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Performance evaluation for the improved PCF filter to apply to the water treatment plant (WTP)

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ABSTRACT

The ultimate object of this study is the replacement of the precipitator plus the rapid sand filter (RSF) used in the conventional water treatment plant (WTP) with single filtration equipment. The pore controllable fiber (PCF) filter which was one of the depth filters using the pump pressure was studied from 2008 to apply to the portable water production. In this study, the PCF was improved by thickening the filter media depth more than 2 times and adjusting the backwash conditions. The feed used in the main study was supplied from the Hoedong catchment of which hydraulic retention time was about 14 d. So, its average turbidity was very low as much as about 5.76 NTU and its particle size was very fine as much as about 8 µm by weight average since it was naturally precipitated for 14 d. The purpose of this study is to discuss problems and to find solutions through performance tests of the improved PCF (let 150 mm PCF) for the WTP process. According to pilot test results, the filter showed more than 99% removal of the turbidity and so the turbidity of the filtrate was as low as 0.066 NTU after increasing the filter media depth to 150 mm even though the raw water's turbidity was as low as 8.97 NTU. Moreover, a similar pilot which was tested on the raw water of the Nacdong river for 2 months from June of 2020 showed that the filtrate turbidity was 0.065 NTU and 99.7% of the turbidity was removed from 24.9 NTU of the feed. These results hint that the PCF could be in a fair way to replace the conventional WTP in the near future. According to the performance data for nine equipment including the PCF and seven of UF membranes evaluated by BWQI that was the public organization of Busan city, Korea from to June 24 to September 17 of 2018, the PCF having 100 mm filter media depth (let 100 mm PCF) was lower than the UF by 0.3% in the turbidity removal but was higher than the UF by 11%, 22.7%, and 20% in dissolved organic carbon, Mn, and trihalomethane formation potential removal, respectively. On the other hand, results of SDI_{15} measurements that were the indirect indicator for colloidal showed 3.3 for the PCF and 2.3 for 6 of the UF by average which were satisfying the RO pre-treatment standard, 5.0 as the colloidal level. The colloidal removal of the 100 mm PCF was slightly worse than membranes through the comparison of the turbidity removal and the SDI_{15} between the 100 mm PCF and membrane. It was found that these problems were coming from the initial filtrate of the PCF. So, it was concluded that the circulation of the initial filtrate of the PCF to the feed is needed to obtain higher colloidal removal from the PCF, and it is expected that this work makes the colloidal removal of the PCF close to the membrane.

Keywords: Drinking water treatment; Potable water production; Fiber filter; PCF filter; Turbidity; Water treatment plant

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1. Introduction

Industrialization being in progress throughout the world is intensifying the gravitation of the population to cities and is generating new small and middle-size cities. These phenomena make a lot of people require enhancing the quality and increasing the volume of the drinking water and so, conventional water treatment plant (WTPs) are faced improving the process and enlarging facilities or new WTPs are required strongly. On the other hand, the construction cost of new piping might be higher than that of new WTP in the case of small and middle-size cities which are usually far from big WTPs. The problem is the land cost to construct the new WTP which is the major part of the total construction cost. If the precipitator which was occupying the biggest area of the WTP process could be excluded, a lot of lands would be saved to construct the new WTP. This concept can be adapted also to old WTPs which need improvement and enlargement.

Researches to make the WTP compact were tried from 2008 by "International Cooperative Research" that was supported by Korean Environmental Protection Agency (EPA) national projects [1]. The main idea was to use only single equipment like a high-performance filter instead of using the precipitator and the rapid sand filter (RSF). Liew et al. used two stages coagulation and filtration process by connecting two pore controllable fiber (PCFs) serially. They used the river water as the raw water in Malaysia and removed the turbidity from 200 NTU (maximum 3,000 NTU) to 0.1 NTU by daily average without the precipitator and the RSF. The test was successfully done for 43 continuous days without stopping the operation. The filter media depth of the PCF used at that time was 60 mm and its capacity was 75 m^3/d. By the successful application of the two-stage PCF process on the WTP to remove the turbidity, it was tested for the pre-treatment of the RO membrane which was used as the main equipment to reuse the sewage effluent and to remove salts from the seawater as follow-up studies [3–6]. The most important indicator of the RO pre-treatment is the SDI_{15} which represents the colloidal level of the pre-treated water indirectly. The SDI_{15} of the filtrate of the two-stage PCF used at the RO pre-treatment research was 2.0~4.0 that was very excellent as the depth filter. In this study, the PCF filter was improved by thickening the filter media depth by about 2 times than the PCF used at the two-stage filtration and increasing the backwash air as much to get adequate backwash action. Various water quality like SDI_{15}, turbidity, dissolved organic carbon (DOC), Mn, and trihalomethane formation potential (THMFP) were analyzed for the feed and filtrates. From these results, we tried to find problems of the 150 mm PCF and to find solutions to close the PCF filtrate to the UF membrane filtrate.

2. Testing methods and materials

2.1. PCF pilot and process flow diagram

Fig. 1 is the photograph of the PCF pilot set at Hoedong catchment located at Busan city of Korea which was the major equipment used in this study and Fig. 2 is the process flow diagram (PFD) of the PCF pilot. Besides this pilot, a part of the data of the similar PCF pilot was included in this study that was set at Korea Water Cluster located at Daegu city of Korea and its capacity was 100 m^3/d.

2.2. Components of the PCF pilot and their role

The role of parts of the PCF pilot was as follows:

- Feed pump: suppling the feed from the raw water tank to the filter through the in-line mixer.
- PACL feeder: dosing the inorganic coagulant (alum or PACL) into the feed.
- In-line mixer: rapid mixing the coagulant with the feed to form the floc.
- Filter media:
  - □ non-woven fine polypropylene (PP) fiber of 43 μm diameter.
  - □ build-up 12~20 million fibers in the pilot after bundling and its depth was 100~150 mm, and the

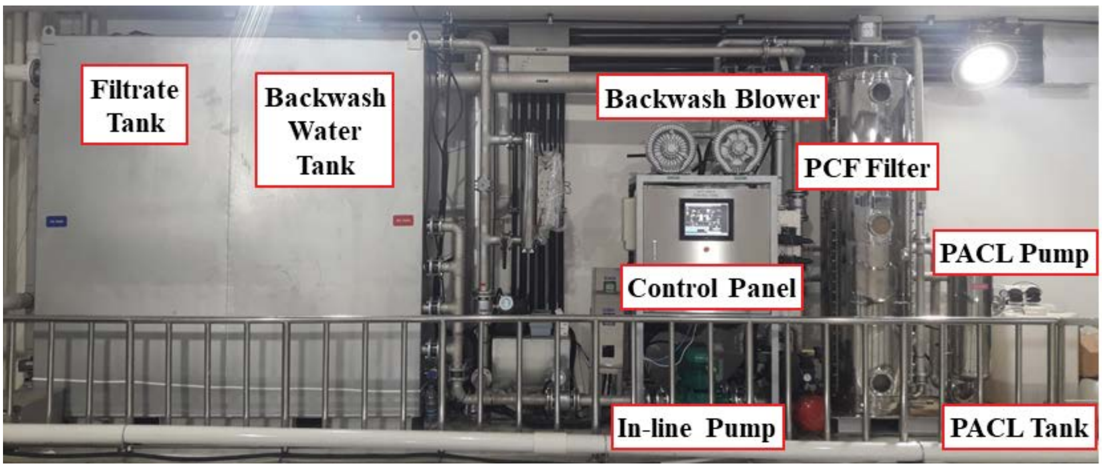

Fig. 1. Photograph of the PCF pilot set at Hoedong catchment.

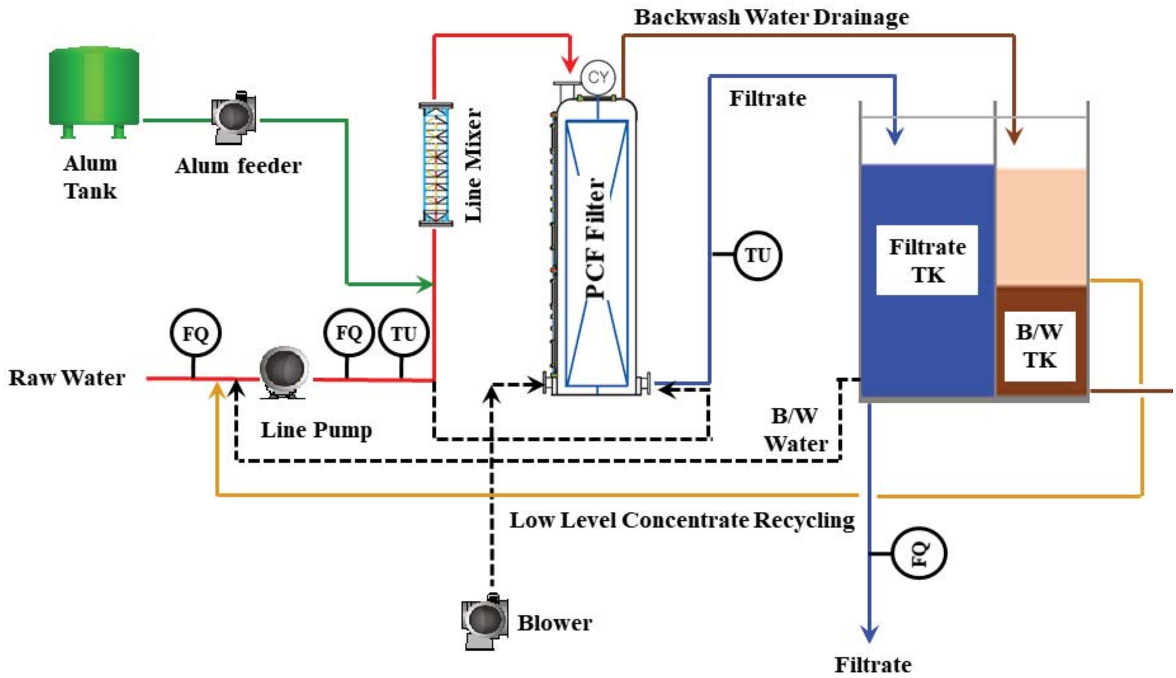

Fig. 2. PFD of the PCF pilot.

porosity of the filter media was about 81.5% at the filtration mode.

