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Investigation into design parameters in seawater reverse osmosis (SWRO) and pressure retarded osmosis (PRO) hybrid desalination process: a semi-pilot scale study

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ABSTRACT

The performance of a seawater reverse osmosis and pressure retarded osmosis (SWRO-PRO) hybrid system for power generation and seawater desalination was investigated using a pilot-scale system. The draw and feed solutions of the PRO process were SWRO brine and permeate, respectively. The PRO system performed better, meaning it had a higher energy recovery rate, at higher draw solution salinities. The PRO performance was further improved by increasing the flow rate of the draw solution as this reduced the concentration polarization effect in the PRO membrane. The performance of the PRO module was investigated experimentally, and the results were compared with simulations. The maximum power density of the PRO membrane module was 14 W/m^2 at 28 bar using a solution with 70,000 mg/L of sodium chloride (NaCl) and draw and feed solution flow rates of 20 LPM and 4 LPM, respectively. We estimated the performance of the PRO membrane module using a simulation that incorporated the temperature of the draw solution. Our model can be used to predict the effects of operational conditions including solution concentrations, the flow rate, the flow ratio of the draw and feed solutions, and the temperature of the draw solution in the PRO system.

Keywords: Desalination; Seawater reverse osmosis (SWRO); Pressure retarded osmosis (PRO); Energy recovery; Power density

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1. Introduction

The increasing demand for portable water for drinking, irrigation, and industrial use, especially in arid and semi-arid regions necessitates the construction of numerous seawater reverse osmosis (SWRO) desalination plants. Because membrane-based seawater desalination processes require less energy than thermal desalination processes such as multi-stage flash distillation, multiple-effect distillation, etc. from 2004 to 2014, 73.7% of global contracted desalination capacity was based on SWRO desalination plants [1]. However, the energy consumption rates of conventional SWRO desalination system must be reduced. Recently, attention has been devoted to an osmotic energy recovery technology in an SWRO desalination system, because it can reduce the overall energy consumption rate required for seawater desalination [2–5]. The novel osmotic energy recovery technology, called pressure retarded osmosis (PRO), can extract osmotic energy (or pressure) by transporting water through a semi-permeable membrane from a low-salinity feed solution to a high-salinity draw solution against an applied hydraulic pressure. Since the PRO technology was first introduced by Loeb [6], most studies have focused on recovering the potentially huge amounts of osmotic energy from estuaries where freshwater meets seawater [7,8]. It is estimated that approximately 2 TW, almost 13% of the total global energy consumption [9], could be obtained in this way. However, the energy recovery (or power generation) technologies based on PRO processes, which use seawater as a draw solution and freshwater as a feed solution, still have a few critical limitations that must be overcome prior to commercialization [10]. The water flux and power density (PD) obtained by available PRO membrane modules are less than 5 W/m^2, which are not high enough to make a PRO technology economically feasible [11,12]. The main reasons for this are that the PRO membranes currently in use have relatively low water permeability, there have not been many attempts to optimize the membrane support layer structure and the PRO membrane modulating method has not been standardized. These factors result in a substantial reduction in the available osmotic energy recovery rate [13,14]. Many PRO studies have focused on the fundamental mechanisms of the salt and water transfer kinetics with lab-scale systems, with the goal of clarifying the properties of the PRO membrane and the PD [7,8,13,15]. Zhang [16] reported that a new hollow fiber membrane comprising a thin film composite (TFC) layer with high porosity produces a maximum PD of 24.3 W/m^2 at 20 bar, using 1 M NaCl solution as brine and deionized water as a feed solution. Although these lab-scale studies are necessary to estimate the relative performance of different membranes and to clarify the energy recovery mechanism of the PRO process, few pilot-scale studies have been conducted to investigate the key design and operational parameters of a PRO system. Additionally, few studies where the PRO membrane module has been modeled have considered performance as the process is scaled up [17]. Feinberg [18] introduced a mathematical PRO model of a full-scale PRO-RED system based on limited experimental results, and developed a novel configuration of a PRO system with the goal of increasing the overall system efficiency. Altaee [19,20] systematically investigated the modeling and optimization of a dual-stage PRO process and a hybrid FO/RO/PRO process. However, it is not possible to evaluate the performance of an entire PRO system using these models. In 2009, Statkraft (Norway) constructed and operated the first pilot PRO power generation plant, taking advantage of the salinity gradient between sea and river water; it was equipped with numerous spiral-wound PRO membrane modules. In 2012, a Japanese research consortium also started conducting research on osmotic power production in seawater desalination processes by harvesting the osmotic energy of seawater brine; a pilot plant with hollow fiber PRO membrane modules was built in Fukuoka. However, only limited results from these pilot-scale studies have been published.

