The influence of the contact zone configuration on the performance of a DAF pilot plant applied to water treatment

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ABSTRACT

This paper presents the results of a study carried out aiming not only to characterize the flow structure into different contact zone (CZ) configurations of a 4.6 m$^3$/h rectangular dissolved air flotation (DAF) pilot plant (DAFPP) fed with synthetic water but also to verify the influence of these changes on the color and turbidity removal efficiencies. MicroADV equipment was used to characterize the flow pattern into different CZ configurations. The CZ shaft wall was maintained in a vertical position and eight different configurations of the CZ were investigated in order to fit different values of hydraulic surface loadings ($HSL_{CZ}$), hydraulic detention time ($T_{CZ}$) and cross-flow velocity ($V_{CF}$) in the CZ of the DAFPP. It was concluded that $T_{CZ}$ ranging from 34 to 65 s associated with $HSL_{CZ}$ ranging from 67 to 180 m/h led to satisfactory turbidity (>91%) and color (>87%) removal efficiencies; but the highest DAFPP performance was verified when applying higher values of $HSL_{CZ}$ (up to 180 m/h) associated with $T_{CZ}$ of 34 s and $V_{CF}$ of 45 m/h, thus resulting in 98.3% turbidity removal (residual of 0.21 NTU) and 96.4% color removal (residual < 2 CU).

Key words | acoustical Doppler velocimeter, contact zone, flotation, water treatment

INTRODUCTION

Nowadays, dissolved air flotation (DAF) is widely recognized as an attractive technique for floc separation in water treatment systems receiving many kinds of raw water, mainly algae laden and colored waters. The success of DAF mainly depends on the following:

(i) An effective pre-treatment of the raw water, including appropriate coagulation/flocculation steps, in order to form flocs with characteristics (size, strength and hydrophobicity) suitable for the flotation step.

(ii) A sufficient air microbubble (0.01–0.1 mm diameter) concentration, which must be provided in order to form a white ‘floc-bubble’ blanket distributed for the full horizontal cross-section of the flotation tank (below the floated sludge layer). The required bubble concentration depends basically on the water quality and pre-treatment and usually stands in the range of 6 to 8 g of air/m$^3$ of water. The bubble concentration in the region of the DAF unit entrance, known as the contact zone (CZ), depends on the type of adopted saturation chamber, its operation pressure, the recycle water flow, water temperature and the kind (and number) of nozzles adopted to depressurize the recycle flow.

(iii) Careful design of the CZ, which must be made because in this zone the mixture of the flocculated water with the air microbubbles takes place. Likewise, the subsequent separation zone (SZ) of the DAF units must be well conceived and dimensioned to promote an efficient separation of the ascending ‘floc-bubble’ aggregates from the clarifying water. Moreover, an efficient way to remove the floated sludge must be provided. It should be noted that the CZ project markedly influences the performance of
the adjacent SZ and, consequently, the floc separation efficiency of the whole DAF system.

Different aspects of the CZ such as modeling, flow characterization and geometric configuration have been studied by several researchers, such as Edzwald (2010), Edzwald et al. (1990), Fukushi et al. (1993), Haarhoff & Edzwald (2004), Lakghomi et al. (2012), Lundh et al. (2000, 2002), Reali (1991), and Shawwa & Daniel (1998), among others. Specifically the study performed by Lundh et al. (2002), where an acoustical Doppler velocimeter (ADV) was applied to characterize the flow structure inside the CZ of a shallow (1.35 m deep) 2:1 rectangular DAF pilot plant, can be pointed out. They evaluated the flow structure of nine different CZ configurations by varying the shaft wall height (SWH), length and inclination but maintaining the same flow and the hydraulic surface loading in the separation zone (HSLCZ). Based on hydraulic principles – but not considering the suspended solids, turbidity or color removal efficiencies – they recommended the following CZ design criteria: HSLCZ around 65 m/h (range: 40–98), SWH around 91 cm (>81 cm), cross-flow velocity (VCF) around 48 m/h (>37 m/h) and hydraulic detention time (TCZ) around 45 s (>33 s).

This paper presents the results of a study carried out aiming to investigate the influence of the main CZ design parameters (TCZ and HSLCZ) not only on the flow structure in the CZ but also on the overall turbidity and color removal efficiencies of a conventional 2.1 m high and 3.8:1 rectangular DAF unit applied to water treatment. Thus, it was possible to associate the flow structure characteristics in the CZ with the color and turbidity removal efficiencies for each investigated CZ configuration.

