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Aggregates Settling Velocity-Direct In Situ Measurement

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Abstract: Settling velocity and size of aggregates were observed by the method where the aggregates were illuminated by light sheet (plane) and their movement and size were evaluated from image analyses of obtained images. The main aim was to measure settling velocities of aggregates in situ. The used model system was an agitated vessel where the aggregation process took place. Such determined settling velocity could advantageously serve as a complex parameter for scale up of separation equipment.

Keywords: Particles, settling, aggregates, laser visualizations, agitated tank

INTRODUCTION

The aggregates are commonly described by their size and shape. But aggregates created in nature by aggregation processes are irregular and non homogenous. The size and shape measurement methods are based on secondary used physical principles (light scattering, electric field etc.) with several presumptions (regular shape, homogeneity) and various degree of accuracy (3). That is why the results of such measurements could be considered as relative ones only because two different methods usually give not consistent values.

The idea was to experimentally determine aggregates behavior in situ, not only for one aggregate (or selected samples) but for large percentage of the

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population. It appeared to us that the settling velocity is the most representative parameter for process calculations because it includes the complex information about the aggregate size, shape and density (1, 4, 5, 7). Our experimental method was based on the image analyzes of pictures taken by camera with the speed of about 100 pictures per second in a plane illuminated by laser beam.

SETTLING VELOCITY AND SIZE MEASUREMENT

Our measurement technique (Fig. 1) anologous to Bouyer (2) uses the same principle as the particle image velocimetry (PIV) system. The particles are visualized by laser beams passing through an agitated suspension and scattering from them. The light sheet illuminates the particles in a thin slice of fluid and the sequence of images is recorded. The camera is placed upright to the laser plane. Continuous laser sheet is used as light and images are taken by a digital camera. Subsequently the images are processed by image analysis. Applying the image analysis we obtain the projected particle area and the median point of particle.

Experimental

The experiments were carried out in a flat bottomed agitated cylinder vessel with diameter $T = 150$ mm. The height of liquid was T. The vessel was

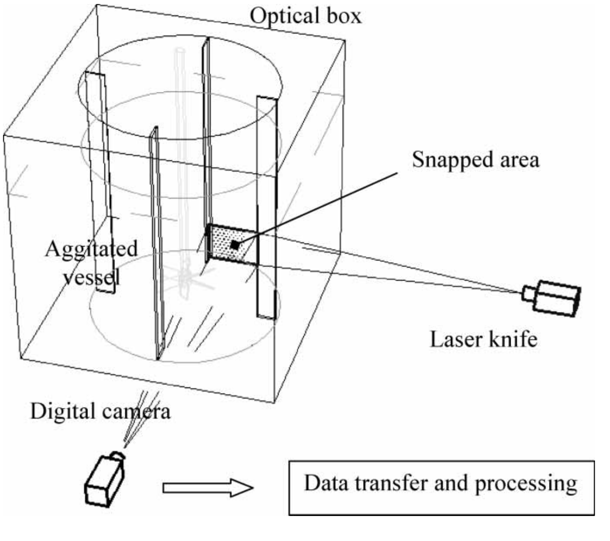

Figure 1. Measuring system.

Table 1. Digital camera settings

Aperture	1.8
Shutter time	5 ms
Noise	8 dB
Frame rate	100/s
Image resolution	700 × 600

equipped with four baffles having the width 0.1 *T*. The tank was agitated by the six pitch-blade turbine with diameter $d = 60$ mm and off-bottom clearance was *d*. The continuous laser knife power input was 20 mW with red laser and wavelength 675 nm. The thickness of the laser plane was 1.1 ± 0.1 mm (the plane beam intensity has Gaussian behavior). The digital camera (Epix Inc.) settings are given in Table 1. The size of recorded area was approximately 30 × 25 mm.

The tank was filled with model suspension consisting of distilled water and SiO_2 powder named SILOXID (manufactured by SILCHEM) with mass/volume moment mean diameter $D[4,3] = 20\ \mu m$ measured by FRISCHT Analysette 22 Compact.

