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Reducing specific energy consumption in Reverse Osmosis (RO) water desalination: An analysis from first principles

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ABSTRACT

The previously derived characteristic equation of RO in Li, 2010 [8] is used to describe single- or multi-stage ROs with/without an energy recovery device (ERD). Analysis is made at both the theoretical limit (with analytical solutions provided if possible) and practical conditions (using constrained nonlinear optimization). It is shown that reducing specific energy consumption (SEC) normalized by feed osmotic pressure, or NSEC in ROs can be pursued using one or more of the following three independent methods: (1) increasing a dimensionless group $\gamma = A_{total}L_p\Delta\pi_0/Q_f$, (2) increasing number of stages, and (3) using an ERD. When γ increases, the feed rate is adversely affected and the NSEC reduces but flattens out eventually. Using more stages not only reduces NSEC but also improves water recovery. However, The NSEC flattens out when the number of stages increases and ROs with more than five stages are not recommended. Close to the thermodynamic limit where γ is sufficiently large, the NSEC of ROs up to five stages approaches 4, 3.60, 3.45, 3.38 and 3.33 respectively. The ERD can significantly reduce the NSEC, theoretically to 1, while the corresponding recovery approaches zero. The NSEC becomes larger when the required water recovery increases. It is found that a combination of all three methods can significantly reduce the NSEC while maintaining a high recovery and a reasonable feed or permeate rate. An NSEC around 2.5–2.8 with an 80% water recovery may be possible using 3–5 RO stages and an ERD of 90% efficiency operated at a γ about 3–5 (or $Q_f = 0.2$–$0.3\ A_{total}L_p\Delta\pi_0$).

1. Introduction

Reverse osmosis (RO) membrane separation is an important desalination technology to produce drinking water. Large-scale production from brackish water and seawater is possible with the current membrane technology. Because the applied pressure requirements reach up to 1000–1200 psi for seawater desalting and 100–600 psi for brackish water desalting, the energy consumption of pumps to drive the membrane module accounts for a major portion of the total cost of water desalination [3,10,31].Significant research efforts, dating back to early development of RO, have been made to reduce specific energy consumption (SEC), or the energy cost per volume of produced permeate, in order to make this technology more affordable to people [32]. Interested readers can refer to [20] for a critical review and perspective of energy issues in desalination processes.

The approaches to reduce SEC in RO processes can be divided into the following categories: (i) using highly permeable membrane material [21,23,35]. Apparently, a membrane with a high permeability allows the water to easily pass through the membrane, which saves energy to pump the feed. (ii) Using an energy recovery device (ERD) [1,6,10,13,18,27]. The ERD is to use the high pressure brine to pass through a rotary turbine that drives an auxiliary pump pressurizing the feed, thus reducing the duty of the primary pump [1,5,16]. (iii) Using intermediate chemical demineralization (ICD) at high recoveries [4]. The ICD step removes mineral scale precursors from a primary RO concentrate stream and allows a further recovery of water in the secondary RO. (iv) Using renewable energy resources to subsidize the electricity energy demand [7,26], and (v) optimizing RO configurations and operating conditions using mathematical models (e.g., [11,15]). The development and implementation of efficient methods have led to a reduction in energy consumption of RO desalination as evidenced by many industrial examples [17,19].

Model-based analysis plays an important role in reducing SEC in the RO processes. It has been shown that operating the RO approaching the thermodynamic limit (where the applied pressure is slightly above the concentrate osmotic pressure) significantly reduces the SEC [21–23,25,30]. Using simplified or first-principles based models, it is also possible to account for capital cost, feed intake and pretreatment, and cleaning and maintenance cost in the optimization framework [9,12,28]. Recent research efforts have been focused on a formal mathematical approach to provide a clear evaluation of minimization of the production cost by studying the effect of applied pressure, water recovery, pump efficiency, membrane cost, ERD, and brine disposal cost [32–35].

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This work aims to provide a comprehensive analysis of single- and multi-stage RO with/without ERD from first-principles, which would guide the design and operation of RO at a lower SEC. Models based on the previously developed characteristic equation of RO are developed in a dimensionless form and relationships between RO configuration, feed conditions, membrane performance, and operating conditions are unambiguously revealed. Optimal results at both the theoretical thermodynamic limits and practical conditions are presented. Suggestions on RO configuration and operating conditions are made to achieve a SEC lower than 3 times of the feed osmotic pressure with a high recovery.

2. Dimensionless characteristic equation of a RO module

The dimensionless characteristic equation of a RO module was derived in the author's previous work [8]. A brief summary is given below to provide sufficient background information for the analysis in the next sections. Consider a general RO module shown in Fig. 1, the mass balances of water and salt in a control volume (represented by dA) can be written as follows [8]:

$$\begin{aligned} -dQ &= dA\cdot L_p\cdot(\Delta P-\Delta\pi) \\ Q/Q_f &= \Delta\pi_0/\Delta\pi \end{aligned} \tag{1}$$

where $-dQ$ is the flow rate of water across the membrane of area dA, L_p is the membrane hydraulic permeability, ΔP and $\Delta\pi$ are the differences in the system pressure and osmotic pressure across the membrane, respectively. Q is the flow rate in the retentate and Q_f is the feed flow rate. $\Delta\pi_0$ is $\Delta\pi$ at the entrance of the membrane channel. Eq. (1) is based on the assumptions of (1) negligible salinity in the permeate, and (2) linear relationship between osmotic pressure and salt concentration [14]. Moreover, the effects of concentration polarization and fouling are not included here.

