Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1189701

57 (2016) 26612–26620
November

Taylor & Francis
Taylor & Francis Group

An optimal design approach of forward osmosis and reverse osmosis hybrid process for seawater desalination

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Received 15 December 2015; Accepted 24 December 2015

ABSTRACT

The forward osmosis (FO) and reverse osmosis (RO) hybrid process uses seawater and wastewater treatment plant effluent as the FO draw solution and feed water, respectively, and the diluted seawater by FO is used as the RO feed water resulting in the less energy consumption than the conventional seawater reverse osmosis applications. This work developed an optimal design approach of the hybrid process by finding the optimal RO recovery and FO permeate flow rate. The optimized RO recovery (e.g. 38.5–66.7% according to the FO permeate flow rate) determined by solving an optimization problem based on the mass balance in the FO-RO hybrid process, minimizes the RO energy consumption (1.86–3.49 kWh/m^3 at 25˚C and 2.41–3.86 kWh/m^3 at 5˚C). The RO energy consumption decreases as the RO recovery increases until it reaches an optimal value. The optimal FO permeate flow rate can be defined with three different perspectives: (1) to minimize the RO energy consumption, (2) to minimize the RO feed flow rate, and (3) to minimize the environmental impacts of the concentrate discharge. Thus, the optimal FO permeate flow rate should be determined based on the weights of the three perspectives. The energy saving achieved by the optimal design approach in this work ranges from 37.6 to 46.7% according to the temperature.

Keywords: Forward osmosis; Reverse osmosis; Hybrid process; Optimal design approach

1. Introduction

The continuous population growth has considerably raised concerns on the sustainability of water and energy resources [1]. Due to water shortage, seawater is considered as a potential alternative water source and it is important to meet the increasing water demand at low energy cost. In fact, water and energy are closely linked together since water production needs energy and vice versa [2]. Various desalination technologies have been developed over the years such as thermal distillation, membrane, freezing, and electrodialysis. Among these desalination technologies, reverse osmosis (RO) process is dominant in the current market due to its relatively low cost and simplicity [3]. It has been improved to reduce the energy consumption and to increase salt and boron rejection

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Presented at the 8th International Desalination Workshop (IDW) 2015, November 18–21, 2015, Jeju Island, Korea

[4,5], but the minimum energy consumption is still limited to a range of 3–5 kWh/m^3 (energy consumption in kWh per unit fresh water production in cubic meters) [6].

As one of efforts to decrease desalting energy, forward osmosis (FO) is being investigated through laboratory and pilot tests [7,8]. The driving force in FO process is the osmotic pressure difference between feed and draw solution, and this process offers many advantages such as lower energy cost, significantly lower membrane fouling potential, easier fouling removal, and higher water recovery [9–13]. Kravath and Davis investigated desalination of Atlantic Ocean seawater by FO using cellulose acetate flat sheet and hollow fiber membranes and glucose solution as a draw solution [14]. Kessler and Moody modeled and tested similar applications of FO for seawater desalination [15]. The research group led by Elimelech at Yale University has constructed an FO pilot desalination plant using a concentrated draw solution of dissolved ammonia and carbon dioxide gases to draw seawater through the FO membrane. Freshwater can then be recovered from the diluted draw solution by heating it to 58℃ so that ammonia and carbon dioxide are captured out of the diluted draw solution [16–18]. Recently, FO process has attracted growing attention in not only seawater desalination, but also many potential applications such as power generation, wastewater treatment (e.g. osmotic membrane bioreactor), food processing, and microalgae harvesting [19–23].

Unlike RO, FO needs a draw solution recovery process to re-concentrate the draw solution by separating the product water from the diluted draw solution. Candidates for the draw solution recovery process are thermal separation, membrane separation, precipitation, combined processes, irrigation, and desert restoration [24]. Several hybrid FO systems with various draw solution recovery processes have been developed for seawater and brackish water desalination, wastewater treatment or both [25].

Among various hybrid FO systems for seawater desalination, this study focused on the membrane-based hybrid systems such as the FO-RO hybrid process, which was firstly utilized by Cath et al. [26]. Using RO as a draw solution recovery is advantageous than a heating process, which needs waste heat to meet the economic feasibility. In the FO-RO hybrid process for seawater desalination, seawater and wastewater treatment plant (WWTP) effluent are used as draw solution and feed for FO, respectively, and the diluted draw solution is used as the RO feed water, which has less osmotic pressure than seawater resulting in less energy consumption in FO-RO process than conventional seawater reverse osmosis (SWRO) system. The diluted RO feed is also beneficial to reduce the flux decline due to cake-enhanced concentration polarization [27]. Cath et al. [26] also carried out the economic feasibility assessment and found the introduction of FO can save costs for seawater desalination, but their analysis was limited to the fixed RO recovery (e.g. 50%). Since the RO feed water is diluted by the FO process, the RO recovery could be higher. Thus, this study focused on the selection of the optimal RO recovery in the FO-RO hybrid system discussed above. The optimal RO recovery as a function of the FO permeate flow rate minimizes the RO energy consumption subjected to the mass balance in the FO-RO hybrid process. The RO energy consumption is calculated by the RO process simulation using a commercial RO design software. Finding the optimal FO permeate flow rate is also a very important procedure for the optimal design approach of the FO-RO hybrid process. The three perspectives to find optimal FO permeate flow rate are also discussed.

