Desalination and Water Treatment
www.deswater.com

doi:10.5004/dwt.2017.20913

79 (2017) 235–242
June

Synergistic effect of chlorination and sand filtration for efficient elimination of invertebrate leakage in BAC filter

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Received 10 December 2016; Accepted 12 May 2017

ABSTRACT

The problem of excessive propagation and leakage of invertebrates in the biological activated carbon (BAC) treatment process have received increasing attention in recent years. Herein, the potential of a combined chlorination and sand filtration process for reducing invertebrate leakage is investigated, based on pilot-scale studies. In this developed design, the chlorine dosage and filtration velocity of the sand filter were optimized. Meanwhile, the abundance of invertebrates, the turbidity, the chlorine concentrations in the inflow water and the effluent were also recorded. It was found that the addition of chlorine could improve the efficiency of invertebrate removal in a sand filtration system. Within the parameters of the filtration velocity (8 m/h) and the operation time (144 h), the average invertebrate removal efficiency of the sand column (particle size: 0.3–0.5 mm) increased from 61.9% (without chlorine added) to 89.9% (with 0.5 mg/L chlorine added). When the filtration velocity increased to 12 m/h, a dose of 1.5 mg/L chlorine was required to obtain a relatively high average removal efficiency (83.0%), as the removal efficiency decreased with the increase of filtration velocity. The invertebrate survival status was confirmed to be the key factor that affected the removal efficiency. Chlorine was effective for inactivating invertebrates, and for further inhibiting their movement and reproduction, which finally resulted in an improved interception function for the sand filtration. Additionally, during the filtration, the head loss and chlorine consumption were too minimal to be of concern.

Keywords: Invertebrate; Chlorination; Sand filtration; Biological activated carbon

1. Introduction

The current situation for safe water supplies in China is of serious concern, due to the increasing problem of resource water pollution. To improve the removal of dissolved organic contaminants [1–3], the biological activated carbon (BAC) treatment process has been introduced in many Drinking Water Treatment Plants (DWTPs) [4]. In considering the long-term use of the BAC process, the issue of biological leakage in the effluent of the activated carbon filter has received increasing more attention [5–7].

In BAC filters, the rough porous surface structure of the activated carbon provides an ideal habitat for the attachment and growth of micro-organisms, including bacteria, protozoans, and lower invertebrates [8]. Under normal conditions, the BAC filter is usually the last filtration barrier before the final disinfection step in a DWTP. The excess invertebrates may therefore flow into the finished water, and eventually into the drinking water supply network. Although no evidence is available to prove that such invertebrates may harm human beings, their potential threat to water supply safety cannot be neglected. Some large invertebrates, such as oligochaetes, copepods, and chironomidaelarvae, are visible to the eye, and their presence in drinking water could easily cause panic or complaints among consumers [9–11]. Some of these invertebrates can protect and transport pathogenic micro-organisms through predation [12–16].

In the past few decades, the number of DWTPs that use the BAC treatment process has rapidly increased in China. However, few studies have been focused on con-

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trolling invertebrates. It has been suggested that an optimized backwashing procedure could reduce the biomass output into the distribution system. However, Schreiber et al. [17] reported that the invertebrate abundance in the filtrate remained high (1720 in d/m^3) after the suggested backwashing procedure if the invertebrates had breed excessively in the BAC filters. Zhu [18] provided an optimized backwashing cycle for BAC filters in different seasons. In winter, spring, autumn, and summer, the backwashing cycles were suggested to be done within 6 d, 4 d, 4 d, and 3 d, respectively. However, adjusting the backwashing cycle did not solve the invertebrate leakage in any fundamental way. Wang et al. [19] suggested a process of backwashing with chloric water to remove invertebrates in the BAC filters. This measure was confirmed to be effective, but it can harm the biomass in the activated carbon, and thus can only be implemented in emergency situations.

