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DPIV TECHNIQUE FOR GRANULAR MATERIAL FLOWS IN SILO MODELS

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ABSTRACT

The Digital Particle Image Velocimetry has been used in measurements of granular material flows in two silo models, with vertical walls and wedge shaped. DPIV technique made possible to register dynamic behavior of flowing grains during central and eccentric discharge. To observe the influence of wall roughness to the mode of flow the lateral smooth walls in the model with vertical walls were lined with a sand paper of medium roughness. The walls in the wedge shaped model were smooth. Recorded images, characteristics and analysis of the flows are presented in the paper. The round particles of amaranth seed filled the investigated models. Through the transparent walls of the models, the images of the flowing material were recorded by the standard PIV technique. Evolution of vector fields, velocity fields, traces of individual particles, material deformations, velocity distributions, shear zones, stagnant zones in the silo models are presented.

1 INTRODUCTION

Granular material flows play an important role in many industries as chemical, pharmaceutical or agricultural. Filling, discharge and storage of granular material in silos or other bins are associated with numerous important problems such as modes of flow, mixing, particle segregation, effect of vibration and aeration, evolution of wall pressures etc. Many non-invasive measurement techniques have been already applied to investigate the flow. The first works [1], where two different colours of material were used, allowed detection of zones of the flow and the stagnant zones. The flow was observed through the transparent walls. To investigate laboratory models other special techniques were used as X-ray pictures [2, 3], ultrasonic measurements, and other non-invasive measurement techniques to register granular flows and also the density and velocity fields in the flowing zone. The techniques as spy-holes, radio transmitters, positron emission [4], magnetic resonance imaging, radioactive tracers, and ultrasonic speckle velocimetry were also applied to analyze the flow. More details on many different techniques used to investigate the flow in small models one can find in references given in [4] or in [5]. But as it was noted in [5]: "each techniques have their drawbacks including cost, spatial resolution, temporal resolution, or invasiveness".

2 EXPERIMENTAL PROCEDURE OF DPIV IN GRANULAR FLOWS

This study presents the new technique DPIV for measurements of flow modes in the models. Unfortunately the application of DPIV to granular flows is limited only to two-dimensional flows and cannot be observed in the whole silo. The method which can solve this problem but in a limited range may be recording the flow with two high resolution cameras, the first one placed from the front wall and the other placed from the lateral wall. Although both cameras would record the flow but just close to the transparent walls of the model. Measurements of granular flows in two-dimensional hoppers by PIV technique was also recently presented by Medina et al. in [6], Steingart and Evans in [7], Ostendorf and Schwedes in [8] also by Sielamowicz et al. in [9, 10]. An Optical Flow technique based on the use of Dynamic Programming [11] has been applied to Particle Image Velocimetry thus yielding a significant increase in the accuracy and spatial resolution of the velocity field. 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. Digital images are recorded directly with a CCD camera and frame-grabber, and can be studied without the unnecessary delay and overhead associated with the digitisation of photographs. DPIV allows for a simple realization of the cross-correlation technique for pairs of two separate images. One of the main drawbacks of classical DPIV is its inability to accurately resolve flow regions characterized by large velocity gradients. This is due to the strong deformation of the particle image pattern within a DPIV search window. A group of researchers like Huang et al. , Tokumaru and Dimotakis , Gui and Merzkirch [12, 13, 14] - proposed several alternative evaluation methods to remove the above limitations. It appeared that the optical flow method may be an interesting alternative, offering high evaluation accuracy without most of the typical DPIV limitations. This technique which was developed for detecting the motion of large objects in a real world scene, has been adopted to measure fluid flow [11], yielding a significant increase in the accuracy and spatial resolution of the velocity field.

In this paper we present the flow modes recognized by using DPIV technique, and the evolution of the flow in silo models. Lueptow et al. in [5] also refers some papers on two-dimensional and three dimensional cases and presents an idea of using of light and dark particles in the investigated mixture. In our investigations we do not use such colored particles. The grains have their natural color, an amaranth grain has a shape of regular round balls of 1 mm diameter, straw-coloured. The surface of the grain is plain.