Evaluation of Measurement

The measurement generally includes the following steps:

i. particle visualization, digital capture of pictures and data transfer to PC
ii. image processing of single pictures
iii. processing of trajectory history
iv. evaluation and reporting. The steps (ii) and (iii) are described in Fig. 3.

The data from single images are processed by image analysis. The commercial software Sigma Scan Pro 5 is used. The sequence of images is automatically processed by macro script in the following steps: image calibration, image threshold, layer filters (fill holes, delete edge objects etc.), objects

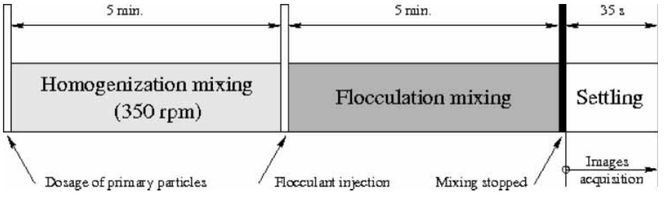

Figure 2. Experimental mode-preparation and settling of aggregates.

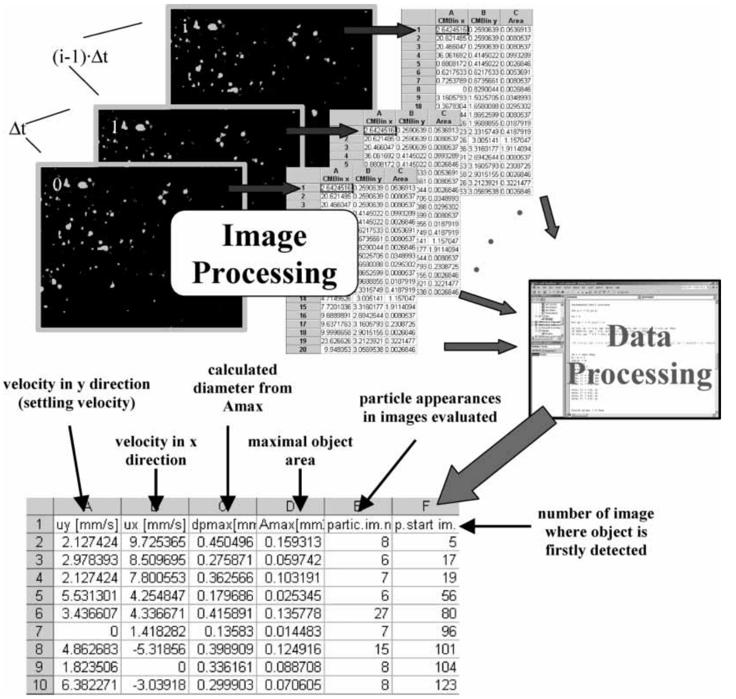

Figure 3. Evaluation procedure.

counting. The final results of the step (ii) are summarized in tables shown in Fig. 3. For each picture data are configured in one table where the projected object areas A_i and the median particle point coordinates x_i, y_i are given.

The following treatment-step (iii)-compares the data from neighboring images. The Excel macro script compares the object size and position. Then the data of object traces are recorded: object area A, center coordinates x, y of area, number of images where the object starts and number of images with an object.

Evaluated are only objects meeting the following conditions:

a) The object areas constructed for two consequently following images as the circles of equivalent radiuses having their centers in the median points of particle has to be cover or touch each other.
b) The object area change between two following images is limited by ratio 5.

In other cases the objects could not be taken as detected particles.

In the last step only the particles appearing in six images and more are subject of evaluation. Application of this rule increases settling velocity resolution and is accompanied by a significant improvement of results.