In most cases, a simple optimization of the backwashing procedures provided only limited improvement in removal of invertebrates. It was therefore deemed necessary to develop a more effective method to control the invertebrate leakage through BAC filters. Yin et al. [20] found that if a sand bed with a height of >300 mm (particle size: 0.6–1.0 mm) was added to a BAC filter, it could remove more than 40% of the rotifers, and nearly 80% of the larger invertebrates (size >200 μm). Installing a membrane would be effective, because it can remove *Giardia* and *Crytosporidium,* which are much smaller than invertebrates [21]. However, membranes are not commonly used in China due to their high construction and operation costs. Shao's [22] research showed that a combination of chlorination and sand filtration could remove invertebrates in the effluent of a BAC filter, with an average removal rate of 70.5%. However, this research was incomplete in two respects: 1) No comparison of the invertebrate removal efficiency was conducted with and without chlorination under same operational conditions, and 2) The relationship between the removal efficiency and the operational parameters was not investigated.

The study was done to build on these previous research efforts, and its objective was to investigate the invertebrate removal efficiency of the integrated chlorination and sand filtration control process in pilot-scale tests, with specific reference to the factors of chlorine dosage, filtration velocity and sand particle size.

2. Methods and materials

2.1 Experimental set-up

A pilot-scale study was conducted in Drinking Water Treatment Plant A (DWTP A), located in the lower reaches of the Yangtze River. DWTP A uses reservoir water as its raw water, and the qualities of this water are given in Table 1. An ozone-BAC treatment process was applied in DWTP A, and the basic operating parameters of the DWTP A are shown in Table 2.

The pilot-scale process train (Fig. 1) consisted of one chlorine-adding system and two parallel sand filters. The effluent of the BAC filter in DWTP A was pumped to the pilot test.

Table 1
Water quality of raw water

Parameter	Value
Temperature, °C	5.5–30
pH	7.78–8.73
Turbidity, NTU	7–28
NH_4^+–N, mg/L	0.03–0.27
COD_{Mn}, mg/L	1.3–4.7
Fe, mg/L	0.01–1.45
Mn, mg/L	0–0.28

COD_{Mn}: Chemical oxygen demand by manganese

Table 2
Basic operating parameters of DWTP A

Operating parameters	DWTP A
Pre-oxidation dosage, mg/L	0.4
Pre-chlorination dosage, mg/L	0.8
Coagulant	PAC
Main ozone, mg/L	0.4
HRT of GAC filter, min	10
Filtering velocity of GAC filter, m/h	12
GAC operation cycle, h	72–120
Residual chlorine, mg/L	1.1–1.3

The sand filters used acrylic columns, each with a diameter of 15 cm and a height of 2.2 m. The sand columns were lined with 600 mm of sand, followed by 10 cm of small gravel and 10 cm of large gravel. The sand grain sizes were 0.6–0.9 mm in Column I, and 0.3–0.5 mm in Column II.

2.2. Sampling and analysis

Invertebrates: The invertebrate samples were collected with a plankton net (10 μm mesh size; Hydro-Bios GmbH, Kiel, Germany). The sampling volume at each collection site was determined as suggested by [23]. For invertebrate enumeration, samples were transferred to a counting plate and allowed to settle for 10 min. The entire counting chamber was scanned, and the invertebrates were counted under a microscope (BX-51, Olympus, Japan).

Conventional indexes: Levels of turbidity were directly determined by a portable turbidimeter (2100 N, HACH, USA), and residual chlorine levels were measured by a portable residual chlorine comparator (HACH, USA). The potassium permanganate index (COD_{Mn}) was determined according to the state standard method [24]. Head loss (h) was calculated by the following formula:

$$h = H - H_{initial} \quad (1)$$

where $H_{initial}$ is the initial height of the liquid level in the column (m), and H is the height of the liquid level in the column at a certain stage of the operation cycle (m). The height of the liquid level was measured by a long tape.

