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Pilot study of the key design and operation parameters of a pressure retarded osmosis (PRO) system for SWRO-PRO hybrid desalination

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ABSTRACT

Seawater reverse osmosis (SWRO) process has been the dominant desalination technology for the last decade; however, it is an energy-intensive process. So, the desalination process is necessary to lower its energy consumption rate for producing high-quality desalinated water. Recently, a novel hybrid SWRO desalination system using pressure retarded osmosis (PRO) technology has been developed and is able to recover a large amount of osmotic power from concentrated brine, and ultimately reduce the overall energy required for desalination. In this study, a pilot plant equipped with an 8-inch thin-film composite spiral wound membrane module was investigated under various operating conditions. The hydraulic pressure and flow rate of the draw and feed solutions in the PRO system were found to have significant effects on the membrane flux, recovery, and power density. One- and two-stage PRO system configurations were evaluated with a pilot system and a mathematical simulation model. With a simulation model, it was also found that the system efficiency can be greatly enhanced by increasing the system temperature. In addition, a relative PRO performance index (PPI) was proposed for comparing the performance of different system configurations, the extractable energy.

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

1. Introduction

Because of the current global issues on energy, environment, and climate change, various studies have examined how to utilize the osmotic power naturally occurring in water systems [1]. The osmotic power (or salinity-gradient energy) can be generated from two aqueous streams with different salinities [2]. The pressure retarded osmosis (PRO) technology introduced by Loeb in 1976 [3] is receiving more attention because it has many promising characteristics for cost-effectively generating a huge amount of osmotic power from natural salinity gradient resources [4,5]. The potential energy capacity generated from natural water systems with PRO technology could be around 2 TW, which is about 13% of the current world energy consumption [6]. The feasibility of membrane-based PRO technology has been investigated for various water resources such as seawater, desalination brine, and wastewater [7]. Many recent studies have tried to integrate PRO technology with a conventional sea water reverse osmosis (SWRO) desalination system, to recover the osmotic power of the seawater brine and ultimately to reduce the overall energy consumption of the desalination process [8].

Thorsen et al. [9] and Wang et al. [10] reported that the power density (i.e., the power generated per unit membrane area) of a PRO membrane should be about 5 W/m^2, to be eco-

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nomically feasible for PRO. The efficiency of a PRO system is greatly affected by the salinity gradient, membrane flux, and operating hydraulic pressure (ΔP). A higher salinity gradient [or osmotic pressure gradient ($\Delta\pi$)] increases the membrane flux, while increasing the hydraulic pressure decreases the membrane flux. Theoretically, the maximum power density is achieved at $\Delta P = \Delta\pi/2$ [11]. Because of the limited PRO membrane area, especially for a flat-sheet and spiral-wound type membrane module, the recovery ratio of the osmotic energy with a single membrane module is not sufficient. Thus, the total energy recovery efficiency of a PRO system can be increased by re-treating the treated draw and feed solutions through the additional membrane modules. Altaee et al. [12] suggested a dual-stage PRO process for higher power generation. The experimental results showed that the power generation in a dual PRO process was 28% higher than in the conventional PRO process depending on the feed solution types. He et al. [13] proposed a systematic model of a salinity power plant involving two PRO modules and the results clearly indicated that the performance of the PRO plant was improved with a two-stage configuration. Several important factors influence multi-stage PRO systems, such as the flow rate and velocity, salt concentrations of the draw and feed solutions, and PRO membrane characteristics. It is also necessary to determine an efficient design or a multi-stage PRO module configuration. However, most PRO studies have been performed with laboratory-scale facilities capable of testing the performance of a PRO membrane coupon or module with a limited surface area [1,11,14,15]. These experimental conditions are not sufficient for investigating all of the performance aspects of a PRO system. For example, the dilution of the draw solution could be minimized because of the very low recovery ratio of the feed solution. In reality, the dilution effect in a large-scale PRO system may be significant if it is equipped with numerous PRO membrane modules with a relatively large membrane surface area [13,16].

In this study, a pilot plant was constructed to study the effect of the hydraulic conditions of the draw and feed solutions, such the flow rate and pressure, on the performance of one- and two-stage PRO systems made with 8-inch PRO membrane modules. In addition, the PRO power density was modeled mathematically and compared with the experimental results.

1.1. SWRO-PRO hybrid desalination processes

In Korea, a national R&D program called Global MVP (GMVP) was launched in 2013 to investigate the feasibility and core technologies of the newly proposed SWRO-PRO hybrid desalination processes and to develop an optimal design for a system with a desalination capacity exceeding 100,000 m^3/d. There are two ways to recover the osmotic power in a SWRO-PRO hybrid desalination system by utilizing (1) a hydraulic turbine and (2) an energy recovery device (ERD). As presented in Fig. 1A, the low-pressure brine from the ERD of a SWRO system is used as the draw solution of a PRO system and the wastewater effluent of a wastewater treatment plant (WWTP) is used as the feed solution. The draw solution is pressurized by a high pressure pump and then it is injected into the PRO system. Due to the osmotic pressure between the draw and feed solutions, the feed solution is transferred to the draw solution side through the PRO membrane, increasing the draw solution volume, which maintains the hydraulic pressure generated by the high-pressure PRO pump. The subsequent turbine generates power from the treated high-pressure draw solution. A pelton turbine should have near 90% efficiency in a large-scale system (e.g., larger than 10,000 m^3/d). Considering the efficiency of other items, such as the generator, the overall efficiency of the energy recovery system could range from 80 to 85% [17]. Fig. 1B shows the major difference of the second SWRO-PRO hybrid desalination system; this involves implementing an isobaric pressure exchanger that transfers the hydraulic energy of the treated draw solution generated by the PRO system into the pretreated seawater. The hydraulic pressure of the PRO system can be controlled by the ERD of the SWRO without a high pressure PRO pump. Together with an ERD (i.e., PX series) manufactured by ERI, the estimated efficiency of the ERD exceeds 97.5%. Compared with a Pelton turbine, the isobaric pressure exchanger is more competitive, with about 15% greater efficiency in terms of osmotic energy recovery.