2. Methods

2.1. Mass balance in the FO-RO hybrid process

Fig. 1 shows a schematic diagram to explain the mass balance in the FO-RO hybrid process. Instead of taking seawater (Q_{sw}, C_{sw}) as the RO feed water, the hybrid process uses the seawater as draw solution for the FO process. The WWTP effluent (Q_{we}, C_{we}) is used as the FO feed. The driving force for water flux in FO is then the osmotic pressure difference between the two water solutions, the seawater and the WWTP effluent. The permeate through the FO membrane ($Q_{p,FO}$, $C_{p,FO}$) joins the seawater to make the RO feed water which is less concentrated than the seawater,

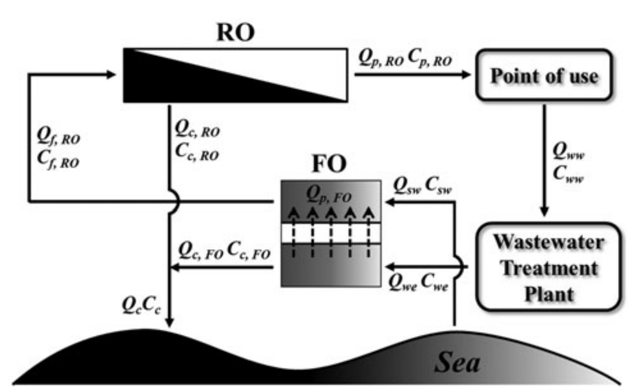

Fig. 1. The schematic of the FO-RO hybrid process.
Notes: Q: flow rate, C: TDS concentration, f: feed, p: permeate, c: concentrate, sw: seawater, ww: wastewater, we: WWTP effluent.

which results in the less energy requirement compared to the conventional SWRO system. The flow rate and total dissolved solids (TDS) concentration of the RO feed water ($Q_{f,RO}$, $C_{f,RO}$) can be calculated by:

$$Q_{f,RO} = Q_{sw} + Q_{p,FO} \tag{1}$$

$$C_{f,RO}Q_{f,RO} = C_{sw}Q_{sw} + C_{p,FO}Q_{p,FO} \tag{2}$$

If the complete rejection by the FO membrane (i.e. $C_{p,FO} = 0$) is assumed Eqs. (1) and (2), the TDS concentration of the RO feed water can be obtained using:

$$C_{f,RO} = \frac{C_{sw}Q_{sw}}{Q_{sw} + Q_{p,FO}} \tag{3}$$

The diluted RO feed water passes through the RO membrane to produce the final product ($Q_{p,RO}$, $C_{p,RO}$) and the RO concentrate ($Q_{c,RO}$, $C_{c,RO}$) is discharged into the sea with the FO concentrate (i.e. the concentrated WWTP effluent; $Q_{c,FO}$, $C_{c,FO}$). The final product flow rate ($Q_{p,RO}$) is a function of the RO recovery (r_{RO}) such as:

$$Q_{p,RO} = r_{RO}Q_{f,RO} \tag{4}$$

and the TDS concentration of the RO concentrate ($C_{c,RO}$) calculated using mass balance such as:

$$Q_{f,RO} = Q_{p,RO} + Q_{c,RO} \tag{5}$$

$$C_{f,RO}Q_{f,RO} = C_{p,RO}Q_{p,RO} + C_{c,RO}Q_{c,RO} \tag{6}$$

where $C_{p,RO}$ is assumed to be zero for the calculation of the log mean average feed-concentrate concentration, which will be introduced in Section 2.2. $C_{c,RO}$ is an important constraint in the FO-RO hybrid system and should be controlled to be lower than the RO concentrate level in the conventional SWRO process (e.g. $C_{c,RO} \le 2C_{sw}$ when $r_{RO} = 0.5$ is assumed).

The final discharge (Q_c, C_c) is the addition of the RO and FO concentrates such as:

$$Q_c = Q_{c,RO} + Q_{c,FO} \tag{7}$$

For environmental protection, the hazardous material concentration in the final discharge should not exceed that in the WWTP effluent, otherwise further wastewater treatments should be introduced to decrease the concentration of the hazardous materials. Assuming the perfect rejection of the hazardous materials by the FO membrane, the total mass of the hazardous materials in the final discharge should be the same as that in the WWTP effluent. Thus, we can control the hazardous material concentration in the final discharge by controlling the final discharge flow rate larger than the WWTP effluent flow rate as described in:

$$Q_c = Q_{c,FO} + Q_{c,RO} \ge Q_{we} \tag{8}$$

Eq. (8) can be rearranged using the FO recovery ($r_{FO} = Q_{p,FO}/Q_{we}$) by:

$$Q_{p,FO}\left(\frac{1}{r_{FO}} - 1\right) + Q_{c,RO} \ge \frac{Q_{p,FO}}{r_{FO}} \tag{9}$$

which can be simplified into:

$$Q_{c,RO} \ge Q_{p,FO} \tag{10}$$

Eq. (10) is another important constraint to find the optimal RO recovery to minimize the RO energy consumption.