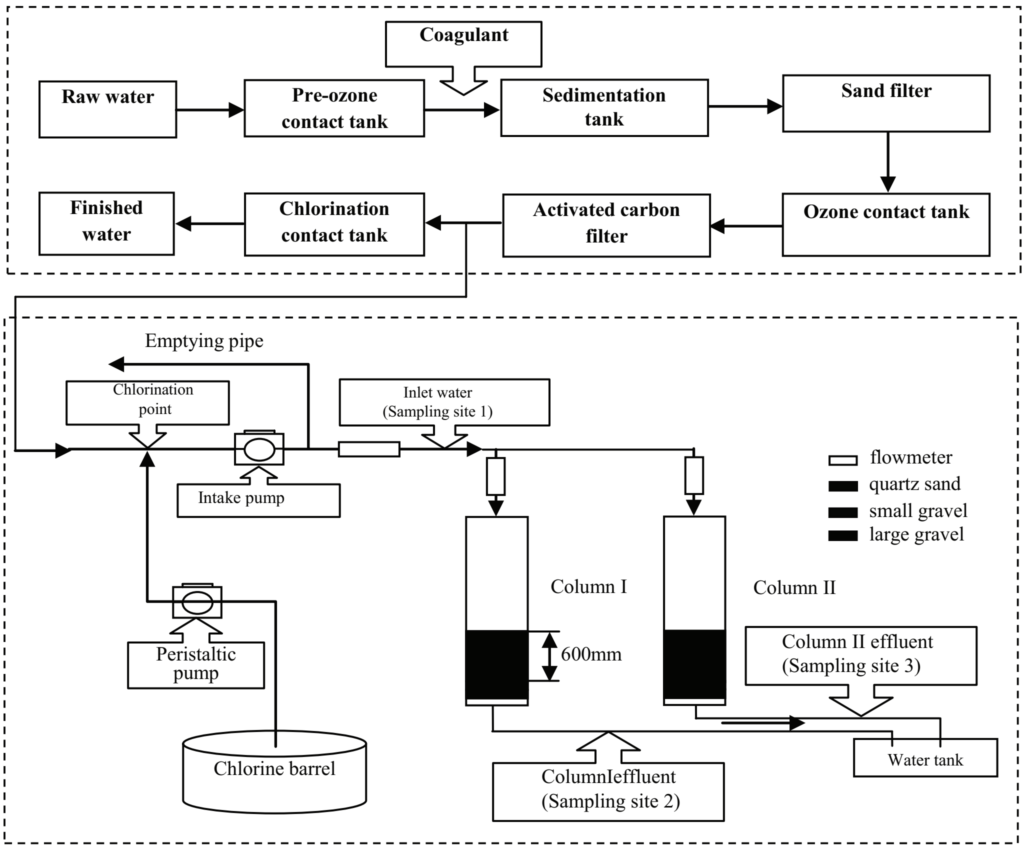

Fig. 1. Ozone–BAC process of DWTP A and the pilot-scale process train of the sand filtration.

3. Results and discussions

3.1. Feed water qualities of the pilot testing system

During the experiment, the feed water temperature ranged between 19.8°C and 27.8°C. Turbidity showed negligible variation, and was generally around 0.1 NTU. The COD_{Mn} was relatively low, ranging from 0.62 mg/L to 1.17 mg/L. As is shown in Table 3, the total abundance of the invertebrates in the feed water ranged from 452.8 ind/m^3 to 3268.4 ind/m^3. Seven categories of invertebrates were detected, namely rotifers, nematodes, gastrotrichs, water mites, copepods, cladocerans and oligochaetes. Among these invertebrates, rotifers were the dominant species, with an average percentage of 94.70%, followed by nematodes at 3.53%.

Table 3
Invertebrates in the feed water of the pilot testing system

Species of invertebrates	Range of abundance (ind/m^3)	Average abundance (ind/m^3)	Average percentage (%)
Rotifers	436.7–3112.5	1161.6 ± 552.6	94.70
Nematodes	3.0–155.9	43.3 ± 36.5	3.53
Gastrotrichs	0–85.9	7.8 ± 20.5	0.63
Water mites	0–29.5	6.1 ± 8.0	0.50
Copepods	0–13.6	4.0 ± 4.1	0.33
Cladocerans	0–11.7	3.3 ± 3.9	0.27
Oligochaetes	0–11.6	0.45 ± 1.9	0.04
Total	452.8–3268.4	1226.6 ± 576.8	100

3.2. Efficiency of invertebrate removal with the pilot testing system

3.2.1. Efficiency of removal by sand filtration without chlorination

When the filtering velocities were 8 and 12 m/h, the invertebrate removal effects of the two pilot-scale filtration columns were as is shown in Fig. 2.