In this study, the key design parameters and operational conditions of an SWRO-PRO hybrid desalination system were evaluated with a semi-pilot scale PRO system composed of a 4 inch TFC PRO spiral-wound membrane. The pilot-scale studies were conducted with a wide range of operating conditions. We varied the salt concentrations, flow rates of the draw and feed solutions, and the pressure applied onto the PRO membrane module. Also, the PD of the PRO membrane module was simulated at different temperatures. We then compared modeled and experimental results to evaluate the effect of temperature on the PRO performance. Together, these findings clarified the effects of the reverse salt flux and concentration polarization of the PRO membrane and helped us identify the optimal operating condition(s) of an SWRO-PRO hybrid desalination system.

2. Methods and materials

2.1. Water flux in the PRO module and modeling

In a PRO system, the draw solution needs to be pre-pressurized before it is injected into the system. Once the high-salinity draw solution and the low-salinity feed solution are introduced to each side of a semi-permeable PRO membrane, the salinity difference between the two solutions naturally generates osmotic pressure through the PRO membrane. The osmotic pressure drives water transfer from the feed solution to the draw solution through a semi-permeable PRO membrane while maintaining a certain level of pressure in the draw solution side. The increased volume of the draw solution induces pressure, which is converted to power by an energy recovery device such as a power generation turbine. The water flux across a PRO membrane is defined by:

$$J_w = A(\Delta\pi - \Delta P) \tag{1}$$

where J_w is the water flux, A is the water permeability coefficient of the membrane, $\Delta\pi$ is the transmembrane osmotic pressure difference, and ΔP is the transmembrane hydraulic pressure difference. The values of the characteristic factors, A and B were obtained from a previous study [21].

The salt permeability coefficient (B) is determined from the equation stated in Lee [15]:

$$B = \frac{J_w(1-R)}{R}\exp\left(-\frac{J_w}{k}\right) \tag{2}$$

where R is the salt rejection of the module, J_w is the water flux, and k is the mass transfer coefficient.

$$k = \frac{ShD}{d_h} \tag{3}$$

where D is the diffusion coefficient of the NaCl, d_h is the hydraulic diameter, and Sh is the Sherwood number:

$$Sh = 0.2\ Re^{0.57}Sc^{0.40} \tag{4}$$

The solute resistivity to salt transport in a porous substrate K_R, which is a function of the structural parameters S and D ($K_R = \frac{S}{D}$), was calculated using Eq. (5) [8] and the water flux:

$$J_w = A\left[\frac{\pi_{\text{Draw\_avg}}\exp\left(-\frac{J_w}{k}\right) - \pi_{\text{Feed\_avg}}\exp(J_wK_R)}{1+\frac{B}{J_w}\left[\exp(J_wK_R) - \exp(-\frac{J_w}{k})\right]}\right] \tag{5}$$

Water flow across a PRO membrane is induced by the transmembrane osmotic pressure difference ($\Delta\pi$). Because the pressure on the PRO membrane is exerted in a direction opposite to the water flow, the water flux (J_w) decreases as the pressure difference (ΔP) increases [22,23]:

$$W = J_w\Delta P = A(\Delta\pi - \Delta P)\Delta P \tag{6}$$

The water recovery rate, R_e was calculated using:

$$R_e = \frac{\Delta V_f}{V_{f,i}} \times 100 \tag{7}$$

where $V_{f,i}$(L) is the initial volume of the feed solution and ΔV_f is its change in volume.

