Energy Consumption Optimization of Reverse Osmosis Membrane Water Desalination Subject to Feed Salinity Fluctuation

Aihua Zhu, Panagiotis D. Christofides,* and Yoram Cohen

Department of Chemical and Biomolecular Engineering, Water Technology Research Center, University of California—Los Angeles, Los Angeles, California 90095-1592

We study the energy consumption optimization of a reverse osmosis water desalination process producing a constant permeate flow in the presence of feed concentration fluctuation. We propose a time-varying optimal operation strategy that can significantly reduce the specific energy consumption compared to time-invariant process operation. We present both computational and experimental results that demonstrate the effectiveness of the proposed optimal operation policy.

1. Introduction

Reverse osmosis (RO) membrane water desalination is now a well established water desalination technology. The water production cost in a typical RO desalination plant generally consists of the cost of energy consumption, equipment, membranes, labor, maintenance, and financial charges. Energy consumption is a major portion of the total cost of water desalination and can reach as high as about 45% of the total permeate production cost.[1−3] The energy cost per volume of produced permeate (i.e., the specific energy consumption or SEC) is significant in RO operation due to the high pressure requirement (up to about 1000 psi for seawater and in the range of 100−600 psi for brackish water desalting). Considerable effort, dating back to the initial days of RO development in the early 1960s has been devoted to minimizing the specific energy consumption of water desalination.[4] More recently, the introduction of highly permeable membranes in the mid 1990s with low salt passage[5] has generated considerable interest,[4,6−8] given their potential for reducing the energy required to attain a given permeate flow, since the operating pressure can be greatly reduced to approach the osmotic pressure difference at the exit of a membrane module (See Figure 1).

In a previous work,[4] we systematically studied the effect of the thermodynamic restriction (i.e., the fact that the applied pressure cannot be lower than the osmotic pressure of the exit brine stream plus pressure losses across the membrane module) on the optimization of the specific energy consumption of an RO process. Specifically, we computed the optimum SEC, corresponding water recovery, and permeate flux for single-stage and two-stage RO membrane desalination systems. We also studied the effect of energy recovery device, membrane cost, and brine disposal costs on SEC. The developed approach can also be utilized to evaluate the energy savings of a two-stage RO system over single-stage RO and the impact of extra membrane area consumption of two-stage over single-stage. Following up on this work, we carried out a systematic study[6] of the energy consumption of *two-pass* reverse osmosis membrane water desalination accounting for key practical issues like membrane salt rejection, presence/absence of energy recovery devices, and thermodynamic restriction. We established that if the salt rejection level of the available membranes can achieve the desired permeate salt content, then a single-pass configuration is more energy favorable than a two-pass configuration for the same level of total water recovery and salt rejection. However, if it is not possible to obtain the desired permeate salt content with the available membranes, then a two-pass configuration has to be used, and in this case, the energy optimal solution is to operate the first-pass using the membranes with the maximum rejection. The computation of the water recoveries for the first-pass and the second-pass that minimize energy consumption were explicitly computed for this case. Our conclusions on the energy consumption comparison between single-pass and two-pass hold when the applied pressure is close to or well above the limit imposed by the thermodynamic cross-flow restriction and also in the presence/absence of energy recovery devices.

In the present work, we extend our previous results to account for the effect of feed salinity fluctuation on energy consumption optimization. Due to seasonal rainfalls, the feedwater salinity may fluctuate both for seawater and brackish water desalination. For example, at one location in the central San Joaquin Valley, the total dissolved solids (TDS) content deviated up to 52% from its annual average.[9] The objective of the present work is to determine the optimal time-varying operating policy to produce a constant permeate flow in the presence of feed salinity fluctuation. Specifically, we propose a time-varying optimal operation policy that can significantly reduce the specific energy consumption compared to time-invariant process operation. We present a series of computational and experimental results that demonstrate the applicability and potential in terms of energy savings of the proposed time-varying optimal operation policy. The operating points located in this work can be used as the

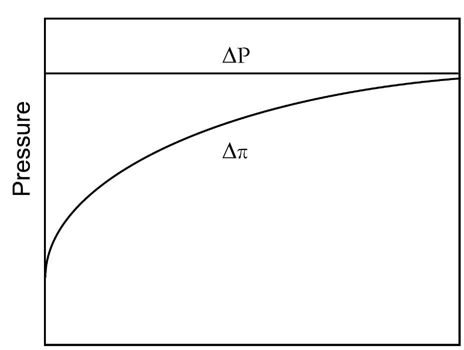

Figure 1. Schematic illustration of the RO system pressure approaching the thermodynamic restriction for cross-flow RO desalting when highly permeable membranes are used.

* Corresponding author. Tel: 310-794-1015. Fax: 310-206-4107. E-mail: pdc@seas.ucla.edu.

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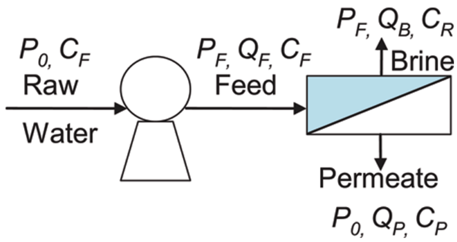

Figure 2. Schematic of a simplified RO system.

set point for control purpose in reverse osmosis desalination systems.[10-12]

2. Preliminaries

2.1. RO Process Description and Modeling. In order to illustrate the proposed approach to energy cost minimization, it is instructive to consider a membrane RO process without the deployment of an energy recovery device (ERD), as shown schematically in Figure 2.

The energy cost for RO desalination is evaluated in the present analysis as the specific energy consumption (SEC) defined as the electrical energy needed to produce a cubic meter of permeate. Pump efficiency can be addressed in the following analysis in a straightforward fashion as presented in ref 4. As a first step, however, in order to simplify the presentation of the approach, the required electrical energy is assumed to be equal to the pump work (i.e., assuming a pump efficiency of 100%). Accordingly, the SEC for the plant shown in Figure 2 is given by

$$\mathrm{SEC} = \frac{\dot{W}_{\mathrm{pump}}}{Q_{\mathrm{p}}} \tag{1}$$

where Q_{p} is the permeate flow rate and $\dot{W}_{\mathrm{pump}}$ is the rate of work done by the pump, given by

$$\dot{W}_{\mathrm{pump}} = \Delta P^* Q_{\mathrm{f}} \tag{2}$$

in which

$$\Delta P = P_{\mathrm{f}} - P_0 \tag{3}$$

where P_{f} is the feed pressure at the entrance of the membrane module, P_0 is the pressure of the raw water, which is assumed (for simplicity) to be the same as the permeate pressure, and Q_{f} is the volumetric feed flow rate.

