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Investigation of the sedimentation process using flow visualization methods

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The aim of the paper was to develop determination methods of sedimentation characteristics using PIV image anemometry and suspension image analysis. Two methods of the investigation of sedimentation process based on visualization techniques were developed. In the first one, using PIV method, vector fields of the velocity of settling particles are determined and then average particle velocities are calculated to establish the so called sedimentation dynamics curve. In the second one, the methods of suspension image analysis are utilized to determine the positions of the upper discontinuity and to establish the sedimentation curve. Laboratory research on the sedimentation of agalit particles suspended in glycerine was conducted (using PIV method). Additionally, industrial research on the sedimentation of water-absorbing granular material used after the first carbonation (carbonation I) was conducted in a sugar factory (using the second method). The research consisted of photographic registration of images of the settling suspension by means of the time-lapse photography technique. A laboratory study was conducted for four values of the volume concentration of agalit particles in glycerine (0.5; 1.0; 1.5 and 2.0 vol%). The research methodology, the scope of the conducted measurements and sample research results together with conclusions are presented in this paper.

Keywords: sedimentation dynamics curve, flow visualization, particle image velocimetry

1. INTRODUCTION

The sedimentation of suspensions is a process utilized in many branches of industry and in environmental engineering. Sedimentation, that is, settling of particles of solid substance in a liquid, makes it possible to thicken suspensions under the influence of gravitational field. This process is used in industry for thickening suspensions in settling tanks, for clarification of liquids (e.g., in water purification) and for classification of granular materials (e.g. in mineral processing). Traditional settling tanks are utilized in municipal sewage treatment plants, water purification stations, industrial plants (pulp and paper mills, tanneries, mineral-processing facilities, etc.).

Correct calculation of the volume, surface area and depth of a settling tank requires knowledge of the sedimentation curve. Usually it is determined by means of so called suspension sedimentation test (Bandrowski et al., 2001; Darby et al., 2016; Hendricks, 2010) in which the behavior of the suspension in a transparent container is observed. However, it happens frequently that the border between the sediment and suspension zones is difficult to distinguish causing significant uncertainty in determination of the sedimentation curve. This issue can be resolved by investigating suspensions with the same concentration of solid particles

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but with different settling heights. It means that several additional sedimentation curves can be obtained and *ipso facto* several different critical points, too. The end of the hindered settling and the start of the compression zone are referred to as the critical point. By connecting consecutive critical points with a line, the curve of sediment build-up can be determined.

An attempt to measure the profiles of sediment velocities in a container by means of Ultrasonic Doppler Velocity Profiler (Metflow SA, UVP-DUO) was undertaken by Kantoush et al. (2006). Using three measuring probes they obtained flow fields in 3D.

In the work of Kantoush et al. (2008) numerical simulations of suspension settling in shallow containers were conducted and the obtained results were tested regarding their compatibility with real-life suspension flows and sedimentation patterns. They investigated the impact of container geometry on sediment transportation and settling, utilizing the methods of numerical simulation and experimental studies. In their research they focused on determining the depth of a prototype container and in their experimental studies they used the PIV method.

Capart at al. (1997) used visualization methods for investigating the kinetics of water-sediment interaction. They devised a special algorithm of particle identification in order to deal with densely packed particles. This allowed the application of digital particle tracking velocimetry (DPTV).

Tan et al. (2012) used experimental study on laboratory-prepared clay and guar gum (used as an analogue for neutral extracellular polymeric substance (EPS)) suspensions to characterize EPS-induced flocculation and the settling velocity of the resultant flocs. Floc size was determined with a laser particle size analyzer, and the settling velocity was estimated by analysing the time-series floc settling images captured by an optical microscope.

In the work of Azema (2006), the agglomeration and dispersion phenomena of mineral suspensions in water and ethanol media have been studied using a granulometric and sedimentation approach (electrophoresis mobility, particle size distribution, clarifying speed, sediment formation). This experimental work has perfectly shown the necessity to achieve a complementary approach to these three optical methods to completely investigate the sedimentation behavior.

Research on the sedimentation of microparticle suspensions in a water supply system was presented in the paper of Hofman at al. (2015). The experimentally obtained values of settling velocities were compared with selected sedimentation models and significant discrepancies between the experimental and calculated velocity values were found.

