Flow structures in a dissolved air flotation pilot tank and the influence on the separation of MBBR floc

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Abstract The objective of the study was to find ways of improvement of the dissolved air flotation process by studying the flow structure. The paper presents experimental data on flow structures and the relation between the flow structure and the removal efficiency. Measurements have been performed in a pilot plant with an Acoustical Doppler Velocimeter. The water velocity was measured in a grid net, giving insight into the flow structure. The removal efficiency was analysed at Malmö wastewater treatment plant in Sweden. The pilot plant separated biological floc from a Kaldnes Moving Bio-Bed Reactor (MBBR). The efficiency of the separation was analysed by measurements of suspended solids in the influent and the effluent. Air content was measured inside the tank and in the re-cycle. The result showed that basically two flow structures existed; the stratified and the short-circuit flow structure. The stratified flow structure seemed correlated to efficient separation of particles while the short-circuit flow structure seemed to have a negative effect, especially when the flow structure was affected by varying the re-cycle rate, i.e. the air content. Conclusively, the flow structure seemed to be correlated to type of flow structure. However, studies with higher concentration of suspended solids for verification were suggested.

Keywords Acoustic Doppler velocimeter; air content; dissolved air flotation; flow structure; moving bio-bed reactor; removal efficiency

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Introduction

Dissolved Air Flotation (DAF) is a commonly used process, both in the treatment of industrial wastewater and in municipal water treatment. The process is based on the idea of removing particles from the water by reducing the density of the floc with micro-bubbles with a mean size of approximately 70 μm, which generates a lifting force transporting the particles to the surface of the water. Accumulated sludge is removed from the surface by scrapers or flooding.

The knowledge of DAF is mainly based on experience and there is a need for research for optimising the process and for producing reliable design criteria. One poorly explored area is the hydraulic characteristics of the process (Haarhoff and van Vuuren, 1993). However, since 1993 the area has received more attention and work has been performed, both experimentally and through modelling, on the contact zone (e.g. Baeyens *et al*., 1995; Shawwa and Smith, 1998) and on the separation zone (O'Neill *et al*., 1997; Fawcett, 1997; Crossley *et al*., 1999; Ta *et al*., 2001; Hague *et al*., 2001). The Lund Institute of Technology in Sweden and PURAC Sweden has an ongoing project on the relation between the flow structure and the removal efficiency. The objective is to find ways of improving the capacity of the process through experimental studies of the flow dynamics and the removal efficiency.

Researchers have observed that bubbles accumulate in the upper part of the flotation tank and seemingly generate a stratification of the separation zone due to density differences between the layers (Jönsson *et al*., 1997; Hedberg *et al*., 1998). The phenomenon has been confirmed by the research group at Lund Institute of Technology, Sweden (Lundh, 2000; Lundh *et al.*, 2000; Lundh *et al.*, 2001). The work has shown that there exists a relationship between the flow structure and factors such as air content, hydraulic loading and contact zone configuration. The continuation of the project has been dedicated to the relation between the removal efficiency of biological floc from a Kaldnes moving bio bed reactor (MBBR) and the mapped flow structure in the separation zone. The MBBR process uses plastic carriers with a density just below the density of water, enabling the carrier to be suspended in the water under mixing conditions. The surface of the carrier is covered with bacteria-produced biofilm that utilises nutrients and organic matter for the metabolism of the bacteria.

The paper will show that basically two types of flow structures exist. Data from the study indicate that one flow structure seems to be beneficial while the other has a negative effect on the separation of floc. The correlation between the removal efficiency of biological floc from the MBBR process and the flow structure in the separation zone of the process will be elaborated.

Methodology

The methodology consisted of measurements of flow structure as well as removal efficiency. Both parameters could not be measured at the same time as the measurement of the water velocity for the flow structure required that a probe be lowered into the tank, which would influence the measurements of suspended solids. Consequently, the flow structure was first mapped inside the pilot plant in a laboratory at Lund Institute of Technology and then evaluated for the corresponding removal efficiency at Malmö wastewater treatment plant that utilises the Kaldnes MBBR process for post-denitrification.

Flow structure

The measurement of the flow structure was performed in the central, vertical longitudinal section of a pilot plant in particle-free water (tap water). An Acoustic Doppler Velocimeter (Nortek, 1987) was used for measuring 3-D mean water velocities in a grid net. Moreover, the assumption was that particles did not affect the flow structure up to a concentration of the order of 800 mg suspended solids per litre, which was initially tested at Malmö WWTP. The result showed that the flow structure was not affected by the existence of biological floc (Lundh *et al.*, 2001) for dilute SS-concentrations (< 25 mgSS/l in incoming water).

