Full-scale dissolved air flotation (DAF) equipment for emergency treatment of eutrophic water
Zhuang Tian, Can Wang and Min Ji

ABSTRACT

Eutrophication of urban rivers has caused severe environmental problems due to the pollution from point and diffuse sources. Although eutrophication can be alleviated by reducing the input to the river system, fast-treating terminal control technologies, especially under emergent situations, should be developed to reduce risks induced by eutrophication. The present study developed an emergency purification device based on dissolved air flotation (DAF) technology. After equipment commissioning and parameter optimization for applications in the field of engineering, the device was found to effectively remove total phosphorus, chlorophyll a, chemical oxygen demand, and turbidity in water by controlling the coagulant dosage and adjusting the gas-liquid mixing pump parameters. Dissolved air in water could enhance dissolved oxygen, and dissolved oxygen in polluted rivers could be raised from 0.2–2 mg/L to 3–3.5 mg/L. Removal of total nitrogen was poor because the majority of nitrogen contents were dissolved. Finally, DAF has been proven to be a promising technology due to its ease of implementation, low equipment investment requirement, and low operation cost.

Key words | dissolved air flotation (DAF), engineering commissioning, eutrophic water, full-scale equipment, urban river pollution, water quality analysis

INTRODUCTION

Many cities, such as Tianjin, Nanjing, Shanghai, Guangzhou and other large cities located in the eastern part of China, are drained by combined sewer systems for economic reasons. In these cities, a part of the domestic sewage is collected mixed with rainwater runoff and transported to a wastewater treatment plant for processing. Under the conditions of dry weather and light moderate rainfall, the combined sewer systems could convey all flows to the wastewater treatment facility. However, the design capacity of combined sewer systems would be exceeded when heavy rainfall events occurred, resulting in the overflow of untreated sewers to nearby surface water.

The overflow would cause immediate and long-term damage to the quality of receiving water bodies, since it contained a mixture of variable pathogenic organisms, viruses, cysts, suspended solids, chemicals, and organics (Chhetri et al. 2016). Consequently, the risk of water eutrophication is increased due to the importing of a large amount of organic matter and nutrients from agriculture and industry (Blanksby 2002; Nijboer & Verdonschot 2004; Li et al. 2014). The risk of algal blooms is also significantly increased (Anderson et al. 2002; Heisler et al. 2008).

Available alternatives for controlling eutrophication can be generally categorized into source controls and terminal treatments. Strategies in source controls consist of tunnels, retention basins, and sewer separation, which cannot be easily upgraded in a short time (Tavakol-Davani et al. 2016).

Terminal treatments (e.g. bio-ecological methods and physicochemical purifications) for dealing with the risk of water eutrophication should be comprehensively investigated.

Bio-ecological technology is a useful tool for treating eutrophic water, but is unsuitable for dealing with sudden pollution (combined overflow pollution and algal bloom) (Uhl & Dittmer 2005; Meyer & Dittmer 2014). Physicochemical treatment, such as sedimentation and flotation, is commonly used in river purification and can rapidly remove suspended solids and any contaminants associated with them. The previous studies concerning chemical coagulation and lamella clarification have demonstrated efficient
removal of total suspended solids (SS) (∼80%), chemical oxygen demand (COD) (∼60%), and total phosphorus (TP) (∼85%) (Jolis & Ahmad 2004). Flotation is an effective alternative to sedimentation and offers several advantages, including short flocculation period, high hydraulic surface loading rate, high solids concentration of sludge (Chung & Young 2013), and less space (Palaniandy et al. 2010).

The dissolved air flotation (DAF) process, one of the flotation technologies, is effective for reducing COD, SS, turbidity, and nutrients. Most laboratory scale research performed using DAF has focused on removal of algae (Henderson et al. 2008, 2009), oil (Naghdi & Schenk 2016), or Giardia and Cryptosporidium (French et al. 2000; Edzwald 2010). However, few studies on the application of DAF for eutrophic water emergency treatment are being developed at present, and they require full-scale performance and influencing factors.

