A Unified Model-Based Analysis and Optimization of Specific Energy Consumption in BWRO and SWRO

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ABSTRACT: A unified mathematical model is developed to describe both brackish water (BW) and seawater (SW) reverse osmosis (RO) desalination processes. The model contains two dimensionless parameters: \( \kappa \), quantifying the effect of retentate pressure drop, and \( \gamma \), reflecting the membrane capacity demand ratio. A \( \gamma \) vs. \( \kappa \) map derived from data obtained from RO desalination plants worldwide is used to show that BWRO and SWRO are in completely different regions. The minimization of specific energy consumption (SEC) is formulated and solved as a nonlinear optimization problem using representative values of \( \gamma \) and \( \kappa \) in both BWRO and SWRO. Several computational case studies are carried out to demonstrate the differences in operating BWRO and SWRO. Discussions are made on the effect of fractional recovery, RO configurations (single-stage, two-stage, and two-stage with booster pump) as well as brine recirculation on SEC.

INTRODUCTION

Specific energy consumption (SEC), or pump energy consumption divided by water production rate, is a very important topic in RO desalination.\(^1,2\) There have been significant research and development efforts in model-based analysis and optimization of RO design and operation.\(^3-9\) Model-based control has also been developed recently to reduce SEC in a pilot-scale RO system.\(^10,11\)

In two previous papers,\(^12,13\) the author provided a comprehensive analysis of single- and multistage SWRO with/without energy recovery device (ERD) from first-principles, based on the assumption of negligible retentate pressure drop. Several dimensionless parameters (\( \gamma \), \( \alpha \), and \( \beta \)) were introduced to show the coupled behavior between membrane property (area and permeability), feed conditions (flow rate and salinity), and operating conditions (hydraulic pressure difference and fractional recovery). Later on, the retentate pressure drop effect was explicitly accounted for in the optimization model for both single-train and multitrain BWRO processes.\(^14,15\) A validation of model-based optimization results was carried out in a BWRO plant in Chino, California, and a 10% decrease in SEC and a substantial reduction in brine disposal cost were demonstrated.\(^16\)

As a continuation of the author’s previous work, this paper aims to utilize a unified dimensionless model to explain the similarities and differences between SWRO and BWRO. The model is based on several dimensionless parameters, including \( \kappa \), quantifying the effect of retentate pressure drop, and \( \gamma \), a previously derived parameter reflecting the membrane capacity demand ratio.\(^12\) Data from both BWRO and SWRO plants worldwide are used to show the typical ranges of \( \gamma \) and \( \kappa \). Using representative values of \( \gamma \) and \( \kappa \) in both BWRO and SWRO, a mathematical model is formulated to reduce SEC by optimizing a dimensionless pressure parameter \( \alpha \). The optimal SECs in both BWRO and SWRO using three different RO configurations (single-stage, two-stage, and two-stage with booster pump) are compared. The effect of brine recirculation on SEC is also discussed.

DIMENSIONLESS RO MODEL

On the basis of assumptions of Darcy’s law for mass transfer and quadratic dependence of retentate pressure drop on velocity, the following mathematical model was derived to describe a single-stage RO process:\(^14\)

\[
-\frac{dQ(x)}{dx} = AL_\pi \left( \Delta P - \frac{Q_0}{Q} \Delta \pi_0 \right)
\]

\[
\frac{d(\Delta P(x))}{dx} = -kQ^2
\]

\[
Q(x) = Q_0 @ x = 0
\]

\[
\Delta P(x) = \Delta P_0 @ x = 0
\]

(1)

where \( Q \) is the retentate flow rate, \(-dQ\) is the flow rate of water across membrane of area \( dA \) (\( dA = Adx \); \( x \) is the distance from entrance normalized by the pressure vessel length, and \( A \) is the total area of all RO elements in this stage), \( L_\pi \) is the membrane hydraulic permeability, \( \Delta P \) and \( \Delta \pi \) are the differences in hydraulic pressures and osmotic pressures across the membrane, respectively. \( \Delta \pi_0 \), \( Q_0 \), and \( \Delta P_0 \) are \( \Delta \pi \), \( Q \), and \( \Delta P \) at the stage entrance. \( k \) is a coefficient describing the pressure drop along the pressure vessel in the retentate stream. Note that the pressure differential in the permeate stream is typically small. More detailed assumptions and justifications of eq 1 are discussed in the author’s previous work.\(^14\) This coupled differential equation captures the profile of driving force and water flux, and is more advanced than standard membrane projection model in literature, which uses averaged flux and driving force.

