Rapid communication

On RO membrane and energy costs and associated incentives for future enhancements of membrane permeability

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ABSTRACT

An analysis of the impact of increasing RO membrane permeability on the reduction in water desalination cost was carried out for RO desalting operated up to the limit imposed by the thermodynamic restriction. The premise of the present assessment is that, the current generation of high permeability RO membranes makes it feasible to carry out RO desalination up to the thermodynamic restriction limit. In this limit, the ratio of membrane to energy cost can be expressed as a function of the water recovery level and a dimensionless cost parameter that accounts for the purchase cost of electrical energy and membrane area, as well as feed water salinity, salt rejection requirement and membrane permeability. The present analysis suggests that, given the present day electrical energy and membrane prices, the benefit of developing membranes of even greater permeability is primarily at low water recoveries for inland brackish water desalting. At low water recoveries, however, there is typically an added cost associated with brine management for inland water desalting. In RO desalting of seawater, on the other hand, the specific cost (i.e., per permeate produced) of energy is much higher relative to the membrane cost, and there is lower economic incentive for developing higher permeability membranes if the objective is to lower the cost of seawater desalination. The analysis suggests that further significant improvement in RO membrane permeability is less likely to be the primary driver for a major reduction in the cost of seawater desalination. However, it is expected that significant reduction in RO water production cost can arise from a variety of other process improvements including, but not limited to, development of improved fouling-resistant membranes, more effective and lower feed pretreatment and brine management costs, optimization of process configuration and control schemes, as well as utilization of low cost renewable energy sources.

1. Introduction

Reverse osmosis (RO) membrane desalination is now a mature process for the production of potable water from seawater and inland brackish water. Current generation RO membranes are of sufficiently high permeability to enable desalting such that the operational feed pressures can now approach the thermodynamic osmotic pressure (Fig. 1) of the produced concentrate (i.e., brine) stream [1,2]. In other words, it is technically feasible to operate the RO process up to the limit of the thermodynamic restriction [3]. It is noted that with low permeability membranes, the applied feed pressure had to be set at a significantly higher level relative to the osmotic pressure in order to achieve a reasonable permeate flux. In contrast, current high permeability membranes enable equivalent or higher permeate productivity at lower pressures, but with the achievable product water recovery now being limited by the concentrate osmotic pressure.

For example, for typical low pressure RO membranes with permeability in the range of $L_p = 0.5$–0.8×10^{-10} m^3/m^2 s Pa (pressure operability in the range of 2067–4134 kPa or 300–600 psi), desalting of brackish water of salinity in the range of 1000–2000 mg/L total dissolved solids (TDS) to water recovery level in the range of 50–75% would result in a concentrate stream having osmotic pressure of 1034–4134 kPa (or 150–600 psi). Given the high permeability of current brackish water membranes, it should be feasible to operate the RO process, at the above recovery levels, with the feed pressure set at or close to the exit brine osmotic pressure, thereby enabling operation at the minimum level of energy consumption [3]. It is also noted that, recent seawater RO desalination studies [4] by the Affordable Desalination Collaboration (ADC) reported 42.5% water recovery (at permeate flux of 2.83×10^{-6} m^3/m^2 s or 6 gfd) at feed pressure of 4654 kPa (675 psi) that was only 15% higher than the osmotic pressure of the exit brine stream (4027 kPa or 584 psi), thereby already approaching the optimal water recovery
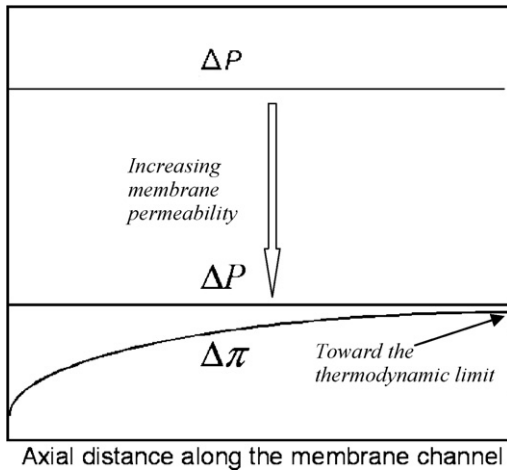
Fig. 1. Schematic illustration of the relationship between imposed feed pressure and feed-side osmotic pressure for low and high permeability RO membranes.

(50% without the use of energy recovery devices; [3]) with respect to energy consumption.

