Energy Consumption Optimization of RO Membrane Desalination Subject to Feed Salinity Fluctuation [⋆]

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Abstract: 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.

Keywords: specific energy consumption optimization, reverse osmosis, thermodynamic restriction, feed concentration fluctuation

1. INTRODUCTION

Reverse osmosis (RO) membrane water desalination is now well established as a mature water desalination technology. However, 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 (Manth et al. (2003); Busch and Mickols (2004); Wilf and Bartels (2005)). 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 (as reviewed in Zhu et al. (2008)), has been devoted to minimizing the specific energy consumption of water desalination. The introduction of highly permeable membranes in the mid 1990s with low salt passage (Wilf (1997)) has generated considerable interest (Zhu et al. (2008)), 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 (Wilf (1997), Song et al. (2003a); Song and Tay (2006)).

In a previous work (Zhu et al. (2008)), 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. In a recent work (Zhu et al. (2009)), we carried out a systematic study of the energy consumption of two-pass reverse osmosis membrane desalination accounting for key practical issues like membrane salt rejection, presence/absence of energy recovery devices and concentration polarization. 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.

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 feed water salinity will fluctuate both for seawater and brackish water. For example, at one location in the central San Joaquin Valley, the total dissolved solid (TDS) deviated up to 52% from its annual average (McCool (2008)). 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 a given feed salinity fluctuation profile.

2. RO PROCESS

2.1 Description and Modeling

In order to illustrate the approach to energy cost optimization it is instructive to consider a membrane RO

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process without the deployment of an energy recovery device (ERD) as shown schematically in Fig. 1.

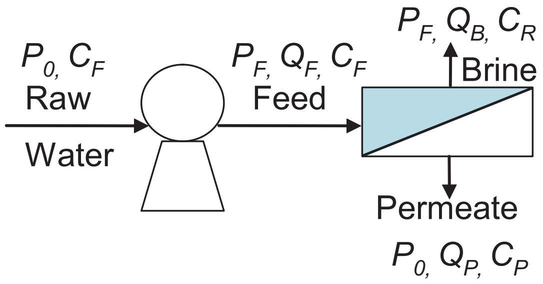

Figure 1. Schematic of simplified RO system.

The energy cost associated with 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 included in the following analysis in a straightforward fashion as presented in Zhu et al. (2008). As a first step, however, in order to simplify the presentation of the approach, the required electrical energy is taken to be equal to the pump work, (i.e., assuming a pump efficiency of 100%). Accordingly, the SEC for the plant shown in Fig. 1 is given by:

$$SEC = \frac{\dot{W}_{pump}}{Q_p} \tag{1}$$

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

$$\dot{W}_{pump} = \Delta P \times Q_f \tag{2}$$

in which

$$\Delta P = P_f - P_0 \tag{3}$$

where P_f is the water 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. In order to simplify the analysis, we initially assume that the impact of the pressure drop (within the RO module) on locating the minimum SEC is negligible; this issue is addressed further in Zhu et al. (2008). It is acknowledged 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.

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

$$Y = \frac{Q_p}{Q_f} \tag{4}$$

and combining Eqs. (1), (2) and (4), the SEC can be rewritten as follows:

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

The permeate flow rate can be approximated by the classical reverse osmosis flux equation Mulder (1997):

$$Q_p = A_m L_p(\Delta P - \sigma\overline{\Delta\pi}) = A_m L_p(\overline{NDP}) \tag{6}$$

where A_m is the active membrane 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 and permeate stream along the membrane module, $(\Delta P - \sigma\overline{\Delta\pi})$ is the average trans-membrane net driving pressure designated as $\overline{NDP}$. We also invoke the typical approximation in Mulder (1997) that the osmotic pressure varies linearly with concentration (i.e., $\pi = f_{os}C$ where f_{os} is the osmotic pressure coefficient and C is the solution salt concentration). For the purpose of the present analysis 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 log-mean average along the membrane (ASTM (2000)) as confirmed in a previous work Zhu et al. (2008),

$$\overline{\Delta\pi} = f_{os}C_f\frac{ln(\frac{1}{1-Y})}{Y} \tag{7}$$

where C_f is the salt concentration of the feed to the membrane module. The osmotic pressures at the entrance and the exit of the membrane module, relative to the permeate stream, are approximate by:

$$\Delta\pi_{entrance} = f_{os}C_f - \pi_p \tag{8}$$

$$\Delta\pi_{exit} = f_{os}C_r - \pi_p \tag{9}$$

where C_r is the salt concentration of the exit brine (i.e., concentrate) 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:

$$C_r = \frac{C_f}{1-Y} \tag{10}$$

Thus, by combining Eqs. (8)–(10), the osmotic pressure difference between the retentate and permeate stream at the exit of the module can be expressed as:

