Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.791771

51 (2013) 5466–5474
August

Taylor & Francis
Taylor & Francis Group

Selection of pretreatment process and reverse osmosis membrane for a wastewater reclamation system for the industrial water use

Yu-Hoon Hwang[a], Chung-Man Moon[a], Yong-Tae Ahn[b], Suhan Kim[c,]*, Jae-Lim Lim[d], Hang-Sik Shin[a]

[a]*Department of Civil and Environmental Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea*
[b]*Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, 128 Sackett, PA 16802, USA*
[c]*Department of Civil Engineering, Pukyong National University, San 100, Nam-gu, Yongdang-dong, Busan, Korea*
Tel. +82 51 629 6065; Fax: +82 51 629 6063; email: suhankim@pknu.ac.kr
[d]*Water Management & Research Center, K-water Institute, 462-1 Jeonmin-Dong, Yusong-Gu, Daejeon, Korea*

Received 17 August 2011; Accepted 23 December 2012

ABSTRACT

Wastewater reclamation offers an attractive solution to water stress problems these days. Because of health concerns in the reclaimed wastewater as drinking water, most of water reuse projects are focusing on the industrial water use. The key water quality constraint to the industrial water reuse is ionic constituents from nearby industrial complexes. Therefore, the reverse osmosis (RO) process must be the main process for a wastewater reclamation system for the industrial water use. The most important target for the design of an RO-based wastewater reclamation system is to minimize membrane fouling. This study focuses on the selection of pretreatment process and RO membrane to minimize the fouling in the RO process. Since raw water is the wastewater treatment plant effluent, high-quality pretreatment and low-fouling RO membrane should be considered for the design of the whole system. A short-term field test for microfiltration (MF) and ultrafiltration (UF) was carried out to see which process showed better performance in terms of the process stability and the pre-treated water quality. Both MF and UF produced the pretreated water of the similar quality, while UF showed more stable transmembrane pressure data than MF. In addition, a short-term field RO-fouling test was introduced to select the best RO membrane among the three tested membranes in terms of the fouling resistance.

Keywords: Wastewater reclamation system; Reverse osmosis; Fouling; Pretreatment; Microfiltration (MF); Ultrafiltration (UF)

1. Introduction

Climate change related to global warming has had negative effects on Korean water supply systems, which mainly depend on surface water. Also, Korea is highly vulnerable to utilize water in the drought due to low intake rate (36%) of river. The nation's water supply has accordingly been challenged in recent years by increased water stress, both in terms of water scarcity and quality deterioration [1].

*Corresponding author.

More than six billion tons of wastewater treatment plant (WWTP) effluents were discharged yearly into various water bodies, including rivers, lakes, seas, and so on [2]. After water reuse master plan has been established in 2005, the reuse of WWTP effluent has been implemented in the most WWTPs (1.75 million tons/d) in Korea. Water reuse has increased gradually from 2.9% (2001) to 9.9% (2007). This trend is comparable with other countries (e.g. US 7.4%, Australia 9.1%) [3]; however, more than half of the reclaimed water (57.9%) is being consumed as cleaning water in WWTPs. Only 1.5% of the reclaimed water is directed toward industrial use. This is much lower than the values of developed countries, such as Austria and Sweden, which direct 20–50% to industrial use [4].

The government has recently recognized that WWTP effluent could be a stable water source. In total, 19 WWTPs were selected for a reuse project, and 440 million tons per year will be reused for industrial use [5]. However, it is very difficult to decide upon a proper reclamation process and operating conditions, because the effluent quality of every WWTP is quite different each other. Moreover, the required water quality could vary according to the purpose of the reclaimed water use. The proper process should be determined by considering the both of source water quality (WWTP effluent) and the consumer's (industry) demand.

In case of industrial water reuse, the salt concentration (ionic concentration) is one of the most important water quality management parameters because of the ionic constituents from nearby industrial complexes. Generally, reverse osmosis (RO) process is selected to remove the dissolved ions. The most important target for the design of an RO-based wastewater reclamation system is to minimize membrane fouling. Thus high-quality pretreatment and low-fouling RO membrane should be considered for the design of the whole system, and these two aspects are the main objectives of this study.

Adequate pretreatment is required to reduce membrane fouling as the RO membranes are very sensitive to foulant materials, such as colloids, inorganic scale, and biofilm [6–10]. Recently, membrane-based pretreatment such as microfiltration (MF) and ultrafiltration (UF) is generally considered as a preferred option to a conventional media filtration in terms of pretreated water quality [11,12]. Since raw water is the WWTP effluent, higher potential of fouling is expected for the RO-based wastewater reclamation systems, which increases the needs for MF and UF as pretreatment option [13].

