High-rate dissolved air flotation for water treatment

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Abstract This paper presents the results of an experimental investigation about the performance of a horizontal flow high-rate pilot scale Dissolved Air Flotation (HRDAF) unit containing inclined parallel plates for treating a coloured and low turbidity raw water. Experiments were performed with the DAF unit in order to verify the influence on flotation of: (i) the water velocity ($V_h$) between the plates, in the range 18 to 96.5 cm.min$^{-1}$ with corresponding Reynolds numbers between 240 and 1060; (ii) the supplied air ($S^*$) value ranging from 2.2 to 8.5 g of air/m$^3$ of water; (iii) the angle of the plates (60º or 70º). The best pilot plant operational condition was obtained applying only 4.0 g/m$^3$ ($S^*$) with $V_h$ around 18 cm.min$^{-1}$ for treatment of water coagulated with a $\text{Al}_2(\text{SO}_4)_3$ dosage of 40 mg.l$^{-1}$. In these conditions, the unit presented very good removal efficiencies of colour (90%, residual of 10 uC), turbidity (88%, residual of 0.8 NTU) and TSS (94%, residual of 1.8 mg.l$^{-1}$). Furthermore, the unit could operate at higher $V_h$ values up to 76 cm.min$^{-1}$ and still present good results. The DAF unit thus behaved as a high rate unit presenting good performance with low air requirement.

Keywords Dissolved air flotation; DAF; flotation; high rate flotation; water treatment; water clarification

Introduction

The high colour and low turbidity water treatment through conventional systems usually presents problems because of low efficiency of the sedimentation basins. These problems are due to the low-density characteristics of the flocs formed after the coagulation/flocculation of this type of water. To obtain more favorable conditions for sedimentation, high coagulant dosages are normally applied, which impose higher costs and increase sludge production in the sedimentation basin complicating problems with final disposal of this sludge. In these situations, the use of the dissolved air flotation units instead of sedimentation basin has produced excellent results (Zabel, 1985; Edzwald, 1995; Reali and Campos, 1995; Marchetto, 1996; Dombroski et al., 1996) at high colour removal efficiency with lower coagulant dosages than those required for sedimentation.

According to Edwards and Amirtharajah (1985), the humic substances are usually responsible for the natural colour of the waters. In the pH conditions found in most superficial waters, these substances occur as negatively charged macromolecules, which cause an aesthetic problem and are precursors of carcinogenic trihalometanes compounds. When pure, the humic and fulvic acids are inoffensive, but they can be hazardous to health because they form stable complexes with heavy metals, e.g. lead, and adsorb pesticides and insecticides (Narkis and Rebhun, 1977).

Dombroski et al. (1996) carried out an experimental investigation using lab scale flotation unit to clarify high colour (260 uC) and low turbidity (5 uT) water. They found that flotation presented excellent results with high colour removal efficiency (over 90%), requiring relatively small coagulant dosages (25 mg.l$^{-1}$ aluminium sulfate).

Besides the success in treatment of high colour and other types of water, such as high suspended algae concentration water, flotation presents additional advantages in relation to sedimentation, such as:

- the produced sludge presents higher suspended solid content dispensing additional sludge thickening units (Zabel, 1985; Reali, 1991);
• it constitutes a high rate process rapidly, reaching steady state conditions (Zabel, 1985);
• it requires lesser coagulant dosages in large number of cases (Mouchet, 1983);
• it requires shorter water flocculation time resulting in smaller units (Dombroski, 1996);
• the microbubbles may strip part of the volatile substances occasionally existing in the water to be treated (Reali, 1991).

Thus, one observes that a growing number of water treatment plants employing flotation has been used throughout the world. From the most recent advances in the flotation technique, the conception of high rate units stands out. In these units, like in high rate sedimentation basins, flat parallel plates are put inside the flotation unit resulting in low Reynolds number flow, thus permitting efficient operation at much higher rates than the conventional flotation units.

This study presents results of research performed on high rate flotation unit (HRDAF) designed for horizontal flow between the inner plates treating high colour and low turbidity water.

