Optical measurement DPIV technique in application in granular material flows in models of silo made of Plexiglas

Irena Sielamowicz *
Bialystok Technical University, ul Wiejska 45, 15-351 Bialystok, Poland
e-mail: sieliren@pb.bialystok.pl
Tomasz A. Kowalewski
Institute of Fundamental Technological Research, Polish Academy of Sciences, ul Swietokrzyska 21, Warsaw, Poland
e-mail: tkowale@ippt.gov.pl
Sławomir Błoński
Institute of Fundamental Technological Research, Polish Academy of Sciences, ul Swietokrzyska 21, Warsaw, Poland
e-mail: sblonski@ippt.gov.pl

Abstract: Flow of grains is investigated in two configurations - in a model of silo with vertical walls and a model with wedge-shapped walls. The models built of Plexiglas replicate the geometry of a silo. The transparent walls of the models allow for flow vizualization and PIV measurements of velocity fields, traces of individual particles, and local deformations and stresses in the material. Two different grains are used in the experiments (amaranthus and flax-seed). These materials develop negligible static electricity when flowing and sliding over Plexiglas. The filling pipe in the model with vertical walls was placed eccentrically near the left wedge of the model and discharge outlet was placed in three positions: 1 cm from the left wedge of the model, in the central line and 1 cm from the right wedge of the model. Uniform and repeatable packing of the materials with no particle segregation is obtained. The experimental setup consists of high resolution camera (SensiCam) permitting to acquire about 200 pairs of 1280x1024 pixels images with frequency of 3.75 Hz. Evolution of grain displacements (and velocity) is performed for each pair of images, taken at the interval of 0.2666 s. High speed camera is used to obtain temporal characteristics of the flows. The evolution of the flow in consecutive stages of the flow in two models are presented. DPIV technique was applied to characterize the flow. While flowing of the grains in eccentric discharge some interesting dynamic behaviour of the material is observed and described in the paper. Some irregular vector lines appeared in the pictures detect the phenomenon of static electricity of the materials. Irregular velocity distribution and vector lines correspond to the shape of grains, conditons of filling and discharge. In the wedge-shaped model vector fields and the traces of particles in the case of symmertic flow are presented.

1. Introduction

Jenike considered mass flow and funnel flow during the discharge of granular material from hoppers (1961, 1964). Later Watson and Rotter (1966) classified funnel flow into semi-mass flow and internal or pipe flow. There are more attempts to characterize the flowing region but there are no reliable methods for predicting the shape of the stagnant zones boundaries Nedderman, (1995). Many researches investigate types of flow and shapes of the flowing regions. In these works some factors play the main role as: the hopper geometry, height of packed materials, the size of particles, material density, material-wall interface friction which influence to the shape of flow patterns (Giunta 1969, Takahashi and Yanai 1973, Nguyen et al. 1979, Watson and Rotter 1996, Waters and Drescher 2000). In the case of eccentric filling and discharge the problem is more complitated. J.W. Carson (2000) stated that "Silos and bins fail with a frequency which is much higher than almost any other industrial equipment." This fact comes from errors which can be divived into four groups: due to design errors, due to construction errors, due to usage or due to improper maintenance. Considering symmertic and eccentric flows different flow patterns in the material may be formed. During symmetric discharge from a densely packed hopper, a plug flow zone forms in the material and it extends upward to the upper surface. This zone widens in time and quickly reaches the hopper walls. In eccentric discharge one may notice a different behaviour of the flowing zone and the behaviour of the material may occur unexpected. That is why the researches have been looking for new possibilities to describe this phenomenon in both cases (central and eccentric filling and discharge).

This paper presents registration of the boundaries of the flowing zones in central and eccentric filling and discharge by DPIV technique. In the case of central discharge 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. Unexpected flow patterns form during non-symmetrical filling and discharge. All data possible obtained from DPIV technique make possible to register it. In fact in practice one can meet a non-controlling method of filling and discharge that results dynamic loads which may even collapse the bin.

Here presented 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. Investigating the behaviour of granular material researches fill the bin with a special way Waters , Drescher (2000). Simplified assumptions are taken to analyze the flow. Also different material models are considered in these analyses as the rigid perfect plastic model and a kinematic material model (Litwiniszyn 1963, Mullins 1972 and 1979, Nedderman and Tüzün 1979, Waters and Drescher 2000), a revised kinematic model Drescher and Ferjani (2004), or "softening" variable-density plastic flow model introduced by Weir (2004), which allows to consider stresses developing during the flow and the funnel-type of flow.

