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Osmotic pressure-driven backwash in a pilot-scale reverse osmosis plant

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ABSTRACT

Osmotic backwash is a physical cleaning method based on water back flow from the permeate side to the feed side driven by osmotic pressure difference across reverse osmosis (RO) membrane. The concept of osmotic backwash was already introduced and verified in laboratory-scale experiments by a few previous studies. In this study, osmotic backwash observed in an RO pilot plant isdiscussed. The pilot plant was originally designed to demonstrate industrial water production with the capacity of 250 m^3/d and the recovery rate of 95.5%. Osmotic backwash was observed accidentally when the plant was stopped, fixed, and re-operated by an unpredictable failure. Osmotic backwash started at the stop of RO operation when applied pressure was dropped below the osmotic pressure. An RO performance analysis with normalized parameters was used to quantify the effect of osmotic backwash. The reduction of fouling was quantified before and after osmotic backwash, but it was limited to remove all the foulants on the RO membrane surface.

Keywords: Reverse osmosis; Osmotic backwash; Membrane fouling; Pilot plant

1. Introduction

As one of the best solutions to the water shortage problem, desalination using reverse osmosis (RO) membrane is a very promising technology. The most important issue in RO membrane process is fouling by inorganic particles, organic matters, and biomolecules [1,2]. Although there are strict water quality standards for RO feed such as Silt Density Index (SDI) and Membrane Fouling Index [3–8], the RO membrane fouling is an inevitable problem.

Membrane cleaning is one of the most practical methods to decrease fouling in RO process. In the case of microfiltration (MF) and ultrafiltration (UF) processes, backwash is introduced as an essential step to minimize fouling. Backwash is a physical cleaning method where cleaning water opposite to the filtration direction sweeps foulants attached to the membrane surface and pores away. However, in RO processes, mechanical pressure-driven backwash is not generally considered, because permeate (product) channel in the spiral wound RO element can be broken in the presence of high pressure as explained in Fig. 1 [9].

A cross-sectional view of the permeate and backwash flow patterns in an unwound membrane leaf of spiral wound RO element is presented in Fig. 1 Each

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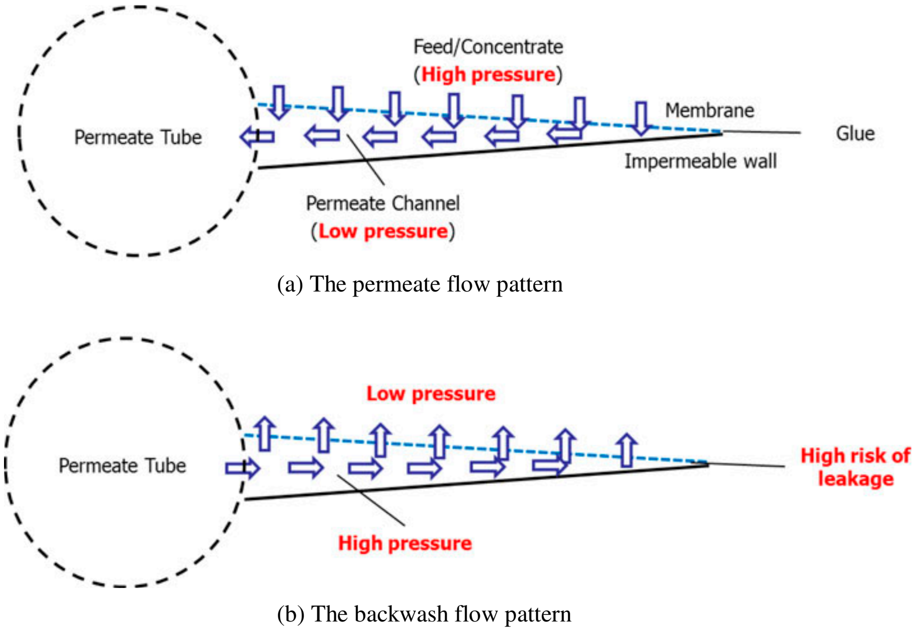


Fig. 1. A cross-sectional view of flow patterns in an unwound membrane leaf of spiral wound RO element.

membrane leaf consists of the membrane and the impermeable walls. One end of both walls is attached to the permeate tube, and the other end is closed by a glue. During filtration, water penetrates through the membrane wall and then moves to permeate tube across permeate channel inside the leaf. If backwash operation is carried out by mechanical pressure, both the permeate tube and channel are in a high pressure to produce water back flow to clean the membrane. Because the permeate tube and channel are not designed to resist high pressure, they are exposed to the danger of breakage.

