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Effect of intermittent operation modes on performance of reverse osmosis (RO) membrane in desalination and water treatment

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Abstract. Seawater desalination is doubtlessly a viable option to supply fresh drinking water. Nevertheless, RO (reverse osmosis) desalination plants in specific areas may be intermittently operated to match the imbalance between water demand and supply. Although a handful of works have been done on other membrane systems, few studies have attempted to mitigate fouling in intermittent RO systems. Accordingly, the objectives of this paper were to examine the effect of the intermittent operation on RO fouling; and to compare four intermittent operation modes including feed solution recirculation, membrane storage in the feed solution, deionized water (DI) recirculation, and membrane storage in DI water. Results showed that intermittent operation reduced RO fouling under several conditions. However, the extents of fouling mitigation were different depending on the feed conditions, foulant types, and membrane lay-up methods. When the feed solution was recirculated during the lay-up, the restoration of the flux was less significant than that by the feed solution feed-up. The use of deionized water during the lay-up was effective to restore flux, especially when the feed solution contains scale-forming salts ($CaSO_4$) and/or colloidal silica.

Keywords: cleaning; flux; fouling; intermittent operation; reverse osmosis; scale formation

1. Introduction

Water scarcity, which is defined as the state of inadequate water resources to meet the water demands, is a critical issue in many semi-arid regions around the world and is expected to become worse by 2025 (Supply and Programme 2014). Moreover, many islands where there is insufficient rain and groundwater are also vulnerable to water scarcity. Since the lack of freshwater severely limits social and industrial developments (Liu *et al*. 2018), it is necessary to consider seawater desalination in these areas, which enables a stable supply of fresh water.

Reverse osmosis (RO) has become the dominant technology in the desalination market (Qasim, Badrelzaman *et al*. 2019). The annual capacity of RO has increased to 3.5 million m^3/day and accounts for approximately 60% of the worldwide installed desalination capacity (Peñate and García-Rodríguez 2012). Compared with distillation technologies such as multistage flash (MSF) and multi-effect distillation (MED), RO is affordable due to lower costs, smaller footprint, and easier operation. Moreover, the energy consumption of RO desalination has been significantly reduced due to the development of efficient RO membranes (Lim *et al*. 2021), the use of energy recovery devices (Song *et al*. 2021), and advanced system engineering (Farahbakhsh *et al*. 2017). RO is suitable not only in large-scale plants but also in small-scale systems (Heijman *et al*. 2009, Ben Ali *et al*. 2020).

However, there are issues to be addressed in RO desalination, and membrane fouling is one of the major performance issues (Van der Bruggen *et al*. 2003, Jiang *et al*. 2017, Karabelas *et al*. 2020). Membrane fouling arises from the accumulation or deposition of particles and colloids, organic matters, soluble inorganic compounds (scaling), and microorganisms (biofouling) into membrane pores or on the membranes surface resulting in the deterioration of the membrane performance (Sim *et al*. 2018, Castilla Rodriguez 2020, Karabelas *et al*. 2020, Matin *et al*. 2021). These issues can reduce the quality of the product water and cause severe membrane flux decline (Oh *et al*. 2009, Chew *et al*. 2017, Matin *et al*. 2019). In general, the operating pressure should be kept high to maintain a constant product flux, this causes increased energy consumption (Chen *et al*. 2014, Kim *et al*. 2019).

If RO systems are intermittently operated, which are often the cases in small-scale desalination plants (Gilau and Small 2008), the fouling propensity may be different (Freire-Gormaly and Bilton 2018, 2019). It has been reported that intermittent operation leads to high membrane fouling rates, especially in photovoltaic RO systems (Schäfer *et al*. 2007, Giannakoudis *et al*. 2010, Freire-Gormaly and Bilton 2018). This may be attributed to the fact that RO brine remains during the lay-up period and results in scale formation (Freire-Gormaly and Bilton 2019). However, it is also possible to mitigate fouling during the lay-up period due to the relaxation of foulant layers and osmotic backwashing (Aftab *et al*. 2020, Cai and Schäfer 2020, Daly *et al*. 2020, Cai *et al*. 2021). Control of

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fouling by the intermittent operation is a common technique in microfiltration processes (Farley and White 1998) and membrane bioreactors (Navaratna and Jegatheesan 2011). However, few works have attempted to alleviate RO fouling during the intermittent operation.

Accordingly, the objectives of this paper were to examine the effect of the intermittent operation on RO fouling; and to compare four intermittent operation modes including i) feed solution recirculation; ii) in situ membrane storage in feed solution; iii) deionized (DI) water recirculation; iv) in situ membrane storage in DI water. The effect of the intermittent operation on flux recovery ratio was examined for feed solutions containing different foulants. The results were compared under various conditions using different feed solutions to advance the understanding of fouling from intermittent operation to help increase the efficiency of small-scale RO systems. To the best knowledge of the authors, there have been few works focusing on the “mitigation” of RO fouling during intermittent operation.

2. Experimental methods

2.1 Feed solutions

Feed solutions were prepared using NaCl (Samchun, Korea), $CaSO_4$ (Sigma Aldrich, U.S.A.), colloidal silica (Nissan chemical, ST-ZL, Japan). NaCl was used to prepare the synthetic seawater and its concentration was set to 32,000 mg/L. $CaSO_4$ was added as a scale-forming salt and its concentration was set to 2,000 mg/L. Colloidal silica was applied as a model foulant of particulate matter and its concentration in the experiments was 200 mg/L. Its particle size ranges from 70 to 100 μm. The compositions of the feed solutions are summarized in Table 1.

