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Application of seawater dilution process to SWRO filtration system for low-energy desalination

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ABSTRACT

This study evaluated possible application of a seawater dilution process (SDP) to a seawater reverse osmosis (SWRO) filtration system for low-energy desalination. The main experiments of this study are to find the effects of the SDP in an SWRO filtration process to reduce seawater salinity. The measured total dissolved solids values were 29,640 mg/L for seawater, 8,720 mg/L for brackish water, and 2,896 mg/L for treated sewage water. In the experiment, two multiple water were blended with seawater to lower salinity. First experiment was conducted seawater with brackish water and found an increase in the permeate flux at 9.6% in the SWRO process. Second experiment was conducted seawater with treated sewage water and delivered an increase in the permeate flux at 12.9%. During the ultrafiltration (UF) operation, the pressure applied in diluted water increased rapidly comparing to seawater because the high concentrations of particulate and organic matter were detected in pretreatment of UF and main treatment of SWRO due to high silt density index and total organic carbon value in supplemental water. Therefore, to optimize application of the SDP, fouling effects should be considered for a longtime operation in membrane processes.

Keywords: Seawater dilution process; Low-energy desalination; Membrane fouling; Reverse osmosis; Salinity

1. Introduction

For over 40 years, reverse osmosis (RO) membrane filtration technology has been developed as representative technology in desalination [1–4]. Indeed, RO has become the most widespread technology in international desalination markets for producing a steady supply of high-quality water from abundantly available sources for desalination, such as ocean or brackish water [1–5]. However, the RO filtration process for seawater desalination requires a high energy consumption of 3–4 kWh/m^3 to operate a

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high-pressure pump (HPP) due to the high osmotic pressure in seawater [2,3,5].

In the field of membrane research, many groups have investigated the best way to reduce the energy consumption of RO operations. Currently, the energy consumption required for operating seawater reverse osmosis (SWRO) plants using advanced technologies such as HPP and energy recovery device has been reduced to between 1.8 and 2.2 kWh/m^3 compared to a conventional SWRO plant [2,3]. In studies on forward osmosis (FO) membrane processes, the development of novel nanocomposite membranes, and the application of renewable energies (e.g. wind, tide, and solar energy sources) to RO membrane processes have attracted further attention to membrane filtration technologies for desalination [2,6–11]. These studies have focused on the development of advanced desalination processes based on the concept of low-energy consumption, compared to existing processes. While minimizing energy consumption in desalination processes is the final objective of future membrane technology, the effluence of pollutants in brine water should be considered to maintain the ecosystem in the ocean [2,5,12]. Plus, water treatment processes for water reuse should be investigated for brackish water, treated sewage water, and industrial wastewater reuse in order to overcome global water scarcity concerns [2,6,7]. As an alternative application, a seawater dilution process (SDP) using low salinity water may be a promising tool to reduce HPP energy consumption and to decrease the salinity of brine in SWRO processes. Cheon et al. [5] applied the SDP to the water treatment process with 30% of energy saving in desalination process at Kitakyushu of Japan. This indicates the osmotic pressure between saline water and the water produced was a key factor for reducing HPP energy consumption in a SWRO process. HPPs, which are required to overcome the osmotic pressure of saline water in SWRO processes, consume more than 80% of the total operating power [1,2,5].

In our study, the SDP using two different water sources (brackish and treated sewage water) has been applied to ultrafiltration (UF) and SWRO processes used in desalination in a SWRO pilot plant located at Incheon of South Korea. This investigation carried out the possibility of using the SDP to increase the energy efficiency as far as membrane fouling factors. Seawater was used as the main water source, and brackish water and treated sewage water used as the supplemental water sources for reducing seawater salinity in desalination. Performances of the SDP using brackish and treated sewage water were evaluated during August to October in 2014.

