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Effects of cleaning conditions of osmotic backwashing on the SWRO operation

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ABSTRACT

The cleaning-in-place method, which is most widely used to remove foulants and maintain the performance of membrane, needs a period of downtime for frequent operation stoppage, which reduces the membrane lifetime, and creates environmental issues related to waste chemicals disposal. On the other hand, the osmotic backwashing induced by the osmotic pressure of maintenance cleaning methods in the seawater reverse osmosis (SWRO) membrane can reduce the number of chemical agents needed and reduce the load on the pretreatment. The cleaning efficiency is affected by various factors such as the total dissolved salt (TDS) of NaCl solutions, backwashing time, and cycle of backwashing during osmotic backwashing. In this study, the cleaning efficiency and the change of backwashing volume were analyzed according to the TDS of the NaCl solutions, backwashing time, and cycle of backwashing. As a result, the cleaning efficiency was improved with an increase in the TDS of NaCl solutions; however, it did not change after a certain point due to the irreversible resistance of the fouling, although the backwashing time increases. Therefore, the optimal backwashing cycle at which the irreversible resistance increase rate was the lowest was confirmed through changes of the backwashing cycle.

Keywords: Cleaning conditions; Maintenance cleaning; Osmotic backwashing; Seawater reverse osmosis

1. Introduction

In the reverse osmosis (RO) process of seawater desalination, various efforts have been made to eliminate the unavoidable phenomenon known as fouling [1]. In general, fouling causes a reduction in production quantity, an increase in operating pressure, a reduction of permeate water quality, and physiochemical damages to membranes. Therefore, methods such as strengthening the pretreatment process to control the fouling of the RO process and recovering RO through chemical cleaning to eliminate intensified fouling have been used [2–6].

Currently, research on fouling controls has been progressing consistently, leading to an increased interest in osmotic backwashing in terms of reduced maintenance. In contrast to regular backwashing in low pressure membrane processes (microfiltration and ultrafiltration), osmotic backwashing is carried out using a very low operating pressure, where osmotic pressure due to the high salinity in raw water is used as the drive pressure. As a result, the power needed to operate a separate pump is eliminated, and effective backwashing is possible by applying raw water and concentrated water to control the osmotic pressure [7–15]. In addition, osmotic backwashing can be carried out in combination with chemical cleaning or by new effective operating methods. The effect of the reduction of fouling is maximized, leading to several benefits including stable RO process management, effective and economical maintenance and administration, and decrease of production cost due to the decrease in initial investment cost.

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Avraham et al. [8] researched the effects of osmotic backwashing according to inflow water concentration, particularly the effects of feed water concentration polarization. They confirmed that as the bulk concentration and membrane surface concentration of raw water during osmotic backwashing increased, the volume of backwashing also increased.

Qin et al. [9–11] implemented osmotic backwashing by generating an osmotic pressure that was greater than that of the drive pressure, without shutdown of operation by injecting NaCl in raw water during osmotic backwashing. They then applied the conditions to the brackish water reverse osmosis (BWRO) process using an operation mode by implementing tests on several operating conditions during long-term operation [9–11].

Their research focuses on osmotic backwashing with bittern injection in raw water and thus needs a separate salt collecting facility. Consequently, economical feasibility and operating efficiency can be compromised to a certain extent. In addition, the BWRO process is operated using a relatively lower pressure than the seawater reverse osmosis (SWRO) process; therefore, the cleaning efficiency due to NaCl injection of the SWRO process was higher. However, when their approach is applied to the SWRO process, cleaning efficiency is expected to be compromised due to the high operating pressure.

Sagiv et al. [12–15] researched the mechanisms produced under several conditions during osmotic backwashing. Especially, they investigated the effects of concentrated polarization in feed and permeate side.

However, an effective evaluation for an SWRO desalination plant according to the cleaning conditions of osmotic backwashing applicable to the SWRO process has not been realized until now. In addition, the research results obtained by Qin et al. [9–11] are problematics in terms of efficiency in application to the seawater desalination process, and research has not yet progressed on this aspect. Therefore, analysis on a variety of feed water conditions and cleaning times is needed to evaluate the effects of osmotic backwashing.

By eliminating irreversible fouling through periodic osmotic backwashing, permeate water quality can be increased, and inorganic fouling due to concentration polarization as well as irreversible fouling due to reversible fouling intensification can be delayed. However, frequent osmotic backwashing reduces permeate water production in the RO process and increases the permeate water volume consumed during backwashing, which reduces recovery. As a result, an effective cleaning condition and optimization of backwashing cycles are necessary.