The use of the PIV technique for granular flows was presented by Lueptow et al. in [5], where the authors recommended application of PIV to study quasi-two dimensional flows in transparent containers.

3 HOW THE SILO FLOWS ARE INVESTIGATED

The fundamental rules on granular material flows in silos were presented by Jenike in his reports [15, 16]. Jenike distinguished radial stress fields (RSF) and velocity fields (RVF) in his investigations and presented the results in a graphical form. The radial velocity field (RVF) presents a particular solution to the full stress equation for an ideal Coulomb material. The radial velocity field (RVF) is derived from the radial stress field on the assumption that material obeys the principal of coaxiality, sometimes known as the principal of isotropy [17]. The methods built by Jenike can predict the existence of stagnant zones in flowing material. The flow channel boundary is also defined as the interface between flowing and stationary solid. The methods based on the concepts of plasticity can predict the existence of stagnant zones but there are no reliable methods for predicting the shape of the stagnant zones boundaries [18]. Watson and Rotter [19] showed the streamlines in a discharging cylindrical bunker and recognized three regions in the solution. Plug flow was found in the upper part of the bunker, where the velocity is presented as the ratio - the volumetric flow rate divided by the cross-sectional area. In the region close to the orifice, velocities of passing particles are high. It was also found that the only region where the velocity of the flowing material cannot be predicted is the intermediate region, located far from the orifice and far from the walls. Waters and

Drescher indicated in [20] that the predicted velocities are higher along the centre line and decrease gradually towards the boundary.

Experimental investigations of flow patterns in converging hoppers have been presented in numerous publications, e.g. Pariseau [21], Blair-Fish and Bransby [4], Tüzün and Nedderman [22], Ooi et al. [4], Sielamowicz et al. [10]. Pitman in [23] investigated stress and velocity fields in two- and three-dimensional hoppers. Dosekun in [24] measured the granular material flow in a wedge-shaped hopper with transparent walls. Insightful experimental investigations devoted to granular flow in conical hoppers are reported in the literature, among others, by Nedderman in [25], Moreea and Nedderman in [17]. Most of above mentioned experiments are made in models. Due to difficulties in monitoring granular flow through opaque walls there are only few full scale experimental investigations reported in silos. It is worth mentioning the paper written by Ooi et al. [4], who presented full scale measurements of flow patterns in a gypsum silo. Investigations concerning stress and velocity fields reported by Jenike [15, 16], Johanson and Jenike [26], gave evidence that for plane strain and axial symmetry, the stress field requires the solution of a system of two hyperbolic partial differential equations. The velocity field could than be computed by solving another system of two linear homogeneous partial differential equations of the hyperbolic type. The radial stress field is assumed to be particularly important for straight conical channels, because evidence was presented elsewhere that all general fields tend to approach the radial stress fields in the vicinity of the vertex. These ideas were further developed by several researches.

Tüzün and Nedderman presented a review article [22] with all the experimental methods that were used to measure velocities in a granular material. They discussed both two and three dimensional flows, and both wedge-shaped and conical hoppers. Later, the measurement techniques of flows and theoretical approaches were developed. Although other authors reported the existence of discontinuities in velocity fields, a series of X-ray pictures and ultrasonic measurements presented practically uniform density of the flowing material. In most of the theoretical models the velocity field analysis was restricted to the advanced stage of flow, which was treated as a pseudo-steady process. Drescher et al. [3] presented experimental results of flow patterns in a plane, wedge-shaped hopper, and also an approach to a theoretical description of discharge. A non-steady discontinuous velocity field was measured using a stereo photographic technique. This review indicates to the importance of flow measurements in silos. Also it is worth noting that the problem of investigation the flow in silos is not satisfied recognized yet and needs more ideas and modern approaches using the latest invented techniques to describe it.

