The influence of floc size and hydraulic detention time on the performance of a DAF pilot unit and their relationship with a mathematical model

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ABSTRACT
The influence of floc size and hydraulic detention time on the performance of a DAF pilot unit and their relationship with a mathematical model was investigated. For this purpose, the following design and operational parameters were considered: the pair hydraulic detention time \( (td_{cz}) \) and hydraulic loading rate in the contact zone \( (HLR_{cz}) \); down-flow loading rate in the clarification zone \( (HLR_{d}) \); particle size distribution \( (d_F) \) and recirculation rate \( (p) \). As reference for DAF performance analysis, the proposed \( \beta .td \) parameter from the mathematical model presented by Reali (1991) was used. Results pointed out that the \( td_{cz} \) is an important factor on DAF performance and that the number of flocs and \( d_F \) are also determinant on DAF efficiency. Further, the \( \beta .td \) parameter was sensitive to both design and operational parameters, which were varied on DAF pilot plant.

Keywords: Particles; image analyses; mathematic model; dissolved air flotation.

INTRODUCTION
Despite of Dissolved Air Flotation (DAF) have been studied and applied for decades there are still some black-boxes, most of them remain in the fundamentals of the process. It is known that micro bubbles and particles sizes are crucial in DAF performance as pointed out by Edzwald (1995). Furthermore, Haarhoff e Edzwald (2001) pointed out that the interaction between bubbles and particles and the tank hydrodynamics as well is a complex and poorly understood phenomenon.

The hydraulic detention time \( (td_{cz}) \) and the hydraulic loading rate in both contact zone \( (HLR_{cz}) \) and separation zone \( (HLR_{d}) \), the recirculation rate \( v/v \) \( (p) \) and the flocculation are all important to design and operational parameters for DAF tanks. All of them are linked to the mixture conditions between bubbles and particles, which also depends on the tank’s hydrodynamic and particle size distribution within DAF reactor.

Thus, this paper intends to bring some insights about both design and operational conditions and their influence on color and turbidity removal by DAF, in the light of a mathematical model proposed by Reali (1991).

BRIEF CONSIDERATION ABOUT DAF MODELS
There are many models, which intend to explain the relationship of DAF operational and design parameters. To mention some: Flint and Howarth, 1971; Reay and Ratcliff, 1973; Cornet and Moisse, 1982; Reali, 1991; Malley and Edzwald, 1991; Fukushi, Tambo and Matsui, 1995; Liers, Baeyens and Mochtar, 1996; Matsui; Fukushi and Tambo, 1998; Leppinen, 2000; Leppinen, Dalziel and Linden, 2001; Han, Kim and Dockko, 2001; Haarhoff and Edzwald, 2001; Kwak et.
In this paper we used the model proposed by Reali (1991), which was also described by Reali e Campos (2002). This model takes into account the collision induced by the turbulent field inside DAF contact zone and by the relative velocities between bubbles and flocs. The author of the model used concepts of coagulation in turbulent field to describe important variables, such as: mean bubbles \( (d_B) \) and floc sizes \( (d_F) \); recirculation rate \( (p) \); hydraulic loading rate in separation zone \( (HLR_d) \) and hydraulic detention time in contact zone \( (td_{cz}) \).

The final equation of the flotation model proposed by Reali (1991) is presented on Equation 1.

\[
\beta_{td} = - \left[ \ln \left( 1 - \frac{n \phi}{S_V p} \left( \frac{d_B}{d_F} \right)^3 \right) \right] \left[ \frac{\pi (1 + p) d_F^3}{6 \phi \alpha} \right]
\]  

In which:
\( \phi \): floc volume concentration in the inlet of the flotation unit
\( p \): recirculation fraction \( (Q_R/Q_{ab}) \), and \( Q_R \) is the recirculation flow \( (L^3.T^{-1}) \);
\( \alpha \): see equations 2 and 3;
\( S_V \): expressed as the dissolved (precipitable) air volume concentration in the recirculated water flow (volume of dissolved air/volume of recirculated water);
\( n \): number of required microbubbles to be attached to each floc to promote its removal after leaving the contact zone. The \( n \) value need to be enough to permit the floc/bubbles aggregates rise with a velocity \( (V_{bf}) \) equal or larger than the downflow rate in the separation zone of the DAF unit. The ‘\( n \)’ value depends on the water temperature, the \( d_B \) and \( d_F \) values and on the specific mass of the air, the water and and the flocs.
\( d_B \): air bubbles diameter, uniformly sized (L)
\( d_F \): floc diameter, uniformly sized (L)
\( \alpha \): the “\( \alpha \)” value can be calculated using Equations (2) or (3), depending on the kolmogorov microscale of turbulence \( (\eta) \) compared to the mean diameter of the floc+bubbles agglomerates.