Defining \( \alpha = \Delta \pi_0 / \Delta P_0 \) \( \gamma = AL_\pi \Delta \pi_0 / Q_0 \kappa = kQ_0^2 / \Delta \pi_0 \) \( q = Q / Q_0 \) \( p = \Delta P / \Delta P_0 \) the following equation is derived:
An integration of eq 2 would provide the profiles of \( p(x) \) and \( q(x) \) along the RO stage. The fractional recovery of water is then calculated as \( Y = 1 - q(1) \), where \( q(1) \) is \( q \) evaluated at \( x = 1 \), or the end of this stage.

It is seen from eq 2 that the RO system is characterized by three different dimensionless parameters \( \alpha, \gamma, \) and \( \kappa \), all described in the form of ratios. As discussed in previous publications, \( \alpha \) is the ratio of osmotic pressure difference to hydraulic pressure difference across the membrane at the entrance of the stage, and \( \gamma \) is the ratio of flow rate across the membrane assuming a constant drive force of \( \Delta \pi_0 \) to the retentate flow rate at the entrance of the stage. \( \gamma \) may be considered as a measure of the membrane capacity demand ratio. \( \kappa \) introduced in this work is the ratio of maximum retentate pressure drop (i.e., the theoretical pressure drop when there is no water recovery, or the retentate flow rate is always the same as the intake flow rate) to the osmotic pressure difference at the entrance of the stage. It is a measure of driving force loss that adversely affects the water production. According to fluid mechanics of channel flow, \( \kappa \) can be described as follows

\[
\kappa = kQ_i^2/\Delta \pi_0 = 2f(L_{ps}/D_{hi})\rho(Q_i/A_c)^2/\Delta \pi_0
\]

where \( f \) is the Fanning friction coefficient, \( D_{hi} \) is the hydraulic diameter between membrane sheets, \( A_c \) is the total cross-sectional area in the RO stage for retentate flow, and \( L_{ps} \) is the total length of the pressure vessel that houses the membrane elements in series. Apparently, \( \kappa \) will reduce if more pressure vessels are put in parallel in a RO stage, or fewer membrane elements are enclosed in a pressure vessel.

The introduction of dimensionless parameters simplifies the analysis of RO processes as the results are scalable. Because BWRO and SWRO differ in \( \Delta \pi_0 \) (around 10–20 psi in BWRO and 390 psi in SWRO), they may exhibit different process characteristics and require different design and operation strategies.

Equation 2 can be easily extended to describe RO networks with complicated configurations. For example, a RO system with \( N \) stages in series may be modeled as follows

\[
\frac{dp(x)}{dx} = -\kappa q_i^2(x), \quad i = 1, 2, ..., N
\]

\[
\frac{dq(x)}{dx} = -\gamma \left( \frac{p(x)}{\alpha_i} - \frac{1}{q(x)} \right), \quad i = 1, 2, ..., N
\]

\[
p(x) = 1, \quad @x = i - 1, \quad i = 1, 2, ..., N
\]

\[
q(x) = 1, \quad @x = i - 1, \quad i = 1, 2, ..., N
\]

where \( p_i \) and \( q_i \) are defined based on the ratio of \( \Delta P(x) \) and \( Q(x) \) in RO stage \( i \) to the ones at the entrance of stage \( i \).

The relationships between \( p \) and \( q \) at the stage level and those at the system level are shown as follows

\[
p(x) = p(x) \prod_{i=0}^{N-1} p_i(k), \quad i - 1 < x \leq i, \quad i = 1, 2, ..., N
\]

\[
q(x) = q_i(x) \prod_{i=0}^{N-1} q_i(k), \quad i - 1 < x \leq i, \quad i = 1, 2, ..., N
\]

where \( p_0(0) \equiv q_0(0) \equiv 1 \). The system recovery at the end of all stages \( Y = 1 - \prod_{i=1}^{N} q_i(1) \).

The parameters \( \alpha, \gamma, \) and \( \kappa \) should be updated as eq 4 is solved sequentially from stage to stage. For example, in a typical two-stage RO process with a 2:1 array to achieve a high system recovery and to maintain a relatively uniform feed pressure. Therefore, \( \Delta \pi_0 \) is solved, \( \alpha, \gamma, \) and \( \kappa \) are determined so that the second stage can be solved in a similar way. The system recovery at the end of the second stage is calculated as \( Y = 1 - q_1(1)q_2(2) \).

