Structural stability and mass transfer properties of pressure retarded osmosis (PRO) membrane under high operating pressures

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Abstract

The fabrication of new membrane that is able to produce stable high power density is essential for the development of pressure retarded osmosis (PRO) technology. In this work, thin film composite (TFC) polyetherimide membranes with three different substrate structures were fabricated and characterized. The PRO performance of the resultant membrane was evaluated through two pressure cycle experiments and stability tests. The primary objective of this work is to systematically study PRO membrane's mechanical stability and mass transfer properties under high operating pressures, which determine the power density of the membrane in the PRO process.

Experiments revealed that water permeability (A_p) and salt permeability (B_p) under different pressures varied. The A_p and B_p are better indicators for examining the variation of PRO membrane structure under pressure. Within the operating pressure range of 17.2 bar, the top polyamide layer of TFC PEI-2# membrane mainly experienced a reversible deformation. In the two pressure cycle tests, the water flux, specific salt flux and power density obtained in the upward and downward measurements in each cycle are close to each other. The first cycle and the second cycle also show excellent reproducibility. The membrane was able to maintain almost unchanged water flux and power density of 12.8 W/m^2 at 17.2 bar over the 10 hour testing time, suggesting the membrane's great potential to be used in practical application in the future.

Keywords: pressure retarded osmosis; thin-film composite; flat sheet membrane; power density; long-term mechanical stability.

1. Introduction

Renewable energy has attracted much attention due to high energy demand for sustainable development and the shortage of fossil fuels along with their impacts to the environment [1]. Osmotic power, which can be harvested by pressure retarded osmosis (PRO) technology, is an emerging renewable energy [2, 3]. The estimated available energy from the mixing of river water and seawater can potentially reach approximately 1600 TW h per year [4, 5]. Other salinity sources, such as brackish water and brine from reverse osmosis (RO) seawater desalination plants, can also be utilized to run PRO processes, which has the potential to produce more energy due to the higher osmotic pressure of RO brine [6].

One of the performance indicators of the PRO system is the power density. It was reported that its threshold needs to be at least higher than 5 W/m^2 to make the system economic viable [4, 5]. The commercially available RO membranes are not suitable for PRO processes, as their bulky support layers can lead to severe internal concentration polarization (ICP), which causes a significant decline in water flux [7]. The cellulose acetate (CTA) and thin film composite (TFC) forward osmosis (FO) membranes produced by Hydration Technologies Inc. (HTI) and others are specially designed to mitigate ICP by using a much more open substrate than their RO counterpart [8-11]. Nevertheless, these membranes do not possess the mechanical strength required to withstand the high pressure applied in the PRO system [6, 12, 13]. It has been reported that the high pressure induced membrane deformation can lead to severe salt leakage, that greatly reduced power density [14], as well as accelerated membrane fouling [14, 15]. In addition to the lack of sufficient mechanical stability, the water permeability of existing osmotically-driven membranes needs to be further optimized for improved PRO performance.

Some recent developments for PRO membrane synthesis are promising. For flat sheet PRO membranes, post treatment is generally applied to the membrane selective layer in order to enhance water flux. Zhang *et al.* fabricated TFC flat-sheet membranes on polyacrylonitrile (PAN) supports with ethanol post treatment. Some other post treatments, e.g., NaOCl exposure [16] and solvent immersion [17, 18] were shown to significantly improve the water permeability (*A* value), although the salt permeability (*B* value) could be adversely affected to moderate the gain in PRO power density [19, 20]. Other investigations in hollow fiber membranes have attempted to enhance membrane mechanical stability by using optimized fibre geometry (thickness and diameter [21]) and stronger polymeric materials [22]. For example, TFC PRO hollow fiber membrane synthesized from polyetherimide (PEI, a polymer with strong mechanical properties) showed an excellent combination of membrane water permeability and mechanical strength [22]. The membrane showed a superior power density of 20.9 W/m^2 at 15 bar (using 1 mM NaCl and 1 M NaCl solution as feed and draw solution, respectively) [22]. Despite promising progress in hollow fibre membranes, attempts in optimizing mechanical strength of flat sheet PRO membrane are rather limited. Indeed, due to the large unsupported distance over feed spacers, flat sheet PRO membranes tend to experience more severe mechanical deformation [6, 14]. Therefore, much effort is deserved to further investigate the mechanical stability of the PRO membranes. Strategies and guiding principles on PRO performance optimization also need to be developed.