Selecting low-fouling RO membrane is also very important to design the wastewater reclamation system. The membrane fouling is resulted from the physico-chemical interfacial interaction between membrane surface and foulants. We hypothesized that there exists the best combination between RO membrane surface and specific foulants in terms of the lowest fouling potential. The fundamental method to find the fouling potential of an RO membrane for specific foulants is to analyze the interfacial forces between membrane and foulants surfaces using the material characterization data [14–16], which is difficult to be applied to complex foulants in WWTP effluents. An easier way compared with the interfacial force analysis is using flow field flow fractionation system [17]. But this method does not account for the fouling or scaling phenomenon in the concentrated region of the latter RO modules in pressure vessels where RO modules are arranged serially. Therefore, a field RO membrane fouling test procedure is introduced to select membrane module resulting in the lowest fouling characteristics.

This study aimed to develop a methodology for a short-term test to determine the treatment process and to test the feasibility of the selected process for industrial use. Pilot tests are generally applied for process determination and verification, but it requires high cost and long-term operation [18]. Moreover, they have limitations in terms of changing the process when the selected process is not suitable. Therefore, it is worthwhile to conduct short-term tests to determine design factors related to process determination and verification by a pilot test. The short-term test could reduce cost and time for the pilot study, and could secure process versatility.

In this study, a short-term field test for coagulation and membrane filtration (MF/UF) were carried out to see which process showed better performance in terms of the process stability and the pretreated water quality. In addition, the suitable RO module having the lowest fouling characteristics was selected by this short term field test.

2. Materials and methods

2.1. Site description and raw water quality

This study was carried out in Yongyeon WWTP located in the Ulsan industrial complex. This area is one of the largest industrialized areas in Korea. Industrial wastewater in the Ulsan industrial complex and domestic wastewater from Ulsan city were combined and treated in Yongyeon WWTP. An advanced biological nutrient removal process is adapted, and the total capacity is 250,000 m^3/d. Table 1 shows the averaged influent and effluent water

Table 1
Averaged raw water quality of Yongyeon WWTP from 2007 to 2009 and required water quality for cooling water

	WWTP influent	WWTP effluent	Required water quality for cooling water
pH	–	7.53	6.5–7.5
BOD (mg/L)	105.9	10.8	–
Turbidity (NTU)	–	5.5	1
Conductivity (μS/cm)	5,396	6,022	150
TDS (mg/L)	2,699	3,025	70
T-N (mg/L)	34.6	14.2	30
T-P (mg/L)	3.67	1.4	4
Hardness (mg/L)		854.2	70
Cl^- (mg/L)	1,535	1,501	30

quality data of Yongyeon WWTP during a recent three-year period (2007–2009) and the required water quality for cooling water which was obtained from a survey targeting nearby industrial complexes.

WWTP effluent could not meet the requirement for the industrial cooling water except total nitrogen and phosphorus (T-N and T-P). The key water quality constraints to wastewater reclamation were ionic constituents because conductivity, total dissolved solid (TDS), hardness, and chloride concentrations exceeded the required water quality as shown in Table 1. This is the reason why the main process should focus on the ion removal such as RO process. Turbidity of WWTP effluent did not meet the requirement either and it can be easily decreased by a proper pretreatment for RO process, the main process for wastewater reclamation system. Therefore, membrane-based pretreatment process (MF or UF as mentioned earlier) followed by RO was selected as a wastewater reclamation process for Yongyeon WWTP effluent reuse.

2.2. Selection of the best pretreatment option

2.2.1. Coagulation

Chemical coagulation was applied to enhance the performance of MF and UF in terms of water quality and process stability. Polyaluminum chloride of 17% was used as a coagulant and the mixing speed was 60 rpm. Fig. 1(a) shows the coagulation tank. The capacity of the coagulation tank is 1 m^3, and the retention time was 15 min. As a preliminary study, several jar tests were conducted to determine the optimal coagulant dosage. The criterion to determine the optimal

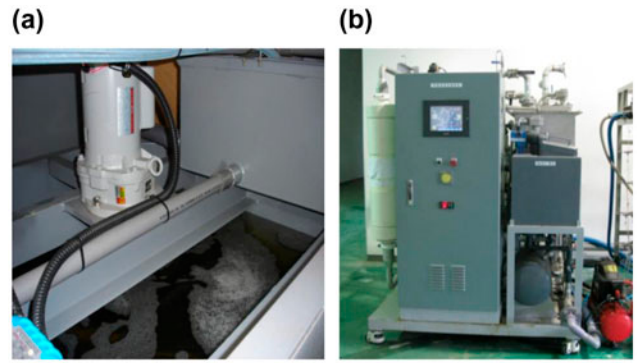

Fig. 1. Experiment equipment for pretreatment ((a) coagulation tank, (b) low-pressure membrane filtration (MF/UF)).

dosage was based on the turbidity of supernatant water at the end of each test. Assessing a coagulant dosage range of 0–40 mg Al_2O_3/L, 16 mg Al_2O_3/L was determined as the optimal coagulant dosage. The optimal coagulant dosage was used for further operation.

2.2.2. MF and UF

As discussed earlier, membrane-based process, such as MF and UF, was adopted as the main pretreatment option for RO. The experiment equipment with changeable hollow fiber membrane module is shown in Fig. 1(b). Operation data, such as trans-membrane pressure (TMP) and temperature, were collected automatically. Both coagulated water and noncoagulated water can be used as feed water for membrane filtration. The membrane filtration cycle consisted of flushing (20 s), filtration (30 min), air scrubbing + backwash (60 s), and draining (30 s).