Methods
The raw water for this study was prepared adding 4 mg.l⁻¹ humic acid (Aldrich, ref. H1 675-2) and kaolin (Fluka, ref. 60609) to a deep well water to obtain turbidity around 6.0 NTU, apparent colour ranging from 94 to 120 uC and true colour from 53 to 75 uC. The raw water alkalinity was always around 27 mg CaCO₃ l⁻¹ associated with pH around 7.0 and temperature around 26°C. Aluminium sulfate was employed as coagulant and soda ash as coagulation pH conditioner.

In the first phase of this study, a laboratory scale batch flotation equipment (see Figure 1) was used to determine the best aluminium sulfate dosage, the appropriate coagulation pH and suitable air quantity (S*) for batch flotation. Tests were performed varying the aluminium sulfate dosage from 10 to 55 mg l⁻¹ and pH value from 5.5 to 7.4. In each batch, flotation essay samples were collected at three different times in order to obtain colour and turbidity efficiencies for batch flotation velocities (Vf) of 4 m.h⁻¹, 8 m.h⁻¹ and 19 m.h⁻¹.

The lab-scale dissolved air flotation installation (Flotatest) is constituted by four flotation columns which operate in parallel, with one saturation chamber, as shown in Figure 1. The flotation columns are operated in intermittent flow (batch). After rapid mixing of the water in the Jar-test unit, with pH correction and coagulant addition, the columns are filled with wastewater. Then the agitator is turned on and flocculation starts. At the same time the water aeration is done into the saturation chamber. After flocculation, the valves that control the flow of the pressurized recirculation from the saturation chamber are opened. Thus, the flotation of the suspended flocs present in the columns is accomplished. The sample

Figure 1  Schematic diagram of the laboratory-scale dissolved-air flotation (LSDAF) unit adapted from Reali (1991)
collection is carried out at points properly situated based on the calculation of batch flotation velocities \((V_f)\), according to Reali (1991). Here, flotation velocity \((V_f)\) is defined as the ratio of the height of the sampling point and the sampling time.

In all batch flotation tests the following parameters were fixed: (i) rapid mix time \((T_{RM})\) of 20 s; (ii) mean velocity gradient during rapid mix \((G_{RM})\) around 100 s\(^{-1}\); (iii) flocculation time \((T_F)\) of 24 min, and (iv) mean velocity gradient during flocculation \((G_F)\) of about 60 s\(^{-1}\).

The second phase of the study was carried out using a special type of flotation unit that was designed to operate with a horizontal, low Reynolds number, flow. For this, several parallel inclined plates were properly assembled into the flotation unit. Initially tests were performed with the plates assembled with a 70º inclination angle (relative to horizontal) in order to identify any possible problems related to the accumulation of floating flocs on the plate surfaces. Subsequently, a 60º inclination angle was also tested.

Figure 2 shows a schematic of the pilot installation. Basically, it contains an “in line” plug flow rapid mix unit and a three chamber flocculation unit connected to a high rate horizontal flow DAF unit, which is 1.06 m long, 0.52 m wide and 1.27 m deep. The flocculation chambers are 0.35 m \(\times\) 0.35 m and 1.0 m deep, having slow vertical mixers. During the experiments the \(T_F\) values was fixed at 24 min and the \(G_F\) applied were 70 s\(^{-1}\) 50 s\(^{-1}\) and 30 s\(^{-1}\) respectively for the first, second and third chamber. Throughout the essays, 40 mg.l\(^{-1}\) of aluminium sulfate was applied to promote coagulation. The gauge into the saturation chamber was maintained around 450 kPa. This chamber was designed based on the recommendations of Reali and Campos (1992).

For each inclination angle different, velocities between the plates \((V_H)\) were tested (from 18 to 96.5 cm.min\(^{-1}\)) with several air quantities \((S^*)\) from 2.3 to 8.5 g/m\(^3\). The air supply rate \(S^*\) was controlled adjusting the pressurized recirculation flow (coming from the saturation chamber) by means of needle valves installed below the DAF unit, for the microbubbles production. Air supply and the affluent flows were measured by means of electromagnetic flow measurement devices. Samples were collected every 15 min for the laboratory determinations. The last three samples of each experiment were mixed to obtain a sample that represented the mean conditions of that experiment. Monitoring was carried out measuring the apparent colour, turbidity, pH and total suspended solids concentration (TSS) of the affluent and effluent water. For the coagulated water only TSS and pH were determined. All of the determinations were based on the recommendations of the Standard Methods for the Examination of Water and Wastewater (1995).