METHODS

Pilot plant

The pilot plant was fed with synthetic water obtained by adding 1.0 mg/L of commercial humic acid (Aldrich 675–2) and 8.5 mg/L of kaolin (Fluka 60609). Synthetic water characteristics: apparent color (mg CU/L): 52 ± 3; UV254 (cm⁻¹): 0.024 ± 0.001; dissolved organic carbon (DOC) (mg/L): 1.5 ± 0.05; turbidity (NTU): 11 ± 2; total solids (mg/L): 8.9 ± 0.8; alkalinity (mgCaCO₃/L): 21 ± 2 and pH: 6.3 ± 0.2. As shown in Figure 1 the dissolved air flotation pilot plant (DAFPP) has: (i) two 15 m³ reservoirs for synthetic water (with mixers); (ii) one ‘in-line’ gas heater to control the synthetic water temperature; (iii) one ‘in-line’ tubular rapid mix unit where the coagulant (Al₂[SO₄]₃.14H₂O) is applied; (iv) a four-compartment flocculation unit having electronically controlled slow vertical mixers operating at the same rotation (each flocculation compartment having 0.5 × 0.5 m² horizontal cross-section, total height of
2.1 m and 0.12 m of free board); (v) a conventional 3.8:1 rectangular 2.1 m high DAF unit having a 1.50 m long and 0.40 m wide SZ and a CZ with fixed width (0.40 m) and variable length and height; (vi) a packed bed (1.2 m high) saturation chamber (1.92 m high and 0.36 m diameter column) whose effluent line is connected to two needle valves installed at the bottom of the contact zone; (vii) a coagulation dosing system; and (viii) two centrifuge pumps associated with electromagnetic flow meters to feed the pilot plant with the synthetic water and to recycle and pressurize the flow of the saturation chamber.

To verify the influence of $T_{CZ}$ and of $HSL_{CZ}$ on CZ flow structure and on DAFPP turbidity and color removal, eight essays were performed. The shaft wall, which defines the CZ inside the first part of the DAF unit (see Figure 1), was always maintained in a vertical position and its width was kept constant (0.40 m). The length and the height of the CZ were varied in different forms to fit $HSL_{CZ}$ values around 67, 90, 127 and 180 m/h and hydraulic detention time ($T_{CZ}$) values around 16, 24, 34, 65 and 88 s.

Aiming to investigate the influence of $HSL_{CZ}$ on flow structure and on DAFPP performance, in the first four essays the $T_{CZ}$ was kept the same, around 34 s, and $HSL_{CZ}$ was varied (67, 90, 127 and 180 m/h). After choosing the $HSL_{CZ}$ value that produced the best results, two more essays (#5 and #6) were performed varying the $T_{CZ}$ (16 and 24 s) but maintaining the same $HSL_{CZ}$ value (180 m/h). Finally, two more experiments (#7 and #8) were carried out by maintaining the lowest tested $HSL_{CZ}$ value constant (67 m/h) but varying the $T_{CZ}$ (65 and 88 s). This way, it was possible to check the influence of the $T_{CZ}$ on DAFPP performance together with evaluating the changes in the flow structure within the CZ. The different $HSL_{CZ}$ and $T_{CZ}$ values were obtained by altering the shaft wall height and thickness (see Figure 1). These different arrangements were obtained by introducing special pieces, constructed using wooden sheets, into the CZ.

Each essay was performed obeying the following procedures: (i) the essay was started by filling the pilot units with synthetic water at the chosen flow and simultaneously dosing the coagulant solution; (ii) after the units were filled, the water recycling system was turned on; (iii) 20 minutes after the DAFPP reached steady-state conditions, the first effluent sample was collected to perform pH, color and turbidity measures; and after this, (iv) clarified and raw water samples were collected for the same measurements every 10 min; and (v) after 60 min of steady-state conditions in the DAFPP, the ADV measurements were started. The following operational parameters were maintained at nearly constant values during all the essays: (i) incoming flow to the DAFPP: 4.60 m³/h (automatically controlled); (ii) recycle flow in the saturation system: 0.46 m³/h (automatically controlled); (iii) gauge pressure within the saturation chamber: 450 ± 5 kPa; (iv) water temperature: 25 ± 1 °C; (v) coagulant dosage: 1.4 mg Al³⁺/L; (vi) mean velocity gradient in the flocculation compartments ($G_f$): around 80 s⁻¹; (vii) total flocculation time: 25.8 min; and (viii) downflow rate in the SZ: 8.43 m/h (considering the net surface area of the SZ).