Removal efficiency

The moving biological bed reactor (MBBR) provided a concentration of about 15–25 mg biological SS/l (Figure 6, left). Water samples were taken in the influent and effluent, which were then analysed for suspended solid. Water samples of 30 ml were taken every second minute for one hour and were collected in a plastic bottle. The analysed value would thus represent the average SS-concentration during one hour. The pilot plant was operated for 2 hours for every condition, defined by hydraulic surface loading and re-cycle rate, and the values in Figure 6 display two-hour averages.

Air content

As the air content in the re-cycled water is determined by the efficiency of the saturator system and as the flow structure shows a strong correlation with the content of air, it was necessary to measure the air content inside the tank in order to achieve a correct relationship (Figure 5) with the flow structure. The air content was measured with an air-collecting apparatus for the air-saturated re-cycle, and with a syringe method for the air content inside the tank (Lundh, 2000; Lundh *et al.*, 2001).

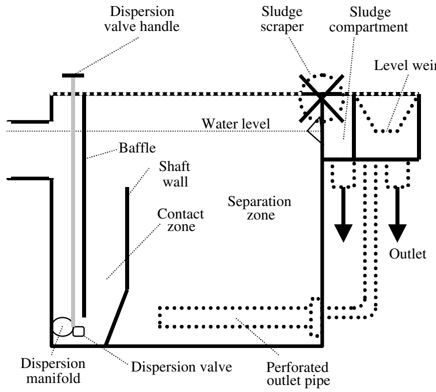

Figure 1 The pilot plant

Pilot plant

The flotation tank was 1.7 m long, 1.35 m high and 0.7 m wide and contained two zones (Figure 1). The contact zone, in which the water entered through a slot at the bottom, was the location for aggregation. When the water movement turned horizontal over the shaft wall it entered the separation zone. At the bottom two perforated pipes brought the clarified water out of the tank. The maximum hydraulic loading was 25 m^3/h, i.e. approximately 25 m/h surface loading over the whole tank. The dispersion was produced in a saturation system with an ejector that brought re-cycled water and air together, and a pressure tank to dissolve the air in the water. The dispersion was added to the main flow in the contact zone. The system could produce about 2.5 m^3/h.

Acoustic Doppler Velocimeter

The function of the Acoustic Doppler Velocimeter (ADV) is based on the Doppler effect. The ADV has a central transmitter with three receivers located in a circle around the transmitter (Figure 2). The receivers are slanted towards a measuring point approximately 5–6 cm from the transmitter.

Lohrmann *et al*. (1994) have reported that the instrument is capable of measuring velocities from 0.4 mm/s to 2.5 m/s. Tests have indicated that the measured velocity could be reduced up to 70% (Lundh, 2000; Lundh *et al*, 2000) in water with high concentration of bubbles. Moreover, the measuring point was located only about 1 cm from the probe transmitter in bubbly water. The flow structures were considered correct but displaced 4 cm upwards.

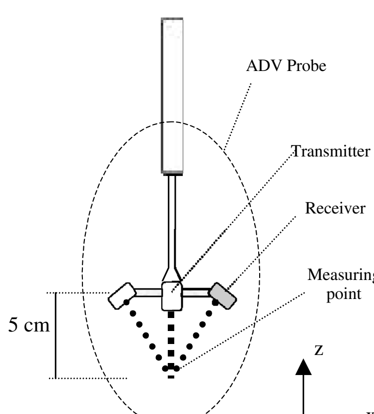

Figure 2 The ADV

Table 1 General variables in the DAF tank for the laboratory study of the flow structure

Measurement*1	Incoming Flow m³/h	Recycle Rate %	Hydraulic Loading m³/h	Surface Loading Tank*4 m/h	Surface Loading c-zone*2 m/h	Surface Loading s-zone*3 m/h
M6	20	8	21.6	19.6	126	23.2
M11	15	5	15.8	14.3	90	16.9
M13	15	15	17.3	15.7	99	18.5
M17	20	10	22	20	126	23.6
M18	10	5	10.5	9.5	60	11.3
M19	10	10	11	10	63	11.8
M20	10	15	11.5	10.5	66	12.4
M21	15	10	16.5	15	94	17.7
M22	20	15	23	20.9	131	24.7

*1 In the study on the removal efficiency the same conditions were examined as presented in the table except for M6 were the re-cycle rate was only 5%, generating V = 22.6 m/h over the s-zone, *2 Calculated for the vertical part of the contact zone, *3 Surface area = 0.93 m^2, *4 Surface area = 1.1 m^2

Operating conditions

The hydraulic loads 10, 15 and 20 m^3/h and the dispersion rates 5%, 10% and 15% were examined, corresponding to hydraulic surface loads presented in Table 1. The gage pressure in the air saturation system was held constant at 5 bar during the measurements. The water surface varied between 124 cm and 127 cm.

