Application of acoustic Doppler Velocimetry in microbubble containing water

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Dissolved Air Flotation (DAF) is a method for separating suspended, microscopic particles in water and wastewater treatment. The basic idea is to generate huge amounts of microscopic bubbles, which should attach to the particles whereby less dense aggregates are obtained, rising to the water surface. The flow structure in a flotation tank is important for the separation efficiency. ADV measurements have been performed in a DAF pilot plant for different hydraulic loads and dispersion flows. The bubbles (volumetric fraction < 3-4 ‰) constituted a difficult environment for the ADV (multi-scattering and attenuation): causing noisy signals although the bubbles did not affect the acoustic wave velocity according to direct measurements. It was judged according to different tests that the ADV could be used to map the flow structure qualitatively. A hypothesis of the multi-scattering process was suggested for the operation of the ADV. Studies of the flow structures indicated the importance of bulk water densities and showed that three states existed depending on the magnitudes of hydraulic load and dispersion flow – rotational flow, stratified flow, short-circuit flow. Only the middle one was advantageous for separation. The transition from the first to the second state was studied and physically explained.

Keywords: Dissolved air flotation, bubbles, flow structure, ADV

1 INTRODUCTION

Production of drinking water in water works or the treatment of municipal wastewater involves a very important and central process concerning the separation of suspended, microscopic particles or flocs from the water, for instance generated through biological or chemical treatment but also existing naturally. Dissolved Air Flotation (DAF) is an efficient method for the separation process with a number of advantages compared to the conventional sedimentation technique, for instance having a small footprint and possibility to separate less dense particles. The basic idea with DAF is to generate huge amounts of microscopic air bubbles (size of the order of 50-100 µm), which should attach to the suspended flocs/particles. In this way less dense bubble/floc aggregates are generated, which should rise to the water surface in the flotation tank, where a sludge layer is formed for subsequent removal. DAF is a relatively complex process and in order to utilize the full potential of the process a profound knowledge is required of the process. Thus, it has been shown [1] that the introduction of bubbles in the flotation tank strongly affects the flow structure and that this in turn affects the separation efficiency. Detailed studies and measurements using a laboratory Nortek Acoustic Doppler Velocimeter (ADV) have been performed on a DAF pilot plant, Fig 1, in order to get insight into the detailed characteristics of the flow structure for different hydraulic loadings and different dispersion flow rates. The presence of bubbles (volumetric proportion up to about 2-4 ‰) constitutes a difficult environment for the ADV. Thus some tests were initially performed in order to assess the applicability of the ADV and a hypothesis was suggested for the operation of an ADV in bubble-containing water based on multiple scattering. Moreover, the paper will discuss different flow structures – rotational flow, stratified flow, breakdown of the stratified flow – basically related to the hydraulic load and the dispersion flow. Finally the mechanism for transition to stratified flow will be discussed.

2 DAF PILOT PLANT

The pilot plant, Fig 1, was 1.2 m long, 0.7 m wide, 1.3 m high with a transparent side. The hydraulic load (0 – 17 m^3/h) was entered (no particles) to the bottom left into a riser shaft (contact zone) ending a few dm:s below the water surface. Huge amounts of micro bubbles were produced by depressurizing water saturated with air at 5 bar via valves into the contact zone where the hydraulic load was entered. The dispersion flow rate was generally about 10 % of the hydraulic load. The hydraulic load together with the bubble flow then entered the separation zone (the main part of the tank), where different flow structures could be obtained. Fig 1 shows the case with a distinct stratified condition with an upper, less dense, bubble-containing layer and bottom layer with more or less clear water. Discharge of (clean) water took place at the bottom via two perforated pipes. The ADV was mounted on a moveable rig on the top of the tank.