As can be seen in Fig. 2, Column II exerted better invertebrate removal efficiency than Column I under the same filtration velocity. When the filtration velocity was 8 m/h (Fig. 2A), the average removal efficiencies (during the 144 h operation) of Columns I and II were 47.7% and 61.9%, respectively, which indicated that the better removal efficiency was achieved with smaller sand grains. As the filtration velocity increased, the removal efficiency decreased. When the filtration velocity was 12 m/h (Fig. 2B) and the backwashing cycle was144 h, then during the last phase of the filtration time, the invertebrate abundance in the effluent was higher than that of the influent in both columns. This result implied the ultra penetration of the invertebrates,

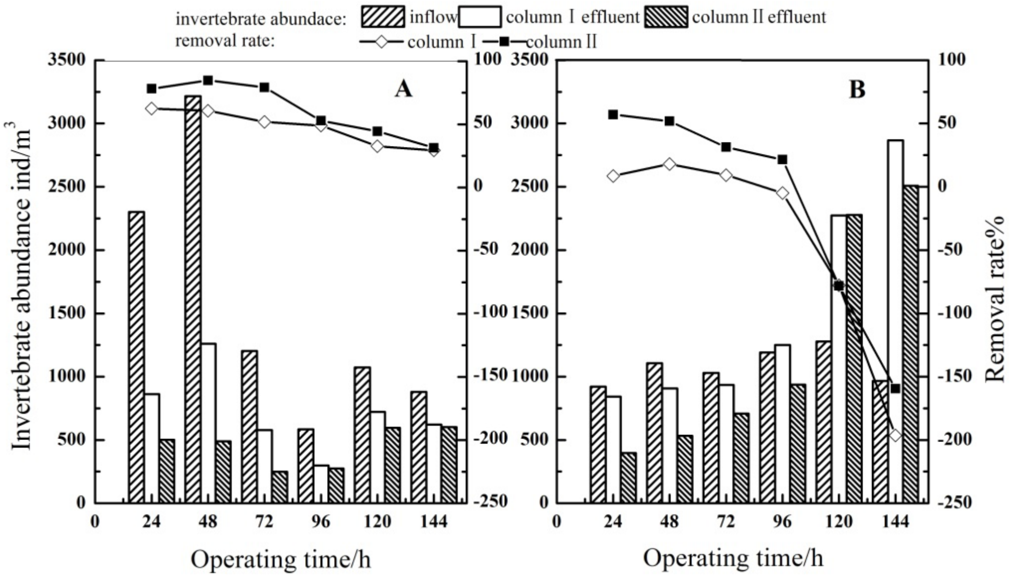

Fig. 2. The invertebrate removal effect of the two columns without chlorination (Filtration velocity: A = 8 m/h; B = 12 m/h).

which was caused by their accumulation, propagation, and their tendency to swim toward the direction of flow in as and layer. Under low filtration velocity (e.g., 8 m/h), the penetration speed of the invertebrates was relatively low, and the removal rate was still around 30% after 144 h.

3.2.2. Removal effect of sand filtration with chlorination

When the filtration velocity and chlorine dosages were 8 m/h and 0.5 mg/L, the corresponding efficiency in removal of invertebrates by the sand columns was as is shown in Fig. 3.

The invertebrate abundance in the inflow ranged from 450 ind/m^3 to 2240 ind/m^3. The average removal rates (during the first 144 h operation) were 77.7% for Column I and 89.9% for Column II. These rates were higher than the removal rates at the same filtration velocity but without the addition of chlorine. Without chlorination, the removal rates for Columns I and II obviously decreased, to about 30% at 144 h. However, after adding 0.5 mg/L chlorine into the influent, the removal rates for Columns I and II were still 84.3% and 93.2%, respectively. Therefore, the backwashing cycle was prolonged. The removal rate for Column II was maintained at more than 80% from 24 h to 336 h, and then it decreased to less than 70% at 360 h. In addition, the invertebrate abundance in the Column II effluent was always lower than 250 in d/m^3, which is the crisis limit according to Preez et al. [25]. Therefore, in this condition, Column II could maintain high removal efficiency for as long as 336 h. In Column I, although the removal rate was volatile, the invertebrate abundance still exceeded 55% during the first 240 h. Therefore, under a low filtration velocity, a small amount of additional chlorine could improve the stability of invertebrate removal efficiency and prolong the backwashing time of the sand filter.

