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Effects of high turbidity inflow on PAC contactor operation and strategy for membrane fouling control in PMR (PAC membrane retrofitting) process

Chansik Kim[a], Suhyun Hwang[a], Myungsu Cho[a], Jae-Pum Park[b], Soo Hong Noh[a,*]

[a]*Department of Environmental Engineering, Yonsei University, 1 Yonseidae-gil, Heungeop, Wonju, Gangwon 220-710, Korea*
Tel. +82 33 760 5561; Fax: +82 33 760 2571; email: drnoh@yonsei.ac.kr
[b]*Department of Water Supply Technology, Korea Water Resources Corporation, 560 Sintanjin-Ro, Daedeok, Daejeon 306-711, Korea*

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ABSTRACT

Recently, global climate change has led to more frequent droughts and torrential rains. It could be reason of unexpected bad effects for water treatment such as taste and odor problems and decreasing of removal efficiencies. In case of membrane process, the inflow of high turbid raw water due to heavy rains may bring sudden increase in the membrane fouling caused by thick and dense cake formation on the membrane surface. Therefore, preparing proper operation methods is necessary for preventing system shutdown due to the membrane fouling, when high turbidity raw water is introduced. Powdered activated-carbon (PAC) membrane retrofitting (PMR) process has been developed as a hybrid process of coarse powder activated carbon (C-PAC) contactor with slurry blanket and submerged membrane for advanced drinking water treatment. PMR pilot plant was installed at W water treatment plant in Korea. Surface water was directly introduced to the plant as raw water. An ultrafiltration membrane module (ZeeWeed® 500C, GE, USA) with 603 m^2 of effective membrane surface area was used in this study. The purposes of this study were to assess the effect of the inflow of high turbid water on the performance of the C-PAC contactor and membrane fouling and to propose a fouling control strategy by adjusting recovery rate. Dissolved organic carbon removal efficiency of the C-PAC contactor was decreased when the high turbidity water was fed. The suspended solids (SS) in the raw water hindered the contact with organic matters and bio-film of biological activated carbon surface. It was confirmed by recovery of the removal efficiency after the raw water turbidity became a normal level. The correlation between SS concentration of the membrane tank and variation of trans-membrane pressure (TMP) was observed during a rainy season. The SS concentration of the membrane tank was selected as a criterion of recovery rate adjustment. When the turbidity of the raw water increased more than 550 NTU with the operating flux of 40 LMH, TMP increased gradually as the suspended solids were accumulated in the tank up to the concentration of 13,000 mg L^{-1}. However, TMP increased sharply when the SS concentration in the tank was over 13,000 mg L^{-1}. The SS concentration limit of the membrane tank was set

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*Corresponding author.

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conservatively below 5,000 mg L^{-1} for stable operation. The SS concentration of the membrane tank was controlled by adjusting recovery rate, and TMP was maintained stable during the inflow of high turbidity raw water. During which applied operating flux was 40 LMH and recovery rate changed between 99.5 and 98%. The SS concentration of the membrane tank was estimated by a mass-balance model which incorporates raw water turbidity with the ratio of SS and NTU. Recovery rate was adjusted according to the estimated SS concentration in the tank and stable operation could be achieved.

Keywords: Membrane; Powdered activated carbon; PMR process; High turbidity; Recovery rate

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1. Introduction

Recently, global climate change has led to more frequent droughts and torrential rains. It could be a reason of unexpected bad effects for water treatment such as taste and odor problems and decreasing of removal efficiencies [1]. When the high turbid water was directly introduced as raw water, membrane processes applied for drinking water treatment could be fouled rapidly because of thick and dense cake formation on the membrane surface. Therefore, appropriate countermeasure is necessary for preventing system shutdown due to the sudden increase in transmembrane pressure (TMP).

Powdered activated carbon (PAC) combined with membrane process has been used in advanced drinking water treatment processes. PAC is dosed to the membrane units by step input or by pulse input, and organic matters and particulates are eliminated by PAC adsorption and membrane filtration [2–4]. To prolong the solid retention times, PAC can be added to a contactor located at the upstream of the membrane tank [5–7]. PAC added to the contactor is carried over to the membrane unit and is discharged with the concentrate stream.