2. Methods and materials

2.1. Mathematical modeling of the performance of a PRO membrane module

The draw solution in a PRO system needs to be pre-pressurized before it is injected into the system. Once the high-salinity draw solution and low-salinity feed solution are introduced to 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 PRO membrane while maintaining the pressure provided by the draw solution. 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 parameters A and B were obtained from a previous study [18].

The salt permeability coefficient (B) is determined from the equation in Lee [19]:

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

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 NaCl, d_h is the hydraulic diameter, and Sh is the Sherwood number [20]:

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

The solute resistivity to salt transport in a porous substrate K_R, which is a function of the structural parameters

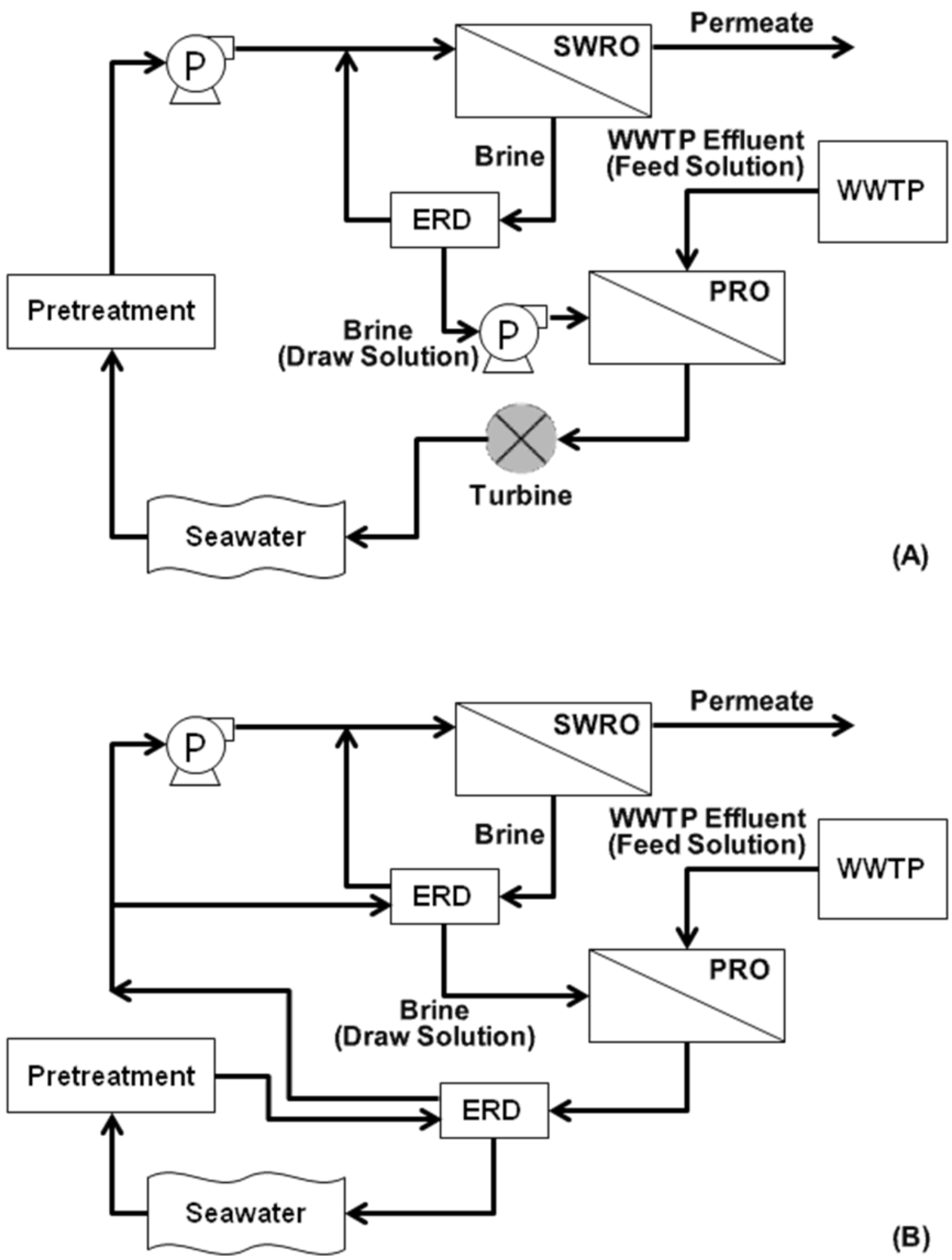

Fig. 1. Conceptual diagrams of SWRO-PRO hybrid desalination systems with (A) a hydraulic turbine and (B) an additional energy recovery device (ERD).