When the filtration velocity was increased to 12 m/h, the removal efficiency significantly decreased compared to that of the 8 m/h velocity under a chlorine dosage of

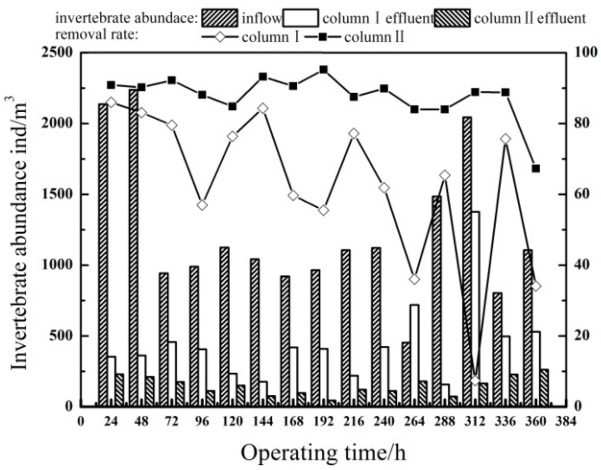

Fig. 3. The invertebrate removal effect from the two columns with chlorination (Filtration velocity: 8 m/h; chlorine dosage: 0.5 mg/L).

0.5 mg/L. This result was still better than the condition at the same filtration velocity with no chlorine added. As shown in Fig. 4A, the removal rate of Column II decreased to less than 35%, and penetration occurred in Column I after 120 h, which implied that backwashing had become unavoidable by that point in time. To improve the invertebrate removal rate under a filtration velocity of 12 m/h, the dosage of chlorine was increased to 1.5 mg/L. The results are shown in Fig. 4B.

The sum of influent invertebrates ranged from 627 ind/m^3 to 1295 ind/m^3, and both columns exerted excellent removal efficiencies. The average removal rates (during the 144 h operation) were 56.5% for Column I and 83.0% for Column II. Furthermore, the invertebrate abundance in the Column II effluent was always lower

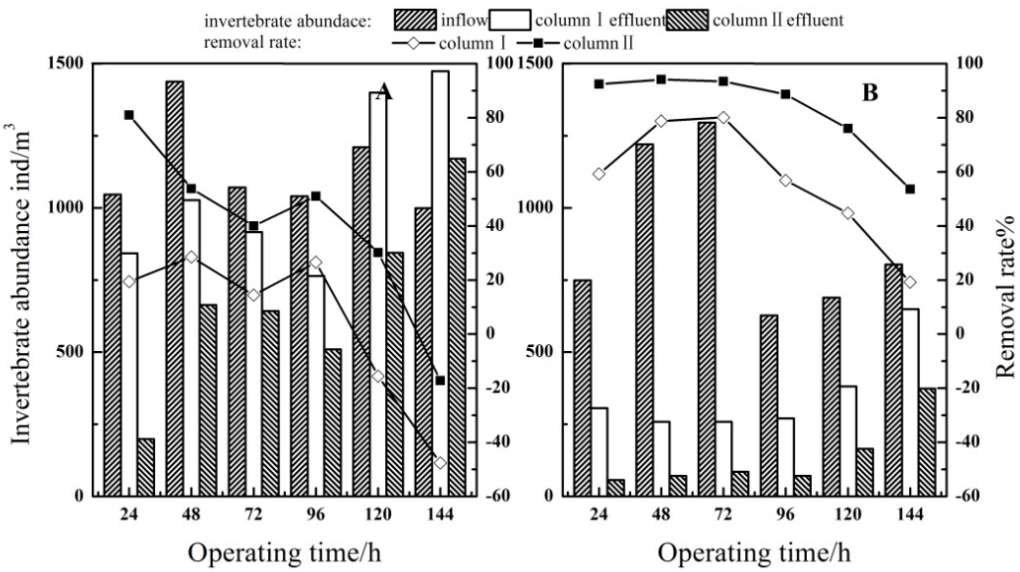

Fig. 4. The invertebrate removal effect in the two columns with chlorination (Filtration velocity: A = B = 12 m/h; chlorine dosage: A = 0.5 mg/L, B = 1.5 mg/L).