When \( \eta \geq [(d_F + d_B)/2] \), the value of the parameter \( \alpha \) is:

\[
\alpha = 0.051 \left( d_F + d_B \right)^3 \left( \frac{\varepsilon}{v} \right)^{0.5} + \frac{\pi}{4} \left( d_B + d_F \right)^2 \left[ \frac{g}{18\gamma} \left( d_B^2 + \frac{\Delta \rho d_F^2}{2} \right) \cdot \frac{V_{bf}}{2} \right]
\]  

(2)

And, for \( \eta < (d_F + d_B)/2 \) the value of \( \alpha \) is:

\[
\alpha = 0.427 \left( d_F + d_B \right)^{7/3} \left( \frac{\varepsilon}{v} \right)^{1/3} + \frac{\pi}{4} \left( d_B + d_F \right)^2 \left[ \frac{g}{18\gamma} \left( d_B^2 + \frac{\Delta \rho d_F^2}{2} \right) \cdot \frac{V_{bf}}{2} \right]
\]  

(3)

In which,
\( \varepsilon \): energy dissipation per mass unit \( (J.kg^{-1}.s^{-1}) \);
\( \Delta \rho \): \( (\rho_F/\rho_p - 1) \)
\( g \): gravity acceleration \( (L.T^{-2}) \)
\( v \): cinematic viscosity of the water \( (L^2.T^{-1}) \)
By choosing the values of the other parameters of Equation (1) is possible to estimate the “\(\beta \cdot td\)” value.

The \(td\) value can be understood as the necessary theoretical detention time in the contact zone to reach the “\(n\)” number of microbubbles attached to each floc. On the other hand, the “\(\beta\)” value takes into account the effectiveness of the contacts and is related to the floc characteristics (mainly the hydrofobicity and ‘porosity’) and to the size and characteristics of the microbubbles. Then, in an ideal situation where all the collisions would be effective (“\(\beta\)” value would be 1.0) the “\(td\)” value obtained by using Equation (1) would represent the necessary theoretical time for all the flocs to reach the desired rising velocity. Furthermore, if assuming a certain “\(td\)” value for the contact zone and calculating the respective “\(\beta td\)” value, it is possible to calculate the “\(1/\beta\)” value, that represents the theoretical number of chocks per floc “available” in the reaction zone to give at least one effective chock.

Resuming, the higher the “\(\beta td\)” value the worse is the situation, because to reach the desired flotation efficiency a higher detention time in the reaction zone would be necessary -considering a fixed “\(\beta\)” value- or higher “\(\beta\)” values (higher hydrophobicity of the flocs, for example) if considering a fixed “\(td\)” value.

In the original work Reali (1991) presents several comparative case simulations of the DAF process by using Equations (1 to 3) to predict the flotation efficiency (in terms of “\(\beta td\)” value) in each case.

**METHODS**

The performance of a DAF pilot plant (1500 L.h\(^{-1}\)) was investigated by varying both particles sizes and hydraulic detention time in the contact zone (Figure 1). A method of image analysis was used for bubbles and flocs measurements, as described in Moruzzi and Reali (2010). A total of 31551 flocs and 11035 bubbles were analyzed. The hydrodynamic performance was measured by means of Residence Time Distribution (RTD) essays presented by Moruzzi and Reali (2010). For velocities pathways identification, an Acoustic Doppler Velocimeter (ADV) was also used, as presented by Reali and Patrizzi (2007). The investigated design and operational parameters are shown in Table 1.

The mathematical model presented by Reali (1991) was used as reference (by means of \(\beta td\) values) for DAF apparent color and turbidity removal (Equation 1) and for the assessment of variables relationship.

**Table 1** – Design and operational parameters for DAF performance analysis. Hydraulic detention time in contact zone (\(td_{zc}\)), contact zone loading rate (HLR), recirculation rate v/v (p) and flocs size* were varied. Fixed conditions: \(P_{sat} 450\pm10\)kPa, T 22±1°C, downflow loading rate (HLR\(_d\)), released system (1/8” needle valve)

<table>
<thead>
<tr>
<th>HLR(_d) (m(^3)/m(^2)day)</th>
<th>HLR(<em>{zc}) (m/h) ; (td</em>{zctheoretical}\times10^2) (h)</th>
<th>p (--)</th>
<th>Flocs mean size (µm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 [8.33]</td>
<td>25 ; 2.50</td>
<td>0.10</td>
<td>270±4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.05</td>
<td>270±4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.05</td>
<td>310±4</td>
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<tr>
<td></td>
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<td>0.10</td>
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<td>310±4</td>
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</tbody>
</table>
Obtained by mean of different gradients of velocity inside flocculation unit, which contained three chambers in series, \((G_f 50s^{-1} \text{ and } G_f 90s^{-1})\) and determined by means of the diameter of an sphere of the same equivalent area \(2D\). Flocculation time was intentionally long (34 min) in order to make narrow the particle distribution size and the circularity.