The permeate product water recovery for the RO process, Y, is an important indicator of the process productivity, defined as

$$Y = \frac{Q_{\mathrm{p}}}{Q_{\mathrm{f}}} \tag{4}$$

and combining eqs 1, 2, and 4, the SEC can be rewritten as follows:

$$\mathrm{SEC} = \frac{\Delta P}{Y} \tag{5}$$

The permeate flow rate is approximated by the classical reverse osmosis flux equation[13]

$$Q_{\mathrm{p}} = A_{\mathrm{m}} L_{\mathrm{p}}(\Delta P - \sigma \overline{\Delta\pi}) = A_{\mathrm{m}} L_{\mathrm{p}}(\overline{\mathrm{NDP}}) \tag{6}$$

where A_{m} is the active membrane surface area, L_{p} is the membrane hydraulic permeability, σ is the reflection coefficient (typically assumed to be about unity for high rejection RO membranes and in this study $\sigma = 1$), ΔP is the transmembrane pressure, $\overline{\Delta\pi}$ is the average osmotic pressure difference between the retentate (brine) and permeate (product) stream along the membrane module, $\Delta P - \sigma\overline{\Delta\pi}$ is the average transmembrane net driving pressure, designated as $\overline{\mathrm{NDP}}$. In order to simplify the analysis, we initially assume that the effect of the pressure drop (within the RO module) on locating the minimum SEC is negligible; this issue is addressed in more details in ref 4. It is important to recognize that fouling and scaling will impact the selection of practical RO process operating conditions and feed pretreatment. However, the inclusion of such effects is beyond the scope of the present paper. We also invoke the typical approximation in ref 13 that the osmotic pressure varies linearly with concentration (i.e., $\pi = f_{\mathrm{os}}C$, where f_{os} is the osmotic pressure coefficient and C is the solution salt concentration). For the purpose of the present work and motivated by our focus on RO processes that utilize highly permeable membranes, the average osmotic pressure difference (up to the desired level of product water recovery), $\overline{\Delta\pi}$, can be approximated as the so-called log-mean average along the membrane as follows[14]

$$\overline{\Delta\pi} = f_{\mathrm{os}} C_{\mathrm{f}} \frac{\ln\left(\frac{1}{1-Y}\right)}{Y} \tag{7}$$

where C_{f} is the salt concentration of the feed to the inlet of the membrane module. The osmotic pressures at the entrance and the exit of the membrane module, relative to the permeate stream, can be approximated by

$$\Delta\pi_{\mathrm{entrance}} = f_{\mathrm{os}} C_{\mathrm{f}} - \pi_{\mathrm{p}} \tag{8}$$

$$\Delta\pi_{\mathrm{exit}} = f_{\mathrm{os}} C_{\mathrm{r}} - \pi_{\mathrm{p}} \tag{9}$$

where C_{r} is the salt concentration of the exit brine (i.e., retenate) stream. For sufficiently high rejection level, the osmotic pressure of the permeate can be taken to be negligible relative to the feed or concentrate streams and C_{r} can be approximated by

$$C_{\mathrm{r}} = \frac{C_{\mathrm{f}}}{1 - Y} \tag{10}$$

Thus, by combining eqs 8-10, the osmotic pressure difference between the brine and permeate stream at the exit of the module can be expressed as

$$\Delta\pi_{\mathrm{exit}} = \frac{\pi_0}{1 - Y} \tag{11}$$

where $\pi_0 = f_{\mathrm{os}} C_{\mathrm{f}}$ is the feed osmotic pressure. Equation 11 represents the well-known inherent limitation to reaching high recovery in RO desalination due to the rapid increase in osmotic pressure with increased water recovery. This limitation implies that in order to ensure permeate productivity, along the entire membrane module, the following lower bound has to be imposed on the applied pressure:

$$\Delta P \geq \Delta\pi_{\mathrm{exit}} = \frac{\pi_0}{1 - Y} \tag{12}$$

Equation 12 indicates that, for a given target recovery, Y, the applied pressure should not be less than the osmotic pressure difference at the module exit. The above inequality is the so-called "thermodynamic restriction" of cross-flow membrane

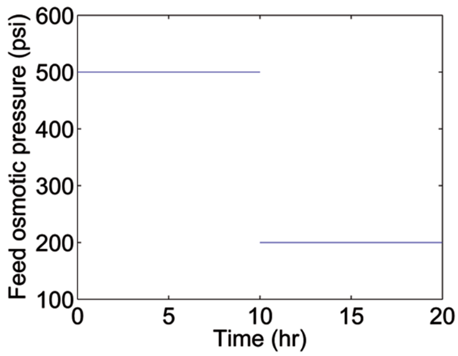

Figure 3. Feed osmotic pressure profile within 20 h.

desalting.[5,8] When considering the above inequality, it is important to recognize that the osmotic pressure at the exit for the bulk solution is the same as at the membrane surface. The above can be understood by considering the simple film model for the concentration polarization module,[13] $CP = C_m/C_b = \exp(J/k)$, where C_m and C_b are the salt concentrations at the membrane surface and the bulk solution respectively, J is the permeate flux and k is the feed-side mass transfer coefficient. Clearly, J will vanish when the thermodynamic restriction limit is reached at the exit and therefore at that limit CP = 1 (i.e., $C_m = C_b$).

2.2. Energy Cost Optimization for a Single-Stage RO without an Energy Recovery Device. The specific energy consumption (SEC) for the RO desalting process can be derived by combining eqs 1−4 and 12, to obtain

$$\mathrm{SEC} \geq \frac{\pi_0}{Y(1-Y)} \tag{13}$$

where SEC is in pressure units. It is convenient to normalize the SEC, at the limit of thermodynamic restriction, with respect to the feed osmotic pressure such that

$$\mathrm{SEC}_{\mathrm{tr,norm}} = \frac{\mathrm{SEC}_{\mathrm{tr}}}{\pi_0} = \frac{1}{Y(1-Y)} \tag{14}$$

In order to locate the analytical global minimum $\mathrm{SEC}_{\mathrm{tr,norm}}$, with respect to the water recovery, one can set $\mathrm{dSEC}_{\mathrm{tr,norm}}/\mathrm{d}Y = 0$, from which it shows that the minimum $\mathrm{SEC}_{\mathrm{tr,norm}}$ occurs at a fractional recovery of $Y = 0.5$ (or 50%) where $(\mathrm{SEC}_{\mathrm{tr,norm}})_{\min} = 4$ (i.e., four times the feed osmotic pressure). The above condition, i.e., $(\mathrm{SEC}_{\mathrm{tr,norm}})_{\min} = 4$ at $Y = 0.5$, represents the global minimum SEC (the equality in eq 13). In order to achieve this global minimum energy cost, the RO process should be operated at a water recovery of 50% with an applied pressure of $2\pi_0$ (i.e., double that of the feed osmotic pressure).

