Tracer experiment and RTD analysis of DAF separator with bar-type baffles

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ABSTRACT

This paper describes the development of a new dissolved air flotation (DAF) separator with a flow streamlining baffle to improve solid separation efficiency. The analysis of the RTD (residence time distribution) curves indicated that the parameter $\theta_{10}$ (dimensionless time at which 10% of tracer has discharged) increased from 0.38 for control reactor to 0.54 for the test reactor, suggesting significant reduction in short circuit flow. The RTD curves were also used to develop a compartment model for white water (rich in micro-bubbles and water flow is turbulent) and clear water (little or no air content and water flow is quiescent) zones in the reactor using a series of CSTR (continuous stirred tank reactors) and plug flow regime respectively. The proportion of the volume occupied by the white water zone was different in control and test configurations. In the test reactor, the fraction of the clear water zone was found to increase from 6 to 37%, resulting in improvement of the suspended solid (SS) removal efficiency from 97 to 99%.

Key words | compartment model, dissolved air flotation, residence time distribution, SS removal

INTRODUCTION

Dissolved air flotation (DAF) is one of the popular methods to remove suspended solid (SS) in wastewater. In the DAF tank, micro bubbles adhere to the flocculated SS in the contact chamber, and bubble-floc aggregates float to the water surface where they are removed. The clear water is then taken out from the outlet pipe located at the bottom of the separation chamber (Edzwald 1995). The SS concentration in the clear water is influenced by both the flotation velocity of bubble-floc aggregates and the flow patterns in the DAF tank (Edzwald 2007). The flotation velocity is influenced by various factors such as floc size, pH, turbulence intensity, and contact time (Fukushi et al. 1995; Kwak et al. 2009). Typically, these factors are required to be experimentally optimized for each wastewater to improve SS removal efficiency (Al-Shamrani et al. 2002; Chuang et al. 2002). On the other hand, performance enhancement attributed to improvement in the flow patterns using flow streamlining structures are of a more fundamental nature and are independent of the wastewater type.

In general two flow zones can be observed in the separation chamber (Lundh et al. 2000). The first zone exists just below the water surface. This flow zone is normally turbulent and rich in micro-bubbles. This zone is identified as white water zone. Below the white water zone, there is little or no air content and water flow is quiescent. This region is called clear water zone (Hedberg et al. 1998). Since solid clarification takes place in the clear water zone, it is desirable to have a higher volume for the clear water zone. Lundh et al. (2002) reported that the shape of the wall dividing the influent contact chamber and separation chamber does not affect the flow patterns. However, it was indicated that increasing the distance between the top edge of the wall and the water surface promoted large circulation flow in the separation chamber. The phenomenon can be explained by considering the buoyant flow that could develop due to the low density water from the contact chamber and the higher density water in the separation chamber. The phenomenon of
buoyant flow in the bubble columns is well described (Kubota et al. 1978). By increasing the height of the inlet and discharging the feed flow close to the surface of the DAF reactor, the buoyancy-driven flow is reduced. This coupled with the baffles which reduce the recirculation flow seems to be effective. Terashima et al. (2009a) reported the effectiveness of baffle-resistance to improve flow in DAF.

The techniques of RTD (residence time distribution) curve from a tracer experiment or CFD (computational fluid dynamics) have been used to characterize the hydraulic performance parameters such as mixing time (Terashima et al. 2009b) and hydraulic efficiency (Stamou 2005) in water treatment reactors. Lundh & Jönsson (2008) reported that the stratified flow structure of a flotation tank was successfully modelled by a compartment model of the tank-in-series model for the top white water zone and the plug flow model for the bottom clear water zone. In this paper, the performance of the DAF reactor with flow streamlining baffles (Terashima et al. 2009a) is studied using the experimental RTD curves and the compartment model.

**METHOD**

**DAF tank configuration**

The details of the two tank configurations are shown in Figure 1. The rectangular tank was divided into two chambers, a contact chamber and a separation chamber. The wall dividing the chambers had a deflecting plate at the top. The flotation tank used in the study was 800 mm wide, 1,071 mm long and 800 mm deep. The total volume of the tank was 0.69 m³ and the surface area was 0.85 m². Influent water entered the contact chamber through a horizontal pipe at the bottom of the contact chamber. Pressurized water, containing micro bubbles, entered vertically at the bottom of the contact chamber. The influent water and pressurized water contacted in the contact chamber and entered the separation chamber from the top of the contact chamber. The clarified effluent was withdrawn from the pipe placed at the bottom of the separation chamber. The baffles were composed of six bars which had the diameter of 32 mm and a length equal to the width of the flotation tank. The vertical and horizontal spacing between the bars was 60 mm (c/c).