4 EXPERIMENTAL SETUP

Experimental setup used for the flow analysis both in the model with vertical walls and in the wedge shaped model consisted of a Plexiglas box, a set of illumination lamps, and a high resolution CCD camera (PCO SensiCam). The Plexiglas silo model with vertical walls has a height of 80 cm, a depth of 10 cm, and a width of 26 cm. The bottom of the model was flat with no inclination however the construction of the model allowed to regular the inclination of the bottom. The model was placed on a stand and a granular material was supplied through a box suspended above the model. The width of the outlet was 1 cm. The 12-bit flow images with resolution of 1280 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 wedge shaped model wall has a shape of a isosceles triangle with the height 80 cm. The depth of the model is 10 cm with a value of inclination of the walls to the vertical 30^{o}. The length of the upper edge of the wall is about 104 cm. The model was placed on a metal rig. The granular flow evolution was recorded using a high resolution CCD camera (2048 x 1536 pixels). The experimental setup permitted to acquire series of about 200 short exposure images and store them on the computer disk. After experiments were done, computer files containing images of the flow were used for the velocity evaluation. Illumination with several fluorescent lamps allowed to obtain shadow-free images of the amaranth seed filling the model. The flow was observed in back-scattered light through a transparent front wall of the model. Time interval between images was kept constant, equal to 1.05s, selected as an optimal value allowing to detect smallest seed displacements in the flow. The seed displacements measured for given time interval delivered local velocity vectors. Pairs or triplets of digital images were taken to assess by the OF-DPIV method velocity field in the flowing material.

5 RESULTS

5.1 Plane model, eccentric discharge, medium rough walls

DPIV technique was applied to measure the flow of the grains. In this section we present some selected results of the flow obtained in the model with vertical walls and eccentric discharge for the 30th second of the flow. The lateral model walls were lined with sand paper of medium roughness. Such case occurs very often in practice when the only one of many discharge outlets in the bottom is required to work. Moreover the walls after many cycles of filling and discharge are not smooth but more or less rough. The lengths of the vectors in the vector field indicate the velocity of the flowing grains. The direction of the vectors indicate the direction of the flow.

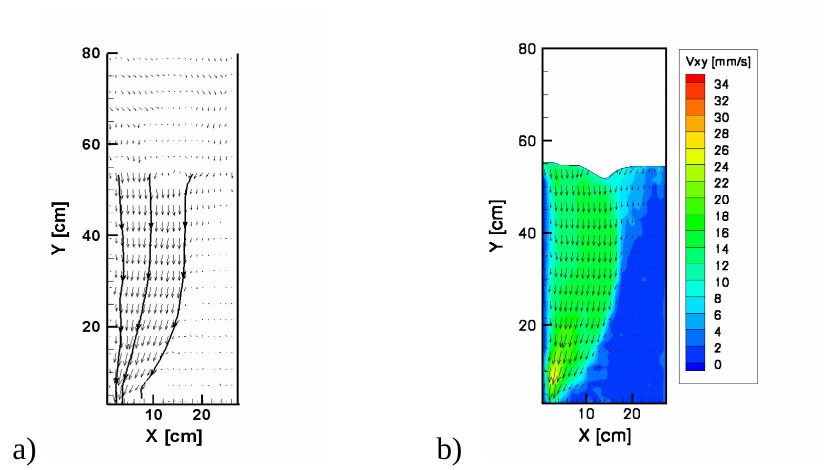


Fig. 1, Eccentric discharge from the left, amaranth seed, medium rough walls, a) vector field, b) velocity magnitude contours for the 30th second of the flow

Figure 1a presents selected streamlines calculated from the vector field. The streamlines represent the motion of virtual particles, indicating the flow structure in the flowing zone. Some disturbances in the flow of the single particles especially near the rough wall and the outlet can be seen. In the stagnant zones there are points which denote vectors of zero value.

