# 전력생산을 위한 나권형모듈에서의 압력지연삼투 수치모사

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# Numerical studies on the pressure retarded osmosis (PRO) system with the spiral wound module for power generation

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## 1. Introduction

In this study, the PRO spiral wound module has been studied. Compared with the previous works [1], two-dimensional modeling was studied in this work. Sea water and fresh water streams are introduced as cross-flows. Water and solute fluxes across membrane, pressure, salt concentration, flow rate, and power density for PRO system were obtained.

## 2. Model developments

In the PRO system, the total mass balance and the mass balance of salt in the draw- and the feed-channels are obtained including the above flux equations as follows.

a) In the draw channel:

$$\frac{du_d}{dx} = \frac{J_w}{t_d} \quad (1)$$

$$u_d \frac{dC_d}{dx} + C_d \frac{du_d}{dx} = \frac{J_s}{t_d} + \frac{J_w C_f}{t_d} \quad (2)$$

The right hand side of equation (2) is the decrease of salt concentration due to the solute flux and the increase of salt concentration due to the water flux from the feed channel through membrane.

b) In the feed channel:

$$\frac{du_f}{dy} = -\frac{J_w}{t_f} \quad (3)$$

$$u_f \frac{dC_f}{dy} + C_f \frac{du_f}{dy} = -\frac{J_s}{t_f} - \frac{J_w C_f}{t_f} \quad (4)$$

The right hand side of equation (4) is the increase of salt concentration due to the solute flux from the draw channel and the decrease of salt concentration due to the water flux through membrane.

The volumetric flow rates (F) of draw- and feed-fluids are the multiplications of velocity (u) and cross-sectional area for each channel (i.e., ($w \cdot t_d$) and ($L \cdot t_f$)) . Then, changes of volumetric flow rate are obtained with equations (1) and (3) as follows.

$$\frac{dF_d}{dx} = wJ_w \tag{5}$$

$$\frac{dF_f}{dy} = -LJ_w \tag{6}$$

Changes of pressure in the channels are obtained with the volumetric flow rate following the Darcy's law.

$$\frac{dP}{dy} = -bF \tag{7}$$

Here, b ($atm \cdot s \cdot m^{-4}$) is the friction parameter.

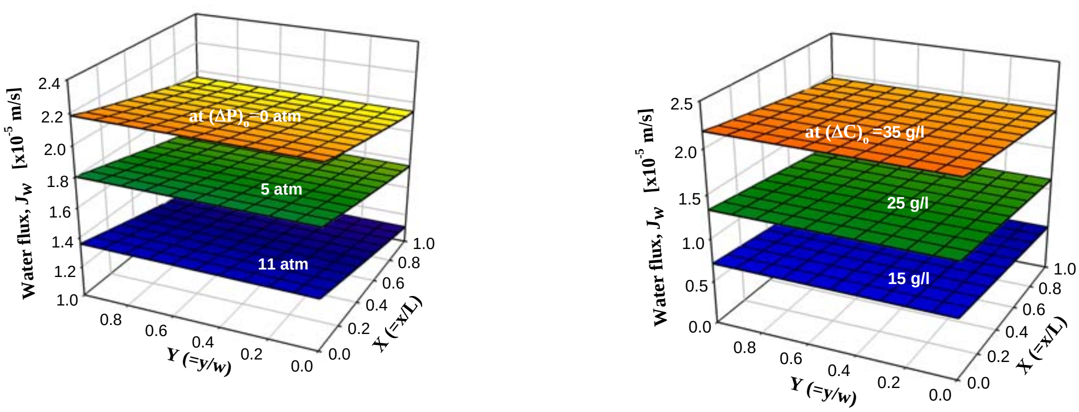
Membrane power density, W ($W \cdot m^{-2}$), can be calculated by multiplying the water flux ($J_w$) and the hydrostatic pressure difference across the membrane ($\Delta P$). [2]

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

## 3. Results and discussion

### *3.1 The water flux across membrane*

The driving forces for the water flux across membrane in the module are pressure difference and concentration difference across membrane. Distributions of the water flux ($J_w$) across membrane at different inlet-pressure differences ($\Delta P_o$) are shown in Fig. 1(a). Effects of the inlet concentration difference ($\Delta C_o$) on $J_w$ are shown in Fig. 1(b).