Figure 1. The pilot plant with hydraulic load and dispersion flow (bubbles) entering the riser shaft to the left

ADV PERFORMANCE

In normal circumstances (clean water with few scattering particles) the ADV works very well with the measurement point located 5 cm below the transducer. The ADV operation is dependent on the behaviour of the acoustic waves (speed and attenuation) in the water. Thus, one might expect that the presence of microscopic air bubbles (≈ 50 μm, volumetric fraction ≤ 4 – 5 ‰) would affect wave propagation significantly. A number of tests were performed in order to evaluate the ADV performance in such conditions. In the first place a 10 MHz acoustic receiver was placed 5 cm below the ADV transmitter in bubbly water. A digital oscilloscope was triggered each time an acoustic pulse was emitted and the received pulse could be visualized on the scope together with the time passed. This time was constant irrespective of the amount of bubbles (≤ about 4 – 5 ‰) corresponding to a wave velocity of 1470 m/s, i.e. the same as for pure water. Theory [2] confirms this finding:

$$c^2 = c_0^2 - \frac{4 \cdot \pi \cdot n \cdot a}{(2 \cdot \pi \cdot f)^2} \qquad (1)$$

c = real wave velocity, c_0 = wave velocity in pure water, n = number of bubbles/unit volume of water ≈ $6.4 \cdot 10^{10}$, a = bubble radius ≈ $25 \cdot 10^{-6}$ m, f = acoustic frequency = 10^7 Hz. This gives c ≈ c_0, i.e. no effect of the bubbles.

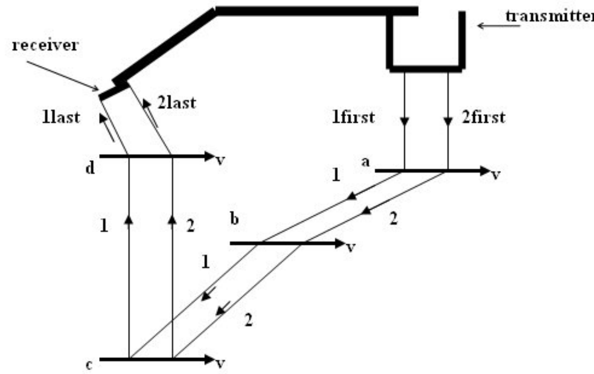

Figure 2. Hypothesis for the assumed multi-scattering process

Another test was performed with the rig and the ADV moved horizontally about 30 cm at a fairly constant speed along the pilot plant with the ADV emerged into the bubbly water. The output from the ADV was recorded giving movement time and the ADV-recorded mean velocity. This latter velocity was corrected for the slow, horizontal water velocity and comparison could then be made with the rig velocity. A clear water test showed that there was almost no difference between the two velocities. A general result was that the ADV velocity was smaller than the rig velocity consistently.

Tests with the ADV in bubbly water strongly indicated that the measurement point was dislocated to a point much closer to the transmitter. However, the operation of the ADV electronics - gating of the receivers to open only during the expected arrival of a pulse in normal conditions - meant that the acoustic waves could not propagate directly from the transmitter to the receiver horizontally (≈ 3 cm) but had to propagate about 10 cm. It was also found that the emitted pulses, although attenuated by the bubbles, were scattered in all directions in the neighbourhood of the transmitter. These facts strongly indicate that multi-scattering on the bubbles takes place for the acoustic waves propagating from the transmitter to the receiver. Fig 2 gives a very simplified illustration of the possible effect of multiple scattering – considering the operation of the ADV using pairs of pulses. Pulses 1 and 2 are emitted consecutively for the determination of the phase difference of the two pulses. Assume a homogeneous velocity field v. Pulse 1 is scattered on a number of single particles, a,b,c,d, and is detected in a direction defined by the very narrow directional properties of the receiver. Pulse 2 is emitted a very short time Δt = 250 μs later and is scattered on the same set-up of particles. During this time period a particle (bubble) with a typical maximum velocity of the order of 20 mm/s will move 5 μm, i.e. an extremely short distance. The very short time scale (250 μs) and the corresponding very small distance (5 μm), that a bubble passes, will most certainly mean, that the velocity for each bubble does not change during this time interval. This will in turn mean that the spatial bubble structure is the same for the two pulses and that the signals at the receiver – emanating from the two emitted pulses - are the result of the same multi-scattering process, i.e. involving the same set of particles/bubbles. Moreover, if the velocity field is exactly homogenous (not necessarily horizontal) the phase difference between the two detected pulses will be independent of the path and is only due to the path difference for the first leg $(1_{\text{first}} - 2_{\text{first}})$ from the transmitter and the last leg to the receiver $(1_{\text{last}} - 2_{\text{last}})$ and will the same as for a scattering particle in the measurement volume for clear water.

