Experimental study on non-woven filamentous fibre micro-filter with high filtration speed

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ABSTRACT

A laboratory study was undertaken to pursue the filter performance of a micro-filter module employing highly porous fibre media under a high filtration rate (>1,500 m/day), faster than that of any conventional filter process. The effects of filtration rate, head loss, raw water turbidity, and filter aid chemicals on filter performance were analysed. In spite of the extremely high filtration rate, the filter achieved an attractive efficiency, reducing the raw water turbidity by over 80%. As with other filter systems, the filter aid used (polyaluminium chloride (PAC)) greatly affected the performance of this particular fibre filter. Long-term repetitive runs were additionally carried out to confirm the reproducibility of the filter performance. Also, a comparison was carried out with other high-rate filter systems which are either being tested for use in experimental studies, or are already commercially available. This study reveals that the filter performance under a high filtration speed is still attractive especially as PAC is used. Due to the high porosity of the fibre, the filter had small head loss even though the filtration rate was high. These results ascertain that it is possible to operate the filters with high filtration rate achieving reliable treatment performance.

Key words | fibre, high speed, micro-filter, turbid water

INTRODUCTION

High turbidity in water bodies can decrease both the photosynthetic activity and concentrations of dissolved oxygen (Liboriussen & Jeppesen 2003), causing a weakened function of the water ecological system. Many studies have identified particles which can serve as transport carriers of diverse pollutants in water bodies (Malcolm and Kennedy, 1970; Yu & Kim 2013; Yu et al. 2013). Furthermore, high turbidity can significantly damage the aesthetic quality of a water environment, having an adverse impact on the utilization of the water (Gelda & Effer 2007; He et al. 2010). With the increasing demand for a safer water supply and the establishment of more stringent regulations for water environmental protection, the removal of turbid matter from raw water is of increasing concern.

Filtration is one of the methods for effectively separating particles from water, and it has been widely used to reduce the turbid matter in drinking water, wastewater and runoff. This method has employed a number of materials such as particle separation filters, including quartz sand, silica sand, anthracite coal, garnet, ceramsite, magnetite and fibre. However, the retention capacity of particulates within the pore spaces of the filter medium has posed a major problem for the use of granular filter media (Yu et al. 2013). In recent years, the development of fibre, a man-made material with excessively high porosity (>90%), has allowed its successful application into filtration processes for the tertiary treatment of wastewater, purification of drinking water and removal of suspended particles from water streams (Lee et al. 2008; Gao et al. 2012; Kim et al. 2013).

Generally, filtration is performed at a rate lower than 450 m/day (Yu et al. 2013). Currently, the filters employing a high rate are very expensive, complex, and have high power and maintenance requirements. These systems also require pre-treatments, which further increase the cost of operation and maintenance. Moreover, filtration at a high rate can lead to a rapid build-up of head loss, attributed to the rapid accumulation of particles in the filter, which decreases the treatment efficiency and the filter’s production rate.

To overcome these problems, the filter media with extremely high porosity is preferred, because they allow many more particles to be accommodated in the filter pore but...
without a great increase in head loss as well the significant impairment to treatment capacity. Although there have been a few systematic studies conducted to evaluate the particle removal capacity of fibre filters (Thakur & De 2012; Borsi et al. 2012), as yet few studies have focused on non-woven fibre filter with a high filtration rate of over 1,500 m/day. The objectives of this study were to test a compact filter system using highly porous fibre media, aimed at treating turbid water under operational conditions using a filtration rate from several to ten times higher than the conventional rapid sand systems, and to evaluate its filtration efficiency with respect to various operational parameters.

**MATERIALS AND METHODS**

**Filter system**

A laboratory-scale filter system consisting of filter modules, a feeding tank, and a wash water tank was built for this study (Figure 1(a) and 1(b)). The filter module was made of colourless transparent acrylic (height, 40 cm; inner diameter, 7 cm). Baffles (distribution plate) with small holes were installed at the top and bottom to uniformly distribute the water flow. The dimensions of the feeding tank and wash water tank were $0.7 \times 1.0 \times 1.0$ m (width $\times$ length $\times$ height, effective volume = 680 L) and $0.5 \times 1.0 \times 1.0$ m (effective volume = 300 L), respectively. Nylon fibres, (Shingang High Tech, Ltd, Korea) were tied to a 5 mm diameter polythene core rope, arranged in a linear non-woven bundle, and fixed to the upper baffle (Figure 1(c) and 1(d)). The polythene bundles had a nominal diameter of 3.5–4.5 cm, and a specific surface area of 1.0–1.6 m$^2$/m. The module was packed with fibre at a length of 27 cm except two experiments with 15 cm, a porosity of 90–95%, and a packing density of 112 g/L, depending on the experiment. The filter system was set up for downflow filtration and washing wherein the water from the tank (feeding or washing tank) was pumped to the module through a pipe with a diameter of 2.0 cm.