- □ used the opening among fibers as the pore and filtered by the depth filtration mechanism.
- PCF filter: a large number of the fiber bundle wrapped around the perforated inner-strainer and the floc were filtered by the opening among fibers.
- Backwash pump: suppling a part of the filtrate from the filtrate tank to the filter at the backwash mode.
- Backwash blower: suppling the air of 0.3 bar at the bottom of the filter at the backwash mode.
- Filtrate tank: store a part of the filtrate and use the backwash water.
- Backwash water tank: keeping the backwash water and clarify solids during the filtration mode. The slurry was discharged on the outside and the clarified water was recovered as the feed.
- On-line turbid meter: measuring and recording the turbidity of the feed before coagulation and the filtrate by the real-time.
- On-line flow meter: measuring and recording the flow rate of the feed and the filtrate by the real-time.
- On-line pressure gauge: measuring and recording the feeding pressure by the real-time.

2.3. Operation principle of the PCF filter

One cycle of the operation consisted of the filtration mode and the backwash mode which were repeated automatically by the PLC. The cycle time was normally 50–60 min when the turbidity of the feed was lower than 20 NTU and the one cycle consisted of 50 min for filtering the feed, 5 min for recovering the clarified water, and 5 min for backwash. The followings are a summary of the filtration and the backwash operation.

2.3.1. Filtration mode

Step 1: Reduce openings among fibers to 1.9~2.6 times by pressurizing fiber bundles on the inner perforated strainer surface up to 100–150 mm depth by lifting bundles to upper-side which was 200–230 mm depth when released.

Step 2: Feeding the coagulated feed to the filter in the direction of out-in by the pump (pumping up to set pressure). 50 min was for filtering the feed and 5 min was for the clarified water recovery.

2.3.2. Backwash mode

Step 1: Enlarging openings among fibers by releasing the pressurized fiber media on the inner perforated strainer surface.

Step 2: The backwash water was supplied into the strainer with the same filtration flow rate and the backwash air supplied simultaneously on the bottom of the filter by the blower.

Fig. 3 shows the schematics of the filtration and the backwash described above.

2.4. Specifications of the fiber filter media and operation conditions

2.4.1. Specifications of the fiber filter media

Table 1 shows specifications of the fiber filter media of the PCF pilot which was tested at Hoedong catchment. The material of the fiber was very hydrophobic PP with 43 μm diameter. 13–20 million of this single fiber were bundled to form two kinds of media (100 mm depth and 150 mm depth) to use as the filter media.

2.4.2. Operation conditions

Table 2 summarizes operation conditions. As shown, a cycle time was 60 min normally consisting of 50 min for the feed filtration, 5 min for recovering the clarifying water, and 5 min for the backwash. The coagulant used was 10% alum or 10% PACL and the dose concentration was automatically controlled by the optimizing logic. The dose concentration was normally 24 ppm (2.4 ppm on the basis of 100% alum or PACL) when the raw water turbidity was under 10 NTU.

2.4.3. Capacity of the filtrate production and the filtration linear velocity

The standard production capacity of the pilot was about 400 m^3/d and the filtration linear velocity was 4.92–5.36 m/h when the feed turbidity was under 10 NTU.

2.5. Characteristics of the raw water

The raw water fed from the Hoedong catchment (area 2.17 km^2, reserving capacity: 18.5 million m^3) that is located

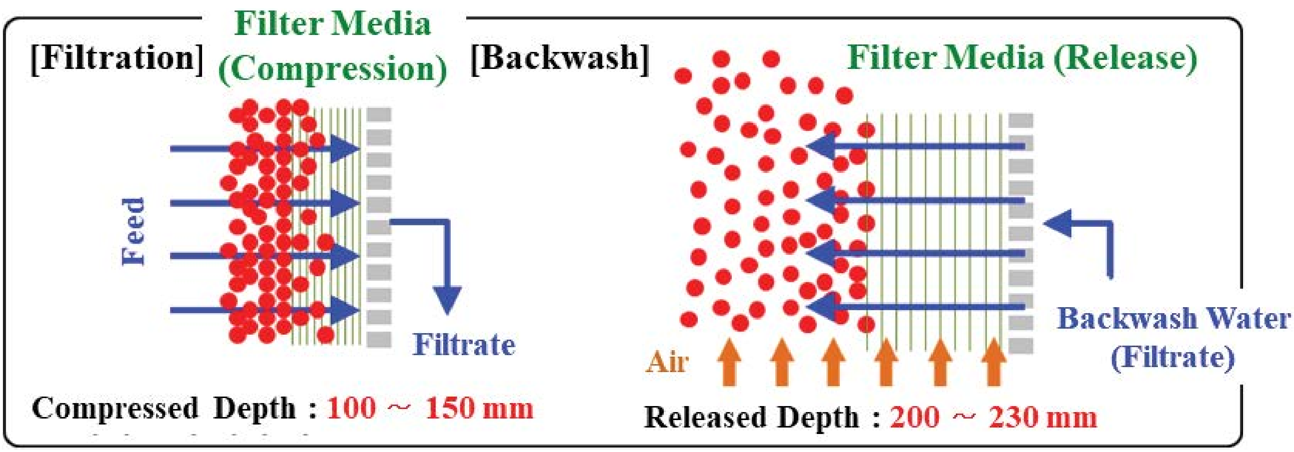

Fig. 3. Schematics of the filtration and the backwash principle of the PCF filter.

Table 1
Specifications of the fiber filter media

Items \ Pilots	100 mm media depth	150 mm media depth
Height (mm)	2,248	2,248
Strainer OD (mm)	240	180
Filter media layer OD (mm)	440	480
Cross sectional area of filter media layer (m^2)	0.107	0.156
Area of filter media outside layer (m^2)	3.107	3.390
Total number of fibers (ea)	13,423,520	19,543,040
Porosity of media (%)	81.8	81.8
Pore size (μm)	76	81
(1). Materials: polypropylene (PP)	(2). Diameter of single fiber: 43 μm	

Table 2
Basic operation conditions at the filtration and at the backwash of the pilot

Modes	Pressure	Duration time		
Filtration	0.7 bar	About 55 min	Rapid mixing (s)	1
			Raw water filtration (min)	50
			Recover clarified water (min)	5
Backwash	Atmosphere	About 5 min	Stand-by (s)	5
			Air + Backwash water (s)	210
			Backwash water (s)	30

upstream of Suyoung river and its hydraulic retention time (HRT) was 14 d. The feed turbidity was not over 30 NTU usually even though the turbidity of Suyoung river was over the hundreds during the flooding season since the most of big particles were already precipitated by the long HRT of the Hoedong catchment.

2.6. Analytical tools used

2.6.1. Turbidity

Two types of turbid meter were used, the table type, and the on-line type. The table type turbid meter was model 2100AN of HACH Co., (USA) and the on-line type was model CUBE-TU 1000 of Daol Co., (Korea) The maximum measuring limit was 400 NTU and 1–100 NTU range was usually used in this study.

2.6.2. Particle size distribution analyzer

Model 780 AccuSizer of Particle Sizing System Co. (Santa Barbara, California, USA) was used to analyze the particle size distribution (PSD).

2.6.3. Other water quality analysis (SDI_{15}, DOC, Mn, THMFP, and Chl-a)

SDI15: SDI BOOSTER PUMP KIT of GE Water Technologies Co. (Minnetonka, MN, USA), DOC: Sievers M9 of Sievers Co. (Boulder, CO, USA), Mn & THMFP: 7900 ICP-MS & GC/ECD 7890B of Agilent Co. (Santa Clara, CA, USA), Chl-a: Algae analyser of BBE Co. (Auckland, New Zealand).

2.7. Chemicals used

10% alum and 10% PACL made by Hongwon Industry (Korea) were used to flocculate colloidal matters including in the feed by the in-line mixer.

3. Results and discussion

3.1. Characteristics of the feed

3.1.1. Turbidity

Fig. 4 shows variations of the feed turbidity sampled and measured by Busan Water Quality Institute (BWQI) for 9 months (July, 2018~March, 2019). Sampling was done 17 times randomly and the turbidity was measured by the table-type turbid meter. According to the results, the average turbidity of the feed was about as much as 5.86 NTU (2.12~15.8 NTU) since big particles were already precipitated by passing through the Hoedong catchment as mentioned before.

3.1.2. Particle size distribution

Fig. 5 shows the PSD of the feed water sampled on January 17, 2019 and analyzed by BWQI. The average particle size based on the number and on the weight was calculated as follow:

$$\overline{L_n} = \sum_{i=1}^{\infty} x_i L_i = \frac{\sum_{i=1}^{\infty} N_i L_i}{\sum_{i=1}^{\infty} N_i} \quad (1)$$

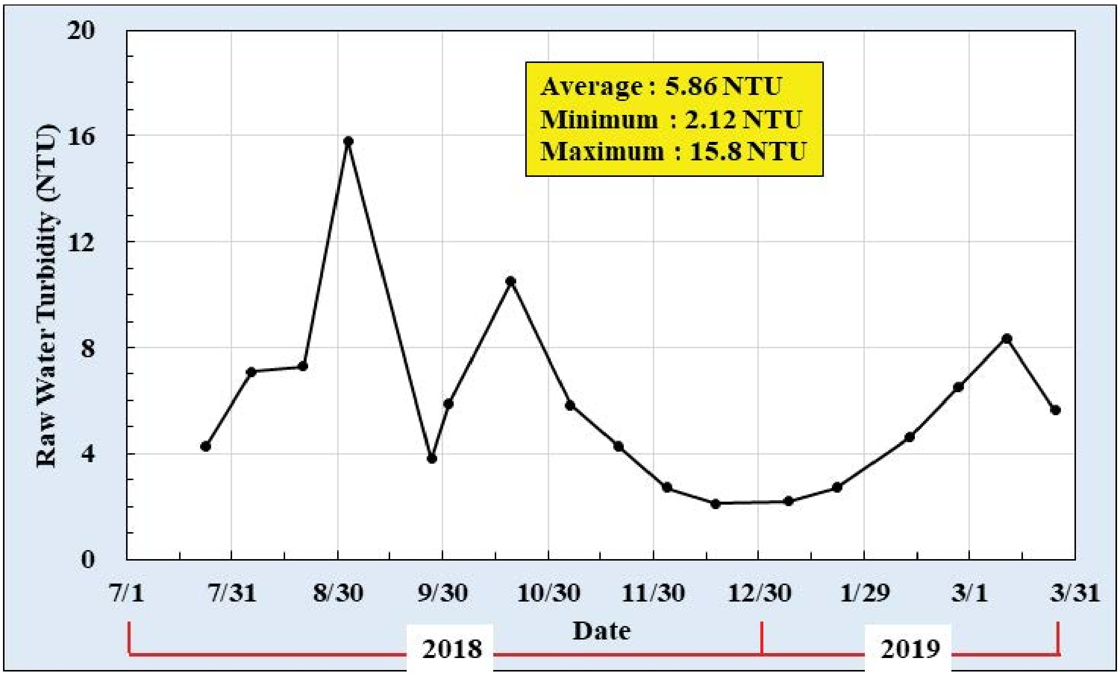

Fig. 4. Turbidity variations of the feed water (measured by BWQI).