PAC + Membrane Retrofitting (PMR) process has been developed as a hybrid process for high-quality drinking water production [8–13]. The process consists of a coarse powder-activated carbon (C-PAC) contactor and a subsequent submerged membrane tank. C-PAC contactor is charged with high concentration of C-PAC having a size of 90–180 μm and the C-PAC is suspended to a certain height as a slurry blanket. The mixing in the contactor and raw water flow rate were controlled such that the C-PAC in the slurry blanket was not washed out. Soluble contaminants are adsorbed onto the C-PAC at the initial stage of operation. Bio-film could grow up on the surface of C-PAC because the raw water is introduced without pre-chlorination. Thus, organic removal of the contactor would be maintained even after adsorption capacity of the C-PAC is exhausted.

The objective of this study was to understand the effects of high turbid water on performance of the C-PAC contactor. Also, the membrane fouling and its control strategy by adjusting recovery rate were assessed in PMR process during rainy season. Variation of C-PAC slurry concentration in the C-PAC contactor was monitored to evaluate the wash out of the C-PAC slurry. Dissolved organic carbon (DOC) removal efficiency of the contactor was observed during two rainfall periods. Correlation of TMP with suspended solids (SS) concentration in the membrane tank was investigated to estimate the maximum SS concentration for the stable operation.

2. Materials and methods

2.1. Experimental setup

A pilot PMR plant was installed at a municipal drinking water treatment facility in Namyangju, Korea. As shown in Fig. 1, the pilot plant was consisted of a C-PAC contactor and a submerged membrane tank with a ultrafiltration membrane module (ZeeWeed® 500C, GE, USA) and its raw water was supplied from Paldang Reservoir without pre-treatment. The cylindrical C-PAC contactor has the effective volume of 16 m^3 with PAC slurry blanket of 30,000 mg L^{-1} in suspension. The submerged membrane module has effective surface area of 603 m^2. Concentrate was periodically rejected from the membrane tank and process recovery rate was adjusted by changing the discharge interval. Turbidity, conductivity, and pH were continuously monitored and recorded in real-time.

SS concentration of the C-PAC contactor was analyzed to assess the loss of C-PAC particles from the contactor. Sampling ports were installed on the side of C-PAC contactor as shown in Fig. 2. DOC concentration of the influent and effluent of the C-PAC contactor was also measured. Water samples were filtered using a syringe filter (0.45 micron) before analysis, and DOC was measured by total organic carbon analyzer (Sievers* 900, GE Analytical Instruments, USA).

