Particle visualisation – a tool for determination of rise velocities

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Abstract Particles from a post denitrifying Kaldnes Moving Bed™ Process were studied using an optical borescope, a visualisation technique that provides opportunities for both qualitative and quantitative studies of the separation mechanism in Dissolved Air Flotation (DAF). Rise rates for particle/bubble aggregates were estimated showing great variability. Two groups of aggregates were distinguished; relatively small flocs (<100 µm) with single bubbles attached rising comparatively slowly and large flocs (>100 µm) with several bubbles attached rising very fast. The high rise rates for large aggregates are discussed, possibly explained and suggested as the reason for the effective separation of large particles noticed in previous studies. Removal efficiency of different size categories of particles in DAF were investigated on the basis of particle size analysis indicating increased separation efficiency with increasing particle size.

Keywords DAF; particle separation; particle size analysis; particle visualisation; rise velocity

Introduction

Water and wastewater particles can be characterised from a number of different perspectives. Properties like size, shape, density and permeability can all influence rise and sink velocities, which in turn are of crucial importance for particle separation in Dissolved Air Flotation (DAF) and sedimentation respectively. In terms of settling the quantitative determination of sink velocity provides a means of characterising settleability. In DAF the rise velocity applies to floatability, but with the important prerequisite of aggregate formation, where interaction between bubbles and particles, to a large extent depending upon surface chemistry properties, is fundamental to the process.

Measurements of sink velocity have for a long time been used for density estimations (Tambo and Watanabe, 1979; Lee et al., 1996) and other purposes. Methodology for such measurements are accordingly well established and described in the literature (see for example Nobbs et al., 2002 for a review). Consequently, methodology considerations, settling characteristics and estimations of sink velocities for different types of flocs are frequently presented in the literature (Li and Ganczarczyk, 1989; Johnson et al., 1996; Hilligardt and Hoffmann, 1997 and others) but experimental data on rise velocities for particle/bubble aggregates in DAF are sparse. However, several interesting theoretical considerations on the separation mechanism and on the preferable particle size are presented by Edzwald (1995), Fukushi et al. (1995), Valade et al. (1996), Bache and Rasool (2001), Haarhof and Edzwald (2001), Han et al. (2001) and Leppinen et al. (2001) revealing some disagreement on the preferable floc size for successful removal in DAF-units. A number of factors could obviously influence the interpretation of suitable floc size but two major tracks could be distinguished whereas Fukushi et al. and Leppinen et al. advocate larger particles. However, suggesting smaller particles does not necessarily exclude the fact that large particles could be efficiently separated as well. Furthermore the distinction between small and large flocs requires attention.
Previous pilot plant studies of separation of biological floc from a post-denitrifying Kaldnes Moving Bed™ Process indicated that a significant part of the particles was separated upstream in the process, i.e. very close to the contact zone (Ljunggren et al., 2001). Furthermore it was concluded that big particles were more easily separated than small ones. Separation efficiency increased with increasing particle size and for particles > 100 µm separation was close to total. Similar findings were recognized in full-scale plants (Ljunggren and Jönsson, 2003). Why big particles were more easily separated and why aggregates were separated upstream in the process still remains to be answered.

The objective of this paper is twofold. The borescope method for visualisation of particle movements is presented together with methodology considerations and experimental data on rise rates of aggregates. The separation mechanism in DAF and practical implications are thereafter discussed on the basis of obtained results and previous findings. Particle size analysis and design of DAF-basins will be assessed in this second part.

Methods
Analyses have been performed at the Sjölunda wastewater treatment plant in Malmö, Sweden, where DAF is utilized for final separation of biological floc from a biofilm process (The Kaldnes Moving Bed™ Process) for post-denitrification. Activated sludge treatment and nitrification in trickling filters precede the MBBR-process for nitrogen removal. No chemicals were added before the flotation unit.

Particle visualisation
Flocs, bubbles and aggregates were dynamically studied with a visualisation technique based on the use of a borescope (Olympus series 5). The optical tube, which measures 1.60 m in length, could be immersed either directly into an operating basin or into a separate beaker or tube filled with water. In this study a plastic tube (1 m in height and 0.06 m in diameter) was used. Flocs, bubbles and aggregates passing close to the window at the end of the borescope were imaged through a lens system on to a CCD video camera (SONY DXC-LS1P CCD), recording images at a rate of 25 frames per second. An image from the camera is composed of 752 pixels per line and 582 lines, which makes it possible to distinguish objects of the size of approximately 20–30 µm. At the other end of the borescope a digital video recorder (SONY DSR-20P) was connected. The set-up was finally connected to a monitor allowing real-time visualisation, freezing of pictures and showing of recordings at 1/10 and 1/5 of the recorded speed. Figure 1 illustrates the set-up.

