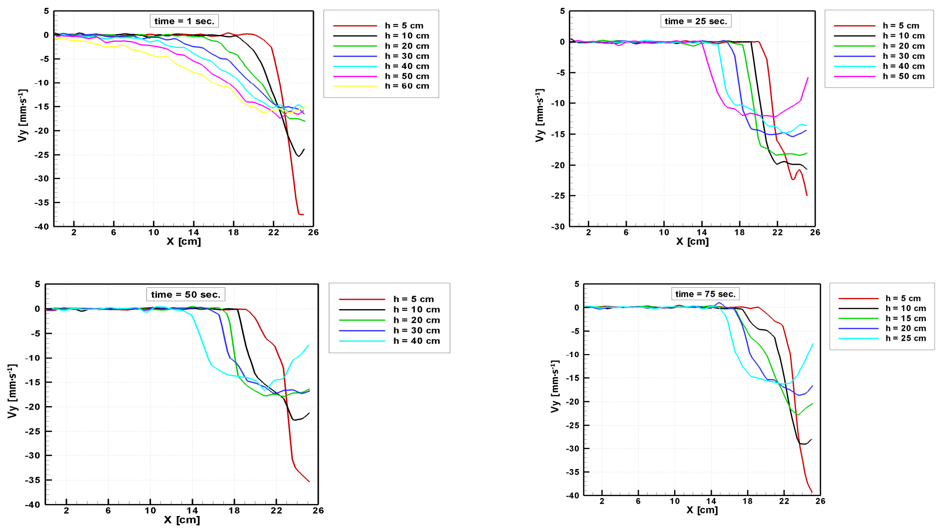
Fig. 1. Velocity contours for eccentric filling in the left part of the model and a) discharge on the right, b) discharge in the central line, c) discharge in the right part of the model

As seen in Figure 1a, the upper surface changes its shape while the material flows and becomes more and more concave. The initial surface was at a constant slope at an angle equal to the material's angle of repose at the beginning of the experiment. In the stagnant zones, the measured velocity is equal zero. In the plug flow region, the velocity vectors in the initial phase of flow are vertical, but they change their traces according to the directions of the flow. In the upper part of the flow, the velocity vectors indicate converging lateral flow towards the flowing zone. The velocity of the flowing material has its maximum in the plug flow zone in the vicinity of the outlet and decreases towards the upper surface and the left model wall. The flow profiles are not symmetric. In the advanced phase of the flow, the lateral dimension of the plug flow region increases. In the plug flow region, the velocity vectors pass vertically towards the outlet. They have different lengths and it is difficult to find a line along which they pass. The velocity vectors indicate here the highest velocities. The velocity vectors pass directly to the outlet but their traces are not vertical in the whole region. Near the boundaries, the vectors pass along curved lines. The length of the vectors and the colour of the contour indicate the magnitude of the velocity. Initially the plug flow width is relatively small. The average flow velocity diminishes with time. In the final phase of the flow, the elevated velocity region at the outlet spreads upwards in the plug flow zone. A similar conclusion on the plug flow zone can be drawn from Figure 1c. The outlet is located on the same side as the filling was made. And now we observe a similar forming of the plug flow, but the velocity in the flowing region is a little lower than in Figure 1a, which is indicated in the colour map. Velocity vectors in the lower part of the flowing region pass almost vertically to the outlet, but only in the region near the stagnant zone the particles have rather low velocity, which is indicated by the colour in Figure 1c. In this case the plug flow zone propagates upward but it does not widen as the model wall does not allow it to develop. It can be seen that the material passes as an avalanche into the flowing region without any disturbances. The case of Figure 1b is a very interesting one. Just at the beginning of the experiment, the material tries to form a symmetric flow in spite of the fact that the model was filled eccentrically. After 25 s of the flow almost a symmetric flow is observed and a plug flow zone in the flow region propagates upward and then widens with height although the fact of the eccentric filling plays here a little role. When the flow region reaches the upper surface, it becomes concave. Shortly after, one may observe nearly uniform channel flow for the entire height of the silo. As seen in Figure 1b, the upper surface changes its shape while the material flows and after 25 s we observe almost symmetric flow. In the stagnant zones, the measured velocity is equal to zero. In the plug flow region, the velocity vectors in the initial phase of flow are still not vertical, but soon they pass directly and vertically to the outlet. In the upper part of the flow, the velocity vectors indicate converging lateral flow towards the flowing zone. After about 50 s of the flow, the velocity of the flowing material has its maximum on the axis of the model near the outlet and decreases towards the top and the model walls. The flow profiles become almost symmetric.