Given that, with the present generation of high permeability RO membranes, it is feasible to operate the RO process over a wide range of practical water recoveries to the limit of the thermodynamic restriction [3], an important question arises as to the merit of developing membranes with yet higher permeabilities than currently available. The energy cost for RO desalting is the product of the feed flow rate and the applied feed pressure [3]. Consequently, RO desalting operation at lower pressures would result in lower energy consumption for a given product water recovery. Therefore, to the extent that a given assembly of high permeability membranes can provide, for a given feed flow rate, the targeted overall permeate flow (or recovery), the energy cost would be independent of the type of membrane used in the process. Of course, this statement would hold provided that, irrespective of the selected membrane, the RO process can be operated up to the limit of the thermodynamic restriction. However, the required membrane area, for a given feed flow rate at a selected target recovery, would decrease with increasing membrane permeability. Therefore, one could argue that, once the capability for operating at the thermodynamic limit has been approached, the benefit of higher permeability membranes is to lower the membrane cost for the process (typically <10% of the overall water production cost while the contribution of energy cost to the overall permeate production cost which is typically >30% [5]).

Given the emerging significance of RO desalination for generating new potable water resources, the present work addresses the question of the benefit of improving RO membrane permeability with respect to the cost of energy and the required membrane area for achieving a targeted product water recovery for a given feed flow rate. The analysis approach considers the implication of the thermodynamic restriction following the recent framework of Zhu et al. [3].

2. Energy consumption for RO operation at the thermodynamic limit

In order to illustrate the relative costs of required RO energy and membrane area, the simple example of a single-stage RO desalting is considered (Fig. 2). Previous studies [7] have shown that, in order to ensure permeate productivity along the entire membrane module, the lower bound (or imposed thermodynamic limit) on the applied pressure ΔP (=$P_f - P_0$, where P_f and P_0 being the water pressures at the entrance to the membrane module and raw feed
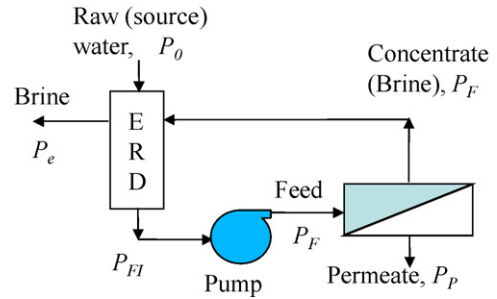

Fig. 2. Simplified schematic of RO system with an energy recovery device (ERD).

water at the source, respectively) is the osmotic pressure difference between the retentate exit (brine) and permeate stream as expressed by the following "thermodynamic" restriction

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

in which the target recovery is Y (=Q_p/Q_f, where Q_p and Q_f are the permeate and feed flow rates, respectively) and R is the fractional salt rejection. For desalting operation at the thermodynamic limit (i.e., $\Delta P = \Delta\pi_{\text{exit}}$) the exit osmotic pressure of the bulk solution is the same as at the membrane surface. The above can be rationalized by considering the simple film model for the concentration polarization modulus [8], $CP = C_m/C_b = \exp(J/k)$, where C_m and C_b are the salt concentrations at the membrane surface and the bulk, respectively, J is the permeate flux and k is the feed-side mass transfer coefficient. The above relations imply that the permeate flux will vanish as the thermodynamic restriction limit is reached at the membrane channel exit where $CP = 1$ and thus $C_m = C_b$.

As shown recently [7], the specific energy consumption (SEC), normalized with respect to the feed osmotic pressure ($SEC_{norm} = SEC/\pi_0$), is equal to or greater than the normalized energy consumption (SEC_{tr}^{norm}) for operation at the thermodynamic limit,

$$SEC_{tr}^{norm} = \frac{SEC_{tr}}{\pi_0} = \frac{(1 - \eta_E(1 - Y))R}{\eta_p Y(1 - Y)} \tag{2}$$

where η_p is the pump efficiency, η_E is the efficiency of the energy recovery device (ERD), $\dot{W}_{pump}$ is the rate of pump work (i.e., $\dot{W}_{pump} = \Delta P \times (Q_f - \eta_E Q_b)/\eta_p$, where η_p is the pump efficiency and Q_b is the brine stream flow rate).

