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Flux behavior and membrane fouling in pressure-assisted forward osmosis

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ABSTRACT

This study investigated pressure-assisted osmosis (PAFO), which uses the external pressure together with osmotic gradient across a membrane, to improve flux through forward osmosis (FO) membranes. Experiments were performed in a laboratory-scale PAFO system, which allows the application of external pressure up to 13 bar on the feed solution side. Deionized water (D.I. water) and synthetic seawater (35,000 mg/L NaCl) were used as feed solutions, and $MgCl_2$ was used as a draw solution. Humic acid was used as a model foulant to examine the characteristics of membrane fouling. A theoretical model based on osmotic transport theory incorporating internal/external concentration polarization, and mass balance equations were used to analyze the performance of FO and PAFO system. Results indicated that the addition of external pressure to the osmotic pressure allowed higher flux in PAFO than FO. Nevertheless, the flux in PAFO was less than the sum of the flux in RO and that in FO, which attributed to the increase in the internal concentration polarization by the external pressure. Under the test conditions in this study, fouling by sodium alginate and humic acid was negligible in FO, RO, and PAFO.

Keywords: Desalination; Forward osmosis; Pressure assisted osmosis; Pressure; Fouling; Model

1. Introduction

Increasing water demands and shrinking water resources have led to the utilization of seawater for fresh water supply. The conventional method to desalinate water is reverse osmosis (RO), which is widely used especially due to its advantage over conventional distillation. Although RO has proven to be a robust method for the desalination of water, its major drawback is its high demand in electric energy [1,2] and the related high costs as well as fouling of

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the membranes. In addition, RO produces a fraction of water-containing high salt contents, which should be properly disposed or treated [3].

In this context, forward osmosis (FO) has drawn attention as an alternative technology for seawater desalination. Instead of using electricity, FO uses an osmotic pressure, allowing the potential for reduced energy consumption. FO also offers additional advantages such as high water retention rates and overall sustainability. It can be also applied for energy production from osmotic pressure gradient between seawater and freshwater [4]. Nevertheless, the water production rate by FO is limited by the concentration of draw solution. This implies that a large amount of draw solutes should be used to obtain high flux in FO, which creates additional problems in the recovery of draw solute [5]. Moreover, reverse solute flux is also an important issue to be considered in FO [6–8].

Recently, pressure-assisted forward osmosis (PAFO) has been proposed as a novel method for FO to increase water flux [9–11]. PAFO adds a medium pressure pump to a conventional FO system. The system takes advantage of additional hydraulic pressure that result in water transport in both mechanisms: flux driven by hydraulic pressure (RO mechanism) and that by osmotic pressure (FO mechanism). Although PAFO has potential for enhancing the efficiency of FO, relative little information is available for fundamental characteristics of water transport and fouling.

The objective of this study is to analyze water flux behavior of PAFO and investigate fouling of PAFO in comparison with FO and RO. Experiments were carried out in a specially designed system for PAFO. A modified model based on osmotic transport theory incorporating internal/external concentration polarization (ECP) and mass balance equations was used to analyze the performance of RO, FO, and PAFO systems.

2. Theory

2.1. Water transport mechanism

There are two kinds of concentration polarization phenomena in osmotically driven membrane processes, including the international concentration polarization (ICP) and the ECP [12]. Depending on the orientation of the membrane, the mechanism for concentration polarization may be different. If the active layer of the membrane contacts with draw solution (Al-DS orientation), feed solution is concentrated in the support layer (concentrative ICP) and draw solution is diluted in the active layer (dilutive ECP). If the active layer of the membrane contacts with feed solution (Al-FS orientation), feed solution is concentrated in the active layer (concentrative ECP) and draw solution is diluted in the support layer (dilutive ICP). Assuming that the solute rejection is sufficiently high, the following equation can be used to describe these phenomena [13]:

$$J_w = A\left(\pi_{D,b}e^{-J_w K_D} - \pi_{F,b}e^{J_w/K_F}\right) \quad \text{for AI-DS} \tag{1}$$

$$J_w = A\left(\pi_{D,b}e^{-J_w/K_F} - \pi_{F,b}e^{J_w K_D}\right) \quad \text{for AI-FS} \tag{2}$$

where J_w is the water flux, A is the water permeability of the membrane, $\pi_{D,b}$ is the osmotic pressure of the draw solution, $\pi_{F,b}$ is the osmotic pressure of feed solution, K_F is the mass transfer coefficient in the boundary layer, $K_D = t\tau/D\varepsilon$ is the solute resistance to diffusion in the support layer, t is the membrane thickness, τ is the tortuosity, D is the diffusion coefficient of solute, and ε is the porosity. $S = t\tau/\varepsilon$ is the structure parameter of the membrane, which is closely related to the extent of internal concentration polarization.

On the other hand, the water flux in RO process is described as follows:

$$J_w = A\left(P_{feed} - \pi_{F,b}e^{J_w/K_F}\right) \tag{3}$$

Combining Eqs. (1–3), the generalized equation for pressurized forward osmosis processes can be derived:

$$J_w = A\left(\pi_{D,b}e^{-J_w K_D} - \pi_{F,b}e^{J_w/K_F} + P_{feed} - P_{drwa}\right) \quad \text{for Al-DS} \tag{4}$$

$$J_w = A\left(\pi_{D,b}e^{-J_w K_F} - \pi_{F,b}e^{J_w/K_D} + P_{feed} - P_{drwa}\right) \quad \text{for Al-FS} \tag{5}$$

If P_{feed} is positive and P_{draw} is zero, this process is defined as the PAFO. If P_{feed} is zero and P_{draw} is positive, this process is defined as the pressure retarded osmosis (PRO). Using Eq. (4) or (5), any osmotic process can be theoretically analyzed. Fig. 1 illustrates the principles for FO, PRO, RO, and PAFO.

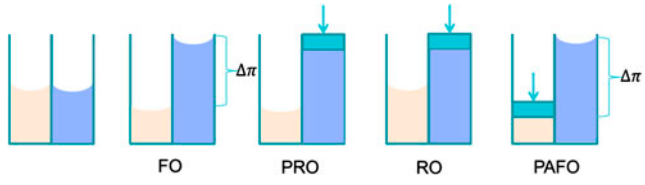

Fig. 1. Basic concepts for FO, PRO, RO, and PAFO.

To consider the effect of cross-flow velocity, the following equations may be used.

$$\mathrm{Sh} = 1.85\left(\mathrm{ReSc}\frac{d_h}{L}\right)^{0.33} \quad \text{for laminar flow} \tag{6}$$

$$\mathrm{Sh} = 0.04\mathrm{Re}^{0.75}\mathrm{Sc}^{0.33} \quad \text{for turbulent flow} \tag{7}$$

where Sh is the Sherwood number, Re is the Reynolds number, and Sc is the Schmidt number, d_h is the hydraulic resistance, and L is the channel length.

2.2. Fouling mechanism

The fouling mechanisms for FO, RO, and PAFO may be different due to their differences in hydrodynamic condition and solution chemistry. In FO, fouling may be less severe due to the lack of external pressure, leading to the formation of loose cake layer. Nevertheless, reverse flux of draw solutes may result in fouling (Fig. 2(a)). On the other hand, fouling in RO is accelerated by cake layer compaction due to external pressure, although there is no effect of reverse solute flux (Fig. 2(b)) [14]. In PAFO, fouling may be less or more significant than FO or RO depending on the conditions of feed solution and operating parameters (Fig. 2(c)). Both external pressure and reverse solute flux exist in PAFO, although their effects are less significant than FO and RO, respectively.