2.2. An SWRO-PRO semi-pilot scale plant system

A schematic diagram of an SWRO-PRO experimental unit is presented in Fig. 1. The draw and feed solutions were injected using the high- and low-pressure pumps. The hydraulic pressure and flow rate of the draw and feed solutions were controlled using a control valve. The pressure, flow rate, concentration, conductivity, and temperature were monitored using a human–machine interface in the SWRO-PRO system. To ensure the accurate conversion of conductivity into concentration, the conductivity meters were calibrated before the experiment. The data were collected every 10 s. The temperature of each tank was adjusted using a temperature controller.

2.3. The spiral-wound PRO module and experimental conditions

The PRO module was produced by Toray Chemical Korea. The PRO module was 4 inches in diameter and 40 inches in length. The PRO module had a 3.8 m^2 membrane with a polyamide active layer. The physical characteristics of this membrane were similar to those reported previously [21].

This PRO membrane module was investigated under various operational conditions. The key operational parameters evaluated include pressure, concentration, and the flow rate of the draw and feed solutions. These parameters are known to significantly influence the energy consumption rate and operational efficiency of the plant. In the PRO experiments, the draw and feed solutions were introduced to the module in the co-current direction.

Unless otherwise specified, all reagents and chemicals were analytical grade. Certified ACS-grade NaCl (Fisher Scientific, MA, USA) was used to prepare SWRO influent at two concentrations: 2.5–3.5%. Two

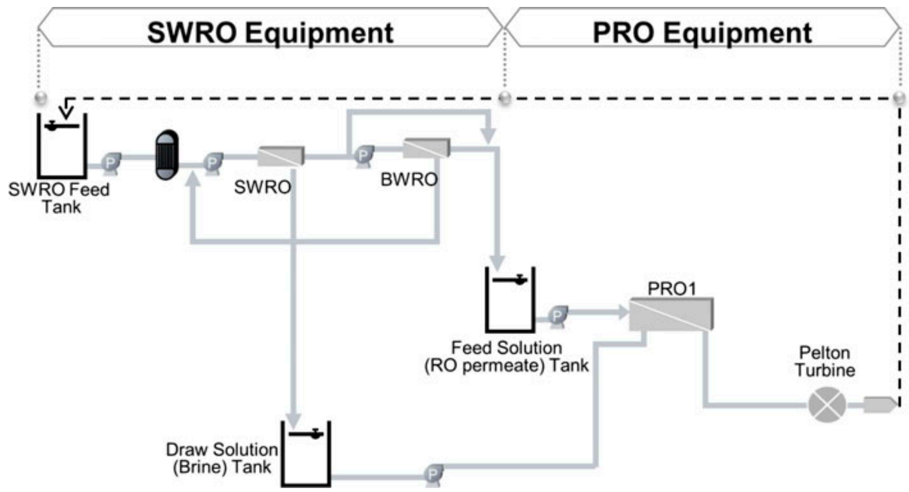

Fig. 1. Schematic diagram of the SWRO-PRO semi-pilot (capacity, 20 m^3/d).

Table 1
The ratios of draw and feed solution

Condition	Draw solution (LPM)	Feed solution (LPM)	Ratio
1	5	2.5	2:1
2	5	5	1:1
3	5	7.5	1:1.5
4	4	4	1:1
5	8	4	2:1
6	12	4	3:1
7	15	4	4:1
8	20	4	5:1

different SWRO brine concentrations, 50,000–70,000 mg/L, were used for the high salinity draw solution and an SWRO permeate was used as a low-salinity feed solution. The flow rates of the draw and feed solutions were 2.4, 5, and 10 L/min. Table 1 lists the ratio of the draw and feed solutions. The applied hydraulic pressure differences, ΔP, were 5, 10, 15, 20, 25, and 30 bar.