3. Optimal Operation Policy for Energy Optimization

3.1. Feed Salinity Fluctuation and Operating Policies. For the purpose of illustration of the proposed optimal operation approach, we consider a simple feed salinity fluctuation profile shown in Figure 3. Specifically, we consider a 20-h time window in which the feed osmotic pressure in the first 10 h is 500 psi, and it is then reduced to 200 psi for the remaining 10 h. For a single-stage RO system with constant feed flow rate Q_f, the average feed osmotic pressure is 350 psi. We will study the minimum specific energy consumption (SEC) of two different cases. In case 1, the operating pressure is a constant, while in case 2, it will change with the instantaneous feed osmotic pressure and will always be double that of the instantaneous feed osmotic pressure. Both cases are operated at the limit of thermodynamic restriction. It is important to point out that the proposed optimal operation policy and the associated analysis can be readily extended to deal with more complex feed salinity fluctuation profiles.

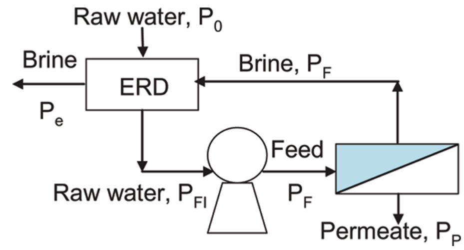

Figure 4. Simplified RO system with an energy recovery device (ERD).

In the presence of the feed salinity fluctuation of Figure 3, the following two operating strategies may be considered: operating strategy A, where the transmembrane pressure is maintained at double that of the average (over the whole 20 h time window) feed osmotic pressure, i.e. 700 psi, and operating strategy B, where the transmembrane pressure is maintained at double that of the instantaneous feed osmotic pressure.

For a built plant to produce the same amount of permeate volume for both operating strategies A and B, the permeate flow rates in the first 10 h and the last 10 h have to be the same. The SEC comparison of operating strategies A and B will be first done for an RO process without an energy recovery device (see Figure 2) and the case of an RO process with an energy recovery device (see Figure 4) will be then addressed. In Figure 4, P_e and P_p are the brine discharge and permeate pressure, respectively, which are assumed here to be equal to P_0.

The rate of work done by the pump on the raw water, in the presence of an ERD, is given by

$$\dot{W}_{\mathrm{pump}} = \Delta P(Q_f - \eta Q_b) \tag{15}$$

where η is the efficiency of the energy recovery device.

With respect to the implementation and robustness of operating strategy B, which requires one to vary the system pressure with respect to the feed salinity fluctuation, it is important to point out the following: a control system could be designed that uses measurements of the instantaneous feed osmotic pressure, $\pi_0(t)$, to automatically maintain the transmembrane pressure at $2\pi_0(t)$ and appropriate adaptation laws could be included in such a control system to deal with RO process variability, which could result in operation significantly above the limit imposed by the thermodynamic restriction (see also subsection 4.3 for more discussion on this issue).

3.2. RO Process without ERD. 3.2.1. Operating Strategy A. At the limit of thermodynamic restriction, according to eq 11, the water recovery in the first 10 h, $Y_1 = 1 - (500/700) = 2/7$ and the water recovery in the last 10 h, $Y_2 = 1 - (200/700) = 5/7$. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h has to be 2.5 times that of the feed flow rate in the last 10 h ($Q_{f,2}$). Therefore, the permeate produced in the first 10 h is

$$V_{p,1} = 2.5Q_{f,2} \times \frac{2}{7} \times 10\ \mathrm{h} = \frac{50}{7}Q_{f,2} \times \mathrm{h} \tag{16}$$

The energy consumption in the first 10 h is

$$W_1 = \Delta P_1 V_{f,1} = 700\ \mathrm{psi} \times \frac{7}{2} \times \frac{50}{7}Q_{f,2} \times \mathrm{h} = 17\,500Q_{f,2} \times \mathrm{psi\ h} \tag{17}$$

Similarly, the permeate produced in the last 10 h is

$$V_{p,2} = Q_{f,2} \times \frac{5}{7} \times 10\text{ h} = \frac{50}{7}Q_{f,2} \times \text{h} \quad (18)$$

which is the same as the permeate volume in the first 10 h as required in this scenario. The energy consumption in the last 10 h is

$$W_2 = \Delta P_2 V_{p,2} = 700\text{ psi} \times \frac{7}{5} \times \frac{50}{7}Q_{f,2} \times \text{h} = 7000Q_{f,2} \times \text{psi h} \quad (19)$$

Therefore, the average SEC for strategy A is

$$\overline{\text{SEC}}^{A} = \frac{W_1 + W_2}{V_{p,1} + V_{p,2}} = \frac{(17500 + 7000) \times Q_{f,2} \times \text{psi h}}{(50/7 + 50/7) \times Q_{f,2} \times \text{h}} = 1715\text{ psi} \quad (20)$$

which can be converted into 11 824 kJ/m^3, meaning that 11 824 kJ of energy is needed to produce 1 m^3 of permeate by adopting operating strategy A.

3.2.2. Operating Strategy B. The water recovery in the last 10 h is the same as the water recovery in the first 10 h (both at 50%). In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h should be the same as the feed flow rate in the last 10 h ($Q_{f,2}'$). The permeate produced in the first 10 h is

$$V_{p,1}' = Q_{f,2}' \times \frac{1}{2} \times 10\text{ h} = 5Q_{f,2}' \times \text{h} \quad (21)$$

The energy consumption in the first 10 h is:

$$W_1' = \Delta P_1' V_{f,1}' = 2 \times 500\text{ psi} \times 2 \times 5Q_{f,2}' \times \text{h} = 10\,000Q_{f,2}' \times \text{psi h} \quad (22)$$

Similarly, the permeate produced in the last 10 h is

$$V_{p,2}' = Q_{f,2}' \times \frac{1}{2} \times 10\text{ h} = 5Q_{f,2}' \times \text{h} \quad (23)$$

which is the same as the permeate volume in the first 10 h, as required in this scenario. The energy consumption in the last 10 h is

$$W_2' = \Delta P_2' V_{f,2}' = 2 \times 200\text{ psi} \times 2 \times 5Q_{f,2}' \times \text{h} = 4000Q_{f,2}' \times \text{psi h} \quad (24)$$

Therefore, the average SEC for strategy B is

$$\overline{\text{SEC}}^{B} = \frac{W_1' + W_2'}{V_{p,1}' + V_{p,2}'} = \frac{(10\,000 + 4000)Q_{f,2}' \times \text{psi h}}{(5 + 5)Q_{f,2}' \times \text{h}} = 1400\text{ psi} \quad (25)$$

which can be converted into 9652 kJ/m^3, meaning that 9652 kJ of energy is needed to produce 1 m^3 of permeate by adopting operating strategy B.