Instead, osmotic backwash can be a good strategy to decrease fouling in RO processes. Osmotic backwash is based on water back flow from the permeate side to the feed side driven by ion concentration differences (i.e. osmotic pressure) across the RO membrane [10–13]. Sometimes high-salinity solution can be used to produce the osmotic pressure gradient for osmotic backwash [14]. When permeate water flows back to the feed channel, it dilutes concentration polarization layer and helps to cleaning the membrane surface to resume its original flow rate. The mechanism of osmotic backwash was discussed in previous studies [10–14] with a small scale experiment using a single spiral wound RO element.

There are few studies to report osmotic backwash phenomena in a pilot- or real-scale RO plant. The key finding of this study is osmotic backwash in an RO pilot plant, which is designed for demonstration of industrial water production using RO processes. The effect of osmotic backwash was quantified using RO performance analysis with normalized parameters such as normalized pressure difference (NPD) and membrane resistance [15,16].

2. Methods

2.1. RO pilot plant

The RO pilot plant used in this study was operated for one year. The main objective of the plant was to demonstrate industrial water production. The pilot data were used to find the optimal operation strategy of a full-scale RO system to produce cooling water for an ironworks. Total dissolved solids (TDS) concentration of raw water varied from 100 to 500 mg/l, and the water quality demand for the cooling water was less than 50 mg/l, which is the reason why a brackish water RO system was designed to meet the demand of the ironworks.

The capacity of the pilot system was 250 m^3/d, and it was composed of two independent RO stages with recovery rates of 85 and 70%, respectively. Since the concentrate of the first stage was used as feed water for the second stage, the recovery rate of the whole pilot system was 95.5% (i.e. $0.85 + 0.15 \times 0.7 = 0.955$). The pressure vessel (PV) array of the first stage was 4:2:1 and that of the second one was 2:1 as shown in Fig. 2. In this study, we used the operation data obtained from the first-stage RO system.

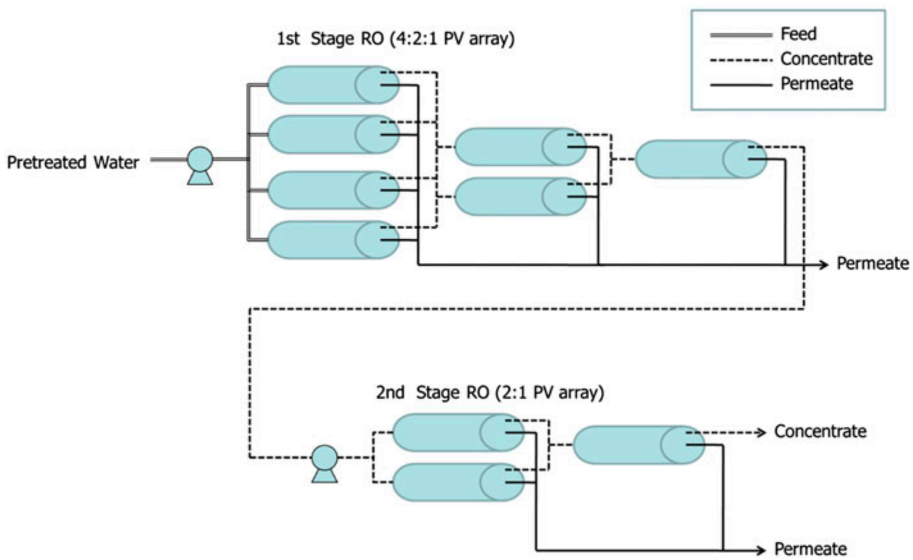


Fig. 2. The flow diagram of the RO pilot plant.

2.2. RO performance analysis

In order to quantify the effect of fouling in a pilot- or real-scale RO plant, RO performance parameters need to be calculated because parameters affecting RO permeate flux are not controlled as in the case of laboratory-scale experiments. There are several normalized parameters to analyze RO performance introduced in ASTM D-4516 [15]. In this study, NPD and membrane resistance were selected as RO performance parameters.