**Turbid water**

Raw water was obtained by mixing tap water with red clay (Figure 1(e)). The particles in raw water with sizes lower than 10 $\mu$m accounted for over 80% of the volume (Figure 1(e) and 1(f)). Also, the concentration of total suspended solids (TSS, mg/L) was proportional to the turbidity (nephelometric turbidity units, abbreviated to NTU), and the relationships between the two factors yielded $\text{TSS} = 3.0781 \text{ turbidity} + 0.20503$ ($R^2 = 0.9978, p < 0.01$, turbidity $< 80$ NTU) and $\text{TSS} = 1.8947 \text{ turbidity} + 94.035$ ($R^2 = 0.9900, p < 0.01$, turbidity $> 80$ NTU), respectively. The raw water was prepared ahead of filtration, and during filtration an agitator worked in the feeding tank to provide a homogenous inflow.

**Experimental design**

A series of experiments were conducted to assess the filtration capacity under different conditions, including varied levels of PAC doses, filtration rates, and turbidity levels in raw water. With the exception of the case of experiments examining the impact of filtration velocities on filter performance, all filtration experiments were performed at a relatively constant filtration velocity (around 1,500 m/day). Generally, every experiment was performed in three runs, with each run taking 90 min. During each experiment, the filtration rate, turbidity of the raw water and effluent, and head loss were checked every 10 min, and particle size distributions (PSD) of the raw water and effluent were investigated every 30 min. A scattered light turbidimeter (2100 Turbidimeter, Hach) was used to measure the turbidity. Particle count and PSD were obtained with a laser-based particle size analyser (PSS Accusizer™ 780).

Pulse washing with intermittent and fast draining steps was adopted to clean the fibres at the end of each run (Figure 1(g)). After 90 min of operation, the filters were cleaned by conducting 10 cycles of filter washing at a velocity of about 20,000 m/day, using tap water. Each cycle was constituted of two consecutive washes using 2 L of tap water, followed by draining. This resulted in a total wash volume of 20 L of water. The turbidity of the outflow from each washing cycle was measured to detect the amount of solids washed from the filter.

**RESULTS AND DISCUSSION**

**Filter efficiency with filter aid**

In this study, PAC was used as a filter aid to investigate its effects on filter performance. Five different PAC doses (0, 0.25, 0.5, 1.0 and 2.0 mg/L) were used for coagulation optimization experiments to determine the optimum dose for turbidity reduction at the average filtration speed of 1,468 m/day.

As shown in Figure 2(a), the effluent turbidity experienced an initial decrease from 16.7 to 12.8 NTU within
Figure 1 | Laboratory filter system (a) filter module; (b) filter system; (c) fibre and its arrangement in filter; (d) SEM micrograph of fibre; (e) red clay; (f) particles in the red clay; (g) cleaning of filter.)
Figure 2 | Effect of PAC dose on filter performance (a) turbidity in raw water and filtered water; (b) removal efficiency; (c) head loss; (d) and (e) particles in raw water and filtered water; (f–h) pathway of particle removal.
10 min, thereafter rapidly increased to 25.8 NTU, with an overall removal efficiency of 63.6% when no PAC was used. Due to the repelling forces which occurred because both the fibre and particles were negatively charged, the particles were primarily removed by mechanical straining as they passed through the fibre, wherein only the particles larger than the void space of fibre were trapped. Therefore, the presence of numerous small micro-particles in raw water resulted in an unfavourable removal efficiency of turbidity.

In contrast, filter aid chemical (PAC) resulted in a significant enhancement of the reduction in turbidity of raw water (Figure 2(b) and 2(c)). However, the effluent turbidity did not always decrease with an increase in PAC dose, and the overall removal efficiencies observed were 88.8%, 91.4%, 88.7% and 84.2 for PAC doses of 0.25 mg/L, 0.50 mg/L, 1.0 mg/L and 2.0 mg/L, respectively. This indicated the optimum dose of PAC to be about 0.50 mg/L, showing that excessive use of the coagulant lowered the filter efficiency, most likely because of the charge reversal of the particles (Figure 2(h)).