than 250 ind/m^3 (the crisis limit) in the first 120 h. This performance level could minimize the risk of penetration by invertebrates from the drinking water purification facilities into the supply network. The removal rate gradually decreased after the first 120 h, and the invertebrate abundance in Column II exceeded the crisis limit. In Column I, the removal rate decreased to less than 20% at 144 h. Therefore, under these conditions, the sand filtration with chlorination could operate for at least 120 h. Hence, under a higher filtration velocity, a larger amount of chlorine was required to obviously improve the invertebrate removal efficiency.

Overall, sand filtration with chlorination after BAC filtration was shown to improve the removal rates of invertebrates, which may be explained by the survival status of the invertebrates. Dead invertebrates could be intercepted as inorganic particles, where as living invertebrates could penetrate the sand bed because of their strong swimming activities. As had been shown by previous research, chlorine could inactivate invertebrates [26,27]. Therefore, during sand filtration with chlorination, some species of invertebrates could be quickly killed by chlorine, and then removed as inorganic particles. Other individuals were injured, and intercepted inside the sand bed. Given that the sand filter was always operating in a chlorine-containing environment, the intercepted invertebrates were finally killed and removed with the increase of contact time. Therefore, the addition of chlorine changed the survival status of the invertebrates, which enhanced the sand filter's efficiency in removing invertebrates.

3.2.3. *Efficiency of the system for removing different invertebrates*

To understand the efficiency of the system for removing different kinds of invertebrates, the rotifers and nematodes were selected as the removal targets, as these were the two

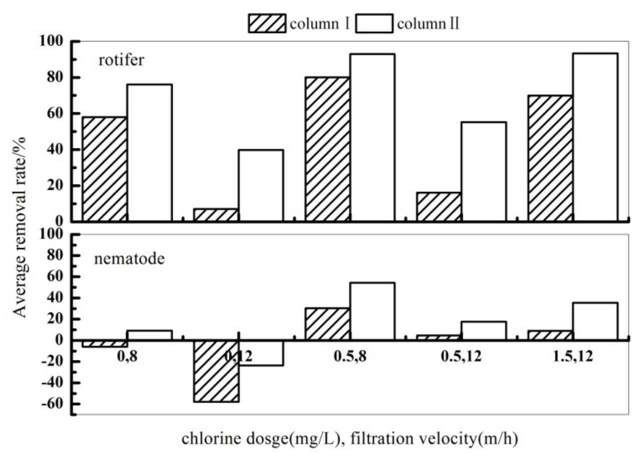

Fig. 5. The average removal rate of rotifers and nematodes.

dominant species in the feed water of the pilot system. Also, as sections 3.2.1 and 3.2.2 showed that the removal rates for the two columns during the first 96 h were relatively stable at different operational conditions, the average removal rates were calculated in this operational range. The results are shown in Fig. 5.

Column II had better efficiencies in removing rotifers and nematodes than Column I. When the chlorine dosage was the same, the efficiency in removing both rotifers and nematodes decreased as the filtration velocity increased. When the filtration velocity was the same, the removal efficiency improved as the chlorine dosage increased. However, the two columns had much better efficiency in removing rotifers than removing nematodes under the same operational condition. In Column II for example, when the filtration velocity was 12 m/h, the average rate in removing rotifers was 39.8% without chlorination, and this increased to 93.3% with a chlorine dosage of 1.5 mg/L. However, for nematodes, the values of the average removal rate ranged from –23.6% to 54.3%. When the filtration velocity was 12 m/h, the efficiencies for removing nematodes were –23.6% without chlorination, and 35.5% with 1.5 mg/L chlorine. Sand filtration without chlorination had poor efficiency in removing nematodes. Under some conditions, ultra penetration of nematodes occurred. The nematode abundance in the effluent was higher than that for the influent. After the addition of chlorine, the removal efficiency was not obviously improved, The highest removal rate was 54.3%, when the chlorine dosage was 0.5 mg/L and the filtration velocity was 8 m/h.

