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Optimization of enhanced sand filtration with secondary-flocculation for polluted water treatment

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ABSTRACT

In order to meet standards for drinking water quality (GB5749-2006) in China, the sand filtration with a high dosage of secondary-flocculation following biological activated carbon (BAC) filter is employed at Nanjiao waterworks, which leads to greatly shortening the running cycle and increasing operating costs. In an effort to reduce the chemical dosage, optimization of sand filtration and BAC filtration were performed. The results show that the enhanced sand filtration and the improvement of water quality of BAC filter effluent can significantly reduce the dosage. Appropriate sand gradation (0.5–0.8 mm), sand filter backwashing with high air flow rate and low water flow rate, the BAC filter with 0.3–0.6 mm carbon operating with appropriate flow rate are beneficial in reducing the dosage of secondary-flocculation. Compared with the full-scale plant, over 60% dosage can be saved by reducing chemical dosage to 0.3 mg/L, thereby decreasing the amount of sludge, increasing the running cycle of the filter, saving the volume of backwash water, and finally reducing operating costs.

Keywords: Biological activated carbon; Dosage; Drinking water; Sand filtration; Secondary-flocculation

1. Introduction

Because of extensive rural industry pollution [1,2] and agricultural nonpoint pollution [3,4], surface water in China is being seriously polluted. Among the 64 river water quality monitoring sections in Jiaxing in 2009, the percentage of Grade III water was only 1.6%, while the percentages of Grade IV, Grade V, and any grade poorer than Grade V were 23.4, 34.4, and 40.6%, respectively [5], based on the Environmental Quality Standards for Surface Water (GB3838-2002) in China. The main pollutants of surface water are thought to be organic matter and ammonia, which are very difficult to be effectively removed using conventional water treatment process. Therefore, biological pretreatment, conventional treatment, and ozonation-biological activated carbon (O_3-BAC) advanced treatment are adopted at Nanjiao waterworks (N waterworks).

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The typical drinking water treatment process is depicted in Fig. 1.

BAC filtration in the process as illustrated above is operated in up-flow, which can maximize the removal efficiency of pollutants. Unfortunately, it may also increase the effluent turbidity and cause leakage of micro-organism [6–8]. Previous studies showed that the particle counts and virus in water can be reduced effectively with a decrease in water turbidity [9–12]. The removal efficiency of *Cryptosporidium* and *Giardia* is up to 99.9% when turbidity is reduced to a level below 0.1 NTU [13,14]. Meanwhile, low-pressure membranes, especially for ultrafiltration (UF) process, have been rapidly developed in the drinking water treatment in recent years, with the increasing concerns on the leakage of micro-organism [15–17]. However, UF process demonstrates a limited ability to remove dissolved inorganic and organic matters, which is a key issue to limit the application of UF process in the polluted drinking water treatment [18–20].

In order to remedy the problem, considering the ability for pollutants removal of BAC and sand filter, a sand filtration process following BAC filtration is employed at N waterworks [21], which has the potential to further remove some pollutants and reduce the turbidity [22]. The objective of N waterworks is to maintain the treated water turbidity not more than 0.1 NTU, so as to ensure the safety of drinking water. Therefore, filtration with secondary-flocculation technology is further adopted at the waterworks [21].

With the above measures, the combined process can guarantee the safety of drinking water. However, the high dosage (with an average dosage of 0.8 mg/L) of secondary-flocculation process, along with the short running cycle of sand filtration is also investigated, which increases the operating costs of waterworks. Therefore, in this study, in order to reduce the chemical dosage of secondary-flocculation, as well as improve the water quality and decrease the operating costs, based on the combined process of N waterworks, the optimization of sand filtration and BAC filtration were performed, with the effluent of BAC filter or sedimentation tank of N waterworks as the influent of the pilot tests. The factors that influence the water quality and the dosage of secondary-flocculation, such as the gradations of sand and carbon, the backwash mode, the BAC filter flow rate, and $KMnO_4$ oxidation enhanced sand filtration, are discussed. Moreover, the objective of this study is to provide guidance for the construction or modification of waterworks, and finally ensure the safety of drinking water.