2.2. Finding the optimal RO recovery

The optimal RO recovery can be defined as the recovery rate of the RO process with which the RO energy consumption is minimized. The RO energy consumption is directly proportional to the product of the RO feed flow rate ($Q_{f,RO}$) and pressure ($P_{f,RO}$) such as [23]:

$$E_{RO} \propto Q_{f,RO}P_{f,RO} \tag{11}$$

The RO feed pressure increases as the average feed-concentrate osmotic pressure ($\pi_{fc,RO}$), which can be assumed to be proportional to the log mean average feed-concentrate concentration ($C_{fc,RO}$) calculated by [28]:

$$C_{fc,RO} = C_{f,RO}\ln[1/(1 - r_{RO})]/r_{RO} \tag{12}$$

Thus, the RO energy consumption increases at higher $C_{fc,RO}$ values and we can define an RO energy index (EI_{RO}) as a function of the RO feed flow rate and the average feed-concentrate concentration as described in:

$$EI_{RO} = Q_{f,RO}C_{fc,RO} = Q_{f,RO}C_f\ln[1/(1 - r_{RO})]/r_{RO} \tag{13}$$

which means the RO energy consumption increases as the RO feed flow rate, concentration, and recovery rate increase. Thus, an optimization problem can be designed to find the optimal r_{RO} to minimize EI_{RO} as described in:

$$\begin{aligned} \text{Min} \quad & f(r_{\mathrm{RO}}) = EI_{\mathrm{RO}} \\ \text{s.t.} \quad & C_{\mathrm{c,RO}} \le 2C_{\mathrm{sw}} \\ & Q_{\mathrm{c,RO}} \ge Q_{\mathrm{p,FO}} \end{aligned} \tag{14}$$

where $f(r_{\mathrm{RO}})$ is a function of r_{RO} defined for the optimization problem and Eqs. (1)–(6) describe the mass balance in the FO-RO hybrid process. In this study, the final product flow rate ($Q_{\mathrm{p,RO}}$) and seawater TDS concentration were assumed to be 1,000 $\mathrm{m^3/d}$ and 35,000 mg/l, respectively. The optimization problem in Eq. (14) was solved using Microsoft Excel Solver with the pre-determined FO permeate flow rate ($Q_{\mathrm{p,FO}}$), which means the optimal RO recovery is a function of the FO permeate flow rate.

2.3. The RO process simulation

In order to calculate the RO energy consumption, the exact pressure and flow rate should be obtained. In this work, a commercial RO process design software, Reverse Osmosis System Analysis program (DOW Filmtec, USA) is used to simulate the RO operation results (e.g. pressure, flow rate) at the optimal RO recover rate, the pre-determined FO permeate flow rates (0–1,600 $\mathrm{m^3/d}$), and the assumed final product flow rate, 1,000 $\mathrm{m^3/d}$. The input data for the simulation are feed water quality (i.e. ion concentrations, pH), product flow rate, permeate flux, recovery rate, RO element type, number of elements per pressure vessel (PV), and the PV arrangements [4]. The selected SWRO membrane is SW30XLE-400i provided by DOW Chemical and the average permeate flux is assumed to be 14 $\mathrm{l/m^2\,h}$. The seawater ion compositions are obtained from the literature [29] and the temperatures for the simulation were 5 and 25˚C, which reflect the coldest and hottest seawater condition in South Korea.

The TDS obtained from the simulation were controlled to be smaller than 500 mg/l, which meets the Korean drinking water standards. The simulated pressure and flow rates were used to calculate the energy consumption per unit production (E_{RO}, $\mathrm{kWh/m^3}$) using [21]:

$$E_{\mathrm{RO}}\ (\mathrm{kWh/m^3}) = \frac{Q_{\mathrm{HP}}P_{\mathrm{HP}} + Q_{\mathrm{BP}}P_{\mathrm{BP}}}{36\eta Q_{\mathrm{p,RO}}} \tag{15}$$

where η, $Q_{\mathrm{HP}}P_{\mathrm{HP}}$, and $Q_{\mathrm{BP}}P_{\mathrm{BP}}$ are pump efficiency (assumed to be 0.9 in this work), the multiplication between high pressure pump (HP) flow rate ($\mathrm{m^3/d}$) and pressure (bars), and the multiplication between flow rate ($\mathrm{m^3/d}$) and pressure (bars) of the booster pump between the first and second stage (BP), respectively. The two-stage RO system with BP is designed for the optimal RO recovery higher than 58% (Fig. 2).

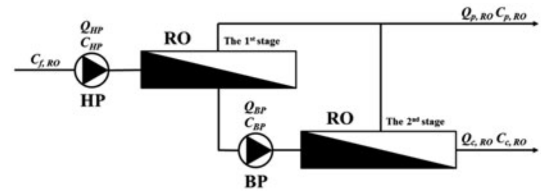

Fig. 2. The schematic of two-stage RO process to achieve high recovery (HP: high pressure pump, BP: booster pump).