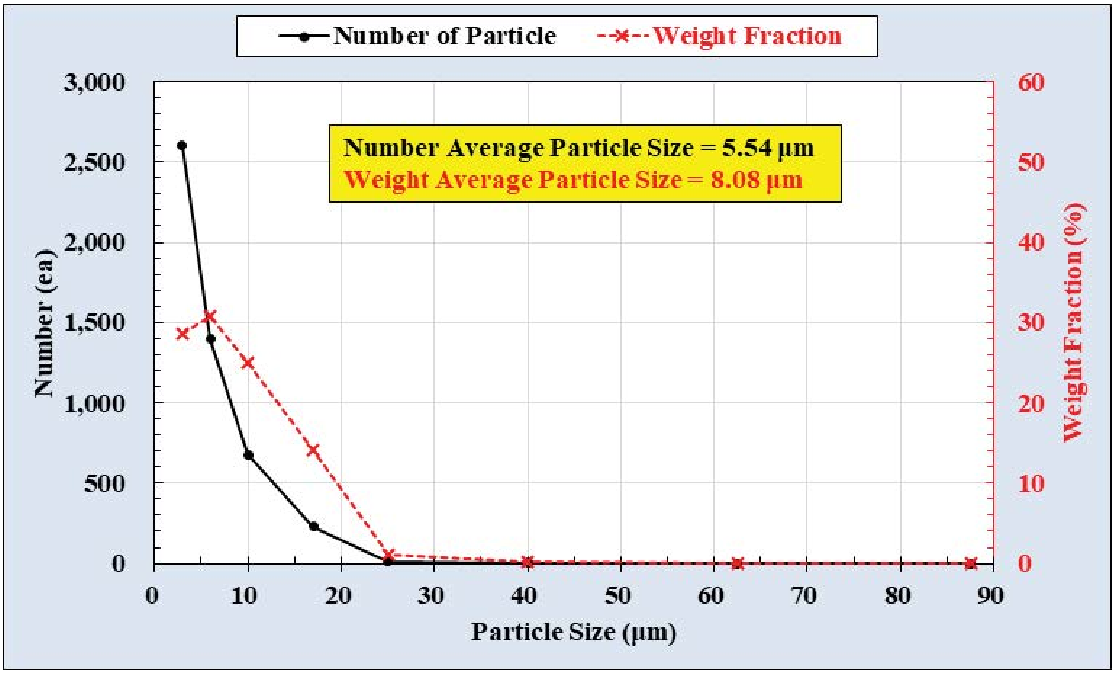

Fig. 5. PSD of the feed sampled on January 17, 2019 (measured by BWQI).

$$\overline{L_w} = \sum_{i=1}^{\infty} w_i L_i = \frac{\sum_{i=1}^{\infty} N_i L_i^2}{\sum_{i=1}^{\infty} N_i L_i} \tag{2}$$

where $\overline{L_n}$ is the average particle size based on the number, $\overline{L_w}$ is the average particle size based on the weight, L_i is the size of the *i*th particle, and N_i is the number of the *i*th particle.

The number average particle size calculated by Eq. (1) was 5.546 µm and the weight average particle size was 8.08 µm calculated by Eq. (2). Particles over 25 µm were almost disappeared at the feed as passing through Hoedong catchment by the precipitation and so particles under 10 µm were 95% by the number (85% by the weight) as shown in Fig. 5. It is known that particles under 10 µm cannot be precipitated well under normal conditions. Therefore, these fine particles may be removed by the precipitation or the filtration after the flocculation using coagulants or membranes having smaller pores than the micro-filter (MF) directly. It is expected some difficulties if the precipitator was used to remove these particles since the amount of seeds was not enough to form the floc in a short time in this kind of water especially.

3.1.3. Other important water quality

Figs. 6 and 7 are concentration variations of DOC, Mn, THMFP, and Chl-a of the feed sampled randomly and measured by BWQI for 10 months from July of 2018 to March of 2019. According to these results, the DOC was not changed much as 2.985 mg/L by average, but the Mn (0.114 mg/L by average), the THMFP (67 µg/L by average), and the Chl-a (8.949 µg/L by average) were rapidly fluctuated according to sampling date.

3.2. Variations of the feed flow rate and the filtration pressure of the PCF pilot

Fig. 8 shows variations of the feed flow rate and the filtration pressure of the 150 mm PCF pilot for two filtration cycles that were recorded every 5 min by on-line sensors for 2 h from 6:23 p.m. to 8:03 p.m. of May 7, 2020. The cycle time was 50 min at this test. The filtration pressure raised up to 1.1 bar linearly from 0.8 bar at initial during the filtration since the filtration resistance was increased as pores were blocked by colloidal captured at the media during the filtration. The feed flow was also reduced by about 13% of the initial flow rate during the filtration.

3.3. Performance evaluation of the PCF pilot by BWQI

BWQI sampled randomly 17 times the 100 mm PCF feed and filtrate for 9 months from July of 2018 to May of 2019, and the turbidity, the DOC, Mn, THMFP, and Chl-a were analyzed. PSDs of the feed and filtrates sampled according to the filtration time July 24, 2018 were also analyzed. In the case of the Chl-a, its concentration in filtrates was too low and so there were no data for the Chl-a of filtrates.

3.3.1. Turbidity removal

Fig. 9 shows the turbidity and its removal measured by the table-type turbid meter. The average turbidity

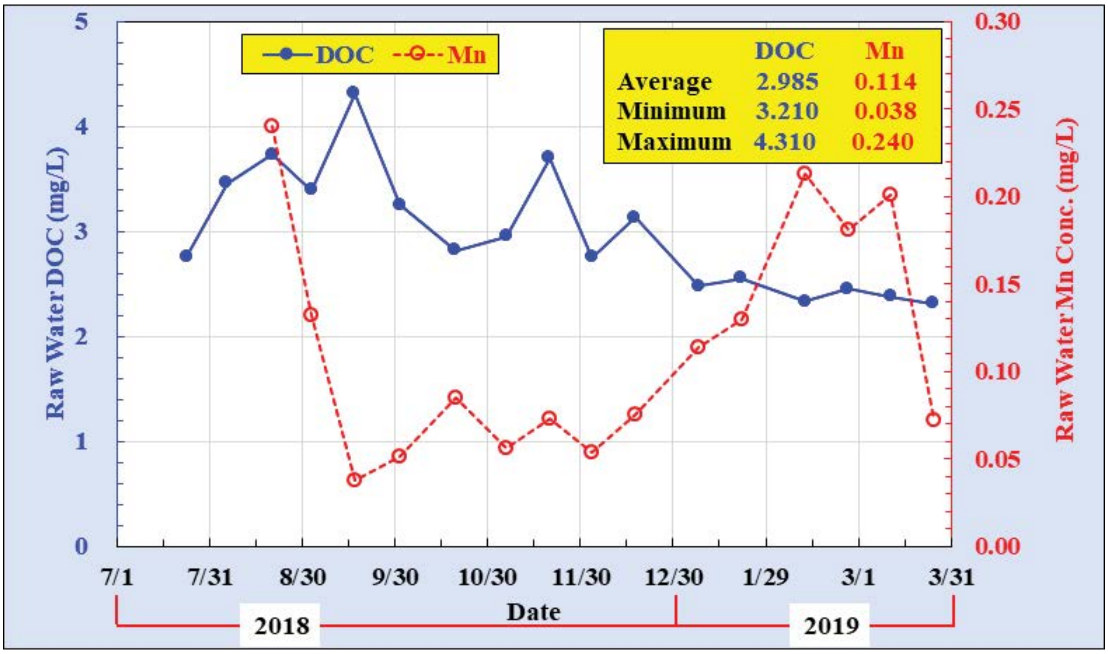

Fig. 6. Variations of the DOC and the Mn of the feed (measured by BWQI).

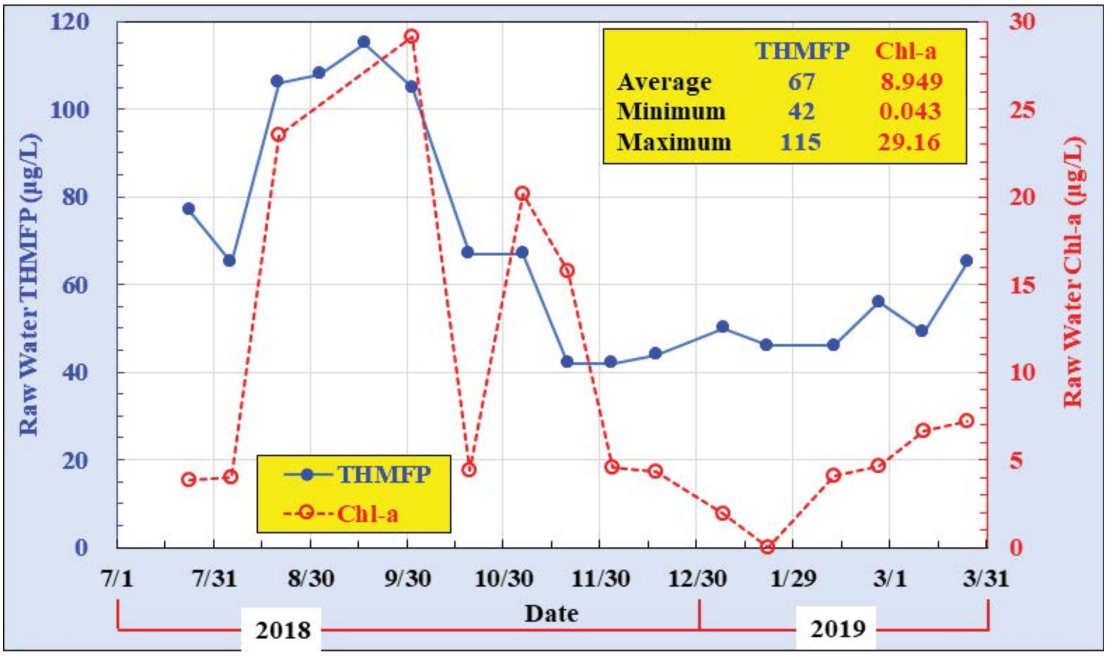

Fig. 7. Variations of the THMFP and the Chl-a of the feed (measured by BWQI).

and its removal of filtrates were 0.093 NTU and 97.8%, respectively. The turbidity removal of the 100 mm PCF was much higher than the normal sand filter (90%–95%) in the consideration of the low turbid feed as much as 5.86 NTU with very fine particles under 10 μm.