2. Experiments and methods

2.1. Experimental setup

The pilot tests influent water was collected from the effluent of sedimentation tank or BAC filter of N waterworks. The main experimental setups include sand filtration with secondary-flocculation unit and BAC filtration unit, and the above two units can run separately or run together. The sand filtration unit has three separate columns with different sand gradations (1#, 2# and 3#), and the BAC filtration unit has two separate columns (4# and 5#).

At N waterworks, the sand filter with 0.75–0.90 mm uniform sand has a depth of 1 m, and the BAC filter with 0.3–0.6 mm carbon has a depth of 2.0 m. Therefore, the operating parameters of the pilot tests, according to the running parameters of N waterworks, are listed in Table 1.

2.2. Experimental procedure

The pilot tests consist of two parts, optimization of sand filtration with secondary-flocculation only, and it with further optimization of BAC filtration. For the first part, the influent of the pilot tests was taken from the effluent of BAC filter of N waterworks, which flew directly to sand filtration with secondary-flocculation, and the effect of backwash mode, sand gradation, and pre-oxidation on the dosage of secondary-flocculation are discussed. While for the other part, the effluent of sedimentation tank of N waterworks was collected as the influent of the pilot tests, which firstly flew to BAC filter, then to sand filter, and the effect of carbon gradation and BAC filter flow rate on water quality and dosage are discussed. Polyaluminum ferric chloride (PAFC) with a specific gravity in the range of

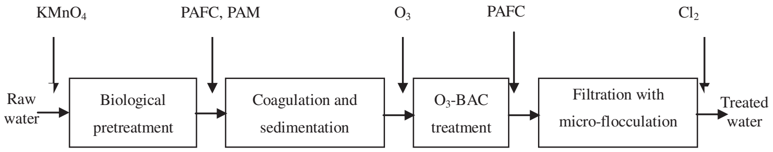

Fig. 1. Drinking water treatment process at N waterworks.

Table 1
Main operating parameters of pilot tests

Sand filter	Size	Φ 100 × 5,000 mm
	Filter media	1#: 1 m-thick sand layer (0.5–0.8 mm)
		2#: 1 m-thick sand layer (0.5–1.2 mm)
		3#: 1 m-thick sand layer (0.75–0.90 mm uniform sand)
	Filter flow rate	5.10–14.01 m/h
	Running mode	Down-flow
BAC filter	Size	Φ 100 × 6,000 mm
	Filter media	4#: 2.0 m-thick carbon layer (0.6–0.8 mm),
		5#: 2.0 m-thick carbon layer (0.3–0.6 mm)
	Filter flow rate	5.10–14.01 m/h
	Running mode	Up-flow

1.24–1.30 and Al_2O_3 content in the range of 10.30–10.91%, the same coagulant as N waterworks, was employed in this study.

Water samples were periodically collected to measure turbidity, particle counts, water temperature, pH, ammonia, permanganate consumption (COD_{Mn}), UV_{254}, Fe, Mn, and so on.

2.3. Analysis methods

Standard methods GB5750-2006 in China were adopted for analysis of all the parameters, turbidity was detected by a 2100 N turbidity meter (Hach, USA), particle counts was measured by a GR-1000A laser particle analyzer (IBR, USA), ammonia was analyzed with the Nessler reagent spectrophotometric method, UV_{254} was measured using a DR5000 spectrophotometer (Hach, USA), Fe and Mn were analyzed with an ICE3000 atomic absorption spectroscopy analyzer (Thermo, USA), COD_{Mn} was detected by acidic potassium permanganate titration, and pH and DO were analyzed with a HQ40d pH and DO analyzers (Hach, USA), respectively.

3. Results and discussion

During the experimental periods, the main parameters of raw water are listed in Table 2. The water quality of the effluent of sedimentation tank and BAC filter of N waterworks is shown in Table 3. Unless otherwise specified, average concentrations during the experimental periods are given in the following studies.