Table 2 shows the characteristics of the hollow fiber MF and UF modules used in this study. These modules were produced by the same manufacturer, and most of the characteristics and operating conditions were similar. The main difference between the two modules was pore size. Pore size is known to be

Table 2
Characteristics of low pressure filtration membrane modules

	Micro filtration (MF)	Ultra filtration (UF)
Pore size	0.02 μm	150 kDa
Net water flux (m/h at 100 kPa)	1.6	0.8
Surface area	29 m^2	
Membrane material	PVDF	
Operation flux	1 m/d	

Table 3
Operating conditions for each pretreatment phase

Phase	Coagulant dosage	Membrane
I	16 mg Al_2O_3/L	MF (0.02 μm)
II	0 mg Al_2O_3/L	MF (0.02 μm)
III	0 mg Al_2O_3/L	UF (150 kDa)
IV	16 mg Al_2O_3/L	UF (150 kDa)

a factor that affects the performance of membrane filtration [19].

During the filtration test, the effects of pore size and raw water characteristics (i.e. coagulated vs noncoagulated WWTP effluent) were evaluated. Four different combinations of pretreatment processes were evaluated; the operating conditions for these processes are shown in Table 3. Each phase was operated for one week. The most suitable process scheme was decided based on the process stability and the quality of the produced water.

The process stability was evaluated by the calibrated TMP increase rate, where calibrated TMP was corrected for temperature using Eq. (1).

$$TMP_{25^\circ C} = TMP_{T^\circ C} \times \frac{\mu_{25^\circ C}}{\mu_{T^\circ C}} \quad (1)$$

where $TMP_{25℃}$ is calibrated TMP at the temperature of 25℃ from $TMP_{T℃}$ (the measured TMP at T℃) and $\mu_{25℃}$ and $\mu_{T℃}$ are the water viscosity at 25℃ and T℃, respectively. The $TMP_{25℃}$ indicates the amount of fouling on MF or UF membrane surfaces.

The pre-treated water quality was evaluated using dissolved organic carbon (DOC) concentration, ultraviolet light absorbance at 254 nm (UV_{254}), turbidity, and Silt Density Index (SDI). SDI is usually applied to predict the fouling potential of RO feed water as well as to determine the efficiency of pretreatment processes [13,17]. DOC, UV254, and turbidity were measured using Apollo 9000 (Teledyne Tekmar, Mason, OH, USA), Beckmann DU650 spectrophotometer (Beckman Coulter, Inc. Fullerton, CA, USA) and 2100Q portable turbidimeter (Hach company, CO, USA), respectively, and SDI was measured using the method described elsewhere [13,17].

2.3. Selection of the lowest fouling RO membrane

2.3.1. Membrane modules

In the case of RO operation, three 4-inch membrane modules (RO A, RO B, RO C) from different manufacturers were applied for the field RO-fouling test. The characteristics of membrane modules are presented in Table 4.

Table 4
Characteristics of RO membrane modules

	RO A	RO B	RO C
Membrane material	Polyamide	Polyamide	Polyamide
Effective membrane area (m^2)	8.0	7.2	7.9
Salt rejection (%)	99.7[a]	99.2[b]	99.5[c]
Permeate flow rate (m^3/d)	8.3[a]	11.0[b]	7.9[c]

[a]Permeate flow and salt rejection based on the following test conditions: 25℃, 15% recovery, 2,000 mg/L NaCl, and 225 psi.
[b]Permeate flow and salt rejection based on the following test conditions: 25℃, 15% recovery, 500 mg/L NaCl, and 145 bar.
[c]Permeate flow and salt rejection based on the following test conditions: 25℃, 15% recovery, 2000 mg/L NaCl, and 225 bar.

2.3.2. Short-term field RO fouling test

A short-term field RO fouling test was designed to accelerate fouling by feeding concentrated water in order to minimize the test time and the number of the test membrane modules. The test was carried out by simply exposing all the test membranes to the same conditions and their relative performances were drawn to select the best membrane in terms of fouling resistance.

A schematic illustration of the test equipment is presented in Fig. 2. The wastewater effluent in the field with no pretreatment was simultaneously supplied to the three RO modules when the RO permeate was discharged. The concentrate was recirculated to the feed tank as concentrated feed water to make a condition to foul the tested RO membranes faster than the normal operation with a single RO element and a limited operation time. Although the concentrate returned into the feed tank, the feed water level should decrease because of the continuous discharge of the permeate water.

