Journal of Membrane Science 339 (2009) 126–137

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Minimization of energy consumption for a two-pass membrane desalination: Effect of energy recovery, membrane rejection and retentate recycling

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ARTICLE INFO

Article history:
Received 12 March 2009
Received in revised form 17 April 2009
Accepted 18 April 2009
Available online 3 May 2009

Keywords:
Membrane desalting
Reverse osmosis
Nanofiltration
Thermodynamic restriction
Two-pass membrane desalination

ABSTRACT

The energy optimization of two-pass membrane desalination, at the limit imposed by the thermodynamic restriction, was investigated and compared with a single-pass membrane desalting operation at the equivalent targeted overall salt rejection and permeate product recovery. The analysis considered the effect of pump and energy recovery efficiencies, membrane rejection, and retentate recycling from the second to the first-pass. The optimization results suggest that when the desired overall salt rejection can be achieved via a single-pass, then this process configuration will result in a lower specific energy consumption (SEC) relative to the two-pass membrane desalting process. However, if the desired overall rejection (or specific ion rejection, e.g., boron) cannot be achieved with the highest available rejection membrane in a single-pass, then a two-pass configuration is a feasible solution. In the latter case, the lowest energy consumption will be attained when a membrane of the highest available salt rejection is used in the first-pass. In cases in which desalting is accomplished at recoveries below the critical water recovery (i.e., the optimal recovery for a single stage), an operational sub-domain may exist in which the SEC for a two-pass process can be lower than for a single-pass counterpart, but only if the single-pass process is not operated at its globally optimal state. Retentate recycling from the second-pass to the first-pass feed can reduce the SEC for the two-pass process. However, optimization solution of the two-pass process is always a single-pass process as the optimal desalination process.

1. Introduction

Reverse osmosis (RO) membrane water desalination is now established as a mature water desalination technology. However, there are intensive efforts to reduce the RO desalination cost in order to broaden the appeal and increase deployment of this technology. Water production cost in a typical RO desalination plant generally includes the costs of energy equipment, membranes, labor, maintenance and financial charges. Energy consumption is a major fraction of the total cost of water desalination and can reach as high as about 45% of the total water 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 1379–4137 kPa (200–600 psi) for brackish water desalting). Considerable effort, dating back to the early 1960s (as reviewed in [4]), has been devoted to minimizing the SEC of RO membrane desalination. The introduction of highly permeable membranes in the mid 1990s with low salt passage [5] has led to a significant reduction in the energy required to attain a given permeate flow, with greatly reduced operating pressure that can now approache the osmotic pressure at the exit of a membrane module. However, the thermodynamic restriction [4,11,12] imposes the requirement that the feed-side pressure cannot be lower than the sum of the osmotic pressure (of the exit brine stream) and pressure losses (in the membrane channel) in order to ensure that permeate product water is produced from the entire membrane surface area.

In a recent work [4], the effect of the thermodynamic restriction on the optimization of the specific energy consumption (SEC) in single and multi-stage RO membrane desalting was studied following a theoretical formalism [4]. It was shown that the optimum recovery level for attaining a minimum SEC operation, for single and multi-stage RO processes, was impacted by the deployment of energy recovery device, membrane and brine management costs. The present work extends our earlier approach [4] to include the effect of membrane salt rejection on the SEC and to evaluate the energy consumption and its optimization for a two-pass membrane desalination process. It appears that the literature regarding the two-pass membrane desalting configuration, which is a relatively new configuration for seawater desalting, is conflicting with respect to the energy efficiency of this process relative to a single stage [6,7,15]. For example, Noronha et al. [6] proposed an approach to optimizing the partial recoveries (i.e., for each pass) in a two-pass desalination process, without energy recovery for overall product

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doi:10.1016/j.memsci.2009.04.039

water recovery in the range of 50–70%. The above study showed that an optimal solution, with respect to the recoveries of each pass, can be obtained via a numerical algorithm, for specific plant configuration and membranes. However, a comparison was not provided of energy consumption relative to a single-stage operation, but it was suggested that energy consumption is higher for a two-pass process. In a later study, Cardona et al. [7] compared the SEC of a two-pass membrane desalination process, which they termed "double-stage", to a single-pass RO process, both without the use of an energy recovery device. Based on a specific case study using standard process model calculations for a target salt rejection of 98.3% and 41.2% water recovery, it was concluded that the two-pass process has a potential for energy savings on the order of 13–15% for the specific case of less than 50% total water recovery. A recent report [15] on extensive pilot studies of a two-pass seawater NF desalination process by the Long Beach Water Department, suggested that the two-pass process would require about 20% less energy, when operating at 42% product water recovery, compared to a single-pass RO membrane desalination process. The above two-pass NF desalination study did not report the use of energy recovery devices and did not present conclusive experimental data or theoretical reasoning for the claimed superiority of the two-pass process.

Previous studies on two-pass desalination have not considered the impact of energy recovery when comparing the SEC for the two-pass membrane desalting configuration relative to single or multi-stage RO process configurations. Moreover, the relatively limited comparisons provided in the literature have not addressed the limitations imposed by the thermodynamic cross-flow restriction on the minimum achievable specific energy consumption [4]. Therefore, in order to provide a formal framework for the assessment of the optimization of specific energy consumption for a two-pass reverse osmosis membrane desalination process, the current study presents a systematic comparison of the SEC optimization for a two-pass versus a single-stage membrane desalination process. The present analysis considers the limits imposed by the thermodynamic cross-flow restriction, use of energy recovery devices, the constraint imposed by membrane rejection, and retentate recycling.

2. The specific energy consumption (SEC) for a single-pass process and the thermodynamic restriction in cross-flow membrane desalting

In order to illustrate the approach to optimizing (i.e., minimizing) energy consumption in reverse osmosis membrane desalination, it is instructive to first consider the simple example of a single-pass membrane desalination process (where the process is classified as RO or NF depends on the level of salt rejection [8]) without the use of an energy recovery device (ERD) as shown schematically in Fig. 1.

The specific energy consumption (SEC), associated with RO/NF desalination, is defined as the energy needed to produce a cubic meter of permeate of a desired salt concentration. Accordingly, the SEC for the desalination plant (Fig. 1) is given by:

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

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

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

in which ΔP is the pressure applied to the raw feed water, given by:

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

where P_f and P_0 are the water pressures at the entrance of the membrane module and raw feed water at the source (for simplicity assumed at atmospheric pressure), respectively, and Q_f is the volumetric feed flow rate. It is further assumed that the pressure drop, along the membrane module, has little effect on locating the minimum SEC as recently shown to be the case [4].

The total water recovery for the RO process, Y_t, which is a measure of the process productivity is defined as:

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

and through the combination of Eqs. (1), (2) and (4), the SEC can be expressed as:

$$\mathrm{SEC} = \frac{\Delta P}{\eta_{\mathrm{p}} Y_{\mathrm{t}}} \tag{5}$$

where the permeate flow rate, Q_p, can be approximated by the classical reverse osmosis flux equation [9]:

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

where A_m and L_p are the membrane surface area and hydraulic permeability, respectively, σ is the reflection coefficient (typically assumed ~1 for high rejection membranes), and the average trans-membrane pressure is denoted by $\overline{\Delta P_m}$ $(= \overline{P_m} - \overline{P_p}$, where $\overline{P_m}$ and $\overline{P_p}$ are the membrane feed-side and permeate pressures, respectively). Given the simplification of negligible pressure drop (relative to the feed-side pressure), it is reasonable to set $\overline{P_m} = P_f$ and also set $\overline{P_p} = P_0$. The average osmotic pressure difference between the concentrate and the permeate streams is denoted by $\overline{\Delta\pi}$, and $\overline{\mathrm{NDP}}$ $(= \overline{\Delta P_m} - \sigma\overline{\Delta\pi})$ is the average transmembrane net driving pressure. The osmotic pressures at the entrance and exit of the membrane module, relative to the permeate stream, are given by:

$$\Delta\pi_{\mathrm{entrance}} = \pi_{\mathrm{f}} - \pi_{\mathrm{p}} \tag{7}$$

$$\Delta\pi_{\mathrm{exit}} = \pi_{\mathrm{r}} - \pi_{\mathrm{p}} \tag{8}$$

where π_f, π_r, π_p are the osmotic pressures of the feed, retentate and permeate streams, respectively. The typical approximation is then invoked whereby the osmotic pressure is approximated to vary linearly with concentration [9]

$$\pi_i = f_{\mathrm{os}} C_i \tag{9}$$

where f_{os} is the osmotic pressure coefficient, C_i is the solution salt concentration, and where the subscript i, denotes the feed (f), retentate (r), or permeate (p) streams. For the purpose of the present analysis, the average osmotic pressure (up to the desired level of product water recovery), is approximated by the log-mean average along the membrane module [10],

$$\overline{\Delta\pi} = f_{\mathrm{os}} C_{\mathrm{f}} \frac{\ln(1/(1 - Y_{\mathrm{t}}))}{Y_{\mathrm{t}}} \tag{10}$$

where C_f is the feed salt concentration.

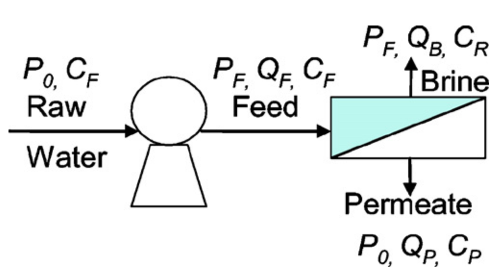

Fig. 1. Schematic of a simplified single-pass RO/NF process.