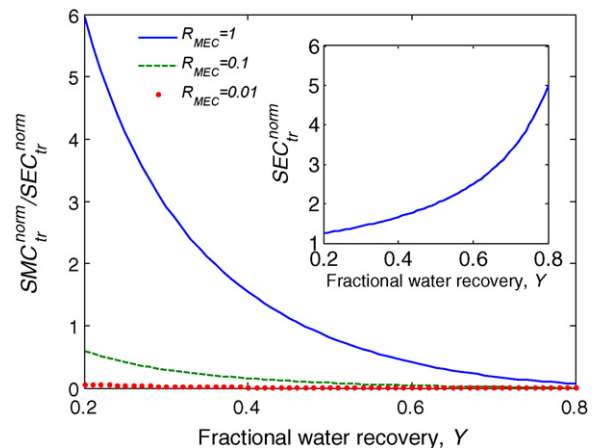**Fig. 3.** Variation of the ratio of normalized specific membrane (SMC_{tr}^{norm}) to specific energy (SEC_{tr}^{norm}) costs for operation up to the limit of thermodynamic restriction with respect to target water recovery. The inset graph is for the normalized specific energy consumption (SEC_{tr}^{norm}) for RO operation up to the limit imposed by the thermodynamic restriction.

For operation at the thermodynamic limit, $SEC_{norm} = SEC_{tr}^{norm}$, the SEC_{tr}^{norm} (i.e., Eq. (2)) increases with product water recovery as illustrated in Fig. 3 (the inset graph), for a target salt rejection of 99% and ideal pump and ERD (i.e., $\eta_p = \eta_E = 1$), with a more rapid rise in energy consumption as the recovery level surpasses about 60%. It is noted that, the rate of pump work is dependent on the imposed pressure, pump and energy recovery efficiencies, feed flow rate, and for a given permeate product recovery it is independent of the membrane permeability. Likewise, the normalized energy consumption, SEC_{tr}^{norm}, is independent of the membrane hydraulic permeability when operating at the limit of the thermodynamic restriction (Eq. (2)). In other words, if the membrane permeability is such that it enables operation, at the desired product water recovery, such that osmotic pressure of the exit brine stream approaches the feed-side pressure, using a more permeable membrane would not reduce the required energy for desalting but may have an impact on membrane and other operational costs as discussed in Section 3.

3. Specific membrane cost (SMC) for RO operation at the thermodynamic limit

In order to assess the water production membrane cost (i.e., amortized membrane cost per produced permeate or hereinafter referred to as the "specific membrane cost") for a given RO desalting task, it is convenient to compare the membrane and energy costs on the same basis of energy units (i.e., Pa m³). This conversion can be achieved [3], given an energy price, e.g., ε($/kWh) and the conversion factor of β(Pa m³/kWh). Accordingly [6], for a single-stage RO process, it is convenient to use the specific membrane cost in terms of energy units (SMC) as given by [3]:

$$SMC = \frac{m \times A_m}{Q_p} = \frac{m}{Q_p}\left[\frac{Q_p}{L_p\left(\Delta P - \sigma\overline{\Delta\pi}\right)}\right] \tag{3}$$

where m is the amortized membrane price in equivalent energy units per unit area ($m = m_A\beta/\varepsilon$, in which, for example, m is in units of Pa m³/m² h, where m_A is the amortized membrane unit price, $/m² h$). As was previously shown [3], the specific membrane cost for RO desalting operation up to the thermodynamic limit (designated as SMC_{tr}), i.e. where $\Delta P = \Delta\pi_{exit}$, normalized with respect to the feed osmotic pressure (SMC_{tr}/π_0) is given by:

$$SMC_{tr}^{norm} = \frac{m}{RL_p\pi_0^2[(1/(1-Y)) - (1/Y)\ln(1/(1-Y))]} \tag{4}$$

as derived from Eq. (3) making use of the log-mean average for the osmotic pressure ($\overline{\Delta\pi} = \pi_0 R\ln(1/(1-Y))/Y$); [9]. It is noted that for operation at the thermodynamic limit ΔP is just $\pi_0 R/(1-Y)$ and thus it can be shown that the SMC (Eq. (3)) is inversely proportional to π_0 and thus $SMC_{tr}^{norm} \propto (1/\pi_0^2)$. Eq. (4) indicates that, for the same product water recovery, the normalized specific membrane cost (SMC_{tr}^{norm}) will decrease with increasing membrane hydraulic permeability, salt rejection and feed osmotic pressure. The use of a more permeable membrane would reduce the required membrane area as well as the required size or number of pressure vessels. One could also argue that the cost of membrane cleaning and replacement would be reduced. However, operation at a higher permeate flux [3] could result in greater degree of fouling which could counteract the above gains.