Results and discussions

Table 1 shows the best results obtained with the preliminary laboratory scale batch flotation unit (Flotatest) essays. It was observed that the 10 m.l\(^{-1}\) aluminium sulfate dosage with 6.3 pH led to satisfactory colour and turbidity removal only in the essay performed with the lowest \(V_f\) of 4 m.h\(^{-1}\), resulting in removal efficiency of about 76%. With higher aluminium sulfate dosages, ranging from 20 to 35 mg. l\(^{-1}\), it was possible to obtain good flotation...
performance in the essays carried out with 8 m.h\(^{-1}\), obtaining colour removal in the experiments of 73% to 84%. From the three \(V_f\) values studied, the best colour and turbidity removal was obtained applying 40 mg.l\(^{-1}\) aluminium dosage associated with 6.3 pH, resulting in 91% colour removal for \(V_f\) of 8 m.h\(^{-1}\). Aluminium sulfate dosages higher than 40 mg.l\(^{-1}\) did not improve the flotation performance for this kind of water. Therefore the 40 mg.l\(^{-1}\) aluminium sulfate dosage was chosen for application in the next phase of the research using the DAF pilot plant.

Although there is no direct correspondence between the flotation velocities obtained in the batch units with the overflow rates applied in the full scale flotation units, the results permit at least an estimation of the effect of different overflow rates on the performance of continuous flow flotation units. Thus, it is possible to observe that, even for coagulant dosage equal to 40 mg. l\(^{-1}\), see Table 1, the batch flotation tests with this type of water, performed with a high \(V_f\) value of 19 m.h\(^{-1}\), one obtains poor results, 56% colour removal, as compared to that obtained with \(V_f\) of 8 m.h\(^{-1}\) (91% colour removal). Table 2 shows the batch flotation results obtained when the air supply (\(S^*\)) was varied, maintaining a constant aluminium dosage of 40 mg.l\(^{-1}\) and a pH around 6.3.

It is possible to observe that in the experiments with low \(V_f\) value (4 m.h\(^{-1}\)) the flotation was efficient even with very low \(S^*\) values (2.1 g air/m\(^3\) water) reaching 90% of colour removal. It was noted that the higher the \(V_f\) values (ranging from 8 and 19 m.h\(^{-1}\)), the greater was the quantity of air required for flotation (8.4 g of air/m\(^3\) water). In the experiment performed with this low \(S^*\) and \(V_f\) of 8 m.h\(^{-1}\), 92% of colour removal and 8 uC residual was
obtained. This air requirement value (8.4 g of air/m^3 water) is in the commonly range (6 to 12 g of air/ m^3 water) found in water treatment plants using DAF.

Pilot plant results
The second phase of the study was carried out using a high rate DAF pilot unit (HRDAF) fed by the same type of raw water used in the preliminary step, and coagulated with 40 mg.l⁻¹ aluminium sulfate at pH around 6.3. Operating the pilot plant with the plate inclination angle of 70º, four sets of experiments (totaling twelve) were performed followed by other five sets of essays (totaling eighteen) with 60º. For each set of experiments the horizontal water velocity (Vh) between the plates was fixed, varying only the S* value. Due to the large amount of information gathered, only the results for the best situations obtained in each set of experiments are presented here.

Table 3 shows the results of these best situations. As an illustration, Figures 3 and 4 show the curves referring to the sets A and F, where the optimum flotation conditions for both inclination angles were achieved. It can be noted in Figure 3 that experiment 2 – performed with a Vh of 18.0 cm.min⁻¹, 4 g/m^3 air supply and 70º inclination – presented the

Table 3  Best removal results and optimum operational conditions for each set experiments

<table>
<thead>
<tr>
<th>Plates angle</th>
<th>Essay sets</th>
<th>Experiment with best results</th>
<th>Reynolds Vh cm.min⁻¹</th>
<th>S* average g/m³</th>
<th>Turbidity (%)</th>
<th>TSS (%)</th>
<th>Colour (%)</th>
<th>Residual values</th>
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<td>4.00</td>
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<tr>
<td></td>
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</table>

The air quantity (S*) is given in g air/m³ of raw water
* See Figure 2
** see Figure 3

Figure 3  Results obtained during the experimental set “A” using the DAF pilot plant, with the Vh and the inclination angle of 18 cm.min⁻¹ (Rey of 240) and 70º, respectively
best results obtaining 94% TSS removal (residual of 1.9 mg/l), 90% colour removal (residual of 10 uC) and 88% turbidity removal (residual of 0.7 NTU).