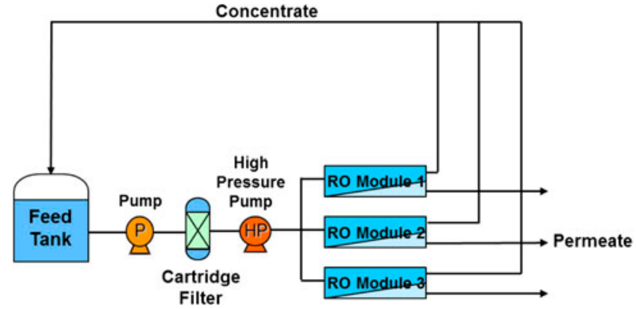

Fig. 2. Schematic illustration of field RO-fouling test.

When the water level of the feed tank reached the lowest value as possible, each stage of the fouling test was ended. Without cleaning the tested membrane and emptying the feed tank, the next stage was started after adding the wastewater effluent to the feed tank. Therefore, feed water will be concentrated through stages and stages for the fast fouling condition. Three RO modules were simultaneously tested with the same starting point, and the results were compared by a linear regression analysis to determine the best membrane module has affording the lowest fouling tendency. During each stage of the fouling test, TDS concentrations of feed and permeate, permeate flux, cross-flow rate, feed water temperature, and TMP were collected with time.

2.3.3. Methodology to quantify the RO fouling

The results of the short-term field RO test should be interpreted to quantify the RO fouling. In case of MF/UF, temperature-calibrated TMP is the parameter to quantify the fouling as discussed earlier. However, the osmotic pressure is additional factor affecting TMP in the case of RO process. So a more complex procedure should be considered in the case of RO process than the temperature calibration in MF/UF as shown in Eq. (1). TMP (Δp) can be described by permeate flux (v_w), the total membrane resistance ($R = R_m + R_f$) including the intrinsic membrane resistance (R_m) and the fouling resistance (R_f) and the osmotic pressure drop ($\Delta\pi_m$) such as:

$$\Delta p = \mu R v_w + \Delta\pi_m \tag{2}$$

R is the fouling parameter of our interest and can be expressed as Eq. (3) by rearranging Eq. (2)

$$R = \frac{\Delta p - \Delta\pi_m}{\mu v_w} \tag{3}$$

Theoretically, the osmotic pressure drop can be quantified using Eq. (4) and (5) [19,20].

$$\Delta\pi_m = f_{os}(C_m - C_p) \tag{4}$$

$$\frac{C_m - C_p}{C_b - C_p} = \exp(v_w/k_m) \tag{5}$$

where f_{os} is the osmotic pressure coefficient and C_m, C_b, and C_p is ion concentration on the membrane surface, in bulk solution, and in the permeate, respectively. k_m is mass transfer coefficient, which is a function of wall shear rate ($\dot{\gamma}_w$), salt diffusivity (D), and channel length (L) as shown in Eqs. (6) and (7) [20,21].

$$k_m = 0.807(\dot{\gamma}_w D^2/L)^{1/3} \tag{6}$$

$$D = kT/6\pi\mu a \tag{7}$$

where Eq. (6) is valid when there is no spacer in the membrane feed channel, k is Boltzmann coefficient, T is the absolute temperature, and a is the characteristic radius of ion. In addition, the viscosity is affected by temperature as shown in Eq. (8) [22].

$$\mu_T = \mu_{298} \exp\left[b \cdot \left(\frac{1}{298} - \frac{1}{T}\right)\right] \tag{8}$$

where μ_{298} is the viscosity at temperature of 298 K and b is an empirical coefficient, respectively. Using Eqs. (3)–(8), we can theoretically estimate the total resistance as the indicator to quantify RO fouling. Because of the difficulty in determination of the mass transfer coefficient (k_m) from a field RO-fouling test, an approximation for the osmotic pressure drop ($\Delta\pi_m$) as shown in Eq. (9) can substitute the Eqs. (4)–(7) [23].

$$\Delta\pi_m \approx \frac{C \cdot (T+47)}{491{,}000} \text{ for } C < 20{,}000 \text{ mg/l} \\ \approx \frac{0.0117 \cdot C - 34}{14.23} \cdot \frac{T+47}{345} \text{ for } C \geqslant 20{,}000 \text{ mg/l} \tag{9}$$

where C is feed water TDS in mg/l.

3. Results and discussion

3.1. Pretreatment

3.1.1. The Process stability

Pretreatment processes were evaluated based on the effectiveness of coagulation and a comparison of the MF/UF membrane. The stability of the pretreatment process was evaluated by the comparison of the temperature-calibrated TMP during the four different phases of operation discussed in Section 2. Fig. 3 shows the trends of the temperature-calibrated TMP at 25℃ and Table 5 presents the increasing rate in the TMP. In the case of phases I and II (MF), the TMP increased very rapidly and the rate of increase was in a range of $1.7\text{–}3.7 \times 10^{-1}$ kPa/h. On the other hand, the UF membrane showed more stable operation compared with the MF membrane. The TMP rate of increase during UF operation ($6.8\text{–}8.6 \times 10^{-3}$ kPa/h) was much lower than that in MF operation (phases III & IV). The effect of coagulation was negligible compared with the effect of the membrane module.