3. Materials and methods

3.1. Feed and draw solutions

Magnesium chloride (Sigma–Aldrich, St. Louis, MO) was used as a draw solute. The concentration of the draw solution ranged from 0.5 to 3 M. Deionized water was used as the feed solution. To examine fouling phenomena, alginate and humic acid were spiked into the feed solution in some test sets.

3.2. FO, PAFO, and RO systems

A schematic diagrams and detailed description of the experimental systems are shown in Fig. 2. A laboratory-scale membrane cell was used for all FO, PAFO, and RO tests. The length, width, and depth of the channel of the membrane cell were 87, 35.5, 1 mm, respectively. The effective membrane area was 0.00306 m^3. Spacers were used on both sides of the membrane channel to support the membrane.

Experiments were carried out on count-current flows where feed solution and draw solution flow in opposite directions to each other. Gear pumps which can operate to variable speed (Micropump, Vancouver, WA) were used to pump draw solution. A high-pressure pump was also used to pressurize the feed solution. The temperatures of both feed and draw solutions were kept constant at 25 °C using a water bath (Fig. 3).

The FO membrane was obtained from Hydration Technologies, Inc. (Albany, OR). The membrane has an asymmetric structure and is made of cellulose triacetate (CTA) supported by embedded polyester mesh. The characteristics of the membrane are given elsewhere [15].

3.3. Test protocols: effect of external pressure

Pure water flux in PAFO was measured at various pressure conditions. The feed and draw solutions for this test were D.I. water and 0.5 M $MgCl_2$ solution, respectively. The cross-flow velocity was 0.27 m/s for both solutions. The tests were repeated twice to check the reproducibility.

3.4. Test protocols: membrane fouling

Sodium alginate (Sigma–Aldrich, USA) and humic acid (Sigma–Aldrich, USA.) were used as model organic foulants. The concentrations were 1,000 mg/L for sodium alginate and 200 mg/L (as TOC) for humic

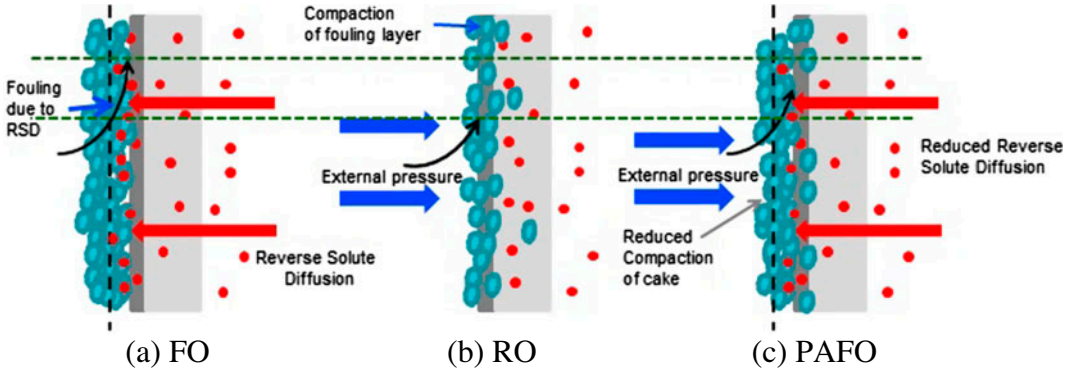

Fig. 2. Comparison of fouling mechanisms in FO, RO, and PAFO.