Method of measurement and the references of direction

The basin was defined in a co-ordinate system to give reference points as to where the measuring volume was located (Figure 3). The velocities also follow the co-ordinate system. Emphasis has been placed on the flow structure rather than the exact value of the velocity. The reason is the difficulty in determining an actual magnitude of the water velocity with the ADV in bubbly water. The direction was, however, believed to be correct (Lundh, 2000). The consequence of this approach is that the scale of the vectors is the same in a plot but could differ between the plots.

Each velocity measurement lasted for approximately 80–120 s with a sample frequency of 25 Hz. After processing the measurement points the average velocities were plotted on vector plots showing the overall flow situation. At the bottom of each vector plot a reference vector defines by length the maximum velocity shown in the plot.

Results and discussion

Two significantly different flow structures were observed (Figure 4). The ***stratified flow structure*** (V = 11.3–12.4 m/h, R = 10%) was defined as an initial water transport in the upper layer that was horizontally orientated and directed towards the outlet wall with some

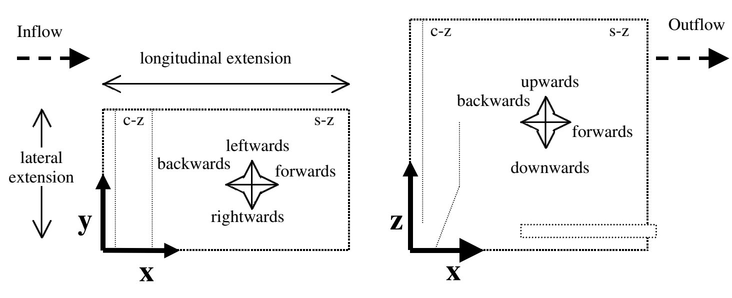

Figure 3 The co-ordinate system of the measurements and the directions referred to in the study

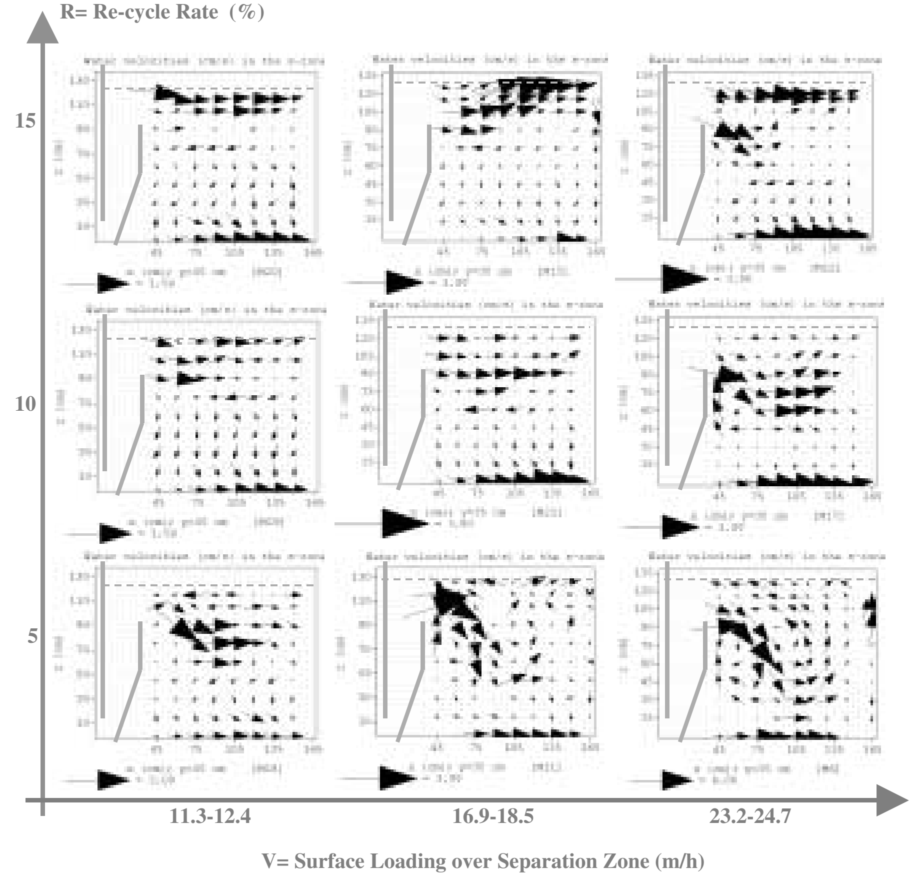

Figure 4 Water velocity profiles (cm/s) illustrating the induced flow structures in the central longitudinal section of the separation zone for re-cycle rates 5, 10 and 15% and hydraulic surface loads 11.3–24.7 m/h over the separation zone. The hydraulic loading changes with re-cycle rate, resulting in the different ranges expressing the hydraulic surface loading on the x-axis. Table 1 presents the condition for each case

re-circulation taking place in the topmost part of the lower layer, which developed into a plug flow.