3.3.2. Particle removal

Fig. 10 shows the PSD of the feed and filtrates of the 100 mm PCF and Fig. 11 shows variations of the particle removal according to the filtration duration time at about 8:00 a.m. of July 24, 2018. As mentioned before, the size of the most of particles in the feed was lower than 25 μm and the trend of the particle removal classified by its size was similar to each other according to filtration time. But the removal at the initial (0 min) was worst and the removal at the final (60 min) was next and the best was at 30 min after starting the filtration. This result consists of the turbidity removal according to the filtration time as shown in Fig. 12. Reasons, why removals were bad

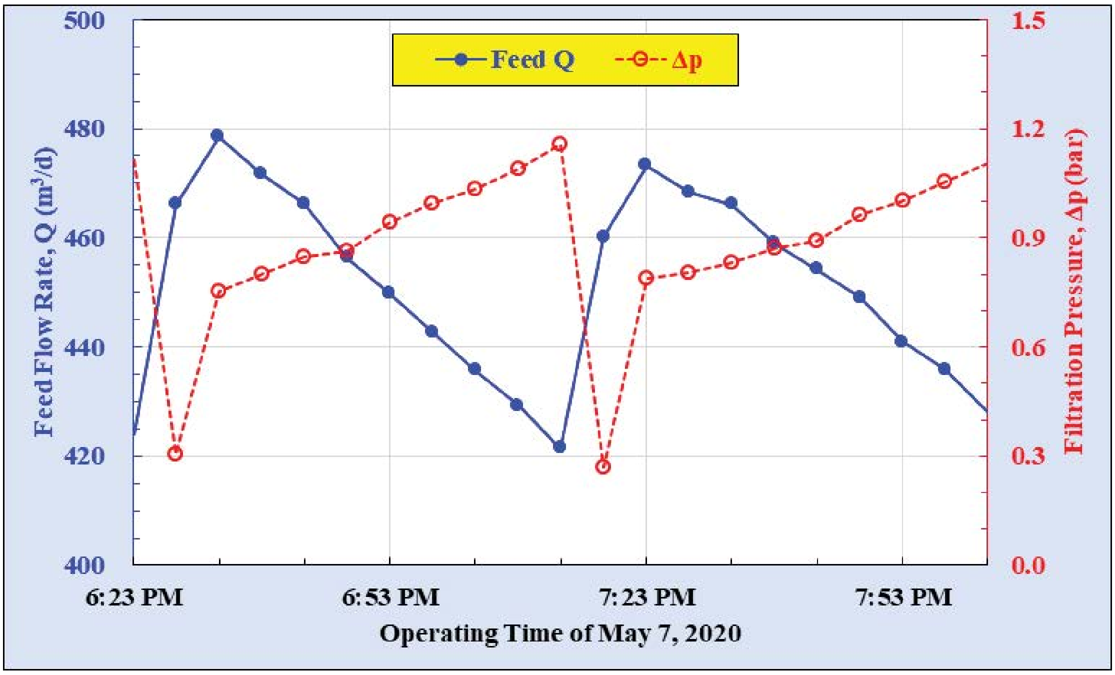

Fig. 8. Variations of the feed Q and the ΔP according to the operation time.

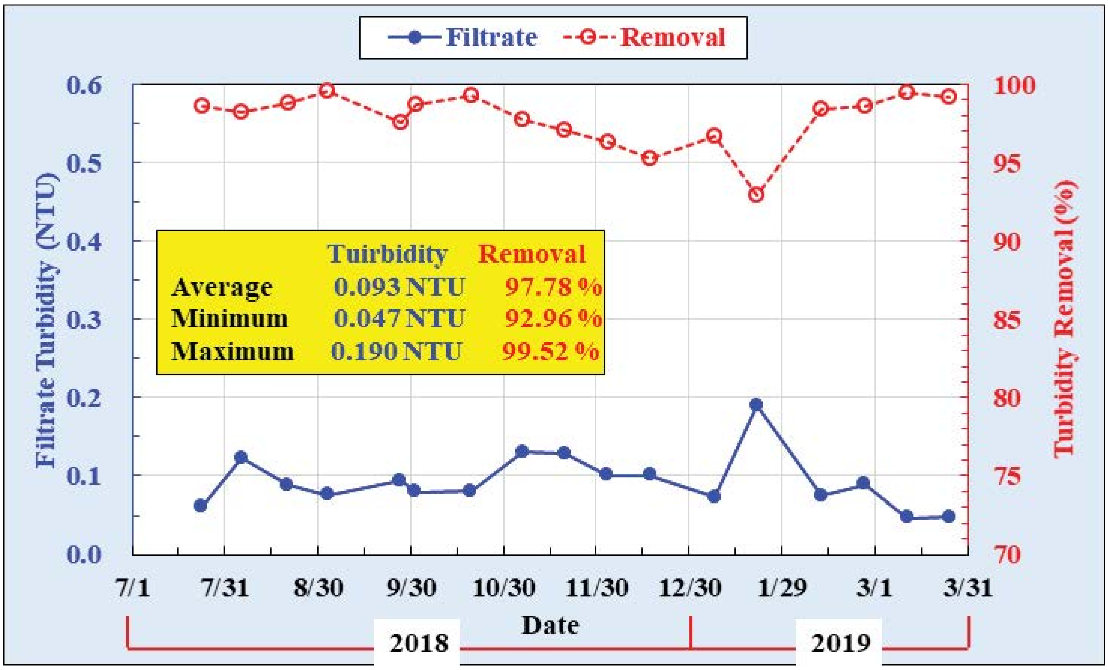

Fig. 9. Variations of turbidity and its removal for the 100 mm PCF (measured by BWQI).

at the initial filtration are that some particles remained at the inside of the media after the backwash was discharged to the filtrate and the removal efficiency was going down since there were no cakes deposited at the inside of the media and so the cake filtration could not have occurred after the backwash. Effects of the cake filtration were increased up to 30 min and so removals were increased. On the other hand, removals at the final after starting 60 min filtration were lower than at 30 min filtration. Moreover, very big particle (about 25 μm) existed in the filtrate at 60 min. This phenomenon was considered that a part of the compressed cake at the inside of the media was pushed to the filtrate by the increased filtration pressure at the final, namely migration effect. In conclusion, the process control to get the stable filtrates should be improved by circulating the initial filtrate to

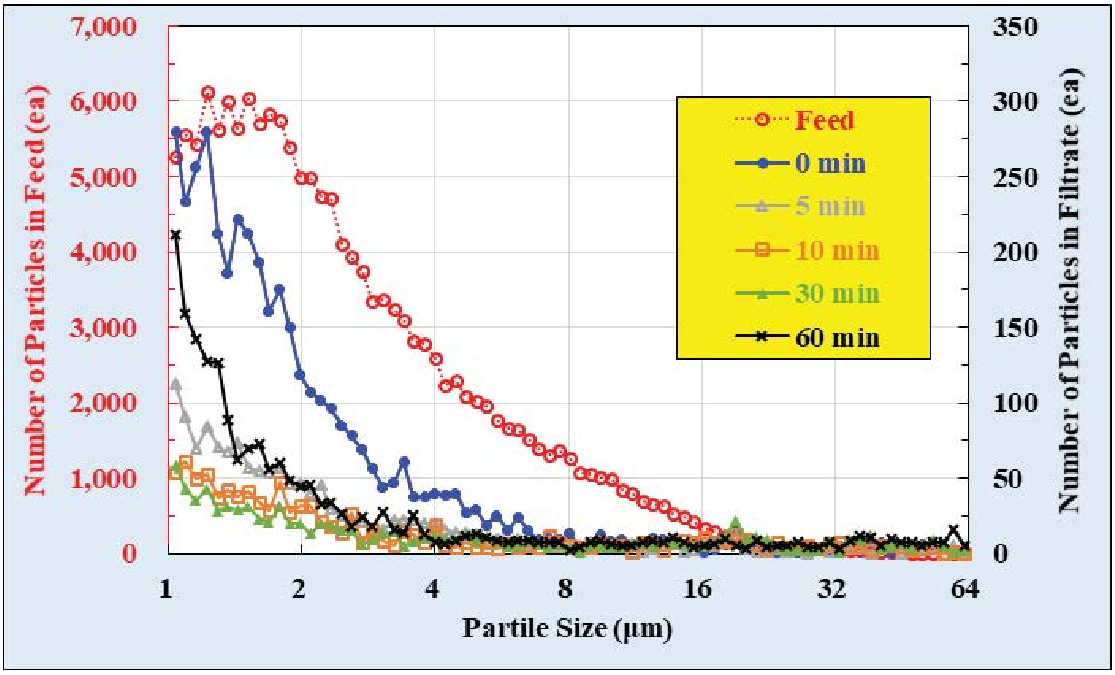

Fig. 10. PSD of the feed and filtrates according to the filtration duration time (measured by BWQI at July 24, 2018).

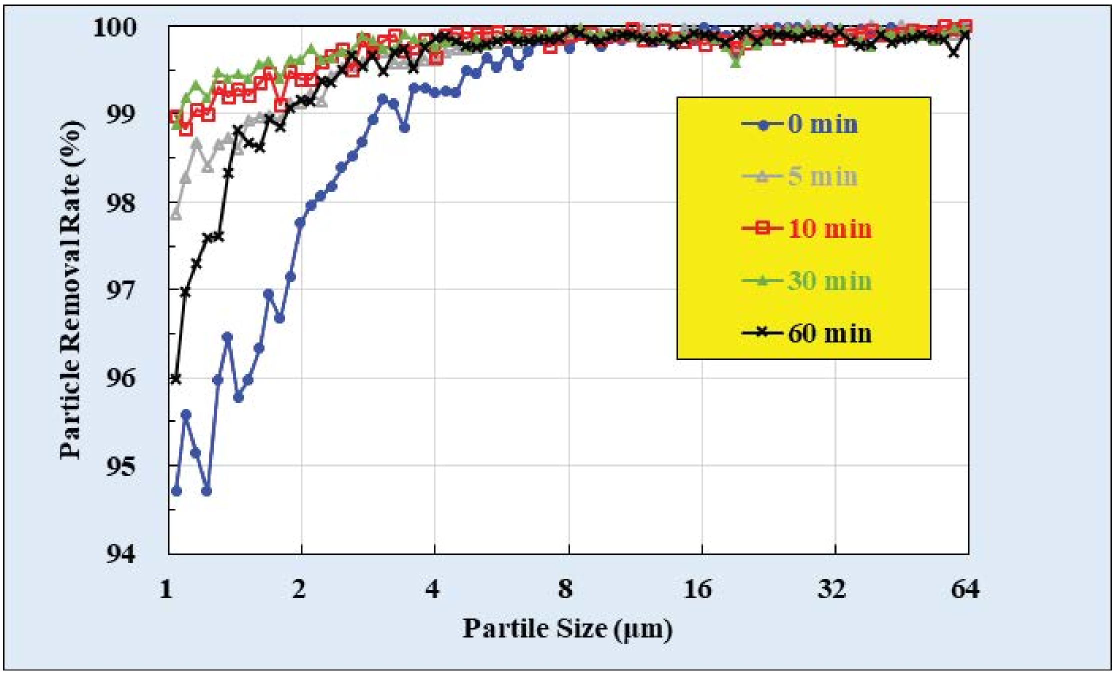

Fig. 11. Variations of the particle number removal according to the particle size and the filtration duration time (measured by BWQI at July 24, 2018).

the feed and stopping the filtration by the on-line turbid meter signal.

