Optimising dissolved air flotation/filtration treatment of algae-laden lagoon effluent using surface charge: a Bolivar treatment plant case study

Russell Yap, Michael Holmes, William Peirson, Michael Whittaker, Richard Stuetz, Bruce Jefferson and Rita Henderson

ABSTRACT

Dissolved air flotation (DAF) incorporating filtration (DAFF) is used at the Bolivar wastewater treatment plant (WWTP) to polish lagoon effluent for reuse. Elevated algal populations are frequently experienced and can lead to increased coagulant requirements and process control issues. Streaming current detectors (SCDs) and a charge demand analyser (CDA) were used to monitor the full-scale plant. This was followed by an optimisation study using a pilot plant with a CDA. It was found that the normal operational charge demand range for DAF at Bolivar was between $-46$ and $-40 \mu$eq L$^{-1}$. Decreasing the pH of coagulation reduced coagulant consumption and facilitated more sensitive CDA responses to changes in alum dose.

Key words | charge demand, dissolved air flotation, streaming current, surface charge

INTRODUCTION

Bolivar wastewater treatment plant (WWTP) (Adelaide, Australia) treats municipal wastewater using activated sludge reactors (ASRs) ahead of a lagoon system with a mean residence time of 21 days. The Bolivar dissolved air flotation incorporating filtration (DAFF) plant can treat up to 120 ML d$^{-1}$ of lagoon effluent and provides water for a range of applications including horticultural irrigation in the Virginia Pipeline Scheme, irrigation of gardens/parks, and car washing/toilet flushing in the Mawson Lakes Reclaimed Water Scheme (Rinck-Pfeiffer 2007). The lagoons are often subject to algal blooms which can reach cell concentrations greater than one million cells mL$^{-1}$. Ideal conditions for algal blooms often coincide with periods of high product demand; typically warmer, sunnier times of year. Such conditions impose peak load on the DAFF plant both in terms of required throughput and treatment requirements.

The presence of algae in DAF influent can impact the treatment of the influent caused by poor coagulation and flocculation. Further complications arise due to the range of algal species present which may have varying responses to the coagulants; a consequence of their varying cell surface properties and variable individual populations (Henderson et al. 2008a). The present approach to coagulant dose optimisation used at the DAFF plant relies upon jar testing and operator experience. Aside from monitoring DAFF influent pH, there is no presently available online metric that can be used to select the appropriate coagulant dose.

The addition of cationic metal coagulants (such as aluminium sulphate (alum), ferric chloride (ferric)) or organic polyelectrolytes to raw water is essential for effective water clarification and filtration processes. In algae-laden water, charge conditions can be further complicated due to a range of cell surface characteristics, algogenic organic matter (AOM) and cell motility, although good cell removal is possible when using charge optimised coagulation (Henderson et al., 2008b, 2010).

Particle charge analysis, as measured by zeta potential (Sharp et al. 2005, 2006; Henderson et al., 2008b, 2010; Morfesis et al. 2009) or streaming current (Bernhardt & Schell 1993; Adgar et al. 2005; Byun et al. 2007; Mayer 2007), can be used to monitor and control coagulation. Literature shows that the two measurements can be
mathematically related (Jefferson et al. 2004). In practice, controlling zeta potential to be between −10 and 0 mV is most effective for optimised water treatment although many plants have been shown to operate between −15 and −10 mV (Jefferson et al. 2004). Effective treatment utilising streaming current has been shown to occur at an inflection point on a dose–response curve (Adgar et al. 2005). In water treatment facilities, online streaming current detectors (SCDs) are more commonly used (Jefferson et al. 2004).

The charge demand (CD) of a given sample can be assessed by monitoring the streaming current while titrating with a chemical with a known opposite charge, such as a polyelectrolyte standard. The titration is continued until the point of zero charge (PZC) is achieved, or the SC is 0 mV. The advantage of a charge titration over SC is that the point of zero charge (PZC) is achieved, or the SC is with a chemical with a known opposite charge, such as a polyelectrolyte standard. The titration is continued until the point of zero charge (PZC) is achieved, or the SC is 0 mV. The advantage of a charge titration over SC is that it is independent of variables such as conductivity, pH, particle or colloid sizes and molecular weight. The use of an instrument similar to a charge demand analyser (CDA) has been documented as being highly effective for coagulant dosage automation in a surface water treatment plant (Bernhardt & Schell 1996).

