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Effect of a biological activated carbon filter on particle counts*

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Abstract: Due to the importance of biological safety in drinking water quality and the disadvantages which exist in traditional methods of detecting typical microorganisms such as Cryptosporidium and Giardia, it is necessary to develop an alternative. Particle counts is a qualitative measurement of the amount of dissolved solids in water. The removal rate of particle counts was previously used as an indicator of the effectiveness of a biological activated carbon (BAC) filter in removing Cryptosporidium and Giardia. The particle counts in a BAC filter effluent over one operational period and the effects of BAC filter construction and operational parameters were investigated with a 10 m^3/h pilot plant. The results indicated that the maximum particle count in backwash remnant water was as high as 1296 count/ml and it needed about 1.5 h to reduce from the maximum to less than 50 count/ml. During the standard filtration period, particle counts stay constant at less than 50 count/ml for 5 d except when influenced by sand filter backwash remnant water. The removal rates of particle counts in the BAC filter are related to characteristics of the carbon. For example, a columned carbon and a sand bed removed 33.3% and 8.5% of particles, respectively, while the particle counts in effluent from a cracked BAC filter was higher than that of the influent. There is no significant difference among particle removal rates with different filtration rates. High post-ozone dosage (>2 mg/L) plays an important role in particle count removal; when the dosage was 3 mg/L, the removal rates by carbon layers and sand beds decreased by 17.5% and increased by 9.5%, respectively, compared with a 2 mg/L dosage.

Key words: Biological activated carbon (BAC) filter, Cryptosporidium, Giardia, Particle counts, Turbidity
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INTRODUCTION

Biological safety in drinking water is critical. Common aquatic pathogens include bacteria, viruses and protozoa (Yang *et al.*, 2003). It is Cryptosporidium, Giardia and viruses that are often responsible for causing many waterborne diseases, especially Cryptosporidium and Giardia (Blair, 1994; Kenzie *et al.*, 1994; Craun *et al.*, 1998). Giardia cysts and Cryptosporidium oocysts are very resistant to common disinfectants such as chlorine, so detection is very important. Traditional analysis procedures have several disadvantages, including inspection difficulties and processes which are time-consuming and complicated. Even worse is the large variation in results which can occur between different laboratories, and the low recovery and low sensitivity of methods (Craun, *et al.*, 1998). Therefore utilities must rely on surrogate parameters for an up-to-date assessment of the Cryptosporidium and Giardia risk at water treatment plants (WTPs).

Turbidity is traditionally an essential parameter for monitoring the efficiency of clarification processes, and represents an important organoleptic character in defining water quality, especially in filtered water. In the contemporary context, turbidity is not only a measure of particles suspended in water, it is also a sanitary index related to biological safety. The main inconvenience of turbidity measurements is that this parameter mainly reflects <1 μm particles (Yang *et al.*, 2003), which means that larger particles could exist in a sample but contribute very little to

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turbidity readings. However, Cryptosporidium exists as a spherical oocyst 4~6 μm in diameter, and Giardia cysts are 10~12 μm in diameter (Hatukai *et al.*, 1997), so turbidity measurement is not sensitive to particles in the size range of Giardia cysts and Cryptosporidium oocysts. Therefore low turbidity of treated water does not indicate their absence in the water.

Particle counters have been widely developed during the last few years and allow us to obtain the total particle counts (TPCs) and particle size distributions (PSDs). It is possible to use particle counters both in laboratory studies and in online measurements, evaluation and optimization. Unlike turbidity, particle counting is more sensitive to particles larger than 1 μm (Hatukai *et al.*, 1997). Usually the pathogen concentration can be correlated from the total particle counts. The treatment goals of the Surface Water Treatment Rule (SWTR) specify a 99.9% removal or inactivation of Giardia cyst or 99.99% removal or inactivation of enteric viruses. The Interim Enhanced Surface Water Treatment Rule (IESWTR) requires 99% removal of Cryptosporidium. Both rules attain these objects by reducing overall effluent particles (Colorado Department of Public Health and Environment, 2002). This is why these rules suggest using particle counters for effluent monitoring to preserve water safety.

Much research has been undertaken to investigate the relationships between particle counts and Cryptosporidium and Giardia. It has been found that there are probably only between 1~3 Cryptosporidium (or its oocysts) and Giardia (or its cyst) when particle counts of 3~10 μm size range are <100 count/ml. Furthermore, when the particle counts of this size range are reduced to <50 count/ml, the probability of Cryptosporidium (or its oocyst) and Giardia (or its cyst) existing is only 0.01%. Thus improvement of particle removal promotes Cryptosporidium and Giardia removal. Particle counters have already been widely utilised in American WTPs, most commonly as a tool to evaluate filter performance and reduce the Giardia and Cryptosporidium risk (Hall and Croll, 1997; Morse *et al.*, 2002). In China, particle counters are only used in a limited number of WTPs: Beijing No. 9 Water Plant applies particle counters for traditional treatment process optimization (Cui *et al.*, 2004); Guangzhou Water Supply Co. uses particle counters to assess the water quality of sand filter effluent and biological activated carbon (BAC) filter effluent (He and Xu, 2004).