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

where $\pi_0 = f_{os}C_f$ is the feed osmotic pressure. Eq. (11) is a simple relationship that illustrates that the well known inherent difficulty in reaching high recovery in RO desalting is due to the rapid rise in osmotic pressure with increased recovery.

2.2 Thermodynamic Restriction of Cross-flow RO Operation

In the process of RO desalting, an external pressure is applied to overcome the osmotic pressure, and pure water is recovered from the feed solution through the use of a semipermeable membrane. Assuming that the permeate pressure is the same as the raw water pressure, P_0, the applied pressure (ΔP) needed to obtain a water recovery of Y should be no less than the osmotic pressure difference at the exit region (Wilf (1997); Song et al. (2003b)), which is given by Eq. (11). Therefore, in order to ensure permeate productivity along the entire RO module (or stage), the following lower bound is imposed on the applied pressure:

$$\Delta P \geq \Delta\pi_{exit} = \frac{\pi_0}{1-Y} \qquad (12)$$

This is the so-called thermodynamic restriction of cross-flow RO (Song et al. (2003a); Song and Tay (2006)) and referred to as the "thermodynamic restriction" in the current work. The equality on the right-hand-side of Eq. (12) is the condition at the "limit of thermodynamic restriction" in the exit of the membrane module and is attained at the limit of infinite membrane permeability for a finite membrane area. It is particularly important from a practical point of view when a highly-permeable membrane is used for water desalination at low pressures. It is emphasized that the constraint of Eq. (12) arises when one wants to ensure that the entire membrane area is utilized for permeate production.

The specific energy consumption (SEC) for the RO desalting process can be derived by combining Eqs. (1)–(4) and (12), to obtain:

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

where SEC is in pressure units. It is convenient to normalize the SEC, at the limit of thermodynamic restriction (i.e., operation up to the point in which the applied pressure equals the osmotic pressure difference between the concentrate and permeate at the exit of the membrane module), with respect to the feed osmotic pressure such that:

$$SEC_{tr,norm} = \frac{SEC_{tr}}{\pi_0} = \frac{1}{Y(1-Y)} \qquad (14)$$

and this dependence is plotted in Fig. 2 showing that there is a global minimum. In order to obtain the analytical global minimum $SEC_{tr,norm}$, with respect to the water recovery, one can set $(dSEC_{tr,norm})/(dY) = 0$ from which it can be shown that the minimum $SEC_{tr,norm}$ occurs at a fractional recovery of $Y = 0.5$ (or 50%) where $(SEC_{tr,norm})_{min} = 4$ (i.e., four times the feed osmotic pressure). The above condition, i.e., $(SEC_{tr,norm})_{min} = 4$ at $Y = 0.5$, represents the global minimum SEC (represented by 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 equivalent to $2\pi_0$ (i.e., double that the feed osmotic pressure).

2.3 Feed Salinity Fluctuation

For the purpose of illustration of the proposed optimal operation approach, we consider a simple feed salinity fluctuation profile shown in Fig. 3. Specifically, we consider a 20-hour time window in which the feed osmotic pressure in the first 10 hours is 500 *psi*, and it is then reduced to 200 *psi* for the remaining 10 hours. 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 difference 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.

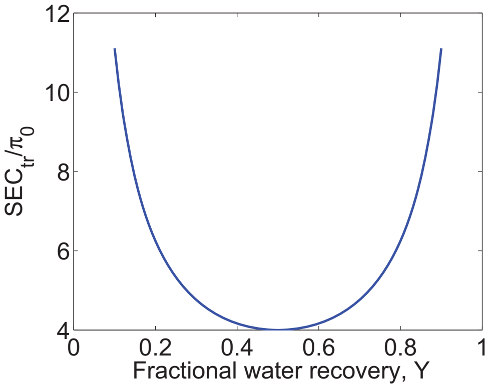

Figure 2. Variation of the normalized SEC with water recovery for a single-stage RO at the limit of thermodynamic restriction.