At the Bolivar DAFF plant, the raw water quality can vary rapidly, resulting in over- and under-dosing. To optimise dose, a sensor that is sensitive to the coagulant demand is required. Current monitoring systems at the Bolivar DAFF plant do not include charge analysis. The aim of this study was therefore to assess the use of charge analysers (two SCDs and a CDA) as a tool for process control. To achieve this, charge monitoring was first undertaken on the full-scale plant to determine the most effective charge monitoring method. A pilot DAF plant was then used to undertake process optimisation using this charge monitoring method.

**MATERIALS AND METHODS**

**Full-scale Bolivar DAFF plant operation**

Treatment at the DAFF plant includes the addition of alum before weir rapid mixing and then a low molecular weight cationic polyelectrolyte before dual stage flocculation. Alum is used as a coagulant and also to adjust the pH of the raw water. Polymer is dosed at a concentration of 0.6 mg L⁻¹. Flocculation is conducted with a 15% recycle ratio to achieve a filtration rate of 9.0 m h⁻¹ and filtration rate of 9.9 m h⁻¹ (Rinck-Pfeiffer 2007). The filtration media consists of sand and filter coal. Pre-chlorination also be used to control motile plankton which can interfere with floc formation. Current treated water requirements are: turbidity <1.5 NTU; pH in the range 6.5–8.5; pathogens (Cryptosporidium oocysts) <1 mL⁻¹. Water quality data from the DAFF plant are recorded via a Supervisory Control and Data Acquisition (SCADA) system. Turbidity of the raw water inlet, the floated and filtered effluent water is continuously monitored and pH is recorded at the raw water inlet and after alum dosing.

**Charge monitoring at the full-scale plant**

From October 2009 to March 2010, online streaming current measurements were obtained at the full-scale plant using two commercially available SCDs: a Milton Roy SC4200/5200 (Iveyland, PA, USA) and a Chemtrac SCM2500XRD (Norcross, GA, USA). Online CD analysis was conducted with a Mütek PCT-20 (BTG, Eclépens, Switzerland). The SCDs, with only one sample stream available on the instruments, were fed with alum-dosed water only. The PCT-20 has the ability to sample up to four process streams simultaneously and was fed with raw water, water treated with alum, and water treated with both alum and polymer. All devices were run continuously and only taken offline for maintenance.

**Pilot DAF plant operation**

The pilot plant consists of an in-line rapid mixer, a single stage up-flow flocculator and flotation. Flocculation effluent is filtered via a standalone sand filter for use as saturated water. Raw water was pumped into the plant at 105 kL d⁻¹ from the same channel as the full-scale DAFF plant to achieve a rotation rate of 9 m h⁻¹. Alum and polymer, from the full-scale DAFF plant, were dosed into a static mixer and before flocculation respectively. A pH meter-pump was used to automatically correct pH utilising a feedback loop across the static mixer. A pH meter-pump was used to automatically correct pH utilising a feedback loop across the static mixer. The DAF effluent turbidity was measured continuously while grab samples were used to analyse the raw water turbidity.

**Pilot-scale optimisation**

The pilot plant was operated over February and March of 2011 for 7 hours per day. Initially, the pilot plant was operated with the same dosing parameters used at the full-scale plant (120–180 mg L⁻¹ of alum with 0.6 mg L⁻¹ of polymer) to assess the performance relative to the full-scale plant. After this period, the polymer dosing was halted and the alum was dosed at a range of rates with the pH maintained at 6.5, 7.0 and 7.5 for dose optimisation. Sodium hydroxide
or hydrochloric acid solutions were used to correct pH to the desired value. For each parameter adjustment made, the pilot plant was operated for 2.5 hydraulic retention times (1.5 hours) before turbidity and CD were recorded and samples taken for algae cell counting. Turbidity and pH were measured by a Hach 2100AN Turbidimeter (Hach, Loveland, CO, USA) and a Hanna Instruments pH210 Microprocessor pH Meter (Hanna Instruments, Nusfalau, Romania), respectively. Only the CDA was installed for monitoring pilot plant operation based on performance of the instrument on the full-scale plant. Zeta potential measurements were also undertaken for comparison purposes using a Malvern Zetasizer Nano ZS (Malvern, Worcestershire, UK). Cell counting was conducted optically using a microscope and haemocytometer.

Results from optimisation experiments were normalised to raw water turbidity and CD values of 30 NTU and $-60 \mu\text{eq L}^{-1}$ respectively, based on average raw water characteristics during full-scale experiments.