The concept of a ***short-circuit flow structure*** (V = 16.9–18.5 m/h, R = 5%) was related to the idea of a short-circuiting of the process, meaning a downward transport of the water leaving the contact zone towards the drainage, levelling into a horizontal, sometimes upward-diagonally orientated flow. The short-circuit flow structure was generated for low air-contents (bottom row) and a similar structure was discovered for high hydraulic loading (towards the right).

The transformation of a stratified flow into a short-circuit flow could be described by the lowering of the boundary between the layers in the separation zone. The boundary starts to be displaced towards the bottom of the flotation tank when the hydraulic loading increases or the air content is decreased. Table 2 shows the conditions when the boundary starts to be displaced below 30–35% of the total water depth above the tank bottom.

However, a displacement of the boundary does not mean that the stratified flow structure suddenly disappears and that the short-circuit flow structure is developed completely. It implies the start of a transition to a short-circuit flow structure. The limit, when a structure resembles a short-circuit more than stratification, seems to depend on two factors – the hydraulic loading and the air content (re-cycle). If there is one specific transfer point (i.e. a

Table 2 Limiting conditions before displacement of the boundary, below 30–35% of the water depth, in a 1:2 DAF tank

Air content in the c-zone*1	Limiting hydraulic surface loading over the s-zone due to air content
ml/l	m/h
3	<11.3*2
6	14.8*3
8	18.5

*1 Derived from the performance of the saturator system and an assumed ideal totally mixed tank
*2 The lower limit was not examined
*3 The value refers to a case presented in Lundh (2000) with a hydraulic surface loading of 12.5 m/h over the whole tank and 10% re-cycle rate

certain combination of hydraulic load and re-cycle) or if the two factors work more independently of each other is difficult to conclude from the limited number of investigated cases. However, the measurements seem to indicate that a low value (5%) of the re-cycle would tend to initiate the transfer at a low hydraulic load (~ 11 m/h) whereas a high value of the re-cycle (15%) will displace the initiation to a higher hydraulic load (~23 m/h). A well established short-circuit flow seems to exist for a re-cycle of less than 10% (5–6 ml air/l). A high hydraulic surface loading seems to have the same effect in generating the short-circuit flow structure as a low air content, but the tendency is not as strong. However, a hydraulic surface loading above 18.5 m/h over the separation zone seems to establish a short-circuit flow.

Despite the low concentration of biological SS into the flotation tank it was possible to detect certain trends in the removal efficiency. The resulting removal efficiencies showed a reduction when the air content was decreased (Figure 6, top right) and when the hydraulic surface loading was increased (bottom right). However, as the incoming SS was low, small changes in the effluent SS concentration would affect the efficiency (in percentage terms) considerably. Thus, the analysis of the removal efficiency was performed in terms of absolute values of the effluent SS concentration.

The result shows that the effluent concentration was 8–9 mg SS/l when the re-cycle rate was 5% but 4 to 7 mg SS/l, when the re-cycle was 10% or higher (Figure 6, top middle). This was valid for all the investigated surface loads. When the hydraulic surface loading was studied for constant re-cycle rates the result indicated that the effluent SS-concentration increased from 3.5 to 4.5 mg SS/l to 5–6 mg SS/l when the surface loading was increased from 11.3–12.4 to 22.6–24.7 m/h over the separation zone for 10% and 15% re-cycle rate (Figure 6, bottom middle). For 5% recycle rate the effluent SS-concentration was constant just above 7 mg SS/l. The difference in effluent concentration was not as pronounced as for the investigations of the air content for constant surface loading. The high load case (30 m/h and 10%) shows a reduced effluent SS compared to the lower load, 10% cases. The reason for this is unknown (measurement error?).

One case provided an inflow concentration of about 160 mgSS/l and the separation resulted in effluent concentrations just below 20 mg SS/l for 10 and 15% but 65 mg SS/l for 5%, displaying the same trend of reduced removal efficiency as for a case with low air content.