The permeate concentration (for a given target recovery, Y_t, and salt rejection, R_t) and retentate concentration at the module exit, can be determined via salt mass balance as:

$$C_p = (1 - R_t)C_f \tag{11}$$

$$C_r = \frac{1 - Y_t(1 - R_t)}{1 - Y_t} C_f \tag{12}$$

and by combining Eqs. (8)–(12), the osmotic pressure difference at the module exit, between the concentrate and permeate streams, can be expressed as:

$$\Delta\pi_{exit} = \frac{R_t \pi_0}{1 - Y_t} \tag{13}$$

Eq. (13) represents the well known inherent limitation to reaching high recovery in RO/NF desalting due to the rapid rise in osmotic pressure with increased water recovery. The above equation implies that in order to ensure permeate productivity, along the entire membrane module, the following lower bound is imposed on the applied pressure (ΔP; Eq. (3)):

$$\Delta P \geq \Delta\pi_{exit} = \frac{\pi_0 R_t}{1 - Y_t} \tag{14}$$

indicating that, for a given target recovery, Y_t, the applied pressure should not be less than the osmotic pressure difference at the module exit [5,11]. The above inequality is the so-called "thermodynamic restriction" of cross-flow membrane desalting [4,11–13]. It is interesting to note that recent field studies by the Affordable Desalination Collaboration (ADC) [16], on desalination of seawater (~32,000 mg/L TDS) for high quality drinking water production, with high permeability RO membranes, have reported water recovery approaching about 42.5% when operating at an applied feed pressure of 4654 kPa (675 psi). According to Eq. (14), desalting the above water, in a process that operates up to the limit imposed by the thermodynamic restriction, would require a minimum applied pressure of 4027 kPa (584 psi); in other words, the ADC desalination plant operates at a feed pressure which is only 15% above the theoretical minimum.

For a desalting operation up to the limit imposed by the thermodynamic restriction (Eq. (14)), the total permeate flow rate, Q_p, is obtained via a differential mass balance of the salt along the membrane module(s) leading to:

$$\frac{Q_p}{AL_p} = \overline{\text{NDP}} = \overline{\Delta P_m} - \overline{\Delta\pi} = \frac{\Delta P}{1 + [\pi_0/(Y\Delta P)]\ln[(1 - \pi_0/\Delta P)/(1 - Y - \pi_0/\Delta P)]} \tag{15}$$

where Y denotes the actual water recovery for applied pressure ΔP (Eq. (3)). For operation at the limit of the thermodynamic restriction (i.e., $\Delta P = R_t\pi_0/(1 - Y)$), Eq. (16) suggests that a highly permeable membrane (i.e., high L_P) and/or large surface area would be required. Although the above averaging of the transmembrane and osmotic pressures can be utilized, it would lead to an implicit equation for the SEC. Thus, the simpler log-mean averaging (Eq. (10)) is preferred in the present analysis in order to illustrate the SEC optimization procedure, without a loss of generality [4]. Accordingly, the use of Eq. (10) leads to the following approximation for the NDP (Eq. (6)) for a desalting operation at the limit of the thermodynamic restriction:

$$\overline{\text{NDP}} = \frac{Q_p}{AL_p} = \frac{R_t\pi_0}{1 - Y_t} - R_t\pi_0 \frac{\ln[1/(1 - Y_t)]}{Y_t} \tag{16}$$

The implication of using the averaging approach for $\overline{\Delta\pi}$, as in Eq. (16), was quantitatively assessed in a recent analysis by the authors [4]. It was shown that the simpler log-mean approximation provided similar results with deviations that were significant only when frictional pressure losses became significant.

3. Optimization of the SEC for a single-pass membrane desalination at the limit of the thermodynamic restriction

3.1. SEC optimization for a single-pass membrane desalting process without energy recovery

In order to compare the SEC for a single-pass process versus a two-pass membrane desalting process, the SEC for a single-pass process is first presented as a function of the target recovery, with and without the use of an energy recovery device (ERD). Subsequently, SEC optimizations of a two-pass membrane process (RO or NF) with and without ERDs are presented and compared with the single-pass process (Section 3.2).

The specific energy consumption (SEC) for a single-pass RO/NF desalting process in the absence of energy recovery (Fig. 1) can be derived by combining Eqs. (1)–(4) and (14), to obtain:

$$\text{SEC} \geq \frac{\pi_0 R_t}{Y_t(1 - Y_t)\eta_p} \tag{17}$$

where the SEC is expressed in pressure units (e.g., kPa). It is convenient to normalize the SEC at the limit of the thermodynamic restriction with respect to the feed osmotic pressure such that:

$$\text{SEC}_{tr,norm} = \frac{\text{SEC}_{tr}}{(\pi_0)} = \frac{R_t}{\eta_p Y_t(1 - Y_t)} \tag{18}$$

An example of the above normalized SEC dependence on the target water recovery (i.e., Eq. (18)) is plotted in Fig. 2 for a target salt rejection of 99% showing that the global minimum $\text{SEC}_{tr,norm}$ increases with decreasing pump efficiency. The optimal water recovery is unaffected by pump efficiency provided that the efficiency is independent of the water recovery and generated feed pressure. The minimum $\text{SEC}_{tr,norm}$, for a specific target salt rejection, R_t, can be found by setting $\partial(\text{SEC}_{tr,norm})/\partial Y_t = 0$ from which it can be shown that the global minimum occurs at $Y_t = 0.5$ (or 50% recovery) where $(\text{SEC}_{tr,norm})_{min} = 4R_t/\eta_p$ (or $(\text{SEC}_{tr})_{min} = 4R_t\pi_0/\eta_p$). This means that in order to operate at the global minimum SEC (whose value increases with decreasing pump efficiency), the desalting process should be operated at an applied pressure equivalent to $2R_t\pi_0$ and at 50% recovery. The operation below 50% wastes energy that is discharged in the high-pressure brine stream, and operation above 50% recovery results in rapid increase in the brine osmotic pressure and correspondingly the required feed pressure.

It is instructive to illustrate the implications of the above analysis by considering the example of a single-pass seawa-

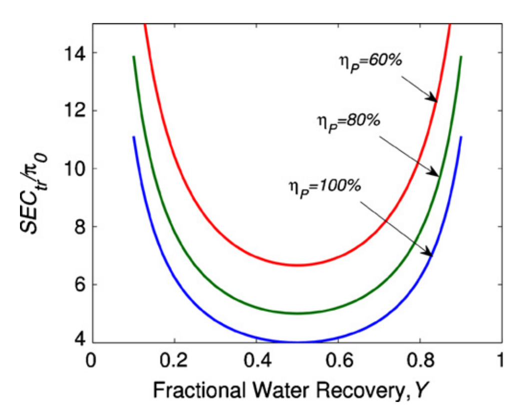

Fig. 2. Variation of the normalized SEC at the limit of the thermodynamic restriction with water recovery for a single-pass RO/NF at a target salt rejection of 99% (*note*: η_p represents the pump efficiency).

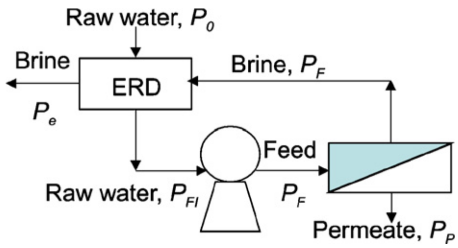

Fig. 3. Simplified RO/NF system with an energy recovery device (ERD).

ter RO plant producing permeate of 500 mg/L total dissolved solids (TDS) from seawater feed of 35,000 mg/L TDS. Accordingly, $\pi_0 = 2533$ kPa (or 25 atm) and target salt rejection is $R_t = 99\%$, the global minimum energy consumption for the above case is $4R_t\pi_0 = 2.8\,\text{kWh/m}^3$. For example, the average permeate water flux, if one considers one of the available commercial RO membranes (e.g., Dow FilmTec SW30XLE-400i) with a permeability of $L_p = 0.78 \times 10^{-10}\,\text{m}^3/\text{m}^2\,\text{s Pa}$, at the above optimal condition, is computed from Eq. (16) as:

$$(\text{FLUX})_{\text{opt}} = \frac{Q_p}{A_m} = L_p\left[\frac{R_t\pi_0}{1-Y_t} - R_t\pi_0\frac{\ln[1/(1-Y_t)]}{Y_t}\right] = 5 \times 10^{-6}\,\text{m}^3/\text{m}^2\,\text{s}\,(\text{or } 10.5\,\text{gallons/ft}^2\ \text{day}) \quad (19)$$

where $Y_{\text{opt}} = 0.5$ and $(\Delta P)_{\text{opt}} = 2R_t\pi_0$. It is important to note that, at the global energy-optimal operating point, the applied pressure and feed flow rate (input process variables), brine and product flow rate (output variables) are fixed for an RO plant with given A_m and L_p. It is noted that the global minimum energy consumption presented here is only for the case of single-pass process without energy recovery devices. As presented by the authors [4], the SEC can be further decreased by utilization of multi-stage configuration and energy recovery devices.

3.2. Effect of energy recovery on the SEC optimization for a single-pass RO/NF process

In order to reduce the required energy for RO/NF desalination, energy can be extracted from the high-pressure concentrate (or brine) stream (Fig. 3) using a variety of energy recovery schemes [17]. The rate of work done by the pump on the raw water, in the presence of an energy recovery device (ERD), is given by:

$$\dot{W}_{\text{pump}} = \Delta P \times (Q_f - \eta_E Q_b) \quad (20)$$

where Q_b is the brine flow rate, which is related to the permeate flow rate (Q_p) and product recovery (Eq. (4)), and η_p and η_E are the efficiencies of the feed pump and of the energy recovery device (ERD), respectively. Thus, the specific energy cost for RO desalting, in the presence of an ERD, $\text{SEC}^{\text{ERD}}(Y,\Delta P,\eta)$, is given by:

$$\text{SEC}^{\text{ERD}}(Y, \Delta P, \eta_p, \eta_E) = \frac{\Delta P(Q_f - \eta_E Q_b)}{Q_p\eta_p} = \frac{\Delta P(1-\eta_E(1-Y_t))}{Y_t\eta_p} \quad (21)$$

The normalized SEC for this configuration (Fig. 3), $\text{SEC}^{\text{ERD}}_{\text{tr,norm}}$, at a given water recovery, Y_t, and salt rejection, R_t, at the limit of the thermodynamic restriction in the presence of an ERD, is obtained from Eq. (21) by using Eqs. (14) and (20) to yield:

$$\text{SEC}^{\text{ERD}}_{\text{tr,norm}} = \frac{(1-\eta_E(1-Y_t))R_t}{\eta_p Y_t(1-Y_t)} \quad (22)$$

The dependence of the normalized SEC (Eq. (22)) on the total water recovery and pump and ERD efficiencies is illustrated in Fig. 4