NPD is a parameter to quantify RO fouling. The increase in NPD indicates the decrease in the actual feed channel height by the increase in fouling layer thickness. NPD is calculated using Eq. (1) [16].

$$\mathrm{NPD} = (P_{\mathrm{in}} - P_{\mathrm{out}})\frac{(Q_{f,n} + Q_{c,n})^{1.5}}{(Q_{f,o} + Q_{c,o})^{1.5}} \quad (1)$$

where P_{in} and P_{out} are pressures at the entrance and exit of RO pressure vessels, respectively, and Q_f and Q_c are feed and concentrate flow rates, respectively. The subscripts n and c in Eq. (1) mean normalized and observed values, respectively.

Membrane resistance is the opposite concept to the normalized permeate flow rate introduced in ASTM D-4516 [15,17]. It means hydraulic resistance to membrane permeation velocity. Higher applied pressure is necessary to keep a constant permeation velocity when membrane resistance becomes higher as a result of membrane fouling. Theoretically, membrane permeation velocity (v_w) can be calculated using Eq. (2).

$$v_m = \frac{\Delta P - \Delta \pi_m}{\mu(R_m + R_c)} \quad (2)$$

where ΔP is transmembrane pressure, $\Delta \pi_m$ osmotic pressure difference, μ viscosity, and R_m and R_c are hydraulic resistance of intrinsic membrane and membrane fouling (cake) layer, respectively. Equation (2) can be converted to a field-specific form as described in Eq. (3).

$$Q_p = \frac{\Delta P - \Delta \pi_m}{\mathrm{TCF} \cdot R} \quad (3)$$

where Q_p is permeate flow rate, TCF a temperature correction factor, and R is the field-specific membrane resistance (the membrane resistance hereafter). Eq. (4) is a re-arrangement of Eq. (3) to calculate R.

$$R = \frac{\Delta P - \Delta \pi_m}{\mathrm{TCF} \cdot Q_p} \quad (4)$$

where the unit of the membrane resistance is the ratio of the unit of pressure to the unit of flow rate, which is different from the unit of theoretical membrane resistance such as R_m and R_c (i.e. m^{-1}). It is more convenient for RO operators to apply the membrane resistance rather than the theoretical one, because the former can be directly calculated using field raw data such as pressure, feed and permeate TDS concentrations, feed temperature, and permeate flow rate. In field applications, transmembrane pressure (TMP; ΔP) can be obtained by monitoring inlet and outlet pressures (P_{in} and P_{out}) permeate pressure (P_p) as described in Eq. (5).

$$\Delta P = \frac{P_{in} + P_{out}}{2} - P_p \tag{5}$$

TCF is calculated using Eq. (6).

$$\mathrm{TCF} = \exp\left[\mathrm{A}\left(\frac{1}{273 + \mathrm{T}} - \frac{1}{298}\right)\right] \tag{6}$$

where T is feed temperature and A is a constant related to RO membrane characteristics. Osmotic pressure difference ($\Delta\pi_m$) can be described as an empirical function of feed temperature (T), feed TDS concentration (C_f), and recovery rate (r) as explained in Eq. (7).

$$\Delta\pi_m = f_{os}(c_m - c_p) \approx \frac{C_{fc}\,(T + 320)}{491{,}000} \text{ for } C_{fc} < 20{,}000 \text{ mg/l} \tag{7a}$$

$$\Delta\pi_m \approx \frac{0.0117\,C_{fc} - 34}{14.23} \times \frac{T + 320}{345} \text{ for } C_{fc} \geq 20{,}000 \text{ mg/l} \tag{7b}$$

$$C_{fc} = C_f \cdot \frac{\ln\frac{1}{1-r}}{r} \tag{7c}$$

$$r = \frac{Q_p}{Q_f} \tag{7d}$$

where C_{fc} and Q_f are feed-concentrate TDS and feed flow rate, respectively. Using Eqs. (4–7), membrane resistance (R) can be calculated from the operation data including pressures, TDS, and flow rates as described in Eq. (8).