The results showed that the system had different levels of efficiency for removing different kinds of invertebrates. Different invertebrates had different degrees of chlorine resistance [18]. Nematodes had stronger chlorine resistance than rotifers. When the chlorine dosage was 2.0 mg/L, the rotifers could be completely inactivated within a contact time of 60 min, whereas the inactivation rate for nematodes under the same condition was zero. Thus, different levels of chorine resistance resulted in different survival rates, which contributed to the differences in the removal efficiency. In addition, a previous study by Yan et al. [28] showed that the inactivation rate for nematodes reached only 87% when the chlorine dosage was 80 mg/L, and the contact time was 180 min. As the chlorine dosage used in DWTPs cannot safely exceed certain levels, there is a clear need to develop new technologies for nematode inactivation that are both efficient and safe.

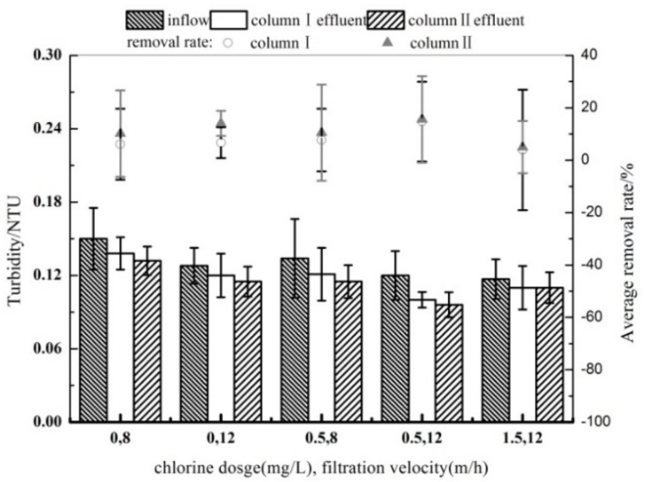

Fig. 6. Average rate of removing turbidity at different chlorine dosages and filtration velocities.

3.3. Changes of turbidity, head loss and residual chlorine

3.3.1. Turbidity

The average turbidities of the inflow and effluent of the two columns were measured, and the results are indicated in Fig. 6.

Fig. 6 reveals that both columns had substantial effects on the removal of turbidity. The average removal rates were 3.9–14.7% for Column I and 5.0–15.6% for Column II. The average removal rates for Column II were a little higher than those for Column I under the same chlorine dosage and filtration velocity. However, the chlorine dosage and the filtration velocity had no obvious effect on the rates of turbidity removal.

3.3.2. Head loss

As Fig. 7 shows, when the chlorine dosage and filtration velocity were the same, the head loss for Column II was a little higher than that for Column I, because Column II used smaller sand particles, and a larger filtration velocity brought a higher head loss. The addition of chlorine had no obvious effect on the head loss. However, even if the filtration velocity was 12 m/h, the largest head loss was only 0.080 m. Therefore, the head loss could be ignored when sand filtration was conducted with smaller sand grains for removing the invertebrates after the BAC filter.