The primary objective of this paper is to systematically study PRO membrane mechanical stability and mass transfer properties under high pressure operating conditions. In this study, thin film composite polyetherimide (PEI) PRO flat sheet membrane was synthesized for the first time. Three types of substrate structures were fabricated for flat sheet PRO membrane formation via phase inversion plus interfacial polymerization methods. The newly developed membranes possessed high water permeability while maintaining low salt permeability. Membrane characterization was performed to study the relationship between membrane structure and PRO performance. The mechanical stability was evaluated systematically through pressure cycle experiments and stability tests.

1. Materials and Methods

1.1 Chemicals and membrane materials

Polyetherimide (Ultem 1000 resins, General Electric Plastics) was chosen for membrane substrate fabrication due to its high mechanical strength. N-Methyl-2-pyrrolidone (NMP, >99.5) from Merck Chemicals was used as the solvent for dope preparation. m-Phenylenediamine (MPD, >99%) and trimesoyl chloride (TMC, >99%) from Sigma Aldrich were used as the monomers for the interfacial polymerization. N-hexane was supplied from Merck with >99.0% purity and was applied as the solvent for the TMC monomer. Isopropyl alcohol (IPA) from Merck was used as a wetting solvent. Sodium chloride (NaCl, Merck) was used to prepare the draw and the feed solutions. The deionized water was supplied by a Milli-Q system (Milli-pore Singapore Pte Ltd) with a resistivity of 18.2 MΩ CM.

1.2 Fabrication of polyamide TFC-PRO membranes

The procedures for the synthesis of polyamide TFC-PRO membranes were adapted from a prior study [9]. In summary, the Ultem 1000 resins were dried at 50 ± 2 ℃ in a vacuum oven for over three days to remove moisture. Three types of casting solutions were prepared and named PEI-1#, PEI-2# and PEI-3#. The composition for each dope solution is shown in Table 1. The membrane substrates were prepared under the same conditions by casting the dope solution onto a glass plate using a casting knife of 200 μm gap, followed by the conventional non-solvent induced phase inversion method. The polyamide selective layer was then formed on the top of the substrate via interfacial polymerization using MPD aqueous solution and TMC N-hexane solution. The concentration for each monomer is also listed in Table 1. The resultant TFC membranes were stored in deionized water before further utilization.

1.3 Membrane characterizations

Membrane morphology was examined by a Zeiss EVO 50 Scanning Electron Microscope (FESEM) from Carl Zeiss Pte Ltd. Membrane samples were prepared in liquid nitrogen before freeze drying. A thin film of platinum was coated on the surface of the samples prior to SEM observation. The roughness of TFC membrane surface was measured by a Park XE-100 Atomic Force Microscopy (AFM) in non-contact mode.

Membrane porosity was determined by measuring the dry and wet masses of the membrane sample according to the gravimetric method that measures the weight of isopropyl alcohol (IPA) as the wetting solvent contained in membrane pores [23]. Tensile modulus of membrane substrate was measured using a Zwick 0.5 kN Universal Testing Machine to indicate the mechanical strength. The flat sheet sample with known width and thickness was clamped at both ends and pulled in tension at a constant elongation velocity of 50 mm/min with an initial gauge length of 25 mm.

2.4 Intrinsic separation properties of polyamide TFC-PRO membranes

The intrinsic separation properties of thin film composite PRO membranes were tested in a cross-flow filtration RO setup referring to Tang et al.[24]. The water permeability A was determined by applying a pressure of 10 bar on the selective layer side with ultrapure water as feed. The A value was calculated according to:

$$A = \frac{J}{\Delta P} \tag{1}$$

where ΔP is the trans-membrane pressure and J is the permeate water flux. The water permeability of the membrane substrate was determined similarly except the applied pressure is 1 bar.

The rejection of NaCl and salt permeability B were measured at 10 bar, using 10 mM NaCl solution as feed solution. Rejection R was calculated based on the conductivity of the feed and permeate streams:

$$R_s = \frac{C_f - C_P}{C_f} \tag{2}$$

where C_f and C_p are the salt concentrations in feed and permeate, respectively. The salt permeability was calculate by the following equation

$$B = \left(\frac{1}{R_s} - 1\right).J \tag{3}$$

A series of water permeability (A_p) and salt permeability (B_p) values under different pressures were also measured using a PRO setup, which was discussed in 3.4 section.