In the advanced phase of the flow, after 50 s of the flow, the lateral dimension of the plug flow region increases. We can say that the central outlet extorts the formation of the central flow. In the plug flow region, the velocity vectors pass already vertically towards the outlet. They tend to put along the symmetry axis and indicate here the highest velocities. Near the boundaries between the flowing region and the stagnant zones, the vectors pass along curved lines directly to the outlet. The length of the vectors and the colour of the contour indicate the magnitude of the velocity. Initially, the formed plug flow width is relatively small and its shape is not symmetric, but after about 30 s it becomes symmetric and the high velocity flow region locates in the vicinity of the outlet. In the final phase of the flow, the elevated velocity region at the outlet spreads upwards in the plug flow zone.

These presented results are only a part of the results obtained in the experiments. Finally it can be noticed that the flowing seed produces different flow patterns according to the position of the outlet as shown in Figures 1 a, b and c., and the usunacThe seed used in the experiments was less homogeneous and contained some natural pollutions.

a)



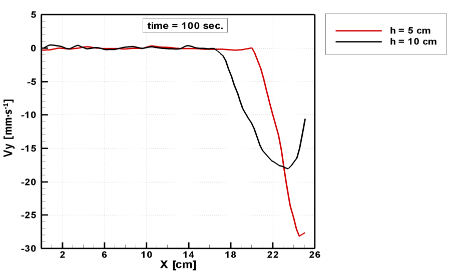
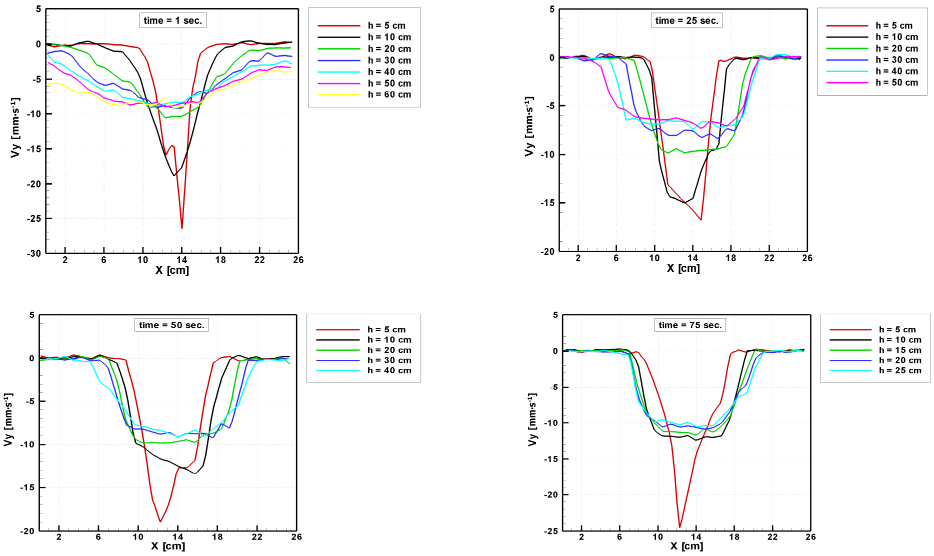
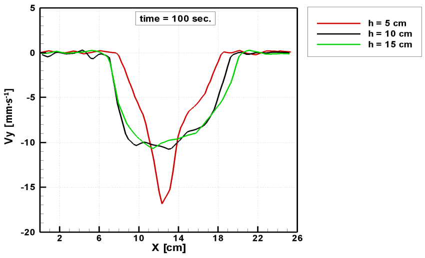