3. Results and discussion

3.1. Effect of a draw solution concentration

The effect of the draw solution concentration on a PRO system with a spiral-wound TFC membrane was evaluated with a feed solution with a concentration of 400 mg/L total dissolved solids. The applied draw solution concentrations, 50,000–70,000 mg/L are typical salt concentration levels found in SWRO desalination brine. As shown in Fig. 2(A), the increase in the concentration of the draw solution from 50,000 to 70,000 mg/L slightly affected the water flux and PD (the estimated power per unit membrane area). The maximum power densities obtained with draw solution concentrations of 50,000–70,000 mg/L were 4.2–5.8 W/m^2, respectively. These power densities are close to the value generally considered necessary ~5 W/m^2, for an economically PRO process [11,12]. Fig. 2(B) presents the feedwater recoveries for draw solution concentrations of 50,000–70,000 mg/L.

The maximum water recovery ratios obtained with draw solution concentrations of 50,000–70,000 mg/L were 33–38%, respectively. As reported previously [24,25], the permeate flow rate was higher when the salt concentration was higher, because of the increased osmotic pressure at the PRO membrane. The increased permeate flow rate led to an increase in the PD of the PRO membrane module. However, the flux behavior was highly non-linear with respect to the draw solution concentration due to the mass transfer resistance and external concentration polarization on the feedwater side [26].

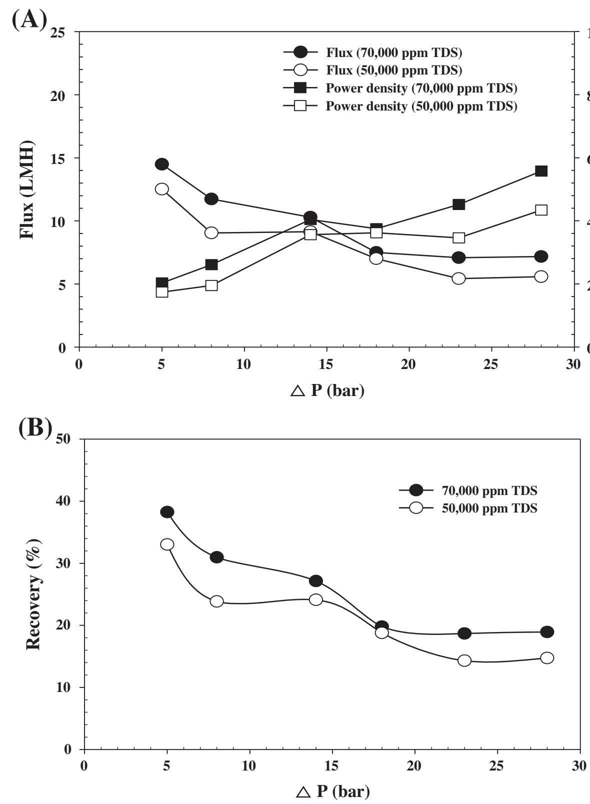

Fig. 2. Effect of applied pressure on water flux and PD (A) and recovery (B) in the PRO system at different draw solution concentrations.