Nowadays the ozonation-BAC treatment process, which integrates the strong oxidation and disinfection capabilities of ozone and the high adsorption and biodegradation capacities of BAC, has become a popular advanced water treatment technology which has been implemented all over the world (Zhou and Qiu, 1998). When ozonation-BAC treatment process is used, BAC becomes the last filtration technology prior to disinfection. Almost all investigations previously undertaken have focused upon the relationships among particle counts, turbidity, Cryptosporidium and Giardia, sand filter performance examination, and the use of particle counters, rather than the impact of BAC filters. This paper presents the results of particle counts in BAC filter effluent obtained by a 10 m^3/h pilot plant.

MATERIALS AND METHODS

Experiment apparatus

Experiments were undertaken at a pilot water treatment plant in South China with a process of pre-ozonation, flocculation-sedimentation, rapid sand filtration, post-ozonation and BAC filtering. The main design parameters for the BAC filter were as follows: 1.20 m of diameter, 4.7 m of total height which includes 1.75 m carbon depth, 0.3 m sand bed and 0.45 m supporting layer, and a 10 m^3/h design flow corresponding to a filtration rate of 8.85 m/h. Two parallel processes were employed, one with a columned carbon filter and the other with a cracked carbon filter. All results were taken from the columned carbon filter, except for those involving comparisons between the two filters.

Analytical methods and the standard requirement

The TPCs were carried out by a continuous online particle counter (Fig.1) and a portable particle measuring sensor (model WPCS, IBR Inc.). This sensor allows up to 8 user selectable channels ranging from 2 to 400 μm with a resolution of 5% or less at 10 μm and a resolution of 9% or less at 2 μm. The following channels were selected during tests: 2~3, 3~5, 5~7, 7~10, 10~20, 20~50, 50~70, 70~100, >100 μm.

Fig.1 IBR particle counter

In China there is no requirement for particle counts. Luo *et al.*(2000) suggest that filtrate particle counts (without size ranges) should be <100 count/ml. By comparison, in American WTPs it is demanded that particles >2 μm should be <50 count/ml (He and Xu, 2004).

RESULTS AND DISCUSSION

PSD of BAC filter effluent

The PSD data presented in Table 1 reveal that particles of 2~3 μm size range comprise the majority (about 75%) of the particles in BAC filtered water. Particles greater than 10 μm are not discussed here since they comprise less than 0.5% of the TPC. This article is only focused on the TPC.

Table 1 PSD of BAC filter effluent

Channel	PSD (%)		
	Max.	Min.	Ave.
1 (2~3 μm)	79.2	70.5	75.3
2 (3~5 μm)	23.5	18.4	20.3
3 (5~7 μm)	4.1	1.7	2.9
4 (7~10 μm)	2.1	0.5	1.1

BAC filter effluent particles in full operational period

1. Backwash remnant water drainage period

Fig.2 gives the particle counts in backwash remnant water. The particle counts reached 1296 count/ml as BAC filter backwash remnant water is drained off directly after backwashing. Then the particle counts decreased dramatically to 100 count/ml after 64 min, but needed about 1.5 h to stabilize at a value less than 50 count/ml.

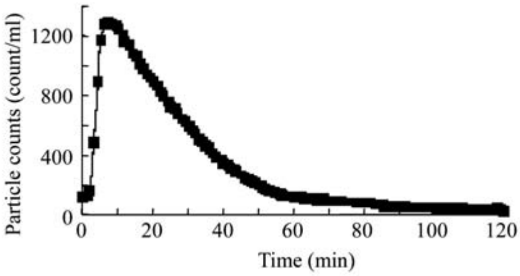

Fig.2 Particle counts (>2 μm) in backwash remnant water of BAC filter

The turbidity standard for the WTP effluent in the program "Southern Area Drinking Water Safety Assurance Technology" is 0.1 NTU. This is also an indication that backwash remnant water drainage is finished. Usually a BAC filter will only need 0.5 h for this to occur, whereas up to 1.5 h is necessary for the particle counts to decrease to 50 count/ml. Thus, if particle counts are used to control the backwash remnant water drainage instead of turbidity, the time taken to stabilize is significantly longer. This also means that the particle count measurements tend to be more sensitive than turbidity.