From eqs 20 and 25, we see that the operating strategy A has a higher SEC than operating strategy B by about 22.5% [(1715 − 1400)/1400 = 22.5%]. Furthermore, in order to equate the total permeate volume in operating strategies A and B, $Q_{f,2}' = 10/7Q_{f,2}$. Thus, the total feed volume in operating strategy B is $2 \times 10/7Q_{f,2} = 20/7Q_{f,2}$, while the total feed volume in operating strategy A is $(2.5 + 1)Q_{f,2} = 3.5Q_{f,2}$. Therefore, in order to get the same amount of permeate volume, operating strategy A requires a higher amount of feedwater, and thus, it has a lower overall water recovery.

3.3. RO Process with ERD of 100% Efficiency. 3.3.1. Operating Strategy A. The water recovery in the last 10 h is 2.5 times that of the water recovery in the first 10 h. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h has to be 2.5 times that of the feed flow rate in the last 10 h ($Q_{f,2}$). Therefore, the permeate produced in the first 10 h is

$$V_{p,1} = 2.5Q_{f,2} \times \frac{2}{7} \times 10\text{ h} = \frac{50}{7}Q_{f,2} \times \text{h} \quad (26)$$

The energy consumption in the first 10 h is

$$W_1^{ERD} = \Delta P_1 V_{p,1} = 700\text{ psi} \times \frac{50}{7}Q_{f,2} \times \text{h} = 5000Q_{f,2} \times \text{psi h} \quad (27)$$

Similarly, the permeate produced in the last 10 h is

$$V_{p,2} = Q_{f,2} \times \frac{5}{7} \times 10\text{ h} = \frac{50}{7}Q_{f,2} \times \text{h} \quad (28)$$

which is the same as the permeate volume in the first 10 h as required in this scenario. The energy consumption in the last 10 h is

$$W_2^{ERD} = \Delta P_2 V_{p,2} = 700\text{ psi} \times \frac{50}{7}Q_{f,2} \times \text{h} = 5000Q_{f,2} \times \text{psi h} \quad (29)$$

Therefore, the average SEC is

$$\overline{\text{SEC}}^{A} = \frac{W_1^{ERD} + W_2^{ERD}}{V_{p,1} + V_{p,2}} = \frac{(5000 + 5000)Q_{f,2} \times \text{psi h}}{(50/7 + 50/7)Q_{f,2} \times \text{h}} = 700\text{ psi} \quad (30)$$

which can be converted into 4826 kJ/m^3, meaning that 4826 kJ of energy is needed to produce 1 m^3 of permeate by adopting operating strategy A.

3.3.2. Operating Strategy B. We now turn our attention to operating strategy B. In this strategy, the operating pressure will always be double that of the instantaneous feed osmotic pressure; therefore, the water recovery in the last 10 h is the same as the water recovery in the first 10 h. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h has to be the same as that of the feed flow rate in the last 10 h ($Q_{f,2}'$). The permeate produced in the first 10 h is

$$V_{p,1}' = Q_{f,2}' \times \frac{1}{2} \times 10\text{ h} = 5Q_{f,2}' \times \text{h} \quad (31)$$

The energy consumption in the first 10 h is

$$W_1^{ERD\prime} = \Delta P_1' V_{p,1}' = 2 \times 500\text{ psi} \times 5Q_{f,2}' \times \text{h} = 5000Q_{f,2}' \times \text{psi h} \quad (32)$$

Similarly, the permeate produced in the last 10 h is

$$V_{p,2}' = Q_{f,2}' \times \frac{1}{2} \times 10\text{ h} = 5Q_{f,2}' \times \text{h} \quad (33)$$

which is the same as the permeate volume in the first 10 h, as required in this scenario. The energy consumption in the last 10 h is

$$W_2^{ERD\prime} = \Delta P_2 V_{p,2}' = 2 \times 200\text{ psi} \times 5Q_{f,2}' \times \text{h} = 2000Q_{f,2}' \times \text{psi h} \quad (34)$$

Therefore, the average SEC is

$$\overline{\mathrm{SEC}}^{\mathrm{B}} = \frac{W_1^{\mathrm{ERD}\prime} + W_2^{\mathrm{ERD}\prime}}{V_{p,1}' + V_{p,2}'} = \frac{(2000 + 5000)Q_{f,2}' \times \mathrm{psi\ h}}{(5 + 5)Q_{f,2}' \times \mathrm{h}} = 700\ \mathrm{psi} \quad (35)$$

which can be converted into 4826 kJ/m^3, meaning that 4826 kJ of energy is needed to produce 1 m^3 of permeate by adopting operating strategy B.

From eqs 30 and 35, we see that in the presence of an ERD with a 100% efficiency, operating strategies A and B have the same SEC. Furthermore, in order to equate the total permeate volume in operating strategies A and B, $Q_{f,2}' = 10/7Q_{f,2}$. Thus, the total feed volume in operating strategy B is $2 \times 10/7Q_{f,2} = 20/7Q_{f,2}$, while the total feed volume in operating strategy A is $(2.5 + 1)Q_{f,2} = 3.5Q_{f,2}$. Therefore, in order to get the same amount of permeate volume, operating strategy A requires a higher amount of feedwater, and thus, it has a lower overall water recovery.

3.4. Effect of ERD Efficiency. In this subsection, we study the effect of ERD efficiency on the optimal operation policy subject to the feed salinity fluctuation. Similarly, two operating strategies A (constant pressure operation) and B (time-varying pressure operation) are compared to determine the effectiveness of strategy B.