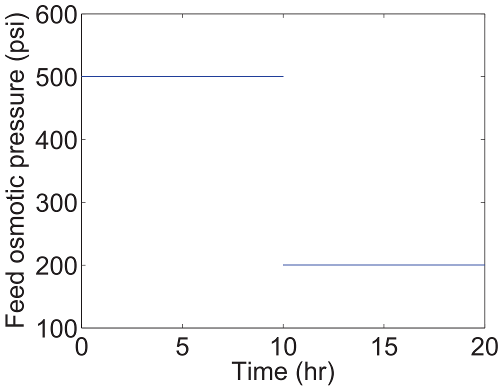

Figure 3. Feed osmotic pressure profile within 20 hours.

3. RESULTS

In the presence of the feed salinity fluctuation of Fig. 3,the following two operating strategies may be considered.

- Operating strategy A: The transmembrane pressure is maintained at double that of the average (over the whole 20-hour time window) feed osmotic pressure, i.e. 700 *psi*.
- Operating strategy B: 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 strategy A and operating strategy B, the permeate flow rates in the first 10 hrs and the last 10 hrs have to be the same. The specific energy consumption (SEC) comparison of operating strategy A and operating strategy B will be first done for an RO process without an energy recovery device (see Fig. 1) and the case of an RO process with an energy recovery device (see Fig. 4) will be then addressed. In Fig. 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:

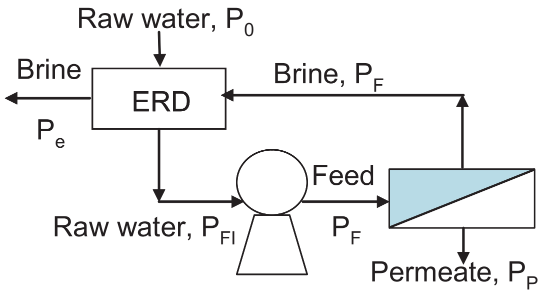

Figure 4. Simplified RO system with an energy recovery device (ERD).

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

where η is the efficiency of the energy recovery device.

3.1 RO Process without ERD

Operating strategy A. At the limit of thermodynamic restriction, according to Eq. 11, the water recovery in the first 10 hrs, $Y_1 = 1 - \frac{500}{700} = \frac{2}{7}$ and the water recovery in the last 10 hrs, $Y_2 = 1 - \frac{200}{700} = \frac{5}{7}$. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs has to be 2.5 times that of the feed flow rate in the last 10 hrs ($Q_{f,2}$). Therefore, the permeate flow and energy consumption in the first and last 10 hrs are:

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

$$W_1 = \Delta P_1 \times V_{f,1} = 17500\, Q_{f,2} \cdot psi \cdot hr \tag{17}$$

$$V_{p,2} = Q_{f,2} \times \frac{5}{7} \times 10\,hr = \frac{50}{7} Q_{f,2} \times hr \tag{18}$$

$$W_2 = \Delta P_2 \times V_{p,2} = 7000\, Q_{f,2} \cdot psi \cdot hr \tag{19}$$

Therefore, the average SEC is:

$$\overline{SEC}^A = \frac{W_1 + W_2}{V_{p,1} + V_{p,2}} = 1715\, psi \tag{20}$$

Operating strategy B. The water recovery in the last 10 hrs is the same as the water recovery in the first 10 hrs (both at 50%). In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs should be the same as the feed flow rate in the last 10 hrs ($Q'_{f,2}$). The permeate flow and energy consumption in the first and last 10 hrs are:

$$V'_{p,1} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \tag{21}$$

$$W'_1 = \Delta P'_1 \times V'_{f,1} = 10000\, Q'_{f,2} \cdot psi \cdot hr \tag{22}$$

$$V'_{p,2} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \tag{23}$$

$$W'_2 = \Delta P'_2 \times V'_{f,2} = 4000\, Q'_{f,2} \cdot psi \cdot hr \tag{24}$$

Therefore, the average SEC is:

$$\overline{SEC}^B = \frac{W'_1 + W'_2}{V'_{p,1} + V'_{p,2}} = 1400\, psi \tag{25}$$

From Eq. 20 and Eq. 25, we see that the operating strategy A has a higher SEC than operating strategy B about 22.5% ($\frac{1715-1400}{1400} = 22.5\%$). Furthermore, in order to equate the total permeate volume in operating strategy A and operating strategy B, $Q'_{f,2} = \frac{10}{7} Q_{f,2}$. Thus, the total feed volume in operating strategy B is $2 \times \frac{10}{7} Q_{f,2} = \frac{20}{7} Q_{f,2}$, 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 feed water, and thus, it has a lower overall water recovery.