The membrane structure parameter (S) was calculated using Eqs. (4) and (5). The water flux (J_w) was obtained from the FO experiments in both orientations and the A and B values were obtained from the RO experiments [9, 24]. Al-DS refers to the orientation of the active layer of the membrane facing draw solution and AL-FS refers to that of the active layer facing feed solution.

$$S = \frac{D}{J_w} \ln\left(\frac{\pi_d - \left(\frac{J_w}{A}\right) + \left(\frac{B}{A}\right)}{\pi_f + \left(\frac{B}{A}\right)}\right) \text{ (AL} - \text{DS orientation)} \tag{4}$$

and

$$S = \frac{D}{J_w} \ln \left(\frac{\pi_d + \left(\frac{B}{A}\right)}{\pi_f + \left(\frac{J_w}{A}\right) + \left(\frac{B}{A}\right)} \right) \quad (\mathrm{AL-FS\ orientation}) \tag{5}$$

2.5 PRO experiments

The PRO setup used in the current study was similar to the one previously reported [22, 25]. The detailed diagram for PRO performance evaluation was shown in Fig. 1. PRO tests were conducted with predetermined pressure values (ranging from 0 to 20.7 bar) applied to the draw solution. At each pressure, the PRO test was continued for 30 min to reach a stable water flux. The water flux was determined by measuring the weight change of dosing DI water with time. The water flux J_w was calculated using Eq. (6)

$$J_w = \frac{\Delta V}{A_m \Delta t} \tag{6}$$

where ΔV is the volume change of dosing water, Δt is the duration of the test, A_m is the effective membrane area. The solute flux was calculated based on the conductivity measurements of the feed solution. The salt concentration of the feed solution can be determined by using a calibration curve. The salt flux J_s was calculated using following equation:

$$J_s = \frac{\Delta(C_{fe} V_f)}{A_m \Delta t} \tag{7}$$

where C_{fe} is the salt concentration and V_f is the volume of the feed solution.

Unless otherwise specified, the testing condition for PRO performance was similar to [25] and set as follows:

- Feed solution: 10 mM NaCl solution; draw solution: 1 M NaCl solution;

- Membrane orientation: AL-DS orientation;
- Cell flow channel dimension: 85mm length × 40 mm width
- Temperature: 23 ± 1 ℃ for both feed and draw solution;
- Cross flow: The cross flow rate used was 0.8 L/min for the draw solution while a flow rate of 0.4 L/min was used for the feed water.
- Spacer: One piece of net-type spacer with a thickness around 1.55 mm and an opening ratio around 0.55, purchased from GE Power&Water (GEOsmonics, SEPA), was used in the draw solution side. Six pieces of RO permeate carriers with a thickness around 0.25 mm and an opening ratio around 0.35, that was from Dow FilmTec RO module (BW30-4040), were used as feed spacer for better support.

The power density was calculated by the product of measured water flux and the effective trans-membrane pressure:

$$\mathrm{W} = J_w \Delta P \tag{8}$$

2.6 Membrane deformation and stability study

Pressure cycle experiment was conducted to study the membrane deformation in PRO process. The setup and flow diagraph are the same as in the Section 2.5. One pressure cycle refers to the applied pressure inside increasing from zero bar to the peak pressure (theoretically, the power density of the membrane at this pressure is the highest) and then return back to zero bar. Two pressure cycles were continuously applied on the membrane active layer to observe the change of water flux, power density and specific salt flux (J_s/J_w). Water permeability (A_p) and solute permeability (B_p) value at different pressures were measured using the PRO setup to detect the deformation of the membrane. It is noted that the A_p and B_p value here are different with the ones measured using the RO setup, where the membranes were supported using a porous flat stainless steel to minimize the deformation. Therefore, the water permeability and solute permeability under the RO mode cannot reflect the deforming situation in the PRO process [12-14]. In this study, the PRO cell was modified to a RO test cell. 10 mM NaCl was introduced to the draw solution channel of the PRO cell and the applied pressure at the draw solution flow channel was increased to a predetermined value. The membrane was supported by spacers used in PRO testing cell and the intrinsic properties obtained in this modified RO testing could directly indicate the membrane deformation situation under PRO testing when the applied pressure in this modified RO setup was equal to the hydraulic pressure on the draw solution side in the PRO tests. The permeate flow in the feed side was collected in certain time interval and the A_p value was calculated using Eq. (1). The B_p value and R_p were calculated using Eqs. (2) and (3), respectively. The detailed procedure can be found elsewhere [25].

The stability of membrane performance was evaluated over ten hours under the PRO condition. The water flux and power density were recorded along the process.