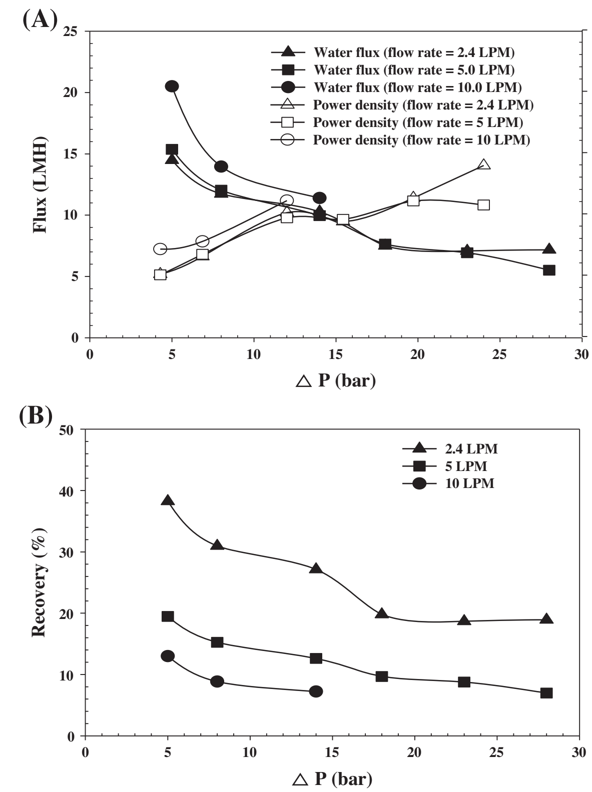

Fig. 3. Effect of draw and feed solutions flow rate on the PRO performance. Water flux and PD (A) and recovery of feed solution (B).

3.2. *Effect of the flow rate of the draw and feed solutions*

One of the key parameters in a PRO system is the flow rate of the draw and feed solutions, as this affects the water transmembrane flux and the overall system efficiency. A higher draw and feed solution flow rate reduces the effect of concentration polarization at the PRO membrane surface.

Fig. 3 presents the operational results obtained from the semi-pilot scale plant including the measured water flux, PD, and water recovery rate at different applied hydraulic pressures. The higher flow rate increased the total permeate volume, which directly enhanced the PD. When the flow rate of the draw and feed solutions was 2.4 L/min, we observed a peak PD of 5.8 W/m^2 at 28 bar of applied hydraulic pressure (Fig. 3(A)). This is consistent with previous findings, where the maximum PD was found to occur when the applied hydraulic pressure was nearly half the osmotic pressure ($\Delta\pi/2$) [15,24]. As shown in Fig. 3(B), the maximum water recovery ratio was obtained when the flow rate of the draw and feed solutions was 2.4 L/min, and the applied hydraulic pressure was 5 bar. The recovery ratio was 38%. Increasing the flow rate can decrease the effect of the PRO membrane concentration polarization; therefore, the membrane flux and PD can also be enhanced. However, in a real desalination plant, the available volume of draw and feed solutions is always limited. To increase the water recovery ratio, and hence the energy recovery ratio, more PRO membrane modules are required [25].

3.3. *Effect of the ratio of draw and feed solutions*

In an SWRO-PRO hybrid desalination system, the availability of draw and feed solutions is always limited. This factor is particularly important in arid regions and countries with limited wastewater effluent available for use as a feed solution or a PRO system. Therefore, it is also necessary to investigate the effect of the ratio of draw and feed solutions in a PRO system. Various ratios of draw and feed solutions were used in the semi-pilot scale plant to evaluate their effect on the system performance parameters. Fig. 4 presents the effects of the feed solution ratio on the PD (Fig. 4(A)), water flux (Fig. 4(A)), and water recovery