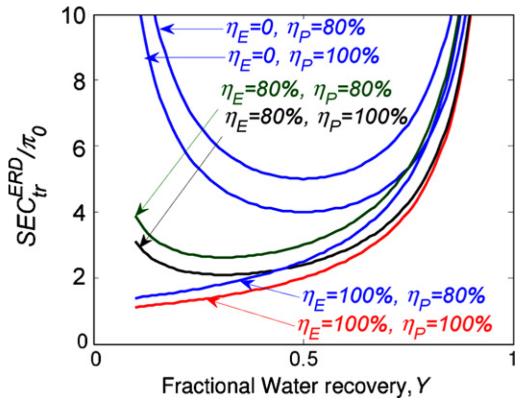

Fig. 4. Variation of the normalized SEC for a target salt rejection of 99% with fractional product water recovery using an ERD in a single-pass RO (*note*: η_p and η_E represent the pump and ERD efficiencies, respectively).

for salt rejection of 99%. The deployment of an ERD shifts the optimal minimum energy location to lower recoveries. As the pump efficiency decreases the SEC increases. Note that the optimum recovery will be unaffected by the pump efficiency if it remains constant (e.g., invariant with water recovery and feed pressure). However, it is apparent that with the use of an ERD, recoveries higher than 50% (i.e., the optimal recovery at the minimum SEC in the absence of an ERD) can be achieved at significantly lower specific energy cost, relative to desalting in the absence of energy recovery (i.e., $\eta_E = 0$, Eq. (18)), e.g., 40% and 50% lower SEC at $Y_t = 0.5$ for ERD efficiencies of 80% and 100% (both for $\eta_p = 1$).

The global minimum SEC for a target salt rejection (i.e., based on Eq. (22)), with respect to water recovery, can be derived by setting $\partial(\text{SEC}^{\text{ERD}}_{\text{tr,norm}})/(\partial Y) = 0$ and solving for the optimal recovery (Y_{opt}) at which $\text{SEC}^{\text{ERD}}_{\text{tr,norm}}$ is at its global minimum. When $\eta_p \neq f(Y_t, \Delta P)$, the following analytical solution is obtained,

$$Y_{\text{opt}} = \frac{\sqrt{(1-\eta_E)}}{1+\sqrt{(1-\eta_E)}} \quad (23a)$$

$$(\text{SEC}^{\text{ERD}}_{\text{tr,norm}})_{\min} = \frac{R_t\left[1+\sqrt{(1-\eta_E)}\right]^2}{\eta_P} \quad (23b)$$

The above equations indicate that as the fractional ERD efficiency (i.e., η_E) increases, Y_{opt} decreases; thus, with increased ERD efficiency, the minimum SEC occurs at lower water recovery. Indeed, it is known in the practice of RO desalting that a higher benefit of energy recovery is attained when operating at lower water recoveries.

4. SEC optimization for a two-pass RO/NF process at the thermodynamic limit

4.1. SEC model equations for a two-pass process

Energy optimization for a two-pass RO/NF (Fig. 5) can be explored similar to the analysis presented for a single-pass process (Section 3.2). In this process, the overall target product water recovery, Y_t, and the overall target salt rejection, R_t, are the results of RO/NF desalting at water recoveries and salt rejections of Y_1, R_1 and Y_2, R_2 in the first and second RO/NF passes, respectively. The general expressions for the SEC are first presented, followed by a discussion of the SEC, with and without energy recovery, relative to the performance of a single-pass process for the same total water recovery and permeate quality.

For a given feed flow rate, Q_f, the total permeate flow rate, Q_p, and total recovery, Y_t, are given by:

$$Q_p = Y_t Q_f = (Y_1 Q_f) Y_2 = Y_1 Y_2 Q_f \tag{24}$$

$$Y_t = Y_1 Y_2 \tag{25}$$

The permeate concentration from the first-pass RO/NF desalting, $C_{p,1}$, i.e., the feed concentration for the second-pass RO/NF desalting, and the permeate concentration from the second-pass RO/NF desalting, $C_{p,2}$, which characterizes the final product water quality, are given by:

$$C_{p,1} = (1 - R_1) C_f \tag{26}$$

$$C_{p,2} = (1 - R_2) C_{p,1} \tag{27}$$

where $C_{p,2}$ can also be expressed as (using Eqs. (26) and (27))

$$C_{p,2} = (1 - R_t) C_f = (1 - R_1)(1 - R_2) C_f \tag{28}$$

with the overall salt rejection given by

$$R_t = 1 - (1 - R_1)(1 - R_2) = R_1 + R_2 - R_1 R_2 \tag{29}$$

The rates of work done by the first-pass pump, $\dot{W}^{1st}_{tr,ERD}$, and the second-pass pump, $\dot{W}^{2nd}_{tr,ERD}$, at the limit of the thermodynamic restriction, are given by (see Eq. (20)):

$$\dot{W}^{ERD}_{tr,1st\,pass} = \left(\frac{R_1 \pi_0}{1 - Y_1}\right)\left(\frac{Q_f - \eta_{E_1}(1 - Y_1) Q_f}{\eta_{P_1}}\right) \tag{30}$$

$$SEC^{tr,ERD}_{norm,2\,passes} = \begin{cases} \left(\dfrac{R_1}{1 - Y_1}\right)\left(\dfrac{1 - \eta_{E_1}(1 - Y_1)}{Y_1 Y_2 \eta_{P_1}}\right) & Y_1 = Y_t \\ \left(\dfrac{R_1}{1 - Y_1}\right)\left(\dfrac{1 - \eta_{E_1}(1 - Y_1)}{Y_1 Y_2 \eta_{P_1}}\right) + \left(\dfrac{R_2(1 - R_1)}{1 - Y_2}\right)\left(\dfrac{1 - \eta_{E_2}(1 - Y_2)}{Y_2 \eta_{P_1}}\right) & Y_t < Y_1 < 1 \\ \left(\dfrac{R_2(1 - R_1)}{1 - Y_2}\right)\left(\dfrac{1 - \eta_{E_2}(1 - Y_2)}{Y_2 \eta_{P_1}}\right) & Y_1 = 1 \end{cases} \tag{34}$$

$$\dot{W}^{ERD}_{tr,2nd\,pass} = \left(\frac{R_2 \pi_{0,2}}{1 - Y_2}\right)\left(\frac{Y_1 Q_f - \eta_{E_2}(1 - Y_2) Y_1 Q_f}{\eta_{P_2}}\right) \tag{31}$$

in which η_{P_1}, η_{P_2} and η_{E_1} and η_{E_2} are the pump and ERD efficiencies for the first and second passes, respectively, and $\pi_{0,2}$ is the osmotic pressure of the feed to the second-pass RO/NF, given by:

$$\pi_{0,2} = f_{os} C_{p,1} = f_{os}(1 - R_1) C_f = (1 - R_1)\pi_0 \tag{32}$$

The SEC for the overall two-pass RO/NF process ($SEC^{ERD}_{tr,2\,passes}$), normalized with respect to the osmotic pressure of the process intake feed water (π_0), at the limit of the thermodynamic restriction, is obtained from the sum of Eqs. (29) and (30),

$$\begin{aligned} \frac{SEC^{ERD}_{tr,2\,passes}}{\pi_0} &= SEC^{tr,ERD}_{norm,2\,passes} = \frac{\dot{W}^{1st}_{tr,ERD} + \dot{W}^{2nd}_{tr,ERD}}{Y_1 Y_2 Q_f \pi_0} \\ &= \left[\frac{R_1}{1 - Y_1}\right]\left[\frac{1 - \eta_{E_1}(1 - Y_1)}{Y_1 Y_2 \eta_{P_1}}\right] \\ &\quad + \left[\frac{R_2(1 - R_1)}{1 - Y_2}\right]\left[\frac{1 - \eta_{E_2}(1 - Y_2)}{Y_2 \eta_{P_2}}\right] \end{aligned} \tag{33}$$

It is important to note that Eq. (33) is only valid for the range of $Y_t < Y_1 < 1$. When $Y_2 = 1$, there is complete salt passage through the membrane; therefore, the second-pass can be eliminated from the two-pass process, and thus the second term in Eq. (33) vanishes; this is equivalent to stating that only the first-pass (or one-stage) exists requiring that $Y_1 = Y_t$ and $R_1 = R_t$. Similarly, when $Y_1 = 1$ this implies that $Y_2 = Y_t$ and $R_1 = 0$ indicating that there is no concentrate stream in the first-pass; thus, pump work is not required for the first-pass since only the second-pass exists (i.e., a configuration equivalent to a single-pass); therefore, the first term in Eq. (33) vanishes. Given the above arguments, the SEC for the overall two-pass RO/NF process is specified as follows:

The product (permeate) water recovery at which the minimum SEC for the overall two-pass RO/NF process is attained can be found, for a given target total recovery (Y_t) and salt rejection (R_t), based on Eq. (34) using a numerical search algorithm to locate a unique set of (R_1,Y_1) that will minimize the SEC subject to the following constraints:

$$Y_t \le Y_1 \le 1 \tag{35a}$$

and

$$0 \le R_1 \le R_t \tag{35b}$$

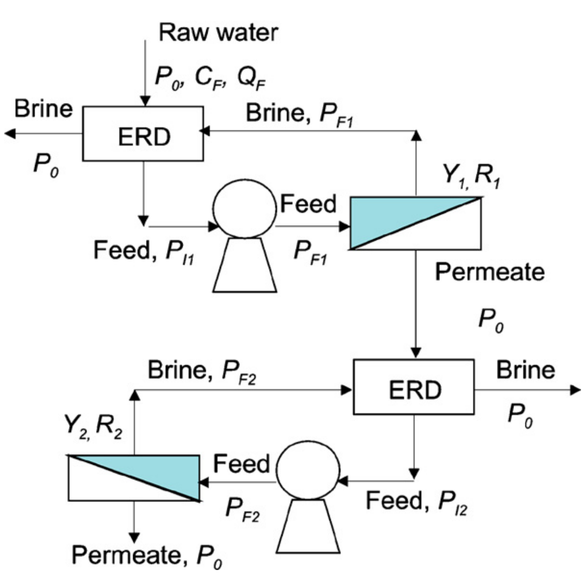

Fig. 5. Schematic of a two-pass RO/NF process with energy recovery devices (ERDs).