3.2 RO Process with ERD: Efficiency is 100%

Operating strategy A. The water recovery in the last 10 hrs is 2.5 times that of the water recovery in the first 10 hrs. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs has to be 2.5 times that of the feed flow rate in the last 10 hrs ($Q_{f,2}$). Therefore, the permeate flow and energy consumption in the first and last 10 hrs are:

$$V_{p,1} = 2.5 \times Q_{f,2} \times \frac{2}{7} \times 10\,hr = \frac{50}{7} Q_{f,2} \times hr \tag{26}$$

$$W_1^{ERD} = \Delta P_1 \times V_{p,1} = 5000\, Q_{f,2} \cdot psi \cdot hr \tag{27}$$

$$V_{p,2} = Q_{f,2} \times \frac{5}{7} \times 10\,hr = \frac{50}{7} Q_{f,2} \times hr \tag{28}$$

$$W_2^{ERD} = \Delta P_2 \times V_{p,2} = 5000\, Q_{f,2} \cdot psi \cdot hr \tag{29}$$

Therefore, the average SEC is:

$$\overline{SEC}^A = \frac{W_1^{ERD} + W_2^{ERD}}{V_{p,1} + V_{p,2}} = 700\, psi \tag{30}$$

Operating strategy B. The water recovery in the last 10 hrs is the same as the water recovery in the first 10 hrs. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs has to be the same as that the feed flow rate in the last 10 hrs ($Q_{f,2}$’). The permeate flow and energy consumption in the first and last 10 hrs are:

$$V'_{p,1} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \tag{31}$$

$$W_1^{'ERD} = \Delta P'_1 \times V'_{p,1} = 5000\, Q'_{f,2} \cdot psi \cdot hr \tag{32}$$

$$V'_{p,2} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \tag{33}$$

$$W_2^{'ERD} = \Delta P_2 \times V'_{p,2} = 2000\, Q_{f,2} \cdot psi \cdot hr \tag{34}$$

Therefore, the average SEC is:

$$\overline{SEC}^B = \frac{W_1 + W_2}{V'_{p,1} + V'_{p,2}} = 700\, psi \tag{35}$$

From Eq. 30 and Eq. 35, we see that in the presence of an ERD with a 100% efficiency, operating strategy A and operating strategy B have the same SEC. Furthermore, in order to equate the total permeate volume in operating strategy A and operating strategy B, $Q'_{f,2} = \frac{10}{7} Q_{f,2}$. Thus, the total feed volume in operating strategy B is $2 \times \frac{10}{7} Q_{f,2} = \frac{20}{7} Q_{f,2}$, 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 feed water, and thus, it has a lower overall water recovery.

3.3 ERD Efficiency between 0 and 1

Operating strategy A. The water recovery in the last 10 hrs is 2.5 times that of the water recovery in the first 10 hrs. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs has to be 2.5 times the feed flow rate in the last 10 hrs ($Q_{f,2}$). Therefore, the permeate flow and energy consumption in the first and last 10 hrs are:

$$V_{p,1} = 2.5 \times Q_{f,2} \times \frac{2}{7} \times 10\,hr = \frac{50}{7} Q_{f,2} \times hr \tag{36}$$

$$W_1^{ERD} = \Delta P_1 \times (V_{f,1} - \eta(V_{f,1} - V_{p,1})) \tag{37}$$

$$V_{p,2} = Q_{f,2} \times \frac{5}{7} \times 10\,hr = \frac{50}{7} Q_{f,2} \times hr \tag{38}$$

$$W_2^{ERD} = \Delta P_2 \times (V_{f,2} - \eta(V_{f,2} - V_{p,2})) \tag{39}$$

Therefore, the average SEC is:

$$\overline{SEC}_{ERD}^{A} = \frac{W_1^{ERD} + W_2^{ERD}}{V_{p,1} + V_{p,2}} = (1715 - 1015\eta)\,psi \tag{40}$$