$$R = \frac{\frac{P_{in} + P_{out}}{2} - P_p - \frac{C_f \cdot \frac{\ln\frac{1}{1-r}}{r}(T + 320)}{491{,}000}}{Q_p \exp\left[\mathrm{A}\left(\frac{1}{273+\mathrm{T}} - \frac{1}{298}\right)\right]} \tag{8}$$

Since the feed water TDS is less than 500 mg/l and the recovery rate is 95.5%, feed-concentrate TDS should be less than 20,000 mg/l in the pilot system. This is the reason why we used Eq. (7a) to describe osmotic pressure difference. For the calculation of membrane resistance in this study, the units for pressures, concentrations, and flow rates were bar, mg/l, and m^3/h, respectively.

3. Results and discussion

3.1. Water quality

The raw water source for the pilot plant was Asan Lake, South Korea, which was located close to a coastal area. Thus salt from the sea intruded the lake during the dry season. This is the reason why raw water TDS varies from 100 to 500 mg/l as shown in Fig. 3. Raw water temperature also varied from 4 to 27°C because of seasonal change. Raw water was taken to a sedimentation basin with an aluminium-based coagulant (poly aluminum chloride) and then treated by a fiber filtration process in order to meet the RO feed water standard (i.e. SDI < 5). Table 1 shows the water quality data of raw water, supernatant water after the coagulation/sedimentation process, and RO feed water.

3.2. Raw operation data

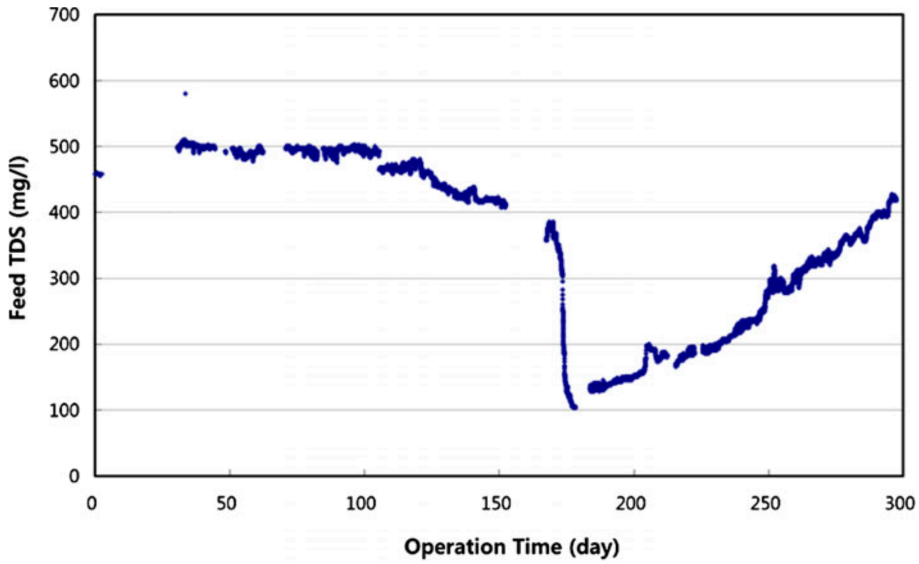
Fig. 4 shows the product TDS, feed/product flow rates, and TMP of the first-stage RO system during the operation period. First, permeate TDS was less than 50 mg/l during the operation period so that the product can meet the demand of the ironworks as discussed earlier. The water production rate was not maintained at the designed value (= 7.9 m^3/h), which means that the system was not operated stably, although RO feed water quality met the SDI. This is because the pilot plant was operated without human operators, and there were frequent troubles in the chemical injection system for RO system.

TMP varied from 8 to 19 bar. In general, the increase in TMP has several meanings such as fouling, the decrease in temperature, the increase in the osmotic pressure drop (i.e. the increase in feed TDS and/or recovery rate of the system) and so forth. Therefore, we cannot quantify the amount of RO membrane fouling with the raw operation data only, which is the reason why RO performance analysis is necessary.