Near the outlet, where the velocity is the highest, convergence of the flow into the orifice is well illustrated by the streamlines.
At the beginning of the experiment, the highest velocity region "plug flow zone" rapidly occurred in the flow region, indicated in the legend with red colour, and is located in the vicinity of the outlet. After filling the upper surface had a shape of the natural angle of repose at the beginning of the experiment. The plug flow zone usually propagates upward and then widens with height. But the left wall of the model lined with sand paper acts like a break and stop free developing it. When the flow region reached the upper surface, the free surface became concave. As it is seen in Figure 1, the upper surface changes its shape while the material flows and the depression forms in the symmetry axis, but it becomes nearly conical in its final stages. In the stagnant zones, indicated with blue colour in the Figure 1 b) the measured velocities are zero. The vectors are points in this region. 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 vicinity of the outlet. The lateral dimension of the plug flow region increases. In the plug flow region the velocity vectors pass vertically towards the outlet. The flow direction changes near the outlet and the velocity vectors pass directly to the outlet but their traces are not vertically in the whole region. Near the boundaries the vectors pass along the curved lines. The length of the vectors and colour of the contour indicate the magnitude of the velocity. Initially the plug flow diameter 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.
Figure 2 presents velocity profiles depicted for this stage of the flow, at the 30th second of the flow. In the legend there are the heights on which the velocities are depicted. Close to the outlet, 10 cm above the outlet the flow region is the narrowest and the velocity have the highest values. Above this level the flow region widened and has almost the same width. The velocities above the bottom level at h=20 and 40 cm are about 15 mm/s. There is only a peak of the highest velocity 18 mm/s at the level h=20 cm between the stagnant zone close to the rough wall and the right part of the flowing zone. Two profiles form a bunch of functions. This phenomenon was detailed described in Medina et al. [6] and Sielamowicz et al. [9, 10].

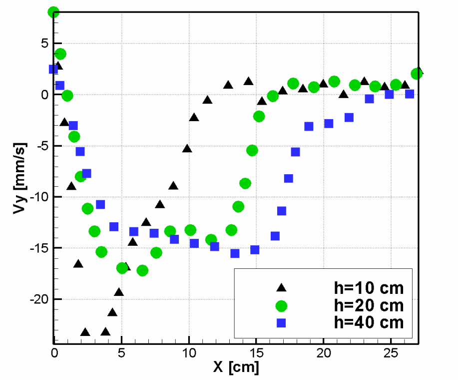


Fig. 2, Velocity profiles. Eccentric discharge from the left, at the 30th second of the flow

Another example of adopting DPIV technique for use in measuring flow velocities was conducted in the same model with rough walls but the mode of discharge was changed. The outlet was placed in the symmetry axis. The vector field presented in Fig. 3 a) relates to the symmetric discharge in the model. In granular material flows the issue of eccentricity is very important in practice. The vectors indicate the regular form of the flow. The central position of the outlet is the most convenient for the flow and for the silo structure. The flow runs more quiet in the symmetrical case and the vector field is almost homogeneous, the vectors of the same length direct vertically to the outlet and in the converging part of the flow they direct towards the outlet. In the converging part of the flow the vector field is also convergent. The plug flow region developed rapidly in the material after opening the outlet. The vectors are the longest in the converging part of the flow. In the flow region above the converging part of the flow the length of the vectors is similar, that indicates the velocities of the same values. This remark relates also to the velocity profiles depicted for the level above h=20 cm. The profiles form a bunch of functions. The upper surface formed after the filling at the angle of repose now after 15th seconds of the flow we observe two depressions in the upper surface.

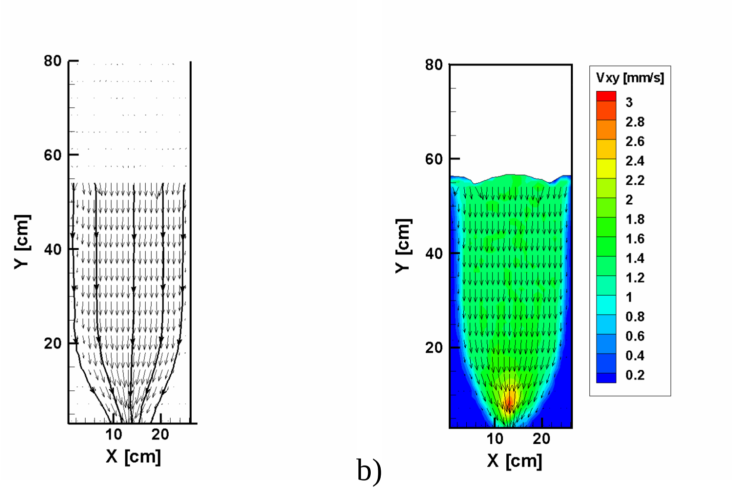


Fig. 3, Central discharge, amaranth seed, medium rough walls, a) vector field, b) velocity magnitude contours for the 15th second of the flow

