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Reducing specific energy consumption of seawater desalination: Staged RO or RO-PRO?

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ABSTRACT

Specific energy consumptions (SECs) in seawater RO desalination employing staged RO and RO-PRO with energy recovery devices are investigated using systematic mathematical methods. The SECs in both configurations are minimized by solving a constrained nonlinear optimization model which optimally selects operating conditions and allocates membrane area between different membrane units. It is shown that both staged RO and RO-PRO are noticeably advantageous over single-stage RO only if a dimensionless parameter $\gamma_{total} = A_{total}L_p\pi_0/Q_0$ is sufficiently large. The RO-PRO outperforms staged RO when internal concentration polarization is not severe, water recovery is low (e.g., 30%) and/or membrane area is abundant (e.g., $\gamma_{total} \geq 1.6$). The staged RO is likely to excel at a high water recovery (e.g., 60%) even though the high-salinity brine enhances the driving force for osmotic energy recovery in the RO-PRO. Both configurations have comparable SECs based on water recoveries of 40% and 50% and a γ_{total} of 0.8, a representative value in industrial seawater RO plants.

1. Introduction

Specific energy consumption (SEC) is a very important topic in seawater reverse osmosis (SWRO) desalination because pump energy consumption accounts for a significant portion of the total cost in an industrial RO plant [1,2]. The invention of energy recovery devices (ERDs) has drastically reduced the SEC in industrial seawater plants by recovering hydraulic energy in the high-pressure RO brine [3,4]. Recently, there has been lots of discussions in literature on pressure retarded osmosis (PRO) that may be used to partially recover the osmotic energy in the RO brine for power generation [5–9] or subsidize pump energy consumption used by the RO in an integrated RO-PRO process [10–16]. These efforts are particularly encouraged by the development of high-performance flat-sheet and hollow fiber polymeric membranes with desired structural, mechanical and permeative properties that are suitable for PRO applications (see, e.g., Refs. [17–19]). Another energy-efficient SWRO desalination is the two-stage RO with interstage booster pump which further recovers water from the first-stage brine [20–25]. While both configurations have reduced SECs, it is noted that they may involve additional membrane cost if the second unit (either RO or PRO) is simply added to the original single-stage RO system [26,27]. In fact, if the same extra amount of membrane is added to a single-stage RO, it reduces the SEC too [21,22]. To put the comparison on an equal footing, the total membrane area should be fixed.

This work aims to investigate SECs in three different RO configurations: single stage RO, two-stage RO (RO-RO) and integrated RO-PRO, all with ERDs, following a systematic computational approach. An optimization model is formulated and solved with specified values of water recovery and total membrane area to minimize the SEC in each configuration so that the comparison is made based on their best conditions. The optimization allows the membrane area to be optimally allocated between two membrane units in both RO-RO-ERD and RO-PRO-ERD. It may also reveal the best operating parameters and the relative magnitude of energy consumption/recovery of each individual unit in the whole process.

2. Mathematical model

As shown in Fig. 1, seawater with flow rate Q_0, osmotic pressure π_0 and hydraulic pressure P is sent to a single-stage RO or PRO unit. Depending on the relative magnitude of transmembrane osmotic and hydraulic pressures, pure water may flow across the semi-permeable

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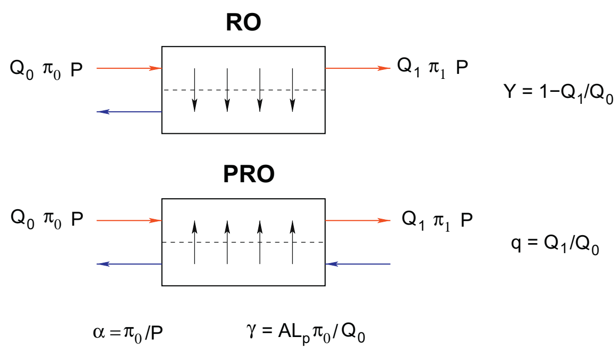

Fig. 1. Schematics of a single-stage RO and a single-stage PRO.

membrane in either direction, resulting in an outlet stream of a different flow rate Q_1 and a different osmotic pressure π_1. With the following simplifications: (i) negligible pressure drop along membrane feed channel, (ii) negligible osmotic pressure in permeate stream in RO or freshwater feed in PRO, and (iii) negligible effect of concentration polarization, it was derived by the author [6,21] that RO and PRO share the same characteristic equation below:

$$\gamma = \alpha\left[1 - q + \alpha \ln \frac{\alpha - 1}{\alpha - q}\right] \tag{1}$$

where dimensionless parameters $\gamma = AL_p\pi_0/Q_0$, $\alpha = \pi_0/P$, and $q = Q_1/Q_0$. Here,A and L_p represent area and hydraulic permeability of the membrane, respectively. Eq. (1) reveals the coupled behavior among design parameter γ, operating parameter α, and performance parameter q in both membrane processes. q and α are both > 1 in PRO and < 1 in RO. In RO, the water recovery $Y = 1 - q$.

The effect of external concentration polarization (ECP) in RO or PRO is not considered in this work. It arises from the difference in solute concentrations in the bulk and on the surface and may be mitigated by optimizing spacer design and/or flow conditions [28]. The internal concentration polarization (ICP) is a unique phenomenon in PRO which may significantly affect water flux while it does not exist in RO [29]. It occurs in the porous supporting layer and cannot be easily reduced by manipulating flow. Moreover, the effect of reverse salt leakage may also adversely affect water flux. Since these detrimental effects are not taken into account in Eq. (1), an efficiency factor η_{PRO} ($\eta_{PRO} \leq 1$) is introduced in this work so that the actual amount of water across the PRO membrane is $\eta_{PRO}(q - 1)Q_0$. This simplification groups the effects of various membrane parameters in a detailed PRO model [9]. When $\eta_{PRO} = 100\%$, it means that the detrimental effects of ICP and reverse salt flux are completely eliminated.