The range of the alum concentrations to be used was assessed by jar testing the day prior to pilot plant tests, using an Aztec Flotation Jar Tester and 1 L of raw water. Saturated water was obtained under pressure from the full-scale plant saturators. Rapid mixing was conducted for 60 seconds at 300 rpm immediately following the addition of coagulant and the pH was adjusted to the desired value using sodium hydroxide or hydrochloric acid solutions. The jars were then flocculated for 10 minutes at 30 rpm followed by flotation for 10 minutes.

**RESULTS AND DISCUSSION**

**Raw water quality**

Lagoon effluent quality was observed to change rapidly as is typical for the plant, requiring close operator attention to ensure the appropriate coagulant dose selection. For most of the 2011 trial period, *Microcystis* sp. dominated the algae population with a presence of up to 99.6% of the cells counted. In contrast, there was no dominant species present in the 2009–2010 trial and fewer total cells resulting in a much smaller alum dose. Turbidities, cell concentration, pH and, consequently, CD were observed to vary significantly throughout this trial period (Table 1). The alum dose applied at the DAFF plant is known to exceed 200 mg L$^{-1}$ alum when the lagoons are subject to algal blooms, and reached 190 mg L$^{-1}$ with a minimum of 120 mg L$^{-1}$ for the trial periods. Due to the highly variable influent raw water quality, jar testing is not an ideal tool for coagulant dose optimisation at this plant given that it cannot be undertaken in real time.

Table 1 | Raw water analysis at the full-scale plant over the experiment periods. NA indicates measurements that were not available

<table>
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<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Ave</td>
</tr>
<tr>
<td>Turbidity NTU</td>
<td>6</td>
<td>201</td>
<td>35</td>
</tr>
<tr>
<td>Alum dose mg L$^{-1}$ as Al$_2$(SO$_4$)$_3$·18H$_2$O</td>
<td>40</td>
<td>151</td>
<td>75</td>
</tr>
<tr>
<td>Total blue-green cyanobacteria count cells mL$^{-1}$</td>
<td>$4.16 \times 10^2$</td>
<td>$3.48 \times 10^4$</td>
<td>$5.63 \times 10^3$</td>
</tr>
<tr>
<td>Total dissolved solids mg L$^{-1}$</td>
<td>1,108</td>
<td>1,280</td>
<td>1,207</td>
</tr>
<tr>
<td>pH</td>
<td>7.7</td>
<td>8.9</td>
<td>8.2</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>NA</td>
<td>NA</td>
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</tr>
<tr>
<td>Conductivity μS cm$^{-1}$</td>
<td>2,165</td>
<td>2,290</td>
<td>2,221</td>
</tr>
<tr>
<td>Dissolved organic carbon mg L$^{-1}$</td>
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<td>NA</td>
<td>NA</td>
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<tr>
<td>Suspended solids mg L$^{-1}$</td>
<td>NA</td>
<td>NA</td>
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Charge analysis at the full-scale plant

Streaming current

In the first weeks of the trial at the Bolivar DAFF plant, the SCDs performed well. For example, during an increase in the alum dose, the streaming current value increased proportionately (data not shown). However, after 6 weeks of continuous monitoring, the signals from the SCDs became increasingly erratic with no response observed from alterations in the alum dose. Despite rigorous manual rinses, the initial performance of the SCDs could not be recovered. Consequently, the SCD measurements were considered to be unreliable for extended runs and were not utilised during the pilot plant operation.

Charge demand

The results from the CDA showed that alum and cationic polymer dosing altered the CD in the water to less negative values. When the alum dose was adjusted there were clear responses in the CD (Figure 1). For example, without alum dosing, the CD was observed to match that of the raw water stream (−58 ± 3 μeq L⁻¹ over this duration). When alum dosing was initially recommenced at a dose of 120 mg L⁻¹ (as Al₂(SO₄)₃·18H₂O), the CD was −30 ± 1 μeq L⁻¹, decreasing to −36 ± 2 μeq L⁻¹ when the alum dose stabilised at 80 mg L⁻¹. The CDA was found to be similarly responsive to alum dosing throughout the trial period of 2009 to 2010. The consistency of the results produced by the CDA can be attributed to its complex cleaning cycle, utilising ultrasound and cleaning solutions, which were able to prevent sensor fouling.