Experimental investigation of batch sedimentation of concentrated bidisperse suspensions was presented by Hernando et al. (2015). The sedimentation of concentrated (30% in volume) bidisperse suspensions was experimentally examined using a laser-induced fluorescence technique. The sediment structure was examined and its constitution was evaluated in the course of time, showing the occurrence of the transition from mixed sediment to mono-sized sediment.

In the work of Lu et al. (2015), automatic and quantitative monitoring of the sedimentation dynamics for non-homogenous systems such as suspension, emulsions at laboratory level was presented. The visualization methods and digital image processing techniques were used to determine the sedimentation curve. The sedimentation curve and sedimentation dynamic equation of a non-homogeneous system were output by numerical fitting.

Determination of sedimentation dynamics curve with digital image anemometry was proposed by the present author (Suchecki, 2016). The proposed research method was tested for small concentrations, not exceeding 2.0 vol%, of solid particles in the liquid.

In this paper the following new methods are presented:

- determination of the sedimentation dynamics using PIV digital image anemometry,
- determination of the sedimentation curve using suspension image analysis.

The suitability of the proposed methods depends on the concentration of solid particles in the liquid. At small volume concentrations allowing to differentiate between single particles in the suspension, the PIV method can be used to determine the sedimentation dynamics curve. At higher volume concentrations the sedimentation curve can be determined by registering suspension images that are subsequently processed and analyzed.

2. EXPERIMENTAL SETUP AND PROCESSING OF MEASUREMENT DATA

Figure 1 shows a scheme of the experimental setup in which the research was conducted on the sedimentation of agalit particles in glycerine. Agalit density was 2450 kg/m^3, diameter of particles 0.4 mm; glycerine concentration (in a mixture with water) was 90%, density 1235 kg/m^3 and kinematic viscosity 1.9×10^{-4} m^2/s. The research was performed for four volume concentrations of agalit particles in glycerine: 0.5, 1, 1.5 and 2.0 vol%. The sedimentation took place in a glass container whose rear wall had been made of frosted glass to obtain better dispersion of light. In order to obtain uniform illumination four halogen bulbs and an additional light-reflecting surface (Fig. 1, pos. 2) were used. The uneven brightness of the measurement area did not exceed 1%. A view of the experimental setup is shown in Fig. 2.

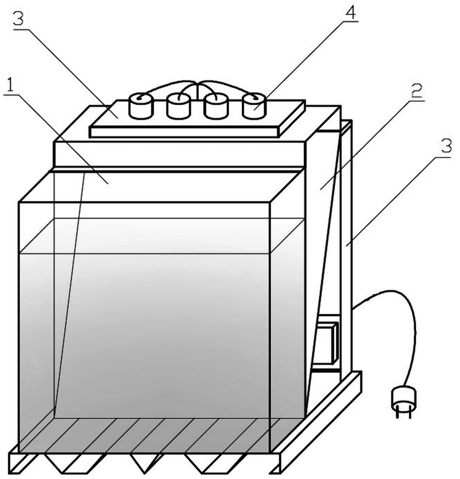

Fig. 1. Scheme of the experimental setup; 1 – glass container, 2 – light reflecting surface, 3 – cover, 4 – halogen bulbs with casings

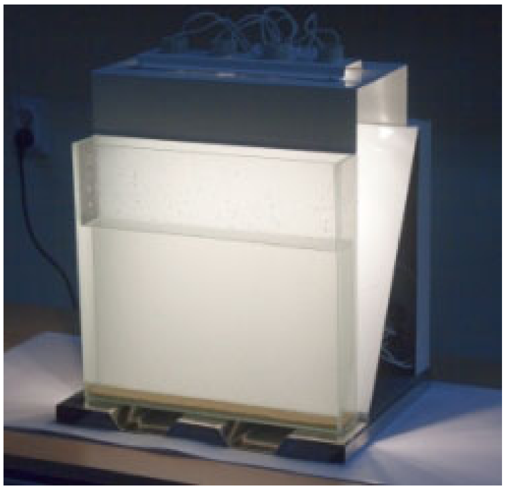

Fig. 2. View of the experimental setup

A container seized 300 × 300 × 50 mm was filled with glycerine. Then a measured dose of agalit particles needed for obtaining the studied volume concentration, was added and the suspension was blended (slow-speed propeller stirrer). When the blending process was over, the recording of images of the settling particles with a Canon EOS 50D camera (resolution of the sensor 4752 pixels × 3168pixels) started. Lens EF-S55-250 mm, ISO 100, aperture value F 4.0, shutter speed 1/200 sec, manual control. Images were taken every two seconds using time lapse technique in series that began at every minute. In the series 15 images per every 2 seconds were registered. The time interval between the last image in the preceding series and the first image in the following series was 1 minute. The series of recorded images allowed to determine the velocity fields of agalit particles in glycerine by means of PIV method and to determine the position of the upper border of the suspension discontinuity in time.