The air content was somewhat higher, perhaps 1–2 ml/l, at Malmö WWTP (Figure 5; calculated air content inside the contact zone; based on measurements of the air content in the re-cycle) than in the laboratory study but was still considered to correlate to the values determining the displacement of the stratified upper layer (Table 2). Visualizations with colour have also shown that e.g. the short-circuit flow structure was developed for 5% re-cycle rate.

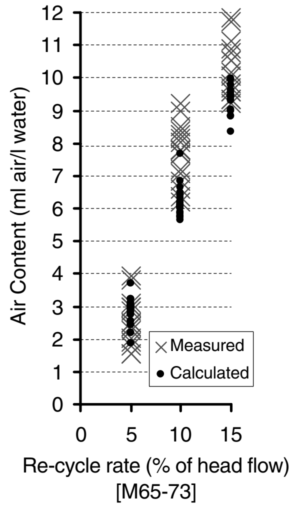

Figure 5 Measured and calculated air content in the contact zone at Sjölunda WWTP

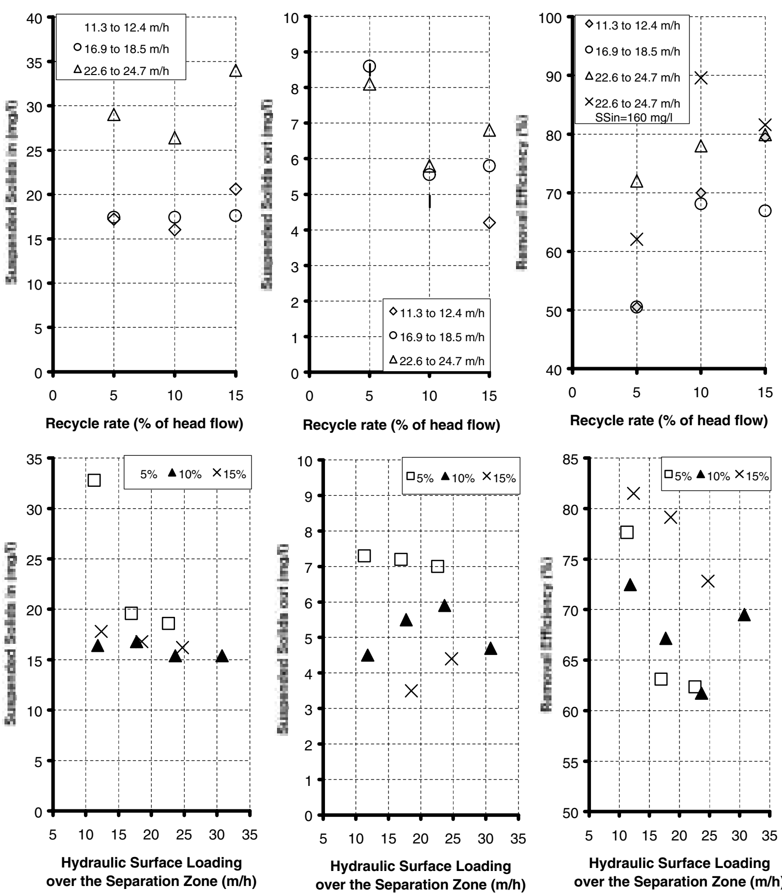

Figure 6 Increase of recycle rate for constant hydraulic surface loading /top/ and increase of hydraulic surface loading for constant recycle rate /bottom/. The case with high concentration of incoming SS of approximately 160 mg SS/l is only shown as removal efficiency for readability reasons

Conclusion

- Basically two types of flow structures were found in the separation zone.
- The stratified flow structure was developed for higher content of air (>10% recycle rate generating >5–6 ml air /l water) and lower hydraulic surface loading over the separation zone (<18.5 m/h).
- The short-circuit flow structure was generated for lower contents of air (<10% recycle rate generating <5–6 ml air/l) and higher hydraulic surface loading (>18.5 m/h) over the separation zone.
- Seemingly, the bubbles do not have only one function; that of producing aggregates with the particles, but also have a crucial importance for the development of the flow structure.
- The result shows that the re-cycle rate (air content) had a significant impact on the removal efficiency. The re-cycle rate should be higher than 10% in order to achieve a good removal of biological floc.
- There was possibly a negative consequence on the removal efficiency due to increased hydraulic surface loading over the separation zone but the result was considered uncertain.
- Conclusively, removal efficiency was found to correlate to the type of flow structure. The stratified flow structure seemed essential for good performance, meaning that efforts should be made in preventing the short-circuit flow structure from developing with a high enough air content.
- More studies with water containing higher concentration of SS have to be performed in order to verify the conclusions.

Acknowledgements

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