International standards, as ASAE Standards (1997) or ENV 1991-4 (1995) relate only to axial symmetric states of stresses and even avoid defining discharge pressure and flow patterns in standards because of continuing uncertainties. And the use of eccentric discharge is even discouraged. Some codes and guides include eccentric discharge but in a very different way (AS 3774 1986, Rotter 1998, Jenike 1967). So far a few approaches have been developed for the design of bins under eccentric discharge (Rotter 1986, Ayuga *et al*. 2001) and solve the problems which occur during eccentric discharge i.e. non-symmetrical bin wall loads which may lead to quite different work of the structure. These additional, unexpected problems are found as a major cause of hopper failures.

There are some attempts to codify rules for eccentric filling and discharge and some investigations on silo wall pressures have been recently completed (Drescher, Ferjani 2004, Blight 1991, Borcz, el Rahim 1991, Molenda *et al*. 2002). Blight found (1991) that near the eccentric outlet the Jenike theory of pressures is also valid for the case of eccentric emptying. Ayuga *et al*. (2001) investigated pressure distribution in discharge process in a silo with central and eccentric outlets and described the influence of outlet eccentricity. Molenda *et al.* (2002) investigated bin loads induced by eccentric filling and discharge of grain. It was found that eccentric discharge induced dynamic moments much more higher than static moments on the bin wall.

Discharge process was registered in different ways by many. Kvapil (1959) used two different colours of material to observe the flow through the transparent walls of the model and registered flow profiles. Using DPIV velocity magnitude contours were presented by Lueptow *et al.* (2000), Ostendorf , Schwedes (2004), Sielamowicz , Kowalewski (2004) or Sielamowicz , Blonski (2004). Optical techniques allow to register the flow patterns and velocity profiles in the flowing material near the transparent silo walls. Early the X-ray technique was frequently applied by Blair-Fish , Bransby (1973) or Drescher *et al*.(1978) to obtain information from deeper flow layers.

This paper is devoted to the application of DPIV (Digital Particle Image Velocimetry) technique in measurements of evolution of granular material flows in plane flow hoppers registrating central and eccentric discharge and in converging model. The evolution of the plug flow zone, velocity magnitude contours, velocity vector fields, velocity distributions on the certain levels in the model, traces of the single particles in both cases are presented in the analysis.

Quenot *et al*. (1998) presented a detailed description of the Digital Particle Image Velocimetry, its development and application. 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. Particle Image Velocimetry (PIV) is a method used for two-dimensional flow structure evaluation. The typical DPIV evaluation procedure is based on the analysis of two successive images of the flow.

2. Experiments

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. Amaranthus and flax-seed as granular materials were used in the experiments.

Properties of the materials used in the experiments:

Granular material	**Wall friction against Plexiglas φ_w [°]**	**Angle of internal friction φ_e [°]**	**Granular material density deposited through a pipe with zero free-fall ρ_b [kg/m^3]**
amarantus	25	28	832 at 1kPa 833 at 8 kPa
flax-seed	26	25	746 at 1 kPa 747 at 8 kPa

2.1. Plane model of silo

The Plexiglas silo model has a height of 80 cm, a depth of 10 cm, and a width of 26 cm. The model was placed on a stand and a 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. The model was filled through a pipe placed in the symmetry axis and then 1 cm from the left edge of the model. The flow was registrated by DPIV technique and the results are presented below.

Symmetric case was considered as symmetric filling and discharge. Then eccentric filling and three cases of discharge were made where the outlet was placed in three positions: 1cm from the left edge of the model, in the symmetry axis of the model and 1 cm from the right edge of the model. In both cases uniform and repeatable packing of the material with no particle segregation was obtained. The plane model was filled with a 78 cm high column of amaranthus. The total time of flow of amaranthus was 60 s**.** In Figure 2 the horizontal axis is given as a normalised width of the model and the vertical axis as a normalized height of the model. Amaranthus grain has a shape of regular round balls of 1 mm diameter, straw-coloured. The surface of the grain is plain. Flax-seed has a shape of flattened rotational ellipse 4mm x 2mm, of brown colour and plain, brilliant surface.