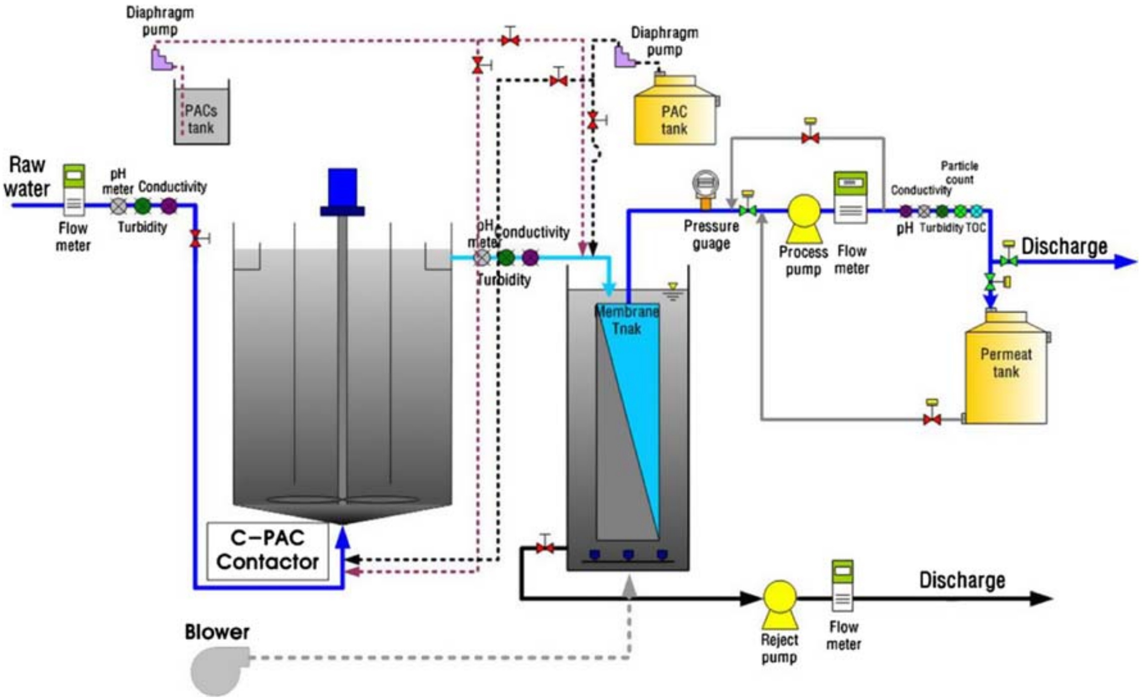


Fig. 1. Experimental set-up of PMR process.

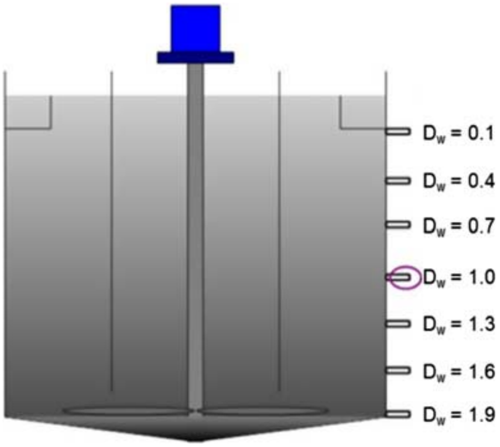


Fig. 2. Sampling ports at different water depths in the C-PAC contactor.

2.2. Reagents

2.2.1. Coagulant

Poly aluminium chloride silicate (PACS) was used as a coagulant to reduce membrane fouling and to improve removal efficiency of organic matters. The PACS was obtained from KG Chemical Co. Ltd. (Korea). Coagulant was added to upstream of the membrane tank.

2.2.2. Powdered activated carbon

C-PAC (DONGYANG Carbon Co. Ltd., Korea) used for slurry blanket has a size of 9–180 μm and C-PAC contactor was charged with the C-PAC. Fresh PAC (DARCO KB-B, Norit, the Netherlands) having average particle size of 27–42 μm was intermittently added into the membrane tank and recycled to the PAC contactor. The fresh PAC moved along water flow without settling and discharged with concentrate of the membrane tank.

2.3. Operating conditions

Inflow of high turbid water was observed at two rainfall periods. Effects of high turbidity of raw water and SS concentration in the membrane tank on the membrane fouling were evaluated during the first rainfall period. Operating conditions during the first rainfall were tabulated in Table 1. During the second rainfall, the SS concentration of the membrane tank was controlled to a certain concentration for stable operation. The limit concentration was maintained by adjusting recovery rate of the membrane tank. Recovery rate was changed between 99.5 and 98.0% as shown in Table 2.

Table 1
Operating conditions of the PMR pilot plant during the first rainfall period

Conditions (-)	Capacity (m^3/day)	Flux (LMH)	Recovery rate (%)	Fresh PAC (mg/L)	Coagulant (mg/L)
A	520	40			
B	260	20			
C	400	30	99.5		
D	450	33		5	10
E	450	33			
F	520	40	97.0		
G	520	40	98.0		

Table 2
Operating conditions of the PMR pilot plant during the second rainfall period

Conditions (-)	Capacity (m^3/day)	Flux (LMH)	Recovery rate (%)	Fresh PAC (mg/L)	Coagulant (mg/L)
A*			99.5		
B*	5	40	98.0	5	10
C*			99.0		
D*			99.5		