Table 2
Raw water quality of N waterworks during experimental periods

	Raw water		
Parameters	Max.	Min.	Ave.
COD_{Mn} (mg/L)	8.80	5.09	6.74
NH_3–N (mg/L)	2.35	0.24	1.34
UV_{254}	0.166	0.133	0.151
DO (mg/L)	2.70	1.30	2.00
pH	8.25	6.87	7.27
Turbidity (NTU)	59.60	29.00	43.80
Fe (mg/L)	2.55	1.12	1.76
Mn (mg/L)	0.48	0.30	0.39

Table 3
Water quality of the effluent of sedimentation tank and BAC filter of N waterworks during experimental periods

	The effluent of sedimentation tank			The effluent of BAC filter		
Parameters	Max.	Min.	Ave.	Max.	Min.	Ave.
COD_{Mn} (mg/L)	5.89	2.43	4.94	3.08	2.11	2.54
NH_3–N (mg/L)	1.08	0.22	0.65	0.45	0.02	0.12
UV_{254}	0.079	0.125	0.113	0.068	0.055	0.060
DO (mg/L)	7.22	8.90	8.06	10.80	7.80	9.20
pH	7.43	7.31	7.37	7.08	7.01	7.03
Turbidity (NTU)	10.20*	2.65	5.49	2.57	1.27	1.76
Fe (mg/L)	0.16	0.10	0.13	ND	ND	ND
Mn (mg/L)	0.63	0.11	0.30	0.8	0.11	0.18

*Note: Turbidity value is high because of the alum floc up float during coagulation and sedimentation process.

3.1. Effect of backwash mode of sand filter

Intended for a better comparison with N waterworks, the sand gradation, and thickness of 3# sand filter are designed the same as N waterworks, then experiments of the effect of backwash mode on water quality and dosage were carried out over 3# sand filtration column. And three different backwash modes (Table 4) were conducted.

It can be seen from Table 5 that the turbidity of initial filtrated water decreased below 0.1 NTU within 10 min after backwashing with all the three backwash modes. But with B backwash mode, the time can be

Table 4
Different backwash modes of pilot tests and waterworks

Backwash mode	q_a (L/m^2 s)*	t_a (min)*	q_w (L/m^2 s)*	t_w (min)*
A	7	2	13.5	7
B	17.36	2	7	7
C**	17.36	1	13.5	6

*Notes: q_a and t_a are the intensity and time of air backwash, respectively; q_w and t_w are the intensity and time of water backwash, respectively.

**C is the same backwash mode as that of N waterworks.

reduced to 8 min. That is, backwash mode with a relative high air flow rate and low water flow rate is the best for this process, which not only can improve water quality, but also can significantly decline the volume of initial filtrated water.

Moreover, experiments over 3# sand filtration column with different dosages of PAFC were carried out under the operating conditions of filter flow rate 14 m/h, B backwash mode. It can be observed from Fig. 2 that the turbidity decreased with an increase in dosage. Through the optimization of the backwash mode of sand filtration, the dosage of PAFC can be reduced from 0.8 to 0.6 mg/L, with a reduction of 25%, meanwhile, the filtration flow rate is double increasing from 7.6 to 14 m/h, which will greatly increase production capacity and reduce operating costs.

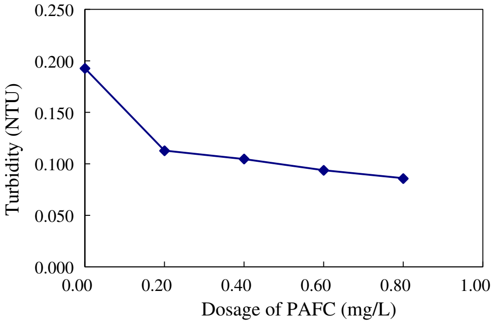

Fig. 2. Turbidity changed with the dosage of PAFC after optimization of the backwash mode.

3.2. Effect of sand gradation

Three different sand gradations in 1#, 2#, and 3# column shown in Table 1 were chosen to evaluate its effect on filtered water quality, and the experiments were carried out with sand filter flow rate of 14 m/h, B backwash mode, and without secondary-flocculation. The results are shown in Fig. 3.