3.3.3. Removal rates of other important water quality

Figs. 13–15 show results of the removal of soluble components, the DOC, the Mn, and the THMFP according to test date and removals were calculated on the basis of the feed (Figs. 6 and 7). As mentioned before, the result of the Chl-a removal was not shown since its concentration of the filtrate was almost 0. The average removal of the DOC was 36.7%, the Mn 52.5%, and the THMFP 53.1% that were much lower than the average removal of the turbidity which was more than 97% since the PCF or the UF membrane was to

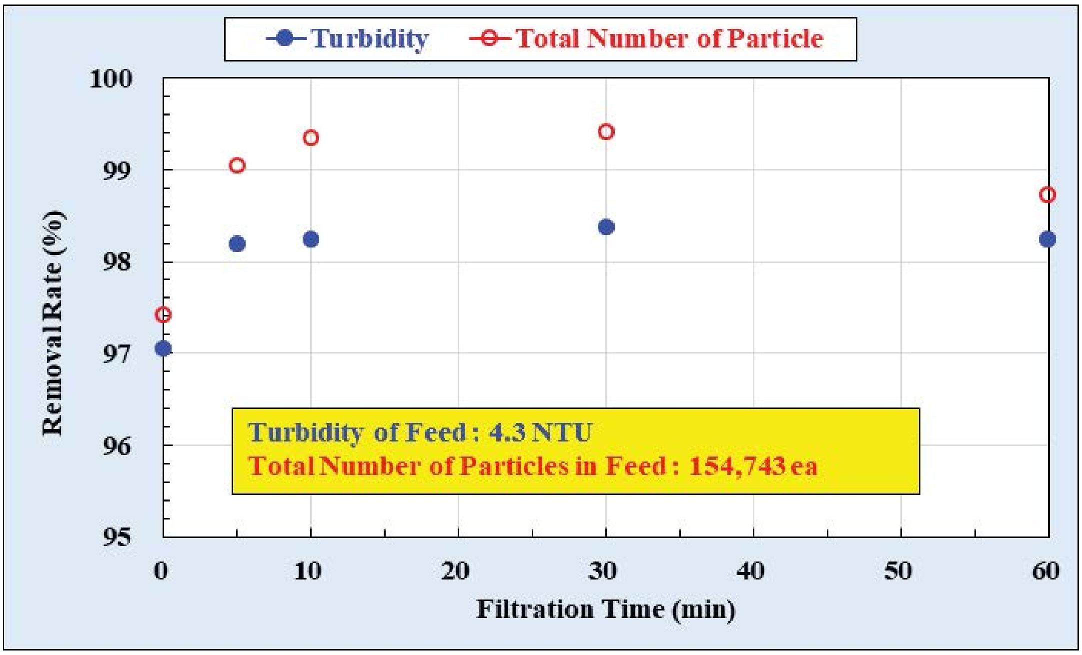

Fig. 12. Variation of the removal of the turbidity and the total number of the particle according to the filtration duration time (measured by BWQI at July 24, 2018).

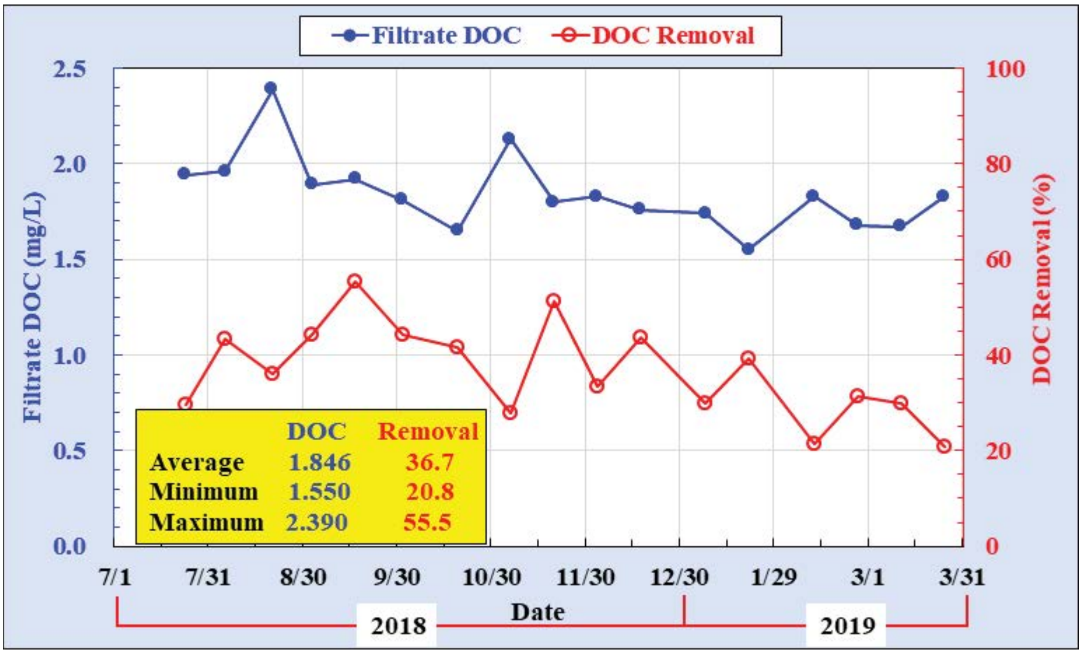

Fig. 13. Variations of the DOC of the filtrate and its removal (measured by BWQI).

remove colloidal. So, removals for these soluble components were so low even though coagulants were dosed.

3.3.4. Comparison of the PCF filtrate with the UF membrane filtrate

Tables 4–8 show the results of the SDI_{15}, the turbidity, the DOC, the Mn, and the THMFP for nine treatment equipment (DAF, 100 mm PCF, and 7 of UF) from 2018 to 2019, and Table 3 is the summary of results comparing the PCF filtrate with UF membrane filtrate. The feed was coagulated by inorganic coagulants and was sampled 4 or 5 times with filtrates at the same time for all equipment. According to the results, the removal of the PCF was much better than that of the DAF in all components. Especially the treated water of the DAF was not enough to measure the SDI_{15} since its value was over 6.0. The SDI_{15} is a very important index to evaluate the quality of the RO

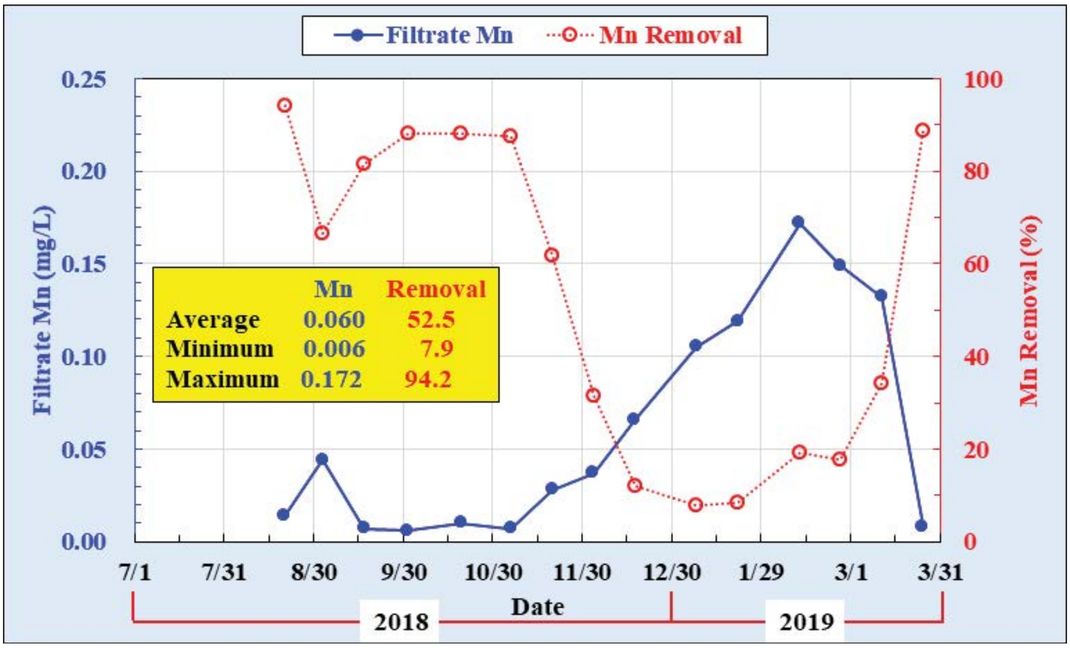

Fig. 14. Variations of the Mn of the filtrate and its removal (measured by BWQI).