2.2. Selected results for plane model of silo

DPIV technique enables to get the evolution of the plug flow zone during gravitational discharge obtained by PIV measurements. The development of a high velocity region is indicated by red colour contour, Ostendorf, Schwedes (2004), Sielamowicz, Kowalewski (2004), Sielamowicz, *et al* (2005). The stagnant zones are indicated by the blue colour of the velocity contour map. The evolution of the flow region and the plug flow was demonstrated. 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 were symmetric. The length of the vectors and colour of the contour indicated the magnitude of the velocity. Initially the plug flow diameter was relatively small. The average flow velocity diminished with time. The high velocity flow region was located in the vicinity of the outlet. Selected traces of individual particles obtained for the flowing amaranthus calculated from the velocity field measured in the model were presented. The experimental results of the traces of selected particles were depicted with red vectors. The black vectors denote the flowing region and the lengths of the vectors denoted the velocity. In the stagnant zones there were points which denoted vectors of zero value. The outer streamlines were close to the boundary lines of the flowing zone. They were not always vertical or smooth. Some irregular lines resulted because the used seeds were less homogeneous and contained some natural pollutions. The shape of the grains, and the kind of the seed surface influence their flowing properties. In Fig. 1 selected velocity profiles of the flowing amaranthus are shown. The profiles of the vertical velocity components across the cavity were obtained at different heights (indicated in legend) and at time steps 3.75 s, 30 s and 52.5 s after the beginning of the experiment. At 5 cm above the outlet (the red line in Fig.1) the velocity profile is symmetrical. After 30 s the velocity reaches its maximum value 40 mm/s. After 52.5 s a slight symmetry disturbance can be seen in this velocity profile. At 10 cm above the outlet the maximum value of the vertical velocity is reached after the time of 3.75 s. It can be noticed that above 20 cm from the outlet the velocity maxima reach similar values in the range between 18-22 mm/s. After 30 s the velocity profiles measured at the levels h = 20, 30, 40 cm are similar.

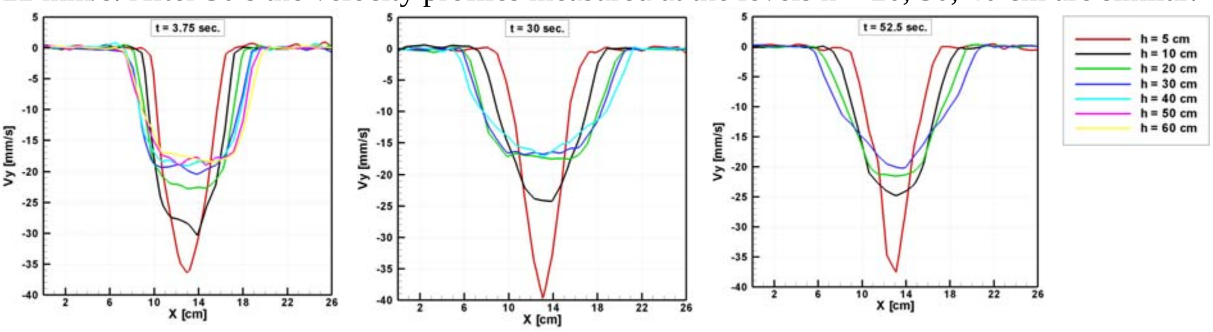
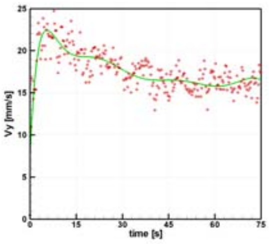
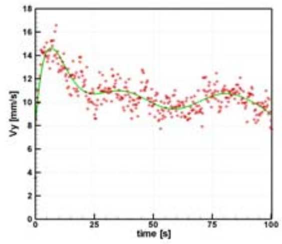


Fig. 1. Velocity profiles for the flow of amaranthus seed (taken from Sielamowicz, *et al*. (2005))

After 3.75 s the similar velocity profiles were obtained for the height of 30, 40, 50, 60 cm which indicates a nearly uniform flow in the upper regions of the silo. The same can be seen in Fig. 1 at t = 52.5 s. There are three levels for h = 10, 20, 30 cm, where "a bunch" of velocity profiles has almost the same values in the range of 20 mm/s-25 mm/s. The shape of the profiles in the bunch is similar too.