Fig. 2. Velocity profiles for the flow of flax-seed obtained for a) eccentric filling and discharge on the opposite side, b) eccentric filling and central discharge, and c) eccentric filling and discharge but on the same side of the model

b)

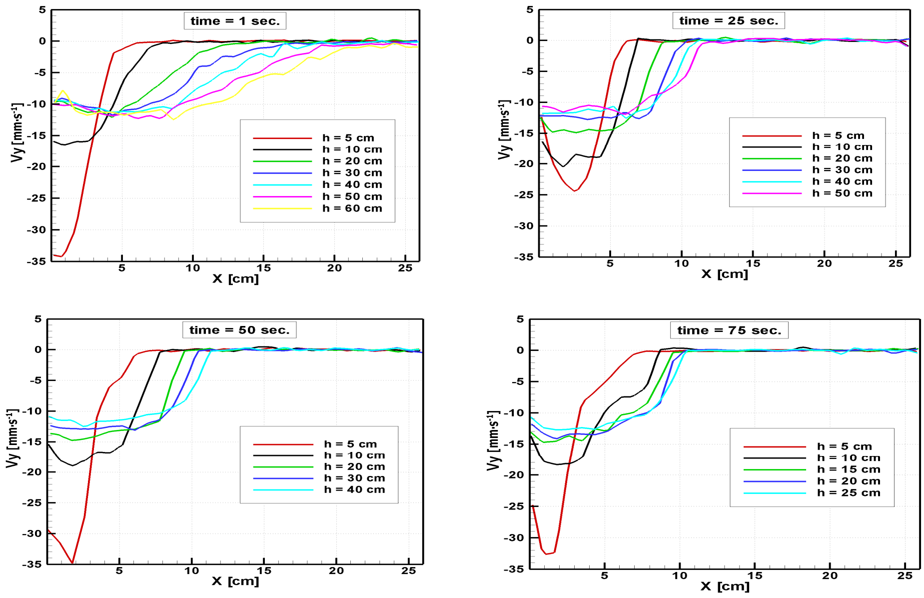


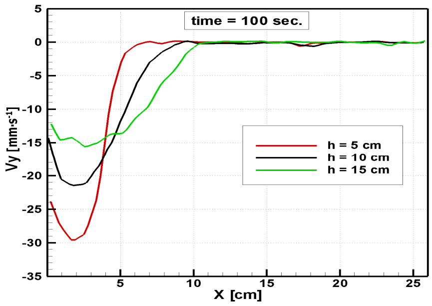


Cont. Fig. 2. Velocity profiles for the flow of flax-seed obtained for a) eccentric filling and discharge on the opposite side, b) eccentric filling and central discharge, and c) eccentric filling and discharge but on the same side of the model

In Figures 2 a, b, c selected velocity profiles of the flowing flax-seed are shown for the three cases of the analysis. The profiles of the vertical velocity components across the cavity were obtained at different heights (indicated in legend) and at time steps of 1 s, 25 s, 50 s, 75 s and 100 s after the beginning of the experiment. In the cases analyzed, we describe the velocities distributions at different levels according to the position of the outlet. In Figure 2, at 5 cm above the outlet (the red line in Fig. 2) one can observe the form of the velocity profile. This profile is a special one because in each case it behaves individually. The other profiles form a bunch of functions on the proper levels. In the case of central discharge, this velocity profile reaches its maximum value in the flowing zone and it is seen that the velocity distribution tries to become symmetric in this zone. Of course, slight symmetry disturbance can be seen in the velocity profiles. At 5 cm above the outlet, this velocity reaches its maximum value of about 40 mm s^{-1} (Fig. 2a).