**ADV measurements**

The principle and procedures of the ADV measurements are explained in detail by Lundh et al. (2002). They also discuss the limitations of the measurements carried out inside flotation units, where the water contains high concentrations of microbubbles. The ADV equipment used in this study (Sontek) was similar to that used by those authors. It was possible to determine more or less continuously (50 samples per second) three velocity components at the measuring point. Then, as adopted by Lundh et al. (2002), the contact zone of the flotation tank was defined in an $xyz$ coordinate system to give reference points as to where the measuring point was located. As can be seen in Figure 1(b), coordinate $z$ gives the height over the CZ bottom, $x$ gives the length starting from the influent side, and $y$ gives the width. The velocities follow the same coordinate system. As in the study performed by Lundh et al. (2002), due to the restrictions concerning ADV in bubbly water, emphasis has been placed on the flow structures rather than on the exact value of the velocity, once the direction of each velocity vector is correct. In this study each ADV measurement took around 2 min with a sample frequency of 50 Hz (6,000 measurements per point). During each essay, ADV measurements at six different $xy$-planes (at six $x$ values) were taken in a way that the measurement points formed a grid (spaced in a range of 2.4 to 3.7 cm, approximately). For each essay, the heights of these six $xy$-planes were chosen in a manner that three of them were situated in the CZ and three above the CZ.
After processing the data, the average velocities were plotted on a vector plot or on a surface plot showing the overall flow situation in the CZ. Unfortunately, during essays 7 and 8 no ADV measurement was taken.

RESULTS AND DISCUSSION

Considering the impossibility of quantifying the mixing intensity by using ADV measurements in bubbly water (Lundh et al. 2002), the evaluation of the mixing characteristics of the flow inside the different contact zone configurations was restricted to the visual observation of the velocity profiles. Each investigated region of the CZ was considered mixed if the flow pattern indicated the presence of turbulence and recirculation of water. Otherwise, in plug flow the velocities are evenly distributed across the section and directed perpendicular to the cross-section.

Due to the lack of space in this paper, although taken and processed for all the first six essays, it is not possible to present the surface plots of velocities obtained during this research work. However, it is believed that the plots shown in Figure 2, which were obtained by using the ADV measurements along the z-axis, can give a satisfactory basis for the present qualitative flow structure analyses.

Moreover, in Table 1 a summary of the qualitative analyses of the CZ flow structures for the first six essays is presented. This summary was made based on observations of the whole set of data obtained by using the ADV probe and regarding the main characteristics of the CZ flow structure, in each investigated section, which are expressed as follows: ‘M’ indicates the presence of mixing in the CZ due to horizontal flow movements in the xy-plane; ‘R’ indicates the presence of return flow coming back from the SZ to the region above the CZ together with mixing conditions; and ‘FF’ indicates the predominance of forward and upward flow leaving the CZ toward the SZ.

Influence of the HSL<sub>CZ</sub> on CZ flow structure and on color and turbidity removal

Essays 1 to 4 were performed by keeping \( T_{CZ} \) (around 34 s) constant and increasing the HSL<sub>CZ</sub> from 67 to 180 m/h. The other variables are shown in Table 1. As can be seen in Figure 2(a)–(d), there was a well-mixed region in the superior half of the CZ in all cases, which is easily observable in Figure 2, mainly for the first three essays.

Figure 2 | The velocity profiles in the central longitudinal and vertical section of the contact zone (CZ) for different CZ lengths and shaft wall heights (H). The thicker lines indicate the CZ limits and the dotted line indicates the water level position.
Still comparing the results of the first four essays ($T_{CZ}$ constant around 34 s) it can be seen that the higher the $HSL_{CZ}$ the more plug-like the flow was (Figure 2(a)–(d)). Moreover, it is also important to highlight that in the first three essays, where the $V_{CF}$ values ranged from 9.4 to 15.2 m/h, a more uncontrolled flow pattern above the contact zone was detected. Furthermore, in these essays, it was possible to observe the undesired presence of some degree of return flow above the top of the shaft wall (some velocity vectors above the top of the shaft wall are directed upwards and backwards in Figure 2(a)–(c)). This return flow comes from the SZ to the region above the CZ. On the other hand, during essay 4, the flow in the final part of the CZ was more uniform, more plug-like and the velocities were directed upwards and forwards above the CZ (without the presence of return flows).