2.2 Membrane and experimental equipment

Two flat sheet RO membranes were used, including SWRO (SWC6-4040, Nitto). The width, length, and depth of the channel of the lab-scale RO membrane module were 3.5 cm, 9.5 cm, and 0.1 cm, respectively. The effective membrane area was 33.25 cm^2. The specifications of the membranes and module parameters were briefly listed in Table 2.

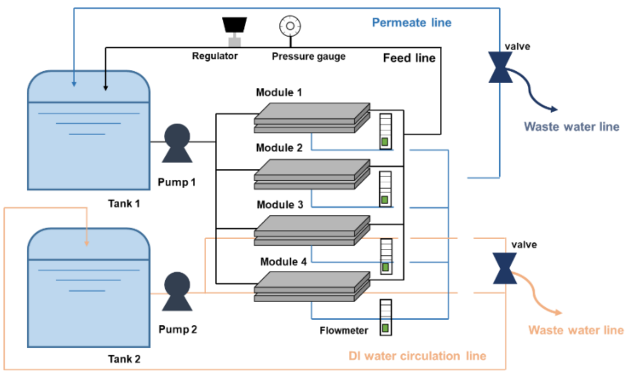
The experimental setup for intermittent RO operation is shown in Fig. 1. Reverse osmosis equipment consists of four flat membrane modules and two inflow tanks. Tank 1 is a feed tank that supplies the feed solution to each module. Tank 2 is a rinse tank that supplies deionized (DI) water to modules. The maximum capacity of each tank is 20 L. The feed solution flow was constant and circulated into the tank by a high-pressure pump. To achieve the same initial flux of 30 L/m2-hr, the pressure was initially adjusted from 22 bar to 45 bar and set to be constant during the RO operation. The feed solution was concentrated by discharging the permeate produced by reverse osmosis to the waste line. The two modules that pass through the rinse tank line were cleaned with DI water in the shutdown cycle. During the operation, feed temperature was kept constant at 23°C using

Table 1 Summary of the operating conditions for RO experiments

Operation mode		Intermittent operation
Cross-flow velocity		1.5 L/min
Initial flux		30 L/m^2-hr
Feed solution	Feed A	NaCl 32,000 mg/L + $CaSO_4$ 2,000mg/L
	Feed B	Seawater
	Feed C	$CaSO_4$ 2,000mg/L
	Feed D	Silica 200 mg/L + NaCl 32,000 mg/L
	Feed E	Silica 200 mg/L + $CaSO_4$ 2,000 mg/L

Table 2 Summary of membrane material and module specification

	Properties
Membrane type	Flat sheet membrane (Nitto SWC6 4040)
Membrane material	Composite Polyamide
Average NaCl rejection (manufacturer specification)	99.7 %
Maximum pressure	68.95 bar
Effective membrane area	33.25 cm^2 (width: 3.5 cm; length: 9.5 cm)



(a)

(b)

Fig. 1 Laboratory-scale intermittent RO experimental setup (a) schematic diagram (b) photography

Table 3 Summary of the operation and lay-up modes for RO experiments

Time		Case 1	Case 2	Case 3	Case 4
14hr	Operation condition	Continuous operation			
3hr	Operation condition	Feed solution circulation (FC mode)	Membrane storage in feed solution (FS mode)	DI water circulation (DC mode)	Membrane storage in DI water (DS mode)
4hr	Operation condition	Continuous operation			
3hr	Operation condition	Feed solution circulation (FC mode)	Membrane storage in feed solution (FS mode)	DI water circulation (DC mode)	Membrane storage in DI water (DS mode)

a heat exchanger coil connected with a water bath. The flux, feed flow rate, and pressure for each module were continuously monitored using electronic flow meters and pressure sensors.

2.3 Lay-up modes

As shown in Table 3, the intermittent operation consists of a filtration cycle and a shutdown cycle. There were four different storage (lay-up) modes during the shutdown cycle:

1. Feed solution circulation (FC mode): During the lay-up time, the feed solution was continuously recirculated while the back-pressure valve was set to open.
2. In situ membrane storage in feed solution (FS mode): The feed solution was filled in the RO system during the lay-up time. No feed solution recirculation was carried out.
3. Deionized (DI) water circulation (DC mode): During the lay-up time, the feed solution was replaced with DI water. Then the DI water continuously recirculated while the back-pressure valve was set to open.
4. In situ membrane storage in DI water (DS mode): The feed solution was replaced with DI water in the RO system during the lay-up time. No DI water recirculation was carried out.

2.4 Normalized flux

The normalized flux J_n was used to analyze the results of the crossflow RO experiments, which is calculated based on:

$$J_n = \frac{J}{J_0} \tag{1}$$

where J_o is the initial permeate flux (L/m^2-hr); J is the moment permeate flux (L/m^2-hr) of the fouled membrane.