For a more effective and optimized osmotic backwashing process operation, studies have been carried out on the effects of osmotic backwashing occurring under a variety of operating conditions, such as raw water concentration, cleaning time, cleaning period, cleaning moment, and cleaning time during cleaning.

2. Materials and methods

2.1. Organic foulants

In this study, humic acid (hydrophobic, Sigma-Aldrich (USA)) and sodium alginate (hydrophilic, Sigma-Aldrich (USA)) were used as organic foulants. Each organic foulant was dissolved in deionized water and passed through a 0.45-μm filter to make the stock solutions. In order to minimize the effects of osmotic backwashing due to the characteristics of each organic matter, two organic matters were mixed at the ratio of 1:1.

2.2. RO membrane

An RO membrane (Woongjin Chemical Co., Ltd., republic of korea) was used by disassembling the flat-type RO membrane to become a spiral-wound-type RO membrane. The membrane material was polyamide, which has limitations due to the weak chemical resistance of Cl^- and weak the propagation of microorganisms. A conservative solution was used with a mixture of 20% propylene glycol and 1% sodium bisulfate to store the membrane. Table 1 shows the characteristics of the SWRO membrane used in this study.

2.3. Membrane operation system

The spiral-wound-type RO membrane was broken up, cut, and used as a flat-type RO membrane. The lab-scale equipment of RO was the SEPA® CF II of GE and was integrated with a high-pressure pump (inflow pipe: 10 mm), impeller, temperature controller, digital press meter, and flow meter (Fig. 1). An NaCl solution vessel was installed so that the NaCl solution instead of the raw water flows into the membrane during osmotic backwashing. In addition, a digital balance was used to measure the permeate flux and the backwashing flux on the permeate side of the membrane. The membrane surface is 0.0126 m^2, and the spacer (thickness: 2 mm) was installed in the feed side. The equipment could operate automatically and continuously.

2.4. Osmotic backwashing protocols

After stabilizing the RO membrane using the distilled water, an experiment was carried out to examine the occurrence of fouling. In raw water conditions of total dissolved salt (TDS) 35,000 mg/L and 25°C, a 10 mg/L mixture of humic acid and sodium alginate was injected into raw water. The operating pressure and circulation flow during the experiment were fixed at 4 MPa and 1 L/min, respectively. When the flux was reduced by 10% of its initial value, osmotic backwashing was carried out under various conditions. The osmotic backwashing method can be classified into two types: (1) decreasing operating pressure to 0, or to less than the osmotic pressure and (2) injecting a high concentration of salt while maintaining the operating pressure. In this study, the first method of removing inflow pressure was used. To minimize the influences while changing filtration into backwashing, the operating pressure was sharply decreased to 0, and a fixed concentration and temperature were maintained through continuous circulation to prevent changes in osmotic pressure [7].

2.5. Equations

Eq. (1) was proposed by Korea Water & Wastewater Works Association to calculate osmotic pressure of high concentration of NaCl solution:

Table 1
Characteristics of the SWRO membrane

Model	RE4040-SH
Material (surface charge)	PA (negative)
Permeate flow rate (m^3/d)	3.8
Stabilized salt rejection (%)	99.75
Max. operating pressure (MPa)	8.27
Membrane resistance (m^{-1})	1.18789×10^{13}

Note: 32,000 mg/L NaCl solution at 800 psig (5.5 MPa) applied pressure, 8% recovery, 77°F (25°C), and pH between 6.5 and 7.0.

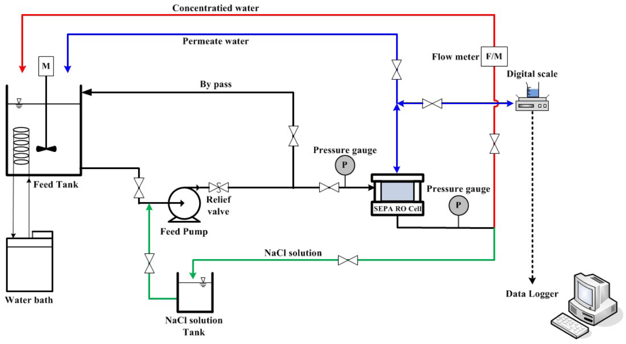

Fig. 1. Schematic diagram of the cross-flow RO membrane test unit.

$$\pi = \frac{0.2626 \times (273.15 + T) \times C}{(1000 - \frac{C}{1000})} \tag{1}$$

where T is the temperature (°C); C is the concentration of NaCl (mg/L); and π is the osmotic pressure (kPa).