Observing the color and turbidity removal in the first four essays (Table 1) it can be seen that, for the investigated range of $HSL_{CZ}$ values (67–180 m/h) and by maintaining the $T_{CZ}$ fixed around 34 s, the higher the $HSL_{CZ}$, the higher the DAFPP color and turbidity removal were. The turbidity removal increased from 91.8% (0.9 NTU remaining) when applying $HSL_{CZ}$ of 67 m/h, to 98.5% (0.21 NTU remaining) when operating with $HSL_{CZ}$ of 180 m/h. The color removal increased from 87.3% to more than 96.4% (residual < 2 CU) in the same situation. Then, it was possible to observe that essay 4 produced not only the best color and turbidity removal but also the more uniform and plug-like flow above the CZ with velocities that were directed upwards and forwards. Additionally, it is important to emphasize that the essays where return flow was observed presented lower turbidity and color removal efficiencies than in essay 4, where no return flow was detected.

### Influence of the $T_{CZ}$ on CZ flow structure and on color and turbidity removal

Observing the velocity profiles regarding essays 5 and 6 (Figure 2(e) and (f)) – where, like in the essay 4, the $HSL_{CZ}$ was maintained at 180 m/h but $T_{CZ}$ was lowered to 16 s and 24 s, respectively – it can be seen that although...
the major part of the velocity vectors in the upper region of the CZ are directed upwards and forwards, some velocity vectors directed upwards and backwards appear above the top of the shaft wall. This represents the presence of returning flow from the separation zone to the region above the contact zone, thus making the flow less plug-like in this region. In contrast, the profile for essay 4 (Figure 2(d)) shows no return flow above the CZ. By comparing the color and turbidity removal obtained during essays 4, 5 and 6 (all performed maintaining HSL\textsubscript{CZ} around 180 m/h), it can be seen (Table 1) that lowering T\textsubscript{CZ} from 34 s (essay 4) to 24 s (essay 6) resulted in a decrease in both turbidity (from 98.5\% to 95.3\%) and color (from >96.4\% to 92.4\%) removal efficiencies. Decreasing T\textsubscript{CZ} to only 16 s (essay 5) caused a sharp decrease in the turbidity (from 95.3\% to 87.6\%) and color (from 92.4\% to 80\%) removal.

Regarding the last two essays – where HSL\textsubscript{CZ} was maintained at 67 m/h and T\textsubscript{CZ} was increased from 34 to 65 s in essay 7 and from 65 to 88 s in essay 8 – it can be observed that the increase of T\textsubscript{CZ} from 34 to 65 s caused an improvement in DAFPP performance (the residual turbidity decreased from 0.90 to 0.67 NTU and the final color decreased from 7 to 5 CU). However, further increase in T\textsubscript{CZ}, from 65 to 88 s, caused a sharp decrease in the performance of the unit and the residual turbidity grew from 0.67 to 1.09 NTU and color from 5 to 11 CU. This shows that, for HSL\textsubscript{CZ} of 67 m/h, there was an optimum value of T\textsubscript{CZ} between 34 and 88 s (probably near 65 s).

**Overall discussion**

The results showed that the CZ configuration associated with HSL\textsubscript{CZ} of 180 m/h, T\textsubscript{CZ} of 34 s and V\textsubscript{CF} of 45 m/h produced the best overall DAFPP performance. Under these conditions a flow structure with a considerable degree of mixing but presenting the most plug-like tendency compared with the other conditions (lower HSL\textsubscript{CZ} values) was observed. This high value of HSL\textsubscript{CZ} does not agree with the range of HSL\textsubscript{CZ} values suggested by Lundh et al. (2002) (40–98 m/h) and by Haarhoff & van Vuuren 1995 (40–100 m/h). However, it is important to say that despite not presenting the best results, the lower HSL\textsubscript{CZ} values investigated in this work (ranging from 67 to 127 m/h) were still capable of promoting satisfactory color and turbidity removal, associated with T\textsubscript{CZ} in the range of 35 to 65 s. On the other hand, the best results obtained in this study when applying the highest HSL\textsubscript{CZ} values agree with the conclusion of the study carried out by Shawwa & Daniel (1998) aiming to investigate the influence of HSL\textsubscript{CZ} (ranging from 30 to 90 m/h) on the hydrodynamic conditions (T\textsubscript{CZ} and mixing degree) inside the CZ of a circular DAF unit. They verified that the higher the HSL\textsubscript{CZ} value the more plug-like the flow was, thus suggesting that higher HSL\textsubscript{CZ} values would provide sufficient mixing conditions for the contact between flocs and bubbles.