4.2. *Effect of ERD efficiency on the SEC for a two-pass desalting process*

For the special case of ERDs of 100% efficiency, the analysis revealed that with the use of energy recovery devices (i.e., ERDs), the global minimum energy, $\left(SEC^{tr,ERD}_{norm,2\,passes}\right)_{min}$, for the two-pass process always occurs (i.e., for any (Y_t, R_t) pair) when the salt rejection is zero in either the first- or the second-pass (i.e., the water recovery is 100% in either the first- or the second-pass). In other words, when $R_2 = 0$, the optimal $SEC^{tr,ERD}_{norm,2\,passes}$ is found at the condition of $R_1 = R_t$, $Y_1 = Y_t$, and thus the operating parameters for the second-pass are $R_2 = 0$, $Y_2 = 1$ (computed from Eqs. (25) and (29)). The above solution indicates that the first-pass fulfills both the target water recovery and salt rejection. Therefore, the second-pass is not required and can be removed from the process. An equally valid optimal solution is when $R_1 = 0$ and $Y_1 = 1$ (i.e., $R_2 = R_t$, $Y_2 = Y_t$), which means that the first-pass is not required since the target recovery and salt rejection are accomplished in the second-pass. The analysis suggests that, if a membrane of the appropriate rejection (and desired flux range) is available, then, at the global optimum, a single-pass RO/NF operation would be more energy favorable than a two-pass RO/NF process.

As an illustration of the above behavior and the impact of ERD efficiency, we consider the simple case of ERD efficiencies of 100% and 80% (the case of $\eta_E = 0$ is considered in Section 4.3) being identical for each pass and pump efficiency of 100%. The results for the $SEC^{tr,ERD}_{norm,2\,passes}$ are shown in Fig. 6a and b, for ERD efficiency of 100% and 80%, respectively, for a target total water recovery of 50% and 99% salt rejection, relative to the normalized SEC for a single-pass process for the same target recovery and salt rejection. As expected, the minimum normalized SEC of the two-pass process is equivalent to the minimum normalized SEC for the single-pass (i.e., single stage) process (i.e., $SEC^{tr,ERD}_{norm,\,1stage} = 2$ for $\eta_E = 1$ and $SEC^{tr,ERD}_{norm,\,1stage} = 2.38$ for $\eta_E = 0.8$ at the target total recovery, Y_t, of 50%). At the lower ERD efficiency of 80% (assumed identical for both the two-pass and single-pass pumps), the $SEC^{tr,ERD}_{norm,2\,passes}$ achievable with the two-pass process increases but the $SEC^{tr,ERD}_{norm,2\,passes}$ trend with recovery and rejection is similar to the case of 100% ERD efficiency (Fig. 6).

For the special case of 100% efficient pumps and ERDs of the same efficiency, for both the two-pass and single-pass processes, it is possible to arrive at an analytical solution for the $SEC^{tr,ERD}_{norm,2\,passes}$ for the overall two-pass process since the optimal solutions fall on the boundaries of $R_1 = 0$ and $R_2 = 0$. For example, when $R_1 = 0$, the optimum Y_2 value is obtained by setting $\left(\partial SEC^{tr,ERD}_{norm,2\,passes}/\partial Y_2\right) = 0$ and solving to obtain the following solution for the optimal water recovery (for the second-pass) at which the minimum SEC is obtained:

$$Y_{2,opt} = \frac{\sqrt{1-\eta_{erd}}}{1+\sqrt{1-\eta_{erd}}} \tag{36a}$$

$$\left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_1=0}\right)_{min} = R_t\left(1+\sqrt{1-\eta_{erd}}\right)^2 \tag{36b}$$

Similarly, when $R_2 = 0$, the optimum Y_1 value is obtained from $\left(\partial SEC^{tr,ERD}_{norm,2\,passes}/\partial Y_1\right) = 0$, leading to the following solution

$$Y_{1,opt} = Y_t \tag{37a}$$

$$\left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_2=0}\right)_{min} = \frac{(1-\eta_E(1-Y_t))R_t}{Y_t(1-Y_t)} \tag{37b}$$

It is noted that the global minimum SEC is the lower of the above two minima (Eqs. (36b) and (37b)). The SEC of the single-pass (or single stage) counterpart is given by Eq. (22) and it is the same as Eq. (37b). Therefore, if $\left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_1=0}\right)_{min} > \left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_2=0}\right)_{min}$, a single-pass process will always be more energy efficient than its two-pass counterpart. However, if $\left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_1=0}\right)_{min} < \left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_2=0}\right)_{min}$, there will be a sub-domain where a two-pass process can be of greater energy efficiency relative to a single-pass process. Finally, if $\left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_1=0}\right)_{min} = \left(SEC^{tr,ERD}_{norm,2\,passes}\Big|_{R_2=0}\right)_{min}$, the optimized two-pass is as efficient as its single-pass counterpart, but it will be less efficient if not optimized. The critical total recovery, $Y_t^{critical}$, at which the transition occurs is determined by Eqs. (36a) and (37a) to give

$$Y_t^{critical} = \frac{\sqrt{1-\eta_E}}{1+\sqrt{1-\eta_E}} \tag{37c}$$

Eq. (37c), which is plotted in Fig. 7, indicates that in the absence of energy recovery (i.e., $\eta_E = 0$) $Y_t^{critical}$ reduces to the optimal recovery for a single-pass process as presented in Section 3.2 (i.e., $Y_t^{critical} = Y_{opt} = 0.5$, Eqs. (23a) and (37c)). On the other hand, for an ideal ERD ($\eta_E = 1$) $Y_t^{critical} = 0$, indicating that a single-pass process is more energy efficient than a two-pass process. For $Y_t \geq Y_t^{critical}$, a single-pass is always equally or more energy efficient than a two-pass process, but for $Y_t < Y_t^{critical}$, there can be a sub-domain in which a two-pass process will be more energy efficient; this would be the case only when the single-stage process is not operating at its optimal recovery at which the global minimum SEC is achieved. It

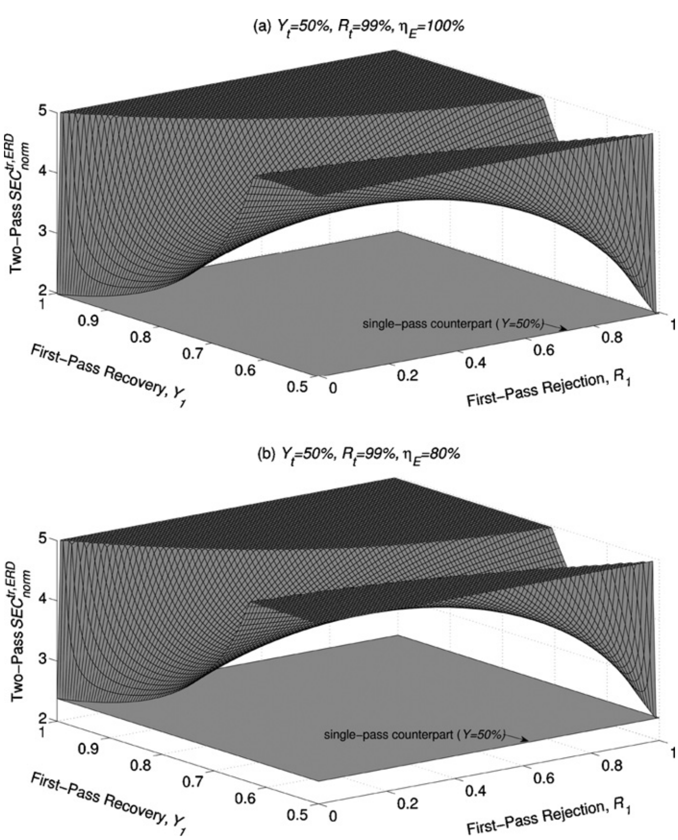

Fig. 6. Variation of normalized SEC of a two-pass membrane desalination process at the limit of the thermodynamic restriction (with ERDs of 100% (a) and 80% (b) efficiency in each pass and $\eta_P = 1$ for all pumps) with respect to salt rejection and water recovery in the first-pass. The target water recovery and salt rejection are 50% and 99%, respectively. In both figures, the plots are truncated at a normalized SEC value of 5 in order to zoom in on the lower SEC region.

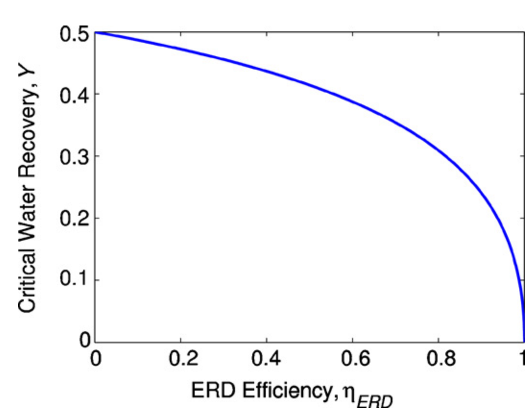

Fig. 7. The effect of ERD efficiency on the critical water recovery above which a single-stage membrane desalting process is more efficient than a two-pass process (Eq. (37c)).

