Removal of bromide and bromate from drinking water using granular activated carbon
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ABSTRACT
Granular activated carbon (GAC) was used to remove bromide (Br\(^-\)) and bromate (BrO\(_3^-\)) from drinking water in both bench- and pilot-scale experiments. The present study aims to minimize BrO\(_3^-\) formation and eliminate BrO\(_3^-\) generated during the ozonation of drinking water, particularly in packaged drinking water. Results show that the Br\(^-\) and BrO\(_3^-\) levels in GAC-treated water decreased in both bench- and pilot-scale experiments. In the bench-scale experiments, when the empty bed contact time (EBCT) was 5 min, the highest reduction rates of Br\(^-\) in the mineral and ultrapure water were found to be 74.9% and 91.2%, respectively, and those of BrO\(_3^-\) were 94.4% and 98.8%, respectively. The GAC capacity for Br\(^-\) and BrO\(_3^-\) removal increased with the increase in EBCT. Reduction efficiency was better in ultrapure water than in mineral water. In the pilot-scale experiments, the minimum reduction rates of Br\(^-\) and BrO\(_3^-\) were 38.5% and 73.2%, respectively.

Key words | bromate, bromide, granular activated carbon, ozone, reduction

INTRODUCTION
Ozone, used as an alternative to chlorine in water treatment, has the advantages of significant effectiveness without generation of the disinfection by-products (DBPs) trichloromethane, haloacetic acids and other regulated DBPs. However, a DBP of bromate (BrO\(_3^-\)), which is a suspected carcinogen, is generated during the ozonation of bromide (Br\(^-\))-containing water. Thus, a maximum contaminant level of 10 \(\mu\)g/L for BrO\(_3^-\) was established by the United States Environmental Protection Agency and by the drinking water standards of China (GB 5749–2006 and GB 8537–2008). A review of BrO\(_3^-\) occurrence also indicated that there have been issues of excessive BrO\(_3^-\) in drinking water in many countries (Xie & Shang 2006a).

To solve the excessive BrO\(_3^-\) problem in drinking water, a number of possible solutions for minimizing BrO\(_3^-\) formation, such as adding ammonia (Von Gunten 2003), reducing the pH (Von Gunten 2003), chlorine-ammonia process (Buffle et al. 2004; Wert et al. 2007) and optimizing the ozonation conditions (Bouland et al. 2004; Van der Helm et al. 2005), have been tested. A granular activated carbon (GAC) treatment method also has been used for the removal of BrO\(_3^-\) generated during the ozonation of Br\(^-\)-containing water (Mills et al. 1996; Siddiqui et al. 1996; Bao et al. 1999; Huang et al. 2004a, b; Huang & Cheng 2008). These strategies are always applied for BrO\(_3^-\) control in domestic drinking water.

The Chinese standards of drinking natural mineral water (GB 8537–2008) and hygienic specifications of factory for drinking natural mineral water (GB 16330–1996) stipulated that ozone is the only disinfectant except ultra-violet irradiation to be used in the drinking natural mineral water treatment process. A survey showed that 64% of the 108 source water samples of natural mineral water contained Br\(^-\) levels above 50 \(\mu\)g/L (Meng 2007). Von Gunten (2003) proposed that in waters with Br\(^-\) levels above 50 \(\mu\)g/L, BrO\(_3^-\) formation may exceed the maximum contaminant level of the drinking water standard under certain treatment conditions. Thus, the high Br\(^-\) concentration in the source water and the ozone application made BrO\(_3^-\) a serious issue in the mineral water industry in China.

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The present study was performed to elucidate the capacity of GAC to remove Br\(^-\) and BrO\(_3\^-\) from waters in bench-scale experiments. The effects of empty bed contact time (EBCT) and source waters on the levels and reduction rates of Br\(^-\) and BrO\(_3\^-\) were evaluated. The efficiency of GAC in removing Br\(^-\) and BrO\(_3\^-\) from water was also observed in the pilot-scale experiments. The results should provide some new references for controlling the occurrence of BrO\(_3\^-\) during the ozonation of water with Br\(^-\).

**METHODS**

### Source water

The mineral water used in the study was five gallons of packaged drinking water, containing 7.07 μg/L of Br\(^-\) and 6.76 μg/L of BrO\(_3\^-\), and was purchased from the market (Guangzhou, China). The ultrapure water, which had no detectable Br\(^-\) and BrO\(_3\^-\), was produced using deionization and nanopure purification coupled with a Milli-Q purification system (Milli-Q system, Millipore) and had a resistivity of 18.2 MΩ cm. Domestic drinking water, containing 18–20 μg/L Br\(^-\) and no detectable BrO\(_3\^-\), was used in the pilot-scale experiments.