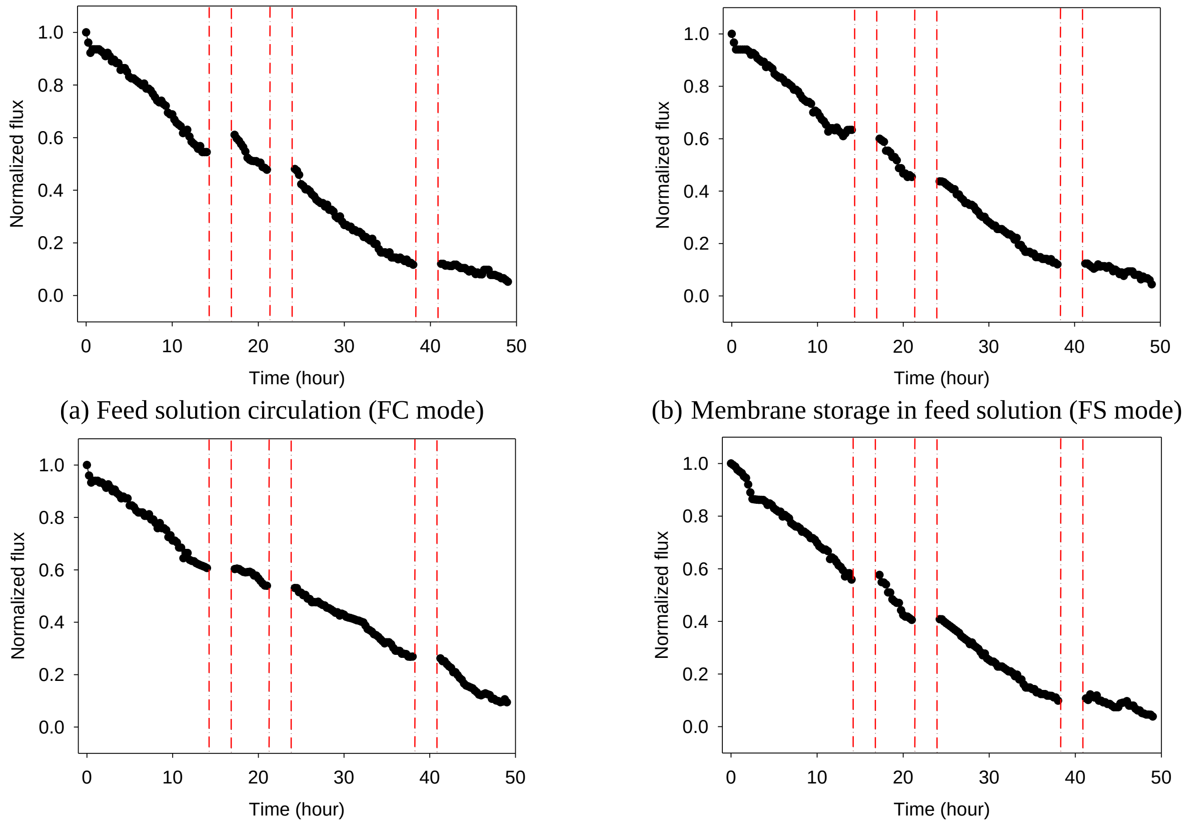
3. Results and discussion

3.1 Intermittent operation of feed solutions with relatively low fouling potential

The effect of the intermittent operation modes on fouling and flux recovery was examined during the intermittent RO operation. The details on the operation conditions are shown in Table 3. The 1st filtration cycle was maintained at 14 hours and the 1st shutdown cycle lasted for 3 hours. Then the 2nd filtration and shutdown cycles were followed and their durations were 4 hours and 3 hours, respectively. This scenario was developed based on the intermittent operation patterns of small-scale desalination plants in Korean islands. In general, the operation time of an intermittently operated desalination plant is 8 hours, corresponding to the working hours of plant operators. Depending on the water demands, it may decrease or increase. Some desalination plants in Korea are operated in less than 12 hours per day (during the ebb tide) because they use seawater mixed with ground water to reduce the applied pressure. The filtration cycles in this work were determined to consider the possibility of thee minimum (4 hours) and the maximum (14 hours) operation times.

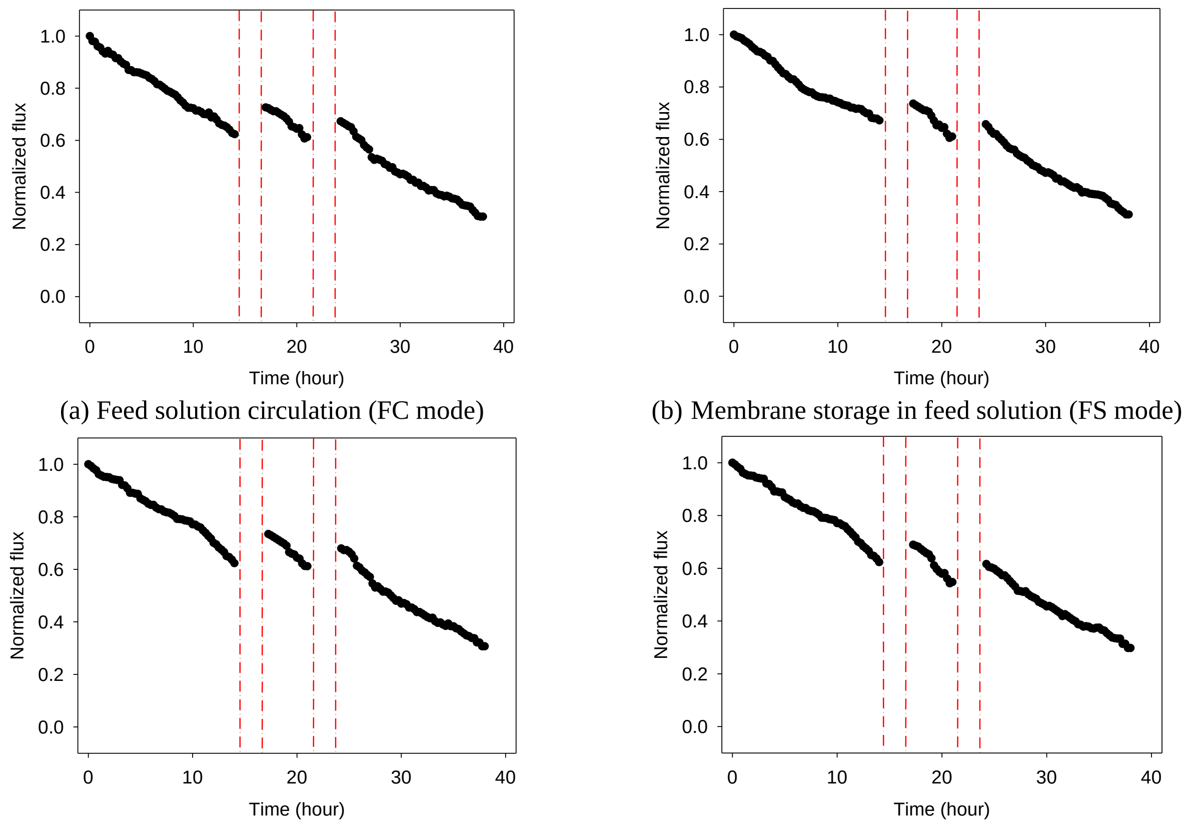
Fig. 2 shows the variations in the normalized flux with time in the case of the NaCl and $CaSO_4$ solution (feed A). In the 1st filtration cycle, the flux continuously decreased with time, resulting in approximately 40% reduction. Although the $CaSO_4$ concentration in the feed was 2000 mg/L, which corresponds to the $CaSO_4$ saturation concentration at low ionic strength, scale formation was not observed. Instead, the flux reduction seems to occur mainly due to an increase in the osmotic pressure of the concentrate. This is because $CaSO_4$ scale formation is delayed in the high ionic strength solution (Choi, Naidu *et al*. 2018). When the feed solution was recirculated during the shutdown period (Fig. 2(a), FC mode), the flux was recovered by about 10% after the 1st shutdown (stop). But the flux was not significantly recovered after the 2nd and 3rd shutdown. When the RO membrane was stored in the feed solution during the shutdown period (Fig. 2(b), FS mode), the flux was not recovered after the shutdown cycle. Similar results were observed in the case of the DI water circulation (Fig. 2(c), DC mode) and the storage of the membrane in the DI water (Fig. 2(d), DS mode). The flux recovery ratio in each case is summarized in Table 4, ranging from 94.7% to 112%. These results suggest that the intermittent operation of the RO membrane is not effective for the feed solution with low fouling and scaling potentials.