2.1. Determining the velocity of particle settling and the curves of sedimentation dynamics

The flow images recorded in RAW format were converted to BMP 8-bit format. Then the diagrams of velocity vector fields were determined using PIV method (Suchecki, 2000; Westerweel, 1993; Willert et al., 1991). The size of the measurement field (interrogation area) was 16 × 16 pixels. The obtained velocity fields were filtered by means of the author's own software (Suchecki and Alabrudziński, 2003) to delete any incorrect vectors and to substitute it by the average of neighbouring vectors.

Sample distributions of velocity fields of agalit particles in glycerine for the concentration of 0.5 vol% after 60 and 600 seconds of sedimentation are presented in Fig. 3. Next, using the histograms of velocity-vector field covering the entire measurement area, the average velocity for each velocity field distribution was determined (Fig. 4). The value of the average velocity refers to a specific moment in time. It was set by means of the correlation of 2 images that had been recorded with the time interval of 2 seconds.

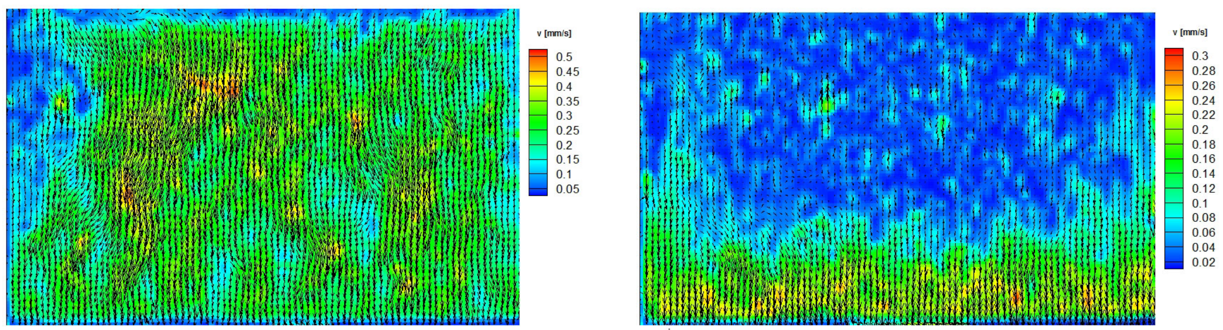

Fig. 3. Distribution of velocity fields of agalit particles in glycerine for the volume concentration of 0.5 vol% after 60 (a) and 600 (b) seconds of sedimentation. In the diagrams, velocity maps determined by means of average square method and appropriate legends are presented