A few factors could be assumed to affect the detected phase difference in reality:

- the velocity field is not homogeneous, which means that the total path difference will be influenced by small variations of velocity magnitudes and directions along the multiple scattering path
- the receiver might be sensitive to variations in the last leg of the path, i.e. the directional sensitivity of the receiver might be broadened

Moreover, if the measurement point is dislocated from 5 cm below the transmitter to only 1 cm from it, the flow velocity in this latter point might be disturbed by the probe, at least in certain flow situations and cause a reduction of the velocity as compared to the undisturbed case.

The general conclusion of the ADV performance, based on tests and mapping of the flow structure in the tank, was that the measurement point seemed to be very close to the transmitter and the horizontal velocities were underestimated but that velocity directions seemed to be more or less correct. As the real velocities were small one has to bear in mind that the ADV measured the movement of the bubbles, which were assumed to move with the water flow in the horizontal direction. Vertical ADV velocities were offset by the rise velocity of the bubbles (≈ 1 mm/s).

3 FLOW STRUCTURE IN THE FLOTATION TANK

The existence of micro bubbles in the flotation tank has two implications – generation of aggregates and influence on the flow structure. The latter aspect is strongly related to the DAF separation efficiency. Detailed ADV measurements were performed in the pilot plant of the average horizontal (v_x) and the vertical (v_z) velocities for different hydraulic loads (Q_l) and different dispersion flows (Q_d) but without particles/flocs in order to study possible flow structures and their characteristics. Flow velocities were mainly in the interval 0 – 2 cm/s (ADV). Averaging time was at least 300 s. The measurements were performed in the longitudinal center plane only. Three significantly different flow structures were identified:

S1: the case with no bubbles or a sufficiently small Q_d giving a large, clockwise rotating flow, Fig 3

S2: the case with sufficiently high Q_d but sufficiently small Q_l giving a stratified flow situation, Fig 4

S3: the case with sufficiently high Q_l where the stratified flow situation broke down.

3.1 Flow structure S1

The flow structure in Fig 3 represents the case with Q_l = 12 m^3/h, Q_d = 0 m^3/h, i.e. no bubbles. Inflow takes place horizontally to the left at the top 16 cm.

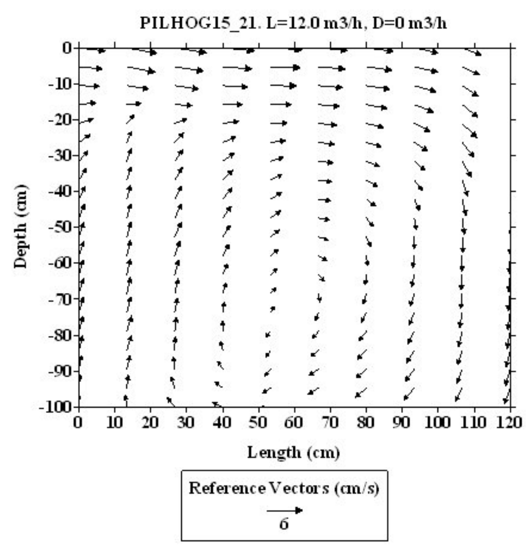

Figure 3. Case S1. ADV-determined flow structure in the pilot plant without any dispersion flow.

Outflow takes places at the bottom. The flow structure could basically be described as a large, clockwise eddy encompassing the entire tank. Particles/flocs entering the tank will be transported horizontally to the downstream wall and then vertically with fairly high velocities to the pipe outlet arrangement on the bottom, i.e. no good separation. The same flow situation will occur for small Q_d (< about 4 % of Q_l). A large amount of bubbles will thus also reach the bottom as the vertical downstream velocity is significantly larger than the bubble rise velocities.