During regular operation, filtered water turbidity at the full-scale DAFF plant was maintained below 1.5 NTU despite fluctuations in raw water pH and CD observed throughout the trial period (Figure 2). Such fluctuations can be attributed to photosynthetic behaviour of algae and the carbonate chemistry in the lagoons. In addition, alterations in pH can influence the CD of some constituents (Bernhardt & Schell 1995). The varying raw water CD reflected changes in the charge dose required for effective water treatment. The CD of the alum dosed water from October 2009 to March 2010, was found to be −30 to −50 μeq L⁻¹ during normal operation. This was found to be equivalent to a zeta potential range of −13 to −4 mV.

The dose of alum applied was quantifiable using the CDA, despite the cationic variability of alum over varying pHs and concentrations (Duan & Gregory 2003). As a typical CD range for the alum dosed water is definable, using the CDA in a feedback loop could allow for dose automation. The addition of polyelectrolyte can have a charge dose that is less dependent on pH than metal coagulants, particularly in the case of highly cationic polymers (Kam & Gregory 2001; Bolto & Gregory 2007). During this trial the addition of 0.6 mg L⁻¹ polymer was found to decrease the magnitude of the CD from 2 to 4 μeq L⁻¹ (data not shown). The adjustment of polymer dose could allow for fine tuning of the CD.

Full-scale/pilot plant charge demand monitoring comparison

Raw water in the pilot plant in 2011 had a more anionic character than observed at the Bolivar DAFF plant in the previous year with a CD of −78 ± 9 μeq L⁻¹ (Figure 3).
compared with $-60 \pm 7 \, \text{μeq L}^{-1}$. Comparing alum dosed water CD, the pilot plant averaged $-46 \pm 6 \, \text{μeq L}^{-1}$ whereas in the full-scale plant it was $-40 \pm 10 \, \text{μeq L}^{-1}$ (equating to zeta potentials of $-8 \pm 4$ and $-11 \pm 3 \, \text{mV}$ respectively, which is typical in comparison to values in the literature (Jefferson et al. 2004)). The increased magnitude of raw water CD compared with 2009/2010 can be explained in part by a greater algal population observed during the pilot plant operation (for example, approximately $1 \times 10^6$ cells mL$^{-1}$ had a corresponding CD of $75 \, \text{μeq L}^{-1}$, while less than $7 \times 10^3$ cells mL$^{-1}$ gave a CD of $-55 \, \text{μeq L}^{-1}$). Despite high influent algal loads and turbidities (10–153 NTU), low turbidities were obtained for floated water (0.69–1.43 NTU). The floated turbidity measured at the full-scale DAFF plant was found to be comparable at between 0.94 and 2.29 NTU for the same period. With the fluctuations in raw water quality and raw water constituents, it may be necessary to alter a CD set point. A higher average alum dosed CD of $-38 \pm 2.1 \, \text{μeq L}^{-1}$ was observed in March 2010, when the algal cell count was between $18.9 \times 10^4$ and $9.7 \times 10^4$. Over late February and early March of 2011, cell counts were an order of magnitude higher at $10.5 \times 10^5$ to $3.1 \times 10^5$ with an average operational CD of $-46 \pm 2.1 \, \text{μeq L}^{-1}$.

**Pilot plant optimisation**

Jar tests were conducted at pH 6.5, 7.0 and 7.5 with all tests resulting in high cell removal (data not shown). It was observed that an increased turbidity removal could be achieved at lower doses at pH 6.5 compared with pH 7.5, although more than 1 log cell removal was observed in the jar tests at all doses and pH values. Similar cell removal was obtained during the pilot plant experiments when compared with the jar tests (Figure 4) and while operating the pilot plant at any of the pH values tested, greater than 1 log cell removal was obtained. Interestingly, the enhanced cell removal was not always reflected in the CD at alum doses applied, which appeared to be more dependent on turbidity. This displays the selectivity of DAF for algal cell removal over turbidity removal. It is accepted that DAF is more effective in removing low density particles from water (Edzwald 2010), suggesting that denser contaminants are responsible for turbidity in the floated water.

During the course of variable alum dose experiments in the pilot plant with no polymer, the full-scale plant was operating at a constant alum dose of 120 mg L$^{-1}$. In a comparison between the trials at pH 6.5, 7.0 and 7.5, a decrease in normalised residual turbidity was observed for the pilot plant relative to the full-scale plant with decreasing pH, particularly at lower dosing concentrations. For a dosing rate of 60 mg L$^{-1}$ as Al$_2$(SO$_4$)$_3$·18H$_2$O, the residual turbidity was 5.8, 7.3 and 9.1 NTU for pH 6.5, 7.0 and 7.5, respectively. In terms of CDA, high turbidity removal was also obtained at less negative CDs.