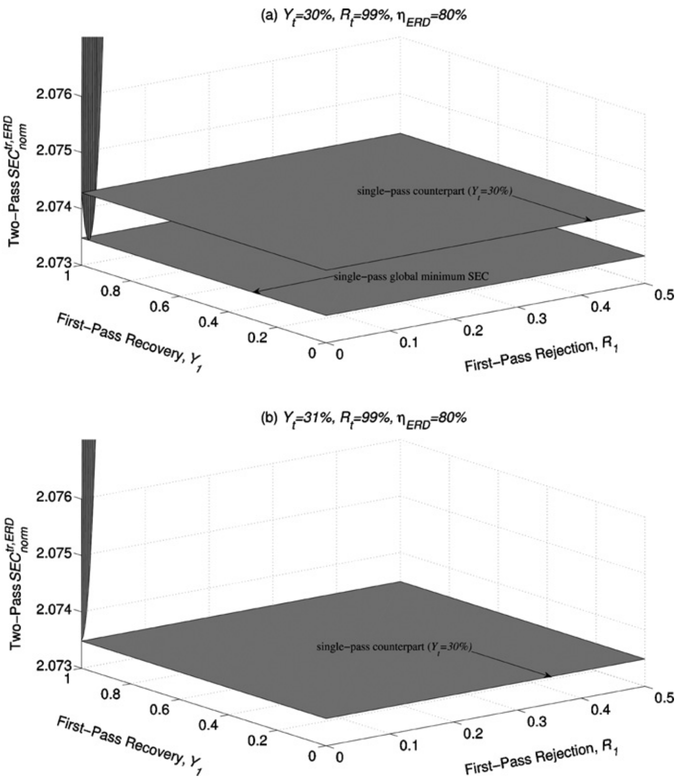

Fig. 8. Variation of SEC of a two-pass RO/NF process and single-pass counterpart with respect to water recovery and salt rejection in the first-pass when the target water recovery is less than (a) and larger than (b) the critical value. (ERD and pump efficiencies are 80% and 100% for the two-pass and single-pass processes and the critical target water recovery is 30.9%). Both plots are set to zoom in on the lower normalized SEC region.

should be recognized, however, that the optimized two-pass process, for the configuration shown in Fig. 5, will always reduce to a single-stage process.

An additional example is presented below for a lower ERD efficiency of 80% (for both passes and for the single-pass operations with $\eta_P = 1$ for all pumps) for which $Y_t^{critical} = 0.309$ (see Eq. (37c)). For $Y_t < 0.309$, there should be a sub-domain, in which a two-pass process will be more energy efficient than its single-pass counterpart. This behavior is illustrated in Fig. 8a, for $Y_t = 0.3$ (i.e., $Y_t < Y_t^{critical}$) and $R_t = 0.99$, demonstrating a local region where $SEC_{norm,2\,passes}^{tr,ERD} < SEC_{norm,1\,pass}^{tr,ERD}$. At $Y_t = 0.31$ (i.e., $Y_t > Y_t^{critical}$) a single-pass is always more energy efficient as shown in Fig. 8b. It is noted that, for the special case of an ideal ERD (i.e., $\eta_E = 1$), $Y_t^{critical} = 0$, a single-pass process will be more energy favorable than a two-pass process given that for all operations $Y_t > Y_t^{critical}$.

The above behavior can be understood by noting that in RO/NF desalting the required feed pressure (or energy, see Eq. (14)) is more sensitive to water recovery than salt rejection. When desalting is accomplished with a two-pass process, the water recovery in each of the two passes will be greater than the target total water recovery (provided that there is permeate production in both passes), as can be verified from Eq. (25) (i.e., $Y_t = Y_1 Y_2$). For example, as can be seen in Fig. 4, when using ideal ERDs (i.e., $\eta_E = 1$), the optimum water recovery approaches zero and the SEC increases with water recovery; therefore, regardless of the target water recovery, the SEC for a two-pass process will be higher than for a single-pass process, due to the fact that even when low rejection membranes are used in the two-pass process, the benefit of reducing the applied pressure (which varies linearly with rejection) is negated by the higher water recovery which results in a much higher osmotic pressure and thus higher applied pressure. On the other hand, when the desired total

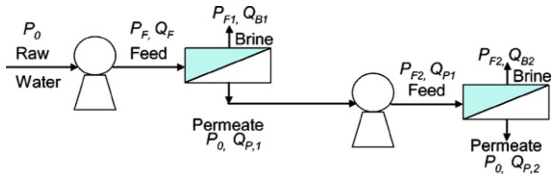

Fig. 9. Schematic of a two-pass RO/NF process without an energy recovery device (ERD).

water recovery is below the optimal recovery, the increased water recovery, in each of the two passes, toward the optimal recovery will reduce the SEC of each pass. For example, in Fig. 4, in the absence of energy recovery, i.e., $\eta_E = 0$, the SEC will be lower when operating at 50% relative to 40% water recovery. Below the critical water recovery (i.e., the optimal recovery for a single-pass process; see Fig. 7), owing to the combined benefit of reducing the salt rejection requirement in each pass, there is a sub-domain in which a two-pass process can be more energy efficient than a single-pass (i.e., single stage) that operates at the same overall target water recovery. Further discussion of the existence of such a domain and comparison with single-pass operation is provided in Section 4.3.

4.3. Energy cost optimization of two-pass RO/NF without energy recovery

In the absence of energy recovery, the two-pass and single-pass desalting processes (Fig. 9) are optimized as discussed in Sections 4.1 and 4.2 by setting $\eta_E = \eta_{E_1} = \eta_{E_2} = 0$. For the condition of $\eta_{E_i} \neq f(Y_i, \Delta P_i)$, Eq. (37c) indicates that the critical water recovery, $Y_t^{critical}$, is 50%, above which the single-pass process will always be more energy efficient than the two-pass process. If $\eta_{E_i} = f(Y_i, \Delta P_i)$, the critical water recovery can only be obtained from a numerical solution of the optimization problem as represented by Eq. (34).

The implication of the above critical water recovery is that, in the absence of energy recovery, a single-pass process is more energy efficient than a two-pass process for $Y_t \geq 0.5$ as illustrated in Fig. 10 for a process with ideal pumps (i.e., $\eta_P = 1$), target total recovery of 60% and salt rejection of 99%. Two solutions are found for the minimum SEC. The first is at $\left(SEC_{norm,2\,passes}^{tr,ERD}\right)_{min} = 4.13$ and $R_1 = 99\%$, $Y_1 = 60\%$. This solution implies that the first-pass fulfills both the water recovery and salt rejection requirements and the second-pass can be eliminated given that it would operate at $R_2 = 0$, $Y_2 = 1$. The second solution which is at $\left(SEC_{norm,2\,passes}^{tr,ERD}\right)_{min} = 4.13$ and $R_2 = 99\%$, $Y_2 = 60\%$, indicates that a second-pass can also fulfill

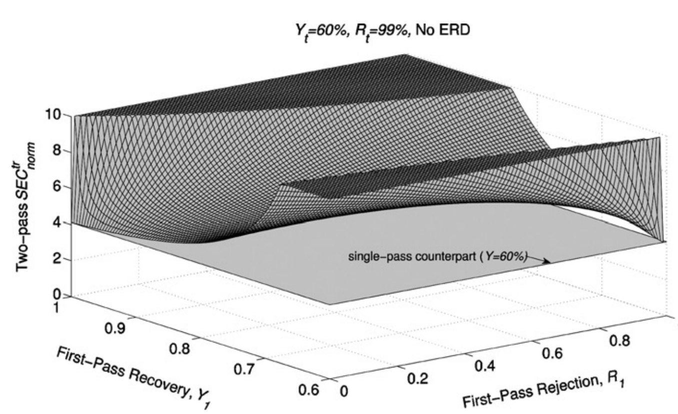

Fig. 10. Variation of normalized SEC of a two-pass membrane desalting process operating up to the thermodynamic restriction (without ERDs and 100% pump efficiency) with respect to salt rejection and water recovery in the first-pass. The target water recovery and salt rejection are 60% and 99%, respectively. The plot is truncated at a normalized SEC value of 10 in order to zoom in on the lower SEC region.

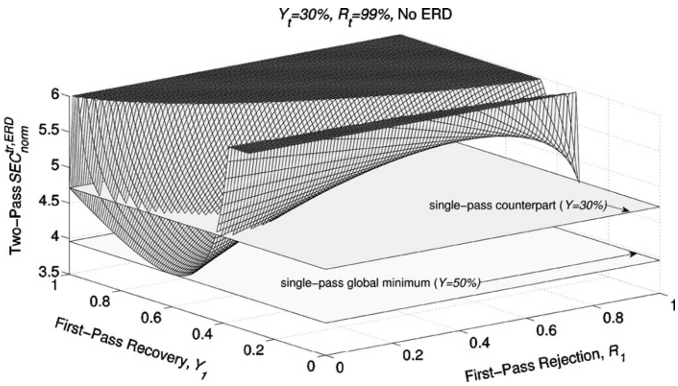

Fig. 11. Variation of the normalized SEC for a two-pass membrane desalting process operating up to the thermodynamic restriction (without ERDs and pumps of 100% efficiency) with respect to salt rejection and water recovery in the first-pass. The target water recovery and salt rejection are 30% and 99%, respectively. The plot is truncated at a normalized SEC value of 6 in order to zoom in on the lower SEC region.

both the water recovery and salt rejection requirements; thus, for this solution the first-pass can be eliminated given that it would operate at $R_1 = 0$, $Y_1 = 1$. In other words, for operation at the limit of the thermodynamic restriction, the energy-optimized two-pass RO/NF process is a single-pass RO/NF process. On the other hand, below the critical total water recovery of 50%, there is an operational sub-domain in which the two-pass process can be more energy efficient than its single-pass counterpart as illustrated in Fig. 11 for $Y_t = 0.3$ and $R_t = 0.99$. Specifically, for the above overall water recovery and salt rejection, the operational points between ($R_1 = 0$, $Y_1 = 60\%$) and the intersection of the single-pass counterpart plane ($\mathrm{SEC}^{\mathrm{tr}}_{\mathrm{norm,1\,pass}} = 4.71$) with the two-pass surface are of lower normalized SEC relative to the single-pass process, by as much as 16% when the first-pass is operated at $R_1 = 0$, $Y_1 = 60\%$. It is important to recognize that, when $Y_t < Y_t^{\mathrm{critical}}$, although a two-pass process can be more energy favorable, in the absence of energy recovery, than its single-pass counterpart (operated at the same overall water recovery, i.e., 30%), this would require operation at low water recovery. It is stressed that the optimized two-pass is actually a pseudo-two-pass, i.e., a single-pass with an unpressurized bypass (since ($R_1 = 0$, $Y_1 = 60\%$), ($R_2 = 99\%$, $Y_2 = 50\%$)), which indicates that a two-pass process can never be more energy efficient than a single-pass process.