Fig. 3 shows the normalized flux in the case of the real seawater (feed B). Compared with the previous case (feed A), the flux recovery ratios are slightly higher in all conditions. In the 1st filtration cycle, the flux was reduced by approximately 35% reduction. When the feed solution was recirculated during the shutdown period (Fig. 3(a), FC mode), the flux was recovered by about 16%, 10%, and 9.7% after the 1st, 2nd, and 3rd stops. When the RO membrane was stored in the feed solution during the shutdown period (Fig. 3(b), FS mode), the flux was recovered after the shutdown cycle but their recovery ratios were slightly lower than those in the FC mode. In the case of the DI water circulation (Fig. 3(c), DC mode) and the storage of the membrane in the DI water (Fig. 3(d), DS mode), the results were similar to the case of the FC mode. The flux recovery ratio in each case is summarized in Table 5, ranging from 103.5% to 117.8%. Since the seawater used in this study may contain potential foulants, the flux pressure but also the foulant deposition. Considering the



(c) DI water circulation (DC mode) (d) Membrane storage in DI water (DS mode)

Fig.2 Normalized flux of intermittent operation by shutdown condition (NaCl + $CaSO_4$)



(c) DI water circulation (DC mode) (d) Membrane storage in DI water (DS mode)

Fig. 3 Normalized flux of intermittent operation by shutdown condition (real seawater)

Table 4 Summary of intermittent RO operation using feed solution containing NaCl 32,000 mg/L + $CaSO_4$ 2,000mg/L

(Feed A) $NaCl+CaSO_4$		Feed solution circulation (FC mode)		Membrane storage in feed solution (FS mode)		DI water circulation (DC mode)		Membrane storage in DI water (DS mode)	
		Flux	Ratio	Flux	Ratio	Flux	Ratio	Flux	Ratio
Absolute flux (L/m^2-hr)	Initial	27.8		27.1		26.9		29.4	
Normalized flux (-)	Initial	1.000		1.000		1.000		1.000	
	1st Stop	0.545		0.634		0.607		0.559	
	2nd Start	0.610	112.0%	0.600	94.7%	0.603	99.4%	0.577	103.2%
	2nd Stop	0.478		0.454		0.539		0.406	
	3rd Start	0.481	100.5%	0.437	96.2%	0.531	98.4%	0.408	100.6%
	3rd Stop	0.117		0.120		0.269		0.098	
	4th Start	0.120	102.5%	0.123	102.5%	0.262	97.5%	0.107	109.0%
	Final	0.052		0.044		0.094		0.038	

Table 5 Summary of intermittent RO operation using real seawater

(Feed B) Real seawater		Feed solution circulation (FC mode)		Membrane storage in feed solution (FS mode)		DI water circulation (DC mode)		Membrane storage in DI water (DS mode)	
		Flux	Ratio	Flux	Ratio	Flux	Ratio	Flux	Ratio
Absolute flux (L/m^2-hr)	Initial	28.9		28.4		28.9		28.5	
Normalized flux (-)	Initial	1.000		1.000		1.000		1.000	
	1st Stop	0.623		0.672		0.623		0.623	
	2nd Start	0.723	116.0%	0.736	109.6%	0.734	117.8%	0.689	110.6%
	2nd Stop	0.612		0.611		0.612		0.548	
	3rd Start	0.673	110.0%	0.657	107.7%	0.657	107.5%	0.616	112.5%
	3rd Stop	0.330		0.346		0.345		0.311	
	4th Start	0.362	109.7%	0.358	103.5%	0.366	105.9%	0.336	107.9%
	Final	0.194		0.194		0.233		0.203	

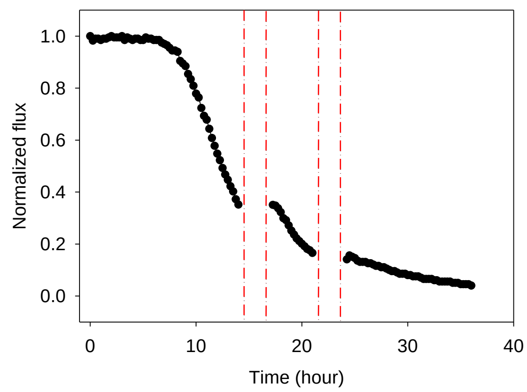
seawater composition, however, no scale formation was expected during the operation, suggesting the fouling is possibly caused by colloids and organic matters. These foulants are expected to be removed by the intermittent operation. Accordingly, it is likely that the intermittent operation slightly mitigates fouling caused by the real seawater.