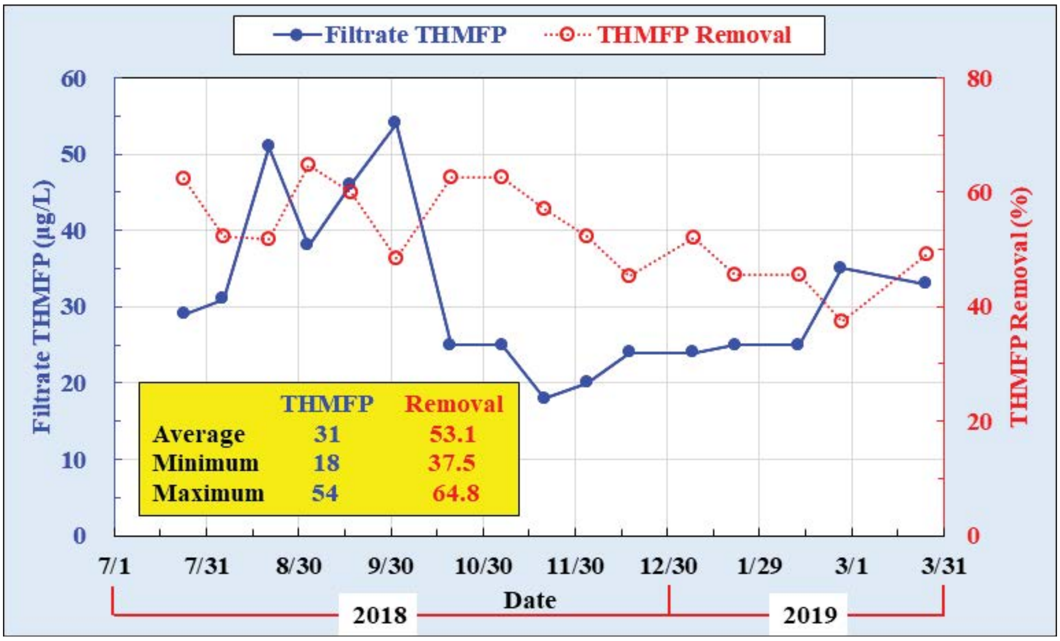

Fig. 15. Variations of the THMFP of the filtrate and its removal (measured by BWQI).

pre-treatment water and is the indirect indicator to evaluate the colloidal level. Table 4 is the result of comparing the SDI_{15} of the 100 mm PCF with various UF's. The SDI_{15} of the 100 mm PCF filtrate was 3.0–3.5 (3.3 by average) and the average SDI_{15} of UF filtrates showed 1.6–2.5 according to the UF manufacturer (2.3 by overall average). So, the SDI_{15} of the 100 mm PCF filtrate was 1.0 higher than that of the UF filtrate by average although it was sufficiently satisfying the criterion of the SDI_{15} as the RO pre-treatment water, 5.0. Moreover, the turbidity of the 100 mm PCF filtrate was 0.018 NTU higher than the UF by average (0.3% lower in removal). It means that the performance of the 100 mm PCF to remove the colloidal was slightly lower than the UF membrane and so the 100 mm PCF should be improved to close to the colloidal removal level of the UF membrane. On the other hand, it was evaluated that removals of the 100 mm PCF were 10%–22.2% higher than the UF membranes in comparison of the DOC, the Mn, and the THMFP according to Tables 6–8. The reasons why the PCF showed higher removal than the UF for a very small amount of soluble components is considered that the filter media of the PCF was polypropylene which is a very hydrophobic material and the filter media depth was about 100 times thicker than the UF membrane. So, the PCF could form the cake layer of the colloidal at the inside of the media during the filtration and the hydrophobic material and the cake deposited could adsorb some of the soluble components. Of course, most of the adsorbed components were discharged to the outside with the cake at the backwash mode.

3.4. Operation results of the PCF pilot by real-time on-line sensors

The PCF pilot was operated continuously and the turbidity of the feed and the filtrate were measured by the on-line turbid meter for 16 d from May 8 to 23 of 2020. At that time, the filter media depth was changed from 100 to 150 mm but other conditions were maintained without change. The average feed turbidity was 8.118 NTU (maximum 16 NTU) which was still under 10 NTU as before. Fig. 16 shows variations of the feed flow rate and the filtration pressure and Fig. 17 shows the turbidity of

Table 4
Comparison of the SDI_{15} of 100 mm PCF filtrates with UF filtrates

Date	PCF Filtrate	UF Filtrate						
		B	*C*	*D*	*E*	*F*	*G*	Average
18/08/06	3.0	1.9	1.8	2.0	1.7	–	1.1	1.7
18/08/21	3.4	3.0	2.5	1.3	0.8	–	2.3	2.0
18/09/17	3.5	2.9	3.4	3.1	–	3.0	3.7	3.2
18/10/20	3.1	2.8	2.1	2.0	1.6	2.1	2.3	2.2
19/01/22	3.4	3.0	2.1	2.2	2.1	2.5	1.8	2.3
Average	3.3	2.7	2.4	2.1	1.6	2.5	2.2	2.3

Table 3
Summary of the filtrate quality of the PCF and UF's by average

Items	SDI_{15}			Turbidity (NTU)					
	PCF	UF	Δ = PCF–UF	PCF	UF	Δ = PCF–UF			
Feed				7.66					
Filtrate	3.3	2.3	+1.0	0.088	0.070	+0.018			
Removal (%)				98.8	99.1	–0.3			
Items	DOC (mg/L)			Mn (mg/L)			THMFP (μg/L)		
	PCF	UF	Δ = PCF–UF	PCF	UF	Δ = PCF–UF	PCF	UF	Δ = PCF–UF
Feed	3.35			0.137			94.2		
Filtrate	2.02	2.39	–0.37	0.022	0.053	–0.031	39.0	57.8	–18.8
Removal (%)	39.7	28.7	+11.0	84.2	61.5	+22.7	58.6	38.6	+20.0

Table 5
Comparison of the turbidity (NTU) of 100 mm PCF filtrates with others

Date	Feed	DAF treated	PCF filtrate				
18/07/24	4.30	1.900	0.061				
18/08/06	7.10	–	0.123				
18/08/21	7.30	0.240	0.088				
18/09/03	15.80	0.730	0.076				
18/09/17	3.80	0.184	0.094				
Average	7.66	0.764	0.088				
Removal (%)		90.0	98.8				
Date	UF filtrate							
	A	*B*	*C*	*D*	*E*	*F*	*G*	Average
18/07/24	0.054	0.050	0.052	–	0.050	0.066	0.054	0.054
18/08/06	–	0.086	0.083	0.094	0.078	0.068	0.077	0.081
18/08/21	0.146	0.052	0.061	0.061	0.057	–	0.057	0.072
18/09/03	0.086	0.064	0.055	0.064	0.050	–	0.048	0.061
18/09/17	0.175	0.063	0.069	0.070	0.049	0.051	0.051	0.075
Average	0.115	0.063	0.064	0.072	0.057	0.062	0.057	0.070
Removal (%)	98.5	99.2	99.2	99.1	99.3	99.2	99.3	99.1

Table 6
Comparison of the DOC (mg/L) of 100 mm PCF filtrates with others

Date	Feed	DAF Treated	PCF Filtrate				
18/07/24	2.76	2.03	1.94				
18/08/06	3.46	–	1.96				
18/08/21	3.73	2.28	2.39				
18/09/03	3.39	1.80	1.89				
18/09/17	3.41	2.10	1.92				
Average	3.35	2.053	2.020				
Removal (%)		38.7	39.7				
Date	UF filtrate							
	A	*B*	*C*	*D*	*E*	*F*	*G*	Average
18/07/24	1.67	1.73	1.66	–	1.63	1.70	1.66	1.675
18/08/06	–	3.30	2.98	3.29	3.00	2.23	3.13	2.988
18/08/21	3.20	2.26	2.97	2.96	2.16	–	2.36	2.652
18/09/03	–	3.00	1.88	2.79	1.76	–	1.76	2.238
18/09/17	2.85	3.13	1.96	2.77	1.98	1.89	2.00	2.369
Average	2.573	2.684	2.290	2.953	2.106	1.940	2.182	2.390
Removal (%)	23.2	19.9	31.6	11.9	37.1	42.1	34.9	28.7

Table 7
Comparison of the Mn (mg/L) of 100 mm PCF filtrates with others

Date	Feed	DAF treated	PCF filtrate					
18/07/24	0.139	0.116	–					
18/08/21	0.240	0.006	0.014					
18/09/03	0.132	0.076	0.044					
18/09/17	0.038	0.004	0.007					
Average	0.137	0.051	0.022					
Removal (%)		63.2	84.2					
Date	UF filtrate							
	A	*B*	*C*	*D*	*E*	*F*	*G*	Average
18/07/24	0.100	0.126	0.137	–	0.114	0.110	0.127	0.119
18/08/21	–	0.004	–	–	0.006	–	0.007	0.006
18/09/03	0.035	0.045	0.077	0.053	0.077	–	0.081	0.061
18/09/17	0.003	–	0.004	0.003	0.008	0.004	0.010	0.005
Average	0.046	0.058	0.073	0.028	0.051	0.057	0.056	0.053
Removal (%)	66.5	57.4	47.1	79.6	62.7	58.5	59.0	61.5

Table 8
Comparison of the THMFP (μg/L) of 100 mm PCF filtrates with others

Date	Feed	DAF Treated	PCF Filtrate	UF filtrate							
				A	*B*	*C*	*D*	*E*	*F*	*G*	Average
18/07/24	77	40	29	30	27	25	–	28	21	28	26.5
18/08/06	65	–	31	–	60	60	59	54	24	52	51.5
18/08/21	106	46	51	99	48	93	106	49	–	47	73.7
18/09/03	108	37	38	92	88	35	89	36	–	35	62.5
18/09/17	115	51	46	112	92	54	98	51	47	52	72.3
Average	94.2	43.5	39.0	83.3	63.0	53.4	88.0	43.6	30.7	42.8	57.8
Removal (%)		53.8	58.6	11.6	33.1	43.3	6.6	53.7	67.4	54.6	38.6

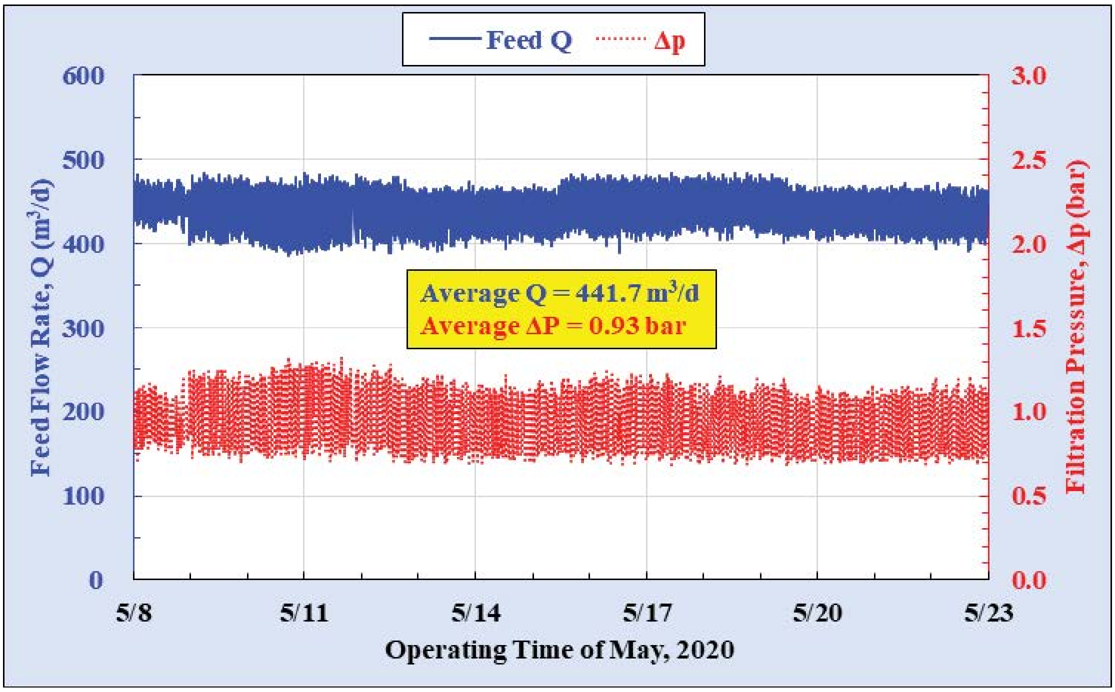

Fig. 16. Variations of the feed flow rate and the pressure difference of the PCF according to the operation time in May 2020.