4.4. The constraint of membrane rejection

The previous optimization of the two-pass process with respect to energy consumption and the comparison with a single-pass process, assumed the availability of a membrane that can achieve the required salt rejection even with a single-pass process. However, if a membrane of the required overall desired rejection (i.e., R_t) in a single-pass is unavailable, then a two-pass is the only feasible approach, whereby the rejection of the available membrane (i.e., of the highest available rejection $R_{\max}$) represents the constraint $R_{\max} < R_t$ that has to be considered when optimizing the two-pass process. Accordingly, in addition to the previous constraints ($Y_t \le Y_1 \le 1$ and $0 \le R_1 \le R_t$; Eq. (35b), the following two additional constraints are introduced in the optimization of Eq. (33):

$$0 \le R_1 \le R_{\max} \quad \text{and} \quad 0 \le R_2 \le R_{\max} \tag{38}$$

For the purpose of illustrating the implications of the above constraints, it is convenient to consider the special case of a two-pass operation with ideal energy recovery (i.e., $\eta_E = 1$) and feed pumps (i.e., $\eta_p = 1$) for both passes. A numerical solution of the above optimization problem (a search for the minimum $\mathrm{SEC}^{\mathrm{tr,ERD}}_{\mathrm{norm,2\,passes}}$ over the rejection range given by Eq. (38) and water recovery range of $Y_t \le Y_1 \le 1$), revealed that the optimal salt rejection for the first-pass is the maximum salt rejection that can be achieved by a membrane of the highest available rejection, i.e., $R_{1,\mathrm{opt}} = R_{\max}$. It is also important to note that, in order to achieve the target overall rejection R_t, $R_{\max}$ should not be less than $1-\sqrt{1-R_t}$ (determined by Eq. (29)). The specific energy consumption of the above two-pass desalination process, at the limit of the thermodynamic restriction, is obtained by substituting $R_1 = R_{1,\mathrm{opt}} = R_{\max}$, $R_t = R_1 + R_2 - R_1 R_2$, and $Y_t = Y_1 Y_2$ in Eq. (34), to yield:

$$\mathrm{SEC}^{\mathrm{tr,ERD}}_{\mathrm{norm,2\,passes}} = \frac{R_{\max}}{Y_2 - Y_t} + \frac{R_t - R_{\max}}{1 - Y_2} \tag{39}$$

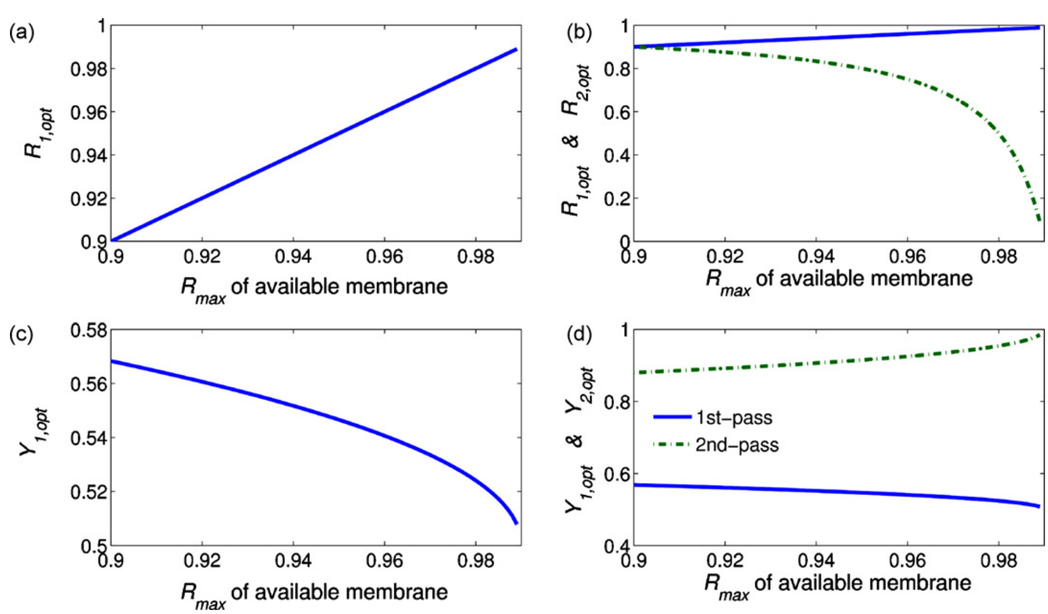

Fig. 12. Optimization of a two-pass RO/NF process with ERDs and pumps of 100% efficiency under the constraint of membrane rejection. (The target water recovery and salt rejection are 50% and 99%, respectively.)

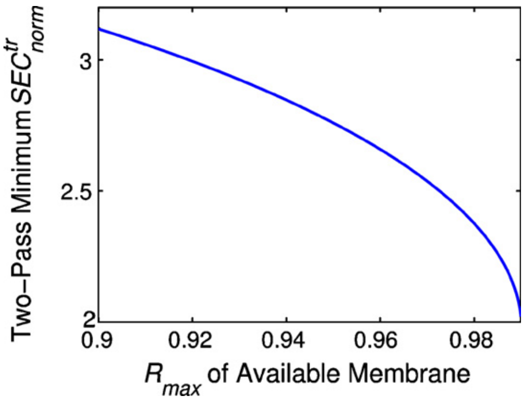

Fig. 13. The variation of the minimum SEC for a two-pass membrane desalination process (Eq. (41)), with ideal pumps and ERDs (i.e., $\eta_P = 1$ and $\eta_E = 1$) and target water recovery and salt rejection of 50% and 99%, respectively, operated up to the limit of the thermodynamic restriction, with the highest rejection of the available membrane (i.e., R_{max}).

where all the efficiencies (pumps and ERDs) are taken to be ideal in this example. From Eq. (39), the second-pass optimal recovery, $Y_{2,\mathrm{opt}}$, is obtained by setting $\left(\partial \mathrm{SEC}^{\mathrm{tr,ERD}}_{\mathrm{norm,2\,passes}}/\partial Y_2\right) = 0$,

$$Y_{2,\mathrm{opt}} = \frac{\sqrt{R_{\max}} + Y_t\sqrt{R_t - R_{\max}}}{\sqrt{R_{\max}} + \sqrt{R_t - R_{\max}}} \tag{40}$$

and the global normalized minimum energy consumption for the overall two-pass process is obtained by substituting Eq. (40) in Eq. (39) yielding:

$$\left(\mathrm{SEC}^{\mathrm{tr,ERD}}_{\mathrm{norm,2\,passes}}\right)_{\min} = \frac{R_t + 2\sqrt{R_{\max}(R_t - R_{\max})}}{(1 - Y_t)} \tag{41}$$

An example of the variation of the salt rejection and water recovery for the two passes, at the optimal minimum energy point (Eq. (41)), as obtained from the above constrained optimization, is provided in Fig. 12a–d, for a target overall salt rejection of 99% and total water recovery of 50%, with the corresponding $\left(\mathrm{SEC}^{\mathrm{tr,ERD}}_{\mathrm{norm,2\,passes}}\right)_{\min}$ shown in Fig. 13. The analysis demonstrates the following behavior, which is apparent in Fig. 12: (a) the optimal rejection for the first-pass is equal to that which is feasible by the available membrane of the highest rejection, with the second-pass rejection decreasing with $R_{\max}$, (b) the optimum first-pass water recovery decreases with increasing $R_{\max}$, while the second-pass water recovery increases with increasing $R_{\max}$. Finally, it is noted that $\left(\mathrm{SEC}^{\mathrm{tr,ERD}}_{\mathrm{norm,2\,passes}}\right)_{\min}$ is a sensitive function of $R_{\max}$ showing, for example, about 58% decrease in the SEC as $R_{\max}$ increases from 0.9 to 0.99. The above analysis demonstrates that when operating a two-pass process it is desirable to operate the first-pass at the highest possible rejection.

5. Effect on the SEC of recycling of the second-pass retentate stream to the first-pass feed stream in a two-pass membrane desalting process

5.1. Analysis

In considering the possible operation of a two-pass process, it is interesting to evaluate the potential impact of recycling the concentrate stream of the second-pass to the feed of the first-pass (in order to reduce the salinity of the primary feed, Fig. 14) on the SEC. The rates of work done by the first-pass pump, $\dot{W}^{\mathrm{1st,recycle}}_{\mathrm{tr,ERD}}$, and second-pass pump, $\dot{W}^{\mathrm{2nd,recycle}}_{\mathrm{tr,ERD}}$, at the limit of the thermodynamic restriction, are given by (see Eq. (20)):

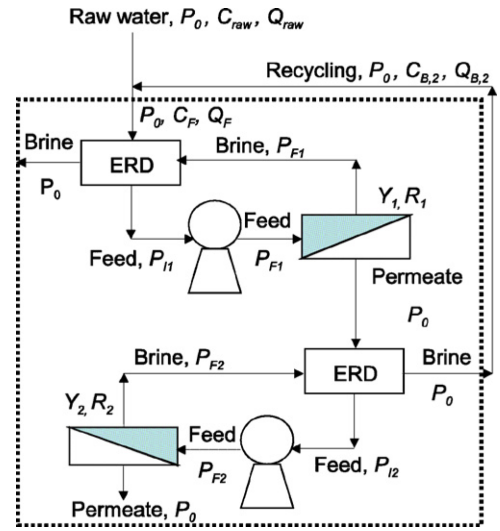

Fig. 14. Schematic representation of a two-pass membrane desalting process with recycling of the concentrate (i.e., retentate) stream of the second-pass to the feed stream of the first-pass.

$$\dot{W}^{\mathrm{1st,recycle}}_{\mathrm{tr,ERD}} = \left(\frac{R_1\pi_{0,1}}{1 - Y_1}\right)\left(\frac{Q_{f,1} - \eta_{E_1}(1 - Y_1)Q_{f,1}}{\eta_{P_1}}\right) \tag{42a}$$

$$\dot{W}^{\mathrm{2nd,recycle}}_{\mathrm{tr,ERD}} = \left(\frac{R_2\pi_{0,2}}{1 - Y_2}\right)\left(\frac{Q_{f,2} - \eta_{E_2}(1 - Y_2)Q_{f,2}}{\eta_{P_2}}\right) \tag{42b}$$

in which η_{P_1}, η_{P_2} and η_{E_1} and η_{E_2} are the pump and ERD efficiencies for the first- and second passes, respectively, R_1, R_2 are salt rejections in the first- and second-pass, respectively, Y_1, Y_2 are the water recoveries in the first- and second-pass, respectively, $Q_{f,1}$, $Q_{f,2}$ are the feed flow rates to the first- and second-pass, respectively, and $\pi_{0,1}$, $\pi_{0,2}$ are the osmotic pressures of the feed to the first- and second-pass RO/NF, respectively, given by:

$$\pi_{0,2} = f_{os}C_{p,1} = f_{os}(1 - R_1)C_{f,1} = (1 - R_1)\pi_{0,1} \tag{43}$$