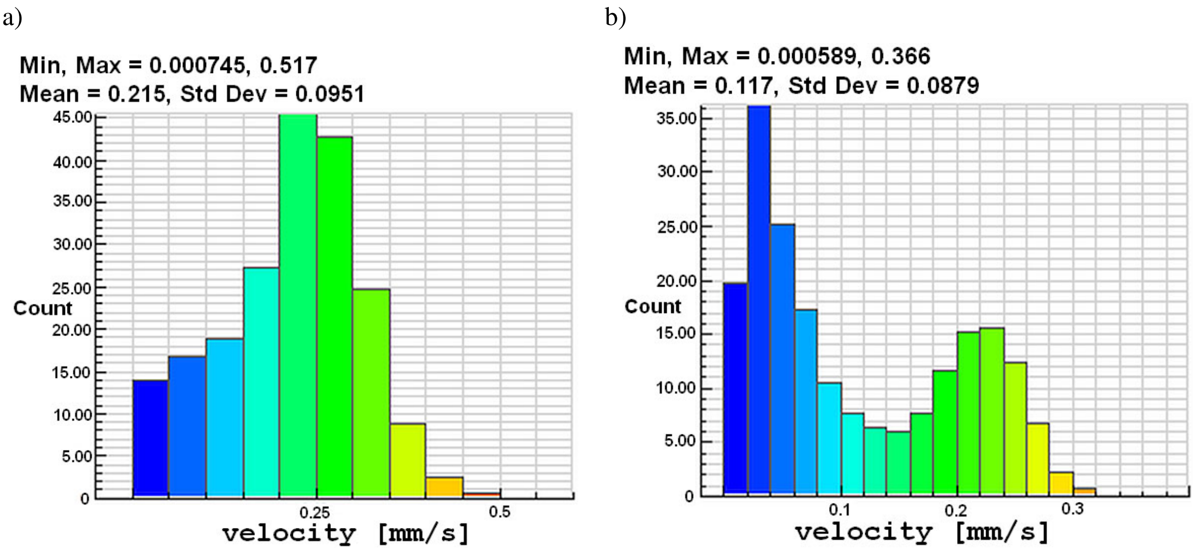

Fig. 4. Histograms of the velocity field of agalit particles in glycerine for the concentration of 0.5 vol%: a) after 60 s; b) after 600 s

Based on the average velocities found for each velocity field, the diagrams of time dependence of the velocity of suspension settling were determined. These diagrams are referred to as the curves of sedimentation dynamics.

Figure 5 shows sample curves of sedimentation dynamics determined by the velocity method for different volume concentrations of agalit particles in glycerine. These curves illustrate the impact of volume concentration on the time dependence of the velocity of settling particles.

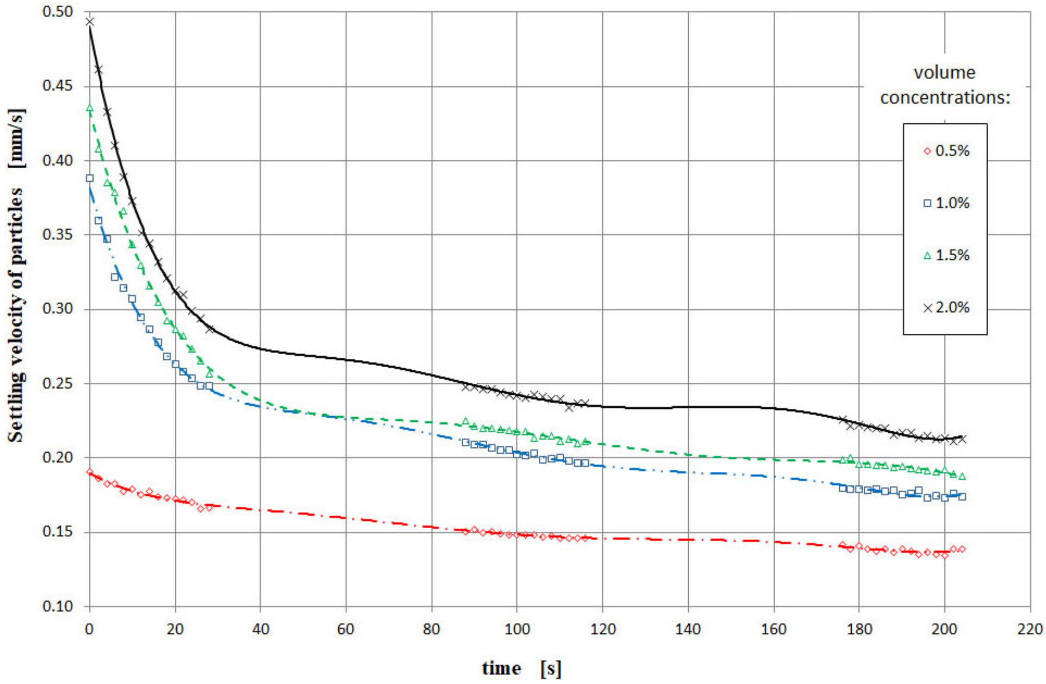

Fig. 5. Impact of the volume concentration of agalit particles in glycerine on their settling velocity as function of time – sedimentation dynamics curves

It can be noticed in the measurement results that an increase in the volume concentration of the agalit particles in glycerine has a significant effect on the velocity of their sedimentation. As can be seen in Fig. 5, at the volume concentrations between 1 vol% and 2 vol% the curves of sedimentation dynamics are similarly shaped. At higher volume concentrations, the average velocity of particle settling increased, especially during the initial stage of sedimentation but after 40 seconds, it significantly reduced. This is related to the interactions between the settling particles and to the generation of hydrodynamic traces in the liquid volume where the particles are moving. The hydrodynamic trace means the liquid movement was induced by a moving particle. This hydrodynamic trace might influence the movement of the consecutive particles. After that, changes in the average velocity of the particles became more balanced due to the fact that most particles reached the container bottom and only few particles were still settling. At the volume concentration of 0.5 vol%, changes of the velocity in time were insignificant due to reduced particle interactions and reduced influence of the hydrodynamic traces on the velocity of settling particles.