**Operating conditions**

The experiments were conducted using treated effluent from a wastewater treatment plant. The hydraulic loading to the DAF reactor was 6 m³ h⁻¹. This included the flows of pressurized water (1 m³ h⁻¹). The hydraulic retention time ($t_h$) was 411 s and the surface loading rate (LV) was 7 m h⁻¹. The pressurized water was generated by a micro-bubble generator with a cascade pump (Nikuni Co., Ltd). In the SS removal experiment, kaolin clay of 120 mg L⁻¹ was added to treated effluent as model particles. Clay does not have exactly the same flotation characteristics as wastewater particles. However, the characteristics of the particles is not expected to affect the results because the aim of the investigation is to measure the relative removal efficiency improvement by the introduction of baffles. The kaolin clay particles were coagulated by adding 34 mg L⁻¹ of PAC (polyaluminum chloride, as Al₂O₃) and flocculated by feeding 3 mg L⁻¹ of an anionic polymer at pH 7.5 before feeding into the contact chamber. The SS concentration of the influent water was 175 mg L⁻¹. The treated water was examined for SS concentration from both of the DAF tanks.

**Observation by video camera**

Video recordings were analysed to elucidate the flow pattern in the separation chamber without baffles. A video camera lens was directed toward the center in the separation chamber and the back of the camera was fitted to the wall surface. The camera was moved in the vertical and horizontal direction to record particle motions.
Tracer experiments

Tracer experiments were conducted to collect data for the RTD curves for both of the tanks. A 40% lithium chloride solution was used as tracer. The solution density was adjusted before injection by mixing it with ethanol. The final density of the injected solution was equal to the density of water. One hundred grams of the solution was fed into the contact chamber through the inlet in a short period of 1 s. The concentration of lithium ion in the effluent water was measured by AAS (atomic absorption spectroscopy) method. As the tracer injection time was quite short (less than 1% of $t_h$) the tracer injection is treated as a pulse input in tracer data analysis.

Analysis of RTD

The RTD curves from the tracer experiments were normalized by using the following Equations (1)–(4) (Levenspiel 1999; Lundh & Jönsson 2005).

$$
E_i = \frac{C}{\sum_{i=1}^{n} C_i \cdot \Delta t_i}
$$

(1)

$$
\theta = \frac{t}{t_h}
$$

(2)

$$
t_h = \frac{V_F}{Q}
$$

(3)

$$
E_\theta = t_h \cdot E_i
$$

(4)

where, $E_i$: exit age distribution in terms of $t$ (s$^{-1}$), $C$: tracer concentration at the outlet (kg m$^{-3}$) at time $t$, $t$: time (s), $\theta$: dimensionless time (–), $t_h$: hydraulic retention time (s), $V_F$: volume of flotation tank (m$^3$), $Q$: flow rate (m$^3$ s$^{-1}$), $E_\theta$: exit age distribution in terms of $\theta$ (–). Meanwhile, some other hydraulic parameters were calculated by Equations (5)–(7).

$$
t_{mean} = \frac{\sum_{i=1}^{n} t_i \cdot C_i \cdot \Delta t_i}{\sum_{i=1}^{n} C_i \cdot \Delta t_i}
$$

(5)

$$
F(\theta) = \int_{0}^{\theta} E_\theta d\theta
$$

(6)

$$
F(\theta_{10}) = 0.1
$$

(7)

where, $t_{mean}$: observed mean residence time (s), $\theta_{10}$: normalized time of 10% tracer discharge (–). The standard parameter of $\theta_{10}$ relates to the degree of short-circuiting. A smaller numerical value of this parameter corresponds to a larger short circuit (Stamou 2002; Li et al. 2006).