PAC is a cationic coagulant, and the charge of the particles in the raw water was changed from negative to neutral when an optimal dose of PAC was employed. During this process, the number of small particles (mainly <2.0 μm) were decreased while the amount of large particles (mainly >7.0 μm) were increased, indicating a potential improvement of filter performance because the large ones were trapped easily (Figure 2(d) and 2(e)). The particles with a neutralized charge had electrostatic attraction with the negatively charged fibre. In addition, no electrostatic repelling force occurred between the neutralized particles. Hence, the neutralized particles entering the filter could be removed by a series of mechanisms, including sedimentation, impaction, interception, adhesion between fibre and particles and adhesion between particles, which are described in Figure 2(f) and 2(g) (Metcalf et al. 2002; Li et al. 2009). Under these conditions, the removal efficiency was obviously elevated. When excessive doses of PAC were used, the neutralization process described above changed the effective charge of the particles from negative to positive. This made the particles more attracted to the supposedly negatively charged fibre, whereas the repelling forces between the particles still existed. Positively charged particles entering the filters could be removed by attraction to the negatively charged fibre, sedimentation, impaction and interception, but not by adhesion between particles (Figure 2(h)). In addition, the PAC dosage decreased the amount of small particles but evaluated the large particles (Figure 2(d) and 2(e)). Therefore, when excessive doses of PAC were employed, while having much better filter performance than that without PAC, the performance was poorer than that observed with the optimum PAC dose (Lee et al. 2008; Guerra 2013). It should be noted that the charge repulsion is less pronounced for the large particles, so there is a necessity to clarify the size of particles to which charge repulsion is effective. Also, the charge repulsion is influenced by the other factors, such as the amount of the charge of the particles, the distance between particles and the dissolved salts in the water, etc. (Gregory 2005; Lebovka 2014; Lin et al. 2008). However, based on the present available data, it is currently impossible to clarify the size of particles to which charge repulsion is effective. Thus, further work needs to be conducted to identify the effective particle size of charge repulsion.

In addition, the head loss increased with increasing PAC dose. After 90 min, the head loss was increased to 13.2, 14.0, 37.5 and 54.8 cm H₂O for a PAC dose of 0.25, 0.5, 1.0 and 2.0 mg/L, respectively, indicating that the PAC dose influenced the build-up of head loss across the filter. As an increase in PAC dose can increase the amount of TSS in the raw water due to the formation of aluminium hydroxide (Tchobanoglous et al. 2002), rapid accumulation of solids can occur in the filter, leading to clogging, head loss build-up, and subsequent increase in effluent turbidity during particle washout. Nonetheless, the head loss was still very small in comparison with that documented in the current literature in which head loss can be evaluated to 1.2–2.0 m (Droste 1996). This implies a great potential of this filter for high-rate filtration with very small head loss which has recently been the target for the filter systems that are currently being developed.

The following experiments attempted to investigate the relationship between the dose of filter aid and filter performance, by using a fixed PAC dosage (0.5 mg/L) with varying raw water turbidity, from 25 to 100 NTU. Filtration efficiency had a similar value around 90% for raw turbidity at 25–50 NTU, but with an increase to 75 or 100 NTU, efficiencies dropped to about 83 and 77%, respectively (Figure 3).

The optimal dose of PAC, 0.5 mg/L, was determined by use of raw water with a turbidity of 50 NTU. However, for raw water with a turbidity value of 25 NTU, the 0.5 mg/L dose of PAC exceeded the actual requirement. As the raw water turbidity increased to 75 or 100 NTU, the PAC dose used was lower than that needed. This test demonstrates that the fibre filter system can have a favourable performance when 0.5 mg/L PAC is applied, but only for raw water with a turbidity lower than 50 NTU (Figure 3). This indicates that as the raw water has turbidity less than that
corresponding to the optimal PAC dose, the filter performance may be not affected by the excessive PAC dose and can still achieve an attractive treatment performance.

Filter performance with different filtration rates

Four different filtration rates (around 1,000, 1,500, 2,000 and 2,500 m/day) were selected to investigate the effect on filter performance, with a constant PAC dose of 0.5 mg/L. As can be seen in Figure 4(a), the turbidity removal efficiencies with filter rate of 1,000, 1,500, 2,000 and 2,500 m/day were 93.8%, 91.7%, 83.0% and 79.8%, respectively, indicating that increasing filtration rate induced a decrease in the turbidity removal efficiency. This was observed because higher filtration rates can cause rapid accumulation of solids and shorter retention time, as well as reduce the chance for contact between the particles and the fibre (Guerra et al. 2014). In addition, the higher filtration velocities contributed to greater shearing action within the filter pores, which enhanced the transport of free and deposited particles through the filter bed. A similar result was also found in the filters employing fibre media (Gao et al. 2012). Nevertheless, in the study by Lee et al. (2008), it was observed that higher filtration velocities (1,440–2,500 m/day) provided lower effluent turbidity, but decreased the filtration time before breakthrough.