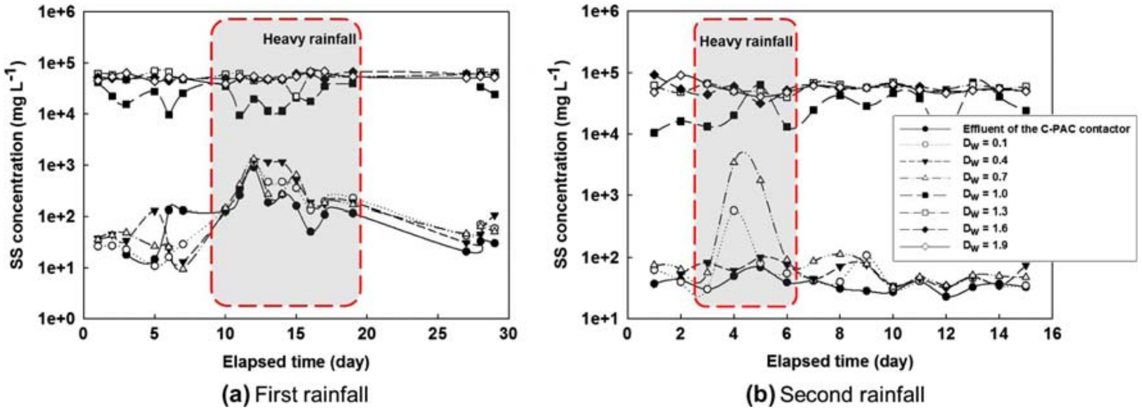
3. Results and discussion

3.1. *Effects of high turbidity inflow on the C-PAC contactor performance*

High turbidity raw water caused by torrential rain has been introduced into to the PMR process. Inflow of water with high turbidity can increase the concentration of suspended solids in the C-PAC contactor. Fig. 3 shows the variation of SS concentration at the different depths of C-PAC contactor during the rainfall. Increase of SS at all sampling points of the C-PAC contactor has been observed while turbid water was entering. After the end of heavy rainfall, the concentration in SS in the contactor was normalized. This result indicated that suspended solids of the feed water were not accumulated in the contactor and C-PAC slurry was not washed out. Therefore, the concentration of C-PAC in the slurry blanket was maintained in the range of 20,000–60,000 $mg\,L^{-1}$ even with high turbidity inflow, because the particle size of the raw water is below 62.5 μm, and the suspended solids were carried over through the slurry blanket in the contactor. Shin et al. [14] reported size distribution of suspended particles in high turbid water of Paldang Reservoir. The raw water was composed of clay (<3.9 μm) of 63.9% and silt (3.9–62.5 μm) of 36.1%, and average turbidity and total suspended solids (TSS) were 313.0 NTU and 246.5 $mg\,L^{-1}$, respectively.

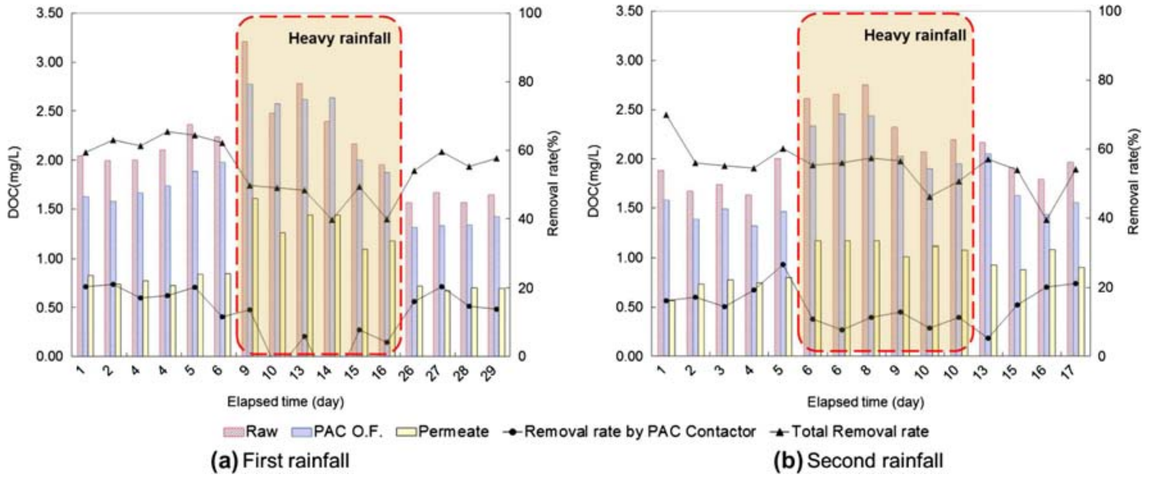
However, the size of PAC in the slurry blanket was optimized to be in the range of 90–180 μm. Thus, the C-PAC particles stayed in the blanket but particles in the high turbid water do not accumulate in the contactor.