The required membrane surface area (A_m), and hence membrane cost (Eq. (3)), for a given permeate productivity, is related to the average net driving pressure, $NDP (= \Delta P - \sigma\overline{\Delta\pi})$ whereby $A_m \propto Q_p/NDP$. The consequence of this dependence can be illustrated via the simple example of desalting at 50% recovery. For instance, desalting seawater with feed osmotic pressure of 2533 kPa (25 atm) (~35,000 mg/L TDS) at water recovery of 50%

would lead to a brine exit osmotic pressure of 5066 kPa (50 atm). Therefore, the average net driving pressure, $NDP (= \Delta P - \sigma\overline{\Delta\pi})$ for the permeate flux would be 1554 kPa (15.3 atm) (assuming $\sigma = 1$). In comparison, desalting of brackish water of 3500 mg/L TDS (osmotic pressure of 253.3 kPa (2.5 atm)) at water recovery of 50% would result in an exit brine osmotic pressure of 506.6 kPa (5 atm) and thus an average NDP of 155.4 kPa (1.53 atm). Therefore, for the same water recovery a higher average NDP would be obtained for the higher osmotic pressure feed, as long as the operation is up to the limit imposed by the thermodynamic restriction; thus, a lower membrane area is required for seawater desalting relative to brackish water at the same recovery level. The above may appear counterintuitive but it is a consequence of operating at the limit of the thermodynamic restriction.

4. Membrane cost relative to energy cost for RO operation at the limit of the thermodynamic restriction

The specific membrane cost relative to the specific energy consumption, for operation at the limit for the thermodynamic restriction is obtained by dividing Eq. (2) by Eq. (4):

$$MER = \frac{SMC_{tr}^{norm}}{SEC_{tr}^{norm}}$$

$$= \frac{R_{EMC}\eta_p Y(1-Y)}{[((1/(1-Y)) - (1/Y)\ln(1/(1-Y)))(1 - \eta_E(1-Y))]} \tag{5}$$

in which R_{MEC} is a dimensionless cost factor defined as:

$$R_{MEC} = \frac{\beta m_A}{\varepsilon L_p(R\pi_0)^2} \tag{6}$$

Eq. (5) indicates that, for a given water recovery, the MER ratio increases with R_{MEC}. This lumped dimensionless R_{MEC} factor can be used to reflect the impact of feed water osmotic pressure, salt rejection requirement, membrane permeability, and the purchase price of electrical energy and membrane module on the MER cost ratio. It is especially striking that this dimensionless factor is inversely proportional to the square of the feed osmotic pressure; this is due to the fact that energy cost and membrane cost are proportional (Eq. (2)) and inversely proportional (Eq. (3)) to the feed osmotic pressure, respectively. The sensitivity of the above dimensionless factor to the osmotic pressure is consistent with the fact that, the contribution of energy cost to the total water production cost will increase dramatically as the feed water osmotic pressure increases as discussed below shown in the following paragraph.

A reasonable quantitative assessment of the relative membrane to energy costs can be provided by considering the magnitude range of the factor R_{MEC}. For the purpose of the present analysis, the estimated membrane price per unit area (m^2), of current low pressure RO membranes (i.e., $L_p = 0.5$–0.8×10^{-10} m³/m² s Pa) is taken to be in the range of 20–40 $/m² [10] (thus $m_A = 0.76$–1.52×10^{-3} $/m² h, assuming membrane life of 3 years, and the U.S. electrical energy price is estimated in the range of 0.05–0.2 $/kWh). It is expected that with improvements in membrane technology, future membrane costs will be likely to be lower compared to current prices. Finally, the range of water salinity of typical interest is about 1000–45,000 mg/L TDS (equivalent to osmotic pressure range of 72.4–3257 kPa). For the above range of parameters, the R_{MEC} ranges from ~0.001 to 1. For example, for seawater of ~35,000 mg/L TDS and for brackish water of 1000 mg/L TDS, R_{MEC} would range from about 0.01 to 1, respectively.

The dependence of the ratio (MER) of membrane to energy costs (in equivalent energy units) on product water recovery is illustrated in Fig. 3, for different values of the dimensionless R_{MEC} number, for the case of ideal pump and ERD (i.e., $\eta_p = \eta_E = 1$). As