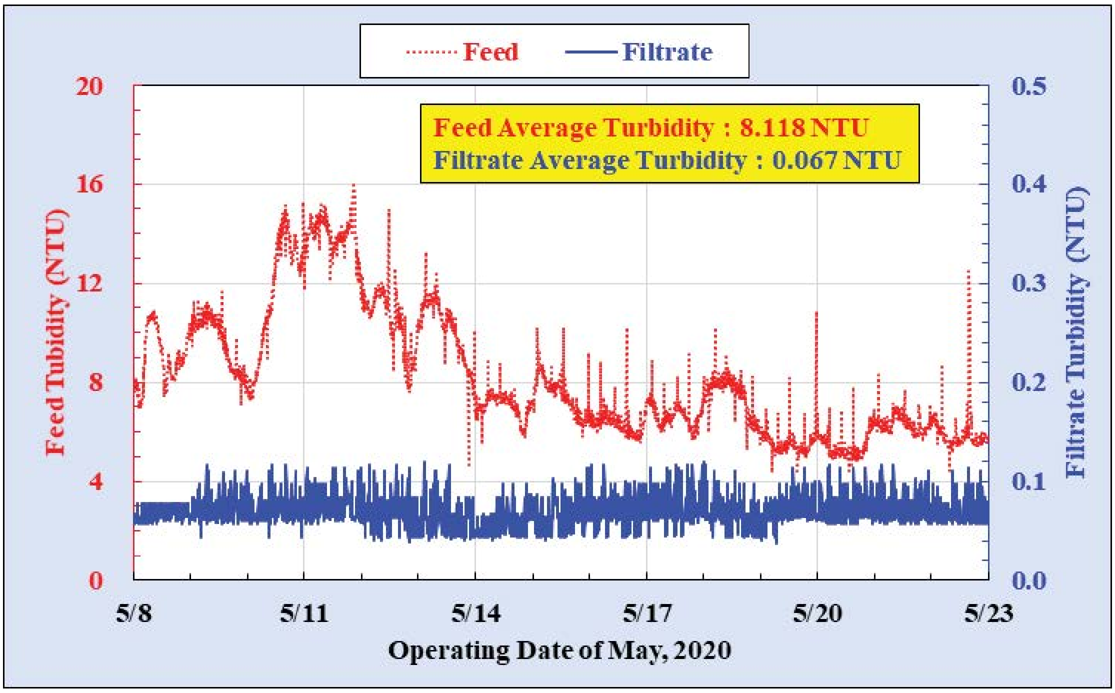

Fig. 17. Turbidity variations of the feed and the filtrate for 16 d in May 2020.

the feed and the filtrate measured by the on-line turbid meter. Operating conditions were 50 min of the filtration cycle, 441.7 m^3/d of the feed flow rate by average, and 0.93 bar of the filtration pressure by average. The average turbidity of the filtrate was 0.067 NTU and the turbidity removal was 99.2% (Fig. 17). It means that the performance of the PCF filter to remove the turbidity was much excellent than any other depth filters.

3.5. Comparison of the filtration performance according to the media depth

Figs. 18 and 19 show the filtration performance of the 100 mm PCF operated on December 3, 2018 and Figs. 20 and 21 show the filtration performance of the 150 mm PCF operated on May 8, 2020. Results are summarized in Table 9. As shown in Table 9, the average filtration

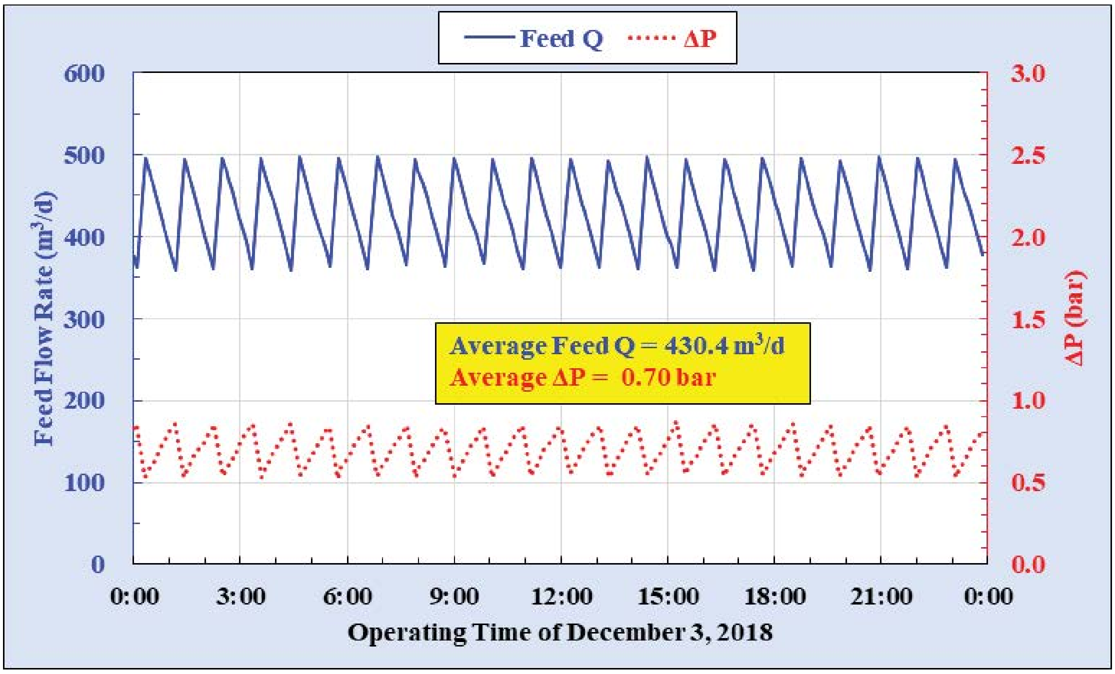

Fig. 18. Feed Q and ΔP variations vs. operation time (media depth: 100 mm).

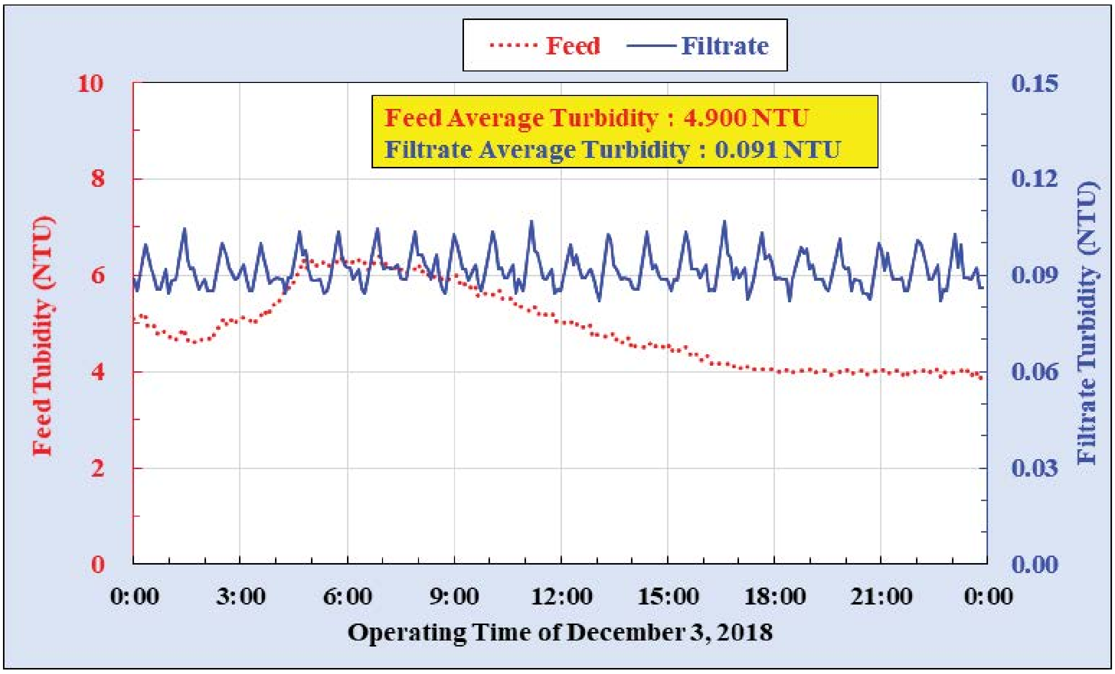

Fig. 19. Turbidity variations according to operation time (media depth: 100 mm).

pressure was raised up 0.94 bar from 0.7 bar as the media depth was increased 150 from 100 mm, but the average filtrate turbidity was fallen down to 0.066 from 0.091 NTU and its removal was increased to 99.3% from 98.1% even though the average feed turbidity of 150 mm PCF was 1.8 times higher than 100 mm PCF's. Therefore, the increase of the media depth was very positive on the point of turbidity removal. But there were still spike peaks in the filtrate turbidity at every initial time of the filtration. As mentioned before, this phenomenon is one of the essential problems of the depth filter, and so the initial filtrate should be circulated to the feed.