2. Experimental method

2.1. Plant site location and feed water source

All experiments were conducted in SWRO pilot plant located at Incheon of South Korea. Feed water consisting of seawater, brackish water, and treated sewage water was sampled from the Song-do seawall at the north retarding basin of Yeongjongdo Island, and the Gongcheon Wastewater Treatment Plant (WWTP), respectively. The seawater sample was used as the main water source in the process, and brackish water and treated sewage water samples were

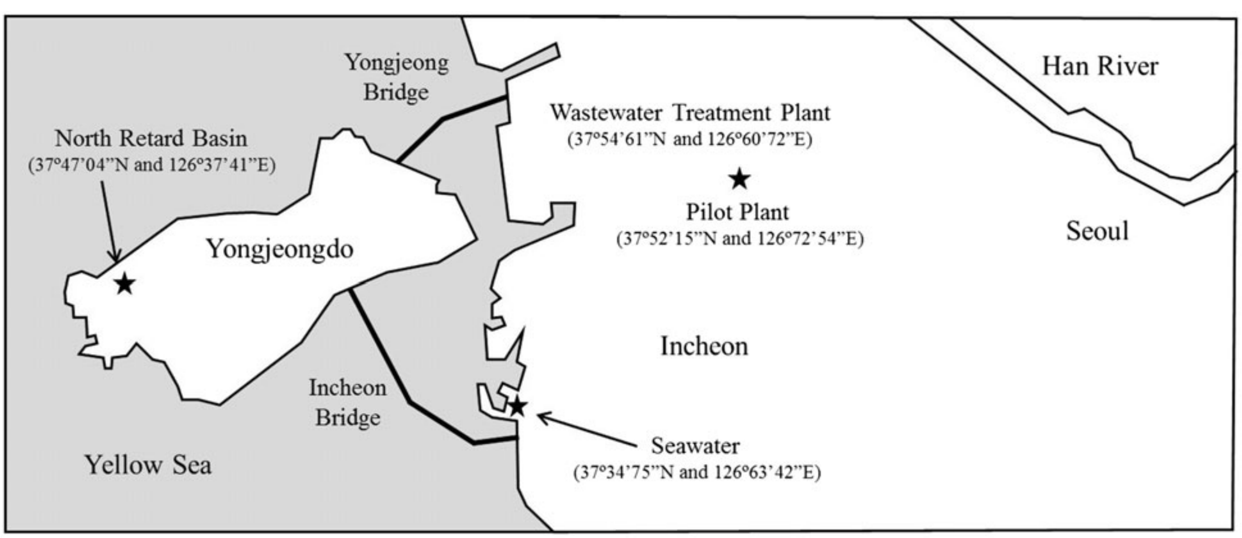

Fig. 1. Map of sampling sites used in this study.

considered as supplemental water sources. A map of the sampling sites is provided in Fig. 1.

All samples were periodically taken at the sites and transferred to the pilot plant, and stored in 20 ton PVC reservoir tanks at ambient outside temperature. The operation period of the pilot plant was from August (summer) to October (autumn) in 2014.

2.2. Pilot plant

The plant has been in operation since June 2014 and has an established SWRO filtration process for low-energy desalination. The process schematic and a sample image of the pilot plant are displayed in Fig. 2. The overall capacity of the process was $4.32\ m^3/d$, and the major components of the process consist of a diluting tank (500 L, Yuil Engineering, South Korea), 0.04 μm flat sheet UF membrane module (Bio-cell, MicroDyn, Germany) as a pretreatment, and one 4-inch membrane vessel having one SWRO membrane module (RE4040-SHN, Toray Chemical, South Korea) as a main treatment. The UF module was operated using a programmable logical control system to ensure continuous backwashing performance during operation. The UF operation conditions were filtration for 780 s, pause for 30 s, backwash for 60 s, and another pause for 30 s. The pressure applied in the UF was maintained in the range of 0–0.4 bar (max. 0.4 bar was suggested by UF manufacturer). In addition, fine air bubbles were continuously supplied into the UF