In this study, a full-scale DAF equipment integrating coagulation, reaction, and separation was built for emergency removal of pollutants in eutrophic water. The removal efficiency of the pollutants in the process was evaluated. This study mainly aimed to (1) optimize the parameters of the full-scale equipment as well as conduct engineering commissioning, (2) maintain long-term operation in the field, and (3) analyze the compositional changes of nutrients in inlet and outlet water.

**MATERIALS AND METHODS**

**Raw water quality**

Raw water was taken from Jizhuangzi River, which is a tributary of the Haihe River in Tianjin and has received many pollutants (including initial rainwater and domestic sewage) from a point source and diffuse sources. The upper reaches of the stream were provided with a pipeline discharge port, which seriously deteriorated the river environment. This district is characterized by warm temperature and a typical semi-humid continental monsoon climate with four distinct seasons. The climate is cold and dry in spring and winter, warm and wet in the summer and autumn. The seasonal distribution of precipitation is uneven, with about 80% of annual rainfall from June to September. After the rainstorm, raw water was drawn from Jizhuangzi River by centrifugal pump and pumped into the integrated equipment for processing. The water quality of the Jizhuangzi River in the case of heavy pollution (equipment operation period) is shown in Table 1.

**DAF integrated equipment**

Figure 1 shows the flow diagram of the treatment process. The integrated device was divided into the coagulation reaction chamber, contact chamber, and separation chamber. The raw water mixed with the coagulant was introduced into the coagulation reaction pool through a tubular mixer, followed by a two-stage mechanical stirring, into the contact chamber. The contact chamber provided an opportunity for

<table>
<thead>
<tr>
<th>Parameter</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD (mg/L)</td>
<td>63–127</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>36–108</td>
</tr>
<tr>
<td>TP (mg/L)</td>
<td>0.72–1.98</td>
</tr>
<tr>
<td>TN (mg/L)</td>
<td>6.61–20.22</td>
</tr>
<tr>
<td>Chl-a (μg/L)</td>
<td>4.36–129.34</td>
</tr>
<tr>
<td>pH</td>
<td>7.31–8.30</td>
</tr>
<tr>
<td>DO (mg/L)</td>
<td>0.25–0.80</td>
</tr>
<tr>
<td>Water temperature(°C)</td>
<td>25.5–31.6</td>
</tr>
</tbody>
</table>

Figure 1 | The flow diagram of the process.
collision and attachment among floc particles and air bubbles. Dissolved air water was obtained using a Swirl gas-liquid mixing pump from NIKUNI company of Japan. Air bubbles with attached flocs were called floc-bubble aggregates. After full mixing, the water mixture was introduced into the separation chamber to raise the floc-bubble aggregates to the surface of the tank. The floating layer was concentrated in a scum trough, and then the scum was collected and removed. A portion of the clarified water at the bottom of the tank entered the gas-liquid mixing pump, and then dissolved air in the water was returned to the contact chamber. The rest of the effluent was discharged into the Jizhuangzi River. The design parameters of the DAF equipment are shown in Table 2, and its panorama is shown in Figure 2.

The integrated equipment regulated the hydraulic retention time of the raw water by controlling the centrifugal pump. When the equipment was running stably, water samples both in the outlet and inlet of the equipment were collected each day. The collected water samples were analysed within 12 hours.

**Analytical methods**

**Water quality analysis**

The water quality indexes were examined in accordance with the most commonly used detection methods for river regulation in China. COD in water was determined by the rapid digestion spectrophotometry method, while chlorophyll a (Chl-a), dissolved oxygen (DO), and turbidity were determined *in situ* using portable tools (Chl-a was determined by an AP-2000 Chlorophyll fluorescence meter (Aquaread, UK); DO was measured by an HQ30d LDOTM portable dissolved oxygen instrument (Hach, USA); turbidity was measured by a 2100P portable turbidity meter (Hach, USA)).