Although the flux decline is less severe for the real seawater than for the simulated seawater, its flux recovery ratio even is higher. As mentioned earlier, the contribution of the $CaSO_4$ scaling is higher for the simulated seawater than for the real seawater. Since $CaSO_4$ scaling leads to severe and irreversible flux decline, the real seawater exhibited a higher flux recovery ratio as well as lower flux loss.

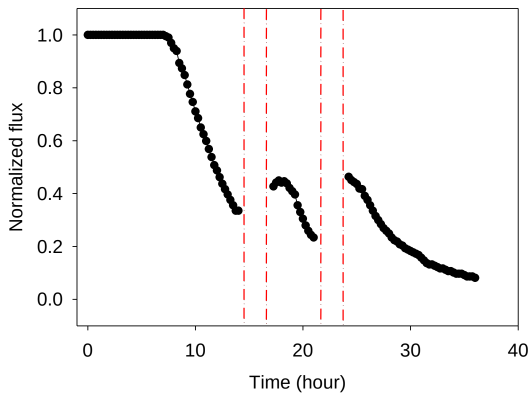
3.2 Intermittent operation of feed solutions with high scaling potential

As shown in Figs. 2 and 3, the effect of the intermittent operation on RO flux was not significant if the feed solutions do not have high fouling potential. In Fig. 4, the $CaSO_4$ saturate solution was used as the feed solution (feed C), which has high scaling potential. Based on these results, the flux recovery ratios were calculated and summarized in Table 6. In the 1st filtration cycle, the flux was reduced by approximately 65% reduction, corresponding to approximately 1.65~1.8 times larger than the previous two cases (feed A and feed B). When the feed solution was recirculated during the shutdown period (Fig. 4(a), FC mode), the flux was not recovered after the 1st and 2nd stops. The flux was rather reduced by 15% after the 3rd stop. On the other hand, the flux was significantly reduced when the RO membrane was stored in the feed solution during the shutdown period (Fig. 4(b), FS mode). The flux recovery ratios after the 1st, 2nd, and 3rd stops were 27.3%, 27.3%, and 98.5%, respectively.

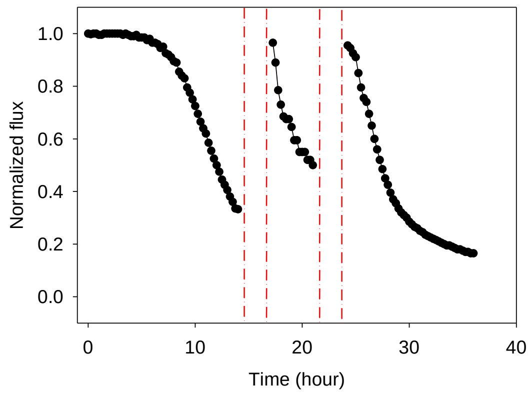
Although the same feed solutions were used in FC and FS mode, the results were quite different. Before the experiment, it was expected that the flux recovery in the FC mode is higher than that in the FS mode due to the existence of the feed motion in FC mode. However, the actual results were the opposite. This is attributed to the effect of feed side pressure during the shutdown cycle. With the feed



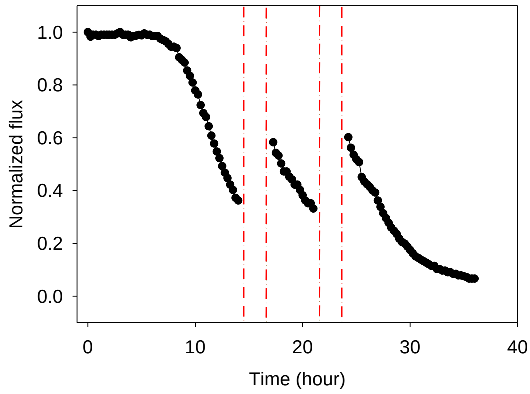
(a) Feed solution circulation (FC mode)



(b) Membrane storage in feed solution (FS mode)



(c) DI water circulation (DC mode)



(d) Membrane storage in DI water (DS mode)

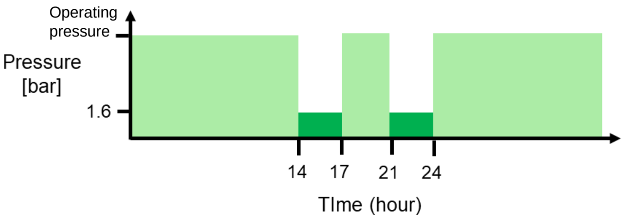
Fig. 4 Normalized flux of intermittent operation by shutdown condition ($CaSO_4$)