3.4.1. Operating Strategy A. The water recovery in the last 10 h is 2.5 times that of the water recovery in the first 10 h. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h has to be 2.5 times the feed flow rate in the last 10 h ($Q_{f,2}$). Therefore, the permeate produced in the first 10 h is

$$V_{p,1} = 2.5Q_{f,2} \times \frac{2}{7} \times 10\ \mathrm{h} = \frac{50}{7}Q_{f,2} \times \mathrm{h} \quad (36)$$

The energy consumption in the first 10 h is

$$W_1^{\mathrm{ERD}} = \Delta P_1(V_{f,1} - \eta(V_{f,1} - V_{p,1})) = 700\ \mathrm{psi} \times \left(25 - \frac{125}{7}\eta\right)Q_{f,2} \times \mathrm{h} = (17\,500 - 12\,500\eta)Q_{f,2} \times \mathrm{psi\ h} \quad (37)$$

Similarly, the permeate produced in the last 10 h is

$$V_{p,2} = Q_{f,2} \times \frac{5}{7} \times 10\ \mathrm{h} = \frac{50}{7}Q_{f,2} \times \mathrm{h} \quad (38)$$

which is the same as the permeate volume in the first 10 h, as required in this scenario. The energy consumption in the last 10 h is

$$W_2^{\mathrm{ERD}} = \Delta P_2(V_{f,2} - \eta(V_{f,2} - V_{p,2})) = 700\ \mathrm{psi} \times \left(10 - \frac{20}{7}\eta\right)Q_{f,2} \times \mathrm{h} = (7000 - 2000\eta)Q_{f,2} \times \mathrm{psi\ h} \quad (39)$$

Therefore, the average SEC is

$$\overline{\mathrm{SEC}}^{\mathrm{A}}_{\mathrm{ERD}} = \frac{W_1^{\mathrm{ERD}} + W_2^{\mathrm{ERD}}}{V_{p,1} + V_{p,2}} = \frac{(17\,500 - 12\,500\eta)Q_{f,2} \times \mathrm{psi\ h}}{(50/7 + 50/7)Q_{f,2} \times \mathrm{h}} + \frac{(7000 - 2000\eta)Q_{f,2} \times \mathrm{psi\ h}}{(50/7 + 50/7)Q_{f,2} \times \mathrm{h}} = (1715 - 1015\eta) \times \mathrm{psi} \quad (40)$$

which will reduce to 700 psi (eq 30) when $\eta = 1$ (subsection 3.3).

3.4.2. Operating Strategy B. The water recovery in the last 10 h is the same as the water recovery in the first 10 h. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h has to be the same as that of the feed flow rate in the last 10 h ($Q_{f,2}'$). Therefore, the permeate produced in the first 10 h is

$$V_{p,1}' = Q_{f,2}' \times \frac{1}{2} \times 10\ \mathrm{h} = 5Q_{f,2}' \times \mathrm{h} \quad (41)$$

The energy consumption in the first 10 h is

$$W_1^{\mathrm{ERD}\prime} = \Delta P_1'(V_{f,1}' - \eta(V_{f,1}' - V_{p,1}')) = 2 \times 500\ \mathrm{psi} \times (10 - 5\eta)Q_{f,2}' \times \mathrm{h} = 5000(2 - \eta)Q_{f,2}' \times \mathrm{psi\ h} \quad (42)$$

Similarly, the permeate produced in the last 10 h is

$$V_{p,2}' = Q_{f,2}' \times \frac{1}{2} \times 10\ \mathrm{h} = 5Q_{f,2}' \times \mathrm{h} \quad (43)$$

which is the same as the permeate volume in the first 10 h, as required in this scenario. The energy consumption in the last 10 h is

$$W_2^{\mathrm{ERD}\prime} = \Delta P_2(V_{f,2}' - \eta(V_{f,2}' - V_{p,2}')) = 2 \times 200\ \mathrm{psi} \times (10 - 5\eta)Q_{f,2}' \times \mathrm{h} = 2000(2 - \eta)Q_{f,2}' \times \mathrm{psi\ h} \quad (44)$$

Therefore, the average SEC is

$$\overline{\mathrm{SEC}}^{\mathrm{B}}_{\mathrm{ERD}} = \frac{W_1^{\mathrm{ERD}\prime} + W_2^{\mathrm{ERD}\prime}}{V_{p,1}' + V_{p,2}'} = \frac{(2000 + 5000)(2 - \eta)Q_{f,2}' \times \mathrm{psi\ h}}{(5 + 5)Q_{f,2}' \times \mathrm{h}} = 700(2 - \eta) \times \mathrm{psi} \quad (45)$$

which will reduce to 700 psi (eq 35) when $\eta = 1$ (subsection 3.3).

The SEC difference between operating strategies A and B is $(1715 - 1015\eta) - 700(2 - \eta)$ psi $= 315(1 - \eta)$ psi. Thus, when $0 < \eta < 1$, the SEC of operating strategy A will be always greater than the SEC of operating strategy B. The fractional SEC increase is

$$\frac{\overline{\mathrm{sec}}^{\mathrm{A}}_{\mathrm{ERD}} - \overline{\mathrm{sec}}^{\mathrm{B}}_{\mathrm{ERD}}}{\overline{\mathrm{sec}}^{\mathrm{B}}_{\mathrm{ERD}}} = \frac{315(1 - \eta)}{700(2 - \eta)} = \frac{315}{700}\frac{(1 - \eta)}{[1 + (1 - \eta)]} \quad (46)$$

which is plotted in Figure 5. For example, when the ERD efficiency is 90%, the fractional SEC increase is 4.1%. Furthermore, in order to equate the total permeate volume in operating strategy A and operating strategy B, $Q_{f,2}' = 10/7Q_{f,2}$.

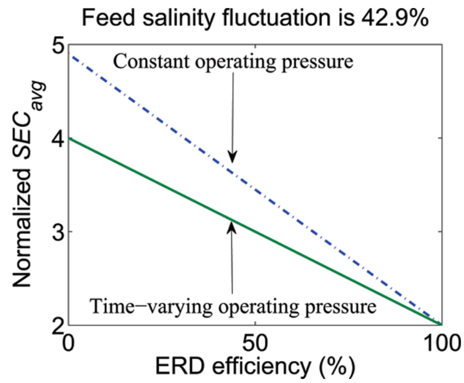

Figure 5. Variation of normalized SEC for operating strategy A (dashed−dotted line) and B (solid line) with respect to ERD efficiency in the presence of 42.9% of feed fluctuation (Figure 3). The SEC is normalized with respect to the average feed osmotic pressure (i.e., 350 psi for the feed fluctuation profile in Figure 3).

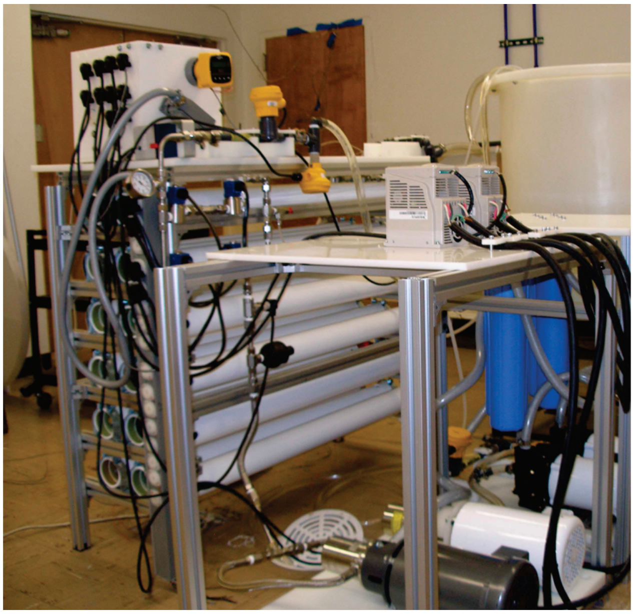

Figure 6. Experimental water desalination system developed at UCLA WaTeR Center and used in the experiments.