Nitrogen (N) and phosphorus (P) were determined by the spectrophotometric method. In brief, the composition of nutrients was fractionated into two parts by filtration. Specifically, the particulate and dissolved matter (1) that were retained on the 0.45 μm membrane were considered the particulate fraction and (2) those passing through the 0.45 μm membrane were considered the dissolved fraction. On the basis of the existing forms of P and the experimental conditions, the relationship between P fractions was obtained as follows: \( TP = \text{dissolved } P + \text{particulate } P; \text{ dissolved } P = \text{dissolved orthophosphate} + \text{dissolved polyphosphate}. \) Considering that

**Table 2 | Operating parameters of DAF integrated equipment**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater treatment capacity</td>
<td>50 m³/h</td>
</tr>
<tr>
<td>Coagulation time</td>
<td>5 min</td>
</tr>
<tr>
<td>Primary flocculation stirring intensity</td>
<td>100 rev/min</td>
</tr>
<tr>
<td>Secondary flocculation stirring intensity</td>
<td>50 rev/min</td>
</tr>
<tr>
<td>Contact time</td>
<td>120 s</td>
</tr>
<tr>
<td>Rising velocity of water flow</td>
<td>12 mm/s</td>
</tr>
<tr>
<td>Separation time</td>
<td>15 min</td>
</tr>
<tr>
<td>Hydraulic load of separation zone</td>
<td>8 m³/h</td>
</tr>
</tbody>
</table>

**Figure 2 | DAF integrated equipment panorama.**
organic N could not be directly measured, an indirect method was adopted as follows: organic N = total nitrogen (TN) – ammonia nitrogen – nitrite nitrogen – nitrate nitrogen.

**Bubble size (diameter) determination**

The performance of dissolved air in water is usually explored using bubble stabilization time, which is an indirect method. In brief, dissolved air in water was poured into a 500 mL cylinder to the fill line (height 23.5 cm), until bubbles completely overflowed the surface of the water. This time was the bubble stability time. When the bubble diameter is small, the floating rate is slow and the bubble floats to the liquid level over a long period. As the bubbles produced by the air dissolving pump in the present study were very small in size (10–100 μm), the flow regime was in a laminar flow state. The relationship between bubble rising velocity \( V \) and bubble size \( D \) can be calculated using the Stokes theorem. The parameters of each unit in the formula are shown below.

\[
V = \frac{g \times \rho \times D^2}{18 \times \mu} \tag{1}
\]

\[
D = \left[ \frac{18 \times \mu}{g \times \rho} \right]^{0.5} \times V^{0.5} \tag{2}
\]

\[
D = C_1 \times V^{0.5} \tag{3}
\]

The fixed value part \( \left( \frac{(18\times\mu)}/(g\times\rho) \right)^{0.5} \) was used as a constant \( C_1 \).

The density of water is 996.2 kg/m\(^3\), the viscosity of water is 0.836 \( \times \) \( 10^{-3} \) Pa·s at 28 °C.

At this point,

\[
C_1 = \left[ \frac{18 \times \mu}{g \times \rho} \right]^{0.5} = 1.241 \times 10^{-5} \tag{4}
\]

The dimensional conversion is as follows.

The bubble diameter unit is μm, and the bubble rising velocity unit is cm/min. Given a new constant \( C_2 \) different from \( C_1 \), the conversion between the two constants is as follows:

\[
C_2 = C_1 \times \left( 10^{-2}/60 \times 10^{-12} \right) = 16.02 \tag{5}
\]

In the following calculation, constant \( C_2 \) takes the value of 16.02. The bubble rising velocity is obtained from the bubble stabilization time, and the bubble diameter is calculated as follows:

\[
D = 16.02 \times V^{0.5} \tag{6}
\]

**RESULTS AND DISCUSSION**

**Parameter optimization of the full-scale DAF equipment**

**Chemical dosage consumption**

Chemicals take the largest individual share of operating costs in physicochemical treatment processes. The proper determination of dosage of chemicals not only can improve the performance but also reduce the running cost.