Table 2. Mixing parameters

Impeller speed [rpm]	Re [−]	ε_V [W/m^3]
100	5934	2.5
130	7714	5
160	9494	10
210	12461	21
260	15428	40
350	20769	98

Experimental Results

The presented results were chosen for one concentration of model suspension 250 mg/l SiO_2, and one concentration of polymer flocculant Sokofloc 16A, which was 0.8 mg/l. The preparation of suspension is described in Fig. 2. The measurements were proved for variable impeller speed giving variable Reynolds number and mixing intensity, see Table 2. The results from image analysis and data processing enabled presentation by various methods. The first is the particular particle velocity behavior hence the data processing included the particle tracking. The points depicted in Fig. 4 follows practically a straight line what is in an agreement with theory of unhindered settling. Figure 5 shows a horizontal movement of a particle that is caused by additional forces (inertia forces etc.). The detected particle area vs. time was depicted in Fig. 6. The detected area practically depends on light conditions, particle movement and particle shape, respectively. The maximum

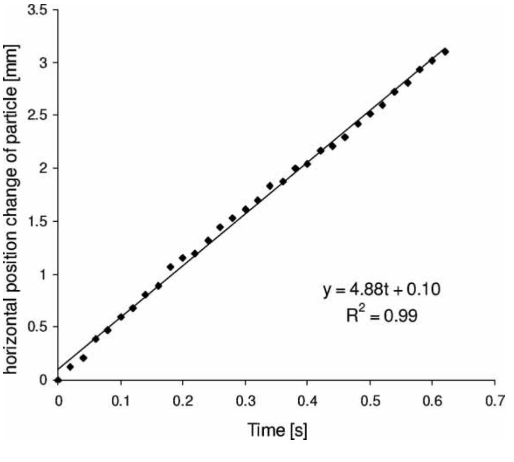

Figure 4. Verticall position change (y direction) of detected object passed through 32 frames. The slope of interpolate line is settling velocity in mm/sec.

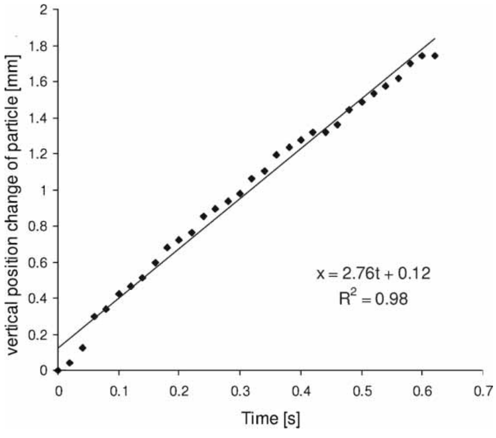

Figure 5. Horizontal position change (x direction) of detected object vs. time. The slope of interpolated line is velocity perpendicular to settling velocity in mm/sec.

value of object area (Amax) was accepted as the real particle size considering that the particle is not fully visualized in other images due to its approaching to the laser plane.

The result interpretation for suspension after mixing is stopped is demonstrated in Fig. 7. The time dependency of settling velocities (u_y) immediately after impeller is switched-off (time = 0 s) was depicted in this picture. The particle velocities in horizontal direction (x) vs. time were depicted in Fig. 8. The measurements have proved that the settling velocity disturbance is quite low after 30 s in all cases. The time

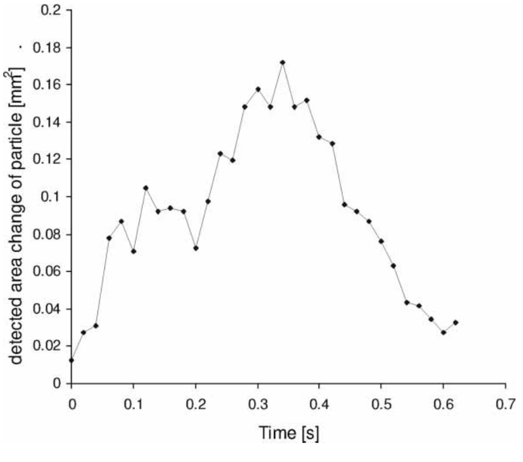

Figure 6. Time change of detected object area.