Thus, the total feed volume in operating strategy B is $2 \times 10/7Q_{f,2} = 20/7Q_{f,2}$, while the total feed volume in operating strategy A is $(2.5 + 1)Q_{f,2} = 3.5Q_{f,2}$. Therefore, in order to get the same amount of permeate volume, operating strategy A requires a higher amount of feedwater, and thus, it has a lower overall water recovery.

In summary, operating strategy A is worse, since we need to process more feedwater to obtain the same permeate and it has a higher SEC. In others words, by adjusting the operating pressure to be double that of the instantaneous feed osmotic pressure, the system needs to process less volume of feedwater to produce the same amount of permeate water and requires a lower SEC.

4. Experimental Study

4.1. Experimental System. In order to test the proposed optimal operation policy, we applied it to an experimental water desalination system (Figure 6) that was recently developed and tested at the UCLA Water Technology Research (WaTeR) Center by the authors and co-workers. The experimental system includes a feed tank, filters, pressure vessels, membrane modules, pumps, variable frequency drivers, valves, actuators, sensors (pH, temperature, conductivity, flow rate), and a data acquisition system. A detailed description of the system can be found in ref 12.

4.2. Experimental Design. On the basis of the theoretical calculations of section 3, an experiment was designed to compare the SEC of the two different operating strategies, A and B, and verify the theoretical calculations. Strategy A is to operate the system at a fixed pressure, while strategy B adjusts the operating pressure to achieve 50% water recovery. Specifically, the experimental procedure is as follows:

1. fix the feed concentration to be $C_{f,1}$;
2. adjust the RO feed flow rate $Q_{f,1}$ and RO feed pressure ΔP_1 to achieve 50% water recovery and record the resulting permeate flow rate $Q_{p,1}$;
3. adjust the RO feed concentration to $C_{f,2}$;
4. adjust the RO feed flow rate $Q_{f,2}$ and RO feed pressure ΔP_2 to achieve the same water recovery and permeate flow rate as those in step 2 (i.e., 50% water recovery and at the recorded $Q_{p,2} = Q_{p,1} = Q_p$);
5. maintain the feed concentration at $C_{f,2}$, tune the RO feed pressure to $(\Delta P_1 + \Delta P_2)/2$ and the permeate flow rate to Q_p, and record the resulting feed flow rate $Q_{f,4}$ and water recovery Y_4;
6. adjust the feed concentration back to $C_{f,1}$;
7. adjust the RO feed pressure to $(\Delta P_1 + \Delta P_2)/2$ and the permeate flow rate to Q_p, and record the resulting feed flow rate $Q_{f,3}$ and water recovery Y_3.

Table 1. Feed Fluctuation Experimental Design[a]

	strategy B		strategy A	
	experiment 1	experiment 2	experiment 3	experiment 4
FC (mg/L)	$C_{f,1}$	$C_{f,2}$	$C_{f,1}$	$C_{f,2}$
PF(gpm)	Q_p	Q_p	Q_p	Q_p
FP (psi)	ΔP_1	ΔP_2	$1/2(\Delta P_1 + \Delta P_2)$	$1/2(\Delta P_1 + \Delta P_2)$
FF (gpm)	$Q_{f,1}$	$Q_{f,2}$	$Q_{f,3}$	$Q_{f,4}$
Y	50%	50%	Y_3	Y_4

[a] FC, feed concentration; FP, feed pressure; PF, permeate flow; Y, water recovery; RF, retentate flow; RC, retentate concentration; SEC, specific energy consumption.

4.3. Experimental Results. Following the procedure described in subsection 4.2, we pick two different feed salinities, i.e., $C_{f,1} = 9000$ mg/L (feed osmotic pressure is 104 psi) and $C_{f,2} = 5000$ mg/L (feed osmotic pressure is 60 psi). The experimental results are listed in Table 2. The first column is the experimental set number as in Table 1. In experiments 1 and 2, the system operates at 50% water recovery, producing 1 gpm of product permeate water, and the resulting feed pressures in the system are 230 psi (10% above the thermodynamic restriction in terms of applied pressure; see eq 12) and 149 psi (24% above the thermodynamic restriction in terms of applied pressure; see eq 12), respectively. According to our experimental procedure, experiments 3 and 4 are operated at the average pressure of experiments 1 and 2, i.e., 190 psi. On the basis of the experimental results of Table 2, we can conclude that varying the feed pressure with time (strategy B) leads to substantial SEC savings. However, it is important to elaborate further on these experimental results and put them into perspective with respect to the type of experimental system used to carry them out. Specifically, referring to the results of Table 2, we observe that the water recovery decreases while the operating pressure increases from 149 to 190 psi for the same feed salinity when switching from experiment 2 to experiment 3. This is due to the physical limitations of the experimental system. In particular, the available settings of retentate valves and pump speed do not allow one to regulate the feed pressure and feed flow rate independently. As a result, in order to increase the feed pressure and maintain the permeate flow to be 1 gpm, the high pressure pumps have to run faster, and thus, more water is discharged in the brine stream, thereby decreasing the water recovery. If it were possible to independently adjust the feed pressure and feed flow rate (with an appropriate pump and valve choice), an estimate of the resulting SEC for such an operation could be computed as follows: specifically, instead of lowering water recovery, the water recovery would increase as shown in Table 3. As limited by the thermodynamic restriction, the maximum water recovery in this case would be $1 - (60/190) = 0.68$ (see eq 12). If the system were to operate (in terms of feed pressure) 10% above the thermodynamic limit pressure, the water recovery would be $1 - \{60/[190/(1 + 10\%)]\} = 0.65$ (see eq 12). If the system were to operate 24% above the thermodynamic restriction,

Table 2. Experimental Results[a]

set	FC (mg/L)	FP (psi)	PF (gpm)	Y	RF (gpm)	RC (mg/L)	SEC (psi)	SEC_{avg} (psi)
1	9000	230	1	0.50	1	35000	460	strategy B
2	5000	149	1	0.50	1	19600	298	379
3	5000	190	1	0.19	4.25	12200	1000	strategy A
4	9000	190	0.57	0.41	0.82	30000	463	805

[a] FC, feed concentration; FP, feed pressure; PF, permeate flow; Y, water recovery; RF, retentate flow; RC, retentate concentration; SEC, specific energy consumption.