The maximum particle count in BAC filter effluent and the time needed before the backwash remnant water drainage period of BAC filter finished is much higher and much longer than those in another research with around 90 count/ml peak value and 15 min, respectively (He and Xu, 2004). This is maybe caused by different activated carbon, operational conditions and water chemistry. These results illustrate the complexity of BAC filter effluent particles that needs further investigation to be better understood. Many factors, such as operational conditions, carbon type used in a BAC filter and water chemistry can all influence the particle counts.

It is apparent from Fig.2 that the main problems with BAC filter backwash remnant water drainage periods are high particle counts and long time duration. Discharging or treating the backwash remnant water is highly advisable for safety.

2. Standard filtration period

The standard filtration period of a BAC filter is defined as the period when the BAC filter effluent particle counts remain constant at less than 50 count/ml after the backwash remnant water drainage period.

There is no doubt that the worst water quality exists when water is first drained off after backwashing. However, particle counts during the standard filtration period tend to vary. It is possible for them to remain below 50 count/ml or exceed this figure depending on the influent water quality and BAC filter management.

Fig.3 gives the particle counts of BAC filter effluent over a standard filtration period of 7 d. Although the particle counts usually remain below 50 count/ml there are also some times when the effluent particle counts increased gradually and peaked above 50 count/ml before decreasing again. This period corresponds with the time for rapid sand filter draining off backwash remnant water, so it appears that the high particle counts in BAC filter influent may be caused by bad sand filter effluent quality. The influence of backwash remnant water drained off by a rapid sand filter is also observed in another investigation (He and Xu, 2004) in which the particle counts of sand filter effluent and BAC filter effluent were compared, though the influence is not as significant (with the maximum particle counts still lower than 70 count/ml) as that in Fig.3, with the maximum particle counts keeping lower than 70 count/ml and higher than 150 count/ml in Fig.3.

After 5 d the particle counts showed a gradual upward trend to 100 count/ml, and on the 7th day, the particle counts increased dramatically to several times this figure. This spike indicates that the carbon filter has reached breakthrough point and it is time for backwashing. The time needed before backwashing is close to 115 h (He and Xu, 2004).

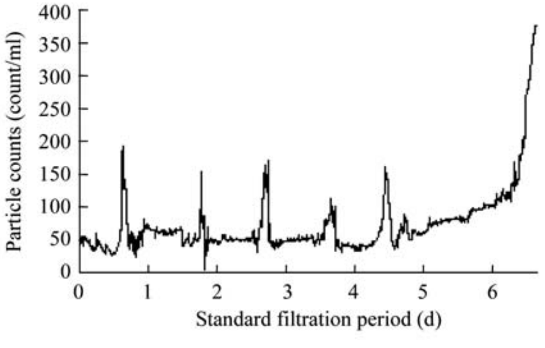

Fig.3 Particle counts (>2 μm) of BAC filter effluent in standard filtration period

Effect of BAC filter design

The removal rates or removal efficiencies of activated carbon layer and sand bed are defined as the difference between the particle counts in influent and activated carbon layer and the difference of particle counts between a activated carbon layer and a sand bed, respectively.

1. Comparison of the activated carbon filter and the sand bed

The maximum particle counts of BAC filtered water are up to 200 count/ml due to the influence of the sand filter backwashing remnant water. But at other times particles can be removed by BAC filter with 33.3% removed by the activated carbon layer and a further 8.5% removed by the sand bed (Table 2).

Table 2 Effects of the sand bed and carbon types on particles removal rate*

Type	Removal rate (%)	
	Activated carbon layer	Sand bed
Columned carbon	33.3	8.5
Cracked carbon	−101.2	45.3

* The sampling time for particle counts is a 1 h interval (considering the residence time of the carbon layer and the sand bed); the whole sampling period is 5 d; the detecting instrument is a portable particle counter; the results are expressed by average removal rate

2. Comparison of columned carbon and cracked carbon

There is a significant difference between cracked carbon and columned carbon in adsorptive capability, physicochemical properties and influence on biological safety. More bacteria are able to adhere to cracked carbon, which allows more bacteria to be protected and correspondingly higher effluent particle counts. Therefore it is necessary to investigate the difference in efficiency between columned carbon and cracked carbon. Table 2 illustrates these results. The cracked carbon layer allowed the effluent particle counts to increase by 101.2% compared to a 33.3% removal by the columned carbon layer. One possible reason is that minor carbon particles are able to be swept away by the effluent water, and a second reason is that dead microfilm will sometimes be swept from cracked carbon into the water. Although the following sand bed removed 45.3% of particle counts, the cracked carbon layer effluent particle counts are higher than that of influent in most situations.