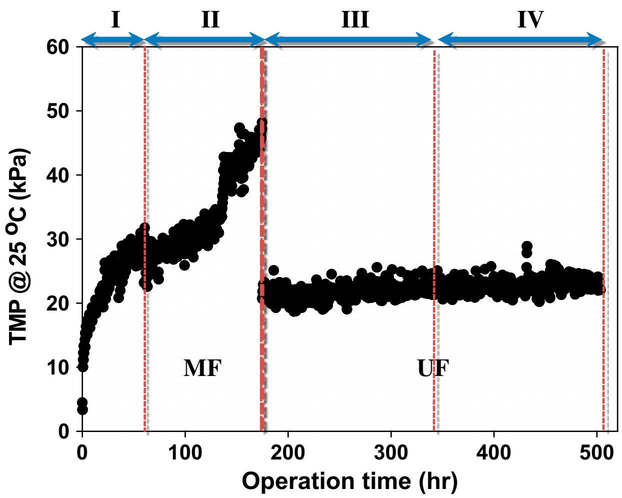

Fig. 3. Temperature-calibrated TMP data during MF/UF operation (I: coagulation & MF, II: non-coagulation & MF, III: noncoagulation & UF, IV: coagulation & UF).

Table 5
TMP increase rate of each pretreatment processes

	Phase I	Phase II	Phase III	Phase IV
TMP increase rate (kPa/h)	0.3664	0.1658	0.0086	0.0068

The different fouling tendency of each pretreatment scheme might be due to the difference of pore size, which is related with pore blocking and constriction phenomenon [13,19]. When the pore size is small enough to retain suspended matters, the pore blocking or constriction phenomena will not occur. This is the reason why UF exhibits much more stable operation compared with MF as shown in Fig. 3.

3.1.2. Product water quality

The product water quality is one of the most important indicators for deciding an appropriate pretreatment process. Table 6 shows the removal rate of DOC, UV_{254}, and turbidity by each pretreatment process scheme. According to the results presented in Table 6, coagulation enhanced the removal efficiency of most constitutes, which matched the general trend that addition of coagulation enhances the product water quality.

Table 6
Contaminant removal rate through each pretreatment scheme (C: coagulation, NC: noncoagulation)

	MF (%)		UF (%)	
	NC	C	NC	C
DOC	27.9	34.5	12.2	16.4
UV_{254}	8.9	24.1	7.09	22.2
Turbidity (NTU)	46.8	66.5	61.7	70.6

Turbidity data of the WWTP effluent were in the range of 1.5–3.0 NTU and those of the pre-treated water were less than 1.0 NTU as expected, since membrane-based operation was introduced to each pretreatment scheme. Both MF and UF showed low removal rate of organic matters although coagulation slightly increase the removal rate. Interestingly, MF with the larger pore size exhibited the higher DOC removal efficiency than UF. This could be due to the generation of a fouling layer inside pore structures, which acts as an additional membrane layer.

SDI was measured to check whether the pretreated water met the water quality standard. Regardless of the pretreatment options, SDI values were lower than 3. Membrane manufacturers recommend a SDI_{15} value lower than 3, but they accept values of 4 or 5 [24].

3.2. Short-term field RO-fouling test

3.2.1. TMP and permeate flux

As discussed in Section 2.3, our short-term field RO-fouling tests were carried out during the several individual stages, and the more severe fouling behavior should be observed in a later stage than that in an earlier stage. Figs. 4 and 5 describe TMP and permeate flux data of the tested RO membranes during the first and the sixth stages, respectively. Because the concentrate returned into the feed tank during the fouling test while permeate was discharged, feed TDS was increased with time. Hence, the horizontal axis in Figs. 4 and 5 denotes not only feed TDS but also operation time.

The three tested RO membranes started with the same permeate flow rate of 3.0 l/min, and the initial permeate flux for each membrane was different because of the difference in the tested RO membrane module area. It would be best if the initial fluxes for the tested membranes are the same. During each stage, the permeate flux decreased and the TMP increased as feed TDS increased with operation time because of the two reasons; (1) the increase in osmotic pressure by the concentrate re-circulation into the feed tank and (2) the fouling.

For each tested membrane, the TMP data in the sixth stage were higher than those in the first stage as shown in Fig. 5, which means that the fouling occurs through stages. RO A and RO C showed the smaller TMP jump (~1 bar) than RO B (i.e. TMP jump