S and *D* ($K_R = S/D$), was calculated using Eq. (5) [21] and the water flux:

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

Water flow across a PRO membrane is induced by the transmembrane osmotic pressure difference ($\Delta\pi$). The water flux (J_w) decreases as the pressure difference (ΔP) increases [22,23] because the pressure on the PRO membrane is exerted in a direction opposite to the water flow. The membrane power density (W) is defined as the product of the water flux (J_w) and the pressure difference (ΔP) as follows:

$$W = J_w\,\Delta P = A(\Delta\pi - \Delta P)\,\Delta P \quad (6)$$

The water recovery rate, R_e was calculated using:

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

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

2.2. ASWRO-PRO pilotsystem

Fig. 2 is a schematic diagram of the SWRO-PRO experimental facility. The pilot plant (20 m^3/d, capacity) consists of SWRO and PRO systems. The PRO system includes the feed pumps and tanks of the draw and feed solutions, five-PRO membrane modules, and a Pelton turbine to generate electricity from the PRO system. The facility can be operated as one- or two-stage PRO systems to evaluate the performance of each operating mode (Fig. 3). The draw and feed solutions were injected using high-pressure pump (plunger type) and low-pressure pump (horizontal centrifugal type), respectively. The hydraulic pressure and flow rate of the draw and feed solutions were controlled with flow control valves. The pressure, flow rate, concentration, conductivity, and temperature were monitored using a human-machine interface (HMI) in the SWRO-PRO system. To ensure the accurate conversion of conductivity into concentration, the conductivity meters were calibrated before the experiment. Data were collected every 10 s.

2.3. The spiral-wound PRO module and experimental conditions

The PRO membrane modules were produced by Toray Chemical Korea. The module was 8 inch in diameter, 40 inch in length, and 18 m^2 in total membrane area. The physical characteristics of the membrane were similar to values reported previously [18]. This PRO membrane module was investigated under various operational conditions. The key operation parameters evaluated included the pressure and flow rate of the draw and feed solutions because these parameters had significant influence on the energy recovery and operational efficiency of the plant. In the PRO experiments, the draw and feed solutions were introduced into the module in a co-current direction. Unless otherwise specified, all reagents and chemicals were of analytical grade. Certified ACS-grade NaCl (Fisher Scientific, Waltham, MA, USA) was used to prepare the SWRO influent at 35,000 mg/L. The SWRO brine concentration was 70,000 mg/L for the high salinity draw solution and a SWRO permeate was used as the low salinity feed solution. The flow rates of the draw and feed solutions were 5, 10 and 15 L/min. The applied hydraulic pressure differences (ΔP) were 5, 10, 15, 20, 25, and 30 bar.

3. Results and discussion

3.1. Effect of hydraulic pressure and flow rates on the one-stage PRO system

As reported in many studies [1,12,24], the applied hydraulic pressure and flow rates of the draw and feed solutions in a PRO system are critical design and operational parameters determining system performance. As the hydraulic pressure of the draw solution is increased, the difference in the osmotic and hydraulic pressure across the PRO membrane is reduced and it induces a decrease in the membrane flux. However, the extractable energy of the PRO system is also proportional to the hydraulic pressure like the permeate flux of the feed solution. Therefore, the theoretical maximum energy (*i.e.*, power density) can be harvested when the hydraulic pressure is nearly half the osmotic pressure ($\Delta\pi/2$) [19,25]. However, the salt permeability is affected by the hydraulic pressure and it negatively affects the osmotic pressure. In addition, the increased pressure can cause defects in the polyamide layer [26]. Therefore, the optimal applied pressure and energy recovery efficiency of a PRO system can vary depending on the water quality of the draw and feed solutions, and the membrane and module characteristics. Fig. 4 shows the performance of the PRO membrane module at different applied pressures (5–30 bar) and flow rates (5–15 LPM) of the draw and feed solutions. The high flow rate resulted in the high flux and power density of the PRO membrane module, however, the recovery of the feed solution was reduced. As the applied pressure was increased, the PRO membrane flux and recovery of the feed solution ($R = Q_{permeate} / Q_{feed\ solution}$) decreased,

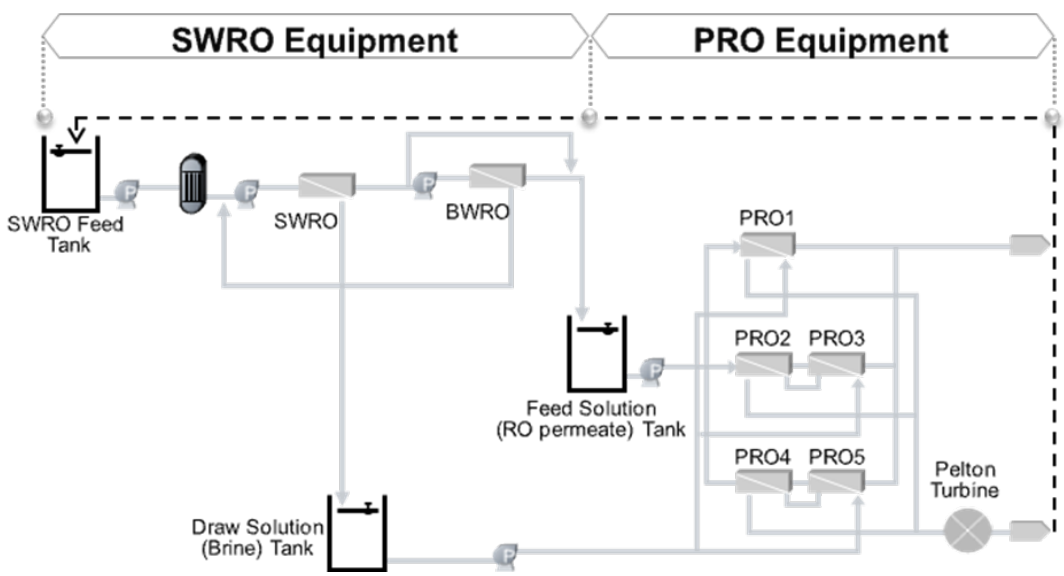

Fig. 2. Schematic diagram of a SWRO-PRO pilot plant (20 m^3/day).