In accordance with laboratory tests, this project used liquid polymeric aluminum chloride (PAC, 10% Al\(_2\)O\(_3\) content) as the coagulant. The flocculation stability and hydrolysis reaction of PAC do not change the pH value of water and do not result in any color problem, which is suitable for engineering applications.

Figure 3 shows that the turbidity, TP, and COD decreased when the dosage increased. Given the dosage of 220 mg/L, the removal efficiency of the above three indexes reached 83%, 83%, 48%, respectively. However, further increase in dosage led to decline in the removal efficiency.

![Figure 3](https://iwaponline.com/wst/article-pdf/77/7/1802/214276/wst077071802.pdf)

In the following calculation, constant \( C_2 \) takes the value of 16.02. The bubble rising velocity is obtained from the bubble stabilization time, and the bubble diameter is calculated as follows:

\[
D = 16.02 \times V^{0.5} \tag{6}
\]
Therefore, the optimum dosage of the equipment for processing eutrophic water was 220 mg/L.

A coagulant is usually added to damage the stability of particles in water. If the dosage is too high, the unstable colloids may recover their stable state, thereby affecting the effluent quality. In this study, the coagulant was mainly used (1) to ensure that the suspended particles in water were surrounded by the hydrolyzed polymer and (2) to meet the requirements of flocculation kinetics. The former factor played a decisive role in determining the optimal dosage.

Reflux ratio of dissolved air in water

The reflux ratio of dissolved air in water is defined as: dissolved air in water/raw water (flow ratio).

Given the limitation of the performance of the gas-liquid separation pump, the reflux ratio range was limited. The equipment showed poor performance when the reflux ratio was 20.87% (Figure 4). Increasing the reflux ratio to 23.81%, the purification efficiency of the equipment reached a high level. Further increase in the reflux ratio did not result in a continued increase in performance.

The proportion of dissolved air in water increased with the reflux ratio. When the number of microbubbles increased, the perikinetic flocculation of the particles became obvious, and floc-bubble aggregates exhibited high buoyancy. Satisfactory results were obtained from the solid-liquid separation. However, the energy consumption of the equipment increased with the increase in the reflux ratio. Therefore, the selection of the optimal reflux ratio should depend on the pollutant removal requirement and the energy consumption.

Gas-liquid separation pump pressure

The gas-liquid separation pump is the key component of the DAF integrated equipment.

Figure 5 shows the relationship between the pressure of the pump and the bubble diameter. The influence of the pump pressure on the bubble stability time was obvious. With the increase in the pressure of the gas-liquid separation tank, the bubble stability time gradually increased, whereas the bubble rising velocity decreased. The bubble diameter also decreased with the increase in the pressure of the gas-liquid separation pump.

In accordance with Henry’s law, the efficiency of dissolved air in water was small when the water temperature increased. Dissolved gas pressure slightly influenced the gas dissolving efficiency, whereas it significantly influenced the bubble diameter. Water temperature should be reduced or the air pump pressure should be increased to improve the air dissolving efficiency. Given that controlling the water temperature is unrealistic in practical engineering, adjusting the pressure of the air pump has practical significance.

Figure 6 illustrates the relationship between the bubble diameter and the removal efficiency. The size range of the particles required for air flotation is generally between 10 and 1,000 μm (Edzwald 1995; Han et al. 2007). In this experiment, when the particle size of microbubbles is higher than 43 μm, the purification performance of DAF equipment declines. The required particle size of the microbubble is 33–43 μm for a good purification performance. Han et al. (2001) found
that, when the particle size of the floc is close to the size of the microbubble, the adhesion efficiency of the two is maximum and the floc-bubble aggregates present good stability. However, the bubble size should not be as small as possible, because small bubble size means enlarged specific surface area, abundant free interface energy, increased thermodynamic instability, and high tendency of bubble aggregation. Too large or small bubble diameter can both reduce air flotation performance (Kiuru 2001).