Table 5 Summary of intermittent RO operation using real seawater

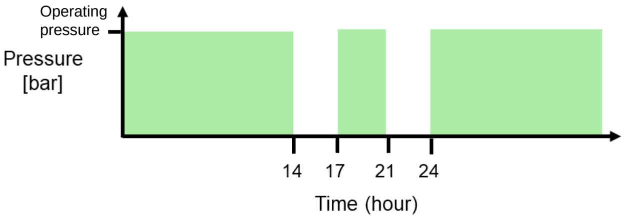
(Feed C) $CaSO_4$		Feed solution circulation (FC mode)		Membrane storage in feed solution (FS mode)		DI water circulation (DC mode)		Membrane storage in DI water (DS mode)	
		35.9		35.5		36.1		35.9	
Absolute flux (L/m²-hr)	1.000		1.000		1.000		1.000		
	0.352		0.335		0.333		0.362		
	0.350	99.6%	0.426	127.3%	0.965	290.2%	0.583	161.0%	
	0.352		0.335		0.333		0.362		110.6%
Normalized flux (-)	0.350	99.6%	0.426	127.3%	0.965	290.2%	0.583	161.0%	
	0.166		0.234		0.500		0.332		112.5%
	0.141	84.9%	0.463	198.5%	0.955	191.0%	0.602	181.5%	
	0.040		0.081		0.165		0.066		107.9%
	35.9		35.5		36.1		35.9		

recirculation, the applied pressure on the feed side was approximately 1.6 bar. (Fig. 5(a)). With no flow on the feed side, there was no external pressure, allowing the removal of scale deposits due to the effect of pressure relaxation (Fig. 5(b)).

As shown in Fig. 4(c), the DI water circulation (DC mode) results in significant flux restorations. After the 1st, 2nd, and 3rd stops, the flux reached approximately the initial value. This indicates that most foulants (scales) were removed by the DI water circulation. It should be noted that the flux recovery ratios by the storage of the membrane in the DI water (Fig. 4(d), DS mode) were lower than those by the DI water circulation (DC mode). The use of DI water during the shutdown period leads to the dissolution of $CaSO_4$ scales. If the DI water is recirculated, the dissolution process may be accelerated. Although the additional pressure of 1.6 bar is applied during the DI water circulation just like the case of FC mode, the dissolution effect seems to be more important than the suppression of foulant (scales) relaxation.

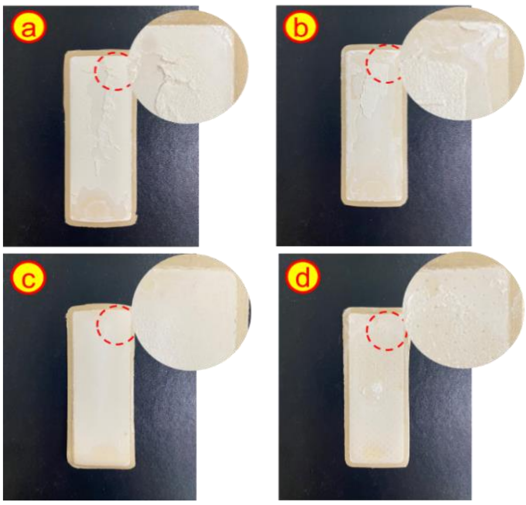


(a) feed solution circulation



(b) shutdown with feed solution

Fig. 5 Variations of applied pressure in the system over time



(b) shutdown with feed solution

Fig. 6 Membrane surface after variable intermittent operation condition: (a) feed solution circulation (FC mode); (b) membrane storage in feed solution (FS mode); (c) DI water circulation (DC mode); (d) membrane storage in DI water (DS mode)

To visually confirm the mechanisms of flux restoration, the RO membranes were taken from the module and visually observed. Fig. 6(a) shows that the scale deposits were significant. The amount of the scale deposits was smaller in Fig. 6(b) than in Fig. 6(a). When the DI water was used, the amount of the foulants on the membrane surface was smaller with the recirculation than without the recirculation. However, with the use of the feed solution during the shutdown cycle, the amount of the foulants on the membrane surface was smaller without the recirculation than with the recirculation. These results matched with the flux recovery patterns shown in Fig. 5.

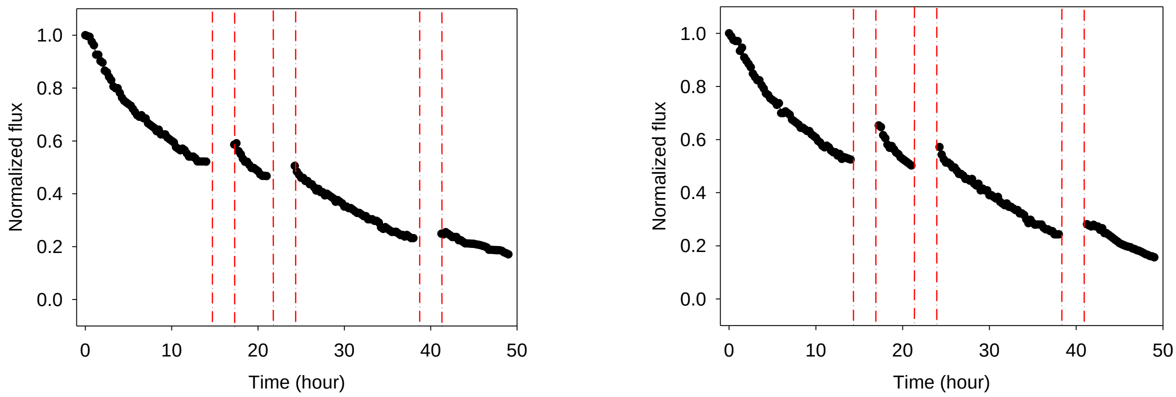
3.3 Intermittent operation of feed solutions containing ions and colloidal foulants

Fig. 7 compares the normalized flux profiles for different lay-up modes for the feed solution containing silica and NaCl (feed D). The corresponding flux recovery ratios were calculated and summarized in Table 7. In the 1st filtration cycle, the flux was reduced by approximately 50% reduction. Compared with the cases with the feed A (NaCl+$CaSO_4$), the flux decline was more significant due to the deposition of colloidal silica. When the feed solution was recirculated during the shutdown period (Fig. 7(a), FC mode), the flux was recovered by about 11.6%, 8.2%, and 7.4% after the 1st, 2nd, and 3rd stops. When the RO membrane was stored in the feed solution during the shutdown period (Fig. 7(b), FS mode), the flux was restored by 24.5%, 13.8%, and 15.6% after the 1st, 2nd, and 3rd stops. In the case of the DI water circulation (Fig. 7(c), DC mode) and the storage of the membrane in the DI water (Fig. 7(d), DS mode), the ratio of flux recovered by the intermittent operation ranges from 15.9% to 40.1%. The colloidal particles on the membrane surface may be released during the shutdown cycle, leading to an increase in the flux after each stop. These results suggest that the fouling caused by colloidal silica may be retarded by the intermittent operation with the use of the feed solution.