Referring to the 60º inclination angle, it can be observed in Figure 4 that experiment 18 – performed with 4.15 g of air/m³ water and \( V_h \) of 23.5 cm.min⁻¹ – presented even better results obtaining 93% TSS (residual of 2.1 mg/l⁻¹), 92% colour removal (residual of 10 uC) and 91% turbidity removal (residual of 0.7 NTU).

Generally speaking, it was observed that the plate inclination angle in the range of 60º and 70º had little influence in the high rate DAF pilot unit performance, because the removal efficiencies obtained were very similar in all the \( V_h \) range studied, as shown in Table 3. Furthermore it was verified that for both angles tested, the pilot plant was able to operate with very high \( V_h \) values, (\( V_h \) within 36 to 46 cm.min⁻¹), and low \( S^* \) values (around 4 g of air/m³ of water). For example, under these conditions, the colour removal decreased only 5% (from 92 to 87%). For higher rates, up to \( V_h \) of 96 cm.min⁻¹ and Rey around 1060, the pilot plant also presented reasonable performance, requiring however, higher \( S^* \) values (8.2 g/m³ and 6.4 g respectively for angles of 70º and 60º). Therefore it is recommended that the design of this type of DAF unit should consider the energy costs related to the air supplied (\( S^* \)) and the investment costs of the unit dependent upon applied \( V_h \).

Conclusions
The batch flotation tests performed using the simple Flotatest equipment were very useful to identify the adequate coagulation conditions (alum dosage and pH) for the study of water flotation. The air requirements (\( S^* \)) previewed using the Flotatest, 8.4 g of air/ m³, were comparable to the values obtained in the high-rate dissolved air flotation (HRDAF) pilot unit where very high \( V_h \) values were applied (96 cm/min and Rey around 1060). The type of pilot flotation unit used in this study was able to operate with excellent performance at high rates (\( V_h \) until 46 cm/min and Rey of 510) requiring an air quantity (\( S^* \)) of around 4 g of air/ m³ of water. This \( S^* \) value is much lower than that normally required in conventional DAF units for water treatment in the range of 6 to 12 g/m³. Even for high \( V_h \) values like 96 cm.min⁻¹ (Reynolds number around 1060), the HRDAF pilot unit has also presented good performance.

For Reynolds numbers in HRDAF pilot unit of up to 510 (\( V_f \) up to 46 cm.min⁻¹), the 60º or 70º inclination plates angles had no influence on its performance, producing water with...
residual colour within 9 and 15 uC, turbidity around 1.0 NTU and TSS between 2.5 and 3.5 mg.l\(^{-1}\). For essays with higher rates (Rey > 510), the 60° angle has shown to be more profitable, requiring lesser air supply (\(S^*\)) than that required when using the 70° angle.

No problems related to any anomalous floc accumulation on the surface of the plates for both inclination angles tested were observed. The high rate DAF unit fast responded to changes in the applied values of \(S^*\) and \(V_h\), diminishing or raising its performance.

In the preliminary essays with the Flotatest (batch flotation tests) associated with a low \(V_f\) value of 4 m.h\(^{-1}\) good flotation performance was observed with only 20 mg.l\(^{-1}\) aluminium sulfate application, that is half the value of dosage adopted during experiment with the pilot unit. Thus, it is recommendable that experiments with the HRDAF unit are conducted to evaluate the possibility of operating with lower optimal coagulant dosages. Furthermore, all processes and flow features of the HRDAF unit need to be conveniently modeled to permit predictions for practical applications. Thus, efforts to generate such models are essential.

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