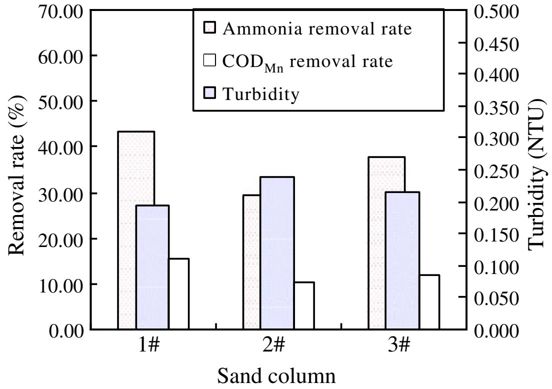

Fig. 3. Turbidity and pollutants removal rates under different sand media without PAFC addition (1#: 0.5–0.8 mm, 2#: 0.5–1.2 mm, 3#: D_{10} = 0.75 mm uniform sand).

Under the same operating conditions, the effluent water quality of 1# filtration columns was the best, whereas that of 3# column was the worst. COD$_{Mn}$ and ammonia removal efficiencies of 2# filtration column (0.5–1.2 mm sand) were only 30 and 10%, respectively, whereas about 43 and 15% removal efficiencies were obtained for 1# column (0.5–0.8 mm sand), respectively. That is, sand with fine particle gradation in 1# sand filtration column is more conducive to the improvement of water quality.

Based on the above results, experiments of the effect of dosage of PAFC on the turbidity were carried out with 0.5–0.8 mm sand (1# column). The results are

Table 5
Turbidity of initial filtrated water changed with time

Backwash mode	Turbidity (NTU)						
	1 min	2 min	3 min	4 min	6 min	8 min	10 min
A	0.53	0.37	0.31	0.22	0.15	0.10	0.085
B	0.45	0.32	0.27	0.20	0.13	0.09	0.079
C	0.55	0.35	0.29	0.21	0.14	0.10	0.082

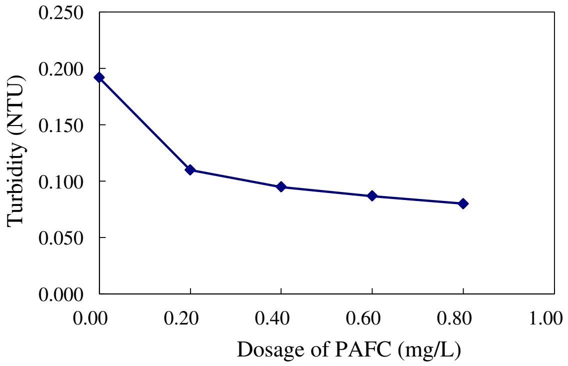

Fig. 4. Turbidity changed with the dosage of PAFC after further optimization of the sand gradation.

shown in Fig. 4. The turbidity can be achieved less than 0.1 NTU with 0.4 mg/L PAFC addition, only 50% dosage of N waterworks, which means that the dosage of PAFC can be further decreased by the optimization of sand gradation.

3.3. Effect of pre-oxidation before secondary-flocculation

As mentioned above, the BAC process with up-flow mode may cause the problem of leakage of micro-organism. Fig. 5 shows that the effect of pre-oxidation with $KMnO_4$ addition on particle counts and COD_{Mn} removal rate under the dosage of PAFC of 0.1 mg/L. It can be found that $KMnO_4$ oxidation process had a more significant role in promoting flocculation. With the increasing dosage of $KMnO_4$, particle counts significantly reduced and COD_{Mn} removal rates increased. Under the $KMnO_4$ dosage of 0.4 mg/L, particle counts reduced by 26% and COD_{Mn} removal rate increased by 8%, compared with without $KMnO_4$ addition. This can be explained that $KMnO_4$ not only can oxidize the organic matter leaking out from BAC filter, but also it will decompose to produce some substances such as hydrated manganese dioxide, which is an effective coagulant aid to enhance flocculation process [23,24].

3.4. Effect of BAC filter flow rate

Under a certain dosage of secondary-flocculation, the water quality of sand filter effluent will depend on the influent water quality, in other words, the water quality of influent may influence the dosage of secondary-flocculation. Therefore, aiming to further decrease the dosage of secondary-flocculation, optimization of BAC filtration was also carried out.