With the assumption of negligible pressure drop in the retentate, an integration of Eq. (1) from the entrance to the end of the membrane channel yields a dimensionless equation as follows [8]:

$$\gamma = \alpha\left[Y + \alpha\, ln\frac{1-\alpha}{1-Y-\alpha}\right] \tag{2}$$

where $\alpha=\Delta\pi_0/\Delta P$, $Y=Q_p/Q_f$, and $\gamma=AL_p\Delta\pi_0/Q_f$. Q_p is the permeate flow rate. α^{-1} is the dimensionless applied pressure, Y is the dimensionless fractional recovery, and γ might be considered as the dimensionless membrane capacity (or, alternatively, the inverse of the dimensionless feed rate). $\beta^{-1}=Y/\gamma=Q_p/AL_p\Delta\pi_0$ is another dimensionless variable that may be considered as the dimensionless average flux or average driving force. α and β are defined in such a way for a better presentation of results in equations and/or figures.

Eq. (2) reveals the coupled behavior between membrane property (area and permeability), feed conditions (feed rate and osmotic pressure) and operating conditions (applied pressure and permeate rate) and therefore may be referred to as the characteristic equation of a RO module.

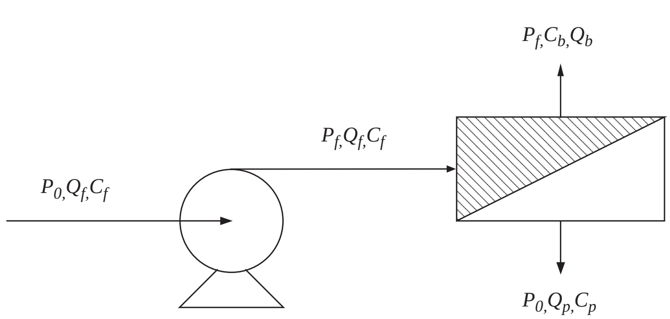

Fig. 1. Schematic of a reverse osmosis water desalination process.

As mentioned earlier, the energy cost in the context of RO water desalination process is typically described using SEC, or the electrical energy demand per cubic meter of permeate [32–35]. For a single-stage RO, it is readily derived that:

$$SEC_m = \eta_{pump}SEC = \frac{Q_f\Delta P}{Q_p} \tag{3}$$

where SEC_m is the modified SEC to reflect the pump efficiency [29]. The pump efficiency is considered to be constant for simplicity in this work. The normalized SEC (or NSEC) is defined as $SEC_m/\Delta\pi_0$ in this work, which is another dimensionless number.

In the operation of RO, rejection of water as brine is necessary because the required applied pressure increases drastically when the retentate becomes more and more concentrated. Fig. 2 shows a diagram of the dimensionless driving force along the RO channel [8]. Note that the driving force at the exit of the membrane must be positive to guarantee a nonzero flux, which implies that $1-Y-\alpha>0$, or $\Delta P>\Delta\pi_0/(1-Y)$. At the theoretical thermodynamic limit, $1-Y-\alpha=0$ or $\Delta P=\Delta\pi_0/(1-Y)$.

3. NSEC in single or multi-stage ROs without ERD

Based on the dimensionless characteristic equation introduced in the previous section, it is convenient to describe a single or multi-stage RO module and to formulate an optimization problem to minimize the NSEC. A list of key parameters in single or multi-stage RO are provided in Table 1.

The minimization of NSEC in a single or multi-stage RO module is formulated as follows:

$$\begin{aligned} \min_{\alpha_j,Y_j}\frac{SEC_m}{\Delta\pi_0} &= \frac{\sum_{j=1}^{N-1}\frac{Y_j}{\alpha_j}+\frac{1}{\alpha_N}}{1-\prod_{j=1}^{N}\left(1-Y_j\right)} \\ s.t. & \\ 0 &= \gamma_j-\alpha\left[Y_j+\alpha_j\, ln\frac{1-\alpha_j}{1-Y_j-\alpha_j}\right](j=1,\dots,N) \\ 0 &= \gamma_{total}-\left[\gamma_1+\sum_{j=2}^{N-1}\gamma_j\prod_{k=1}^{j-1}(1-Y_k)^2\right] \\ 0 &= \gamma_j-\gamma_{j+1}\left(1-Y_j\right)^2(j=1,\dots,N-1) \\ 0 &\le \alpha_j(j=1,\dots,N) \\ 0 &\le 1-\alpha_j(j=1,\dots,N) \\ 0 &\le \alpha_{j+1}-\alpha_j/\left(1-Y_j\right)(j=1,\dots,N-1) \\ 0 &\le \left[1-\prod_{j=1}^{N}\left(1-Y_j\right)\right]-Y_{min} \end{aligned} \tag{4}$$

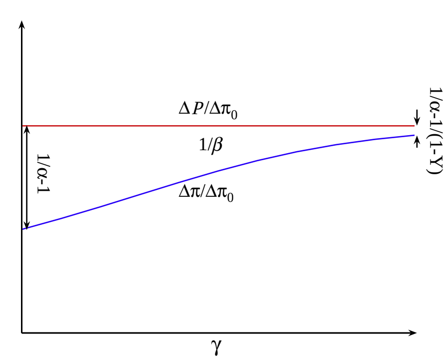

Fig. 2. Schematic of normalized dimensionless driving force (or dimensionless flux) along the membrane channel.