### Bench-scale experiments

The bench-scale experiments were performed using a 4.5 cm × 80 cm glass column packed with 400 g GAC. The GAC used in the experiment was the same as the GAC5 reported by Zhang et al. (2011) with 648.42 mg/g iodine adsorption value. The length of the GAC bed was 38 cm. Both the mineral and ultrapure waters were used as source waters. The source waters were spiked with various levels of Br\(^-\) or BrO\(_3\^-\) to produce test solutions, which were carefully pumped into and out of the GAC column using YZ1515x peristaltic pumps (Baoding Longer Precision Pump Co., Ltd, Hebei, China). The EBCT was controlled by the water flow rate using the peristaltic pumps. The influent and effluent samples were periodically collected for Br\(^-\) and BrO\(_3\^-\) detection and were taken in parallel every time.

### Pilot-scale experiments

The pilot-scale experiments were carried out using domestic drinking water as the source water and were performed in a set of 2 T/h equipment for mineral water treatment. The equipment was as follows: three storage tanks for the source water, three sets of ultra-violet irradiation apparatus, a tank of sand for filtration, two tanks of GAC, a set of instruments for fine filtration comprising sequential 10, 5, 1 and 0.22 μm filters, a set of ozone generation instruments, two sets of ozone contact instruments, apparatus for the addition of CO\(_2\) and a storage tank for the treated water.

The pilot-scale experiments for determining GAC capacity for Br\(^-\) reduction were initiated after the addition of various concentrations of KBr\(^-\) into the source water until the mixture was fully stirred, then the solutions were treated by using the sand filter, GAC, fine filter and ozonation. The samples were periodically collected and examined before and after GAC treatment. Two samples were taken in parallel every time. The GAC used in the experiment was the same as the GAC11 reported by Zhang et al. (2011) with 953.27 mg/g iodine adsorption value.

The pilot-scale experiments for detecting GAC capacity for BrO\(_3\^-\) reduction was initiated after the addition of 60 μg/L of KBrO\(_3\) into the water source until the mixture was fully stirred, then the solution was treated as in the Br\(^-\) reduction experiments. The BrO\(_3\^-\) concentration in the influent sample of the GAC system was controlled using the ozone dose during ozonation. The samples were periodically collected and examined before and after GAC treatment. Two samples were taken in parallel every time. The GAC used in the experiment was the same as the GAC2 reported by Zhang et al. (2011) with 832.96 mg/g iodine adsorption value.

### Analytical method

Br\(^-\) and BrO\(_3\^-\) levels were measured using a Dionex ion chromatograph (ICS1500) equipped with AS19 analytical/AG19 guard columns, an ASRS300 anion suppressor and an AS40 automatic sampler. A value of 0.50 μg/L was used to facilitate statistical analysis if the detected result was lower than the detection limit of 1 μg/L.
rates of Br\(^-\) or BrO\(_3\)\(^-\) were calculated as: \([\text{influent } \text{Br\(^-\)} \text{ or BrO\(_3\)\(^-\)}]/[\text{initial } \text{Br\(^-\)} \text{ or BrO\(_3\)\(^-\)}] - [\text{effluent } \text{Br\(^-\)} \text{ or BrO\(_3\)\(^-\)}]/[\text{initial } \text{Br\(^-\)} \text{ or BrO\(_3\)\(^-\)}]\) \times 100%.

RESULTS AND DISCUSSION

Bench-scale experiments

Removal of Br\(^-\) from the mineral water

In mineral water with an initial Br\(^-\) content of 50.00 and 105.59 μg/L, the Br\(^-\) contents of the treated water were respectively 36.84 and 66.14 μg/L after 2 min, and 24.09 and 43.14 μg/L after 5 min. When the initial Br\(^-\) was 192.57, 264.47 and 596.13 μg/L, the Br\(^-\) contents of the treated water were 59.56, 114.59 and 149.39 μg/L after 5 min. The Br\(^-\) reduction rates were between 26.3 and 41.9% after 2 min and between 51.8 and 74.9% after 5 min (Figure 1).