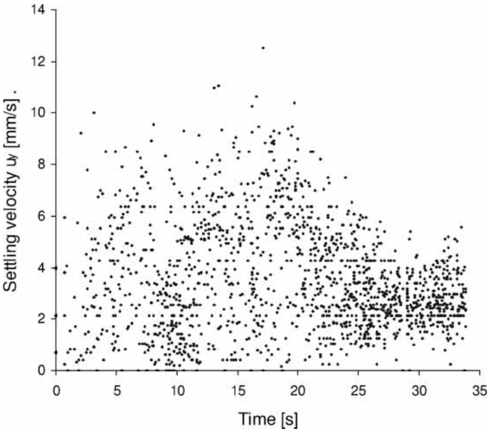

Figure 7. Aggregates settling velocity vs. time after 5 min mixing at 260 rpm ($\varepsilon_v = 40\ W/m^3$).

dependency of equivalent diameter obtained from detected particle area was depicted in Fig. 9.

The equivalent diameter d_{peq} was calculated from maximal particle detected area Amax. All these results give information about aggregates motion and also about suspension agglomerates "quality". That means that even smaller particles created at higher mixing intensity might sediment uniformly due to more compact structure and higher density, consequently. Data of particle size and settling velocity were obtained simultaneously. The aggregate equivalent diameter histograms are depicted in Fig. 10.

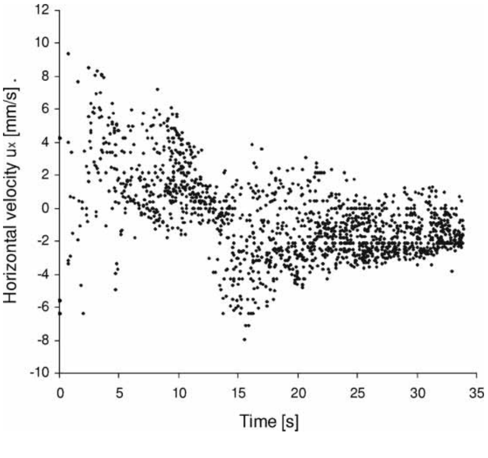

Figure 8. Aggregates horizontal velocity vs. time after 5 min mixing at 260 rpm ($\varepsilon_v = 40\ W/m^3$).

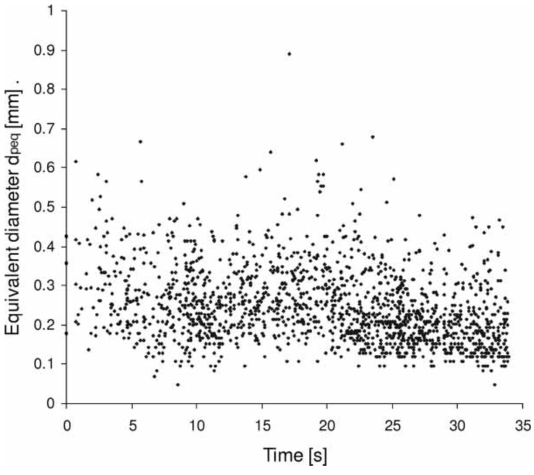

Figure 9. Aggregate equivalent diameter vs. time after 5 min mixing at 260 rpm ($\varepsilon_v = 40\ \mathrm{W/m^3}$).

There the abscissa represents the diameter of aggregate, which was equivalent to sphere diameter with the same projection. The ordinate shows the relative number of aggregates what means the number of real aggregates divided by the maximum sum of all of all measured aggregates. In our case the maximal sum of aggregates was achieved for 260 rpm (1560 aggregates/35 s). The settling velocity histograms depicted in Fig. 11 were evaluated from identical particles as depicted in Fig. 10. Both particle size and

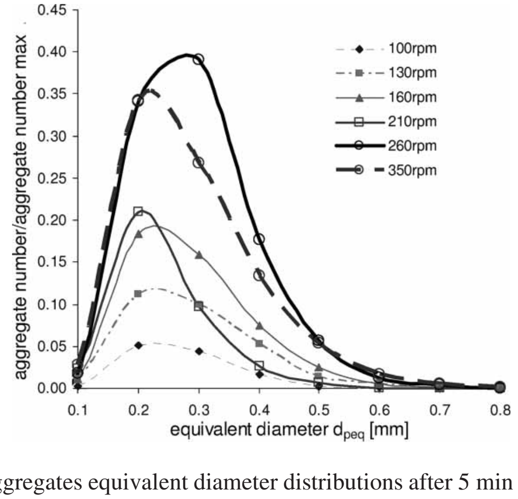

Figure 10. Aggregates equivalent diameter distributions after 5 min mixing at different impeller speed. Particles captured within 35 seconds of the experiment.