In the case of eccentric flow the plane model was filled with flax-seed in asymmetrical way as it was described above. The results presented below show the evolution of the flow and velocity distributions in theses cases.

a) 

b) 

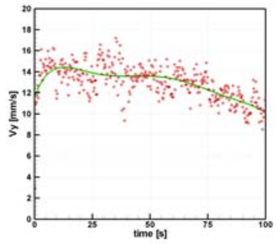
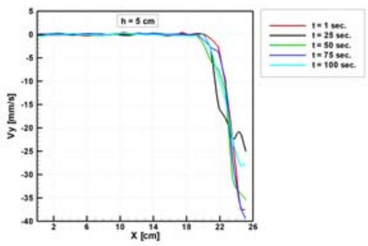
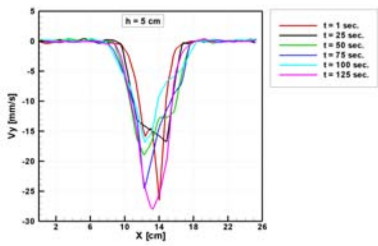
c) 

Fig. 2. Vertical velocity distributions for flax seed in the model with eccentric filling 1 cm from the left edge of the model and discharge from a) the right, b) in the central line, c) in the left.

DPIV technique application made possible to obtain the velocity variation in time in the model. It is interesting to notice that in Figs 2 a, c the velocity distributions differ rather slightly. But Fig. 2 b shows the velocity distribution for the central discharge. It is seen that the velocity distribution tends almost to the symmetrical flow in spite of the way of filling. And the velocity is the lowest in the middle part of the flow. Some selected results of velocity distributions of the analysis are shown for eccentric flow in Figures below.

a) 

b) 

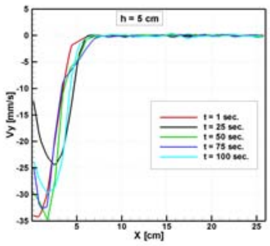
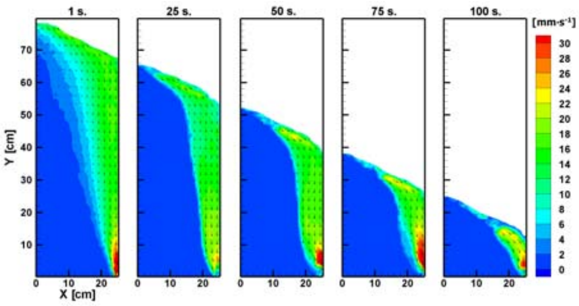
c) 

Fig.3 Vertical velocity profiles for selected levels in the model for eccentric filling and discharge a) from the right, b) in the central line and c) from the left.

In Fig. 3 in each case the velocity profiles create a bunch of functions that means that vertical velocity is constant on certain levels in consecutive phases of the flow. Material during flow has quite different density than at the beginning of the experiment and these conclusions regard to the three cases of discharge.

a) 

b)

c)

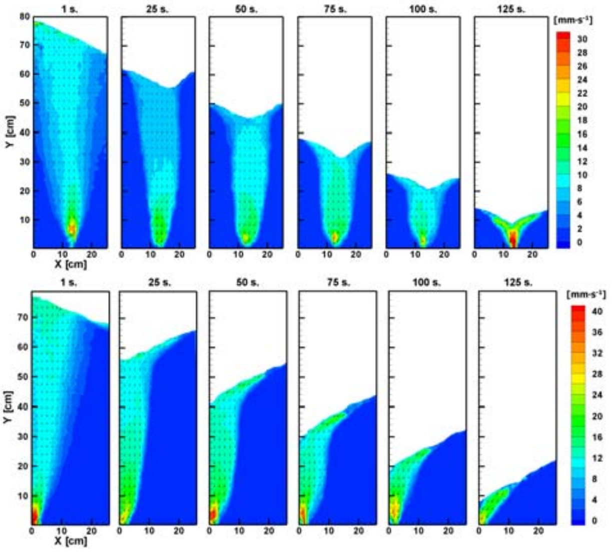
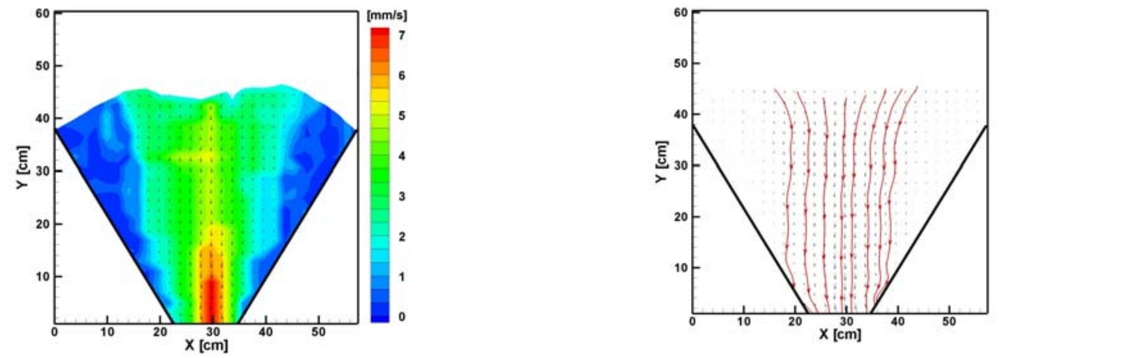