The SEC normalized by the feed osmotic pressure, or NSEC, is a dimensionless number

\[
\text{NSEC} = \frac{q_i \Delta P_{pump}}{\eta_{pump} (Q_0) \Delta \pi_0}
\]

where \( \Delta P_{pump} \) is the pressure increase across the pump, \( \eta_{pump} \) is the pump efficiency. Note that \( \Delta P_p = P_{bp} + \Delta P_{pump} - P_{ip} \) where \( P_{bp} \) is the feed pressure before pump, and \( P_p \) is the permeate pressure. Therefore

\[
\text{NSEC} = \frac{1}{\eta_{pump} (1 - \prod_{i=1}^{N} q_i(1))}
\]

The minimization of NSEC in a single- or multistage RO is then formulated as an optimization problem as follows

\[
\min \quad \frac{1}{\alpha_i} - \frac{(P_{bp} - P_p) / \Delta \pi_0}{\prod_{i=1}^{N} q_i(1)}
\]

s. t.

\[
\frac{dp_i(x)}{dx} = -\kappa_i q_i^2(x), \quad i = 1, 2, ..., N
\]

\[
\frac{dq_i(x)}{dx} = -\gamma \left( \frac{p_i(x)}{\alpha_i} - \frac{1}{q_i(x)} \right), \quad i = 1, 2, ..., N
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\]

The optimization of a RO network with more complicated configurations can be formulated using methods developed in the author’s previous work. For a two-stage RO with interstage booster pump, the optimization problem (neglecting pump efficiency and assuming \( P_{bp} = P_p \) for simplicity) may be formulated as follows
in parentheses. In all calculations, osmotic pressure is estimated based on TDS data using an online calculator (http://www.lennntech.com/calculators/osmotic/osmotic-pressure.htm), if it is not provided in the literature.

A significant difference between BWRO and SWRO is observed. For BWRO, $\gamma_1$ is typically about 0.1 (even $\gamma_{total}$ is less than 0.2 if multiple stages are used), whereas $\kappa_1$ is between 1 and 6. For SWRO, $\gamma_1$ is between 0.5 and 1.5, whereas $\kappa_1$ is less than 0.2. The differences are presented in the $\gamma$ vs. $\kappa$ map in Figure 1. These differences are mainly caused by the fact that


**Figure 1.** $\gamma$ and $\kappa$ in BWRO and SWRO.

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In eq 9, $\gamma_{total}$ is defined based on the total area of all RO elements in both stages ($\gamma_{total} = A_{total} \Delta \pi_{w} / Q_{w}$). Note that while $A_{total} = A_1 + A_2$, $\gamma_{total} \neq \gamma_1 + \gamma_2$. Inequality constraint $\alpha_1 \leq \alpha_i / p_i(1)/q_i(1)$ is included to ensure non-negative pressure increase across the interstage pump.

The optimization models described by eqs 8 and 9 can be solved using common constrained multivariable nonlinear optimization packages, e.g., fmincon in Matlab.

**RESULTS AND DISCUSSION**

Analysis of BWRO and SWRO Plant Data. Data of BWRO and SWRO plants worldwide are analyzed and the parameters $\alpha$, $\gamma$, and $\kappa$ are either calculated directly based on their definitions or correlated to match plant measurements including pressure differentials and recoveries. The results are summarized in Table 1. $\gamma$, $\kappa$, and $\alpha$ reported here are based on the first stage for plants employing multistage operation as they change from stage to stage. For these plants, $\gamma_{total}$ are provided.

![Table 1. Correlation of Plant Data with Mathematical Model](https://dx.doi.org/10.1021/ie40310831/ind.Eng.Chem.Res.2013,52,17241–17248)

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**Figure 1.** $\gamma$ and $\kappa$ in BWRO and SWRO.
its lowest attainable level. It is worth noting that the maximum recovery is limited by the ability to produce potable quality permeate in SWRO\textsuperscript{33} and the occurrence of silica precipitation in BWRO.\textsuperscript{34}

From Figures 2, 3, and 4, one can read optimal operating conditions for typical BWRO and SWRO processes using representative values of $\gamma$ and $\kappa$. The results are shown in Table 2. Apparently, NSEC is only slightly above 4 in SWRO but much larger in BWRO. To achieve the optimal NSEC, $\Delta p_0$ is 2.3 and 17 times $\Delta p_0$ in SWRO and in BWRO, leading to a significant difference in water recoveries. The optimal recovery in BWRO is much larger. The dimensionless driving forces at the entrance and exit of the stage ($p/(\alpha - 1/q)$) are provided in the same table. It appears that SWRO is operated near the thermodynamic limit, but BWRO is far away from it.

**Comparison of SEC between Single-Stage and Two-Stage Designs.** Both single-stage and two-stage designs have been used in RO operation, and there are still debates on which one is more efficient from a viewpoint of energy consumption.\textsuperscript{35} In this subsection, several case studies will be used to clarify the effect of RO configurations on SEC in both BWRO and SWRO.