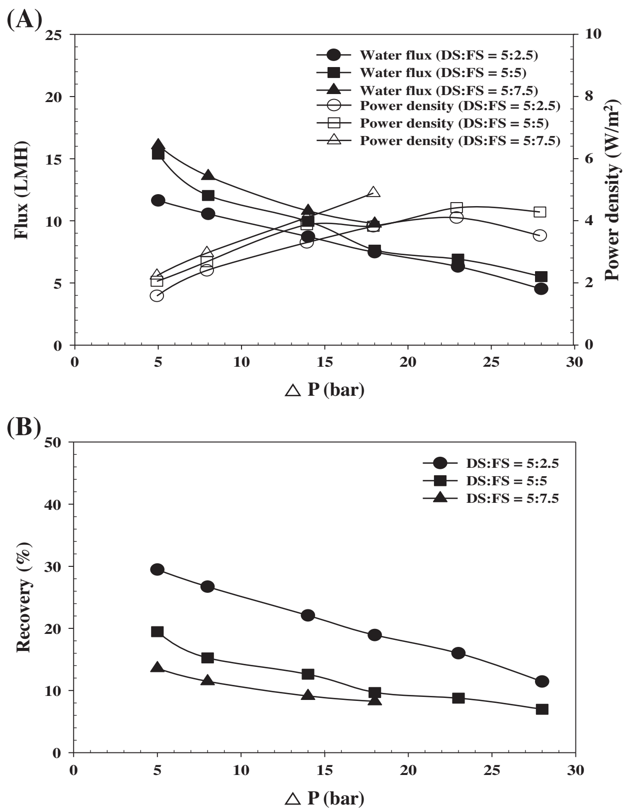

Fig. 4. Impact of various feed solution ratios on PRO performance. Draw solution was fixed as 5 L/min and feed solution was changed from 2.5 to 7.5 L/min. Ratio is 1:0.5, 1:1, 1:1.5, respectively. Water flux and PD (A) and recovery (B).

(Fig. 4(B)). Increasing the flow rate of the feed solution from 2.5 to 7.5 L/min did not result in significant differences in the PD and flux. The maximum power densities at feed solution flow rates of 2.5, 5, and 7.5 L/min were 4.0, 4.3, and 5.0 W/m^2, respectively. However, higher water recovery was achieved by decreasing the flow rate of the feed solution.

Fig. 5 presents the effects of the draw solution ratio on the flux (Fig. 5(A)), PD (Fig. 5(B)), and water recovery (Fig. 5(C)) as the flow rate of the draw solution was varied and the flow rate of the feed solution was fixed at 4 L/min. The experimental results showed that the flux, PD, and water recovery increased as the draw solution flow rate increased. At a draw solution flow rate of 20 L/min, the maximum PD of 14.7 W/m^2 and the maximum recovery rate was 33%. This finding was attributed to the lower concentration polarization effect, which increased the PRO membrane flux and hence the PD. Together, these results indicate that varying the draw solution flow rate results in a greater increase in the PD, flux, and water recovery than varying the feed solution flow rate. Previous studies [25–27] have reported that a higher PD can be achieved by increasing the draw solution flow rate than by increasing the feed solution flow rate. Therefore, to generate more power from the PRO process, we recommended increasing the draw solution flow rate.