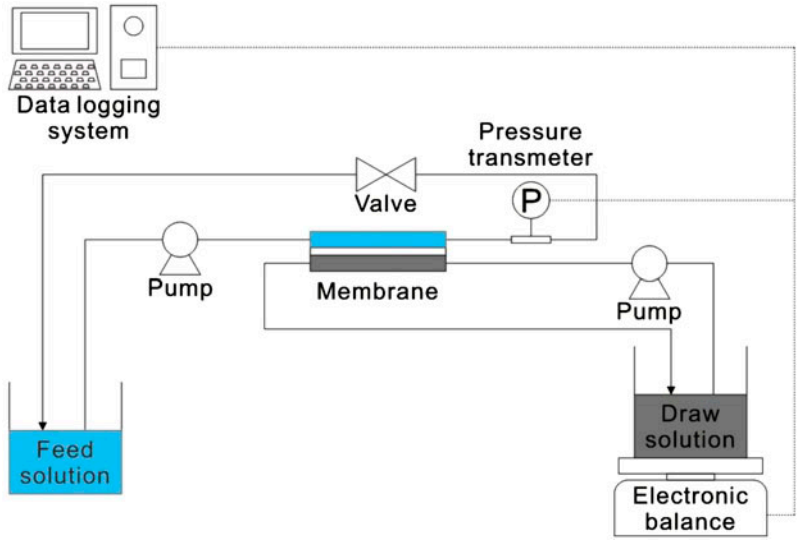

Fig. 3. Schematic diagram for experimental set-up.

acid. The cross-flow velocity was 0.017 m/s for both solutions. The concentrations of draw solutions were 3 M in FO mode and 1.5 M in PAFO mode.

4. Result and discussion

4.1. Effect of external pressure on water flux in PAFO

To begin, the water permeability of the FO membrane was measured in RO mode. As shown in Fig. 4, the water permeability was estimated to 0.61 L/m^2-h-bar. Although the data are not shown, the integrity of the membrane was tested using 100 mg/L NaCl solution. It was confirmed that there was no leak or damage of the membrane up to 13 bar of applied pressure.

The water flux curves obtained from the PAFO tests are depicted in Fig. 4. The initial water flux is 4.0 L/m^2-h in FO mode (no external pressure). As the external pressure increases, the water flux increases from 4.0 to 8.0 L/m^2-h. It is evident from the results that the water flux can be increased by adding the external pressure to osmotic pressure. Nevertheless, the increase in flux by additional pressure was smaller than the expected value (sum of fluxes in FO and RO). This implies that the water permeability of the FO membrane was different for different operation modes (RO mode and PAFO mode).

Using the results in Figs. 4 and 5, the flux in PAFO can be analyzed based on the mechanisms of water transport. Fig. 6 shows the dependence of water flux by FO mechanism (driven by osmotic pressure) and that by RO mechanism (driven by hydraulic pressure)

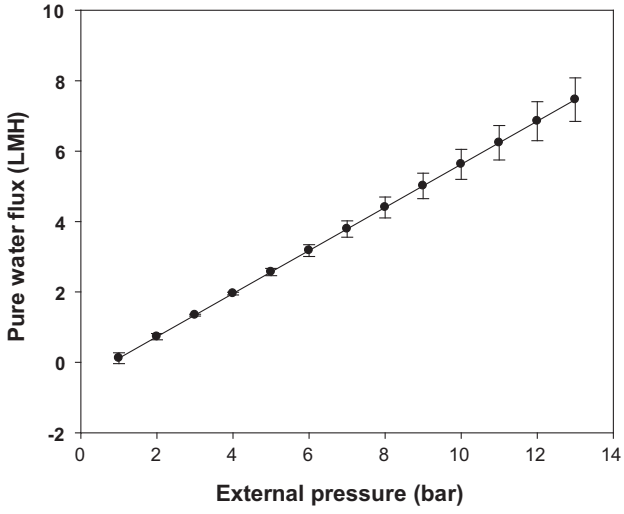

Fig. 4. Pure water flux of the FO membrane in RO mode.

on the applied pressure. The flux by FO mechanism was estimated by the difference between the flux in PAFO (Fig. 5) and that in RO (Fig. 4). The results indicated that the flux by FO mechanism is affected by the applied pressure. Initially, it is 4.0 L/m2-h and decreases to 3.5 L/m^2-h. This is attributed to an increase in ICP by increased water transport as described in Eq. (5).

4.2. Prediction of water flux in PAFO

Using Eq. (5), the water flux in PAFO can be theoretically predicted. This model considers the effect of external pressure on ICP based on the film theory.