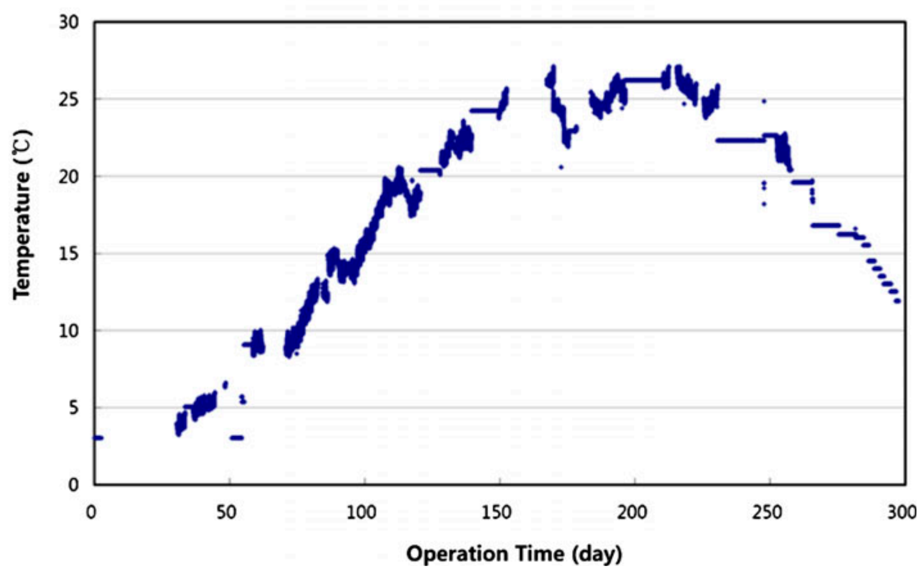
3.3. RO performance analysis and osmotic backwash

NPD and membrane resistance were calculated using Eqs. (1,8) with using applied pressure, empirical osmotic pressure, permeate flow rate, and TCF. The increases in NPD and membrane resistance mean the build-up of fouling or scaling layers on the RO membrane surface.

Fig. 5 shows changes in NPD and membrane resistance during the operation period. Cleaning in place (CIP; cleaning the fouled RO membranes using chemicals) was carried out three times. Both NPD and



(a) Feed water TDS



(b) Feed water temperature

Fig. 3. The feed water quality and temperature for the RO pilot plant.

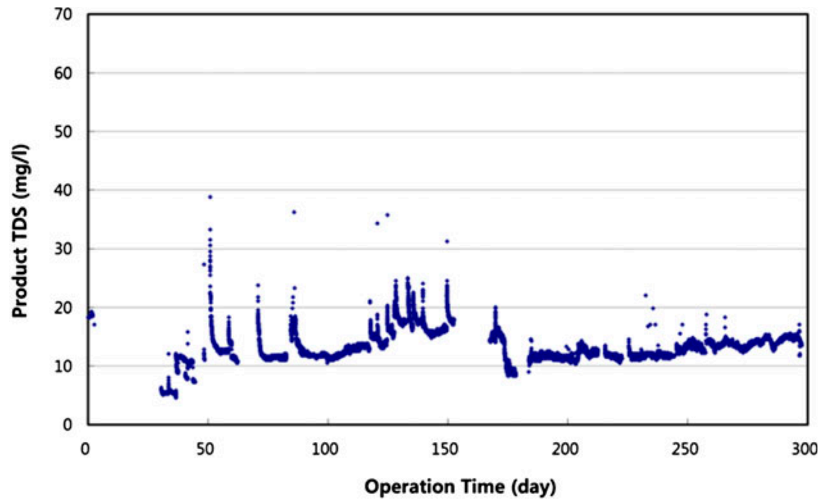
Table 1
Water quality summary

Parameters	Raw water	Supernatant water	RO feed water
Turbidity (NTU)	10–190	0.13–1.82	0.02–0.26
DOC[a] (mg/l)	1.91–5.78	3.05–4.98	3.12–4.42
SDI	>6.66	>6.66	<5
TDS (mg/l)	100–500		
Temperature (℃)	4–27		