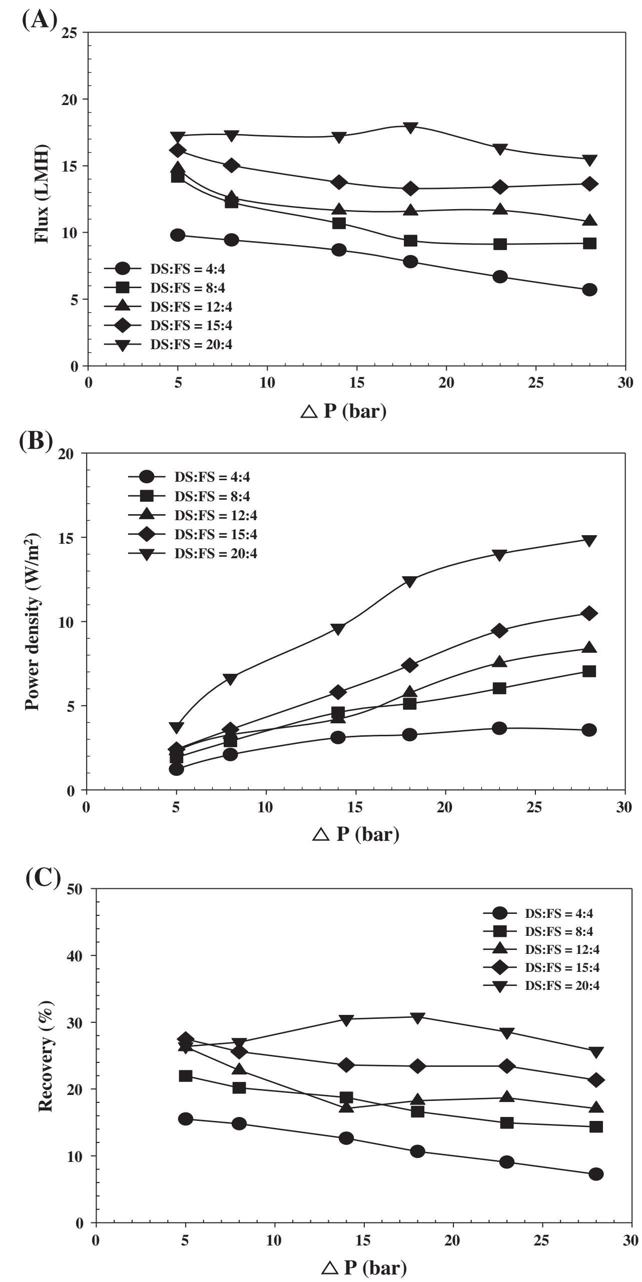

Fig. 5. Impact of various draw solution ratios on PRO performance. Feed solution was fixed as 4 L/min and draw solution was changed from 4 to 20 L/min. Ratio is 1:1, 2:1, 3:1, 3.75:1, 5:1, respectively. Water flux (A), PD (B), and recovery (C).

3.4. Calculation of PRO membrane parameters for simulation

In order to predict the PD of the PRO membrane, the water permeability (A), salt permeability (B), and membrane structure parameter (S) were used [5,13]. The values of the characteristic factors, A and B were obtained from previous studies using Eqs. (1) and (2) [23]. The relationship between the water permeability (A) and temperature is $J_T = J_{20^\circ C} \times \exp[0.0225 \times (T - 20)]$ [28,29]. The relationship between salt permeability (B) and temperature is $B_T = 0.5372 \times \exp(0.0202 \times T)$. Because the water permeability (A) and salt permeability (B) are both dependent on the temperature, the PD of the PRO membrane is also temperature dependent [13,30]. For example, She [13] found that when the temperature increased from 25 to 35℃, the maximum PD improved, increasing from 3.8 to 5.1 W/m^2. Similar results were observed by Anastasio [30]; the authors observed an improvement in the peak PD from 1.3 W/m^2 at 20℃ to 4.0 W/m^2 at 40℃. Table 2 lists the effects of temperature on water and salt permeability. Water permeability increased by 44% when the temperature increased from 5 to 30℃: Values were 1.639 L/m^2/h/kgf/cm^2 at 5 and 30℃, respectively. Salt permeability increased by 57% when the temperature increased from 5 to 30℃.

3.5. Comparison of simulated and experimental data

Fig. 6 presents the experimental and simulated water flux and PD as a function of applied hydraulic pressure and temperature. Clearly, the PRO performance was significantly improved when the temperature increased from 5 to 30℃. Previous studies have reported similar improvements in water flux at higher temperatures [28,30–32]. According to the observed results, the maximum simulated PD that can be achieved at 28 bar is 9 W/m^2. Firstly, increasing the temperature will increase both the A and B values of the PRO membrane (Table 2). An increase in the A value has a positive effect, improving both the water flux and PD, while an increase in the B value is likely to reduce the water flux and PD due to the increased reverse salt flux and thus the enhanced internal concentration polarization (ICP) [13,28], which is reflected in Eq. (5). Secondly, while increasing the temperature from 5 to 30℃, the diffusivity (D value) of the sodium chloride increased from 0.80 to 1.68×10^{-9} m^2/s,