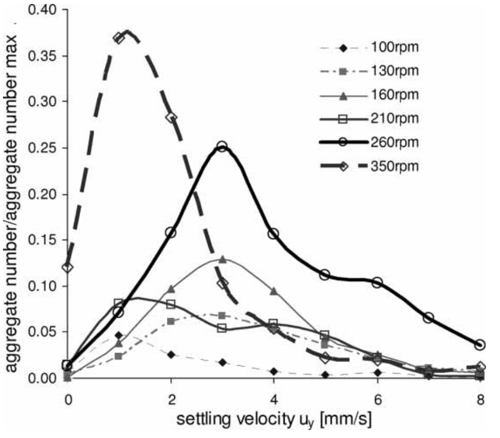

Figure 11. Aggregates settling velocity distributions after 5 min mixing at different impeller speed. Particles captured within 35 seconds of the experiment.

settling velocity was evaluated from one experimental course and set. It worth to note that despite of difference in settling velocities particle sizes are almost identical. Plausible explanation of this effect is an increase of density and more compact structure. It follows from our measurements: (i) The aggregation by impeller speeds 100, 130, 160 rpm produced a large percentage of non aggregated fractions. (ii) Impeller speed 210 rpm produced small particles but the percentage of non aggregated fraction was low. (iii) The optimum impeller speed from the point of highest settling velocities was 260 rpm.

The same result was obtained and published by Šulc (6), who used the turbidity measurements. (iiii) Impeller speed 350 rpm after aggregation produced some percentage of small particles with settling velocity near zero. The settling velocity measurement method supplied more information than those presented here but the complex evaluating form needs another development and validation.

RESULTS AND DISCUSSION

From the view of purification processes aggregation is a complex problem, hence classification of aggregation needs a more complex approach. In the nature aggregation is going on natural substances and aggregates formed are not homogeneous. In the first step of aggregation all impurities are removed and separable aggregates are formed. This process has to be controlled by chemical tests. The second step is an optimization of aggregate physical properties influencing the sequent separation process. From common purification methods (filtration, flotation, settling etc.) there are demands on homogeneity of particle size, shape and density. It was found useful to cover and check all these parameters together by means of settling velocity because it includes them. The proposed settling velocity measurement method allows to obtain more global information about aggregates process behaviour than particle size measurement methods, moreover, the proposed experimental method can be applied in situ and in relatively large volume (not only for manually selected aggregates). Measured data can be advantageously used for separation equipment design and scale up.

Analogically to particle size distribution curves the aggregates settling velocity histograms were experimentally determined and plotted. Such histograms can be advantageously used for calculation and design of settling equipment and flocculation reactors. Frequency data plotted on y-coordinate were normalized so it ranges in the interval from 0 to 1 what makes them easily comparable with the other results obtained by different methods. Our experimental results proved that an increase of mixing intensity makes aggregates structure more solid so the aggregates density is getting higher.

The accuracy of the used method is given by system properties mainly: image resolution, frame rate, particle concentration etc. The system and evaluation scripts have been set to eliminate these errors.

In situ measurements are more exact and nearer to practical applications but there appears the problem of suspension flow. It could be solved in future by combination with PIV (Particle Image Velocimetry).

APPENDIX

Reynolds number in agitated vessels is calculated from equation:

$$\mathrm{Re} = \frac{n \cdot d^2 \cdot \rho}{\mu}, \tag{1}$$

where n is impeller speed, d is impeller diameter, ρ is suspension density and μ is dynamic viscosity of the suspension. Specific energy dissipation is calculated from equation:

$$\varepsilon_V = \frac{P}{V}, \tag{2}$$

where V is an agitated volume and P is impeller power input calculated by equation:

$$P = P_0 \cdot \rho \cdot n^3 \cdot d^5, \tag{3}$$

where the P_0 is impeller power number (for six pitch-blade turbine measured speeds the power number is approximately constant $P_0 = 1.6$).

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