Compartment model

The hydraulic characteristics in the separation chamber of the DAF tank could be represented by two stratified zones (Lundh et al. 2000) of top white water zone and bottom clear water zone as shown in Figure 2 (left). Based on this stratification scheme, the hydraulics in DAF was modelled with a compartment model as shown in Figure 2 (right) (Levenspiel 1999; Lundh & Jönsson 2005). The contact chamber was modelled as a mixing flow vessel. The top white water zone was modelled as a series of CSTR (continuous stirred tank reactors) while the bottom clear water zone was represented by a plug flow regime. The tracer
concentration in the contact chamber was calculated based on a simple mass conservation, Equation (8).

$$\frac{\Delta C}{\Delta t} = \frac{Q \cdot (C_{IN} - C_C)}{V_C}$$  \hspace{1cm} (8)

where, \(C_C\): tracer concentration in the contact chamber (kg \(m^3\)), \(C_{IN}\): tracer concentration at the inlet (kg \(m^3\)) and \(V_C\): contact chamber volume (m\(^3\)). Similarly, the tracer concentration in the each mixing vessel in the CSTR of the white water zone was calculated by following Equations (9)–(10).

$$\frac{\Delta C_j}{\Delta t} = \frac{Q \cdot (C_j - C_{j-1})}{V_j}$$  \hspace{1cm} (9)

$$V_j = \frac{V_T}{N}$$  \hspace{1cm} (10)

where, \(C_j\): tracer concentration at No. \(j\) modelled vessel in the CSTR of the white water zone (kg \(m^3\)), \(V_j\): volume of No. \(j\) modelled vessel (m\(^3\)), \(V_T\): top white water zone volume (m\(^3\)), \(N\): number of CSTR (-). The transport in the clear water zone was modelled as a simple vertical transport not reflected in the shape of the RTD curve. The time conversion was expressed by following Equations (11)–(12).

$$t \rightarrow t + \delta t$$  \hspace{1cm} (11)

$$\delta t = \frac{V_B}{Q}$$  \hspace{1cm} (12)

where, \(\delta t\): time delay in the clear water zone (s), \(V_B\): bottom clear water zone volume (m\(^3\)). A total volume of the flotation tank was a summation of the each hydraulic portion and a conceptual dead volume, as shown in Equation (13).

$$V_F = V_C + V_T + V_B + V_D$$  \hspace{1cm} (13)

where, \(V_D\): dead volume (m\(^3\)). The volume of the contact chamber \((V_C)\) was the actual volume of the contact chamber in the pilot plant. The active volume \((V_A = V_C + V_T + V_B\) m\(^3\)) is expressed by the parameter, \(t_{\text{mean}}\) or \(\theta_{\text{mean}}\) from RTD analysis as in Equation (14) (Levenspiel 1999).

$$\theta_{\text{mean}} = \frac{t_{\text{mean}}}{t_h} = \frac{V_A}{V_F} = \frac{V_F - V_D}{V_F}$$  \hspace{1cm} (14)

The ratio of white water zone volume \((V_T)\) to separation chamber volume \((V_S = V_T + V_B\, m^3)\) was defined by a new parameter \(\eta_T\) (-) as in Equation (15).

$$\eta_T = \frac{V_T}{V_S}$$  \hspace{1cm} (15)

The compartment model included the two parameters, \(N\) and \(\eta_T\). These parameters are determined to fit the experimental data to calculated RTD so as to maximize the correlation coefficients under the condition that \(N\) is a natural number.

**RESULTS AND DISCUSSION**

*Video camera observation*

The existence of micro-bubbles and/or flocs and the movement of water were analysed to elucidate the flow pattern in the control DAF tank (Figure 3). The image shows that the flow pattern in the DAF tank can be described by three vertically stratified zones of white water zone, transition zone and clear water zone. The white water zone was dominated by strong circulating flow while the bottom clear water zone was mostly quiescent. The bubbles were observed to be confined mostly to the white water zone, whereas the SS flocs existed in all the three zones. While the observed SS concentration difference between the white water zone and transition zone was steep, a gradual decrease in SS concentration was observed along the height of transition and clear water zone. These video
observations highlight the importance of having a sufficient volume of clear water zone for good clarification. For the purpose of the compartment model, the transition zone can be considered as part of the white water zone and can be modelled with CSTR.