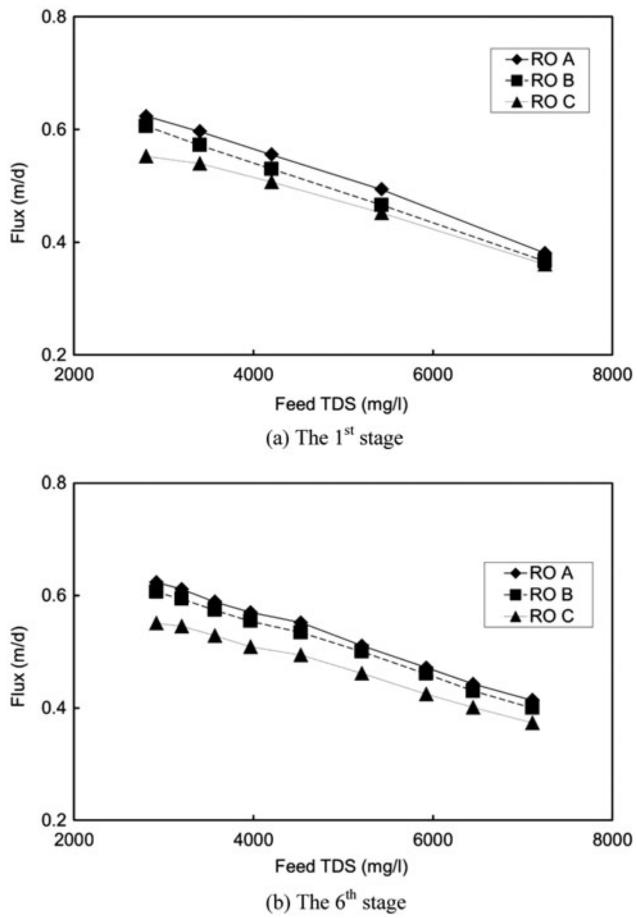

Fig. 4. Permeate flux data during the short-term RO field fouling test.

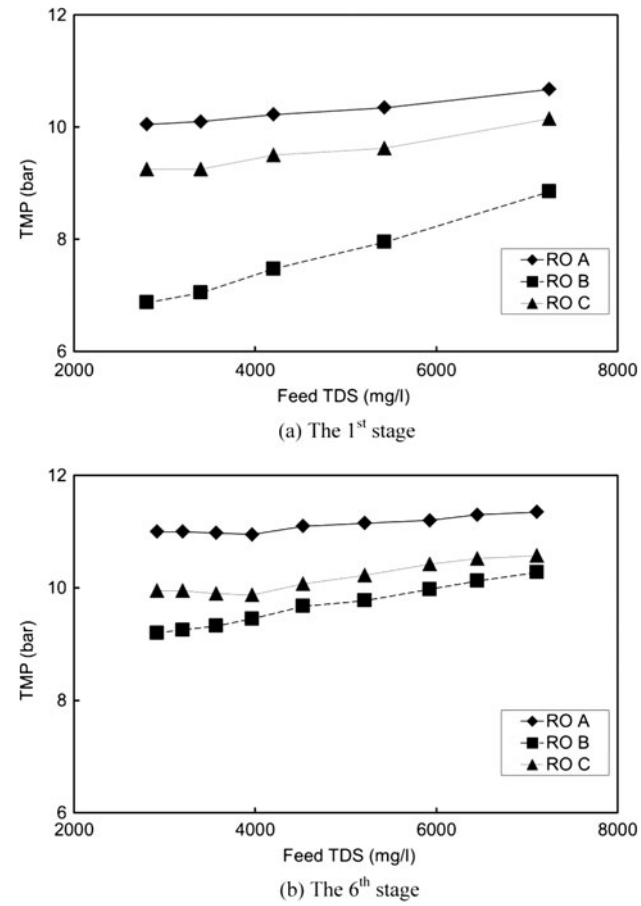

Fig. 5. TMP data during the short-term RO field fouling test.

of ~ 2 bars), which may imply that RO A and RO C are more resistant to the fouling by Yongyeon WWTP effluent than RO B. However, the TMP data cannot be perfectly matched with the RO membrane fouling as discussed in Section 2.3.3. Therefore the total membrane resistance (Eq. (3)) was calculated using temperature and TDS of feed water and TMP to clearly estimate the amount of fouling.

3.2.2. Total membrane resistance

Fig. 6 describes the total membrane resistance of the tested RO membranes during the first and sixth stages of the short-term field fouling test. The initial membrane resistance of RO A, RO B, and RO C were 1.34×1.0^{14}, 0.81×1.0^{14}, and $1.35 \times 1.0^{14}\,m^{-1}$, respectively. Considering the initial membrane resistance is almost the same as the intrinsic membrane resistance, we can find that RO B is low-pressure membrane with high permeability. Salt rejection of RO B during the test was in the range of 96–97%, while RO A and RO C exhibited salt rejection in the range of 98–99% during the test.

The difference in the total membrane resistance data in the first and sixth stage can be a good indicator to quantify the amount of fouling. As shown in Fig. 6, RO B showed the dramatic increase in the total membrane resistance through the first and the sixth stages, which means that this membrane is not eligible as a low-fouling RO membrane for Yongyeon WWTP. The difference in the increase in the total membrane resistance through stages for the cases of RO A and C was not so big, and thus, these two membranes can be thought to have the similar resistance to fouling by Yongyeon WWTP. Moreover, the initial flux of RO A is higher than that of RO C as described in Fig. 4, which means that RO A was tested in adverse condition compared to RO C. This maybe implies that RO A could be found as better membrane than RO C in terms of fouling resistibility though the short-term field RO-fouling test if both membranes were tested in the same initial flux condition.