Table 3. Experimental Results and Analysis[a]

set	FC (mg/L)	FP (psi)	PF (gpm)	Y	SEC (psi)	SEC_{avg} (psi)
1	9000	230	1	0.50	460	strategy B
2	5000	149	1	0.50	298	379
3	5000	190	1	0.65 (0.6)	292 (316)	strategy A
4	9000	190	1	0.4 (0.32)	475 (594)	384 (452)

[a] FC, feed concentration; FP, feed pressure; PF, permeate flow; Y, water recovery; RF, retentate flow; RC, retentate concentration; SEC, specific energy consumption. Data inside and before the parentheses in strategy A are calculated on the basis of the assumption that the RO processes are operated 24% and 10% above the corresponding thermodynamic limit pressures, respectively.

Table 4. Additional Experimental Results and Analysis[a]

set	FC (mg/L)	FP (psi)	PF (gpm)	Y	SEC (psi)	SEC_{avg} (psi)
1	9000	230	1	0.50	460	strategy B
2	5000	149	1	0.50	298	379
3	5000	190	1	0.63	302	strategy A
4	9000	190	1	0.36	528	415

[a] FC, feed concentration; FP, feed pressure; PF, permeate flow; Y, water recovery; RF, retentate flow; RC, retentate concentration; SEC, specific energy consumption. Data in 3 and 4 for strategy A are calculated on the basis of the assumption that the feed pressures are 17% above the corresponding thermodynamic limit pressure, respectively.

the water recovery would be $1 - \{60/[190/(1 + 24\%)]\} = 0.6$ (see eq 12 and the numbers shown in the parentheses of Table 3). Similarly for experiment 4, the system cannot reach the permeate flow of 1 gpm, while operated at 190 psi, due to the physical limitations discussed above. However, a similar calculation to the one made for experiment 3 would lead to a water recovery of $1 - \{104/[190/(1 + 10\%)]\} = 0.4$ (if the system were to operate 10% above the thermodynamic restriction) and $1 - \{104/[190/(1 + 24\%)]\} = 0.32$ (if the system were to operate 24% above the thermodynamic restriction), as shown in Table 3. Finally, another average case is to operate the RO process with feed pressures that are 17% (i.e., average of 24% and 10%) above the thermodynamic limit pressure for both experiments 3 and 4, as shown in Table 4; this would lead to water recoveries of $1 - \{60/[190/(1 + 17\%)]\} = 0.63$ and $1 - \{104/[190/(1 + 17\%)]\} = 0.36$, respectively. In this case, the average SEC is 415 psi for strategy A, which is about 9.5% higher than the average SEC of strategy B. In summary, in all of the cases (Tables 2−4), the average SECs are 384−452 and 379 psi for strategies A and B, respectively; therefore, it can be concluded, both from the experimental results and the analysis, that it is better, from an energy optimization point-of-view, to adjust the feed pressure to target 50% water recovery (strategy B) instead of adopting a constant operating pressure (strategy A).

5. Effect of the Feed Salinity Fluctuation Percentage on Energy Savings

The effect of the fluctuation amplitude on energy savings can be studied following the same procedure presented in subsection 3.4. Assuming that the average osmotic pressure is π_0, the osmotic pressure in the first 10 h is $(1 + \sigma)\pi_0$ $(0 < \sigma < 1)$, and the osmotic pressure in the last 10 h is $(1 - \sigma)\pi_0$. Therefore, the feed fractional fluctuation is σ. Similarly, the following two operating strategies may be considered: operating strategy A, where the transmembrane pressure is maintained at double that of the average feed osmotic pressure, i.e. $2\pi_0$, and operating strategy B, where the transmembrane pressure is maintained at double that of the instantaneous feed osmotic pressure.

5.1. Operating Strategy A. The water recovery in the last 10 h, $Y_1 = 1 - [(1 + \sigma)\pi_0]/2\pi_0 = (1 - \sigma)/2$, and in the last 10 h, $Y_2 = 1 - [(1 - \sigma)\pi_0]/2\pi_0 = (1 + \sigma)/2$. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h has to be $(1 + \sigma)/(1 - \sigma)$ times that of the feed flow rate in the last 10 h ($Q_{f,2}$). The permeate produced in the first 10 h is

$$V_{p,1} = \frac{1 + \sigma}{1 - \sigma} \times Q_{f,2} \times \frac{1 - \sigma}{2} \times 10\text{ h} = 5(1 + \sigma)Q_{f,2} \times \text{h} \quad (47)$$

The energy consumption in the first 10 h is

$$W_1^{ERD} = \Delta P_1(V_{f,1} - \eta(V_{f,1} - V_{p,1})) = 2\pi_0\left[(1 - \eta)\left(\frac{10(1 + \sigma)}{(1 - \sigma)} + 5\eta(1 + \sigma)\right)\right]Q_{f,2} \times \text{h} = 10\left[\frac{2(1 - \eta)(1 + \sigma)}{1 - \sigma} + \eta(1 + \sigma)\right]\pi_0 Q_{f,2} \times \text{h} \quad (48)$$

Similarly, the permeate produced in the last 10 h is

$$V_{p,2} = Q_{f,2}\frac{1 + \sigma}{2} \times 10\text{ h} = 5(1 + \sigma)Q_{f,2} \times \text{h} \quad (49)$$

which is the same as the permeate volume in the first 10 h, as required in this scenario. The energy consumption in the last 10 h is

$$W_2^{ERD} = \Delta P_2(V_{f,2} - \eta(V_{f,2} - V_{p,2})) = 2\pi_0[10 - \eta(10 - 5(1 + \sigma))]Q_{f,2} \times \text{h} = 10[2(1 - \eta) + \eta(1 + \sigma)]\pi_0 Q_{f,2} \times \text{h} \quad (50)$$

Therefore, the average SEC is

$$\overline{\mathrm{SEC}}^{\mathrm{A}}_{\mathrm{ERD}} = \frac{W_1^{\mathrm{ERD}} + W_2^{\mathrm{ERD}}}{V_{\mathrm{p},1} + V_{\mathrm{p},2}} = \frac{10\left[\frac{2(1-\eta)(1+\sigma)}{1-\sigma} + \eta(1+\sigma)\right]}{2 \times 5(1+\sigma)Q_{\mathrm{f},2} \times \mathrm{h}}\pi_0 Q_{\mathrm{f},2} \times \mathrm{h} + \frac{10[2(1-\eta) + \eta(1+\sigma)]}{2 \times 5(1+\sigma)Q_{\mathrm{f},2} \times \mathrm{h}}\pi_0 Q_{\mathrm{f},2} \times \mathrm{h} = \frac{\frac{2(1-\eta)(1+\sigma)}{1-\sigma} + 2\eta(1+\sigma) + 2(1-\eta)}{1+\sigma}\pi_0 = 2\left[\frac{(1-\eta)}{1-\sigma} + \frac{(1+\eta\sigma)}{1+\sigma}\right]\pi_0 \quad (51)$$