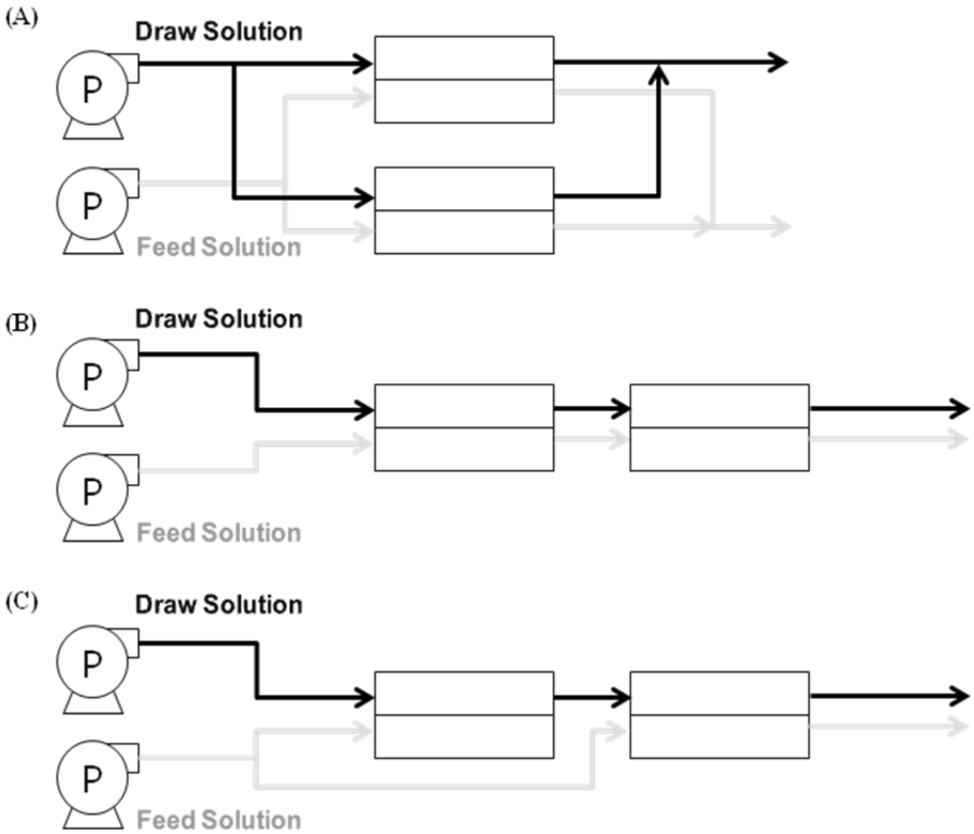

Fig. 3. Schematic diagram of three PRO system configurations: (A) one-stage, (B) two–stage in a series array, and (C) two-stage in a parallel array.

while the power density increased. The maximum power densities at 5 and 10 LPM were 3.4, and 5.08 W/m^2, respectively, near 25 bar, while the maximum power density was 6 W/m^2 at 15 LPM and 16 bar. The membrane flux and recovery at 10 LPM were decreased 46.2 and 13.1%, respectively, which resulted from the pressure increase from 5 to 30 bar. There was a pilot system limitation to increase the applied pressure larger than 20 bar at 15 LPM.

The pilot system was operated at different flow rates of the draw and feed solutions, which influence the membrane surface velocity, salt dilution rate [21], and ultimately the actual osmotic pressure through the PRO membrane. As presented in Fig. 4A, the membrane flux was enhanced by applying higher flow rates, which were induced by the reduced effect of the internal and external concentration polarization on the active and support layers of the PRO membrane. However, the draw and feed solutions may have optimal operation flow rates in a real large-scale SWRO-PRO hybrid desalination plant considering the availability of the draw and feed solutions (e.g, brine and wastewater effluent) and the system operation limitations. A higher flow rate of the draw solution requires a higher pressure of the feed solution to inject the feed solution into the PRO membrane module, and the PRO membrane cannot be operated at above a certain feed solution pressure because of the membrane damage caused at a high pressure, especially to the feed side, which is another limiting factor of a PRO system.

3.2. Effect of hydraulic pressure and flow rates on two-stage PRO systems

Operating the pilot plant at 5–15 LPM of the draw and feed solutions, the maximum power density was obtained between 25 and 30 bar, but the feed solution recovery was greatly decreased by the increase of the applied pressure. For example, at a flow rate of 10 LPM, the recovery decreased from 57 to 21%, as the hydraulic pressure was increased from 5 to 30 bar. A large amount of osmotic energy remained between the draw and feed solutions treated by the PRO membrane module, and this can be extracted by additional PRO membrane modules. Therefore, a multiple-stage PRO system can be applied until there is no more osmotic energy between the two solutions.

In this study, two different PRO membrane arrays were also investigated, as shown in Figs. 5 and 6. The two-stage PRO system arrayed in series has two pressure vessels each equipped with an 8-inch PRO membrane module. The same flow rates of the draw and feed solutions were provided by the pumps and it was operated in a co-current mode. Fig. 5 shows the experimental results obtained at hydraulic pressures from 5 to 25 bar and flow rates from 5 and 10 LPM. Similar to the operational result trends of the one-stage PRO system, the overall flux and recovery decreased as the hydraulic pressure increased. The calculated power density increased to near 20 bar and then decreased at higher hydraulic pressures. However, there were differences in the values of the experimental