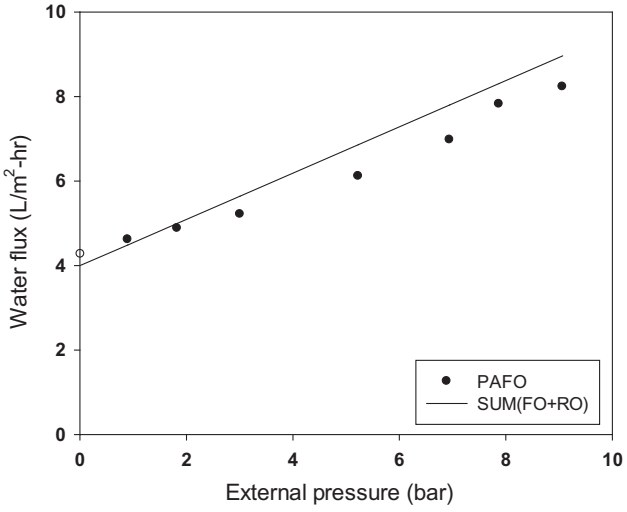

Fig. 5. Water flux in PAFO was compared with the sum of fluxes in FO and RO.

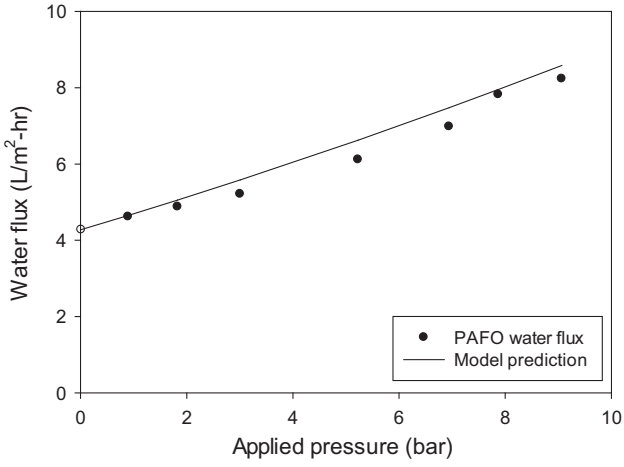

Fig. 7. Comparison of model prediction and experimental flux in PAFO.

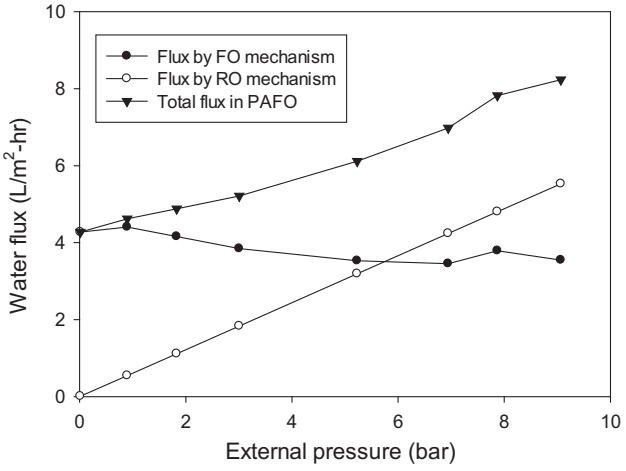

Fig. 6. Analysis of water flux in PAFO based on water transport mechanisms.

The results are shown in Fig. 7. The model parameters A, K_F, and K_D were obtained from a separate set of experiments and used for this model prediction. Although the model estimates the flux slightly larger than the experimental values, it appears to be useful to predict the flux in PAFO. The R^2 value was 0.988.

In summary, PAFO allows higher flux than FO by increasing driving force for water transport. Nevertheless, it also increases ICP and reduces the flux by FO mechanism. It is likely that there are pressure conditions for high flux and manageable ICP in PAFO operations. Therefore, the prediction model seems to be useful to explore the pressure conditions in PAFO operations.