DOC removal efficiency of the C-PAC contactor was reduced during the rainfall as shown in Fig. 4 when the high turbid water was introduced in the PMR process. Before the rainfall, the removal efficiency of the C-PAC contactor was maintained about 20%. However, the removal rate decreased significantly to near 0% during the rainfall, but the overall removal was maintained 45% mainly due to the removal of DOC in the membrane tank. Biological activated carbon (BAC) particles could be covered with small particles during the periods and these particles would hinder the contact of bio-film on the C-PAC surface and organic substances in the water. After the heavy rainfall, DOC removal effi-



(a) First rainfall **(b)** Second rainfall

Fig. 3. Variation of SS concentration at different water depths in the C-PAC contactor during the rainfall.



(a) First rainfall **(b)** Second rainfall

Fig. 4. Variation of DOC concentrations and its removal efficiency during the rainfall.

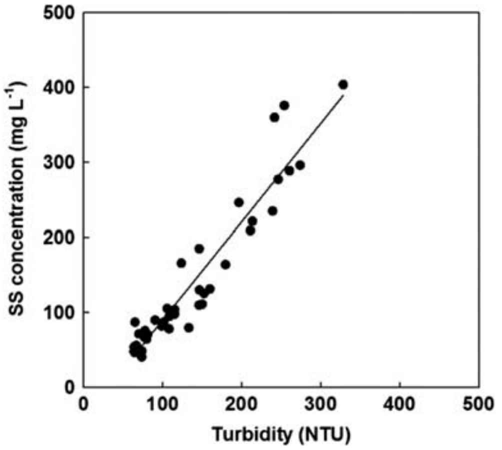


Fig. 5. The correlation of turbidity with SS concentration of raw water.

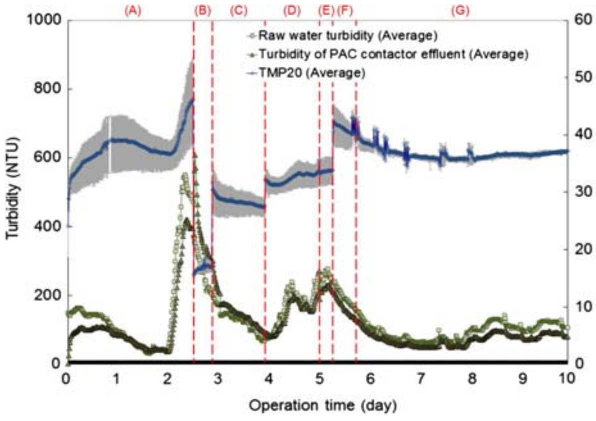


Fig. 6. Variation of turbidity and TMP during the first rainfall.

ciency of the contactor was recovered back to the normal conditions.

Addition of coagulants to the high turbidity surface water was reported to reduce PAC adsorption capacity. Cook et al. [15] conducted methylisoborneol adsorption experiments in four water sources under coagulation conditions specific to the respective water treatment plants (WTPs). They determined that the PAC adsorption was adversely affected by the higher water turbidity (26–118 NTU). The authors attributed this to the tighter binding of PAC in the denser floc structure formed at high turbidity conditions, thus reducing the effective contact time resulting in less active concentration of PAC.

Ho et al. [16] reported similar results to Cook's research. They noted that the PAC adsorption efficiencies were reduced by increasing of alum dose in the presence of high turbidity and have verified that these findings are related to the size of the flocs. In fact, incorporated PAC particles into the larger flocs formed in the presence of turbidity and in high alum dose were observed and these could be a major reason of reducing the mixing efficiency and the bulk diffusion kinetics of the adsorbate.