The hydraulic loading rate in contact zone \((HLR_{cz})\) was determined by the ratio of the total inlet flow and the final transversal area of the contact zone. On the other hand, the hydraulic loading rate in the separation zone \((HLR_d)\) was calculated by considering the down-flow area only. The pictures of flocs were taken inside the last flocculation chamber without extracting samples, in order to avoid sample deformation. The sizes of flocs were based on the 2D sphere with the same area on the projected plan. A long-term flocculation of 34 minutes was adopted to avoid size and morphological dispersions, minimizing the samples errors. All adopted procedures for images acquisition, treatment and size determination were described by Moruzzi e Reali (2007b and 2010). 31551 flocs were counted in order to guarantee samples with 95% of interval of confidence and sample errors lower than 1%. In Figure 2 are shown one typical floc picture, after image binarization. Bubbles distribution size was also measure as described by Moruzzi and Reali (2010).

Further, the following conditions were maintained during the essays: in-line rapid mix; flocculation \(G_f 50s^{-1} \text{ or } 90s^{-1} \text{ and } T_f 34 \text{ min.}; Psat 470±20KPa; 2.25 \text{ mgAl}^{3+}/L, 22±1\degree\text{C, needle valves of } 1/8".\) Prepared water: pH 6.50; Turbidity of 5 (NUT); Apparent color of 52 (Hu); True color of 10 (Hu); Alkalinity of 24 (mg CaCO\(_3\) L\(^{-1}\)); Hardness of 15 (mg CaCO\(_3\) L\(^{-1}\)); Conductivity of 28 (\(\mu\text{Scm}^{-1}\)); Total Solids (TS) of 150 (mgL\(^{-1}\)); Fixed solids (FS) of 72 (mgL\(^{-1}\)); Volatile Solids (VS) of 78 (mgL\(^{-1}\)); Total Suspended Solids (TSS) of 2.2 (mgL\(^{-1}\)); Fixed Suspended Solids (FSS) of 0.96 (mgL\(^{-1}\)); Volatile Suspended Solids (VSS) of 1.3 (mgL\(^{-1}\)); Total Dissolved Solids (TDS) of 147.8 (mgL\(^{-1}\)); Fixed Dissolved Solids (FDS) of 71.1 (mgL\(^{-1}\)); Volatile Dissolved Solids (VDS) of 76.7 (mgL\(^{-1}\)); Absorbance 254nm of 0.060.

**RESULTS AND DISCUSSION**
Figure 3 shows the particle size distribution for both 50 and 90 s\(^{-1}\) flocculation gradients. The displacement to large ranges is clear, when the gradient was changed from 90 to 50 s\(^{-1}\), despite flocculation time was the same (34 minutes). As mentioned before, this high flocculation time was adopted in order to make distribution narrower and circularity as near to 1 as possible, since
the focus was evaluate the effect of flocs size instead of optimizing the process. However, only the mean diameter is used for the model input and its values were measured for two conditions, thus resulting on values of $270\pm4\ \mu m$ for 90s$^{-1}$ and $310\pm4\ \mu m$ for 50s$^{-1}$.

![Figure 3](image)

**Figure 3** Relative and cumulative number frequency of particles size distribution. a) $G_f\ 90s^{-1}$ e $T_f\ 34$ min. for 21256 flocs analyzed; 2.25 mgAl$^{3+}$L$^{-1}$. b) $G_f\ 50s^{-1}$ e $T_f\ 34$ min. for 10295 flocs analyzed; 2.25 mgAl$^{3+}$L$^{-1}$. Circularity of 0.62.

**Analysis of $\beta td$ and $1/\beta$ values**

The effect of flocs diameter ($d_F$) and bubble size ($d_B$) on the parameter $\beta td$ was analyzed based on the experimental results (Figure 4). For each floc mean size ($270\pm4\ \mu m$ for 90s$^{-1}$ and $310\pm4$ for 50s$^{-1}$), different bubbles mean sizes were input in the model, for the two values of recirculation applied in the experiments ($p$ of 0.05 and 0.1 (v/v)). Lower values of $\beta td$ were obtained for $p$ of 0.1 and for bigger $d_B$. This obviously occurred because the model take into account the kinetics only, however the effect of hydrophobicity cannot be neglected while choosing bigger bubbles.