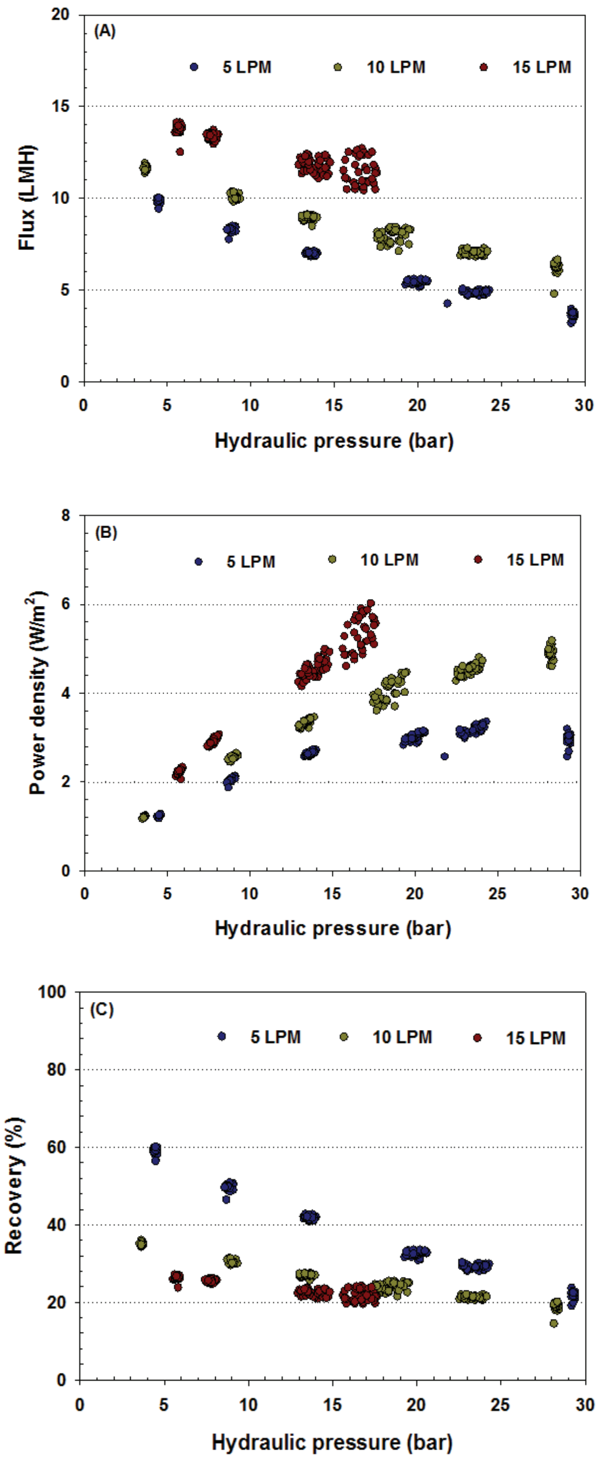

Fig. 4. The performance of the PRO membrane module at different applied pressures and flow rates of the draw and feed solutions with the one-stage PRO system: (A) permeate flux, (B) power density, and (c) recovery of the feed solution.

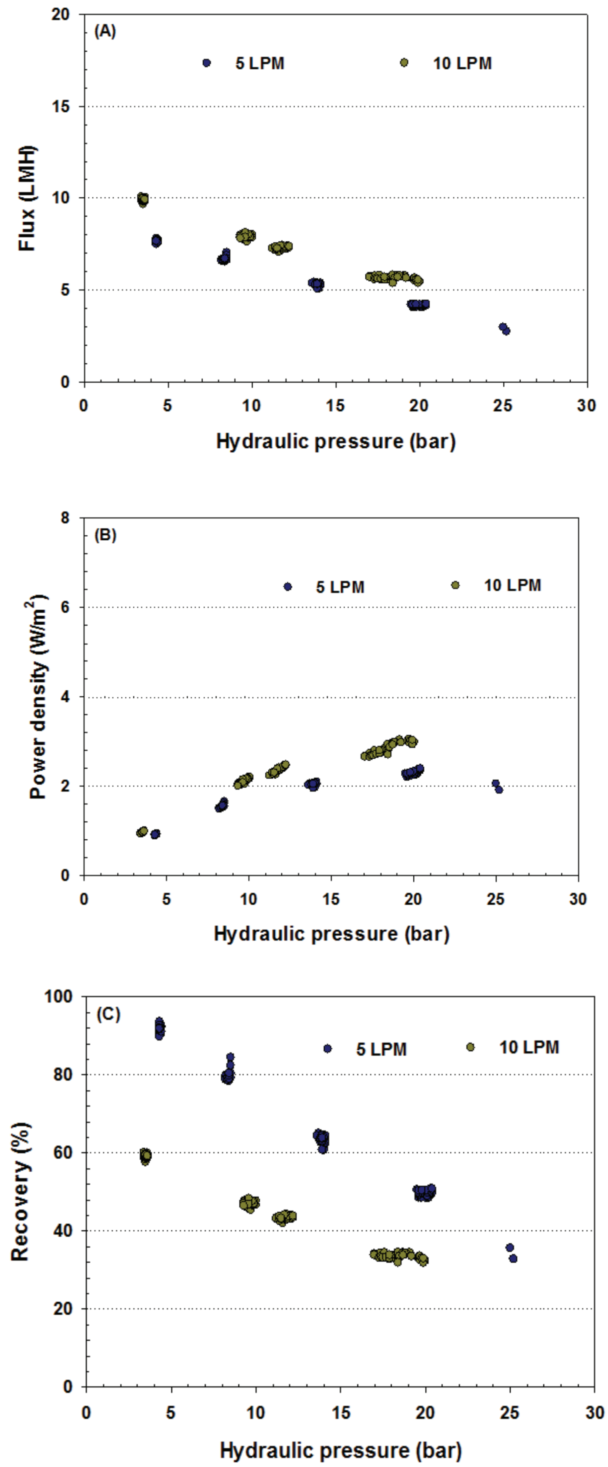

Fig. 5. The performance of the PRO membrane module at different applied pressures and flow rates of the draw and feed solutions with the two-stage PRO system in series array: (A) permeate flux, (B) power density, and (c) recovery of the feed solution.