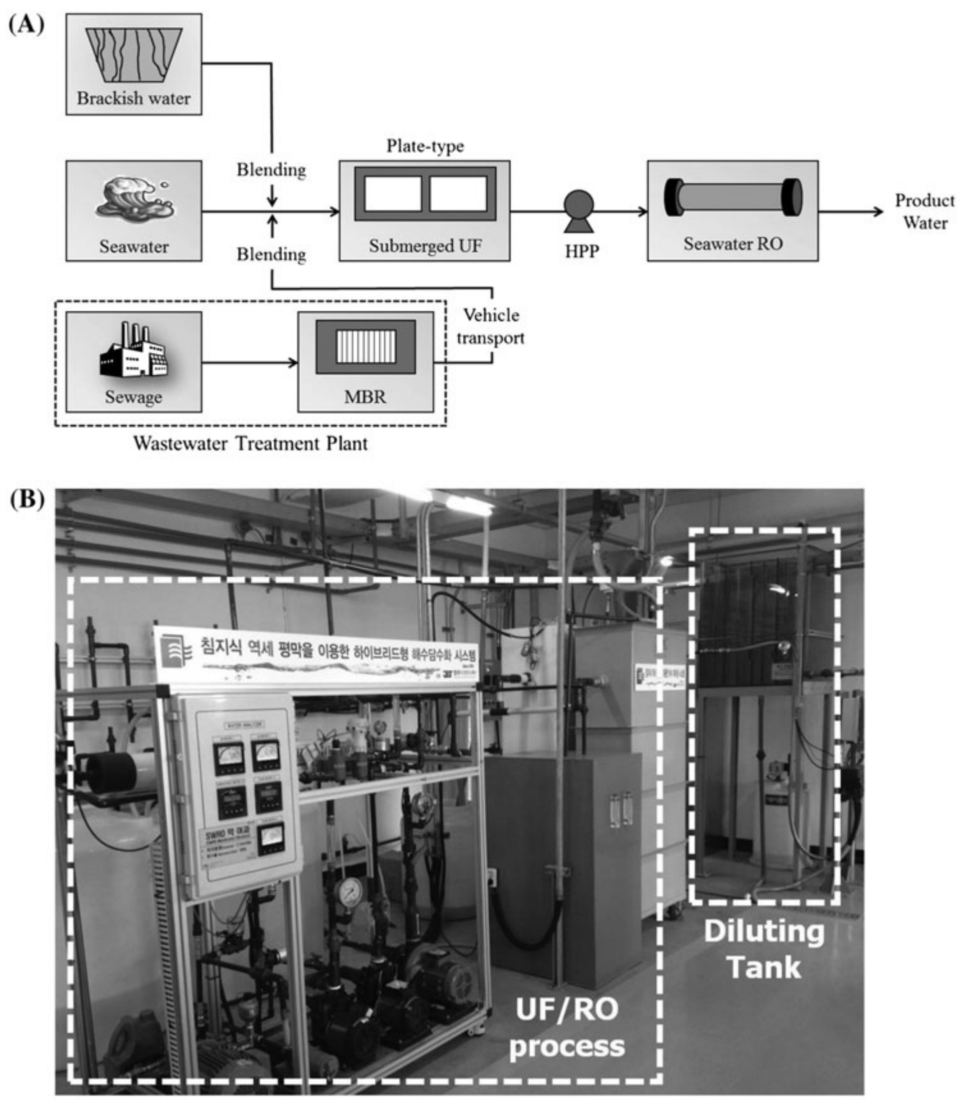

Fig. 2. The schematic image (A) and pilot plant ($4.32\ m^3/d$ capacity) (B) of SWRO filtration system applied with SDP process.

chamber to prevent particulate fouling on the membrane surface. The SWRO module was operated by HPP (3CP1241, CAT Pump, USA) at a constant applied pressure of 55 bar, at a recovery rate of 32%. The applied pressure was controlled by a flow valve of brine. The initial water production flow was measured to be about 3.15 L/min (4.54 m^3/d), and the salt rejection was calculated to be 99.7%; these results were in compliance with manufacturer's recommendations. The UF and SWRO membrane specifications are shown in Table 1.

Monitoring parameters in the pilot plant were divided into two categories: water quality parameters and membrane fouling parameters. Water quality parameters included pH (Alpha pH 200, EUTECH, Singapore), temperature (KN-2000 W, KONICS, South Korea), turbidity (TB 400, Yokogawa Electronic, Japan), and conductivity (Alpha COND 200, EUTECH, Singapore) and membrane fouling parameters included applied pressure and permeate flux were monitored using real-time online monitoring systems during pilot plant operation. A total organic carbon (TOC) analyzer (TOC-L, Shimadzu, Japan) was used to determine the mass concentrations of organic carbon in the feed water. Ion concentrations of Ca^{2+} and Mg^{2+} in the feed water were measured using ion chromatography (ICS-300, Dionex, USA). Slit density index (SDI) was determined using an SDI test kit (Yuil Engineering, South Korea) using a 0.45-μm microfilter (MF) membrane (Millipore, USA) to predict the particulate fouling potential in the UF and RO processes.