The results presented in Figure 5 were obtained by varying $d_F$ for two values of $p$ (0.05 and 0.1) and $dB$ (25 and 50 μm). The $\beta td$ values were lower for $p$ of 0.1 and for $d_B$ of 50 μm, indicating that the bigger the number of bubbles and $d_B$ the better, once there would be more bubbles per floc and higher velocities. The curve discontinuity indicates the change on the relationship of $d_F + d_B$ and the size of the smallest eddy ($q$) according to equations 2 and 3. It is also clear that there is a limit on $d_F$ values (around from 1000 to 1500 μm) from which $\beta td$ start increasing.

The relationship between $\beta td$ and DAF pilot plant performance was made considering the average values of efficiency obtained during the trials on pilot plant on steady state condition (Figure 6). The $\beta$ value was assumed equal to 1, thus considering that every collision was effective, i.e. every collision results on aggregates of bubble and floc. This is a hypothetical situation, however it affects the $td$ value only but the curve trend and shape are not changed.

There was a clear trend between the residuals of apparent color and turbidity and those values of $\beta td$, as predicted by the model once it describes the flocs removal as inverse proportional in terms of $\beta td$. The simplification of the model and the errs inherent of experimental certainly influenced on the results, however the trend between DAF efficiency (obtained by experimental trials on pilot plant) and $\beta td$ values (predicted by the model) was pretty clear.

Further, according to the model concept, it is possible to predict from $\beta td$ value, the number of available bubble chock per floc within the contact zone by means of the $\beta^{-1}$ value (Figure 7).

The results presented on Figure 9 were determined from the values of $\beta td$ (Figure 6) and the $td$ values, obtained from stimulus-response tests presented by Moruzzi and Reali (2010).
According to the definition presented by Reali (1991), the higher the $\beta^{-1}$ value the better, once it indicates higher bubble floc chocks available within the contact zone. So, higher values of available chocks indicate a more likely flocs removal, as presented on Figure 7.

**Figure 4** $\beta$td and bubbles mean diameter relationship for different values of $p$. a) $d_0$ of 274\(\mu\)m; b) $d_0$ of 306\(\mu\)m. Fixed: $HLR_d$ of 200m.day\(^{-1}\); volumetric flocs concentration of 0.00213 m\(^3\).m\(^{-3}\) of water, $Sv$ 0.076m\(^3\) of air.m\(^{-3}\) of water and $Gf$ of 8s\(^{-1}\). Based on the model of Reali (1991) and on the experimental results in DAF pilot plant.

**Figure 5** $\beta$td and flocs mean diameter ($d_F$) relationship for different values of $p$. a) dB of 25\(\mu\)m; b) dB of 50\(\mu\)m. Fixed: $HLR_d$ of 200m.day\(^{-1}\); volumetric flocs concentration of 0.00213 m\(^3\).m\(^{-3}\) of water, $Sv$ 0.076m\(^3\) of air.m\(^{-3}\) of water and $Gf$ of 8s\(^{-1}\). Based on the model of Reali (1991) and on the experimental results in DAF pilot plant.
The mathematical model proposed by Reali (1991) was used as reference on analysis of DAF efficiency. For DAF performance analyzes, pilot plant essays varying operational and design parameters were carried out. The hydraulic detention time \( (td_{c,c}) \) and loading rate in the contact zone \( (HLR_{c,c}) \), down-flow loading rate \( (HLR_d) \) in the clarification zone, particle size distribution \( (d_F) \) and recirculation rate \( (p) \) were varied on DAF trials.

The results pointed out that the proposed value of \( \beta td \) by Reali (1991) model could be used as a potential tool for qualitative and comparative analyses of DAF for both design and operational parameters at contact zone.

Referring to the design parameters of the DAF contact zone, results pointed out that there is a strong relationship between \( p \) and \( td_{c,c} \) on DAF performance. Higher \( td_{c,c} \) may require lower values of \( p \) for the same DAF efficiency, keeping all other parameters constant. Although extensive essays must confirm this hypothesis, it can be assumed that once lower \( td_{c,c} \) is required, higher \( p \) values could be applied in order to keep the DAF performance. Alternatively, the configuration of contact zone could be modified in order to increment \( G \) values, which would increment \( \beta^{-1} \), consequently. Evidently, the \( td_{c,c} \) is also related to water characteristics, coagulation and flocculation once all these parameters can modify the \( d_F \), the flocs/bubbles balance and the \( \beta^{-1} \) as well. This finding prompts further researches in order to better understand the complexity of DAF process.

CONCLUSIONS
Based on the results, it can be concluded:
- The hydraulic detention time in contact zone \( (td_{c,c}) \) has an important role on 2nd generation DAF efficiency;
- The \( \beta td \) value proposed by Reali (1991) was sensitive on DAF performance for the studied conditions and can help to assess design parameters of DAF contact zone;
- The obtained $\beta_{td}$ values indicated that might exist an optimal range of flocs size, which could result on maximum DAF efficiency.

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REFERENCES