In conclusion, particulates in the raw water were not accumulated in the PAC contactor and did not affect maintaining of C-PAC slurry blanket. However, high turbid water could temporarily decrease DOC removal in the C-PAC contactor. Particles appeared to form larger flocs which covered the BAC particles, thus reducing the bulk diffusion kinetics of the organic matters. DOC removal efficiency of the contactor was returned to normal range within 10 days at each rainfall period.

3.2. Prediction of suspended solids concentration in the membrane tank

Suspended solids accumulated in the membrane tank affects the membrane fouling. Fouling control based on the variation of feed water turbidity is not effective because the membrane fouling is related with the SS concentration of the membrane tank. Thus, fouling control strategy based on the SS concentration in the membrane tank is desirable. Prediction of SS concentration in the tank is needed. The mass balance equation of suspended solids in the membrane tank can be expressed as follows with the following assumptions.

$$\text{SS concentration of the membrane tank} = \frac{(\text{volume of inflow} \times \text{SS concentration of inflow} - \text{volume of outflow} \times \text{SS concentration of outflow})}{\text{volume of the membrane tank}}$$

Assumptions:

1. The whole quantity of suspended solids in raw water is introduced into the membrane tank without settling down to the PAC contactor.
2. Suspended solids of the membrane tank do not increase due to the overflow of C-PAC from the C-PAC contactor.
3. The membrane tank is completely mixed and the SS concentration of it is uniform.

This equation can be rewritten with operating parameters such as flow rates and tank volume, assuming that the SS concentration is zero at initial time.

$$\text{At time} = 0, \qquad C_{\mathrm{SS},t=\mathrm{o}} = 0$$

$$\text{At time} = 1, \qquad C_{\mathrm{ss},t=1} = \left(\frac{Q_{\mathrm{P}}}{R} \times 100 - T_{t=1} \times K_{\mathrm{SS/Tur.}}\right)\Delta t/V_{\mathrm{T}}$$

$$\text{At time} = 2, \qquad C_{\mathrm{ss},t=2} = right \qquad C_{\mathrm{SS},t=1} + \left[\left(\frac{Q_{\mathrm{P}}}{R} \times 100 - T_{t=2} \times K_{\mathrm{SS/Tur.}}\right) - C_{\mathrm{ss},t=2} \times \left(\frac{100 - R}{R} \times Q_{\mathrm{p}}\right)\right]\Delta \mathrm{t}/V_{\mathrm{T}}$$

$$\text{At time} = n, \qquad C_{\mathrm{ss},t=n} = \left(\frac{V_{\mathrm{T}}}{k}\right)^{n} \times C_{\mathrm{SS},t=0} + \frac{(Q_{\mathrm{P}} \times 100 \times R_{\mathrm{SS/Tur.}} \times t)}{k \times R} \times \sum_{i=1}^{n} T_i \left(\frac{V_{\mathrm{T}}}{k}\right)^{n-i} k = V_{\mathrm{T}} + \left(\frac{100 - R}{R}\right) Q_{\mathrm{P}} \times \Delta t$$

where C_{ss} = suspended solids concentration in the membrane tank ($\mathrm{mg\,L^{-1}}$); Q_{p} = treated water flow rate ($\mathrm{L\,t^{-1}}$); R = recovery rate (%); T = turbidity of inflow water (NTU); $R_{\mathrm{SS/Tur.}}$ = suspended solids concentration/turbidity ratio of inflow water ($\mathrm{mg\,L^{-1}\,NTU^{-1}}$); V_{T} = volume of the membrane tank (L).

The SS concentration of the membrane tank was predicted by using real-time measurement of NTU of raw water which is converted to SS concentration of the raw water using a calibration correlation. The correlation between raw water turbidity and its SS concentration is shown in Fig. 5 and the average ratio of SS/NTU was 0.95.

3.3. Strategy for membrane fouling control in the PMR process during inflow of high turbidity water

Major contributor to the increase in TMP during the rainfall is the SS concentration at the membrane tank. In general, water viscosity increases with increasing concentrations of suspended solids, and it makes reduction of shear forces caused by aeration at near the membrane surface. The reduction in shear stress tends to decrease cake removal efficiency and to accelerate membrane fouling. Therefore, a strategy for control of the SS concentration by adjustment of recovery rate is used for preventing an abrupt membrane fouling and consequential system shutdown.