Generally, energy recovery device (ERD) is used to save the energy consumption in SWRO processes. However, the effect of ERD was not considered in this work to investigate the energy-saving effect of FO process only. Since the effect of ERD is dependent upon the RO recovery, the energy-saving efficiency by ERD is not constant, but varies according to the type of the process (e.g. SWRO and the FO-RO hybrid processes). Thus, it is difficult to find the pure effect of FO process on the energy consumption in consideration of the ERD effect.

3. Results and discussion

3.1. The optimal RO recovery

The optimal RO recovery minimizes the RO energy consumption at a given FO permeate flow rate and it can be determined by solving the optimization problem in Eq. (14). Fig. 3 shows the effect of the RO recovery (r_{RO}) on the RO energy consumption (E_{RO}) at 25˚C for FO permeate flow rates ($Q_{\mathrm{p,FO}}$), 500 and 1,000 $\mathrm{m^3/d}$. The ratio of the RO concentrate flow rate to the FO permeate rate ($Q_{\mathrm{c,RO}}/Q_{\mathrm{p,FO}}$) is plotted to identify if an RO recovery value satisfies the constraint, $Q_{\mathrm{c,RO}} \ge Q_{\mathrm{p,FO}}$, which means the hazardous material concentration in the final discharge of the FO-RO hybrid process should not exceed that in the WWTP effluent for environmental protection discussed in Section 2.1. Thus, the RO recovery values less than a value at a dashed vertical line in Fig. 3(a) and (b), satisfy the constraint, $Q_{\mathrm{c,RO}} \ge Q_{\mathrm{p,FO}}$.

The RO energy consumption decreases as the RO recovery increases until it reaches its minimum value. Since the final product flow rate ($Q_{\mathrm{p,RO}}$) and the FO permeate flow rate ($Q_{\mathrm{p,FO}}$) are fixed in Fig. 3, the seawater intake flow rate (i.e. $Q_{\mathrm{i}} = Q_{\mathrm{p,RO}}/r_{\mathrm{RO}} - Q_{\mathrm{p,FO}}$

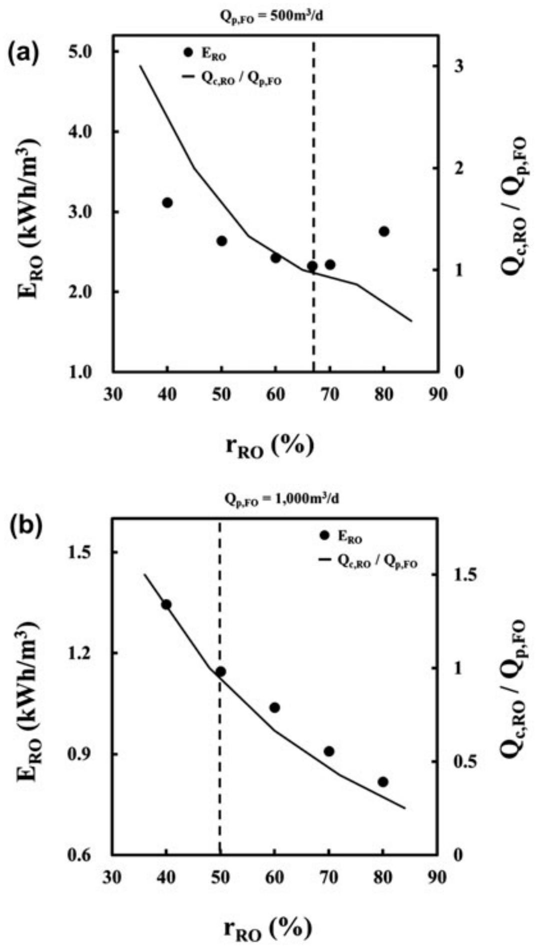

Fig. 3. The effect of the RO recovery on the RO energy consumption at 25°C for FO permeate flow rates: (a) 500 m^3/d and (b) 1,000 m^3/d.

rearranged from Eq. (1)) decreases at higher recovery rates resulting in the more diluted RO feed concentration ($C_{f,RO}$), which leads to decreasing RO energy consumption. However, the higher RO recovery induces the more concentrated RO concentrate and needs higher pressure requirement, which leads the increasing RO energy consumption. This is the reason why the RO energy consumption re-rises after it reaches its minimum as shown in Fig. 3(a). Consequently, the RO energy consumption is a result of trade-off of these two opposite effects of the RO recovery. The optimal RO recovery rates to satisfy all constraints and minimize the RO energy consumption at the FO permeate flow rates of 500 and 1,000 m^3/d are 66.7 and 50.0%, respectively, and the corresponding minimal RO energy consumptions are 2.33 and 1.87 kWh/m^3, respectively (Fig. 3).