In order to predict energy consumption in the SWRO process, the specific energy consumption (SEC), which is defined as the electrical energy required to produce permeate in a cubic meter, was used in this study [13]. We assumed a pump efficiency of 100% and applied constant pressure of 55 bar. In addition, to simplify the approach, the energy consumption was assumed to be equal to the pump work. Based on our results, the SEC was calculated by:

$$\text{Specific energy consumption (SEC)} = W_{\text{pump}}/Q_{\text{p}} \tag{1}$$

where Q_p is the permeate flow rate in a SWRO process and W_{pump} is the rate of work done by the HPP.

2.3. Experimental conditions in SDP

Seawater was diluted using brackish and treated sewage water at specific dilution ratios. The dilution ratios between seawater and brackish water (or treated sewage water) were maintained in the range of 10:0–8:2 to reduce salinity in seawater to 25,194 mg/L (85% salinity in seawater at 29,640 mg/L). Seawater was diluted using the supplemental water in a dilution tank at a specific dilution ratio. The dilution ratio of seawater and supplemental water was precisely controlled using a centrifugal pump (CM 3-3, GroundFos, Taiwan) and an electromagnetic flow meter (FEP 311, ABB Inc., USA).

3. Results and discussion

3.1. Feed water quality

Feed water characteristics in the pilot plant experiment are provided in Table 2. In the table, the turbidity of seawater has monitored as high fluctuation from 1.8 to 12.1 NTU due to tidal effects in the Yellow Sea. Measured TDS values were 29,640 mg/L

Table 1
Configuration of UF and SWRO modules in the pilot plant

	Pretreatment (UF)	Main treatment (RO)
Configuration	Submerged flat sheet membrane	Spiral wound membrane
Pore size	0.04 μm	Non-pore
Material	Polyether sulfone (PES)	Thin film composite Polyamide (PA)
Surface area	10 m^2	6.9 m^2
Operating conditions	• Recovery rate: 95% • Operation with air bubbling • Periodic backwashing	• Recovery rate: 32% • Applied pressure: 55 bar (Const.) • Salt rejection: 99.7%
Manufacturer	Bio-cell, MicroDyn, Germany	RE4040-SHN, Toray chemical, South Korea

Table 2
Quality of feed water used in this study

	pH	Turbidity (NTU)	TDS (mg/L)	TOC (mg/L)	Cl^- (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)
Seawater (Main)	8.10	1.8–12.1	29,640	1.81	16,405	1,109	362
Brackish water (Supplemental)	8.56	8.06	8,720	3.50	4,460	281	161
Treated sewage water (Supplemental)	7.13	<1	2,896	5.30	1,323	84	56

for seawater, 8,720 mg/L for brackish water, and 2,896 mg/L for treated sewage water. While the supplemental water was a valuable resource for decreasing the salinity in the SDP, TOC was considered to avoid organic fouling effects in UF and RO membrane processes. Measured TOC values were 3.50 mg/L for brackish water and 5.30 mg/L for treated sewage water. Mg^{2+} concentration of 1,109 mg/L and Ca^{2+} concentration of 362 mg/L in sea water were much higher than in the supplemental water (Mg^{2+}: 281 mg/L and Ca^{2+}: 161 mg/L in brackish water and Mg^{2+}: 84 mg/L and Ca^{2+}: 56 mg/L in treated sewage water). This indicates that the SDP is able to slightly support reduction of inorganic scaling in a membrane process and high TOC concentrations in brackish water and treated sewage water present organic fouling possibilities in Table 2 during a SDP. Therefore, while diluting seawater with supplemental water, two factors as reduction of particulate fouling and organic fouling should be considered during operation of UF and SWRO processes.

As shown in Fig. 3, seawater turbidity sharply fluctuated during operation of the pilot plant. This is because of the tidal effects in the Yellow Sea as an increase in the mass concentration of particulate matter in the feed water. In the Korean peninsula, the tidal effects in the Yellow Sea are much stronger than in either the East Sea or South Sea. In contrast, the turbidity of brackish and treated sewage water did not fluctuate as there were not any artificial or natural effects at the sites. Specifically, the treated sewage water was treated using a membrane bio reactor process in the WWTP.

As the seawater TDS (29,640 mg/L) was much higher than for the brackish water (8,720 mg/L) and treated sewage water (2,896 mg/L), supplemental waters having low salinity were used to decrease the osmotic pressure in SWRO membrane filtration by mixing with seawater. Seawater dilution ratios for brackish or treated sewage water obtained by varying the conductivity and resulted in a proportional relationship with the diluted water (Fig. 4). The conductivity in diluted water was proportionally correlated with the dilution ratio of an R-square value of 0.99. In Fig. 4, the conductivity of the water diluted with treated sewage water decreased more than with brackish water due to different TDS value for each water sample. The SDP using treated sewage water obtained more salinity decrease than brackish water with seawater.