The osmotic pressure of the permeate was calculated using Van't Hoff equation (Eq. (2)) due to the low concentration [16]:

$$\pi = iMRT \tag{2}$$

where i is the Van't Hoff factor (for NaCl, $i = 2$); M is the molarity (mol/L); R is the gas constant (0.0821 L atm/K mol); and T is the Kelvin temperature (K).

Total filtration resistance (R_T) was subdivided as shown in the following equation:

$$R_T = R_m + R_{ob} + R_i \tag{3}$$

where R_m is the membrane resistance (m^{-1}); R_{ob} is the reversible resistance (m^{-1}); and R_i is the irreversible resistance (m^{-1}).

While osmotic backwashing (m^{-1}) removes R_{ob}, it does not remove R_i.

The following assumptions were made to classify $\Delta\pi$ and R_T:

- $\Delta\pi$ is only affected by NaCl concentration.
- R_T is affected by colloid materials.

3. Results and discussion

3.1. Cleaning efficiency according to the cleaning time and NaCl solution

In general, an NaCl solution is almost constant because raw water is used as the circulated water during osmotic backwashing. In this study, experiments were conducted under various NaCl solutions because concentrated water (brine) could be used as the circulated water. In the case of using concentrated water as circulated water, the cleaning efficiency is changed because the applied osmotic pressure differs from that when using various NaCl solution. Cleaning efficiencies under various osmotic backwashing conditions were analyzed according to the operating time.

To confirm the cleaning efficiency, 10 mg/L of a mixture of humic acid and sodium alginate was injected, under conditions of TDS 35,000 mg/L, circulation flux 1 L/min, and 25°C. When the flux decline rate (FDR) was 10%, osmotic backwashing was performed to analyze the cleaning efficiency of the osmotic backwashing at the same fouling rate in the conditions of TDS 35,000, 50,000, and 70,000 mg/L of NaCl solutions. The TDS of backwashing water was fixed at 300 mg/L in the experiment.

The results of flushing are shown in Table 2. It is difficult to predict the cleaning efficiency in the case of flushing because fouling occurrence is hindered in the cross-flow operation. However, with time, consolidated fouling matters due to operation pressure loosen, and the cleaning efficiency is confirmed. This also suggests that the removal efficiencies of fouling by osmotic backwashing are affected by the shear force due to circulation flow. In addition, Table 2 presents the relationship between the change of NaCl solution and the backwashing volume during osmotic backwashing. The inflow backwashing volume increases according to the TDS of the NaCl solution and cleaning time. Also, the increase of permeate TDS after osmotic backwashing is proportional to the TDS of the NaCl solution and cleaning time. Sagiv and Semiat [12] found that salt concentration has the strongest effect on backwashing volume. Avraham et al. [8] showed that the accumulated backwashing volume increased when the solution concentration was increased to a certain level and then decreased. This is attributed to the secondary concentration polarization layer at the permeate side.

It is estimated that as the concentration of NaCl solution increases, the value of $\Delta\pi$ also increases, leading to higher drive pressure during backwashing, and hence, the cleaning efficiency is increased. However, although the cleaning efficiency was fixed, the contaminated membrane cannot be cleaned completely with osmotic backwashing, and irreversible fouling removal must be performed through further chemical cleaning. The effects of changes in the osmotic backwashing cycle are analyzed to determine the cleaning cycle, which minimizes the increase of irreversible fouling.

When the relationship between cleaning efficiency and the volume of backwashing water inflow during osmotic backwashing is examined, it was confirmed as shown in Table 2 that cleaning efficiency does not change when the volume of backwashing water was increased. Therefore,

Table 2
Comparison of cleaning efficiency, concentrating rate, and backwashing water volume according to osmotic backwashing time categorized by the TDS of the NaCl solution

Back washing time (min)	NaCl solution TDS									
	Flushing	35,000 mg/L			50,000 mg/L			70,000 mg/L		
	CE (%)	CE (%)	BV (mL)	CR (%)	CE (%)	BV (mL)	CR (%)	CE (%)	BV (mL)	CR (%)
15	0	13.8	17.8	175.0	15.0	18.1	190.0	18.6	25.1	257.0
30	0	18.3	22.0	181.0	20.0	27.4	223.0	32.8	28.7	304.0
45	0	22.0	26.1	195.0	27.0	29.7	251.0	37.1	33.2	313.0
60	10.1	22.0	30.2	204.0	33.0	33.9	261.0	45.1	38.6	342.0
75	15.8	23.0	33.8	214.0	32.7	35.8	272.0	52.5	46.7	353.0
90	14.9	22.4	35.9	221.0	33.2	37.1	277.0	52.1	52.7	366.0