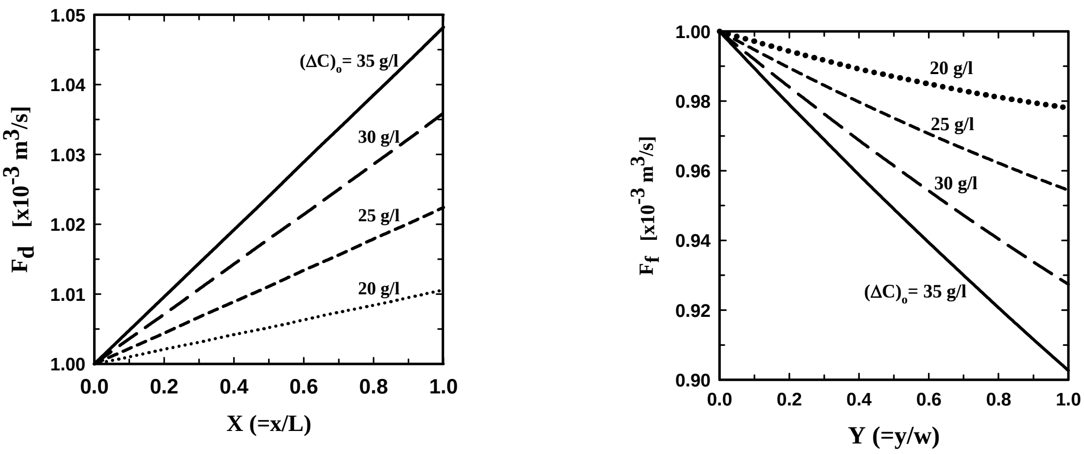

(a) (b)

Fig.1 Distributions of the water flux ($J_w$) across membrane at different (a) inlet-pressure differences ($\Delta P_o$) and (b) inlet-concentration differences ($\Delta C_o$) between feed- and draw-channels. Here, $\Delta P_o$ is ($P_{do}$-$P_{fo}$) and $\Delta C_o$ is ($C_{do}$-$C_{fo}$). $P_{do}$ and $C_{do}$ are fixed at 12 atm and 35 g/l, respectively.

In both Fig.'s 1(a) and 1(b), $J_w$ decreases about 10% along the direction of draw-fluid in our system and increases slightly along the direction of feed-fluid. The concentration of draw-fluid gets small because of the input of water from the feed-fluid. However, the concentration of feed-fluid changes very small. So $\Delta C$ gets small along the direction of flow and the osmotic pressure difference ($\Delta\pi$) also becomes small. As a result, $J_w$ decreases along the direction of draw-fluid.

### *3.2. Changes of concentrations and flow rates of channel-fluids*

When the difference between the inlet concentrations of two channel-fluids decreases, the water flux across membrane due to osmotic pressure difference decreases. As a result, changes of the flow rates in two channels appear similarly as those of concentration differences between two channels do. In other words, as the inlet concentration difference ($\Delta C_o$) becomes large, the flow rate in the draw-channel ($F_d$) increases as shown in Fig. 2(a) and that in the feed-channel ($F_f$) decreases as shown in Fig. 2(b). The water flux decreases for the PRO system when the feed fluid contains more salt.[3]