White paper or aluminium foil was attached to the outside of the tube for better illumination at the imaging level. At the bottom of the tube an arrangement was set up providing the possibility of adding dispersion water, i.e. micro bubbles in appropriate amounts.

![Figure 1](https://iwaponline.com/wst/article-pdf/50/12/229/419500/229.pdf)
(corresponding to full-scale recirculation ratios). Rising flocs, bubbles and aggregates have also been studied by filling the tube with water collected directly from one of the basins (the contact zone) in the full-scale plant.

The tube was filled with water from the denitrifying MBBR-process, and the window of the borescope was immersed a few centimetres below the water surface. Pouring water into the tube obviously creates unwanted water movements, but with the imaging level located close to the surface there was time for water movements to attenuate before recording of flocs, bubbles and aggregates. Vertical bulk water movements would disturb measurements severely, since flotation only should rely on natural buoyancy forces. Pressurised tap water of the same temperature was subsequently released at the bottom of the plastic tube.

Temperature control is a factor of great importance, since temperature differences easily create internal currents. Water temperature was very close to room temperature and repeatedly controlled during the measurements. The illumination from the borescope could, however, locally increase temperature, why the borescope occasionally was turned on and off during the measurements. Temperature at the imaging level remained relatively unchanged during the measurements (increase < 0.1°C).

The methodology was verified by velocity measurements of rising bubbles, which were compared to theoretically computed rise velocities for the same bubbles. The presence of vertical water movements could hereby be controlled and eliminated as a source of error. The drag coefficient for rising air bubbles was adjusted to \( C_D = \frac{16}{R} \) (Mei et al., 1994). Table 1 presents theoretically computed and experimentally measured rise rates for bubbles of typical sizes in dissolved air flotation.

The theoretical results are very sensitive to the estimation of bubble size, but the comparison clearly shows that measured and theoretical rise rates are of the same magnitude and in fact very similar, which is an indication of significance in the measurement of rise velocity of aggregates.

The accuracy of measurements of rise velocity, \( v_r \), was determined by estimating the errors in time, \( t \), and length, \( s \), respectively. Time for passage over the screen (2 mm in reality) can be determined with a possible error of ± 1 frame, corresponding to 0.04 s. The precision for measurement of distance passed could be estimated to less than 1 cm on the monitor, corresponding to no more than ± 0.2 mm in reality. The total error in measurements could thereby be expressed according to:

\[
\frac{dv_r}{v_r} = \frac{ds}{s} + \frac{dt}{t} = \frac{0.2}{2} + \frac{0.04}{1} = 0.14
\]

Rise rates could in other words be estimated with an accuracy of 10–15%.

Figure 2 shows an example of a sequence of images of the visualization of a rising, large aggregate with several, at least six visible, bubbles attached. The vertical extent of each image is 2 mm. Thus, the size of the aggregate is about 300 µm and the sizes of the bubbles about 60 µm. The rise velocity of this aggregate will consequently be 4.5 mm/s (corresponding to 16.2 m/h).

**Table 1** Rise rates at 20°C

<table>
<thead>
<tr>
<th>Bubble size (µm)</th>
<th>Theoretical rise rate (mm/s)</th>
<th>Measured rise rate (mm/s)</th>
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<tbody>
<tr>
<td>50</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>65</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>75</td>
<td>4.6</td>
<td>4.7</td>
</tr>
<tr>
<td>85</td>
<td>5.9</td>
<td>5.9</td>
</tr>
<tr>
<td>115</td>
<td>10.8</td>
<td>8.8</td>
</tr>
</tbody>
</table>

\( dv \)

\( v \)

\( ds \)

\( s \)

\( dt \)

\( t \)

\( C_D \)

\( R \)

\( v_r \)

\( \frac{dv_r}{v_r} \)

\( \frac{ds}{s} \)

\( \frac{dt}{t} \)

\( 0.14 \)

\( 10–15\% \)
Particle size analysis

Particle sizes were analysed with a calibrated particle counter, HIAC ROYCO 9064 with a sensor, HRLD-600, capable of counting and sizing particles within the size range of 4–600 µm. The instrument operates according to the light-blocking method, which means that individual particles are counted and sized. A size measure of a particle is interpreted as the diameter of a spherical particle. Particle size analysis was performed immediately after sampling, i.e. at the wastewater treatment plant, in order to prevent changes in the particle size distribution. The measurements are very sensitive and sample handling with clean procedures are obviously extremely important. Furthermore, samples were continuously stirred and repeatedly analysed. Dilution was not required. Particle size analysis in connection to DAF or settling could easily be disturbed by chemicals, for example residual coagulants, active during measurements (Vlaski, 1996). However, no chemicals were added and the results from the particle size analysis of the suspension in question appeared to be relatively stable.