The filter media of 2.0 m thick of carbon layer (0.3–0.6 mm) in 5# column is the same as that at N waterworks. Similarly as the above, heading for a better comparison with N waterworks, the sedimentation tank effluent water of N waterworks went through 5# BAC filtration column, and then went through 1# sand filtration column. The BAC filter flow rate of 5.10, 6.37, 8.92, 9.55, and 14.00 m/h was conducted, respectively. Fig. 6 illustrates the influence of the BAC filter flow rate on turbidity removal. It can be observed that no significant difference was observed between the filter flow rate of 5.10 and 8.92 m/h. However, with continuously increasing in filter flow rate, the turbidity removal rate significantly decreased. The removal rate decreased from 83 to 64%, when the filter flow rate increased from 8.92 to 9.55 m/h.

The influence of the BAC filter flow rate on ammonia and COD_{Mn} removal is illustrated in Fig. 7. It can be observed that both ammonia and COD_{Mn} removal rates increased with the filter flow rate increasing from 5.10 to 8.92 m/h. This can be explained that carbon expansion degree increased

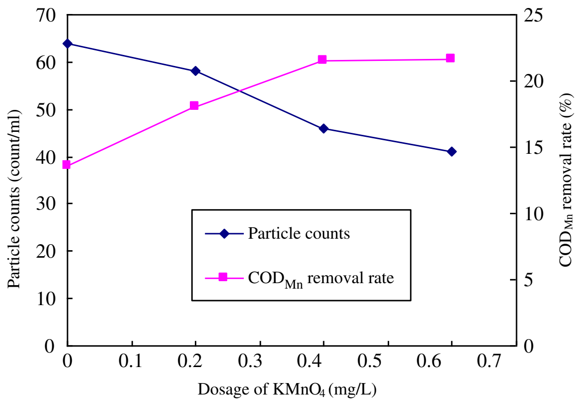

Fig. 5. Effect of $KMnO_4$ pre-oxidation on particle counts and COD_{Mn} removal with 0.1 mg/L PAFC addition.

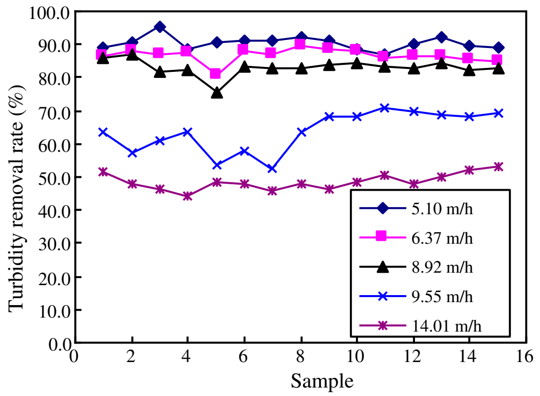

Fig. 6. Effect of BAC filter flow rate on turbidity removal.

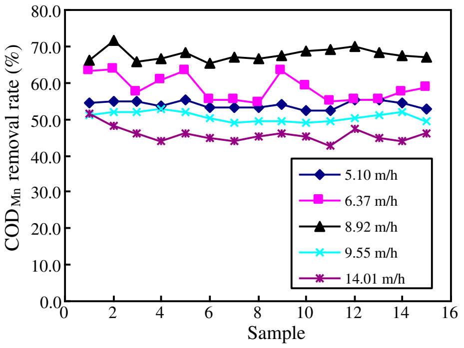

Fig. 7. Effect of BAC filter flow rate on ammonia and COD$_{Mn}$ removal.

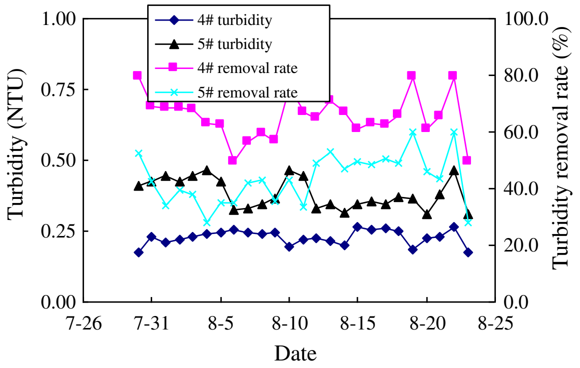

Fig. 8. Effect of carbon gradation on turbidity removal.