Table 1 summarizes the RO process simulation results at the optimal RO recovery rates as a function of the FO permeate flow rate. The five columns from the left end mean the input parameters for the simulation while the six columns from the right end mean the output results, which can be used to calculated the RO energy consumption using Eq. (15) and to review the final product water quality ($C_{p,RO}$) if it is less than 500 mg/l. Table 1 clearly shows that the RO feed concentration decreases at the higher FO permeate flow rates, which leads the lower pressure requirements resulting in the higher energy saving by the introduction of FO to the RO-based desalination system.

3.2. The optimal FO permeate flow rate

The FO permeate flow rate is a key parameter for the optimal design of the FO-RO hybrid process for seawater desalination. There can be three different perspectives to define the optimal FO permeate flow rate: (1) to minimize the operation cost, (2) to minimize the capacity, and (3) to minimize the environmental impacts of the final discharge from the hybrid process. In this study, the three perspectives are specifically regarded as (1) to minimize the RO energy consumption, (2) to minimize the RO feed flow rate, and (3) to minimize the final discharge flow rate and to control the final discharge concentration close to the seawater concentration level.

In the first perspective, the optimal FO permeate flow rate minimizes the RO energy consumption because it occupies the most portion in the operation cost of the FO-RO hybrid process. The FO permeate flow rate has both positive and negative effects to decrease the RO energy consumption. Positively it decreases the RO feed concentration resulting in the less pressure requirement and negatively it increases the RO feed flow rate resulting in higher pumping energy described in Eq. (15). Thus, the RO energy consumption (E_{RO}) decreases as the FO permeate flow rate ($Q_{p,FO}$) increases until it reaches its minimum and then it slightly increases at the higher $Q_{p,FO}$ values (Fig. 4).

As shown in Fig. 4, the minimal E_{RO} values are 2.41 and 1.86 kWh/m^3 observed at $Q_{p,FO}$ = 800 m^3/d at 5°C and $Q_{p,FO}$ = 1,300 m^3/d at 25°C, respectively. Compared to the conventional SWRO process (i.e. $Q_{p,FO}$ = 0), these minimal values are equivalent to 37.6% at 5°C and 46.7% at 25°C of energy saving thanks to the introduction of FO. The optimal $Q_{p,FO}$ in the first perspective lies between 800 and 1,300 m^3/d according to the temperature. Since the change of E_{RO} is almost negligible in this range (Fig. 4), the optimal $Q_{p,FO}$ can be determined to be 800 m^3/d because the smaller $Q_{p,FO}$ means the less capital cost of the FO process.

Table 1
The summary of the RO process simulation results at the optimal RO recovery rates as a function of the FO permeate flow rate

Input					Output					
$Q_{p,FO}$ (m^3/d)	Q_{sw} (m^3/d)	r_{RO} (%)	$C_{f,RO}$ (mg/l)	T (°C)	PV array[a]	P_{HP} (bar)	Q_{HP} (m^3/d)	P_{BP} (bar)	Q_{BP} (m^3/d)	$C_{p,RO}$ (mg/l)
0	2,000	50.0	35,000	5	10:0	62.59	2,000	0	0	72.27
				25		56.61	2,000			237.54
100	1,800	52.6	33,158	5	10:0	61.83	1,900	0	0	71.31
				25		56.04	1,900			235.68
200	1,600	55.6	31,111	5	10:0	60.55	1,800	0	0	69.54
				25		54.98	1,800			231.32
300	1,400	58.8	28,824	5	7:3	57.49	1,700	7	878.69	65.40
				25		51.39	1,700	7	813.93	219.35
400	1,200	62.5	26,250	5	7:3	54.76	1,600	9	787.19	62.60
				25		48.85	1,600	9	724.83	211.40
500	1,000	66.7	23,333	5	7:3	51.72	1,500	11	693.92	59.24
				25		46.05	1,500	11	631.42	202.15
600	1,000	62.5	21,875	5	7:3	50.26	1,600	3	762.34	52.77
				25		44.02	1,600	3	679.57	180.57
700	1,000	58.8	20,588	5	7:3	47.89	1,700	0	856.47	47.01
				25		40.77	1,700	0	764.61	159.48
800	1,000	55.6	19,444	5	10:0	43.44	1,800	0	0	42.52
				25		35.73	1,800			140.80
900	1,000	52.6	18,421	5	10:0	41.12	1,900	0	0	38.52
				25		32.89	1,900			126.35
1,000	1,000	50	17,500	5	10:0	39.27	2,000	0	0	35.27
				25		30.67	2,000			114.83
1,100	1,000	47.6	16,667	5	10:0	37.78	2,100	0	0	32.57
				25		28.88	2,100			105.42
1,200	1,000	45.5	15,909	5	10:0	36.53	2,200	0	0	30.28
				25		27.42	2,200			97.57
1,300	1,000	43.5	15,217	5	10:0	35.48	2,300	0	0	28.31
				25		26.2	2,300			90.90
1,400	1,000	41.7	14,583	5	10:0	34.58	2,400	0	0	26.62
				25		25.17	2,400			85.15
1,500	1,000	40.0	14,000	5	10:0	33.81	2,500	0	0	25.09
				25		24.28	2,500			80.13
1,600	1,000	38.5	13,461	5	10:0	33.14	2,600	0	0	23.75
				25		23.51	2,600			75.71

[a]One pressure vessel (PV) contains eight SWRO membrane elements connected in serial. 10:0 means a single-stage SWRO system with 10 PVs and 7:3 means a two-stage SWRO system with 7 PVs in the first stage and 3 PVs in the second stage.