Fig. 4 Velocity contours for considered cases of the flow and discharge from a) the right, b) in the central line and c) from the left.

In Fig. 4 presented velocity contours show the velocities in the whole model. The changed position of the outlet made quite different the velocity values in the material. It appears that when the outlet was placed on the opposite side than the filling pipe was, the velocity is much higher than in the case when the outlet was placed on the same side of the model. In the case of central discharge Fig.4b we can observe rather slowly flow but the material tends to form a symmetrical pattern of flow.

2.3 Selected results for converging model

The granular material (amaranthus) after central filling, formed the upper free surface of a constant slope at an angle equal to the material's angle of repose. With progressing discharge the upper surface lowers. The evolution of the upper surface for flowing amaranthus seed is shown in Fig.5. Figure 5 also presents vector fields in the material. It is seen that the width of the plug flow zone increases rapidly. The boundaries of the flow region away from the outlet are vertical. In the vicinity of the outlet the boundaries of the flow region are slightly curved and the velocity vectors are directed towards the outlet. The vectors located near the upper surface are directed towards the flow region and they indicate the direction of the flow in this region. DPIV images indicate also that instantaneous velocities at various locations in the flow region appear as vertical and constant within this region, but decrease with time. One can observe the channel of the flow where the material density becomes rapidly lower than in the surrounding material after the opening the outlet. Points indicates velocities equal zero. The height of the material was divided into three levels 150, 300 and 450 pixels.
Fig. 5 present velocity vectors and velocity contours in the flowing amaranthus in the initial phase of the flow after 45 s of the flow. It is seen that the material changes its initial density rapidly and practically the whole material becomes loose. Only near the walls the narrow stagnant zones can be observed. The time 95 s is approximately 1/3 of the total flow time. The flow region widened rapidly and almost the whole material is in motion. Fig. 5 b) shows that in the flow region vectors are directed vertically to the outlet. The vector lines are slightly curved near the upper surface. In Fig. 5 b the traces of individual particles are shown and it is seen that in the flow region velocity vectors pass vertically towards the outlet, however, some disturbances can be noticed which come form the natural pollution of the seed.



a)Velocity vectors and velocity contours for the time t=45 s

b) Traces of individual particles for the time t=45 s

Fig.5 Velocity contours and traces of individual particles for the flow in converging model

In this experimental analysis free gravitational discharge of granular materials are presented. DPIV technique made possible to observe evolution of the plug flow in the flowing material. After opening the outlet a plug flow zone rapidly forms in the material and reaches the height of the packed material during the first 10 seconds after beginning of the flow. From the beginning of the flow till about 160 s of the flow, the evolution of the plug flow zone is represented by a slightly concave line.

3. Conclusions

In this paper, we present possibilities of the DPIV technique as a new one in the analysis of flow evolution and dynamic behaviour of densely packed cohesionless materials in plane model with three positions of the outlet and in converging model. This analysis allowed for the evaluation of velocity vectors for each point of the flow. In further experimental work, one can use data obtained here to predict the stresses in the flowing material using velocity gradients inside the flowing zone. It is well known that this parameter plays the main role in such analysis. And the DPIV technique seems to be a sufficient diagnostic tool of quasi two-dimensional granular flows. However, evaluation of the stresses on the bin wall is still a challenging task. The velocity of the granular material near the wall is equal or close to zero and cannot be used to calculate the wall stresses. The velocity gradients measured on the boundary of the stagnant zone could offer useful values for calculating wall stresses. Such evaluation, combined with the stresses measured at the wall by electrical transducers, could offer the possibility to verify theoretical descriptions of mechanical properties of granular media.

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