To evaluate the water quality of feed water in the membrane process, SDI and TOC values in the feed water were determined using an SDI test and TOC analysis. Fig. 5 presents the SDI values of feed water

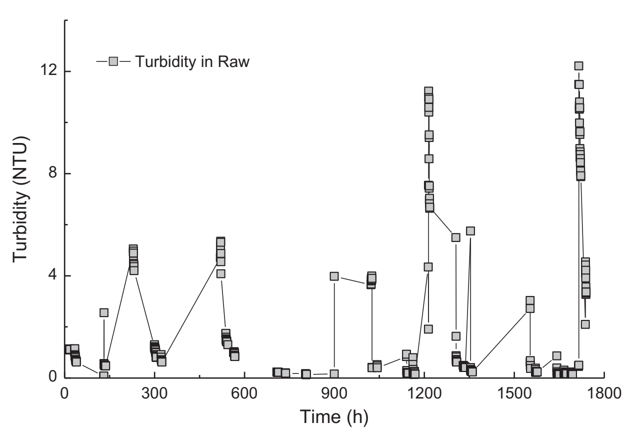

Fig. 3. Variation of turbidity in seawater as a function of time.

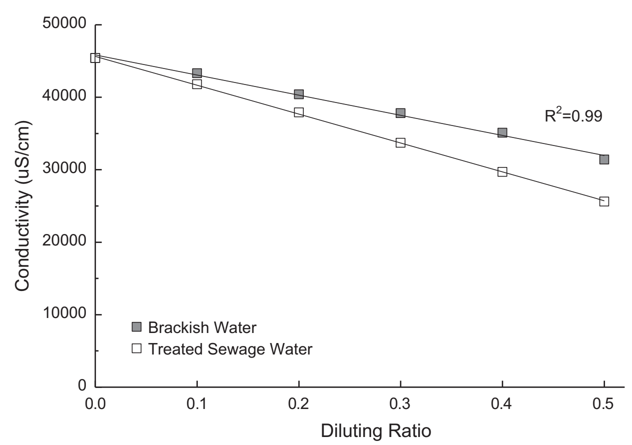

Fig. 4. Relationship between seawater diluting ratio with brackish water (or treated sewage water) and conductivity.

in SDPs having brackish or treated sewage water. To conduct the SDI experiments, seawater samples were analyzed two times during different time periods. It was resulted in SDI value of 5.82 and 4.67 by different input water values (#1: 5.82 NTU, #2: 4.63 NTU) due to tidal effects. The SDI values in brackish water and treated sewage water were 6.29 and 5.25 higher than in seawater and diluted water. During the operation of the pilot plant, SDI for UF-treated water showed at 0.16 for seawater diluted by brackish water and 0.35 for seawater diluted by treated sewage water with removal efficiencies up to 97%. As a result, SDI values of the UF-treated water represent reduction of particulate fouling and an excellent water quality (SDI < 1) for RO feed water.

Fig. 6 displays the TOC concentrations of feed water using brackish and treated sewage water dilution. TOC values were measured at 1.85 mg/L for seawater, 3.50 mg/L for brackish water, and 5.30 mg/L for treated sewage water. These values explain possible biological and organic fouling in the membrane process with the SDP, comparing to normal membrane processes. In the SDP with treated sewage water, TOC concentration of 3.34 mg/L, which was higher than that of diluted water at 2.70 mg/L, was measured in UF-treated water. The TOC results explain two possibilities: less than 40 nm colloidal nanoparticles exist in feed water, and microorganisms grow in UF permeate line or tanks, which positively affect biological membrane fouling in SWRO process.