It was interesting to observe that in the present study, when T\textsubscript{CZ} was maintained around 34 s, the decrease of the HSL\textsubscript{CZ} from 180 to 67 m/h (passing by 127 and 90 m/h) caused a gradual decrease in DAFPP performance. Specifically for the lower HSL\textsubscript{CZ} value (67 m/h), the clarification efficiency was improved when T\textsubscript{CZ} was increased from 34 to 65 s, thus probably indicating that HSL\textsubscript{CZ} values lower than 180 m/h would require T\textsubscript{CZ} higher than 34 s (up to 65 s). Moreover, as commented before, for HSL\textsubscript{CZ} of 67 m/h it was verified that the increase of T\textsubscript{CZ} from 65 to 88 s caused a sharp decrease in color and turbidity removal, hence indicating that for this chosen HSL\textsubscript{CZ} value there was an optimal T\textsubscript{CZ} range (34–65 s in this study), above or below which there was a decrease in the clarification efficiency.

Summarizing, it is possible to suppose that there is a particular optimal T\textsubscript{CZ} value (or range of values) for each HSL\textsubscript{CZ}, and that this T\textsubscript{CZ} value decreases as the HSL\textsubscript{CZ} increases. In the present study the optimal T\textsubscript{CZ} for HSL\textsubscript{CZ} of 67 m/h was probably around 65 s and for HSL\textsubscript{CZ} of 180 m/h around 34 s. It is important to note for the present case that, even considering the optimal T\textsubscript{CZ} values for both extreme HSL\textsubscript{CZ} values tested, that is, 67 and 180 m/h, this last was conducive to superior color and turbidity removal efficiencies. Finally, regarding V\textsubscript{CF}, it was possible to observe that values below 45 m/h caused a decrease in DAFPP performance, thus confirming the design criteria suggested by Lundh et al. (2002) (V\textsubscript{CF} > 37 m/h) and partially agreeing with that reported by Haarhoff & van Vuuren (1999) (20 < V\textsubscript{CF} < 100 m/h). However, it is important to mention the fact that in essay 8, even when increasing V\textsubscript{CF} from 15.8 m/h (associated with T\textsubscript{CZ} of 65 s and HSL\textsubscript{CZ} of 67 m/ h) to 33.3 m/h (T\textsubscript{CZ} of 88 m/h), color and turbidity removal sharply decreased, hence indicating that this excessive T\textsubscript{CZ}
was so harmful for the flotation process that the supposed benefit from the increase of the $V_{CF}$ was not predominant. A possible explanation for this is that exaggerated $T_{CZ}$ values could have led to an excessive agglutination of the microbubbles, thus lowering the formation of stable ‘floc-bubble’ aggregates. However, further research is needed to verify the influence of $V_{CF}$ on DAF unit performance and how the concentration (and size) of the microbubbles present in the recirculated water can affect the flow pattern in the CZ and the process efficiency.

CONCLUSIONS

For the 3.8:1 rectangular (2.1 m high) DAFPP and synthetic water used in this study, the results permit the following to be concluded:

(i) In a general view, the flow structures measured by using the ADV equipment were similar to that observed by Lundh et al. (2002) in a shallower 2:1 rectangular DAF unit; moreover, their recommendations concerning $T_{CZ}$ and $V_{CF}$ agreed with the results of the present research; regarding the $HSL_{CZ}$, the results of the present study have shown that, providing $T_{CZ}$ ranged from 34 to 65 s, the higher the $HSL_{CZ}$, the higher the overall DAFPP performance was.

(ii) $T_{CZ}$ below 34 s associated with $V_{CF} < 45$ m/h caused a sharp decrease in the turbidity and color removal together with the presence of return flow from the SZ to the CZ of the DAFPP. On the other hand, for $HSL_{CZ}$ of 67 m/h, 88 s was shown to be an excessive $T_{CZ}$ value that caused a sharp decrease in the clarification efficiency, thus indicating that, for each $HSL_{CZ}$ value, there was an optimal $T_{CZ}$ value (around 65 s for a 67 m/h $HSL_{CZ}$ and 34 s for 180 m/h).

(iii) $T_{CZ}$ values ranging from 34 to 65 s associated with $HSL_{CZ}$ values in the range of 67 to 180 m/h led to satisfactory turbidity (higher than 91%) and color (higher than 87%) removal, but, the best DAFPP performance was verified when applying $HSL_{CZ}$ of 180 m/h associated with a $T_{CZ}$ of 34 s and with a $V_{CF}$ of 45 m/h (98.3% turbidity removal with residual of 0.21 NTU and more than 96.4% color removal with residual < 2 CU).

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