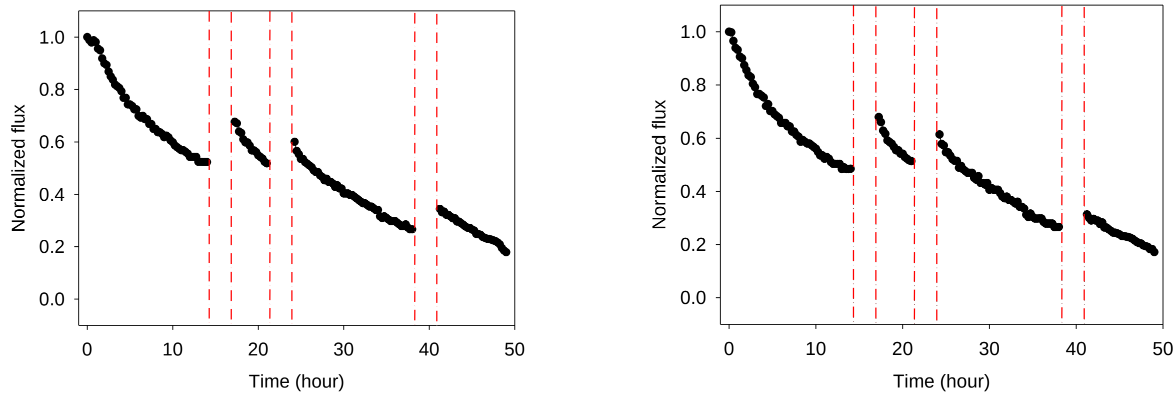
When the feed solution containing silica and $CaSO_4$ was used, the overall trends were substantially changed as shown in Figure 8 and Table 8. In the 1st filtration cycle, the flux decreased by approximately 55% due to the combined effect of colloidal deposition and scale formation. The application of the feed solution circulation during the shutdown cycle (Fig. 8(a), FC mode) led to substantial flux recovery. The flux recovery was found up to 166.7%. Similar results were observed by the application of feed solution storage (Fig. 8(b), FS mode) but the maximum flux recovery was higher (up to 257.5%). The results were more pronounced when DI water was used during the shutdown cycle (Fig. 8(c), DC mode, Fig. 8(d), DS mode). In both cases, the flux was restored to the level that is close to the initial value, indicating a majority of foulants on the membrane surface were removed during the shutdown period. Although the flux decline was resumed in the new filtration cycle, the final flux after 50 hours was higher in the DC and DS modes than the other modes. This is attributed to the behaviors of colloidal silica during the intermittent RO operation: If the colloidal silica particles exist in the $CaSO_4$ scale layers on the membrane, they are removed together with the scales during the shutdown period. The dissolution of the scales may be accelerated if it is combined with the physical removal assisted by the colloidal silica. As a result, a more efficient recovery of flux is observed in these cases.

3.4 Comparison of flux recovery efficiency by intermittent operation

Table 9 summarizes the flux recovery efficiency for different feed solutions and different lay-up modes. The symbol ( ) indicates the cases with the flux recovery ratio ranging from 95 to 105%. The symbol ( ), ( ), and ( ) indicate the cases with flux recovery ratios of 105 ~ 150%, 150 ~ 200%, and more than 200%, respectively. The intermittent operation was relatively ineffective to recover flux during the RO filtration of the feed A (NaCl+ $CaSO_4$).

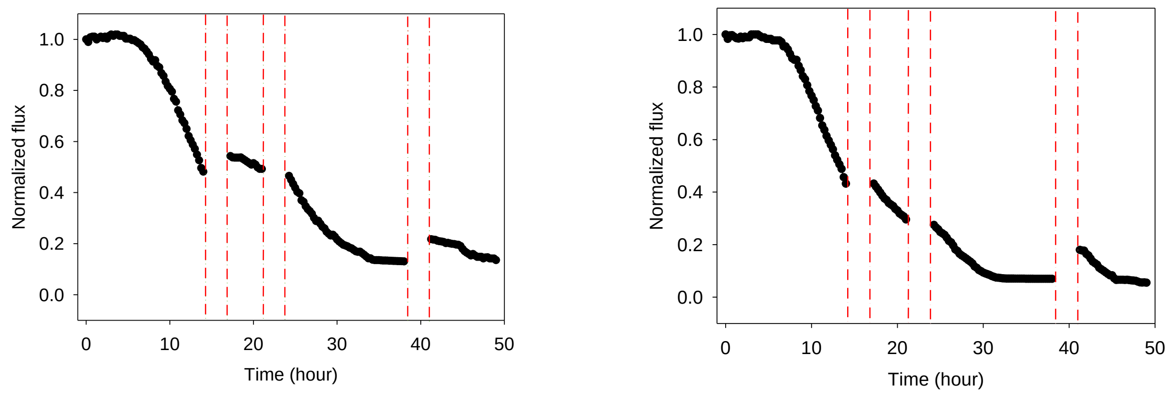


(a) Feed solution circulation (FC mode) (b) Membrane storage in feed solution (FS mode)