results compared with the one-stage system. The maximum values of the membrane flux and power density at 5 LPM (10 LPM) were decreased 22.2% (14.9%) and 28.4% (40.7%), respectively, while the maximum recovery was increased 33.0% (24.7%). Although the additional PRO membrane module increased the overall recovery, it negatively affected the membrane flux and power density of the system. Fig. 6 shows a similar result trend obtained with a two-stage PRO system using a parallel array, which split the flow of the feed solution to the first and

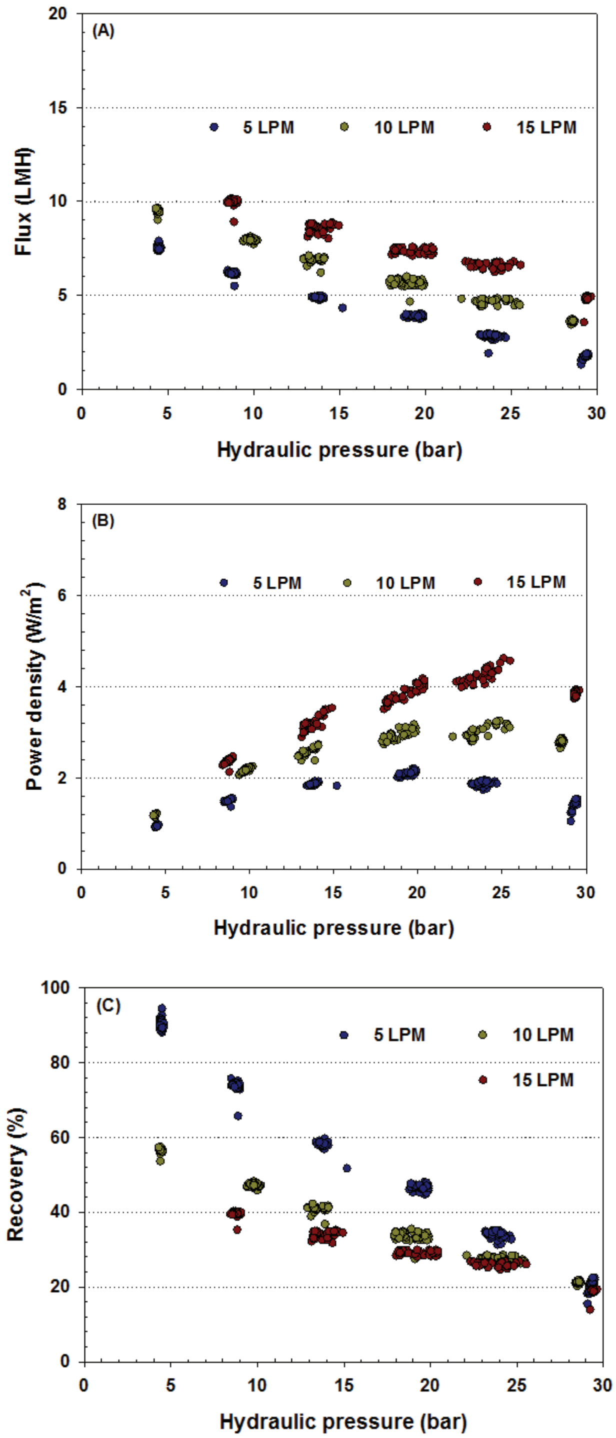

Fig. 6. The performance of the PRO membrane module at different applied pressures and flow rates of the draw and feed solutions with the two-stage PRO system in parallel array: (A) permeate flux, (B) power density, and (c) recovery of the feed solution.

second membrane modules equally, as shown in Fig. 3C. The maximum values of the flux and power density at 5 LPM (10 LPM) were 22.2% (19.7%) and 34.3% (37.7%), respectively, and the maximum recovery increased 31.4% (21.7%).

3.3. Comparison of the performance of one- and two-stage PRO system configurations

Since no PRO system has been implemented in a large-scale SWRO desalination plant, there are no guidelines for the system design and configuration. Moreover, it is not obvious how to evaluate the system performance and economic feasibility. Currently, the power density of the PRO system has been used as a representative performance parameter for the PRO membrane and module [27]. However, considering the entire system, other factors should also be considered when evaluating the performance of various system designs and configurations; these include the extractable energy, construction and operation costs (CAPEX and OPEX) of the PRO system, and potential values of the draw and feed solutions (e.g., brine and wastewater treatment plant effluents) used by the system. A relative PRO performance index or PPI was proposed using the following formula:

$$\text{Relative PRO Performance Index, PPI} = \frac{\text{Extractable Energy}}{CAPEX + OPEX + VDS + VPS}$$

where the extractable energy is the product of the hydraulic pressure of the draw solution side and the increased volume of the draw solution by the permeation of the feed solution (= ΔP × Q, bar/L/minute). VDS and VFS are the potential values of the draw and feed solutions, respectively. CAPEX includes the facility construction costs, including the PRO membrane modules and pressure vessels, high-pressure pump, ERD, and pipes. OPEX is determined mostly by the operating costs of the high-pressure pump and ERD. The potential values of the draw and feed solutions are their costs to be reused or treated. Although the denominator of the PPI cannot be estimated exactly at present, the relative PPI of each system configuration was compared assuming that the sum of CAPEX, OPEX, VDS, and VFS is the same for all of the PRO configurations in this study (i.e., assuming the sum is 1). Fig. 7 compares the relative PPI of the one and two-stage PRO systems. At 5–20 bar of the hydraulic pressure, the relative PPI of the one-stage PRO configuration is slightly larger than that of both two-stage PRO configurations, *i.e.*, the series and parallel modes (e.g., 3.2% and 4.8%, respectively at 10 LPM and 20 bar). However, if the cost of the pressure vessels and piping for the one-stage PRO configuration, and the loss of the potential values of the draw and feed solutions to be treated or reused is reduced, the two-stage PRO configurations are more competitive. For more explicit comparison, further investigations of various PRO system designs need to define all of the factors influencing the relative PPI objectively.