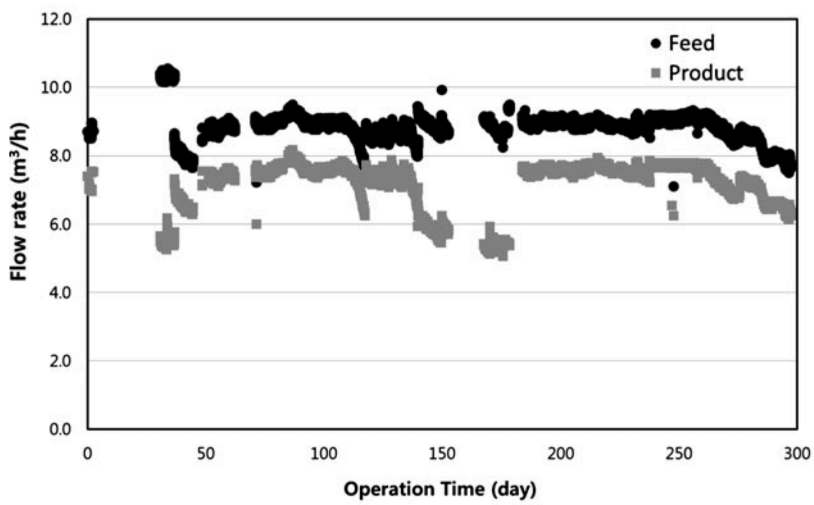
[a]DOC: Dissolved organic carbon.

membrane resistance show the trend of fouling more clearly than the raw operation data. Fouling occurred during a period between two adjacent CIPs (i.e. NPD and membrane resistance increased during the period) and decreased just after a CIP as shown in Fig. 5.

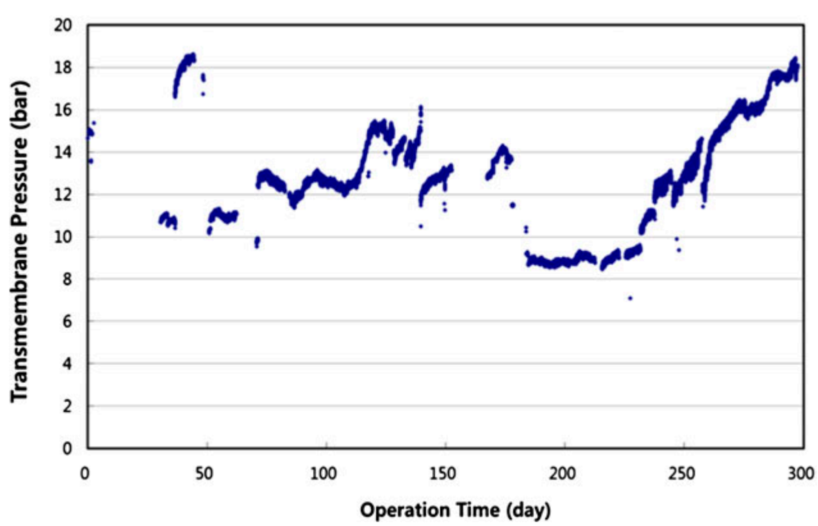
Osmotic backwash was accidentally observed when the system was stopped suddenly with a failure between the 117th and 118th operation day as shown in Fig. 6. A huge drop in NPD (i.e. about 2.5 bar and 50% of original value) was observed after the sudden stop of the system. Membrane resistance also decreased from 1.7 to 1.4 during the same period.



(a) Product (permeate) TDS



(b) Feed and product flow rate



(c) Transmembrane pressure (TMP)

Fig. 4. The first stage-RO system operation data: product water quality, flow rate, and TMP.

Theoretically, the osmotic pressure gradient from permeate to feed/concentrate side becomes dominant to produce water back flow when applied pressure has gone. In addition, fouling parameters like NPD and membrane resistance represented considerable decreases when the applied pressure was gone and re-applied as shown in Fig. 6, and the water table in permeate tank was slightly higher than the highest position of RO membrane elements. Therefore, we regarded this phenomenon as osmotic backwash.