3. Results and discussion

3.1 Morphology and characteristics of the PEI flat sheet substrates

Three types of substrates were fabricated by the phase inversion method according to the recipes listed in Table 1. The FESEM images of the resultant PEI flat sheet substrates are shown in Fig. 2. From the cross-section of each substrate, it can be seen that two distinct layers were formed (Figs. 2(A), (B) and (C)). A sponge-like structure occurred in the top section while the bottom part contains relatively large finger-like pores. The ratio of sponge-like structure to the finger-like macrovoid structure follows the order of PEI-3# > PEI-2# > PEI-1#, corresponding to the increase of polymer concentration in the polymer dope solution, as listed in Table 1. It seems that a more concentrative polymer solution tended to form a sponge like structure due to delayed demixing of the dope solution [26]. It is well recognized that the finger-like macrovoid structure is favourable for FO process due to reduced ICP [27-30]. However, such a structure is vulnerable in the PRO process because the structure may encounter heterogeneous compaction and uneven deformation under a high pressure [17, 31, 32]. In contrast, the sponge-like structure is more suitable for PRO process for the advantages of strong mechanical strength to minimize the deformation under high hydraulic pressures [4, 19, 33], but it has the constraint of high mass transfer resistance. Comparing the three substrates, the PEI-2# possesses a medium portion of the sponge-like structure. In addition, it was observed that the pore size on the top surface of the substrates reduced with increasing the polymer solution, as shown in Figs 2(a), (b) and (c). From the AFM micrographs of the three substrates shown in Fig.3, it can be seen that the roughness (R_a) of the substrate surface increased with an increase in the polymer concentration. The R_a of PEI-1# was around 63.8 nm, while the R_a of PEI-2# and PEI-3# was 100.6 nm and 156.7 nm, respectively.

The properties of PEI flat sheet membrane substrates are shown in Table 2 in terms of water permeability, thickness, porosity and mechanical strength. With an increase in PEI concentration, the water permeability and porosity reduced while the mechanical strength was increased. These trends are in consistent with their corresponding cross-section structure and surface pore size, shown in Fig. 2. Obviously, the sponge-like structure is able to well distribute the stress in the membrane, which contributes to the better mechanical property [22]. However, the high concentration of PEI also leads to a thicker membrane sacrificing the water permeability and porosity. It seems that PEI-2# membrane is a balanced case, possessing a relatively high pure water flux (483 LMH), good porosity (73%) and reasonably high Young’s modulus (150 MPa).

3.2 Intrinsic separation properties of TFC flat sheet membranes

The intrinsic separation properties of TFC flat sheet membranes evaluated using a RO setup are summarized in Table 3. The water permeability of TFC PEI #1 membrane is as high as 2.28±0.2 LMH/bar with low salt permeability of 0.67±0.04 (LMH) while the water permeability of TFC PEI #2 and TFC PEI #3 membranes is 2.09±0.3 and 1.65 ± 0.5 LMH/bar, respectively. This trend is in line with the pure water permeability of the substrate. Since the selective layers of the three TFC membranes were fabricated using the same interfacial polymerization condition, it suggests that the water permeability of the TFC membrane is highly affected by the substrate structure. The solute permeability for all the TC membranes is relatively small. The structure parameters (*S*) of PEI -1# and PEI-2# membranes are similar or even smaller compared with the commercial HTI membrane, which is around 590-1400 µm [12, 19, 32]. The lower *S* value benefits the PRO process to achieve high water flux and high power density.

3.3 PRO Performance of the TFC- PEI membranes

The TFC-PEI membranes were tested in the active layer facing draw solution configuration using 1.0 M NaCl as the draw solution and 10 mM NaCl as the feed solution, and the results are shown in Fig.4. The draw solution used was to simulate the seawater brine with similar osmotic pressure, while the feed solution was to simulate river water. A wide range of pressure of 3.4 -20.7 bar (50 – 300 psi) was applied in the draw solution side to examine the PRO performance of three TFC membranes.

It can be seen from Fig.4(a) that the water flux decreases with increasing the applied pressure due to the decrease of the driving force across the membrane. On the other hand, reverse salt diffusion was widely observed in osmotically driven membrane processes. The specific salt flux, defined by the ratio of salt flux to water flux (J_s/J_w), was normally used as an indicator. The salt permeation to the feed side through the membrane results in an elevation of salt concentration in the feed water and thus a decrease of the driving force. As depicted in Fig 4(b), the three membranes show slow salt increase in the low pressure range. However, with the increase of applied pressure over 17 bar, the J_s/J_w value for TFC PEI-1# rises much higher than the TFC PEI-2# and TFC PEI -3# membranes, which suggests the deformation of TFC PEI-1# membrane due to its lower mechanical properties (see Table 2).