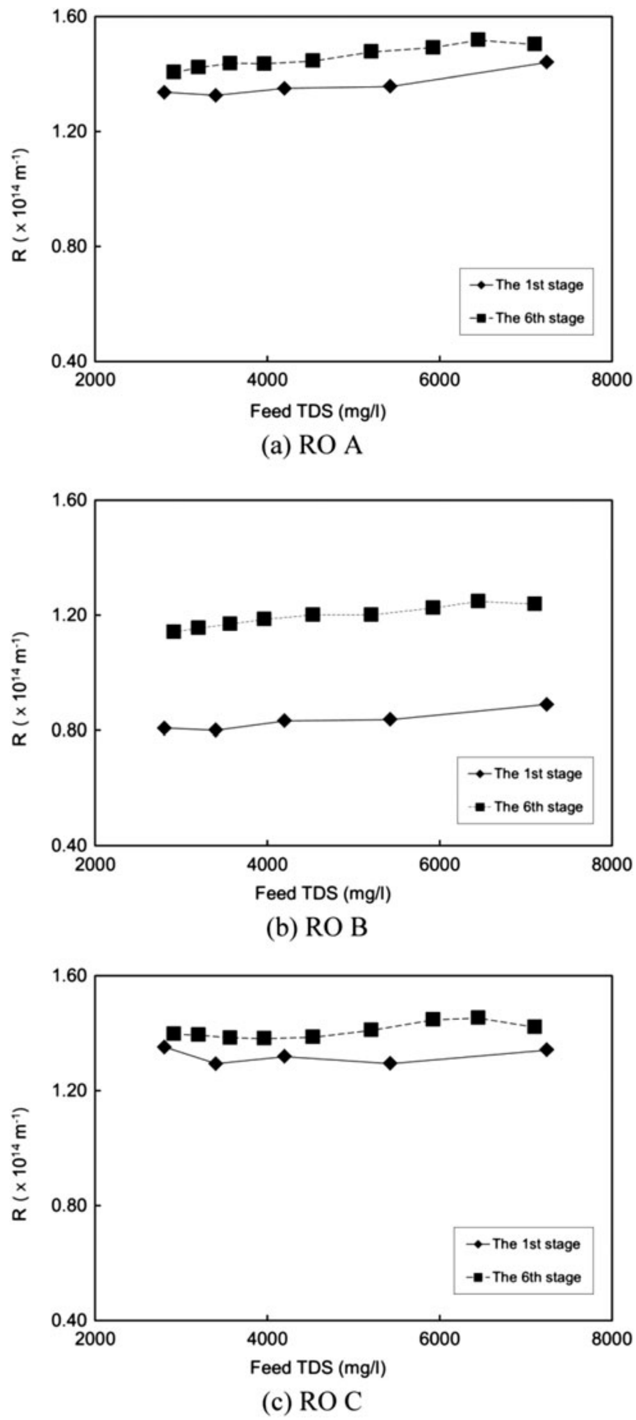

Fig. 6. Total membrane resistance data during the short-term RO field fouling test.

3.3. Pilot plant operation to verify the short-term field test

Based on the short-term field test, the most suitable combination of the unit processes was found to be coagulation–UF–RO A in terms of the operation stability. The selected pretreatment process (coagulation–UF) showed the higher process stability and product quality than other combination, while RO A showed the highest fouling resistibility among the tested RO elements. Although the operation stability is not the only criterion, it is one of the most important parameters to select unit processes (and membranes) in a membrane-based wastewater reclamation plant because this type of plant is generally exposed to high risk of membrane fouling.

In order to verify the short-term test result, a pilot plant was installed in the site of the same WWTP. The pilot plant had the total treatment capacity of 72 m^3/d, and it was operated for one year. The specific operation conditions were applied as 16 mg Al_2O_3/L for coagulation, 1 m/d for UF, and recovery of 75% for RO based on the short-term test results. The stable product quality could be achieved during the operation period. The operation cost (chemical, electricity, and membrane) was estimated to be 372.5 KRW/m^3 (=0.33 USD/m^3) according to the one-year operation data.

4. Conclusion

RO process is a key process for a wastewater reclamation system for industrial use because the water quality constraint is ions from nearby industrial complexes. The most important target for the design of RO process is to minimize membrane fouling, which can be achieved by the selection of the best pretreatment process and RO membrane. Because raw water is the WWTP effluent, pretreatment with high product water quality and low fouling RO membrane should be considered.

A short-term field test for MF and UF was carried out to see which process was better in terms of the process stability and the pretreated water quality. Both MF and UF produced the pretreated water of the similar quality appropriate for RO feed water. However, UF was better than MF in terms of the process stability because TMP increase in UF was much slower than that in MF. In our test condition with Yongyeon WWTP in Korea, the UF pore size is too small for the foulants to intrude the pore structure.