2.2. Determination of the sedimentation curve using the method of suspension-image analysis

In the classic sedimentation test, the time dependence of the position of the upper limit of the suspension discontinuity is being determined optically. Using the method of image analysis, the consecutive images of the settling suspension are first recorded and then the readings of the upper border of suspension discontinuity are taken from the recorded images. In the reported research, the positions of the upper limit of discontinuity were determined by means of a special algorithm implemented in Matlab software.

The determination of a sedimentation curve is performed in the following stages. First, the color palette of consecutive suspension images is being changed from RGB to binary, and binary images are stored in the computer memory (Fig. 6). Then, thresholding is carried out with the upper and lower threshold values. The lower and upper values of the thresholds are selected experimentally. In this case the lower and upper thresholds were respectively 10% and 76%. After binarization and thresholding, only two pixel values – white and black – remain in each image (Fig. 7). White pixels represent solid particles and black ones represent the liquid. Additionally, there was an assumption that the percentage quantity of white pixels above the line of discontinuity border might be maximally 0.2%.

Fig. 6. Image of suspension for volume concentration of 1.5 vol%

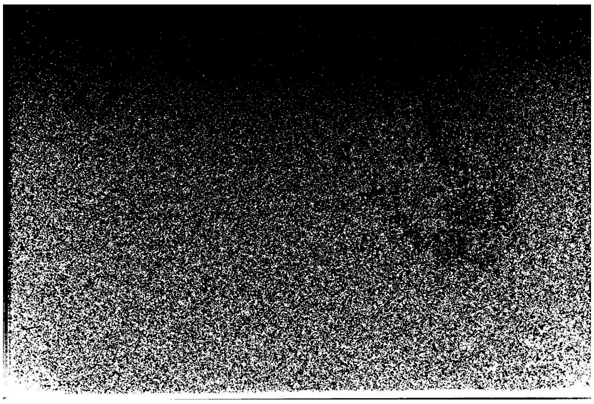

Fig. 7. Negative image of suspension after binarization and thresholding

In the subsequent stage, the position of the upper border of discontinuity is being established. This is done by identifying the border line and determining its distance from the bottom of the container. Initially, the image is converted into a matrix. Since the image was binarized, each matrix element may equal 1 which corresponds to a white pixel, or may equal 0 which corresponds to a black pixel. Next, the summation of elements in each matrix row is performed starting from the lowest one, and a check is made whether or not the obtained value is not less than the predefined number of white pixels in the rows above the discontinuity border. This number is usually derived from the required percentage of white pixels that has been assumed depending on the volume concentration of particles, and the checked condition reflects the fact that the velocities of settling particles are differentiated so that no sharp border is created between the suspension and clear liquid. The position of the line in which the assumed condition has been fulfilled is recorded as the position of upper discontinuity and its distance to the container bottom is determined. In order to finalize the procedure, a line is drawn on the suspension image and a text field with the distance value in pixels is added, and the resulting figure is stored as a graphical file (Fig. 8). The height of the line position on the upper discontinuity border is determined for consecutive images that are registered in the known time intervals. On this basis the sedimentation curve is determined.

Fig. 8. Suspension image with the line drawn at the upper limit of discontinuity and added text field

When studying sedimentation curves, the distance values defining the time dependence of the positions of the upper discontinuity border are recorded in column format in a text file which significantly facilitates their processing by calculation software. Figure 9 illustrates the sedimentation curves determined for the studied volume concentrations of agalit particles in glycerine.