3.6. Filtration performance of the 150 mm PCF for higher turbid feed

The feed used for the pilot test performed at Hoedong Catchment contained very small particles of 5.546 µm

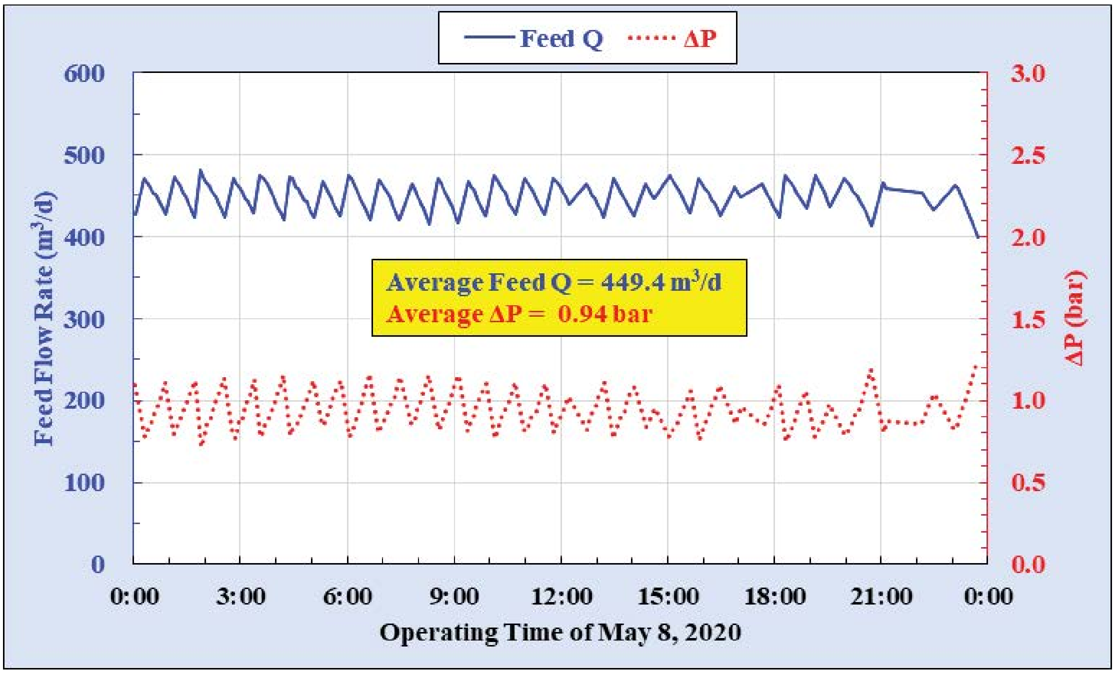

Fig. 20. Feed Q and ΔP vs. operation time (media depth: 150 mm).

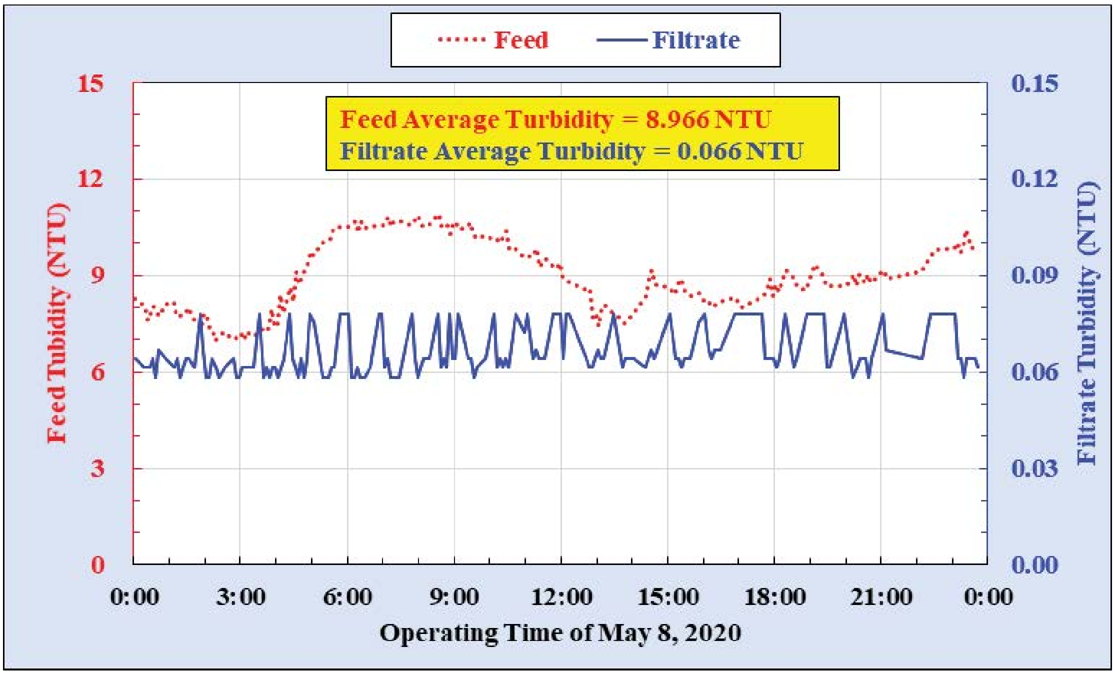

Fig. 21. Turbidity variations according to operation time (media depth: 150 mm).

by the number average (weight average: 8.08 μm) and its average turbidity was as low as 5.7 NTU. This kind of very clean raw water is not common as the feed of the WTP having some scale. So, a new 150 mm PCF pilot of 100 m^3/d which was similar to the Hoedong pilot was set at the Korea Water Cluster located at Daegu city of Korea. The raw water was supplied from the Nacdong river directly and its minor components like DOC, Mn, and THMFP, etc., were expected similar to Hoedong except for the particle size and its turbidity which were bigger and higher than Hoedong. The pilot was operated for 2 months from July of 2020 to September of 2020. The measurement was done by the table-type turbid meter and 29 filtration cycles were selected randomly. Samples to measure the turbidity were the feed and filtrates of 10 min intervals per cycle of 60 min. Fig. 22 shows the turbidity of the feed

Table 9
PCF performance comparison according to the filter media depth

Media depth (mm)	Operation date	Average feed flow rate		Average turbidity			Average ΔP (bar)
		Flow rate (m^3/d)	Linear velocity (m/hr)	Feed (NTU)	Filtrate (NTU)	Removal (%)	
100	18-12-03	430.4	5.77	4.900	0.091	98.1	0.70
150	20-05-07	449.4	5.52	8.966	0.066	99.3	0.94

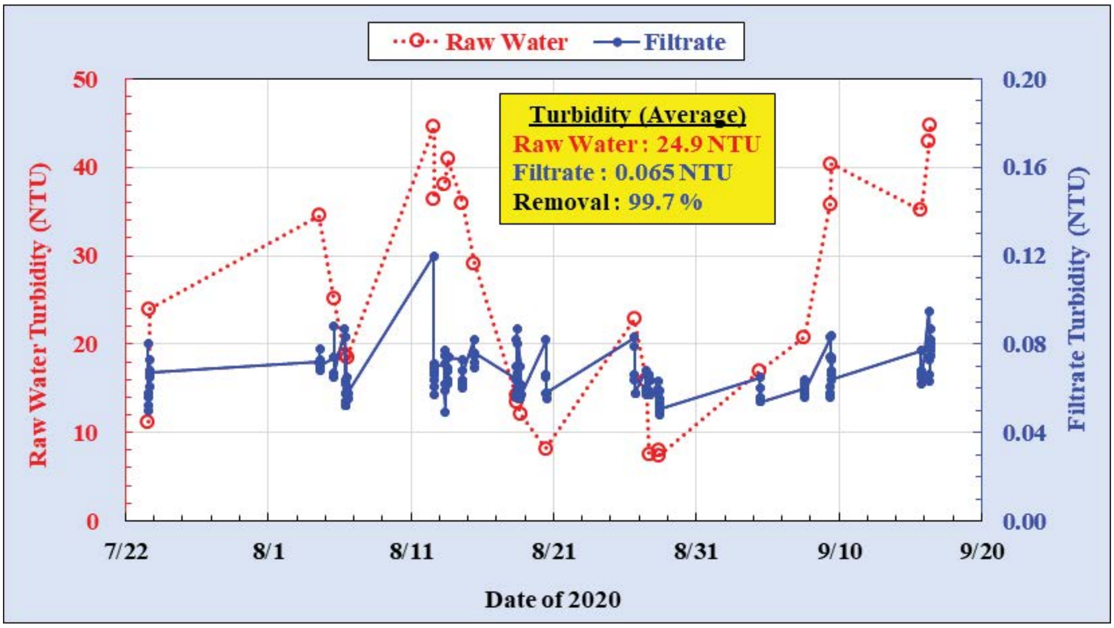

Fig. 22. Variations of the feed turbidity and its removal of the similar 150 mm PCF pilot set at Korea Water Cluster in 2020.

and filtrates sampled at 10 min intervals according to the operation date. According to the result, the feed turbidity was 24.9 NTU by average which was much higher than Hoedong's, but the filtrate turbidity was 0.065 NTU by average (average turbidity removal 99.7%) which was similar to Heodong's (0.066 NTU with 99.3% removal).

4. Conclusions

The ultimate object of this study is the replacement of the precipitator plus the RSF normally used in the conventional WTP to a single PCF filter and the goal of this study was to evaluate the filtration performance of the improved PCF filter by thickening the filter media depth from 100 to 150 mm.

The particle size in the feed used at the Heodong catchment pilot test was very fine under 25 μm (5.54 μm by the number average, 8.08 μm by the weighted average) since the most of particles were already precipitated by passing through the catchment having 14 d of HRT. More than 99% of the turbidity was removed from the feed of 5.7 NTU containing such very fine particles by the 150 mm PCF of about 400 m^3/d with dosing 24 mg/L of 10% inorganic coagulant dosing. Moreover, 99.7% turbidity was removed from 25 NTU feed by the 150 mm PCF of 100 m^3/d set at Korea Water Cluster. This means that the performance of the 150 mm PCF to remove the turbidity was very excellent.

On the comparison of the 100 mm PCF with the DAF and seven of UF's for four components removal (turbidity, SDI_{15}, Mn, and THMFP) which were done by BWQI that was a public organization in Busan city of Korea, the DAF was worse than the 100 mm PCF in all component removal. Removals of the DOC, the Mn, and the THMFP by the 100 mm PCF were 39.7%, 84.2%, and 58.6%, respectively, which were 11%–22.7% higher than the UF membrane. It was considered that such big differences in soluble components removal between the PCF and the UF were coming from the adsorption on the filter media and on the cake forming at the inside of the filter media of the PCF since the filter media of the PCF was much higher hydrophobic and much thicker than the UF. But the turbidity removal of the 100 mm PCF was 98.8% which was 0.3% lower than the UF's and the SDI_{15} of the 100 mm PCF was 3.3 which was 1.0 lower than the UF's. It means that the 100 mm PCF was slightly lower than the UF in the colloidal removal even though filtrates of the 100 mm PCF were sufficiently satisfying the criterion of the SDI_{15} as the RO pre-treatment water, 5.0.

The turbidity of the PCF filtrate was enhanced to 0.066 from 0.091 NTU and its removal was also enhanced to 99.3% from 98.1% after changing the filter media depth to 150 from 100 mm. But spike peaks of the filtrate turbidity at the initial filtration were still found by the on-line turbid meter. If such initial filtrate would be circulated to the feed by the control logic with some hardware, it was expected that the PCF performance to remove the colloidal would be much close to the UF's, and then the comparability of the PCF will be superior to the UF's in the market since the PCF has merits in the size, the price, and the operation cost than the UF.

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