The feed, brine and permeate flow rates of the second-pass, $Q_{f,2}$ and $Q_{b,2}$, $Q_{p,2}$ respectively, calculated by solute mass balances, are given as:

$$Q_{f,2} = Q_{p,1} = Y_1(Q_{raw} + Q_{b,2}) \tag{44a}$$

$$Q_{b,2} = (1 - Y_2)Q_{p,1} \tag{44b}$$

$$Q_{p,2} = Y_t Q_{raw} \tag{44c}$$

where Q_{raw} is the raw feed water flow rate, Y_t is the overall target water recovery, and Y_2 is defined by:

$$Y_2 = \frac{Q_{p,2}}{Q_{p,1}} \tag{44d}$$

The relationship among Y_1, Y_2 and Y_t are obtained by combining Eqs. (44a)–(44d):

$$Y_t = \frac{Y_1 Y_2}{1 - Y_1(1 - Y_2)}$$
$$Y_1 Y_2 = \frac{Y_t}{1 - Y_t}(1 - Y_1) \tag{45}$$

The feed concentration to the first-pass, $C_{f,1}$, which is the flow-rate-weighted average of the raw water stream concentration (C_{raw}) and second-pass brine stream concentration ($C_{b,2}$)), is given by:

$$C_{f,1} = \frac{C_{raw}Q_{raw} + C_{b,2}Q_{b,2}}{Q_{raw} + Q_{b,2}} \tag{46}$$

where $C_{b,2}$ is given by:

$$C_{b,2} = \frac{1 - Y_2(1 - R_2)}{1 - Y_2} C_{p,1} \tag{47}$$

and R_2 is given by:

$$R_2 = 1 - \frac{C_{p,2}}{C_{p,1}} \tag{48}$$

in which $C_{p,1}$ and $C_{p,2}$, the permeate concentration of the first and second passes, respectively, are given by:

$$C_{p,1} = (1 - R_1) \times C_{f,1} \tag{49}$$

$$C_{p,2} = (1 - R_t) \times C_{raw} \tag{50}$$

where R_t is the target water recovery. The relationship between $C_{f,1}$ and C_{raw} is derived by combining Eqs. (43)–(50):

$$\frac{C_{f,1}}{C_{raw}} = \frac{1 - Y_1(1 - Y_2)}{1 - Y_1(1 - R_1)[1 - Y_2(1 - R_2)]} \tag{51}$$

while the relationship among R_1, R_2 and R_t is given by:

$$\begin{aligned} R_t &= 1 - \frac{C_{p,2}}{C_{raw}} = 1 - \frac{(1 - R_2)(1 - R_1)C_{f,1}}{C_{raw}} \\ &= 1 - \frac{(1 - R_1)(1 - R_2)[1 - Y_1(1 - Y_2)]}{1 - Y_1(1 - R_1)[1 - Y_2(1 - R_2)]} \end{aligned} \tag{52}$$

The normalized two-pass SEC for a given total target water recovery, Y_t, and overall salt rejection, R_t, is derived from the combination of Eqs. (42)–(52),

$$\begin{aligned} &\mathrm{SEC}^{tr,ERD,recycle}_{norm,2\,passes} \\ &= \frac{\mathrm{SEC}^{ERD,recycle}_{tr,2\,passes}}{\pi_0} = \frac{\dot{W}^{1st,recycle}_{tr,ERD} + \dot{W}^{2nd,recycle}_{tr,ERD}}{Y_1 Y_2 Q_{f,1} f_{os} C_{raw}} \\ &= \frac{[1 - Y_1(1 - Y_2)]}{1 - Y_1(1 - R_1)[1 - Y_2(1 - R_2)]} \\ &\times \frac{\left(\frac{R_1}{1-Y_1}\right)\left(\frac{1-\eta_{E_1}(1-Y_1)}{\eta_{P_1}}\right) + \left(\frac{R_2(1-R_1)Y_1}{1-Y_2}\right)\left(\frac{1-\eta_{E_2}(1-Y_2)}{\eta_{P_2}}\right)}{Y_1 Y_2} \end{aligned} \tag{53}$$

Eq. (53) which is applicable for operation at the limit of the thermodynamic restriction, is subject to the constraints of $0 \le R_1 < 1$, $0 \le R_2 < 1$, $0 < Y_1 \le 1$, $0 < Y_2 \le 1$, and Eqs. (45) and (52).

In illustrating the impact of recycling the second-pass retentate stream to the first-pass feed stream, the efficiencies of the feed pumps are taken to be independent of water recovery and feed pressure. The feed flow rate to the second-pass will be lower than in the first-pass, and thus the second-pass feed pump will operate at a lower efficiency relative to the first-pass feed pump – a well-known characteristic pump behavior. Therefore, in the present conservative analysis we consider the efficiency of the first- and second-pass feed pumps to be identical. As a consequence, the energy optimization is only affected within a pump efficiency factor which will drop out of the comparative analysis when considering the ratio of energy consumption for the two-pass and single stage processes. Extensive numerical optimizations have been done for different salt water recoveries, salt rejections and ERD efficiencies in the range [0–1], all for ideal feed pumps (i.e., $\eta_P = 1$). Specific examples, that illustrate the process with second-pass retentate recycle are presented in Sections 5.2–5.4 for desalting, with energy recovery at 100% and 80% efficiency and without energy recovery, at water recovery of 30% which was the typical recovery level employed in a recently published study [15] on two-pass membrane desalting of seawater.

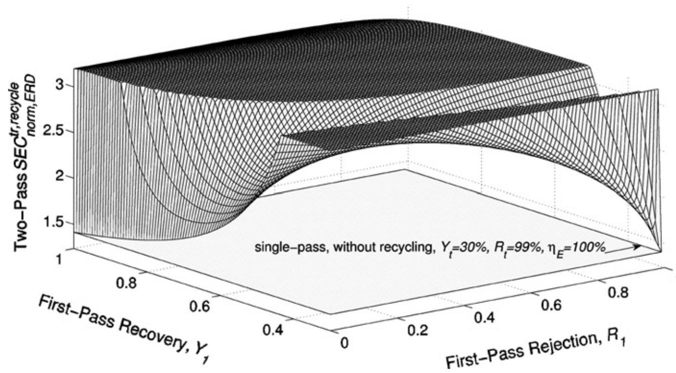

Fig. 15. Variation of the normalized SEC of a two-pass membrane desalting process (with ERDs of 100% efficiency in each pass) with respect to salt rejection and water recovery in the first-pass, operated up to the thermodynamic restriction, for operation with recycling of the second-pass brine stream to the first-pass feed stream. The target water recovery and salt rejection are 30% and 99%, respectively. The plot is truncated at a normalized SEC of 3.2 in order to zoom in on the lower SEC region. The bottom plane in the figure identifies the optimum salt rejection of the first-pass (i.e., zero for this case).

5.2. Two-pass desalting with retentate recycling and 100% energy recovery

For the case of desalting with ideal energy recovery devices (i.e., 100% efficiency), the normalized two-pass SEC is obtained from Eq. (53) by setting $\eta_{E_1} = \eta_{E_2} = 1$. As an example, the normalized SEC, with ideal pumps ($\eta_{P_1} = \eta_{P_2} = 1$) is plotted in Fig. 15, for desalting operation at the limit of the thermodynamic restriction, for a target overall water recovery (Y_t) and salt rejection (R_t) of 30% and 99%, respectively. The bottom plane in Fig. 15 is the normalized SEC for a single-pass process without recycling, also operating at the limit of the thermodynamic restriction, with the same target recovery and salt rejection as above. The results depicted in Fig. 15 show that a single-pass process (without recycling) is more energy efficient than a two-pass with retentate recycling, provided that both cases target the same overall water recovery and salt rejection.

5.3. Two-pass desalting with retentate recycling with non-ideal energy recovery

Illustration of the effect of non-ideal energy recovery on the normalized two-pass SEC is shown in Fig. 16, for the case of 80%

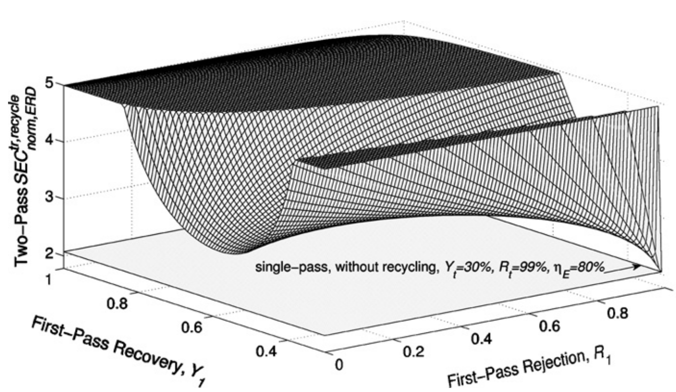

Fig. 16. Variation of normalized SEC of a two-pass process (with ERDs of 80% efficiency in each pass) with respect to salt rejection and water recovery in the first-pass, operated up to the thermodynamic restriction, for operation with recycling of the second-pass brine stream to the first-pass feed stream. The target water recovery and salt rejection are 30% and 99%, respectively. The plot is truncated at a normalized SEC of 5 in order to zoom in on the lower SEC region. The bottom plane in the figure identifies the optimum salt rejection of the first-pass (i.e., 99% for this case).