After the first observation of osmotic backwash, we introduced osmotic backwash by intentionally stopping and re-starting the system. The osmotic backwash frequency was once a day. As shown in Fig. 5, osmotic backwash was applied to the system for about four months. Osmotic backwash can decrease the fouling rate but is limited to wash off all the foulants on the membrane surface as shown in the operation period between the first and second CIP because the timing of the osmotic backwash introduction was too late. However, it will be very effective to apply osmotic backwash from the initial stage of RO system operation. After the second CIP, RO membrane fouling was hardly observed, while osmotic backwash was

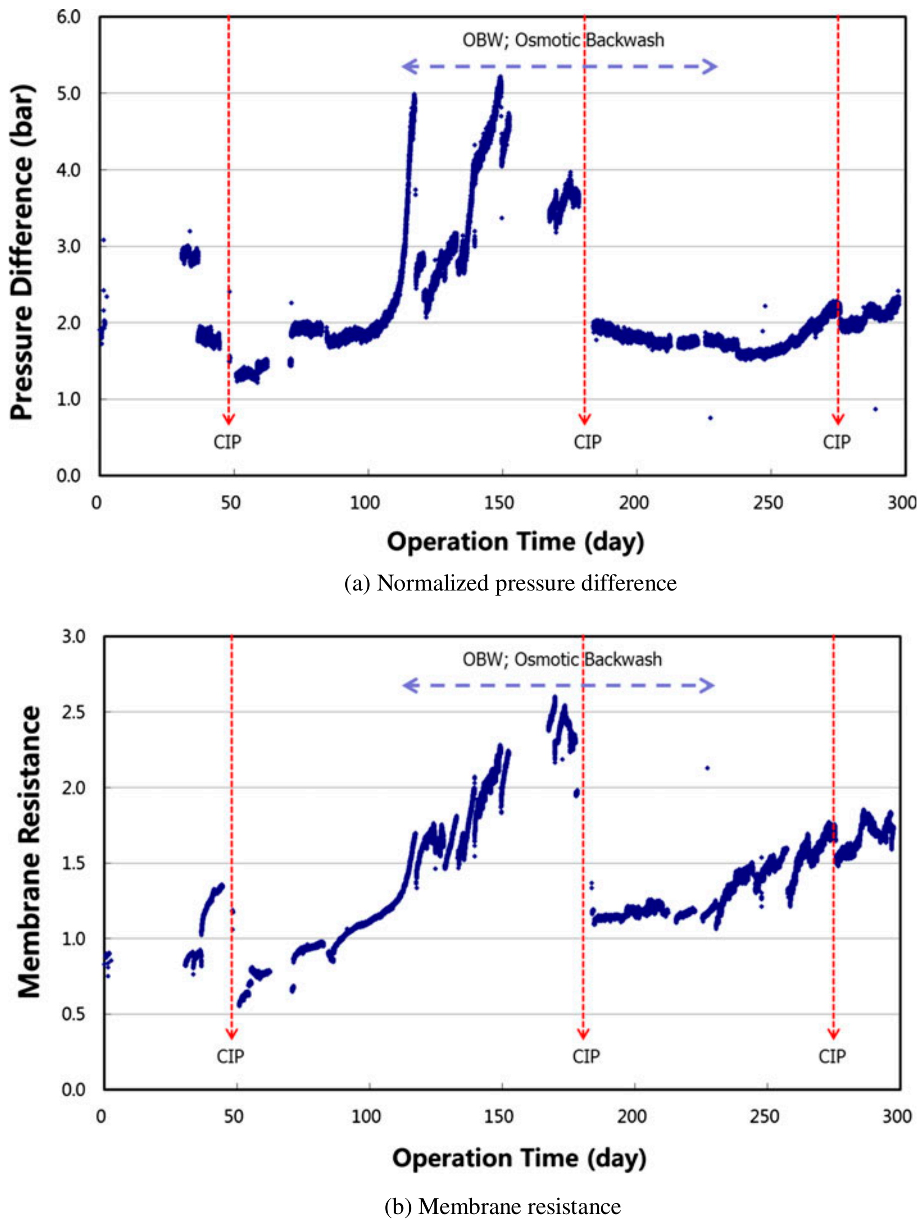
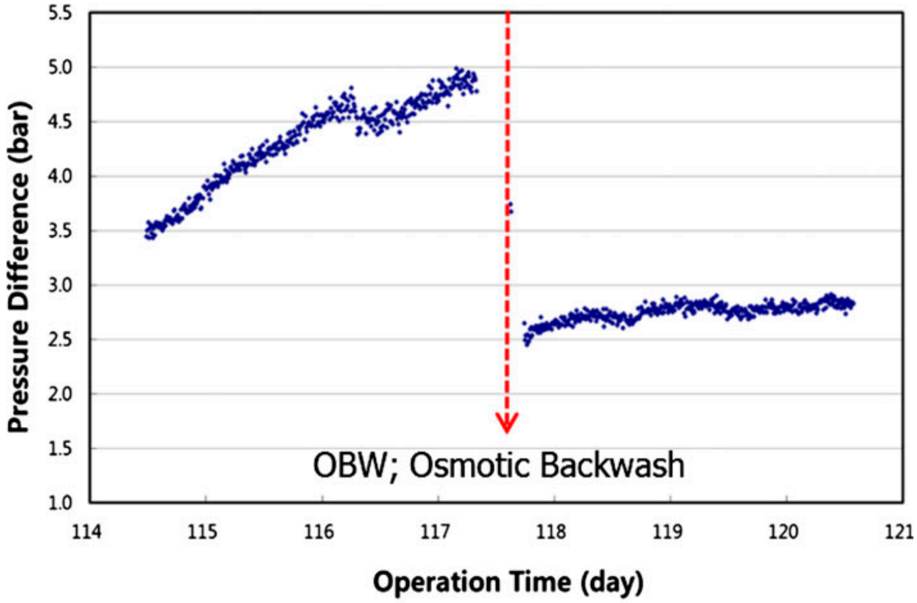
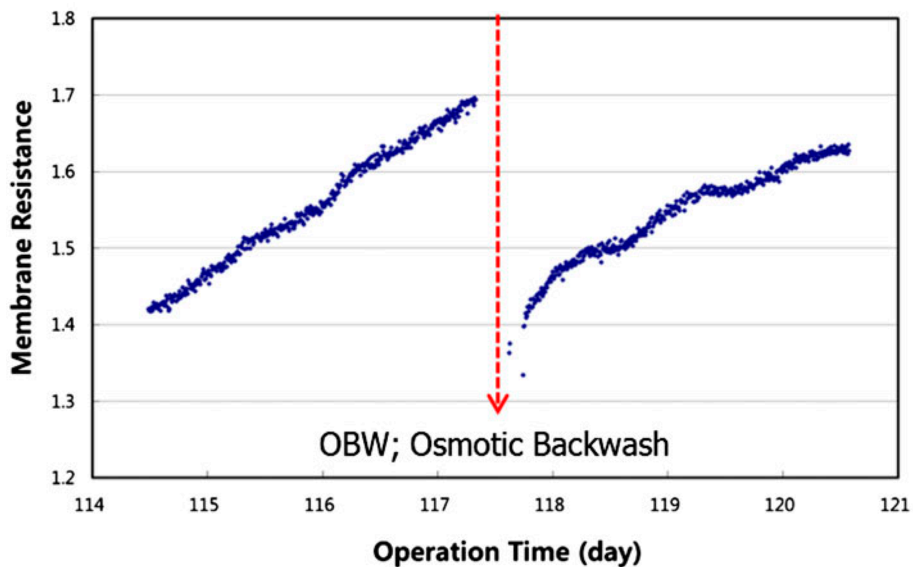


Fig. 5. The RO performance data including CIP and osmotic backwash period.



(a) Normalized pressure difference



(b) Membrane resistance

Fig. 6. The effect of osmotic backwash on the RO performance data.

applied as shown in Fig. 5. Therefore, it will be most efficient for osmotic backwash to be applied to an RO operation as early as possible.

4. Conclusions

Osmotic backwash is not a new concept but was already introduced in previous studies [10–14]. But there have been few researches reporting this phenomenon occurring in a pilot- or real-scale RO plant. In this research work, osmotic backwash was observed in a pilot-scale RO pilot system that was tested to demonstrate industrial water production. Osmotic backwash started at the stop of the RO operation when applied pressure was dropped below the osmotic pressure difference across membrane.

RO performance analysis with normalized parameters (NPD and membrane resistance) was used to quantify fouling phenomena and the effect of osmotic backwash from the raw operation data (TMP, feed/permeate flow rates, and water quality). NPD and membrane resistance were decreased as osmotic backwash happened. However, the effect of osmotic backwash is limited to wash off the fouled membrane surface by itself as in the case of mechanical backwash in dead-end MF or UF system.

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