Effect of BAC filter operating parameters

1. Effect of filtration rate

The effects of the filtration rate on particle removal by the activated carbon layer and the sand bed were investigated by varying the filtration rate over a short period of time. From the results presented in Table 3, an increase in the filtration rate resulted in a decrease in particle removal by the activated carbon layer but an improvement in particle removal by the sand bed. This can be explained by a high filtration rate causing a stronger scouring effect on carbon particles and causing small carbon particles and microorganisms to be washed into the water, whilst the sand bed is effective at removing small particles. To achieve lower BAC filter effluent particle counts, a sand bed under the carbon layer is necessary.

2. Effect of post-ozonation dosage

Since post-ozonation and BAC filter processes are invariably combined in advanced drinking water treatment, the influence of post-ozone dosage was also examined in this study. The author's previous study (Wu *et al.*, 2007) suggests that pre-ozonation will influence the PSD, turning coarser particles into smaller ones, leading to a negative effect on flocculation and sedimentation compared to better removal by the sand bed.

Table 4 gives the results of the effect of post-ozone dosage on particle removal by the BAC filter. Adding a low post-ozone dosage did not significantly affect the removal efficiency of particles by the carbon layer, but higher dosages are responsible for a notable variation. The particle removal rates were reduced to 30.7% and 27.8% when 1.5 mg/L and 2.0 mg/L post-ozone were used, respectively, compared to the 33.3% removal efficiency when no post-ozone was added. Further increases in post-ozone dosage (3.0 mg/L) resulted in a dramatic decrease in particle reduction (10.3%).

It was found that increases in post-ozone dosage resulted in a decrease in particle removal by the activated carbon layer, but this influence can be alleviated by improvements in particle removal by the sand bed, the function of which is the same as described in Table 3. As the post-ozone dosage increased from 2.0 mg/L to 3.0 mg/L, the removal rate by the carbon layer declined from 30.7% to only 10.3%, while the removal efficiency by the sand bed increased by 9.5% (from 16.5% to 26.0%). The differing effects of the carbon layer and the sand bed indicate that the particle counts removal rate should be considered when choosing post-ozone dosage or, alternatively, that the height of the sand bed should be increased to solve the problem.

CONCLUSION

Using particle counters for filtrate effluent monitoring is suggested as particle counting is more sensitive than traditional turbidity based monitoring.

Table 3 Effect of filtration rate on particle removal rate

Filtration rate (m/h)	Influent (count/ml)	Activated carbon layer effluent (count/ml)	Sand bed effluent (count/ml)	Removal by the activated carbon layer (%)	Removal by the sand bed (%)
4.42	71	43	40	38.9	6.9
6.19	85	46	42	31.3	9.5
8.85	67	57	52	33.3	8.5
10.60	74	52	47	29.7	10.4
13.30	80	57	51	28.7	10.8

Table 4 Effect of post-ozone dosage on particle removal rate

Post-ozone dosage (m/h)	Influent (count/ml)	Activated carbon layer effluent (count/ml)	Sand bed effluent (count/ml)	Removal by the activated carbon layer (%)	Removal by the sand bed (%)
0	85	57	52	33.3	8.5
1.0	78	53	47	32.5	10.3
1.5	63	44	38	30.7	13.2
2.0	70	51	43	27.8	16.5
2.5	65	53	42	19.2	21.3
3.0	80	72	53	10.3	26.0

It is necessary to allow about 1.5 h for backwash remnant water particle counts to decrease from a peak value 1296 count/ml to less than 50 count/ml, and therefore treatment or drainage of backwash remnant water is recommended.

In a standard filtration period, the BAC filter effluent particle counts usually stay constant at less than 50 count/ml over 5 d, except when affected by backwash remnant water from the sand filter, so it is also advisable to treat or drain this backwash.

Carbon characteristics affect the removal efficiency of particle counts. A columned carbon layer allowed a 33.3% removal of particle counts and the following sand bed removed a further 8.5%, whilst a cracked carbon layer caused effluent particle counts to increase by 101.2%, although the following sand bed removed 45.3% of particles. The effects of a cracked carbon filter on particle counts should be further investigated.

A variation in filtration rates and low post-ozone dosages (<2 mg/L) do not significantly affect the removal efficiency of either carbon layers or sand beds. However, further increases in post-ozone dosages (from 2.0 mg/L to 3.0 mg/L) result in a dramatic 17.5% decrease in the removal rate by the carbon layer, and a lesser improvement in removal (9.5%) by the sand bed. Thus it is necessary to consider the effect on particle count removal when varying post-ozone dosages.

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