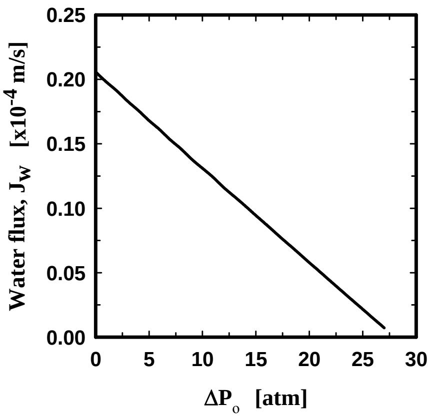


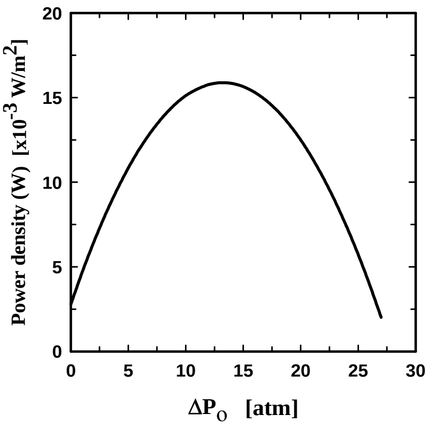

(a) (b)

Fig.2 Distributions of the volumetric flow rate (a) in the draw-channel and (b) in the feed- channel at different inlet NaCl concentration differences between draw- and feed- channels ($\Delta C_o$). Here, $\Delta C_o$ is ($C_{do} - C_{fo}$). $C_{do}$, $\Delta P_o$, and $P_{fo}$ are 35 g/l, 11 atm, and 1 atm, respectively.

### *3.3. The power density*

A hydro-turbine extracts work from the expanding draw solution volume.[4] Part of the water from the draw-fluid goes to the turbine to generate power and the rest of the water returns to the pressure exchanger to pressurize sea water, i.e., draw-fluid. Hence, the pressure of draw-fluid is important. The power density of our system was calculated at different inlet pressures of draw-fluid while fixing the pressure of feed-fluid at 1 atm. As in equation (8), power density is obtained by multiplying the water flux ($J_w$) and the pressure difference ($\Delta P$).[2] So, for comparison, the water flux and the power density, estimated for the different inlet pressure differences ($\Delta P_o$), are shown in Fig. 3(a) and (b). The water flux decreases with the increasing difference between inlet pressures ($\Delta P_o$) of draw- and feed-fluids as shown in Fig. 1(a) and Fig. 3(a). Hence, the power density increases at first and then decreases with the increasing $\Delta P_o$ as shown in Fig. 3(b). In other words, the power density increases at first because of the increasing $\Delta P_o$. and decreases later because of the decreasing $J_w$.




(a) (b)

Fig.3 Changes of (a) the average water flux ($J_w$) across membrane and (b) the power density with $\Delta P_o$ (=$P_{do}$-$P_{fo}$). Here, $P_{fo}$ is fixed at 1 atm and $P_{do}$ is between 1 and 26 atm.

**References**

[1] A. Achilli, T.Y. Cath, and A.E. Childress, Power generation with pressure retarded osmosis: An experimental and theoretical investigation, J. Membr. Sci., 343(1-2) (2009) 42-52.

[2] N.Y. Yip, A. Tiraferri, W.A. Phillip, J.D. Schiffman, L.A. Hoover, Y.C. Kim, and M. Elimelech, Thin-film composite pressure retarded osmosis membranes for sustainable power generation from salinity gradients, Environ. Sci. Technol., 45 (2011) 4360-4369.

[3] J.R. McCutcheon and Menachem Elimelech, Modeling water flux in forward osmosis : Implications for improved membrane design, AIChE J., 53 (2007) 1736-1744.

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**Symbols**

| | |
|---|---|
| $C_d$, $C_f$ | Concentration of salt in the channel, g/l |
| $F_d$, $F_f$ | Volumetric flow rate in the channel, $m^3$/s |
| $J_w$ | Water flux, m/s |
| $J_s$ | Solute flux, mol/$m^2$s |
| $t_f$ , $t_d$ | Height of the channel, m |
| $v_f$, $v_d$ | Velocity of fluid in the channel, m/s |
| L | x-directional length in the feed channel, m |
| w | y-directional width in the draw-channel, m |
| W | Power density, W/$m^2$ |
| $P_d$, $P_f$ | Pressure in the channel, atm |
| b | Friction parameter in the channel, atm·s/$m^4$ |