The power density is an important parameter in PRO process. Theoretically, the peak power density for a pair of 10 mM NaCl and 1 M NaCl solutions should be achieved at around 24 bar. However the experimental data in Fig 4(c) shows that the power density decreases after reaching 17.2 bar, which is believed to be attributed to the concentrative ICP in the porous substrate, caused by the significant reverse salt diffusion to the feed water (see Fig. 4(b)). The highest power density achieved by the TFC PEI-1# at 17.2 bar is 16.7 ± 0.33 W/m^2, followed by the second highest power density of 12.8 ± 0.52 W/m^2 obtained by the TFC PEI-2# at the same pressure. Due to the low mechanical property of the TFC PEI-1#, the TFC PEI-2# membrane was selected for further study.

Fig. 6 shows the effect of different salt concentrations in the feed solution on the power density of TFC PEI-2# PRO membrane. The feed solution used was DI water, synthetic river water (10 mM NaCl), waste water RO retentate (40 mM NaCl) and concentrated waste water RO retentate (80mM NaCl), respectively. A 1 M NaCl solution was used as draw solution to simulate the seawater retentate. It can be seen from the figure that with increasing salt concentration in feed solution, the power density presents a decline trend. For instance, when the salt concentration increased from DI water to 80 mM NaCl, the peak power density decreased from 14.6 to 8.8 W/m^2. This phenomenon is not unexpected because of enhanced ICP that lowered down the driving force across the membrane.

3.4 Stability of the TFC- PEI membrane in pressure cycle tests

3.4.1 Change of membrane structure under pressure

In PRO process, a high pressure applied on the draw solution side may affect membrane integrity, leading to membrane deformation such as enlarged membrane surface area, reduced membrane thickness and even membrane collapse. In other words, the polyamide selective layer and membrane substrate may experience reversible or irreversible or both reversible and irreversible changes [34].

To examine the variation of the membrane structure under pressure, a series of water permeability (A_p) and salt permeability (B_p) values under different pressures were measured using a PRO setup. The schematic diagram of PRO setup is presented in Fig. 6 along with a typical RO setup for comparison. It can be seen that due to the strong support by a flat porous stainless steel support, the membrane tested in the RO cell is able to retain its original shape, and assumed no deformation occurs. In contrast, the membrane mounted in the PRO cell was supported by two woven spacers to enhance mass transport while against the high pressure from the draw solution side. Hence, the membrane tends to be deformed under pressure, as illustrated by Fig. 6(b). Therefore, the A and B values obtained using the RO cell cannot accurately reflect the membrane separation property in the PRO process [25]. The A_p and B_p values as well as the rejections of the membranes obtained from the measurement in the PRO cell would be better indicators to present the membrane separation property at different pressures, which is believed to be associated with the structure of the top polyamide selective layer of the membrane. Figs. 7(A) and (B) show the morphologies of the polyamide layer without pressure impaction and after testing under 17 bar, respectively. No obvious change can be observed on the top surface. However, from Fig. 8 we can see that both A_p and B_p increased with increasing the applied pressure. It seems that the membrane active layer has subjected to a certain degree of deformation. Interesting, as the applied pressure reduced, the A_p and B_p can return to the previous values. When the second cycle was performed, all the data points show considerable consistency with the first cycle. It indicates that, within the operating pressure range of 17.2 bar, the top polyamide layer experienced most likely an elastic deformation, which is reversible.

Figs. 5 (a) and (b) depict the cross sections of the membrane substrate without and with 17.2 bar pressure impaction, respectively. Different from the top polyamide layer, the porous substrate has been compacted with ~3.5% deduction in the membrane thickness. Obviously, the change in the substrate is permanent, which is irreversible.

3.4.2 Impact of membrane structure change on the PRO performance

During the PRO pressure cycle tests, a series of pressure (i.e., from 0 to 17.2 bar) were applied on the draw solution side. Each testing point was lasted for 30 minutes to obtain a stable water flux. After reaching the peak pressure, the pressure was decreased stepwise back to zero. Two pressure cycles were completed to examine the water flux, specific salt flux and power density variations. The results are shown in Fig 9. It is observed that the data obtained in the upward and downward measurements in each cycle are closed to each other. By comparing the first cycle with the second cycle, the water flux, specific salt flux and power density show excellent reproducibility. The water flux, specific salt flux and power density returned to the original values after two cycles of tests. Referring to Fig. 8 which shows the A_p and B_p as a function of applied pressure, it is further confirmed that the deformation of the membrane selective layer is reversible under given testing conditions within 17 bar. The impact of irreversible change in the substrate on the PRO performance seems to be negligible in the given testing condition.