c)





Cont. Fig. 2. Velocity profiles for the flow of flax-seed obtained for a) eccentric filling and discharge on the opposite side, b) eccentric filling and central discharge, and c) eccentric filling and discharge but on the same side of the model

At 10 cm above the outlet, the maximum value of 30 mm s^{-1} of the vertical velocity is reached after the time of 25 s. It can be noticed that above 20 cm from the outlet the velocity maxima reach similar values in the range between 8-25 mm s^{-1}. For the case of eccentric filling and central discharge (Fig. 2b), 5 cm above the outlet the velocity is about 35 mm s^{-1}. At other levels, the velocity profiles form a bunch of functions and the velocity is about 7-10 mm s^{-1}. After the time of 75 s only at the height 5 cm above the outlet the velocity is 25 mm s^{-1} and on other levels (10 cm-25 cm), the velocity is about 10-12 mm s^{-1}. For the case of eccentric filling and discharge (Fig. 2c), the velocity profiles are not so convergent as in the case given in Figure 2a. Again, at 5 cm above the outlet the velocity reaches its maximum of 35 mm s^{-1}. At 20-60 cm above the outlet, the velocity is rather constant at about 10 mm s^{-1}. After

25 s of the flow at 30 cm-50 cm above the outlet, the velocity is also rather constant at 10-12 mm s^{-1}. The highest value of the velocity can be noticed at 5 cm above the outlet. Still at 5 cm the velocity is 30-35 mm s^{-1}. At 10-40 cm above the outlet the velocity value is in the range of 11-18 mm s^{-1}.

CONCLUSIONS

In this paper the use of a new measurement technique – DPIV – is presented. The data on the evolution of the flow in central and eccentric flows is shown. The experiments were conducted on a plane model of silo made of Plexiglas. Detailed velocity vector fields, velocity distributions in the two mentioned flows, with a detailed analysis of the influence of the position of the outlet for the flow, is presented. Interesting disturbances and details concerning the changed positions of the outlet in the flow were observed and registered by DPIV. The method appears to be a useful tool for two-dimensional flows.

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CENTRYCZNE I NIECENTRYCZNE PRZEPŁYWY MATERIAŁÓW GRANULOWANYCH W ZBIORNIKACH REJESTROWANE OPTYCZNĄ TECHNIKĄ DPIV

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Streszczenie. W pracy przedstawione jest zastosowania nowej techniki optycznej DPIV w badaniach naturalnych procesów przepływów materiałów granulowanych w płaskim modelu silosu zbudowanego z płyty poliwęglanowej. Przezroczyste ściany modelu silosu umożliwiają pomiary pól prędkości czy lokalnych naprężeń w materiale za pomocą techniki PIV. Szczelinę wylotową w modelu zlokalizowano w trzech różnych miejscach. Wykorzystano siemię lniane jako granulowany materiał w eksperymentach. Materiał ten wykazuje nieznaczne własności elektryzujące w czasie płynięcia i ślizgania się po płycie poliwęglanowej ściany modelu. Stanowisko badawcze stanowi kamera o wysokiej rozdzielczości (SensiCam) pozwalająca na wykonanie około 200 par obrazów o wymiarach 1280x1024 pikseli, z częstotliwością 3,75 Hz. Badanie przemieszczeń ziaren (i ich prędkości) wykonano dla każdej pary obrazów, pobranych co 0,267 s. Seria obrazów cyfrowych płynącego materiału w modelu jest analizowana techniką PIV. Scharakteryzowano strefy płynięcia oraz strefy zastoju materiału. Pokazano zmianę lokalnej prędkości w czasie proponowaną metodą umożliwiającą przedstawienie dynamiki zachowania materiału granulo-wanego. Fluktuacje ruchu materiału prowadzą do zmian wartości naprężeń w ścianie.

Słowa kluczowe: siemię lniane, technika DPIV, centryczny i niecentryczny przepływ