Results and discussion

Results from the particle visualisation and the particle size analysis are presented separately and followed by an integrated discussion and interpretation of data with emphasis on the separation mechanism in DAF.

Particle visualisation

Different types of particles, with respect to origin and pre-treatment, will certainly show different characteristics, and the following results therefore naturally only apply to the specific biological flocs investigated in this study. Table 2 presents the velocity distribution for 113 studied aggregates from Sjölund wastewater treatment plant.

There was a great variation in rise velocity. The studied aggregates varied between 1.8 and 37.8 m/h, but approximately 2/3 aggregates showed a rise velocity between 5–15 m/h. Not only the rise rates showed great variability but also the number of attached bubbles to the flocs, which varied between 1 and 15 visible bubbles. The statistical significance could naturally be questioned and the above presented aggregates merely serve as an indication of aggregate rise rates and their variation. The results are however in accordance with previously obtained data based on 101 aggregates sampled directly from the full-scale plant (Jönsson, 2000). By investigating the velocity categories in Table 2 some tendencies could
be observed. Two groups of aggregates with different characteristics were distinguished. Aggregates rising very fast, for example the ones rising with a velocity $> 20 \text{ m/h}$, were all relatively big and had numerous bubbles, at least 5–10, attached. The slowest rising aggregates ($< 5 \text{ m/h}$) were all relatively small and had just single bubbles attached. The limits are obviously somewhat arbitrary but big aggregates refer to flocs several hundreds of microns in size. In the group with aggregates rising $> 20 \text{ m/h}$ the smallest floc measured 300 µm. Small aggregates refer to flocs, close to, or smaller than approximately 100 µm.

Numerous bubbles attaching to the large particles could obviously be related to the bigger surface area allowing for attachment of several bubbles and increased probability of contact between floc and bubbles. Explanations related to floc structure and surface properties are moreover possible.

The technique could certainly be further developed, possibly by the use of stroboscopic light allowing for better temporal resolution and reduced heating effects. The borescope could then be immersed directly into full-scale basins opening up for new studies, for example of aggregation phenomena in the contact zone and real-time visualisation of aggregates in both the contact and the separation zone.

**Particle size analysis**

In previous studies (Ljunggren *et al.*, 2001) it was concluded that separation efficiency increased with increasing particle size in the use of DAF for separation of biological floc from the Kaldnes Moving Bed™ Process, utilised for post denitrification. Figure 3 illustrates the phenomena with previous and novel measurements from the full-scale flotation plant at Sjölunda wastewater treatment plant. The hydraulic surface loading was 2–2.5 m/h and the dispersion rate slightly exceeded 10%. The analysed size intervals are replaced with the average particle size for the respective intervals.

The figure illustrates that the separation efficiency increases with increasing particle size. Separation is almost complete for particles $> 100 \text{ µm}$. In order to further evaluate separation characteristics, number and volume distributions were distinguished. An estimation of the total particle volume of each size interval $(dp_2 - dp_1)$, could be expressed by the number of particles registered in each interval, $N$, multiplied with a representative (equivalent) particle volume, $dpr$, estimated from the following equation:

$$\frac{\pi}{6} \cdot \frac{dpr^3}{dp_1} \cdot \frac{N}{\Delta dp} = \frac{\pi dpr^3}{6} \cdot N$$

Figure 4 illustrates the particle number- and volume distributions respectively.

The amount of suspended solids was approximately 40 mg/l and in order to achieve the stringent effluent requirements on phosphorus at least 80% of the suspended solids need to be removed. The figure illustrates several interesting aspects. Theoretically, 80% of the particles are $< 20 \text{ µm}$ and $< 1\%$ are $> 100 \text{ µm}$, but particles $< 20 \text{ µm}$ only constitute $< 5\%$ of the volume and thereby probably of mass. Particles $> 100 \text{ µm}$ comprise approximately 65% of volume. In order to achieve a mass reduction of approximately 80%, only 5% of the

<table>
<thead>
<tr>
<th>Rise velocity (m/h)</th>
<th>Frequency (%)</th>
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<tr>
<td>$&lt; 5$</td>
<td>12</td>
</tr>
<tr>
<td>5–10</td>
<td>45</td>
</tr>
<tr>
<td>10–15</td>
<td>20</td>
</tr>
<tr>
<td>15–20</td>
<td>15</td>
</tr>
<tr>
<td>$&gt; 20$</td>
<td>8</td>
</tr>
</tbody>
</table>
particles need to be removed (particles > 60 µm), which according to Figure 4 are relatively easily removed with the DAF-process. The reliability in the volume estimations is dependent upon a number of factors besides the statistical significance for the size measurements. Flocs are not spherical and effective density will decrease with increasing floc size. The volume estimations can therefore be questioned from a number of aspects, but the proportions between number and volume is nevertheless highlighted and the importance of removing big particles illustrated.