with filter flow rate increasing, thereby increasing mass transfer rate of pollutants to the activated carbon surface, providing more contact chance between pollutants and activated carbon [8]. That is, an increase in the carbon layer expansion degree played a positive role in the removal rate of pollutants. Meanwhile, with filter flow rate increasing, the hydraulic residence time reduced, which played a negative function on pollutant removal. When the filter flow rate was over 8.92 m/h, positive function was less than negative influence, thereby resulting in a decrease in pollutants removal rate. Therefore, the flow rate of BAC filter has a dual function on pollutants removal. An optimal pollutants removal rate can be achieved with appropriate flow rate of BAC filter. The best removal rate achieved at the filter flow rate of 8.92 m/h in this study.

3.5. *Effect of carbon gradation*

The influent of the pilot tests was taken from the sedimentation tank effluent of N waterworks, 0.6–0.8 mm and 0.3–0.6 mm carbon were chosen as 4# and 5# BAC filter media, respectively, the filter flow rate was 8.92 m/h, and the BAC filter was operated in up-flow mode. Fig. 8 shows the effect of carbon gradation on turbidity removal. During the experimental periods, the average of turbidity of 4# BAC filter effluent was 0.23 NTU, with an average removal rate of 65.5%, while the average of turbidity of 0.38 NTU, with an average of 43.4% for 5# BAC filter. This can be explained that the carbon expansion degree in 4# BAC filtration column is smaller than that in 5# BAC column under the same operating conditions, because the size of carbon in 4# BAC filtration column (0.6–0.8 mm) is larger than that in 5# column (0.3–0.6 mm). Therefore, it can be more effective to remove turbidity and particle matters.

The results of the effect of carbon gradation on ammonia and COD$_{Mn}$ removal rates are shown in Fig. 9. During the experimental periods, the concentrations of ammonia of the BAC filter effluent were 0.16 and 0.15 mg/L for 4# and 5# BAC filtration columns, respectively. This can be partly explained that the carbon in 5# column (0.3–0.6 mm) can achieve a relatively higher expansion degree, and make contact chance between carbon and pollutant more sufficiently, which is benefit to removing ammonia. But no obvious

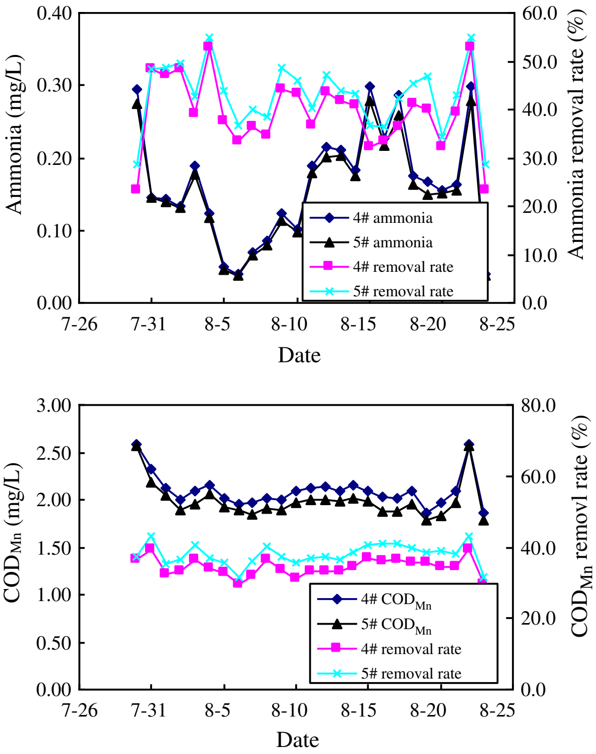

Fig. 9. Effect of carbon gradation on ammonia and COD$_{Mn}$ removal.