In the present experiment, the microbubble diameter was in the range of 33.4–50.8 μm. With the increase in the bubble diameter, the removal efficiency of turbidity and TP obviously decreased, and the removal of COD was insignificant. According to the conditions of coagulation and the hydraulic parameters design of the air flotation tank, the DAF integrated equipment can achieve good purification performance when the bubble diameter is controlled at 33.4–43.4 μm.

**Long-term removal performance of the full-scale DAF equipment**

Figure 7 shows the removal efficiency of turbidity, Chl-a, COD, TP and TN when the equipment is kept running at optimum parameters.

For turbidity, Chl-a, and COD good purification performance was obtained. In particular, turbidity removal was stable at 80%, Chl-a removal reached 71%, and COD removal was up to 61%. However, the purification of nutrients showed different results. The highest removal of TP was 83%, and the removal of TN was only approximately 15%. The difference may be related to the existence of the components of nutrients.

**Composition changes between the influent and effluent wastewater**

**P composition**

We did an analysis of the changes in the P composition between the influent and effluent. TP removal achieved was as high as 83.8%, particulate TP removal reached 97.8%, but the dissolved P removal was only 56.5%. Moreover, dissolved orthophosphate removal was 78.7%, and dissolved polyphosphate removal was only 15%.

Al3+ and orthophosphate formed particulate phosphate precipitation to remove most of the dissolved orthophosphate. The solubility of AlPO4 precipitation was significantly influenced by the pH value. When the pH value was neutral, the solubility of AlPO4 was smallest. The natural river pH value was neutral alkaline, and AlPO4 solubility was very small. Given the adsorption and complexation reaction of the hydrolysis products of coagulant and phosphate, the vast majority of particulate P could be removed by an adsorption bridging and catching-sweeping mechanism (Boisvert et al. 1997; Lã Rling et al. 2014). Alum floc and phosphate precipitation could remove part of the dissolved P by adsorption (Morse et al. 1998).

**N composition**

As N components were mostly dissolved in raw water, the TN removal efficiency was not ideal at only 14.1%. In particular, ammonia nitrogen removal was 25.6%, and organic N removal was 8.9%. The content and form of nitrite nitrogen and nitrate nitrogen were not changed.

The equipment was ineffective for N removal. Given that the vast majority of N contents were dissolved, the floc alum adsorption bridging and sweep function could
not work. Phosphate precipitation and alum flocs also could not adsorb N. Therefore, N removal requires further biological methods (Li et al. 2007).

CONCLUSION

The DAF equipment can meet the requirements of purification in 5 min coagulation time for emergency treatment of eutrophic water. When given the PAC dosage of 220 mg/L, dissolved air in water reflux ratio of 23.81% and the gas-liquid separation pump pressure of 0.38 MPa, the turbidity, TP, and Chl-a achieved good purification performance and their removal efficiencies were stable at 80%, 72%, and 71%, respectively. The removal efficiency of COD was up to 61%. And by adjusting the three parameters of PAC dosage, dissolved air in water reflux ratio, and gas-liquid separation pump pressure, the equipment can purify the river of different pollution levels. Increasing the above three parameters can satisfy the purification requirements for highly polluted river water. At the same time, the DAF equipment had a good effect on the increase in dissolved oxygen in polluted water.

The field running showed that the designed device fits well and the anticipated design objectives are achieved. The DAF integrated equipment not only has stable operation but also has low running costs (sewage treatment reagent cost was 2.0 ¢ per ton of raw water, lower by 30% than that for sedimentation, and the power generation cost was 2.1 ¢ per ton of raw water). The designed device is very suitable for the emergency treatment of eutrophic water.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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