**Figure 3** Relative difference in number concentration of particles in different size categories before and after DAF. Each point reflects an average of five different measurements sampled the same day. Each measurements were in turn analysed five times.

**Figure 4** Particle number- and volume distribution based on five different measurements of the same sample.

The separation mechanism – rise velocities and floc size

Different rise velocities might explain the difference in separation efficiency between small and large flocs. The rise velocities for big aggregates (> 100 µm) with several bubbles...
attached were significantly higher than for smaller aggregates with single bubbles attached. A possible explanation could be that the attached bubbles do not considerably affect the drag force, but significantly reduce aggregate density, i.e. the bubbles contribute with a relatively high air volume without changing the overall shape of the floc. Rise velocities for small aggregates with one bubble attached were considerably reduced compared to the rise velocity for the bubble alone. The reduction could be attributed to either added mass from the floc or increased flow resistance, especially if the floc is larger than the bubble. Consider one spherical 100 µm floc attached to a 75 µm bubble. The buoyancy force, \( F_{\text{lift}} \), and the virtual weight of the floc, \( F_{\text{vw}} \), will be respectively (assuming \( \rho_{\text{floc}} - \rho_{\text{water}} = 50 \text{ kg/m}^3 \)):

\[
F_{\text{lift}} = \rho_{H_2O} \cdot \frac{\pi \cdot d^3}{6} \cdot g = 22 \cdot 10^{-10} \text{ (N)}
\]

\[
F_{\text{vw}} = m \cdot g = 2.6 \cdot 10^{-10} \text{ (N)}
\]

The virtual weight of the floc is of minor significance to the overall buoyancy and therefore to the rise velocity. The floc will on the contrary add significantly to the resistance, i.e. drag will increase. Assuming sufficiently low Reynolds’ number (“creeping flow”) implies flow resistance proportional to the length scale of the body and thus flow resistance for the idealised aggregate will increase by (at least) 30% (100/75 \( \approx \) 1.3). The reasoning could be an explanation for the effective removal of big particles. More bubbles can be and are attached, which in turn together effectively reduce aggregate density without affecting the drag force.

**Practical implications**

In design of flotation tanks the rise velocities are believed to be of fundamental importance, since the applied hydraulic surface loading is related to the rise rate. Effective upstream separation of suspended solids, possibly partially explained by high rise velocities for big flocs, could involve practical consequences on design of DAF-basins, i.e. the length-width ratio of the separation zone. Other explanations for the upstream separation could be related to the bulk movement of water. In order to create a platform for discussion and further evaluation, preliminary measurements with reduced basin length were performed in a pilot plant (described in Ljunggren et al., 2001) placed at Sjölanda wastewater treatment plant. Table 3 presents a selection of separation rates obtained at different basin lengths in the pilot plant. The hydraulic surface loading could obviously be increased, but the reduced basin length did not result in a deteriorated separation result, which is an interesting aspect, since the required separation zone area was relatively small.

**Conclusions**

Rising aggregates can be visualised and dynamically studied with an optical tube (borescope). The technique shows good potential for qualitative and quantitative studies of the separation mechanism in DAF.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Separation of suspended solids (%) for different relative separation zone lengths (( L_{\text{sep}} )) and hydraulic surface loadings (( v_s ))</th>
</tr>
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<tbody>
<tr>
<td>( L_{\text{sep}} = \frac{1}{2} )</td>
<td>( v_s = 20 \text{ m/h} )</td>
</tr>
<tr>
<td>84%</td>
<td>84%</td>
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</table>
Rising aggregates from the Kaldnes Moving bed™ Process utilised for post denitrification at the Sjölunda wastewater treatment plant in Malmö were mapped with respect to rise velocities showing great variability in rise rates. Two groups of aggregates were distinguished; relatively small aggregates (< 100 µm) with single bubbles attached rising comparatively slowly and big aggregates (> 100 µm) with several bubbles attached rising very fast. The high rise rates for big aggregates could explain the effective separation of big particles noticed in previous studies.

Acknowledgements
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References