3.2. Operating results for UF and RO pilot plant

In the UF and RO membrane processes, the conductivity, pH, applied pressure, and permeate flux in the feed and produced water were measured using

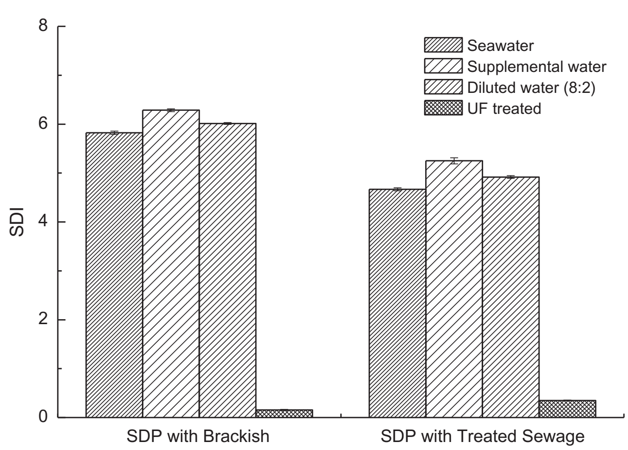

Fig. 5. SDI values of samples in SDPs having brackish or treated sewage water.

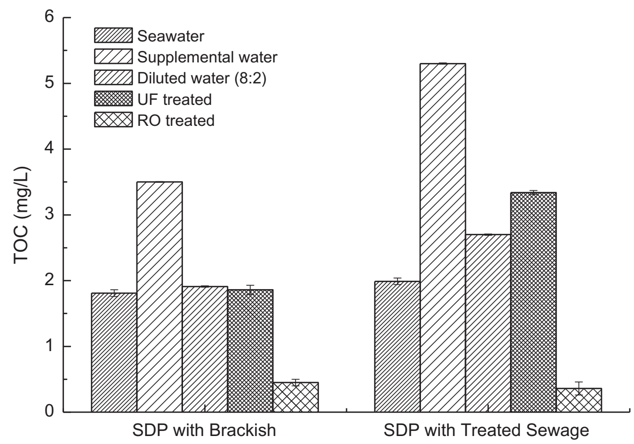

Fig. 6. TOC concentrations of feed water in SDPs having brackish or treated sewage water.

online monitoring systems. In this study, SDPs having brackish water or treated sewage water in the UF and RO processes were evaluated in order to develop a more energy efficient process.

As a result, Fig. 7 presents the permeate flux and pressure applied in the UF process, which was operated using a feed pump at a constant frequency. The applied pressure was controlled in the range of −0.1 to −0.4 bar (maximum operating value). When the pressure applied in the UF process reached over −0.4 bar, a backwashing process was conducted to recover and protect the membrane. In the UF operation for seawater, the applied pressure was slightly increased from −0.2 to −0.3 bar affected by the particulate matter in seawater. In the UF operation using water diluted with brackish and treated sewage water (ratio of 8:2), the applied pressure more rapidly increased. This finding indicated that membrane fouling was significantly accelerated by high particulate and organic matter concentrations in diluted water. In other words, a significant synergistic effect on membrane fouling with a combination of particulate and dissolved organic matters might occur during operation [14]. Longtime backwashing (during 2 h) was conducted using UF-treated water to recover UF membrane performance, required the applied pressure over 0.4 bar for reducing membrane fouling. The recovery rate of UF membrane performance was measured approximately 80%.

The operating results for conductivity and permeate flux in SWRO processes are shown in Fig. 8. The RO feed water pretreated by the UF membrane satisfied with the condition of less than SDI 1 for RO feed water [15]. In addition, less fouling occurred compared to existing MF pretreatments. When the

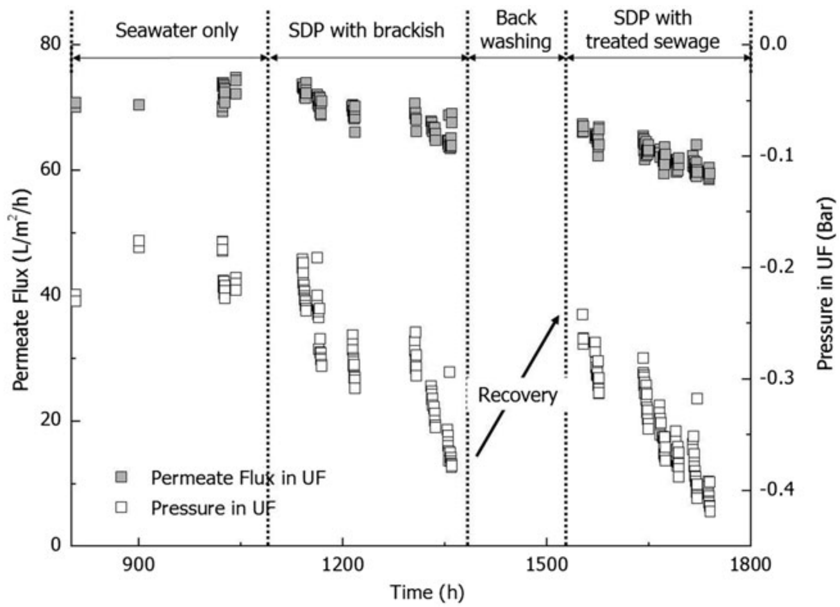

Fig. 7. Variation of permeate flux and applied pressure in UF process (seawater, seawater diluted by brackish water, and seawater diluted by treated sewage water).