Note: CE: cleaning efficiency, BV: backwashing volume, and CR: concentrating rate.

along with the reduction in the rate of inflow due to the concentration polarization of the permeate water side, cleaning using the drive pressure of $\Delta\pi$ that was generated during osmotic backwashing is limited.

An increase of NaCl solution led to a subsequent increase of $\Delta\pi$, allowing for the easier removal of reversible fouling during osmotic backwashing. It is possible that cleaning efficiency could be increased further by increases in $\Delta\pi$ if the TDS of the NaCl solution was increased further. However, this is ultimately believed to have limitations due to irreversible fouling. Also, the cleaning efficiency increased along with increases in cleaning time, but the effects after a certain point were negligible and this is estimated to be due to the limitation of osmotic backwashing for irreversible contaminations. Therefore, high TDS of inflow water and long cleaning times can provide increases in cleaning efficiency, but can also cause a reduction of productivity in cleaning cost and the SWRO process. Therefore, TDS of inflow water and cleaning time should be determined after sufficient consideration.

3.2. *Cleaning efficiencies of osmotic backwashing according to cleaning cycle*

The previous experiment confirmed that irreversible fouling was not able to be removed even with increases in cleaning time or raw water TDS concentration during osmotic backwashing. In general, when the concentration of organic matters on the membrane surface is excessive, cake and gel layer formations are reported to cause irreversible fouling [17].

Accordingly, an extension of the operation period could be possible by removing the irreversible fouling source through a periodic osmotic backwashing process; the removal of this source is expected to delay irreversible fouling production. Therefore, tests to analyze the effects of changes in the cleaning period on irreversible fouling were carried out, and ultimately, the cleaning period with the least increase in irreversible fouling can be identified.

To determine the cleaning efficiency, a 10 mg/L mixture of humic acid and sodium alginate was injected into raw water under TDS of 35,000 mg/L, a circulation flow of 1 L/min, and 25°C. In order to estimate irreversible fouling, the osmotic backwashing was applied under the condition of the lowest cleaning efficiency in the previous experiment. Cleaning cycles were performed at intervals of 4, 8, 12, and 24 h, and the experiments were carried out for each condition.

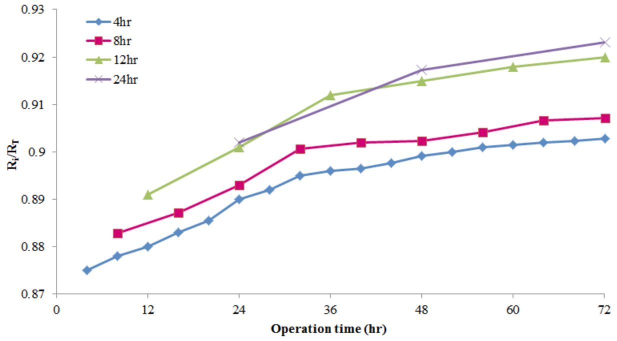

Fig. 2. R_i/R_T according to each cleaning period.

In the case of the operation without osmotic backwashing, FDR shows 24% and the decrease rates of the test groups improved with a longer cleaning time. Fig. 2 shows the R_i/R_T value to identify the increase of irreversible fouling. When looking at the slope of the graph according to the increases in irreversible fouling through the drift curve in Table 3, the 4- and 8-h intervals did not significantly differ, while the other intervals showed relatively sharp slopes of irreversible fouling.