Figure 5 shows a plot of CD versus alum dose. With increasing alum dose, the CD of coagulated water became less negative. Coagulation resulting in floated water turbidities below 2 NTU corresponded to CDs greater than $-45 \, \text{μeq L}^{-1}$ in all tests. At pH 7.0 and 7.5, plateaux of CD was observed for elevated alum doses. When the
coagulation pH was maintained at 6.5, CD showed a near linear response with respect to alum dose. The charge response to alum dosing without pH control showed a region of increasing CD followed by a plateau. As the pH affects the ratio of cationic hydrolysis products in the water, the raw water pH can influence the coagulated CD at any given alum concentration. The varying nature of the raw water may contribute to more negative CD values at pH 6.5 and 7.5. Algae cell populations were lower with approximately $5 \times 10^4$ cells mL$^{-1}$ versus approximately $5 \times 10^5$ cells mL$^{-1}$ at pH 7.0 and without pH control.

Comparing CDs at pH 6.5 and 7.5, it can be seen that the CD of coagulation for effective flotation can vary. For example, 80 mg L$^{-1}$ of alum is required to achieve a turbidity below 2 NTU at pH 6.5 which corresponds to a CD of $-45$ μeq L$^{-1}$; in contrast at pH 7.5, 100 mg L$^{-1}$ was required, resulting in a CD of $-39$ μeq L$^{-1}$. The plateau regions observable at pH 7.0 and 7.5 correspond to regions in which the lowest turbidity was achieved for the respective pH values. If applying CDA as a process control tool the plateau regions could cause dosing feedback loops to be insensitive to changes in alum concentration, particularly at higher concentrations. The more linear CD – alum dose response at pH 6.5 indicates an increasing cationic nature of coagulant across the alum dose range tested. The observable CD changes in coagulation at pH 6.5 would thus be more ideal for process automation with a CDA alone.

It is notable that the treatment of lagoon effluent at the Bolivar DAFF plant is not operated to achieve specific natural organic matter (NOM) removal. NOM in raw water can have a significant effect on the required coagulant to achieve desired water quality (Henderson et al. 2010). At the Bolivar DAFF plant any removal of NOM is a result of achieving desired turbidity removal. The presence of organic substances can interfere with the coagulant action and charge response in removing turbidity; however, by monitoring CD their influence in terms of charge contribution is taken into account. For many highly heterogeneous systems, such as lagoons, contaminants may have varying anionic characteristics and consequently unpredictable stoichiometry. In these cases, a tool such as CDA is a useful aid to rapidly determine the required coagulant dose.

**CONCLUSION**

Due to fouling, the SCD measurements were found to be unreliable when used for extended periods of time at the Bolivar DAFF plant. CDA remained responsive to varying alum doses and varying raw water quality throughout the trials. By monitoring CD at the Bolivar DAFF plant, it was observed that the CD in raw water varied by up to $10 \mu$eq L$^{-1}$ over the course of 24 hours suggesting that the effective coagulant dose required may change accordingly.

The operational range for CD for alum dosed water in the full-scale DAFF plant was $-46$ to $-36 \mu$eq L$^{-1}$ from October to December 2009, and $-51$ to $-35 \mu$eq L$^{-1}$ from January to March 2010. The pilot plant showed a similar range, $-52$ to $-40 \mu$eq L$^{-1}$, whilst replicating the full-scale operation. Over all of these periods, the CD of alum treated water remained between $-46$ and $-40 \mu$eq L$^{-1}$, suggesting that an operational range can be used as a set point for automation. As there is limited sensitivity of the CDA response at pH 7.0 and 7.5 for higher doses of alum, further testing of the use of a CDA as an automation tool is required when operating at pH of greater than or equal to 7.

The use of acid or base to regulate lower pH values during coagulation allowed for increased turbidity removal at lower alum doses. Furthermore, high turbidity removal was also obtained at less negative CDs. Operating under charge neutralisation conditions gave more sensitive CD responses. Ultimately, CDAs can be used to monitor coagulation immediately after chemical dosing giving rapid feedback which can facilitate chemical dosing automation.

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