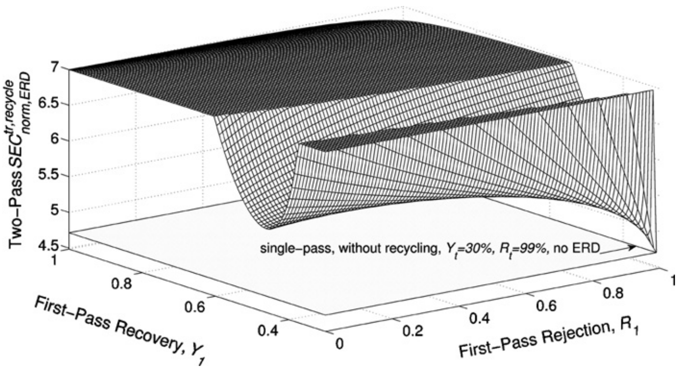

Fig. 17. Variation of normalized SEC of a two-pass process (without ERDs in either pass) operated at the thermodynamic restriction, with the recycling of the second-pass brine stream to the first-pass feed stream, with respect to salt rejection and water recovery in the first-pass. The target water recovery and salt rejection are 30% and 99%, respectively. The plot is truncated at a SEC value of 7 in order to zoom in on the lower SEC region. The bottom plane in the figure identifies the optimum salt rejection of the first-pass (i.e., 99% for this case).

energy recovery (i.e., $\eta_{E_1} = \eta_{E_2} = 0.8$ in Eq. (53)) and ideal pumps (i.e., $\eta_{P_1} = \eta_{P_2} = 1$), for the same target overall water recovery and salt rejection as in Fig. 15 (i.e., $Y_t = 0.3$ and $R_t = 0.99$). The results show that, for a desalting operation up to the limit of the thermodynamic restriction, a single-pass process is more energy efficient than a two-pass process even with complete recycling of the retentate stream of the second-pass.

5.4. Two-pass desalting with retentate recycling without energy recovery

For the case of desalting without energy recovery, the normalized two-pass SEC as obtained from Eq. (53) by setting $\eta_{E_1} = \eta_{E_2} = 0$. An example of the above system performance with respect to the normalized SEC, for the same target recovery and salt rejection as in Figs. 15 and 16 (i.e., $Y_t = 0.3$ and $R_t = 0.99$) is shown in Fig. 17 for operation up to the thermodynamic restriction, also with ideal feed pumps ($\eta_{P_1} = \eta_{P_2} = 1$). The results indicate that, for the same target of total recovery and salt rejection, a single-pass process operation will be always more efficient than a two-pass process with recycling irrespective of the distributions of the water recovery and salt rejection between the two passes. Although membrane desalting via a two-pass process with recycling is less energy efficient than a single-pass process, recycling in a two-pass process is a rationale approach to decreasing the specific energy consumption of a two-pass process.

It is emphasized that the present comparative analysis of the two-pass and single stage (or single-pass) processes considered energy cost which is a major direct factor affecting water production cost. It should be recognized, however, that there are other considerations involved in the cost analysis of membrane desalination plants that include, but are not limited to, product water recovery constraints that may be imposed by mineral scaling, fouling and operational pressure limits, membrane and brine management costs [4], as well as costs associated with feed pre-treatment and post-treatment, in addition to investment costs. It is acknowledged that considerations of plant capital and operating costs, in addition to energy cost, can affect the optimal product water recovery at which the cost of water production is minimized. However, inclusion of the above considerations will not alter the present conclusions regarding the relative energy efficiency of the two-pass to the single stage (or single-pass) desalination processes. There can also be situations in which the use of a two-pass process is desirable, irrespective of its lower energy efficiency, such as in the case of difficult to achieve rejection of certain species as in the requirement for boron removal [18]. Finally, we note that considerations of process optimization of operation above the pressure limit imposed by the thermodynamic restriction and the effect of concentration polarization [14] are the subject of an ongoing study.

6. Conclusions

A systematic evaluation was carried out of the energy consumption of two-pass membrane desalination relative to a single-pass process operating at the limit of the thermodynamic restriction. The present analysis considered both the impact of pump and energy recovery efficiencies, membrane rejection, and the possibility of retentate recycling from the second to the first-pass. The present results indicate that if the desired overall salt rejection can be achieved in a single-pass, then a single-pass configuration will be more energy favorable than a two-pass process configuration for the same level of total water recovery and salt rejection. However, if a membrane is not available to achieve the desired rejection in a single-pass, then a two-pass configuration will be the viable alternative, with the lowest energy consumption attained when the first-pass uses a membrane of the highest available salt rejection. It is noted that for certain cases in which desalting is accomplished at recoveries below the critical water recovery (i.e., the optimal recovery for a single stage), there can be an operational sub-domain in which the two-pass process can be more energy efficient than a single-pass counterpart (but only if the latter which is not operating at its globally optimal state). Although retentate recycling from the second-pass to the first-pass feed can reduce the energy consumption for the two-pass process, the optimization solution of a two-pass process is a single-pass process.

Acknowledgments

The present work was supported, in part, by the California Department of Water Resources, the Metropolitan Water District of Southern California, the University of California Water Resources Center, the United States Environmental Protection Agency and the International Desalination Association (IDA) Channabasappa Memorial Scholarship awarded to Aihua Zhu.

Appendix A.

In order to illustrate the implication of operating a two-pass membrane desalting process with retentate recycling subject to membrane rejection constraint (from the first-pass concentrate to the first-pass feed), we consider the following example of a two-pass desalting process operating at $R_t = 0.99$ and $Y_t = 0.5$ (i.e., the optimal recovery for a single-pass without energy recovery) with ideal pumps ($\eta_P = 1$) and ideal energy recovery ($\eta_E = 1$)), and where the highest rejection membrane available is of $R_{max} = 0.9$. The impact of recycling on the SEC can be assessed by first considering the optimal SEC without recycle, and then adding the recycle stream to the process and recalculating the resulting SEC as per Eq. (53) for the above case of ideal pump and ERDs,

$$\left(\mathrm{SEC}^{\mathrm{tr,ERD}}_{\mathrm{norm,2\,passes}}\right)_{\mathrm{recycle}} = \frac{[1 - Y_1(1 - Y_2)]}{1 - Y_1(1 - R_1)[1 - Y_2(1 - R_2)]} \times \left[\frac{R_1}{Y_2(1 - Y_1)} + \frac{R_2(1 - R_1)}{1 - Y_2}\right] \tag{A1}$$

For the above example, the optimum salt rejection for the first-pass and second-pass recovery are $R_1 = 0.9$ and $Y_2 = 0.88$, respectively (Fig. 12a-d). Upon adding the recycle stream the overall water recovery based on the total feed to the first-pass is given as

$$Y_f = \left(\frac{Y_t Q_{raw}}{Q_{f,1}}\right) \tag{A2}$$

where Q_{raw} is the raw feed to the first-pass and $Q_{f,1}$ is the actual first-pass feed.

$$Q_{f,1} = Q_{raw} + Q_{b,2} \tag{A3}$$

in which the retentate stream flow rate (recycled to the first-pass feed) is given as

$$Q_{b,2} = \left(\frac{(1-Y_2)}{Y_2}\right) \times Y_t Q_{raw} \tag{A4}$$

The water recovery for the two-pass process with retentate recycling, as calculated from Eqs. (A2)–(A4), is $Y_f = 0.47$ which is lower than the actual total recovery of 50% (Note: $Q_{f,1} = 1.0682 Q_{raw}$ and $Q_{b,2} = 0.0682 Q_{raw}$).

The first-pass water recovery, Y_1, retentate (i.e., concentrate) stream flow rate ($Q_{b,1}$), and first-pass retentate concentration ($C_{b,1}$) are calculated as

$$Y_1 = \frac{Y_t}{Y_2} \tag{A5}$$

$$Q_{b,1} = (1 - Y_1) Q_{f,1} \tag{A6}$$

$$C_{b,1} = \frac{(C_{raw} Q_{raw} - C_{p,2} Q_{p,2})}{Q_{b,1}} \tag{A7}$$

which after substitution of the appropriate numerical values result in $Y_1 = 0.5318$, $Q_{b,1} = 0.5 Q_{raw}$ and $C_{b,1} = 1.99 C_{raw}$. Finally, the first-pass feed and permeate concentrations (Eq. (11) and (12)) and second-pass rejection (Eq. (26)) are computed from

$$C_{f,1} = \left[\frac{(1-Y_1)}{(1 - Y_1(1-R_1))}\right] C_{b,1} \tag{A8}$$

$$C_{p,1} = (1 - R_1) C_{f,1} \tag{A9}$$

$$R_2 = \frac{1 - C_{p,2}}{C_{p,1}} \tag{A10}$$

resulting in $C_{f,1} = 0.984 C_{raw}$, $C_{p,1} = 0.0984 C_{raw}$, and $R_2 = 0.8984$.

Given the above resulting values of the two-pass process (Eq. (A1)) with second-pass concentrate recycling to the first-pass, $\left(SEC^{tr,ERD}_{norm,2\,passes}\right)_{recycle}$ is computed to be 2.83, compared to $SEC^{tr,ERD}_{norm,2\,passes} = 3.12$ without recycle, representing a 9.3% reduction in the energy consumption with retentate recycling. The above example with complete second-pass brine recycle represents the maximum possible energy saving (i.e., frictional loses are neglected). Nonetheless, the normalized SEC for a two-pass process with complete retentate recycling is still 43% higher than the energy consumption for a single-pass process for the same overall target water recovery and rejection (i.e., $SEC^{tr,ERD}_{norm} = 1.98$, Eq. (22)).

Nomenclature

C	salt concentration (mol/l)
C_f	feed salt concentration (mol/l)
C_p	permeate salt concentration (mol/l)
C_r	retentate salt concentration (mol/l)
ERD	energy recovery device
L_p	membrane permeability (m/s Pa)
ΔP	applied pressure, transmembrane pressure (Pa)
Q_f	feed flow rate (m^3/s)
Q_p	permeate flow rate (m^3/s)
Q_b	brine flow rate (m^3/s)
R	salt rejection
SEC	specific energy consumption
Y	water recovery

Greek letters

η	efficiency
π	osmotic pressure (Pa)
$\overline{\Delta\pi}$	average osmotic pressure difference (Pa)

Subscripts

1	first-pass
2	second-pass
2 passes	two-pass process
E	ERD
norm	normalized to the feed osmotic pressure
opt	optimum
p	permeate
P	pump
t	total/target
tr	thermodynamic restriction

Superscripts

1st	first-pass
2nd	second-pass
recycle	retentate recycling of the second-pass to the feed of the first-pass

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