Fig. 3 presents the cleaning efficiency categorized according to each cleaning period. Under equal cleaning conditions, the cleaning efficiency was affected by the cleaning period. Particularly, as shown in Fig. 4, the effects due to cleaning moment were substantial, but the cleaning efficiency decreased rapidly as fouling progressed further. Therefore, equal cleaning conditions should be maintained in order to either reduce the cleaning period or change the cleaning conditions to limit decreased cleaning efficiency. Qin et al. [11] found that the RO membrane fouling rate of 2 d frequency osmotic backwashing was considerably faster than that of daily frequency osmotic backwashing, although it

Table 3
Increase rate of irreversible fouling determined by the drift curve categorized by each cleaning period

Cleaning period (h)	Slope	R^2
4	0.011	0.963
8	0.012	0.982
12	0.016	0.982
24	0.019	0.99

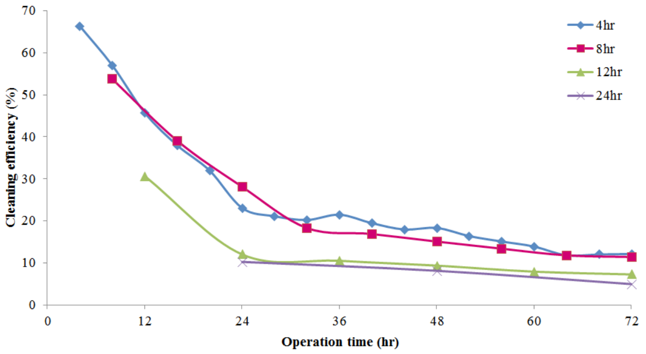

Fig. 3. Changes in cleaning efficiency according to each cleaning period.

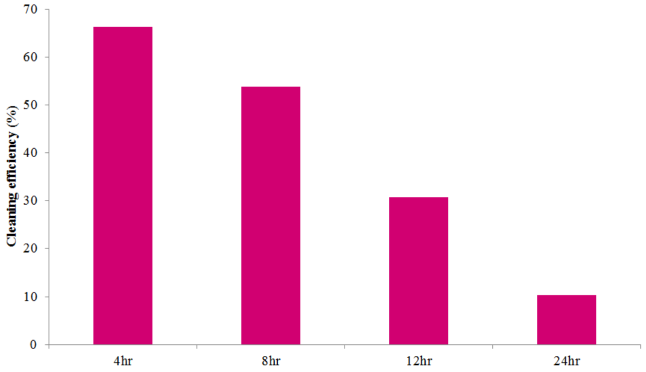

Fig. 4. Changes in cleaning efficiency according to each cleaning moment

was slightly better than that without the direct osmosis-high salinity cleaning.

In the experiment, as the length of the cleaning period was reduced and the frequency of osmotic backwashing increased, the rates of decrease of flux and increase of irreversible fouling reduced somewhat, but were not proportional to the frequency, and the cleaning efficiency declined after a certain period. The cleaning period was reduced, and the volume of backwashing water increased as it reduced, ultimately leading to a reduction in operating efficiency. Therefore, it is desirable to find the most effective cleaning period rather than the shortest cleaning period by finding the period that has the least increase of irreversible fouling.

3.3. Empirical model

The experimental data, which are drawn from the previous section, suggest a co-relationship through empirical Eq. (4):

$$E = a(S)^{b}(T)^{c}(F)^{d} \tag{4}$$

where E is the cleaning efficiency (%); S is the concentration of RO membrane feed water (mg/L) during osmotic backwashing; T is the osmotic backwashing time (min); and F is the flux decline rate (%) before osmotic backwashing.

In linearized form, Eq. (4) can be written as follows:

$$\ln E = \ln a + b\ln S + c\ln T + d\ln F \tag{5}$$

To obtain coefficients b and c of Eq. (5), the co-relationship of the factors in Table 2, including cleaning performance, concentration of NaCl solution, and osmotic backwashing time, were analyzed using nonlinear regression. The result showed $b = 0.8394$ and $c = 0.3992$ ($R^2 = 0.89$). The coefficient $d = -1.6708$ ($R^2 = 0.99$) was obtained from logarithmic plotting of the initial FDR and cleaning performance. In the case of coefficient a, 0.0321 was the intercept value of the logarithmic plots. Therefore, Eq. (4) had the following coefficients:

$$E = 0.0321(S)^{0.8394}(T)^{0.3992}(F)^{-1.6708} \tag{6}$$

The value of R^2 0.94 was obtained by a comparison between the experimental data and empirical model.

4. Conclusions

In this study, the effects of osmotic backwashing conditions in an SWRO process were analyzed. Cleaning efficiency, filtration resistance, and backwashing volume were analyzed to determine the effects under the various conditions using NaCl solutions. The cleaning efficiency of the process of applying concentrated water as circulated water during osmotic backwashing is superior to that of the raw water. The cleaning time and period of the osmotic backwashing show increased the efficiency, productivity, and economic feasibility; these factors thus facilitate future long-term studies. Also, the empirical model could assist in determining the cleaning performance in studies on a full-scale process.

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