Even if the best combination of pretreatment processes was selected, RO feed water still has high-fouling potential because of the high organic concentration in WWTP effluent. This study proved that coagulation helped to slightly remove the organic matters, but this is not enough. Hence, it is very important to select RO membranes with high-fouling resistibility. A short-term field RO-fouling test was introduced to select the best RO membrane among the three tested membranes in terms of low-fouling characteristics. The total membrane resistance based on the fundamental theories of RO membrane process was calculated using the field test data to clearly quantify the amount of fouling by each tested membrane.

Acknowledgments

This research was supported by the Program for the Construction of Eco Industrial Park (EIP), which was conducted by the Korea Industrial Complex Corporation (KICOX) and the Ministry of Knowledge Economy (MKE).

References

[1] H. Chang, J. Franczyk, D.H. Bae, I.W. Jung, E.S. Im, W.T. Kwon, Effect of climate change and population growth on water resources in Korea, IAHS Publ. 315 (2007) 172–178.
[2] Statistics of sewerage 2007, Ministry of Environment, Korea, 2008.
[3] G.W. Miller, Integrated concepts in water reuse: Managing global water needs, Desalination 187 (2006) 65–75.
[4] Sustainable water use Part 1: Sectoral use of water, European Environmental Agency, 1999.
[5] The master plan for Wastewater reuse PFI, Ministry of Environment, Korea, 2009.
[6] R.J. Xie, E.K. Tan, S.K. Lim, E. Haw, C.P. Chiew, A. Sivaraman, A.N. Puah, Y.H. Lau, C.P. Teo, Pretreatment optimisation of SWRO membrane desalination under tropical conditions, Desalin. Water Treat. 3 (2009) 183–192.
[7] M. Beery, J.H. Kim, J.-U. Repke, Membrane-based SWRO pretreatment: Knowledge discovery in databases using principal component analysis regression, Desalin. Water Treat. 15 (2010) 160–166.
[8] S.H. Kim, C.S. Min, J. Cho, Comparison of different pretreatments for seawater desalination, Desalin. Water Treat. 32 (2011) 339–344.
[9] S. Kim, I.S. Lee, K.J. Kim, D.M. Shon, L.S. Kang, Dual media filtration and ultrafiltration as pretreatment options of lowturbidity seawater reverse osmosis processes, Desalin. Water Treat. 33 (2011) 329–336.
[10] J.L. Lim, N.S. Park, S. Kang, C.H. Kim, S. Lee, S. Kim, Iron and manganese fouling in microfiltration as a pretreatment of seawater reverse osmosis processes, Desalin. Water Treat. 33 (2011) 323–328.
[11] M. Wilf, M.K. Schierach, Improved performance and cost reduction of RO seawater systems using UF pretreatment, Desalination 135 (2001) 61–68.
[12] G.K. Pearce, UF/MF pre-treatment to RO in seawater and wastewater reuse applications: A comparison of energy costs, Desalination 222 (2008) 66–73.
[13] D. Cha, H. Park, S. Kim, J.L. Lim, S. Kang, C.H. Kim, A statistical approach to analyze factors affecting silt density index (SDI), Desalin. Water Treat. 45 (2012) 276–283.
[14] S. Kim, M. Marion, B.H. Jeong, E.M.V. Hoek, Crossflow membrane filtration of interacting nanoparticle suspensions, J. Membr. Sci. 284 (2006) 361–372.
[15] S. Kim, E.M.V. Hoek, Interactions controlling biopolymer fouling of reverse osmosis membranes, Desalination 202 (2007) 333–342.
[16] S. Lee, S. Kim, J. Cho, E.M.V. Hoek, Natural organic matter (NOM) fouling due to foulant-membrane physicochemical interactions, Desalination 202 (2007) 377–384.
[17] S. Kim, S. Lee, C.H. Kim, J. Cho, A new membrane performance index using flow field flow fractionation (fl-FFF), Desalination 247 (2009) 162–168.
[18] L.S. Tam, T.W. Tang, G.N. Lau, K.R. Sharma, G.H. Chen, A pilot study for wastewater reclamation and reuse with MBR/RO and MF/RO systems, Desalination 202 (2007) 106–113.
[19] K.J. Hwang, C.Y. Liao, K.L. Tung, Effect of membrane pore size on the particle fouling in membrane filtration, Desalination 234 (2008) 16–23.
[20] A. Subramani, S. Kim, E.M.V. Hoek, Pressure, flow, and concentration profiles in open and spacer-filled membrane channels, J. Membr. Sci. 277 (2006) 7–17.
[21] S. Kim, E.M.V. Hoek, Modeling concentration polarization in reverse osmosis processes, Desalination 186 (2005) 111–128.
[22] X. Jin, A. Jawor, S. Kim, Eric.M.V. Hoek, Effects of feed water temperature on separation performance and organic fouling of brackish water RO membranes, Desalination 239 (2009) 346–359.
[23] ASTM D-4516, Standard practice for standardizing reverse osmosis performance data, American Society for Testing and Materials, 2010.
[24] C.K. Teng, M.N.A. Hawlader, A. Malek, An experiment with different pretreatment methods, Desalination 156 (2003) 51–58.