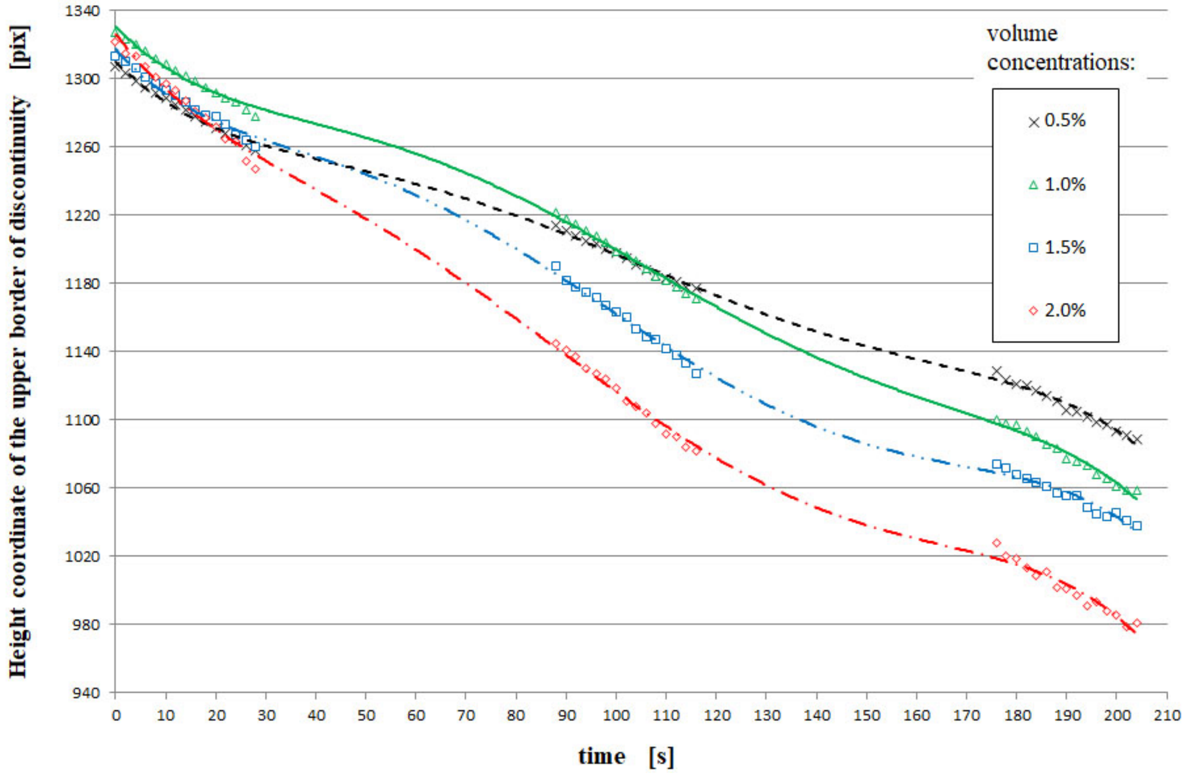

Fig. 9. Sedimentation curves determined with analysis of suspension images

While analyzing the research results presented in Fig. 9, similarly to the case illustrated in the diagram of the curves of sedimentation dynamics (Fig. 5), it may be noticed that an increase in volume concentration of agalit particles in glycerine has a significant impact on the velocity of their sedimentation. Fig. 9 allows to draw conclusions similar to those from Fig. 5. It should be noted that the speed of sedimentation is associated with the diagram of sedimentation curve (Fig. 9). Fig. 5 depicts the curve of sedimentation dynamics which presents the change of suspension velocity in time. At the initial stage of sedimentation, until second 20 of the process, the differences between velocities of agalit particles settling in glycerine are visible more clearly in the diagram of the curves of sedimentation dynamics (Fig. 5) as compared to the sedimentation diagram (Fig. 9).

This is a consequence of the average settling velocity of suspension particles being determined by the PIV method of image anemometry that allows to take the velocities of all the particles visible on the sedimentation image into account. It can thus be concluded that the curves of sedimentation dynamics provide more precise information than the sedimentation curves obtained from the analysis of suspension images. However, applicability of the method of determining the curves of sedimentation dynamics may be restricted by the volume concentration of solid particles in suspension. If the volume concentration is so high that the distinction between individual particles in the suspension image is not possible, the PIV method cannot be used. Nevertheless, it is possible to determine sedimentation curves by means of the analysis of suspension images. This is exemplified by a study of sedimentation under industrial conditions described below.

2.3. Research on sedimentation of the granular material used for beet-juice dewatering after carbonation I

In sugar technology, carbonation is a process of saturating limed beet juice with carbon dioxide aimed to precipitate calcium carbonate sediment that facilitates separation of colloidal impurities (so called non-sugars) from the juice. Calcium hydroxide present in the limed juice reacts with carbon dioxide forming calcium carbonate crystals that adsorb colloidal impurities and make the subsequent filtration more effective. In some sugar factories, a granular dewatering (water-absorbing) material is added to the juice to enhance the effect of carbonation.

The sedimentation of dewatering granules present in the beet juice after the process of the first carbonation was investigated in Pfeifer & Langen sugar factory. The aim of the research was to determine sedimentation characteristics of the granule-containing suspension and to check the usefulness of the visualization methods under industrial conditions.