The second perspective to define the optimal $Q_{p,FO}$ is to minimize the RO feed flow rate ($Q_{f,RO}$). Since the final product flow rate ($Q_{p,RO}$) is fixed at 1,000 m^3/d in this work, $Q_{f,RO}$ (=$Q_{p,RO}/r_{RO}$) is minimized when the RO recovery (r_{RO}) is maximized. According to Fig. 4, the maximum r_{RO} (=66.7%) is observed at $Q_{p,FO}$ = 500 m^3/d, which is the optimal $Q_{p,FO}$ in the second perspective. As $Q_{p,FO}$ becomes higher than this optimal value, r_{RO} decreases because the RO concentrate flow rate ($Q_{c,RO}$) should exceed $Q_{p,FO}$ to satisfy the constraint, $Q_{c,RO} \geq Q_{p,FO}$ for the environmental protection discussed in Section 2.1.

Fig. 5 shows the effect of the FO permeate flow rate ($Q_{p,FO}$) on the water quality (C_c) and flow rate (Q_c) of the final discharge of the FO-RO hybrid process, which is related to the third perspective to define the optimal $Q_{p,FO}$ (i.e. to minimize the final discharge flow rate and to control the final discharge concentration close to the seawater concentration level). In Fig. 5, the concentration of the FO concentrate ($C_{c,FO}$)

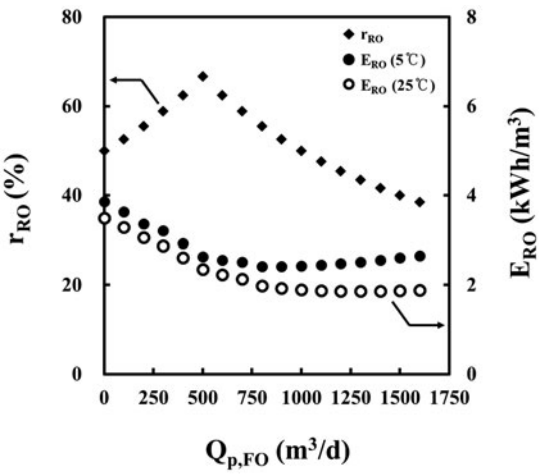

Fig. 4. The effect of the FO permeate flow rate on the optimal RO recovery and the RO energy consumption.

is neglected and the FO recovery (r_{FO}) is assumed to be 50% just for simplification. The TDS concentration of the RO concentrate ($C_{c,RO}$) is limited to the concentration level of SWRO concentrate (e.g. $C_{c,RO} \le 2C_{sw}$ for $r_{RO} = 0.5$) and the TDS concentration of the final discharge ($C_{c,RO}$) decreases at higher $Q_{p,FO}$ values as shown in Fig. 5(a). Because the final discharge goes to the sea, it will be the best if C_c is the same as the seawater TDS concentration (C_{sw}) to minimize the environmental impacts of the final discharge. Thus, the optimal $Q_{p,FO}$ is determined to be 500 m^3/d when C_c equals to C_{sw}, and it can become a bit larger than 500 m^3/d if $C_{c,FO}$ is not neglected.

As shown in Fig. 5(b), the final discharge flow rate (Q_c) is constant as $Q_{p,FO}$ increases up to 500 m^3/d because $C_{c,RO}$ is limited to the value twice as high as C_{sw} (Fig. 5(a)). By solving the optimization problem in Eq. (14), the optimal r_{RO} is determined to minimize the RO energy consumption (E_{RO}) and to satisfy the constraint, $C_{c,RO} \le 2C_{sw}$, which makes the sum of $Q_{c,RO}$ and $Q_{c,FO}$ (=$Q_{p,FO}$ if $r_{FO} = 0.5$) to equal to $Q_{c,RO}$ of the conventional SWRO (i.e. $Q_{p,FO} = 0$). If $Q_{p,FO}$ exceeds 500 m^3/d, the constraint, $Q_{c,RO} \ge Q_{p,FO}$, makes Q_c to be higher than 1,000 m^3/d as shown in Fig. 5(b). In this case, the optimal $Q_{p,FO}$ is less than 500 m^3/d to minimize Q_c. Since the optimal $Q_{p,FO}$ values are 500 m^3/d in Fig. 5(a), and less than 500 m^3/d in Fig. 5(b), the optimal value to satisfy the both considerations is consequently 500 m^3/d in the third perspective to define the optimal $Q_{p,FO}$. As a result, the optimal FO permeate flow rates ($Q_{p,FO}$) in three different perspectives discussed earlier are 800, 500, and 500 m^3/d, respectively. For the optimal design of the FO-RO hybrid process, the one value for the optimal