3.2 Flow structure S2

The flow structure in Fig 4 represents the case with Q_l = 10 m^3/h, Q_l = 0.98 m^3/h, i.e. $Q_d \approx$ 10% of Q_l. Inflow takes place horizontally to the left at the top 35 cm. Increasing Q_d from 0 to about 4 % of Q_l, maintaining Q_l constant, will abruptly change the flow structure from S1 to a stratified situation, S2, according to Fig 4, due to density differences given by different volumetric air contents. There is an upper, bubble-containing, less dense layer, where water moves horizontally towards the downstream wall. After that a horizontal return flow occurs, containing a less amount of bubbles. Beneath, a downward, bubble-free, denser plug-like flow with

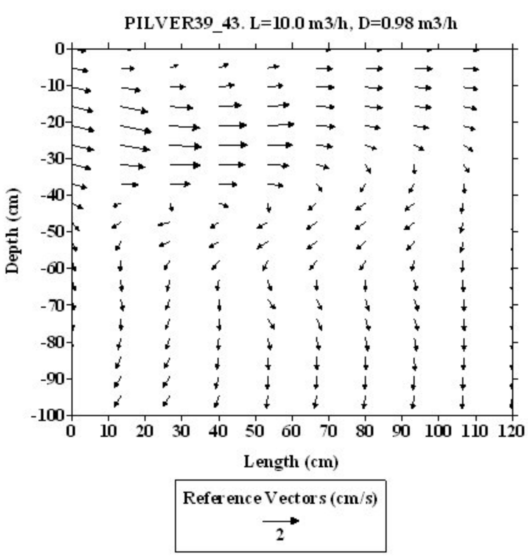

Figure 4. Case S2. ADV-determined flow structure in the pilot plant. $Q_d \approx$ 10 % of Q_l , Q_l = 10 m^3/h

low velocities arises towards the outlet. Such a stratified situation is beneficial for the separation efficiency. Aggregates, bubbles and particles entering the tank will tend to stay in the upper layers as the vertical, downward velocities are small as compared to S1 where a concentrated, vertical high-velocity region existed. Increasing Q_l will tend to extend the upper layer downwards, thus causing aggregates, particles and bubbles to approach the outlet arrangement with possible deteriorating separation.

3.2 Flow structure S3

Increasing the hydraulic load to Q_l = 16.4 m^3/h and with Q_d = 1.45 m^3/h, i.e. $Q_d \approx$ 9 % of Q_l causes the stratified structure to break down and a "short-circuit" flow is obtained (not shown here due to lack of space) and aggregates, particles and bubbles will have a high probability of reaching the bottom outlet thus causing a deteriorating separation.

4 TRANSITION TO THE STRATIFIED CASE

The transition from rotational to stratified conditions in terms of hydraulic load and dispersion flow (i.e. the degree of density differences) were studied experimentally. The procedure was as follows. The ADV probe was located at the far end wall of the tank. A constant hydraulic load Q_l was applied with a very low dispersion flow Q_d which did not affect the flow structure. Q_d was then increased gradually to a steady-state value between 2 – 10 % of Q_l. The ADV vertical velocity was recorded simultaneously in order to determine the value of Q_d at the transition. This was characterized by an abrupt change of the vertical velocity. The procedure was repeated for a different Q_l. It was found that transition occurred for $Q_d \approx$ 4 % of Q_l in the studied interval 4.0 ≤ Q_l ≤ 12.3 m^3/h.