Turbidity and SS concentration of the raw water and SS concentration of the membrane tank were continuously monitored during the first rainfall. Variation

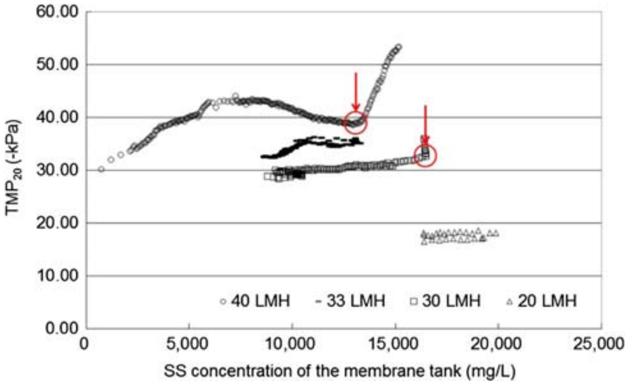


Fig. 7. Variation of TMP with SS concentration of the membrane tank at different operating flux (Recovery rate: 99.5%).

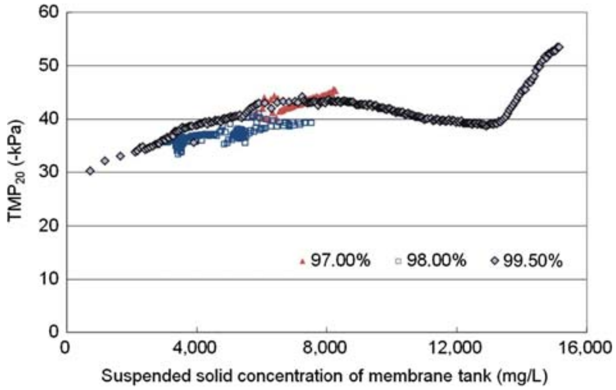


Fig. 8. TMP variation with suspended solid concentration of the membrane tank at different recovery rate (capacity: 530 m^3 day^{-1}, Flux: 40 LMH).

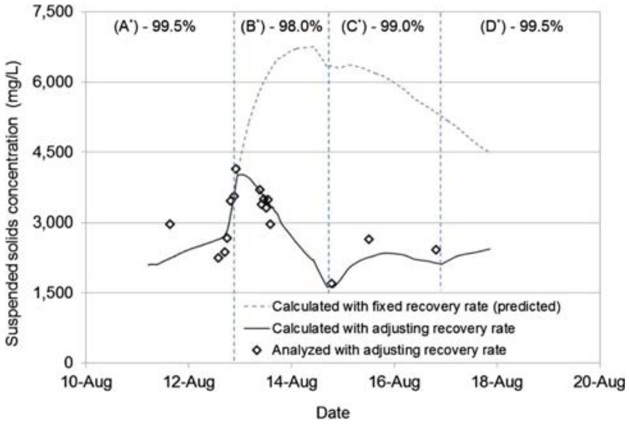


Fig. 9. Calculated and analyzed SS concentration with recovery rate during the second rainfall.

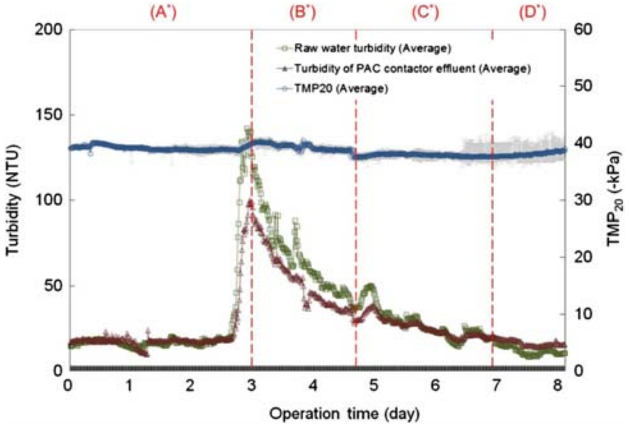


Fig. 10. Variation of turbidity and TMP during the second rainfall.

of TMP with turbidity of raw water was shown in Fig. 6.