3.4. Model-based estimation of the power density

Using Eqns. (1) to (7), the power densities of the one- and two-stage PRO systems were estimated and then compared with the experimental results obtained at three types of inlet flow rates of the draw and feed solutions of 5, 10, 15 LPM and 25°C. For the calculation, the water permeability (A), salt permeability (B), and membrane structure parameter (S) were used [1,21]. The values of A and B were obtained from previous studies using Eqns. (1) and (2) [23]. The relationship between the water permeability (A) and temperature (T) is [20,28]. The relationship between the salt permeability (B) and temperature (T) is [28]. As presented in Fig. 8, the estimated

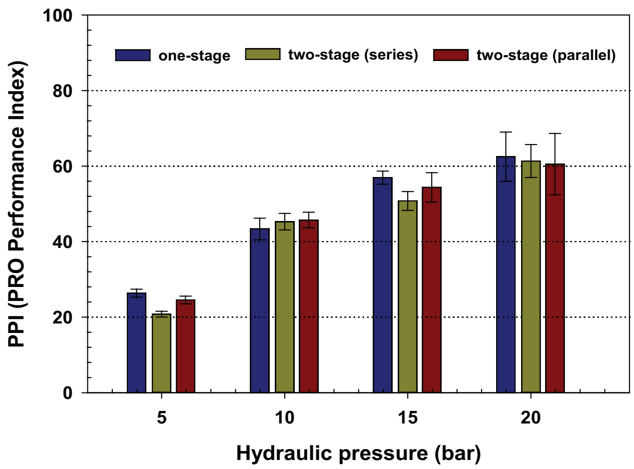

Fig. 7. The relative PRO performance index comparison of the one-stage PRO system and the two-stage PRO systems in series and parallel arrays at 10 LPM of the draw and feed solutions.

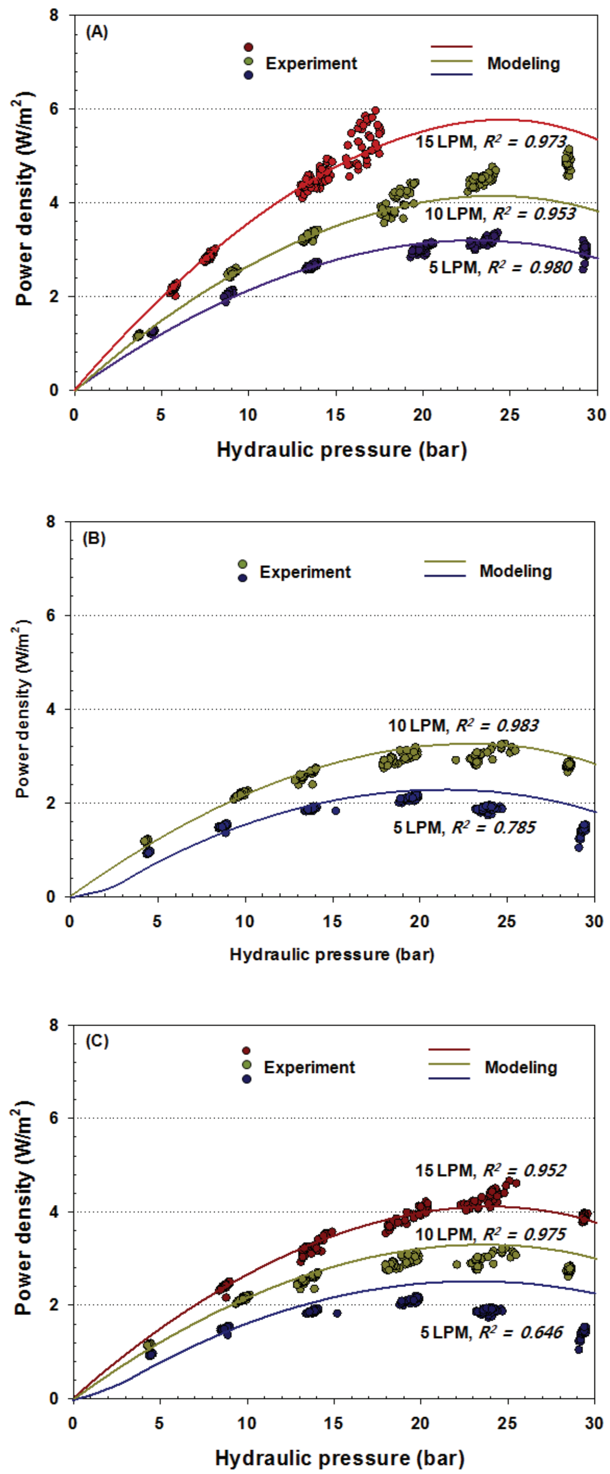

Fig. 8. Comparison of experimental and simulated power density at 5, 10, 15 LPM and 25°C: (A) one-stage, (B) two-stage in a series array, and (C) two-stage in a parallel array.

results for each system configuration were close to the experimental values at different hydraulic pressures. The maximum power density was obtained at 25 bar and the values estimated were 4.16, 4.03, and 4.1 W/m² for configurations (a), (b), and (c) presented in Fig. 8, respectively.