Operating strategy B. The water recovery in the last 10 hrs is the same as the water recovery in the first 10 hrs. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs has to be the same as that the feed flow rate in the last 10 hrs ($Q_{f,2}$'). Therefore, the permeate flow and energy consumption in the first and last 10 hrs are:

$$V'_{p,1} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \tag{41}$$

$$W_1^{'ERD} = \Delta P'_1 \times (V'_{f,1} - \eta(V'_{f,1} - V'_{p,1})) \tag{42}$$

$$V'_{p,2} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \tag{43}$$

$$W_2^{'ERD} = \Delta P_2 \times (V'_{f,2} - \eta(V'_{f,2} - V'_{p,2})) \tag{44}$$

Therefore, the average SEC is:

$$\overline{SEC}_{ERD}^{B} = \frac{W_1^{'ERD} + W_2^{'ERD}}{V'_{p,1} + V'_{p,2}} = 700(2 - \eta)\,psi \tag{45}$$

The SEC difference between operating strategy A and operating strategy 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,

$$\frac{\overline{SEC}_{ERD}^{A} - \overline{SEC}_{ERD}^{B}}{\overline{SEC}_{ERD}^{B}} = \frac{315}{700} \frac{(1 - \eta)}{[1 + (1 - \eta)]} \tag{46}$$

which is plotted in Fig. 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, $Q'_{f,2} = \frac{10}{7} Q_{f,2}$. Thus, the total feed volume in operating strategy B is $2 \times \frac{10}{7} Q_{f,2} = \frac{20}{7} Q_{f,2}$, 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 feed water, and thus, it has a lower overall water recovery.

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

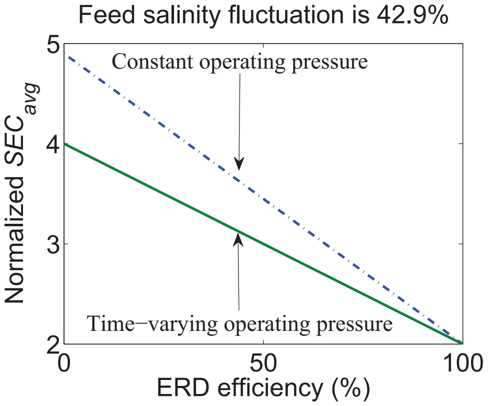

Figure 5. Percentage SEC increase when feed pressure is not adjusted. vs. ERD efficiency.

4. DISCUSSION

4.1 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 Section 3.3. Assuming the average osmotic pressure is π_0, the osmotic pressure in the first 10 hrs is $(1 + \sigma)\pi_0$ $(0 < \sigma < 1)$, and the osmotic pressure in the last 10 hrs is $(1 - \sigma)\pi_0$. Therefore, the feed fractional fluctuation is σ. Similarly, the following two operating strategies may be considered.

- Operating strategy A: The transmembrane pressure is maintained at double that of the average feed osmotic pressure, i.e. $2\pi_0$.
- Operating strategy B: The transmembrane pressure is maintained at double that of the instantaneous feed osmotic pressure.

Operating strategy A. The water recovery in the last 10 hrs, $Y_1 = 1 - \frac{(1+\sigma)\pi_0}{2\pi_0} = \frac{1-\sigma}{2}$, and in the last 10 hrs, $Y_2 = 1 - \frac{(1-\sigma)\pi_0}{2\pi_0} = \frac{1+\sigma}{2}$. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs has to be $\frac{1+\sigma}{1-\sigma}$ times that of the feed flow rate in the last 10 hrs ($Q_{f,2}$). The permeate flow and energy consumption in the first and last 10 hrs are:

$$V_{p,1} = \frac{1+\sigma}{1-\sigma} \cdot Q_{f,2} \cdot \frac{1-\sigma}{2} \cdot 10\,hr = 5(1+\sigma) \cdot Q_{f,2} \cdot hr \tag{47}$$

$$W_1^{ERD} = \Delta P_1 \times (V_{f,1} - \eta(V_{f,1} - V_{p,1})) \tag{48}$$

$$V_{p,2} = Q_{f,2} \times \frac{1+\sigma}{2} \times 10\,hr = 5(1+\sigma) \cdot Q_{f,2} \cdot hr \tag{49}$$

$$W_2^{ERD} = \Delta P_2 \times (V_{f,2} - \eta(V_{f,2} - V_{p,2})) \tag{50}$$

Therefore, the average SEC is:

$$\overline{SEC}_{ERD}^{A} = \frac{W_1^{ERD} + W_2^{ERD}}{V_{p,1} + V_{p,2}} = 2\pi_0\left[\frac{(1-\eta)}{1-\sigma} + \frac{(1+\eta\sigma)}{1+\sigma}\right] \tag{51}$$