The dimension of the stagnant zones is similar on the other sides of the model, close to the rough walls. As we mentioned before the rough walls act like a break and the stagnant zones are wider than in the case when the flow runs in the model with smooth walls. The results may be further compared to the velocity magnitude contours presented in Sielamowicz et al. (2005, 2006).

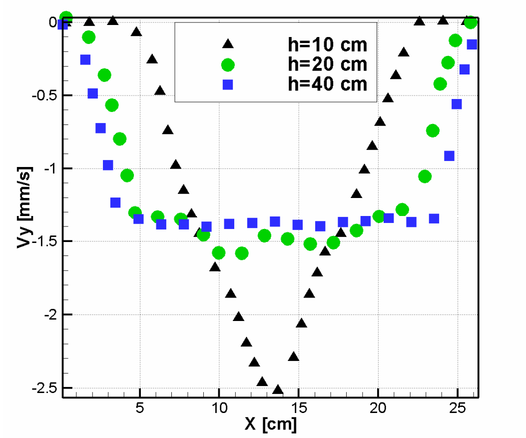
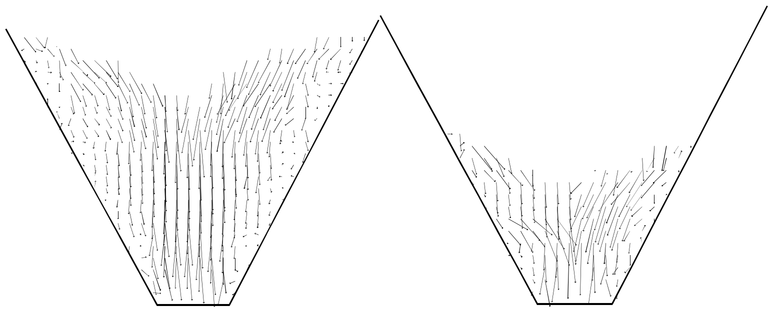


Fig. 4, Velocity profiles. Central discharge, at 15th second of the flow

5.2 Wedge shaped model, central discharge, smooth walls

The flow in the converging part of the silo is specially difficult to investigate. In the flowing material a special phenomenon - shear zones occur. In this paper we present some results of the experiments.

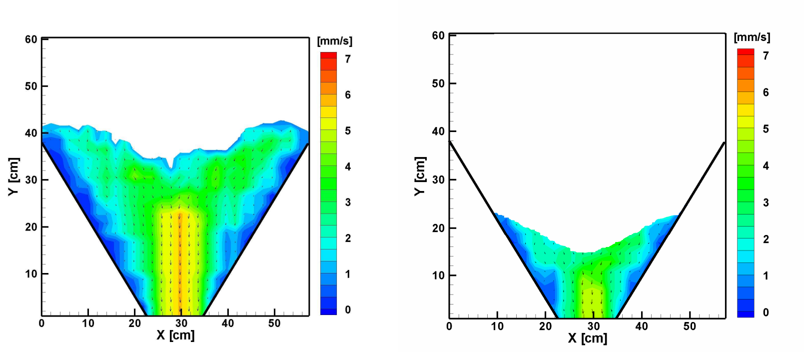
Amaranth seed developed negligible static electricity when flowing and sliding over Plexiglas. Figure 5 presents the vector field in the flowing amaranth after 95th and after 195 sec of the flow.



a) 95th sec of the flow b) 195th sec of the flow

Fig. 5, Vector fields in the wedge shaped model, a) for the 95th and b) 195th sec of the flow