expected, the membrane cost decreases relative to the energy cost with increased product water recovery and decreasing R_{MEC}. As an example, for $R_{MEC} = 0.01$ (e.g., achieved for desalination of 35,000 mg/L TDS seawater with the Dow FilmTec SW30XLE-400i, $L_p = 0.78 \times 10^{-10}$ m³/m² s Pa), the ratio of the specific membrane cost (SMC_{tr}) to the specific energy consumption (SEC_{tr}) is in the range of 3–12%. For seawater desalination, the percentage of the energy cost (%EC) is usually ∼40–50% of the total water production cost [5]. For the above range, the contribution of specific membrane cost to the total water production cost, which can be estimated as the product of the above two factors (i.e., %EC × SMC_{tr}/SEC_{tr}), is about 1.2–6% of the total water production cost, which is within the range of membrane cost reported in the literature [5]. This suggests that the maximum benefit one may expect from future improvements in membrane permeability is a decrease of the total water production cost by about the same percentage. It is noted, for example, that doubling of the membrane permeability will decrease the specific membrane cost (see Eq. (4)) by half, and thus will decrease the total water production cost by ∼0.6–3%. It is also acknowledged that the capital cost of pressure vessels is directly impacted by the membrane area (e.g., lower membrane area may require reduced number or size of pressure vessels). For the above range of membrane cost contribution to the total water production cost, inclusion of pressure vessels cost (amortized over 30 years; [10,12]) would result in a reduction of the total water production cost by ∼0.7–3.5%. Admittedly, despite the above modest percentage in water production savings, the absolute dollar savings may be significant for large RO plants. The decision of whether the above is achievable will depend on whether it will be possible to operate the RO process at a higher flux while avoiding the biofouling and mineral scaling problems that remain as obstacles to high flux RO operation.

For desalination of mildly brackish water of ∼1000 mg/L TDS, $R_{MEC} = 1$ and the estimated MER decreases from 6 to 0.04 as the water recovery increases from 20% to 80%, respectively. This behavior implies that at low water recovery, the use of higher permeability membranes will be beneficial in reducing the overall water production (Fig. 3) since the specific membrane cost is higher than the specific energy consumption (both expressed in terms of equivalent energy units). Indeed, it has been reported that membrane cost is an important factor for brackish water desalination [5] at moderate recoveries (≲60%). However, for inland water desalting, feed pretreatment and brine management costs will both increase with decreasing water recovery, thus reducing the economic incentive for operating at low water recoveries. On the other hand, as product water recovery is increased the specific energy cost will rise while the SMC will decrease, thus providing diminished economic incentive for developing more permeable membranes for brackish water desalting at high recovery.

While the above example focused on the use of ideal feed pump and ERD, it is important to state that operation with non-ideal pump and ERD (i.e., $\eta_p < 1$ and $\eta_E < 1$) will lower the MER (Eq. (5)) and thus the present conclusions are valid for the entire range of pump and ERD efficiencies.

It should be recognized that the development of low pressure (high permeability) RO membranes has progressed rapidly starting in about the 1990s. The earlier higher pressure membranes were of lower permeability and thus the operating feed pressures were typically much higher than the brine osmotic pressure at the targeted recovery and thus operation at the thermodynamic limit was not practical. The current generation of RO membranes are already of permeability levels that are sufficient (or nearly so) to enable operation approaching the thermodynamic restriction limit, while providing the practically desired permeate flux. Therefore, it is reasonable to conclude that significant reduction in the cost of RO water desalination is less likely to arise from the development of significantly more permeable membranes, but is more likely to arise from effective and lower cost of feed pretreatment and brine management, development of fouling and scale resistant membranes, optimization of process configuration and control schemes (e.g., to account for variability of feed salinity [11] and even temporal fluctuation of electrical energy costs), as well as utilization of low cost renewable energy sources.

5. Conclusions

A simple analysis of the specific membrane cost relative to specific energy cost, for RO desalination, was carried out to assess the range of water recovery over which improvements in membrane permeability would be beneficial to reducing RO water production cost. With the current generation of high permeability RO membranes it is now feasible to operate the RO desalting process up to (or very near) the limit imposed by the thermodynamic restriction. Therefore, as illustrated in the present analysis, given the present day electrical energy and membrane prices, there may be a benefit in developing membranes of even greater permeability at low water recoveries for inland brackish water desalting. However, for inland water desalting at low water recovery there are typically added costs associated with feed pretreatment, as well as the cost of and various practical limitations of brine management. On the other hand, for seawater RO desalting the energy cost is much higher than membrane cost (compared on the basis of equivalent energy units), and there is little economic incentive for developing higher permeability membranes if the objective is to lower the cost of seawater desalination. The ratio of membrane to energy costs is dependent on the water recovery level and a dimensionless cost factor (R_{MEC}) that includes the impact of feed water salinity, membrane permeability, salt rejection requirement and purchase costs of electrical energy and membrane area. The present analysis suggests that further significant improvements in RO membrane permeability are less likely to be the major driver to achieving further significant reduction in the cost of RO desalting. Future reduction in RO water production cost can arise from a variety of other process improvements including, but not limited to improved fouling-resistant membranes, lower cost of feed pretreatment and brine management, advanced control schemes, process optimization, as well as low cost renewable energy sources,

Acknowledgements

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