5.2. Operating Strategy B. The water recovery in the last 10 h is the same as the water recovery in the first 10 h. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 h has to be the same as the feed flow rate in the last 10 h ($Q_{f,2}'$). The permeate produced in the first 10 h is

$$V_{\mathrm{p},1}' = Q_{\mathrm{f},2}' \times \frac{1}{2} \times 10\ \mathrm{h} = 5Q_{\mathrm{f},2}' \times \mathrm{h} \quad (52)$$

The energy consumption in the first 10 h is

$$W_1^{\mathrm{ERD}\prime} = \Delta P_1'(V_{\mathrm{f},1}' - \eta(V_{\mathrm{f},1}' - V_{\mathrm{p},1}')) = 2 \times (1+\sigma)\pi_0 \times (10 - 5\eta)Q_{\mathrm{f},2}' \times \mathrm{h} = 10 \times (1+\sigma)(2-\eta)\pi_0 Q_{\mathrm{f},2}' \times \mathrm{h} \quad (53)$$

Similarly, the permeate produced in the last 10 h is

$$V_{\mathrm{p},2}' = Q_{\mathrm{f},2}' \times \frac{1}{2} \times 10\ \mathrm{h} = 5Q_{\mathrm{f},2}' \times \mathrm{h} \quad (54)$$

which is the same as the permeate volume in the first 10 h, as required in this scenario. The energy consumption in the last 10 h is

$$W_2^{\mathrm{ERD}\prime} = \Delta P_2(V_{\mathrm{f},2}' - \eta(V_{\mathrm{f},2}' - V_{\mathrm{p},2}')) = 2 \times (1-\sigma)\pi_0 \times (10 - 5\eta)Q_{\mathrm{f},2}' \times \mathrm{h} = 10 \times (1-\sigma)(2-\eta)\pi_0 Q_{\mathrm{f},2}' \times \mathrm{h} \quad (55)$$

Therefore, the average SEC is

$$\overline{\mathrm{SEC}}^{\mathrm{B}}_{\mathrm{ERD}} = \frac{W_1^{\mathrm{ERD}\prime} + W_2^{\mathrm{ERD}\prime}}{V_{\mathrm{p},1}' + V_{\mathrm{p},2}'} = \frac{10(1-\sigma+1+\sigma)(2-\eta)\pi_0 Q_{\mathrm{f},2}' \times \mathrm{h}}{(5+5)Q_{\mathrm{f},2}' \times \mathrm{h}} = 2(2-\eta)\pi_0 \quad (56)$$

The SEC difference of operating strategy A from operating strategy B is $\{2[(1-\eta)/(1-\sigma)] + [(1+\eta\sigma)/(1+\sigma)] - 2(2-\eta)\}\pi_0$. When $0 < \eta < 1$, the SEC of operating strategy A will be always greater than the SEC of operating strategy B. The fractional SEC increase is

$$\frac{\overline{\mathrm{SEC}}^{\mathrm{A}}_{\mathrm{ERD}} - \overline{\mathrm{SEC}}^{\mathrm{B}}_{\mathrm{ERD}}}{\overline{\mathrm{SEC}}^{\mathrm{B}}_{\mathrm{ERD}}} = \frac{2\left[\frac{(1-\eta)}{1-\sigma} + \frac{(1+\eta\sigma)}{1+\sigma}\right] - 2(2-\eta)}{2(2-\eta)} = \frac{2\sigma^2(1-\eta)}{(2-\eta)(1-\sigma^2)} > 0 \quad (57)$$

which is plotted in Figure 7 when the efficiency of the ERD is set to be 90%. The greater-than-zero sign in eq 57 shows that strategy B is always superior to A in terms of energy utilization, irrespective of the feed salinity fluctuation percentage and ERD efficiency. Figure 7 shows that, as the feed salinity fluctuation percentage increases, the time-invariant operation increases the SEC more remarkably. Furthermore, while in some cases there is only marginal energy savings, it is still worthwhile to adopt the proposed time-varying operating strategy, since future feed salinity fluctuation profiles are unknown. Finally, in order to equate the total permeate volume in operating strategies A and B, $Q_{f,2}' = (1 + \sigma)Q_{f,2}$. Thus, the total feed volume in operating strategy B is $2(1 + \sigma)Q_{f,2}$, while the total feed volume in operating strategy A is $[(1 + \sigma)/(1 - \sigma) + 1]Q_{f,2} = (1 + [2\sigma/(1 - \sigma)] + 1)Q_{f,2} > (1 + 2\sigma + 1)Q_{f,2}$. Therefore, in order to get the same amount of permeate volume, operating strategy A requires a higher amount of feedwater, and thus, it has a lower overall water recovery.

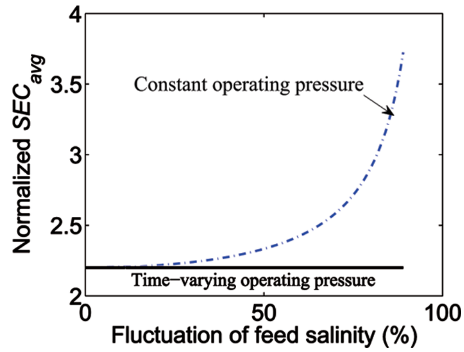

Figure 7. Variation of normalized SEC for operating strategies A (dashed−dotted line) and B (solid line) with respect to feed salinity fluctuation in the presence of an ERD of 90% efficiency. The SEC is normalized with respect to the average feed osmotic pressure (i.e., 350 psi for the feed fluctuation profile in Figure 3).

6. Conclusion

Building upon our previous work on the effect of thermodynamic restriction on energy consumption optimization of reverse osmosis membrane desalination,[4] the present work has addressed a practical problem of energy-optimal process operation in the presence of feed salinity fluctuation, which is common in both seawater and brackish water desalination. Our analysis can be used to predict the energy savings of the proposed optimal operating policy relative to constant pressure operation. On the basis of a simple model for a reverse osmosis membrane desalination plant and the feed concentration fluctuation profile, we found that the specific energy consumption can be substantially reduced, providing the same permeate flow. Even though in some cases there is only marginal energy savings, it is still worthwhile to adopt the proposed operating strategy given the lack of knowledge of future feed salinity profile. The other benefit of using the proposed approach is that it requires less feedwater, since it has a higher overall water recovery than the time-invariant operating strategy. Higher overall water recovery will be more favorable, especially when the concentrate stream disposal cost is high.

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