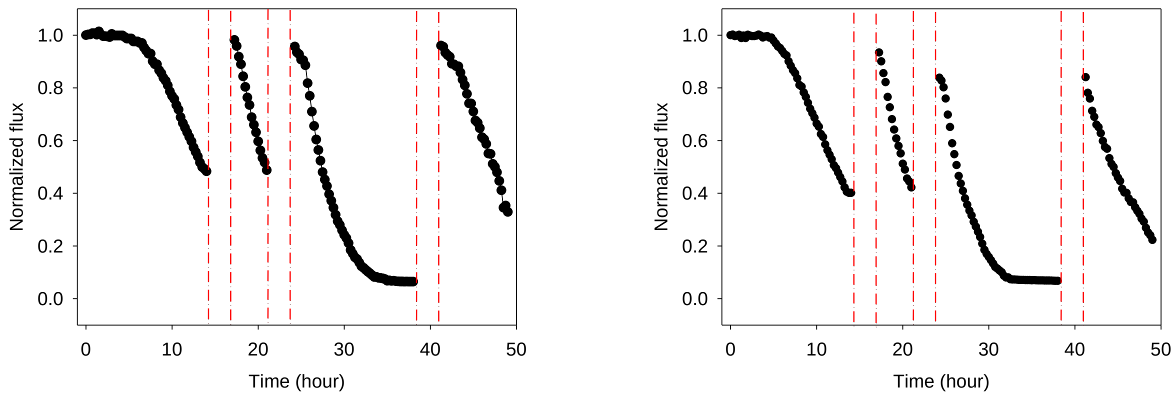


(c) DI water circulation (DC mode) (d) Membrane storage in DI water (DS mode)

Fig. 7 Normalized flux of intermittent operation by shutdown condition (Silica + NaCl)



(a) Feed solution circulation (FC mode) (b) Membrane storage in feed solution (FS mode)



(c) DI water circulation (DC mode) (d) Membrane storage in DI water (DS mode)

Fig. 8 Normalized flux of intermittent operation by shutdown condition (Silica + $CaSO_4$)

Table 9 Summary of fouling control effect by intermittent RO under different operating modes

Feed	Feed solution circulation (FC mode)	Membrane storage in feed solution (FS mode)	DI water circulation (DC mode)	Membrane storage in DI water (DS mode)
(Feed A) NaCl + $CaSO_4$ (Ions + Scale)	○	○	○	○
(Feed B) Real seawater (Mixed foulants)	◔	◔	◔	◔
(Feed C) $CaSO_4$ (Scale)	○	◑	◕	◑
(Feed D) Silica + NaCl (Colloids + Ions)	◔	◔	◔	◔
(Feed E) Silica + $CaSO_4$ (Colloids + Scale)	◔	◑	◕	◕

○: Ineffective (95 ~ 105%)
◔: slightly effective (105 ~ 150%)
◑: moderately effective (150 ~ 200%)
◕: highly effective (> 200%)

This was slightly more effective for the feed B (real seawater) than for the feed A. On the other hand, the intermittent operation using DI water during the lay-up results in significant flux improvement for the feed C ($CaSO_4$). This suggests that the fouling due to scale formation may be retarded by these methods. When the feed solution was used instead of the DI water during the shutdown cycle, the intermittent operation was less efficient to alleviate fouling due to scale formation. The intermittent operation was also effective to mitigate fouling caused by colloidal silica (feed D). When the feed solution contains both colloidal silica and scale-forming ions, the flux recovery by the intermittent operation was even more pronounced.

It is interesting to note that the effectiveness of the fouling control by intermittent operation is different depending on the feed water. Since each feed water has different foulants, the fouling control effect may be different. In addition to the foulant types, the pressure effect may be also important. In the RO tests, the pressure was adjusted from 22 bar (Feed C and Feed E) to 45 bar (Feed A, B, and D) to achieve the same initial flux of 30 L/m^2-hr. This may affect the extent of membrane fouling. If the applied pressure is higher, the foulant layer is consolidated and thus becomes more irreversible. As shown in Table 9, the efficiency of fouling control by intermittent operation was relatively low for Feed A, which corresponds to the operation under a high pressure (45 bar). On the other hand, the fouling control efficiency was higher for Feed C and Feed E, which corresponds to the operations under a lower pressure (22 bar). Accordingly, it can be concluded that the fouling control efficiency by the intermittent operation is affected not only by the foulant type but also the operating pressure.

4. Conclusions

In this work, the effect of the intermittent operation on RO membrane fouling was investigated as a function of operating conditions including foulant types and the lay-up modes. The following conclusions were withdrawn:

1. The intermittent operation of the RO membrane is not effective to recover flux when the feed solutions with low fouling and scaling potentials were used.
2. It was found that the intermittent operation reduced RO fouling due to scale formation and/or colloidal fouling. The use of DI water during the shutdown cycle was more effective to restore flux than that of the feed solution due to the dissolution of scales by DI water.
3. Compared with the case with the feed solution circulation (FC mode), the storage of membrane in the feed solution (FS mode) results in a high ratio of flux recovery. This is attributed to the hydraulic pressure (1.6 bar) imposed on the membrane during the feed solution circulation, leading to less efficient removal of foulants during the shutdown cycle.
4. Although it has been reported that the intermittent RO operation increases the fouling rate, the results of this study suggest the possibility of fouling mitigation. Nevertheless, it is necessary to confirm the feasibility of this approach through a series of long-term RO experiments.
5. Based on the results, the tentative washing conditions are suggested as follows: 14 hour of RO operation and 4 hour of DI water circulation (DC mode). This is just a tentative process because the interval and frequency were not optimized.

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