Fig. 5 a, b, relates to the velocity magnitude contours made in DPIV in Figure 6. When flowing the material slides on the converging wall of the model. The boundary between the flowing material and the stagnant zones forms in the shape of “stairs”. They are shear zones. It means that along the boundary between the flowing material and the stagnant zone the material slides ones almost horizontally and after vertically. In this case the form of the boundary between flowing and stagnant material is quite different than in the model with vertical walls. Shear zones occur only in the converging parts in the silos. On the horizontal sections of the boundary between the flowing material and the stagnant zones, arches may form. This phenomenon is very dangerous for the silo structure. The frozen or the wet parts of the material may slip down rapidly striking to the silo bottom. This may cause the silo vibrations and failure of the structures.



a) 95th sec of the flow b) 195th sec of the flow

Fig. 6, Velocity magnitude contours for flowing amaranth at 95th and 195th sec of the flow

The region of the highest velocity developed in the symmetry axis. It reaches the upper surface, opens it and then the lateral parts of the material flows into the flowing region in an avalanche manner.

5.3 Deformations in the material, model with vertical walls, smooth walls

In this section we present another possibilities which gives DPIV technique. In the model with vertical, smooth walls we registered the deformations which the material undergoes. Figure 7 presents the deformations after the 1st second of the flow in the three cases of discharge in the model with vertical walls. Filling was made on the left.

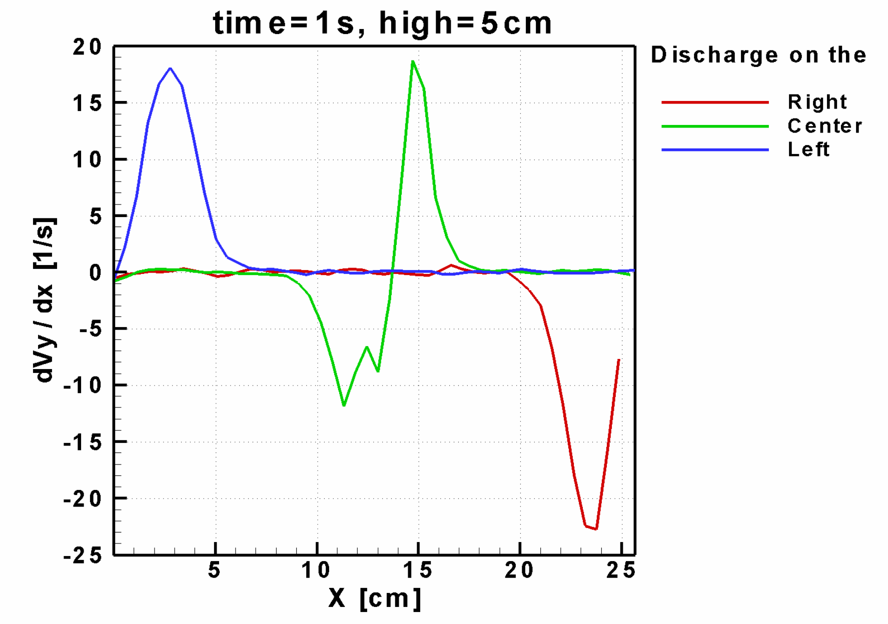


Fig. 7, Deformations in the material registered in the model with smooth walls

6 CONCLUSIONS

Application of the DPIV technique to the analysis of flow evolution in a densely packed cohesionless material in silo models is presented in this paper. This analysis of the flow made possible to evaluate the velocity of vectors for each point of the flow. The investigations of the flow in quasi two-dimensional structures made by the DPIV technique proved that this technique appears a useful diagnostic tool. It gave us a possibility to quantify flow regions, detect a radial velocity field, shear zones, and to measure transient variation of the velocity profiles at selected heights in the model. Accuracy of DPIV measurements allows to obtain velocity gradients inside the flowing zone. However, evaluation of hopper wall stresses is still a challenging task. The velocity gradients measured on the boundary of the stagnant zone could offer useful values for calculating wall stresses.

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