**Tracer experiment**

The $E$-curves and $F$-curves from the tracer experiments are shown in Figure 4. The lag time, time elapsed between the tracer injection and its first appearance at the reactor effluent, was noted to be higher for the test reactor (DAF with baffles). The higher lag time suggests presence of a larger clear water zone with plug flow regime. The $\theta_{10}$ for the control and test DAF was 0.38 and 0.54 respectively, suggesting lesser short circuit flow in the test DAF. The $\theta_{\text{mean}}$ for the control and test DAF was 0.86 and 0.90 respectively. The parameter $\theta_{\text{mean}}$ is representative of the ratio of active volume to total volume. And the higher value of $\theta_{\text{mean}}$ indicates a smaller dead volume to total volume ratio. The ratio of dead volume to total volume is 0.14 for the control DAF and 0.10 for the test DAF from Equation (14).

**Compartment model**

The RTD curves were used to develop the compartment model for the DAF reactors. Figure 4 shows the model simulation results with the experimental results. The measured and modelled RTD curves fit well for both of the control and test reactors (correlation coefficient is 0.98 and 0.99 respectively). The hydraulics for both the reactors could be expressed by the compartment model. For both the reactors, three CSTR ($N$) in series were found to represent the system well. Lundh & Jönsson (2005) reported that the number of CSTR in a DAF reactor ranges from two to four. Our study gives the number in this range. The $\eta_T$ value for the control and test reactor was estimated to be 0.94 and 0.63 respectively, suggesting that the fraction of the bottom clear water zone was higher in the test reactor than in the control reactor.

In the test DAF reactor, the baffles near the inlet provide a resistance to the flow and weaken the recirculation flow in the white water zone, resulting in smaller volume of white water zone. Lundh & Jönsson (2005), using a compartment model, presented the changes in hydraulic patterns at different operating condition of LV and recirculation ratio of pressurized water. In this study, we showed that introduction of baffles results in an increase in volume of the clear water zone represented by the plug flow regime in the compartment model. The volume ratio of the clear water zone ($\eta_B = 1 - \eta_T$) will contribute to the SS removal efficiency. In the control DAF, the $\eta_B$ was only 6%, which was supported by the fact that the very small volume of clear water zone was observed by the video camera. It was found to increase from 6 to 37% by the introduction of the baffles. Previous CFD simulations conducted with the video camera observation visually showed that bar-type baffles enlarge the clear water zone (Terashima et al. 2009).

The tracer study results could also be correlated to the SS removal performances of the two reactors. The effluent SS concentration for the control and test reactor was
5.1 and 1.7 (mg L\(^{-1}\)) respectively. The bar-type baffles reduced the effluent SS to one third. The effect of flow streamlining baffles, which leads to improved solid removal efficiency, is explained through RTD curve analysis.

As raw water characteristics, coagulation and flocculation of SS affect the SS removal efficiency in a DAF reactor, it is quite difficult to compare the hydraulic performance of two DAF configurations experimentally. The RTD analysis method presents a suitable approach for comparing the hydraulic efficiency of the reactor, which then can be used to develop performance models. In recent years, reactor RTD curves can also be estimated with good accuracy using CFD calculation. The combination of this RTD analysis and CFD calculation allows the estimation of the structural improvements, involving the baffles, inlet-outlet arrangement and length to wide the ratio and so on, only by the computation. These calculations are also useful in evaluating reactor scale-up effects.

**CONCLUSION**

The solid separation efficiency of a new configuration of DAF with flow streamlining bar baffles was analysed using the experimental RTD curve. For the DAF reactor with baffles, the parameter \(\theta_{50}\) increased from 0.38 to 0.54, suggesting significant reduction in short-circuiting flow. The RTD curve was used to develop a compartment model. The white water zone was modelled as a series of CSTR while the clear water zone was represented by a plug flow regime. The measured and modelled RTD curves were found to fit well for both the control and new baffle reactor. The volume ratio of the bottom plug flow region was found to increase from 6 to 37% for the reactor with baffles. The bar-type baffles reduced the effluent SS to one third. The effect of flow streamlining baffles, which leads to improved solid removal efficiency, is explained through RTD curve analysis. The approach of using RTD curves to describe the hydraulic performance of a reactor was found to be very useful in explaining the observed performance differences in control and test reactors.

**REFERENCES**


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