Because the RO and PRO units shown in Fig. 1 are the basic building blocks in a complex membrane-based desalination process, the development of Eq. (1) greatly facilitates system-level analysis and optimization. In the following paragraphs, the optimization models for both staged RO and RO-PRO with ERDs will be presented.

A RO-RO-ERD process is shown in Fig. 2. The potential energy in the brine is used to partially pressurize the feed. If both pumps have the same efficiency, the SEC normalized by the feed osmotic pressure is:

$$\begin{aligned} NSEC &= \frac{Q_0[P_1 - \eta_{ERD}(1 - Y_1)(1 - Y_2)P_2]/\eta_{pump} + Q_1(P_2 - P_1)/\eta_{pump}}{Q_0 Y_{total}\pi_0} \\ &= \frac{1}{\eta_{pump} Y_{total} Q_0 \pi_0}[Q_0 P_1 - \eta_{ERD} Q_1 P_2(1 - Y_2) + Q_1 P_2 \\ &\quad - Q_0(1 - Y_1)P_1] \\ &= \frac{1}{\eta_{pump} Y_{total}}\left[\frac{1}{\alpha_1} - \frac{\eta_{ERD}(1 - Y_2)}{\alpha_2} + \frac{1}{\alpha_2} - \frac{1 - Y_1}{\alpha_1}\right] \\ &= \frac{1}{\eta_{pump} Y_{total}}\left[\frac{Y_1}{\alpha_1} + \frac{1}{\alpha_2} - \frac{\eta_{ERD}(1 - Y_2)}{\alpha_2}\right] \end{aligned} \tag{2}$$

where subscripts 1 and 2 in P, α and Y represent their values in the 1st and 2nd stage, respectively, η_{ERD} is the ERD efficiency, η_{pump} is the pump efficiency, and Y_{total} is the total water recovery: $Y_{total} = 1 - (1 - Y_1)(1 - Y_2)$. Note that the pressure before the feed pump is $\eta_{ERD}(1 - Y_1)(1 - Y_2)P_2$, $Q_j\pi_j = Q_0\pi_0$, $\alpha_1 = \pi_0/P_1$, $\alpha_2 = \pi_1/P_2$, and $\pi_1 = \pi_0/(1 - Y_1)$. For an N-stage RO with interstage booster pumps, it may be derived that:

$$NSEC = \frac{1}{\eta_{pump} Y_{total}}\left[\sum_{j=1}^{N-1} \frac{Y_j}{\alpha_j} + \frac{1 - \eta_{ERD}(1 - Y_N)}{\alpha_N}\right] \tag{3}$$

where $Y_{total} = 1 - \prod_{j=1}^{N}(1 - Y_j)$.

To minimize the NSEC of the whole desalination process subject to a specified total membrane area (A_{total}) and a total water recovery (Y_{total}), the design parameter γ_j and operating parameter α_j are varied, which optimally allocate the stage-level recoveries Y_j (because of the coupled relationship among γ, α and Y shown in Eq. (1)). As a result, the optimization problem is formulated as follows:

$$\begin{aligned} \min_{\alpha_j, Y_j, \gamma_j} NSEC &= \frac{1}{\eta_{pump} Y_{total}}\left[\frac{Y_1}{\alpha_1} + \frac{1}{\alpha_2} - \frac{\eta_{ERD}(1 - Y_2)}{\alpha_2}\right] \\ s.\ t. & \\ 0 &= \gamma_j - \alpha_j\left[Y_j + \alpha_j \ln \frac{1 - \alpha_j}{1 - Y_j - \alpha_j}\right], \quad j = 1, 2 \\ 0 &= \gamma_{total} - [\gamma_1 + \gamma_2(1 - Y_1)^2] \\ 0 &= [1 - (1 - Y_1)(1 - Y_2)] - Y_{total} \\ 0 &\leq \gamma_j, \quad j = 1, 2 \\ 0 &\leq \alpha_j, \quad j = 1, 2 \\ 0 &\leq 1 - \alpha_j, \quad j = 1, 2 \\ 0 &\leq Y_j, \quad j = 1, 2 \\ 0 &\leq 1 - Y_j, \quad j = 1, 2 \\ 0 &\leq \alpha_1/(1 - Y_1) - \alpha_2 \end{aligned} \tag{4}$$

where $\gamma_{total} = A_{total}L_p\pi_0/Q_0$ is the total dimensionless area of

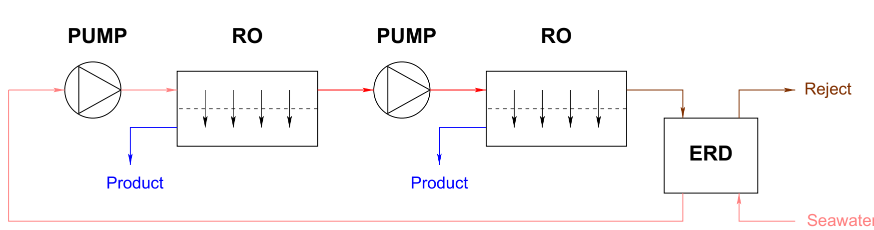

Fig. 2. A two-stage RO process with interstage booster bump and ERD.