This stability of PRO membrane was also tested under a high pressure for the first time. Fig. 10 presents the water flux and power density of TFC PEI-2# membrane under 6.9 bar and 17.2 bar, respectively, over ten hours. The membrane was able to maintain almost unchanged water flux and power density of 12.8 W/m^2 at 17.2 bar over the long testing time, again, confirming that the membrane possesses superior structural stability. This result suggests that the membrane has great potential to be used in practical application in the future.

3.5 Comparison with other PRO flat sheet membranes

The performance of the TFC PEI-2# flat sheet membrane is summarized in Table 4 together with some results reported in the literature. The TFC PEI-2# membrane can produce a stable power density of 12.8 W/m^2 at 17.2 bar, using synthetic river water and seawater brine as feed and draw solutions, respectively. Although this result is less than the highest power density reported (18.09 W/m^2) using DI water and seawater brine as feed and draw solutions, the salt permeability of TFC PEI-2# (0.87 LMH) is much lower than the reported membrane (2.87 LMH) [18]. Moreover, the stability of newly-developed PRO membranes was not reported [16, 18, 20, 35-38]. From the view of practical applications, the stability of PRO membranes is extremely important, which should be included in any PRO membrane evaluation.

4. Conclusions

Flat sheet PRO membranes with three types of substrate structures have been fabricated via phase inversion and interfacial polymerization methods. Membrane characterization was performed to study the relationship between membrane structure and PRO performance. The structural stability was evaluated systematically through pressure cycle experiments and stability performance tests. The following conclusions can be drawn from the current study:

(1) By varying the polymer concentration of membrane dope solution, the best of the three prepared membrane substrates was identified, which possesses high water permeability of 483 LMH/bar and high porosity of 73.5%.

(2) The polyamide layer was synthesized on the surface of flat sheet substrate. The resultant TFC PEI-2# membrane can achieve a stable power density of 12.8 W/m^2 at 17.2 bar, using 1M NaCl solution as draw and 10 mM NaCl solution as feed, respectively.

(3) Water permeability (A_p) and salt permeability (B_p) under different pressures were measured using a PRO setup. A_p and B_p are better indicators for examining the variation of PRO membrane structure under pressure. Within current operating pressure range of 17.2 bar, the top polyamide layer of TFC PEI-2# membrane mainly experienced a reversible deformation.

(4) The structural stability of TFC-PEI 2# membrane was evaluated systematically through two pressure cycle tests. The water flux, specific salt flux and power density obtained in the upward and downward measurements in each cycle are close to each other. The first cycle and the second cycle also show excellent reproducibility.

(5) The stability of PRO membrane was also tested under a high pressure for the first time. The membrane was able to maintain almost unchanged water flux and power density of 12.8 W/m^2 at 17.2 bar over the 10 hour testing time, suggesting the membrane's great potential to be used in practical application in the future.

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Nomenclature

A	water permeability of the selective layer, L/(m^2 hr bar) (LMH/bar)
A_m	membrane area, m^2
B	NaCl salt permeability of the selective layer, L/(m^2 hr) (LMH)
A_p	Water permeability of the selective layer at different pressure, L/(m^2 hr bar) (LMH/bar)
B_p	NaCl salt permeability of the selective layer at different pressure, L/(m^2 hr) (LMH)
c_f, c_p	concentration of feed water and permeate in RO, ppm
c_d, c_{fe}	concentration of draw solution and feed water in FO or PRO, M
D	NaCl diffusion coefficient in water (m^2/s)
J	Permeate water flux in RO, LMH
J_s	NaCl salt flux, mole/(m^2 hr)
J_w	water flux, L/(m^2 hr) (LMH)
ΔP	pressure difference across the membrane, bar
R_s	NaCl salt rejection, %
R_p	NaCl salt rejection at different pressure, %
S	structure parameter, mm
Δt	predetermined time interval, hr
V_f	volume of feed water, L
ΔV	volume change, L
W	power density, W/m^2

Greek letters

π_d, π_f	osmotic pressure of draw solution and feed water, bar
$\Delta\pi$	osmotic pressure difference across the membrane, bar

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