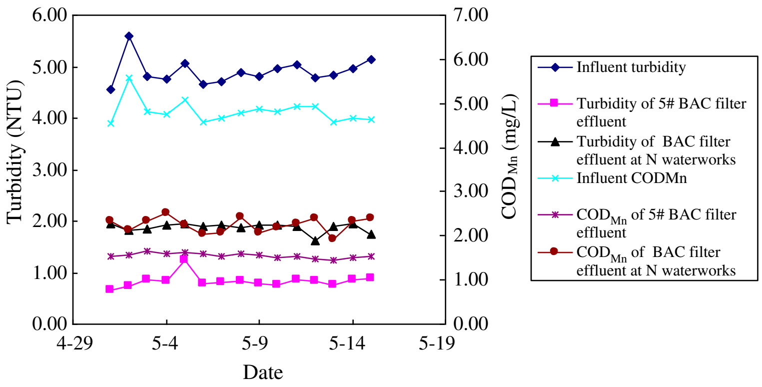

Fig. 10. The water quality after optimization of BAC filter.

difference between the two BAC filtration columns was observed in ammonia removal rate due to the low ammonia concentration of the influent.

During the experimental periods, the average concentration of COD_{Mn} of influent water was 3.19 mg/L, while that of the BAC filter effluent was 2.09 and 1.97 mg/L for 4# and 5# BAC column, respectively. BAC filtration column with 0.3–0.6 mm carbon is better than that with 0.6–0.8 mm for COD_{Mn} removal. This can be explained that the specific surface area of media in 5# BAC filtration column is bigger than that in 4# column, and makes more contact chance with pollutant, which leads to higher COD_{Mn} removal efficiency.

3.6. Water quality and the dosage of PAFC after the optimization

Compared to N waterworks, Fig. 10 shows that the water quality improved after the optimization of BAC filtration process. It can be observed that the average effluent turbidity of the BAC column is 0.83 NTU, while that of N waterworks 1.88 NTU. For COD_{Mn}, the average value of effluent is 1.55 mg/L, much lower than that of N waterworks 2.25 mg/L. This shows that the optimization of BAC filtration is benefit to water quality improvement significantly.

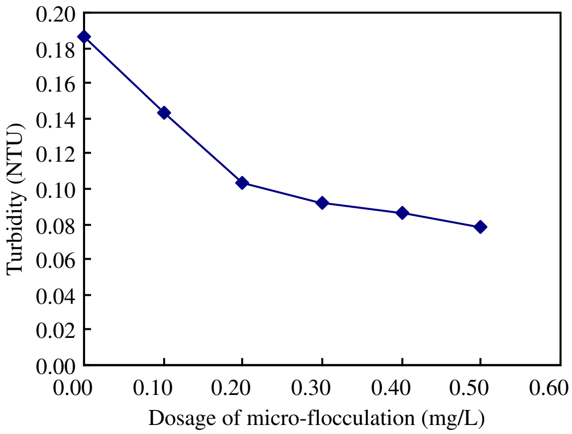

Fig. 11. Turbidity changed with the dosage after optimization of BAC and sand filter.

Fig. 11 shows that the turbidity changed with the dosage after optimization of BAC and sand filtration. The turbidity of BAC and sand filter effluent was less than 1 and 0.1 NTU, respectively, and the dosage of PAFC can be reduced to 0.3 mg/L, saving dosage consumption over 60%, compared to N waterworks.

4. Conclusions

In order to solve the problem of high dosage of secondary-flocculation process, the influence of the optimization of sand filtration and BAC filtration on the dosage were investigated. The main conclusions generated from this study are as follows:

(1) It is indicated that a sand filtration process following BAC filtration plays a key role in removing turbidity, and then controlling *Giardia* and *Cryptosporidium* and ensuring the biological safety of the effluent.
(2) It is confirmed that over 60% dosage of PAFC can be reduced, compared with the full-scale plant, through enhancing sand filtration and improving water quality of BAC filter effluent, therefore increasing the running cycle of sand filter, significantly declining the volume of backwash water and decreasing the operating costs.
(3) For the influent of low turbidity, backwash mode of sand filter with a relative high air flow rate and low water flow rate, fine sand gradation, and fine carbon gradation are beneficial in removing pollutants and saving the dosage of PAFC.

(4) Flow rate of BAC filter has a dual function on pollutants removal. An optimal pollutants removal rate can be achieved with appropriate flow rate of BAC filter.

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