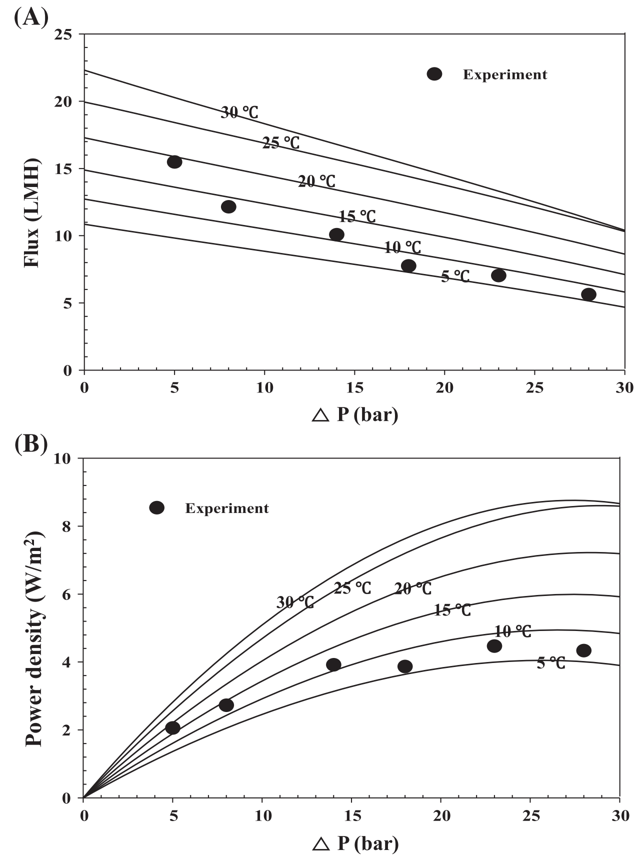

Fig. 6. Experimental and simulated water flux (A) and PD (B) for the PRO module. Simulation results were obtained from Eq. (5). Experimental conditions: The draw and feed solutions were 70,000 mg/L NaCl and 400 mg/L RO permeate, respectively. The inlet flow rates of draw and feed solutions were maintained 5 LPM at 25℃.

Table 2
Values of the characteristics factors of the PRO membrane

Temperature (℃)	A (L/m^2/h/kgf/cm^2)	B (L/m^2/h)	S (mm)	Diffusivity D (10^{-9} m^2/s)
5	1.639	0.418	1.12	0.80
10	1.834	0.463	1.12	0.94
15	2.053	0.512	1.12	1.09
20	2.297	0.566	1.12	1.27
25	2.57	0.627	1.12	1.47
30	2.93	0.985	1.12	1.68

which corresponds to a 52% enhancement in the mass transfer coefficient (Table 2).

The values of the water flux and PD obtained in the experiments were compared to the theoretical predictions. We found that the water flux and PD at increasing hydraulic pressures were significantly overestimated by Eq. (5). This mismatch between the experimental values and the theoretical predictions can be attributed to variation in the PRO membrane modulating method. As discussed in earlier research [13,20], this deviation might be affected by the increased ICP and reverse salt diffusion. The dead space in the PRO membrane module, which is created by the membrane modulization may also have a significant effect.

4. Conclusion

We evaluated key design factors and operating conditions in a newly developed SWRO-PRO hybrid desalination plant. In the semi-pilot scale studies, the PRO system performed better, having a higher energy recovery rate, with higher draw solution salinities. This result was due to the increased osmotic pressure, including a stronger driving force across the PRO membrane. The performance of the PRO was further improved by increasing the flow rate of the draw solution, as this reduced the effect of concentration polarization of the membrane. However, due to the limited volumes of the draw and feed solutions, increasing the draw solution flow rate beyond its optimal level is not beneficial, as it will negatively affect the economic viability of the entire SWRO-PRO system. Under simulated conditions, the most significant factor affecting the performance of the PRO module was the temperature. This study was able to predict the effects of variations in operating parameters such as solution concentrations, flow rates, the flow ratio of the draw and feed solutions, and the temperature of the draw solution, on the PD, water flux, and draw solution recovery in the PRO system.

The SWRO-PRO hybrid desalination process requires further investigation. In future studied, the newly developed spiral-wound and hollow fiber types of PRO membranes will be evaluated with respect to variations in key operational conditions such as the concentrations and flow rates of the draw and feed solutions, the applied pressure, and temperature. This research will enable us to determine the optimal permeate flux, feed solution recovery, and PD in our pilot plant. To evaluate the economic feasibility of a full-scale SWRO-PRO hybrid desalination plant, a commercial-scale PRO membrane module, 8 inches or larger, will also be studied.

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