During the first rainfall season, turbidity of raw water has been increased up to 550 NTU and TMP was sharply increased with increasing the raw water turbidity (condition A). Under various conditions, the process was operated to analyze the correlations between TMP and the SS concentration of the membrane tank.

Variation of TMP with SS concentration of the membrane tank at different operating flux was shown in Fig. 7. When the system was operated at lower fluxes, TMP was maintained stable even at higher suspended solids concentration. The TMP sharply increased at the SS concentration of above 13,000 mg L^{-1} with operating flux of 40 LMH. When the operating flux decreased from 40 to 30 LMH, sudden increase of TMP was observed at higher concentration of 17,000 mg L^{-1}. When the flux of 20 LMH applied, however, TMP was maintained even when the SS concentration of the tank increased up to 20,000 mg L^{-1}. This result indicates that the critical concentration could be determined by the membrane operating flux.

Fig. 8 shows TMP variation with SS concentration of the membrane tank at different recovery rate of 97–99.5% at the fixed operating flux of 40 LMH. Sudden TMP increase was observed at the SS concentration of above 13,000 mg L^{-1}. The recovery rate affects SS concentration of the membrane tank which also affects membrane fouling. However, the change in the recovery rate did not influence in the fouling directly in the range of the SS concentration of 4,000–8,000 mg L^{-1}.

The SS concentration limit of the membrane tank was set conservatively to 5,000 mg L^{-1} for stable operation. After then, recovery rate was programmed to adjust based on calculated SS concentration by monitoring the raw water turbidity and using the mass balance equation. During the second rainfall, applied operating flux was 40 LMH, and recovery rate was changed between 99.5 and 98.0%.

Fig. 9 shows the calculated and analyzed SS concentration with recovery rate. Predicted SS concentration could increase up to 7,000 $\mathrm{mg\,L^{-1}}$ with fixed recovery rate of 99.5% without recovery rate adjustment. However, recovery rate was adjusted to maintain SS concentration between 2,000 and 5,000 $\mathrm{mg\,L^{-1}}$ by using mass balance equation (bold line) and the analyzed SS ranged between 1,700 and 4,200 $\mathrm{mg\,L^{-1}}$. In other words, SS concentration of the membrane tank was maintained below 5,000 $\mathrm{mg\,L^{-1}}$ which regarded as the concentration limit and calculated values were well fitted to the analyzed SS.

The highest turbidity of the raw water was 160 NTU during the second rainfall as shown in Fig. 10. Observed TMP has ranged from 37.5 to 40.5 kPa. When the recovery rate was adjusted to maintain the SS concentration in the membrane tank at below 5,000 $\mathrm{mg\,L^{-1}}$, rapid increase in TMP was prevented and stable operation was possible during the second rainfall period.

4. Conclusions

In this study, effects of high turbid raw water on PMR pilot operation were evaluated. Concentration of C-PAC in the slurry blanket, DOC removal efficiency of the C-PAC contactor and membrane fouling trend were monitored during two rainfall periods. The following conclusions were derived:

(1) Accumulation of suspended particles of the raw water in the C-PAC contactor and carrying over of C-PAC particles was not occurred during heavy rainfall, and high turbidity inflow could not affects the concentration of the slurry blanket in the contactor.

(2) DOC removal efficiency of the C-PAC contactor decreased during the rainfall periods. Particles in the raw water appeared to form larger flocs which covered the BAC particles, thus reducing the bulk diffusion kinetics of the organic matters. However, DOC removal efficiency of the contactor was returned to normal range within 10 days of each rainfall period.

(3) TMP increased gradually as the SS concentration of the membrane tank was raised. However, TMP increased sharply when the SS concentration was over 13,000 $\mathrm{mg\,L^{-1}}$. The SS concentration limit of the membrane tank for stable operation appeared to be 5,000 $\mathrm{mg\,L^{-1}}$.

(4) The SS concentration of the membrane tank was controlled by adjusting recovery rate between 98 and 99.5%. The mass balance equation was developed to predict the SS concentration in the membrane tank by using SS/NTU ratio of the raw water. Stable operation was maintained, when the recovery rate was programmed to adjust based on calculated SS concentration even the raw water turbidity was up to 160 NTU during the second rainfall.

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