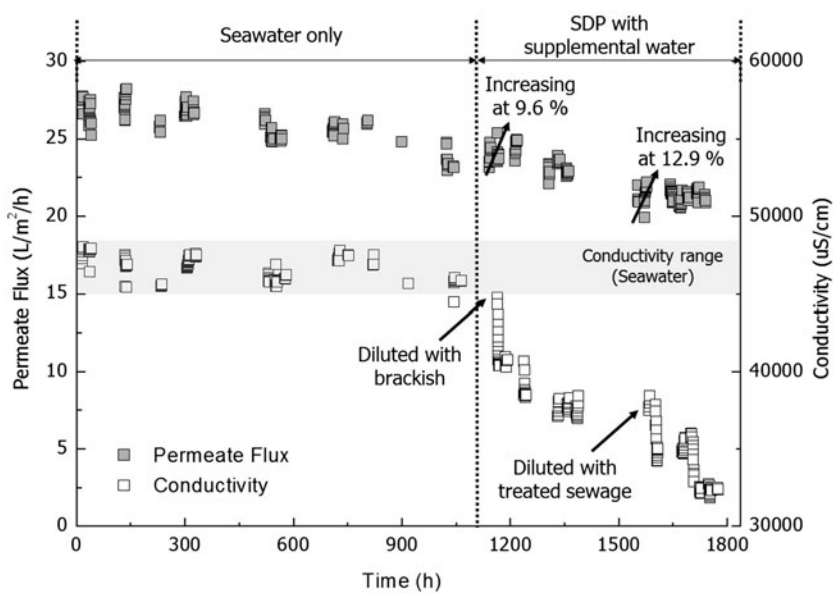

Fig. 8. Variation of permeate flux and conductivity in the SWRO process (seawater, seawater diluted by brackish water, and seawater diluted by treated sewage water).

seawater was diluted with brackish water at a ratio of 8:2, the conductivity of the diluted water decreased from 45,705 to 40,528 μS/cm with the osmotic pressure decrease in the SWRO process and the permeate flux increased by 9.6%. In the case of dilution with brackish water, the conductivity further decreased to 37,879 μS/cm, with a 12.9% permeate flux increase. According to our investigations, we predicted that SEC with the SDP was decreased by 9.6% for seawater diluted by brackish water and 12.9% for seawater diluted by treated sewage water at the constant rate of work done by the pressure pump. Zhu et al. [13] presented that energy consumption in SWRO was inversely correlated with a permeate flow rate. However, after a long operation, the permeate flux of water diluted with treated sewage water in the process decreased compared to other water sources. It confirms that nanosized organic material in the diluted water passing through the UF membrane played a vital role as a foulant in the SWRO membrane process. Therefore, we concluded two main findings; SDPs using supplemental water can support a reduction in the osmotic pressure for low-energy desalination and different water use for dilution can accelerate organic fouling in SWRO processes.

4. Conclusions

In this study, the application of SDP using supplemental water such as brackish and treated sewage water in seawater desalination process was investigated in a pilot-scale SWRO process. As a result, the SDP positively impacted on a low-energy desalination process and water reuse while different water use for dilution can accelerate organic fouling. Therefore, deep investigation is necessary for optimizing SDP using different water sources in order to reduce the operation and maintenance (O&M) costs such as physico-chemical cleaning and replacement of membrane. In addition, tidal effects and supplemental water qualities are a key factor to affect optimization of the SDP in a SWRO process. Thus, as a future approach for optimization of the SDP in a SWRO process, I suggest that the implementation of an ultraviolet disinfection system is one of positive options to control organic/bio foulants in a longtime operation. Accordingly, the SDP is one of positive options to use multiple water sources with lowering desalination costs while more investigation is needed to use it as appropriate alternatives for future desalination technology.

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