It should be remarked that the volume concentration of dewatering granules in water was much higher than the volume concentration of agalit particles in glycerine in Fig. 8 and this makes it impossible to distinguish individual particles in the suspension image. In such a situation the curve of sedimentation dynamics cannot be determined by the PIV method, but the sedimentation curve can be established by the analysis of suspension images.

The research was conducted with the experimental setup presented in Figs. 1 and 2. The glass container was filled with suspension taken directly from the sugar factory at a temperature of about 60 °C and volume concentration of the granules of about 14 vol% and the recording of sedimentation images was started. Images were recorded in five series. In the first series 193 images were taken every second, in the second series 30 images every 5 seconds, in the third series 18 images every 10 seconds, in the fourth series 29 images every 30 seconds and in the fifth series 7 images every minute. In total 277 images were recorded and the duration of the sedimentation experiments was 32 minutes and 43 seconds.

In order to determine the sedimentation curve, the method of analysis of suspension images was applied. Examples of suspension images with the lines indicating the upper border of discontinuity recorded at the initial moment and after 105 seconds of sedimentation are shown in Fig. 10. In Fig. 11 diagrams

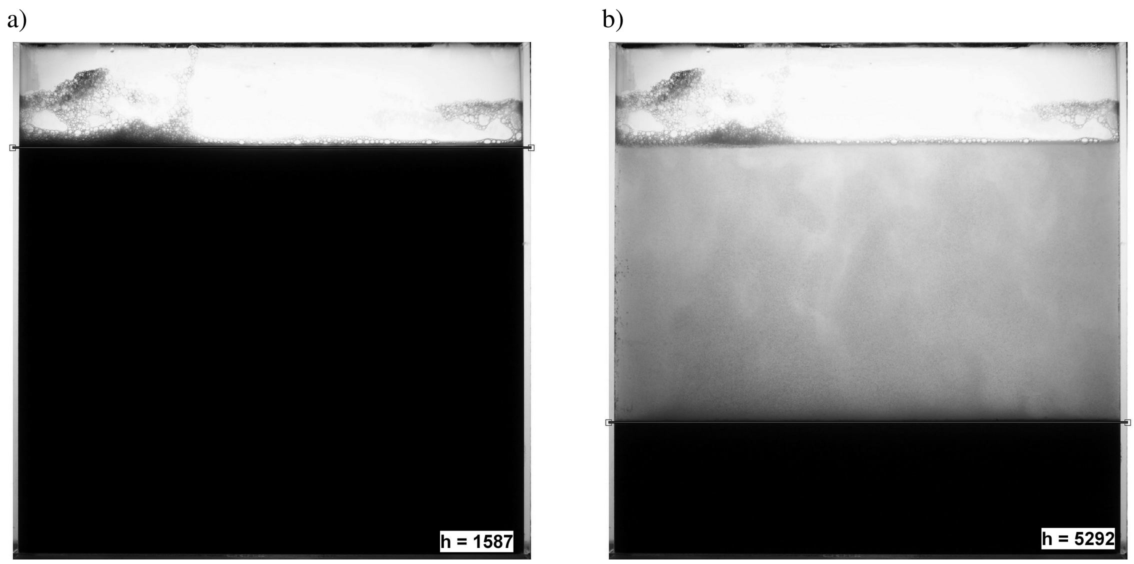

Fig. 10. Images of the suspension of dewatering granules at their concentration of about 14 vol% in the beet juice after carbonation I, with lines indicating the position of the upper border of discontinuity: a) at the process initiation, b) after 105 seconds of the process duration

of sedimentation curve of dewatering granules in the beet juice after the process of carbonation I are presented.