An explanation for the transition was put forward based on a balance between buoyancy and kinetic energy, Fig 5. In the rotational case a significant

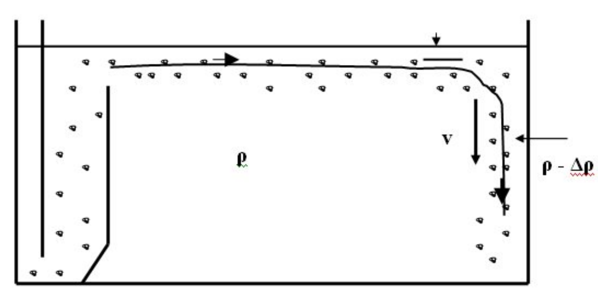

Fig 5. Definition sketch for the explanation of the transition to the stratified flow in the DAF tank

flow velocity v is obtained along the far end vertical wall. This represents a certain kinetic energy

$$E_k = \frac{\rho \cdot vol \cdot v^2}{2} \qquad (2)$$

for a water element with volume = vol. Assume that the rotational water contains a small amount of bubbles, volumetric content m ‰, corresponding to a bulk water density ρ – Δρ, and that the ambient water is free of bubbles, Fig 5. The buoyancy force, F_b, on the water element during its downward movement will be

$$F_b = \Delta\rho \cdot vol \cdot g \qquad (3)$$

where Δρ is the density difference between the water element and the ambient water. Thus, if the kinetic energy is large enough the water element will be able to overcome the buoyancy force and reach the bottom of the tank. However, if the kinetic energy is not sufficiently large the flow will come to a standstill after some distance y along the vertical wall. Thus, in principle:

$$E_k = F_b \cdot y \qquad (4)$$

which gives:

$$y = \frac{v^2 \cdot \rho}{2 \cdot \Delta\rho \cdot g} \qquad (5)$$

During the starting phase of the pilot plant the hydraulic load rapidly reaches the steady state flow rate. However, the bubble generation in the dispersion flow is a rather gradual process meaning that the initial volumetric air concentration is very low, for instance of the order of 0.05 ‰ corresponding to Δρ ≈ 0.05 kg/m^3. Assuming v ≈ 0.02 m/s one obtains:

$$y \approx \frac{0.02^2 \cdot 10^3}{2 \cdot 0.05 \cdot 9.81} \approx 0.4 \ m$$

In reality the buoyancy force will be smaller and probably not constant as the downward moving water element along the wall is not surrounded by clear water but with water containing a small amount of bubbles and consequently with a somewhat lower density, making ≈ Δρ smaller and y even larger. This implies that the bubble containing water element will pass along the vertical wall all the way to the bottom (outlet pipes) and the rotational structure will be maintained. When the dispersion water has been flowing for a while, its amount of bubbles increases very significantly and that goes for Δρ too. Thus for m ≈ 1 ‰ (Δρ ≈ 1 kg/m^3) one obtains for y:

$$y \approx \frac{0.02^2 \cdot 10^3}{2 \cdot 1 \cdot 10} = 0.02 \ m$$

i.e. the downward flow will be stopped more or less abruptly, which is in qualitative agreement with visual observations and with ADV measurements of the downward velocity. A density induced barrier with fairly bubble-free water below it is formed, i.e. less dense water elements have not got sufficient kinetic energy to penetrate the barrier. m ≈ 1 – 5 ‰ means that the water elements are stopped almost immediately at the barrier. However, there is of course a continued supply of bubble-containing water to the barrier area, which means that this flow will be diverted horizontally towards the upstream part of the tank and an upper, bubble-containing layer is formed.

CONCLUSIONS

The ADV has been used in micro bubble containing water in a flotation tank, which potentially is a difficult environment for the instrument. However, reasonable velocity data were obtained, at least qualitatively. Direct measurements showed that the acoustic wave velocity was not affected by the bubbles, also confirmed by theory. A number of different tests indicated that velocity directions were fairly correct, whereas velocity magnitudes were underestimated. The measurement point seemed to be located ver1y close to the transmitter. A possible explanation is hypothesized.

Three different kinds of flow structures were identified depending on the hydraulic load and/or the dispersion flow. Beneficial stratified flow conditions occurred for hydraulic loads less than about 16 m^3/h and dispersion flow rates larger than 4 % of the hydraulic load.

Transition to stratified flow was studied experimentally and occurred at Q_d ≈ 4% of Q_l. An explanation was provided based on the balance between buoyancy and kinetic energy.

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