The benefit of the model simulation is that it can predict the PRO system performance with various critical parameters, which may not be easily controlled in a pilot-scale plant [29,30]. Similar to reverse osmosis (RO) and forward osmosis (FO) systems, temperature is a critical design and operating parameter greatly influencing the PRO system [13,25]. Increasing temperature influences the solute mass transfer, water flux, external and internal concentration polarization (ECP and ICP), and membrane fouling, via decreased water viscosity, increased water diffusivity, and changes in the membrane foulant characteristics, and osmotic pressure [31]. In the simulation model, the values of both A and $B$are influenced by increasing temperature. An increase in A would improve the water flux, while an increase in B would negatively influence the water flux because of the enhanced ICP induced by the increase in the reverse solute flux [1]. However, A dominates B when determining the water flux, as shown in Eq. (5). The increased diffusivity would also reduce ICP, and thereby increase the water flux. Since real SWRO desalination plants operate at temperatures up to 35°C depending on the plant location, the one-stage PRO system was simulated at temperatures from 5 to 35°C, as presented in Fig. 9. The estimated value of A increased from 1.64 to 3.22 L/m²/h/kgf/cm² as the temperature increased from 5 to 35°C, while the value of B increased from 0.42 to 1.09 L/m²/h. In addition, the diffusion coefficient increased from 8.0$10^{-10}$ to 1.9$10^{-10}$ m²/s. As a result, the maximum power density was enhanced by 60% (from 1.93 to 4.88 W/m²) and the average increment per 10°C was increased by 30%, although the difference between 25 and 35°C was only 13%. The hydraulic pressure inducing the maximum power density changed slightly from 22 to 25 bar as the temperature was increased from 5 to 35°C, which was influenced by the change in osmotic pressure. For the two-stage PRO systems with the series and parallel arrays, a similar trend in the experimental results was observed and their maximum power densities were 4.69 and 4.71 W/m² at 35°C, respectively.

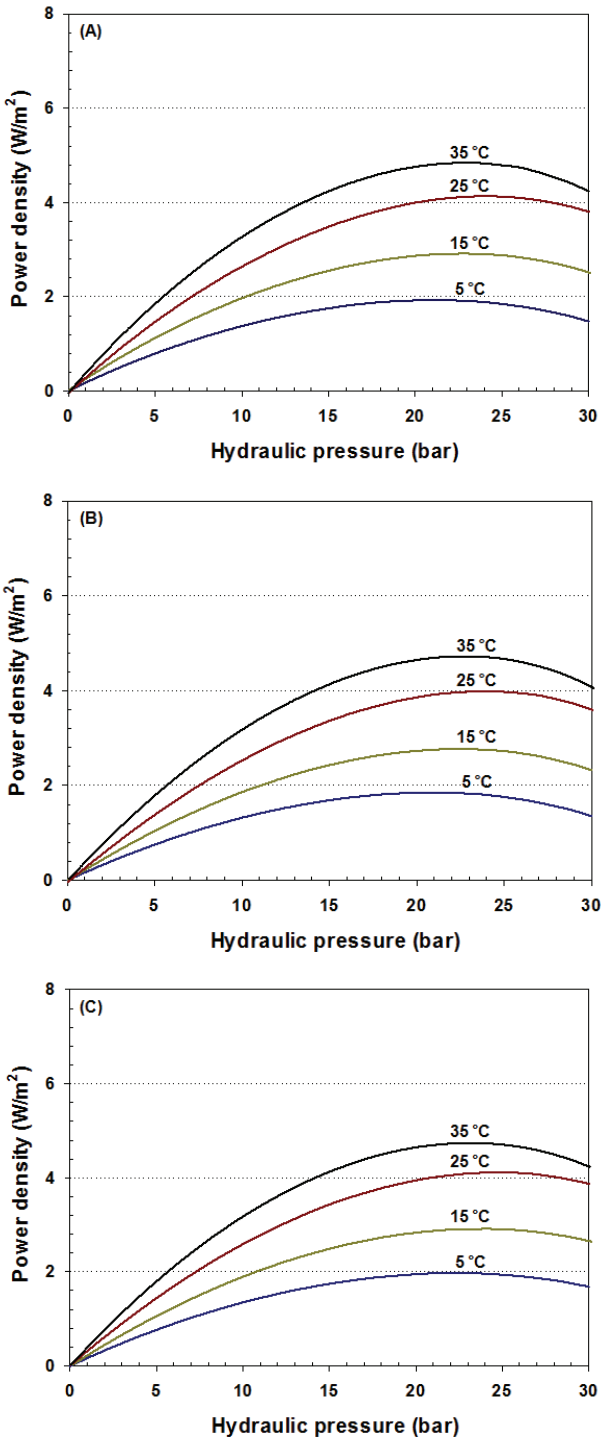

Fig. 9. Simulated power density at various temperature from 5 to 35°C at 10 LPM of the draw and feed solutions: (A) one-stage, (B) two-stage in a series array, and (C) two-stage in a parallel array.

4. Conclusion

Key design and operating parameters of the proposed SWRO-PRO hybrid desalination processes were evaluated with a pilot plant. This pilot-scale study found that the applied hydraulic pressure and flow rate of the draw and feed solutions in a PRO system were critical for determining the membrane flux, recovery, and power density. Because the effects of these two parameters on the membrane flux, recovery and power density can be similar or conflict each other depending on their values, there were optimal operating conditions for the PRO system. Similar trends in the experimental results were obtained for both the one and two-stage PRO system configurations. A mathematical simulation of the PRO system was used to study the effect of temperature on the PRO performance and it found that the system efficiency can be enhanced by increasing the temperature of the system. The relative PPI was proposed and considered the extractable energy, capital and operating costs, and potential values of the draw and feed solutions. Although not all of the relative PPI parameters are clearly defined at present, the index is very useful for investigating various PRO system configurations, and the feasibility of a large-scale SWRO-PRO hybrid desalination plant. The results of the pilot-scale study were used to design a demonstration plant (240 m^3/d) of the SWRO-PRO hybrid desalination process, which was constructed in Busan, Korea in 2015. Using the demonstration plant, the entire system will be optimized and the economic feasibility of the SWRO-PRO hybrid process will be investigated.

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