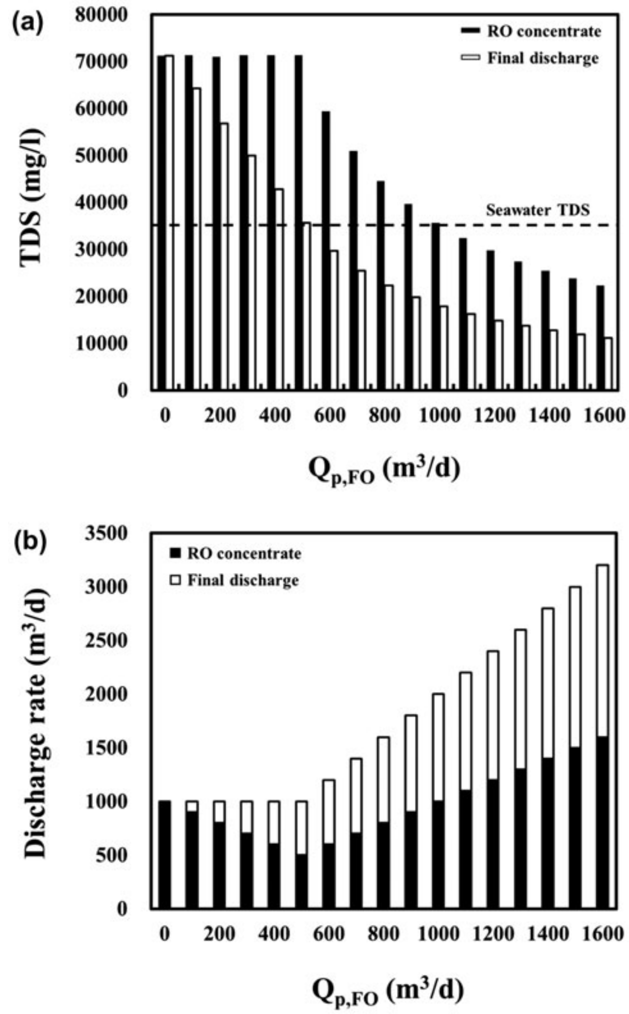

Fig. 5. The effect of the FO permeate flow rate on (a) the water quality and (b) flow rate of the final discharge of the FO-RO hybrid process.

$Q_{p,FO}$ should be determined based on the weights of the three perspectives. Because energy saving is generally considered to be the first priority of the introduction of the FO process to the conventional SWRO process, the first perspective (i.e. to minimize the RO energy consumption) could have more weight than other two perspectives. Thus the optimal FO permeate flow rate in this case study could be 800 m^3/d, but the optimal value may be limited by the construction cost of the FO process.

4. Conclusions

The introduction of FO process to the conventional SWRO system makes the FO-RO hybrid process with less energy requirements. The optimal design approach of the FO-RO hybrid process developed in this work enables the energy saving ranged from 37.6 to 46.7% according to the temperature. The procedures for the optimal design approach are as follows:

(1) Find the optimal RO recovery as a function of using the optimization problem to minimize the RO energy consumption subjected to the mass balance in the hybrid process and the constraints related to the RO concentrate limitation and the environmental protection. The optimized RO recovery (e.g. 38.5–66.7% according to the FO permeate flow rate) minimizes the RO energy consumption (1.86–3.49 kWh/m^3 at 25˚C and 2.41–3.86 kWh/m^3 at 5˚C).
(2) Find the optimal FO permeate flow rates using the optimal RO recovery in three different perspectives: (i) to minimize the operation cost, (ii) to minimize the capacity, and (iii) to minimize the environmental impacts of the final discharge from the hybrid process.
(3) Select the one optimal value for the optimal FO permeate flow rate among the three values obtained in the previous procedure. The selection should be based on the weights of the three perspectives. Generally, the first perspective (to minimize the operation cost) could be most preferred, but the optimal FO permeate flow rate may be limited by the construction cost of the FO process.

Acknowledgment

This work was supported by the Pukyong National University Research Abroad Fund in 2014 (C-D-2014-0720).