Other studies suggested that when the Br\(^-\) levels in water are greater than 50 μg/L, the BrO\(_3\)\(^-\) produced under certain treatment conditions may exceed the drinking water standard of 10 μg/L (Amy et al. 2000; Von Gunten & Pinkernell 2000). Thus, this method cannot remove the excessive BrO\(_3\) when the initial level of Br\(^-\) in the source water is greater than 190 μg/L. Other methods should be considered to control BrO\(_3\) produced during the ozonation of drinking water with Br\(^-\).

Removal of Br\(^-\) from the ultrapure water

In ultrapure water with an initial Br\(^-\) content of 30.62 and 91.27 μg/L, the contents of the treated water were respectively 11.71 and 24.28 μg/L after 2 min, and 11.56 and 16.35 μg/L after 5 min. When the initial Br\(^-\) was 192.60, 395.98 and 599.39 μg/L, the Br\(^-\) contents of the treated water was respectively 18.23, 34.95 and 72.19 μg/L after 5 min. The Br\(^-\) reduction rates were between 61.74 and 86.58% after 2 min and between 62.26 and 91.17% after 5 min (Figure 2).

The GAC capacity for Br\(^-\) reduction was better in the ultrapure water than in the mineral water, which may be attributable to the more complex properties of the latter compared with the former. Meanwhile, GAC efficiency for Br\(^-\) removal increased when EBCT was increased for both mineral and ultrapure waters. This may provide greater chances for GAC to absorb Br\(^-\).

Removal of BrO\(_3\)\(^-\) from the mineral water

In the mineral water with an initial BrO\(_3\)\(^-\) content of 18.12, 31.48, 57.40, 81.10 and 110.01 μg/L, the BrO\(_3\)\(^-\) levels in the treated water were respectively 4.36, 7.81, 14.29, 20.39 and 10.47 μg/L after 2 min, and 0.71, 3.33, 3.51, 12.69 and 7.19 μg/L after 5 min (Figure 3).
6.13 μg/L after 5 min. The removal rates were greater than 75% when EBCT was longer than 2 min, and the maximum reduction rate was 94.4% (Figure 3). With increasing EBCT, the BrO\textsubscript{3} levels of the treated water decreased, and the removal rates increased. These results were consistent with the report of Huang \textit{et al.} (2004a, b) stating that BrO\textsubscript{3} removal improves when EBCT is increased.

**Removal of BrO\textsubscript{3} from the ultrapure water**

In the ultrapure water, the initial BrO\textsubscript{3} contents were respectively 11.23, 24.05, 51.05, 75.63 and 104.65 μg/L. When EBCT was 2 min, the BrO\textsubscript{3} levels in the treated water were efficiently removed, and the desired criterion of less than 10 μg/L was achieved. The reduction rates were between 87.8 and 98.8% after 5 min (Figure 4). When EBCT was increased, the BrO\textsubscript{3} levels of the treated water decreased, and the removal rates increased.

These results suggest that the GAC capacity for BrO\textsubscript{3} and Br\textsuperscript{-} removal was better in ultrapure water than in mineral water. This result may be attributed to the competitive adsorption between Br\textsuperscript{-}/BrO\textsubscript{3} and natural organic matter or other anions, such as Cl\textsuperscript{-}, Br\textsuperscript{-} and SO\textsubscript{4}\textsuperscript{2-}. Competitive adsorption has been reported to reduce the capability of GAC for absorbing BrO\textsubscript{3} (Mills \textit{et al.} 1996; Bao \textit{et al.} 1999; Huang \textit{et al.} 2004a, b; An \textit{et al.} 2008).

**Pilot-scale experiments**

**Removal of Br\textsuperscript{-}**

Domestic drinking water with different initial BrO\textsubscript{3} content was used as the source water. The results show that the Br\textsuperscript{-} concentrations in the treated water decreased (Table 1). Therefore, GAC may be used for the removal of Br\textsuperscript{-} from source waters.

**Removal of BrO\textsubscript{3}**

The source water was used to make a solution containing 60 μg/L of BrO\textsubscript{3}. Table 2 shows that when the ozone concentration is 0.73 mg/L, the concentration of produced BrO\textsubscript{3} increased steeply and exceeded 10 μg/L standard. Nevertheless, the excessive amount of BrO\textsubscript{3} decreased to less than 10 μg/L after GAC treatment. Therefore, GAC may be used to eliminate the BrO\textsubscript{3} generated during the ozonation of drinking water.