Operating strategy B. The water recovery in the last 10 hrs is the same as the water recovery in the first 10 hrs. In order to produce the same amount of permeate volume, the feed flow rate in the first 10 hrs has to be the same as the feed flow rate in the last 10 hrs ($Q_{f,2}$'). The permeate flow and energy consumption in the first and last 10 hrs are:

$$V'_{p,1} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \qquad (52)$$

$$W_1'^{ERD} = \Delta P'_1 \times (V'_{f,1} - \eta(V'_{f,1} - V'_{p,1})) \qquad (53)$$

$$V'_{p,2} = Q'_{f,2} \times \frac{1}{2} \times 10\,hr = 5Q'_{f,2} \times hr \qquad (54)$$

$$W_2'^{ERD} = \Delta P_2 \times (V'_{f,2} - \eta(V'_{f,2} - V'_{p,2})) \qquad (55)$$

Therefore, the average SEC is:

$$\overline{SEC}^B_{ERD} = \frac{W_1'^{ERD} + W_2'^{ERD}}{V'_{p,1} + V'_{p,2}} = 2(2-\eta) \cdot \pi_0 \qquad (56)$$

The SEC difference of operating strategy A from operating strategy B is $(2[\frac{(1-\eta)}{1-\sigma} + \frac{(1+\eta\sigma)}{1+\sigma}] - 2(2-\eta)) \cdot \pi_0$. 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:

$$\frac{\overline{SEC}^A_{ERD} - \overline{SEC}^B_{ERD}}{\overline{SEC}^B_{ERD}} = \frac{[\frac{(1-\eta)}{1-\sigma} + \frac{(1+\eta\sigma)}{1+\sigma}]}{(2-\eta)} - 1 \qquad (57)$$

which is plotted in Fig. 6 when the efficiency of the ERD is set to be 90%. Fig. 6 shows that as feed salinity fluctuation percentage increases, time-invariant operation increases SEC more remarkably. Even in some cases there is only marginal energy savings, it is still worthwhile to adopt the proposed operating strategy accompanied by the control algorithms developed at UCLA M3 group regarding reverse osmosis water desalination system (McFall et al. (2008); Bartman et al. (2008)) since we will not be able to know what the future salinity profile would exactly be. Furthermore, in order to equate the total permeate volume in operating strategy A and operating strategy B, $Q'_{f,2} = (1+\sigma)Q_{f,2}$. Thus, the total feed volume in operating strategy B is $2(1+\sigma) \cdot Q_{f,2}$, while the total feed volume in operating strategy A is $(\frac{1+\sigma}{1-\sigma} + 1)Q_{f,2} = (1 + \frac{2\sigma}{1-\sigma} + 1)Q_{f,2} > (1 + 2\sigma + 1)Q_{f,2}$. Therefore, in order to get the same amount of permeate volume, operating strategy A requires a higher amount of feed water, and thus, it has a lower overall water recovery.

5. CONCLUSION

Based on a model for a reverse osmosis membrane desalination plant and the feed concentration fluctuation (which is common in both seawater and brackish water desalination) profile, the proposed approach requires less amount of feed water and decreases specific energy consumption by as much as 22%, providing the same permeate flow. Experimental results confirming the proposed operating policy will be presented at the conference.

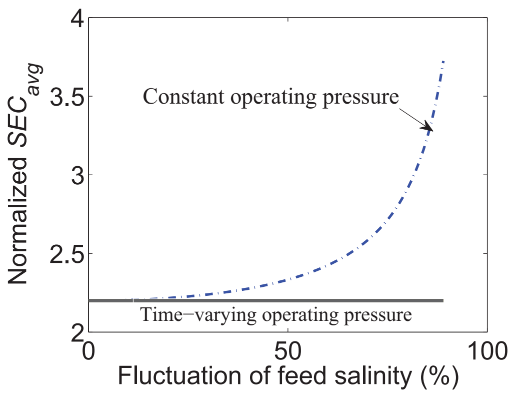

Figure 6. Percentage SEC increase without adjusting the operating pressure vs. feed concentration fluctuation percentage.

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