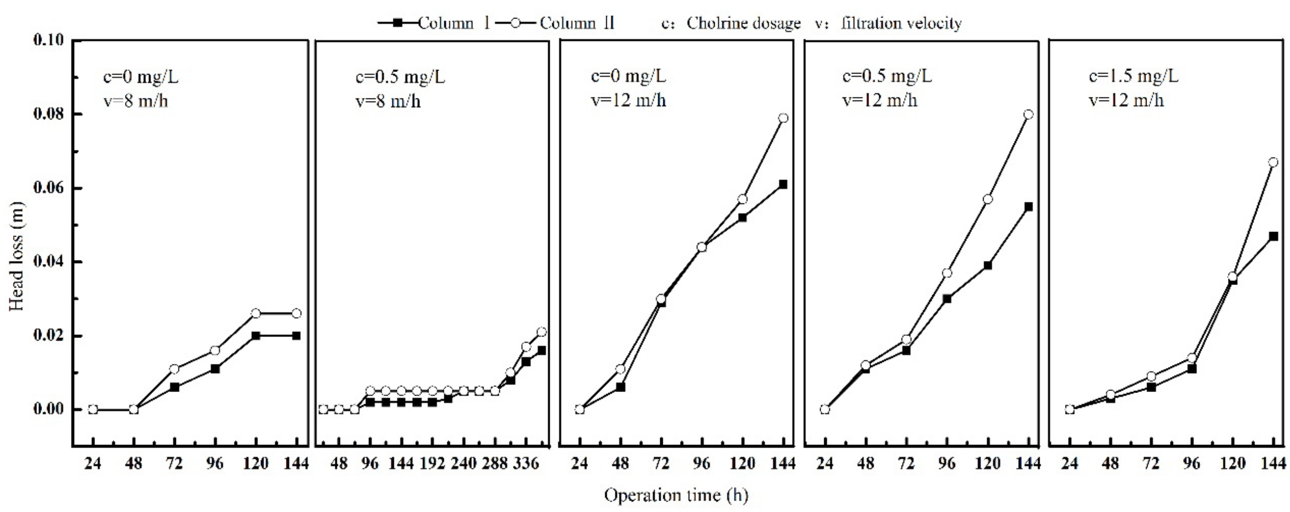

Fig. 7. Changes of head loss at different chlorine dosages and filtration velocities (set with the initial head loss as 0).

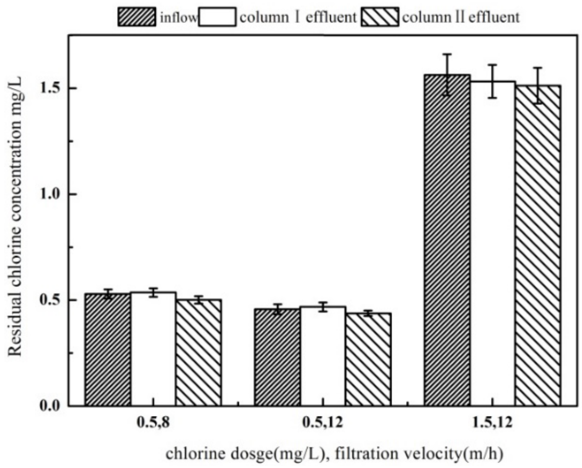

Fig. 8. Changes of the residual chlorine concentration.

3.3.3. Residual chlorine consumption

The residual chlorine concentrations of the inflow water and effluent were monitored during sand filtration with chlorination (Fig. 8). The chlorine dosage was set to 1.5 mg/L as an example, and the average chlorine concentration of the influent was 1.56 mg/L. After filtration, the effluent chlorine concentrations in Columns I and II were 1.53 and1.51 mg/L, respectively. The chlorine consumption was minimal during sand filtering. The basic chlorine consumption was very limited because of the low organic matter content in the BAC effluent. Silica sand does not absorb chlorine, and the filtration time was short. Therefore, if chlorine was properly added to the effluent pipeline of the BAC filter, additional chlorine was not necessary after the sand filtration.

4. Conclusions

In China, increasing attention has been paid to the leakage of invertebrates through BAC filters. This study has proposed an effective and feasible method to remove invertebrates. The following conclusions can be drawn from the study:

1. Sand filtration after the BAC filter did not achieve satisfactory efficiency in removing invertebrates, but the addition of chlorine could improve the rates of invertebrate removal. The head loss and the residual chlorine consumption during filtration were minimal.
2. Invertebrate survival status was the key factor that affected the removal rate. Certain doses of chlorine could inactivate invertebrates or inhibit their movement and reproduction, thereby intensifying the preventive function of the sand filtration.
3. The efficiency in removing nematodes was still limited, in that the amount of chlorine permissible in DWTPs could not inactivate all nematodes. Therefore, further studies are required to develop new technologies for preventing nematodes from entering the product water reservoirs.

Acknowledgments

This work was supported by the National five-year water special project (2012ZX07403-002-04).We acknowledge the support of the waterworks taking part in this investigation. Special thanks to the anonymous reviewers for their helpful comments.

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