The filtration rate also affected the build-up of head loss across the fibre filter (Figure 4(b)). When the rates were less than 1,500 m/day, the head loss varied between 0 and 10 cm, and was not dependent on the filter rates ($p < 0.05$). While increasing filtration rates to 2,000 and 2,500 m/d, head loss of 25 and 43 cm were recorded, respectively, after filters were operated for 60 min. The increase in head loss with increasing filtration rates have also been reported in various studies such as Gao et al. (2012), Lee et al. (2010), Yu et al. (2015) and Guerra (2015). It has been identified that as the headloss is increased to a specific value the filter operation has to be suspended due to the constrained particle capture efficiency and the lower head loss increase is favourable (Boller & Kavanaugh 1995; Droste 1996). Thus, compared to these studies, the application of the filter at a filtration rate of 2,500 m/day can still be acceptable as minimal head loss is allowed for operation.

A comparison with other studies towards filtration rate and filter efficiency

Figure 5(a) illustrates a comparison with other high-rate filter systems, which are either being tested for use in...
experimental studies or are already commercially available. It can be seen that the fibre micro-filter system tested in this study showed attractive removal efficiencies in the range of all filtration rates tested. When the filtration velocity was similar to that used in other research, this system possibly provided a better filtration performance. Even though the filtration rate was evaluated up to 2,500 m/day, the filter system still achieved around 80% reduction of influent turbidity. In addition, it should be noted that the treated raw water was different among these studies, thus, the evaluation is only comparable on the basis of high filtration rates.

**Filter cleaning**

After fibre filter cleaning, the particle recovery was calculated based on the recovered mass and captured mass, and the results are presented in Figure 5(b). It can be seen that the highest rate was achieved from the first run (81% on average), and it was found that the particle recovery was affected by the number of times that the filter was washed. The average particle recoveries were 81%, 72% and 65% for the first, second and third wash, respectively. This result suggests that increasing the number of washes may have induced a lower recovery. Some pathways were formed during the first wash, and these pathways were not completely blocked by the trapped particles as the second run was operated. For the following wash, detachment of the particles due to the hydraulic shear force was reduced, contributing to a lower recovery. Meanwhile, more pathways were created during the second wash, therefore the particle recovery decreased as the number of washes increased. These findings are a reasonable explanation for our results; however, this argument is not when compared to the existing research or supported by the scientific evidence available, because the studies related to filters using fibre and operated with high filtration rate are relatively few. Thus, further study towards this argument should be conducted.

However, this recovery efficiency is lower than those reported in other studies (Tanaka et al. 1995; Lee et al. 2008). One possible reason is that the constituents in red clay (e.g. Fe and Mn) are more difficult to be removed from the filter. This argument needs further identification. However, the poor filter cleaning is a great challenge which has to be solved in this type of high-rate filter system. In addition, most of the solids were recovered during the first 2 L of washing with a particle recovery of more than 50%. This was caused by the very high washing velocity.
that was used during filter cleaning. The remaining portion of the solids was recovered during the following washes and was observed to decrease after every wash. Moreover, it was found that a negligible amount of solids were recovered after 10 L of water have been used. Therefore, for the cleaning method used in this study, the recommended amount of wash water can be 10 L.

**Continuous repetitive filter operation**

In order to investigate the reproducibility of the effectiveness after filter washing, a continuous filter operation including nine runs was performed in a period of 15 hours (Figure 5(c)). During the first run, the effluent turbidity rapidly increased from 2 to 5 NTU within 90 min of operation. However, during the succeeding runs after the first cleaning, the effluent turbidity became higher when compared to the first run with a range of 5–10 NTU regardless of the number of times the filter was used and cleaned. It was found that this decrease in the turbidity removal can be attributed to the formation of larger voids within the fibre interstices and around the fibre media during high velocity washing. These larger voids were formed by the pathways occupied both by the wash water and the detached particles as they were washed out from the filter. As a result, a great number of particles during the second and third runs were allowed to pass through these larger voids without being captured by the fibre (Amirtharajah 1985).

Furthermore, the head loss was slightly smaller after washing, but this did not vary depending on the number of times the filter was washed (p < 0.05). These results (Figure 5(c)) demonstrate that this type of micro-filter system, employing fibre, could provide a reliable treatment performance despite the extremely high filtration rate used.

**CONCLUSIONS**

The experimental results showed that fibre filters have a great potential for a more economical and compact treatment of highly turbid water at high filtration rates in terms of the compactness and applicability. Due to the high porosity of the fibre, the filter had the potential for significantly reducing turbidity with minimal head loss depending on the operating condition. Also, these results demonstrate that this type of micro-filter system, employing fibre, could provide a reliable treatment performance despite the extremely high filtration rate used. Still, this study only provides a preliminary test on the performance of the filter and further studies should be done in order to improve and optimize the filter design and performance.

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**REFERENCES**


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