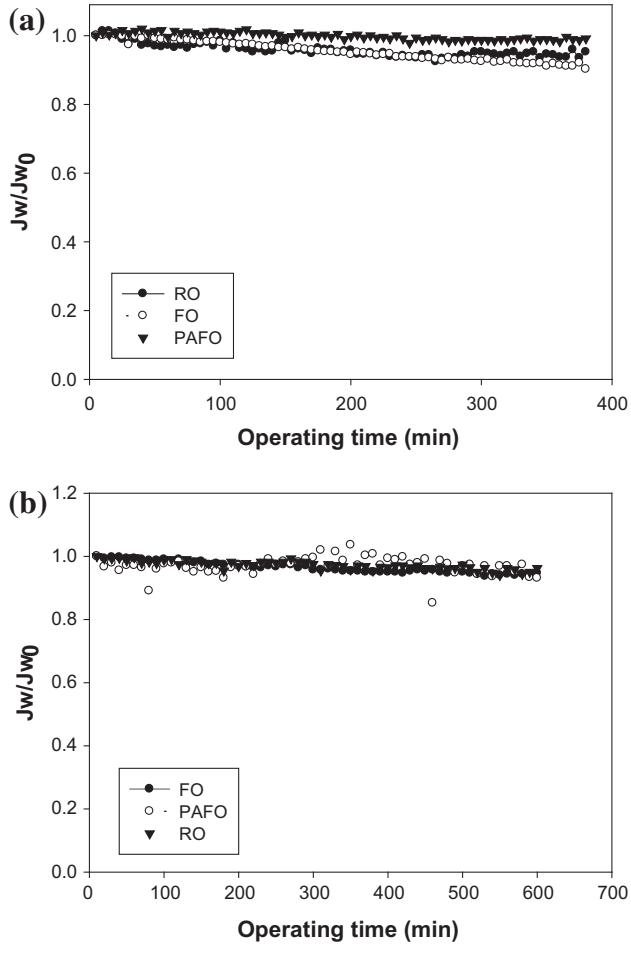

Fig. 8. Comparison of normalized fluxes (J_w/J_{w0}) in FO, RO, and PAFO (a) sodium alginate (b) humic acid.

4.3. Fouling test

Sodium alginate and humic acids were used as model foulants to compare fouling behaviors in FO, RO, and PAFO. For three operation models, the initial flux was set to be constant by adjusting pressure and draw solute concentration. When sodium alginate was used as a model foulant, there were slight differences in flux for three operation modes, which seem to be almost negligible (Fig. 8(a)). When humic acid was used as a model foulant, the flux differences were negligible (Fig. 8(b)), and this is attributed to the low fouling rates, which make it difficult to distinguish the differences in flux. A set of long-term tests as well as accelerated fouling tests will be required to compare fouling in PAFO.

5. Conclusions

In this study, we investigated the characteristics of PAFO, which applies hydraulic pressure in addition to osmotic pressure. The following conclusions were withdrawn:

(1) The external hydraulic pressure has a significant impact on PAFO flux. For instance, using 0.5 M $MgCl_2$ as the draw solution, we were able to obtain approximately two times improvement in flux by increasing pressure up to 9 bar on feed side. This suggests that the flux in the PAFO process can substantially increased by applying both hydraulic and osmotic pressures.
(2) A simple model based on the film theory could predict the PAFO flux. The model calculations indicated that the ICP increases with increasing the hydraulic pressure. Accordingly, the effect of pressure on ICP, which reduces the efficiency of PAFO, should be also considered.
(3) Under the conditions in this study, fouling rates were not high not only in FO but also in RO and PAFO. It is likely that the hydraulic pressure does not affect FO fouling in short-term operations. Nevertheless, further works including a set of long-term tests are required for better understanding of the effect of hydraulic pressure on FO membrane fouling.

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