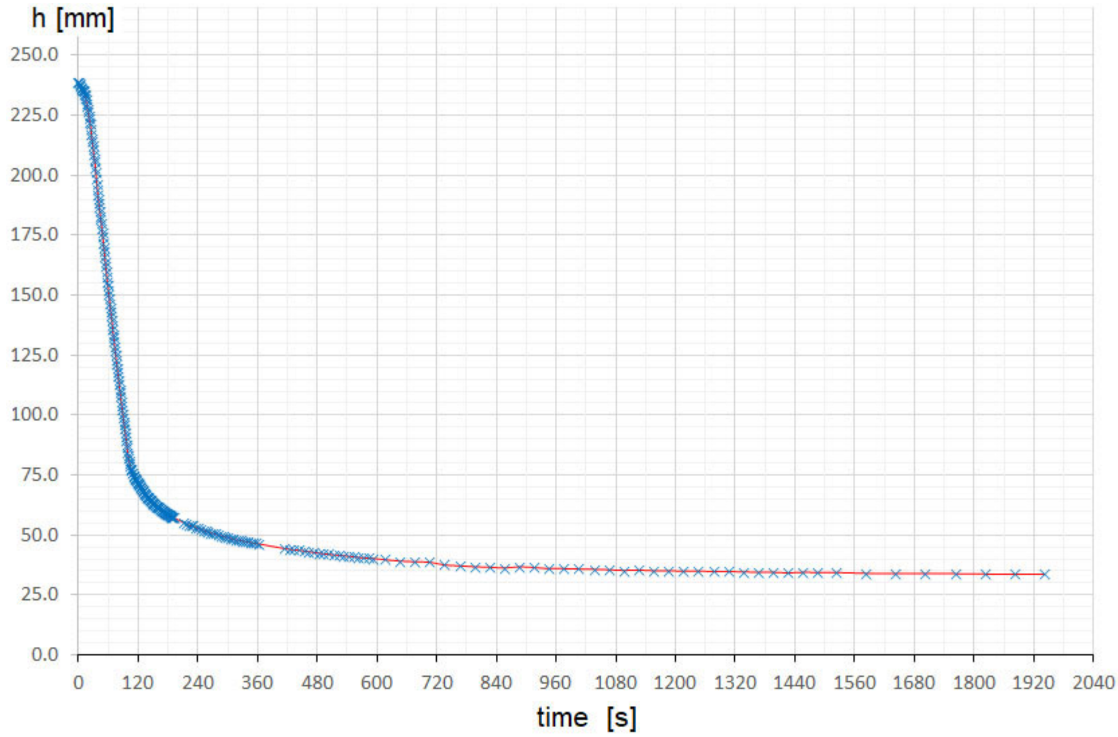

Fig. 11. Sedimentation curve of dewatering granules in beet juice after the process of carbonation I determined using the method of suspension image analysis. The concentration of the granules was about 14 vol%

As can be seen in the measurement results presented in Fig. 11, the maximum velocity of the settling granules occurs at the beginning of the process and lasts for about 2 minutes. After this period the velocity is significantly decreased and after about 14 minutes, the sedimentation is completed.

3. CONCLUSIONS AND DISCUSSION

The proposed methods of investigating the process of suspension sedimentation based on visualization methods were developed in the Flow Visualization Laboratory of the Department of Process Equipment of the Warsaw University of Technology (Płock Campus).

The method of determining the velocity of suspension particle sedimentation in time, so called sedimentation dynamics curves lies in determining the velocity fields of suspension particles using PIV method, followed by determining the average velocity fields in time, based on the average velocities of the particles.

The method of determining the sedimentation curve by means of image analysis involves recording of time series of images of the settling suspension.

The accuracy of the obtained curve of sedimentation dynamics depends on the quality of recorded flow images. The image quality can be affected by numerous factors, such as the illumination of the observed flow area, presence of air bubbles in the suspension, suspension stirring, etc.

- During the computer-aided image processing, air bubbles attached to the container wall or present in the suspension can be recognized as solid particles, and *ipso facto*, give false information on particle movements in the suspension. The effective disposal of air bubbles influences significantly the obtained results.

The use of PIV method for the entire sedimentation area increases the accuracy of determination of the sedimentation curve. Complete automation of the measurements is also possible and in the investigation of suspensions with variable concentration of solid particles, it can significantly improve the determination accuracy of sedimentation curves over longer time periods.

Determining the sedimentation curves by means of the classic method (so called sedimentation test), i.e. by the observation of the behavior of suspension in a transparent container can be biased by random error of identification of the border between suspension zones (e.g., these can be difficult to distinguish) in consecutive time moments. In the proposed method of determining the sedimentation curve by means of image analysis, the random error is eliminated so only systematic error can appear. Since the images of suspension zones with the identified line of the upper discontinuity border are recorded in graphic files, this allows to minimize or even eliminate the systematic error. Thus it can be concluded that the method based on the analysis of suspension images is more reliable, compared with the classic method. Also in this case, full automation of measurements is possible to facilitate process control, e.g., to select optimal doses of the granular material used in the process of beet juice carbonation.

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