References

[1] M.A. Shannon, P.W. Bohn, M. Elimelech, J.G. Georgiadis, B.J. Mariñas, A.M. Mayes, Science and technology for water purification in the coming decades, Nature 452 (2008) 301–310.
[2] H. Lee, H. Ryu, J.-H. Lim, J.-O. Kim, J.D. Lee, S. Kim, An optimal design approach of gas hydrate and reverse osmosis hybrid system for seawater desalination, Desalin. Water Treat. 57 (2016) 9009–9017.
[3] L. Chekli, S. Phuntsho, J.E. Kim, J. Kim, J.Y. Choi, J.-S. Choi, S. Kim, J.H. Kim, S. Hong, J. Sohn, H.K. Shon, A comprehensive review of hybrid forward osmosis systems: Performance, applications and future prospects, J. Membr. Sci. 497 (2016) 430–449.
[4] S. Sarp, S. Lee, X. Ren, E. Lee, K. Chon, S.H. Choi, S. Kim, I.S. Kim, J. Cho, Boron removal from seawater using NF and RO membranes, and effects of boron on HEK 293 human embryonic kidney cell with respect to toxicities, Desalination 223 (2008) 22–30.
[5] B. Park, J. Lee, M. Kim, Y.S. Won, J.H. Lim, S. Kim, Enhanced boron removal using polyol compounds in seawater reverse osmosis processes, Desalin. Water Treat. 57 (2016) 7910–7917.
[6] S. Kim, D. Cho, M.S. Lee, B.S. Oh, J.H. Kim, I.S. Kim, SEAHERO R&D program and key strategies for the scale-up of a seawater reverse osmosis (SWRO) system, Desalination 238 (2009) 1–9.
[7] M. Khayet, T. Matsuura, Membrane Distillation Principles and Application, Elsevier, Amsterdam, 2011.
[8] T.Y. Cath, A.E. Childress, M. Elimelech, Forward osmosis: Principles, applications, and recent developments, J. Membr. Sci. 281 (2006) 70–87.
[9] J.R. McCutcheon, M. Elimelech, Influence of concentrative and dilutive internal concentration polarization on flux behavior in forward osmosis, J. Membr. Sci. 284 (2006) 237–247.
[10] M. Elimelech, W.A. Phillip, The future of seawater desalination: Energy, technology, and the environment, Science 333 (2011) 712–717.
[11] A. Achilli, T.Y. Cath, E.A. Marchand, A.E. Childress, The forward osmosis membrane bioreactor: A low fouling alternative to MBR processes, Desalination 239 (2009) 10–21.
[12] B. Mi, M. Elimelech, Organic fouling of forward osmosis membranes: Fouling reversibility and cleaning without chemical reagents, J. Membr. Sci. 348 (2010) 337–345.
[13] C.R. Martinetti, A.E. Childress, T.Y. Cath, High recovery of concentrated RO brines using forward osmosis and membrane distillation, J. Membr. Sci. 331 (2009) 31–39.
[14] R.E. Kravath, J.A. Davis, Desalination of sea water by direct osmosis, Desalination 16 (1975) 151–155.
[15] J.O. Kessler, C.D. Moody, Drinking water from sea water by forward osmosis, Desalination 18 (1976) 297–306.
[16] Q. Schiermeier, Water: Purification with a pinch of salt, Nature 452 (2008) 260–261.
[17] J.R. McCutcheon, R.L. McGinnis, M. Elimelech, A novel ammonia-carbon dioxide forward (direct) osmosis desalination process, Desalination 174 (2005) 1–11.
[18] B.S. Chanukya, S. Patil, N.K. Rastogi, Influence of concentration polarization on flux behavior in forward osmosis during desalination using ammonium bicarbonate, Desalination 312 (2013) 39–44.
[19] F. Lotfi, S. Phuntsho, T. Majeed, K. Kim, D.S. Han, A. A.- Wahab, H.K. Shon, Thin film composite hollow fibre forward osmosis membrane module for the desalination of brackish groundwater for fertigation, Desalination 364 (2015) 108–118.
[20] S. Zhao, L. Zou, C.Y. Tang, D. Mulcahy, Recent developments in forward osmosis: Opportunities and challenges, J. Membr. Sci. 396 (2012) 1–21.
[21] S. Kim, S. Paudel, G.T. Seo, Forward osmosis membrane filtration for microalgae harvesting cultivated in sewage effluent, Environ. Eng. Res. 20(1) (2015) 99–104.
[22] S. Kim, Scale-up of osmotic membrane bioreactors by modeling salt accumulation and draw solution dilution using hollow-fiber membrane characteristics and operation conditions, Bioresour. Technol. 165 (2014) 88–95.

[23] S.H. Park, B. Park, H.K. Shon, S. Kim, Modeling full-scale osmotic membrane bioreactor systems with high sludge retention and low salt concentration factor for wastewater reclamation, Bioresour. Technol. 190 (2015) 508–515.
[24] L. Chekli, S. Phuntsho, H.K. Shon, S. Vigneswaran, J. Kandasamy, A. Chanan, A review of draw solutes in forward osmosis process and their use in modern applications, Desalin. Water Treat. 43 (2012) 167–184.
[25] K. Lutchmiah, A.R.D. Verliefde, K. Roest, L.C. Rietveld, E.R. Cornelissen, Forward osmosis for application in wastewater treatment: A review, Water Res. 58 (2014) 179–197.
[26] T.Y. Cath, J.E. Drewes, C.D. Lundin, A novel Hybrid Forward Osmosis Process for Drinking Water Augmentation using Impaired Water and Saline Watersources, Colorado School of Mines, Golden, CO, 2008.
[27] S. Kim, S. Lee, E. Lee, S. Sarper, C.H. Kim, J. Cho, Enhanced or reduced concentration polarization by membrane fouling in seawater reverse osmosis (SWRO) processes, Desalination 247 (2009) 162–168.
[28] ASTM, Standard Practice for Standardizing Reverse Osmosis Performance Data, D 4516-00 American Society for Testing and Materials, West Conshohocken, 2010.
[29] Dow Liquid Separations, Filmtec Reverse Osmosis Membranes Technical Manual, The Dow Chemical Company Form No. 609-00071-0705, 2005.