**Table 1** | Effects of GAC on Br\textsuperscript{-} in water

<table>
<thead>
<tr>
<th>Influent content (μg/L)</th>
<th>Effluent content (μg/L)</th>
<th>Reduction rates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.87</td>
<td>37.84</td>
<td>42.56</td>
</tr>
<tr>
<td>80.51</td>
<td>47.37</td>
<td>41.17</td>
</tr>
<tr>
<td>97.10</td>
<td>59.67</td>
<td>38.54</td>
</tr>
</tbody>
</table>

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**Figure 3** | Effect of GAC on BrO\textsubscript{3} in mineral waters. Unbroken lines: BrO\textsubscript{3} (μg/L); dotted lines: BrO\textsubscript{3} reduction rates (%). Initial BrO\textsubscript{3} in water: (▪) 18.12 μg/L; (▴) 31.48 μg/L; (△) 57.40 μg/L; (◇) 81.10 μg/L; and (◆) 110.01 μg/L.

**Figure 4** | Effect of GAC on BrO\textsubscript{3} in ultrapure water. Unbroken lines: BrO\textsubscript{3} (μg/L); dotted lines: BrO\textsubscript{3} reduction rates (%). Initial BrO\textsubscript{3} in water: (▪) 11.23 μg/L; (▴) 24.05 μg/L; (△) 51.05 μg/L; (◇) 75.63 μg/L; and (◆) 104.65 μg/L.
For both Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−}, the reduction rates were lower in the pilot-scale than in the bench-scale experiments. The variations in the results may be attributable to the different source waters and GAC used in the experiments.

In the present study, GAC appeared to be capable of reducing both Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} concentrations in drinking water, which may be attributable to the similar inorganic characteristics of Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−}. Nevertheless, the removal mechanism of BrO\textsubscript{3}\textsuperscript{−} using GAC should be different from that of Br\textsuperscript{−}. The process of BrO\textsubscript{3}\textsuperscript{−} removal by GAC was reported to initially be an adsorption, followed by a two-step reduction reaction (Siddiqui et al. 1996). A limited amount of data is available on investigations of the GAC mechanism for Br\textsuperscript{−} elimination. Therefore, studying the GAC mechanisms for Br\textsuperscript{−} removal is necessary.

Both the physical and chemical effects simultaneously act on the adsorption-reduction process during the GAC treatment for BrO\textsubscript{3}\textsuperscript{−} reduction (Huang & Cheng 2008). Source water quality and EBCT also affect GAC capacity for BrO\textsubscript{3}\textsuperscript{−} removal (Bao et al. 1999). Therefore, ascertaining the optimum EBCT and investigating how both GAC and water properties affect the removal of Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} are important.

In addition, other strategies for the reduction of the BrO\textsubscript{3}\textsuperscript{−} generated during the ozonation of the water with Br\textsuperscript{−}, such as ultra-violet irradiation (Meunier et al. 2006), ion exchange membrane bioreactor (Matos et al. 2005) and BrO\textsubscript{3}\textsuperscript{−} reduction using zerovalent iron (Fan et al. 2006; Xie & Shang 2006b) and TiO\textsubscript{2} (Noguchi et al. 2002), are also available. However, a number of problems, such as high cost and the quality of the treated water, limit the use of these methods, especially for packaged drinking water.

Based on the current experiments, GAC was effective in removing Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} contents from drinking water. GAC technology may be used to reduce BrO\textsubscript{3}\textsuperscript{−} formation and to eliminate BrO\textsubscript{3}\textsuperscript{−} generation during the ozonation of water with Br\textsuperscript{−}. However, further investigations on the actual conditions and influence factors of using GAC technology should be conducted because of the limited data available.

### CONCLUSIONS

In the present study, Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} levels in the solutions of water sources were efficiently eliminated using GAC. In the bench-scale experiments, the removal contents and rates of Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} increased with increasing EBCT, and the GAC capacity to reduce Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} contents was better in ultrapure water than in mineral water. Although the effects of GAC on Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} were weaker in the pilot-scale experiments than in the bench-scale experiments, GAC still showed the capability of eliminating Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} contents in the pilot-scale experiments. The minimum reduction rates of Br\textsuperscript{−} and BrO\textsubscript{3}\textsuperscript{−} were 38.5% and 73.2%, respectively. Therefore, GAC can be employed in water treatment facilities to minimize BrO\textsubscript{3}\textsuperscript{−} formation by decreasing Br\textsuperscript{−} contents and to eliminate the BrO\textsubscript{3}\textsuperscript{−} generated in ozonated water.

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### REFERENCES