For BWRO, the effect of retentate pressure drop on water recovery is first quantified before the detailed comparisons. Equation 2 was applied to an industrial two-stage BWRO train in Chino, California.\textsuperscript{14} This BWRO train has 28 pressure vessels in parallel in the first stage and 14 in the second stage. Each pressure vessel houses 7 Dow FILMTEC BW30–400 RO elements in series. The BWRO train does not have an interstage booster pump or ERD. It was derived from plant data that $k_1 = 2.12 \times 10^{-5}$ psi/gpm\textsuperscript{2} and $L_p = 0.11$ gfd/psi.\textsuperscript{14} The model predictions using these two parameters were able to match plant data collected in a wide range of operating conditions.\textsuperscript{16} On the basis of these parameters, it is calculated that $\kappa_1 = 5.5$ and $\gamma_1 = 0.035$.

A comparison of simulation results with/without retentate pressure drop is shown in Figure 5. When the pressure drop effect is completely ignored (or assuming $k_1 = k_2 = 0$), the calculated recovery is 91%, leading to an over prediction of about 12% compared to its measured value of 81%. This case study indicates that the retentate pressure drop should not be ignored in BWRO where $\kappa$ is large.

With the above information, one would expect that if all 42 pressure vessels are laid out in parallel in just one stage, this BWRO plant could be more energy-efficient because of reduced retentate pressure drop. The detailed comparison is shown in Figures 6 and 7. The overall retentate pressure drop ratio is only 4% in the single-stage design as compared to 24% in the two-stage design. There are two factors that contribute to such a significant difference. First, the channel area for retentate flow in the single-stage configuration is 1.5 and 3 times of the one in the first and second stage in the two-stage design, respectively. The increased channel area leads to a reduced retentate velocity along the pressure vessel. Second, the total pressure vessel length in the single-stage design is only a half of

| Table 2. Comparison between Single-Stage BWRO and SWRO under typical Operation Conditions |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| RO type         | $\gamma$ | $\kappa$ | $\alpha_{opt}$ | NESC$_{opt}$ | $Y_{opt}$ | $p(0)/(\alpha - 1/q)(0)$ | $p(1)/(\alpha - 1/q)(1)$ |
| BWRO            | 0.05      | 1        | 0.059          | 22.9          | 0.75    | 16.1                     | 12.7                     |
| SWRO            | 1         | 0.1      | 0.438          | 4             | 0.54    | 1.28                     | 0.05                     |
| Thermodynamic Limit\textsuperscript{12} | $\infty$ | 0        | 0.5            | 4             | 0.5     | 1                        | 0                         |
the one in the two-stage design. A less retentate pressure drop results in a higher driving force for water production (see Figure 7). It is shown that the predicted water recovery in the single-stage design is 89% with the same \( Q_0 \) and \( \Delta P_{\text{pump}} \). To maintain the same production, \( Q_0 \) and/or \( \Delta P_{\text{pump}} \) may be lowered in the single-stage configuration. For example, the calculation shows that a \( \Delta P_{\text{p}} \) of 163 psi (10% lower than 180 psi in the current two-stage design) could keep the 81% recovery with the same \( Q_0 \). Therefore, the single-stage configuration is more effective than its two-stage counterpart in BWRO from a viewpoint of SEC (about 10% lower in this case). However, it should be noted that the two-stage design has a less drastic change in retentate flow per stage and less tendency for concentration polarization because of a higher velocity.

The same conclusion may be drawn for SWRO, even though the difference between single-stage and two-stage configurations is small, given the fact that \( \kappa \) is close to zero in SWRO. However, it is worth pointing out that when an interstage booster pump is used in conjunction with the two-stage design in SWRO, it would be advantageous over the single-stage design, according to the author’s published theoretical analysis. The computational analysis is based on the assumption \( \kappa = 0 \). The works also show that when \( \gamma_{\text{total}} < 0.2 \), the optimal solution is corresponding to a zero pressure increase in the interstage booster pump, or the two-stage configuration is essentially one-stage. There are industrial cases to substantiate reduced SEC in SWRO brine conversion using interstage booster pumps. For example, in the SWRO plant in Las Palmas III, Spain, an increase of 8% in the recovery of and an improvement of 12.65% in the specific energy consumption were observed after interstage booster pumps were installed.

To theoretically validate whether a booster pump would always reduce SEC for a nonzero \( \kappa \) in SWRO and BWRO, the optimization problems described by eqs 8 and 9 are solved for three different configurations (single-stage, two-stage, and two-stage with booster pump, see Figure 8) using representative values of \( \gamma \) and \( \kappa \). In order to have a fair comparison, all three configurations have exactly the same membrane properties and flow characteristics. These mean that \( \gamma_{\text{total}} = A_{\text{total}}L_p\Delta \pi/Q_0 \) is the same in all configurations. However, it should be noted that if the pressure loss parameter is \( \kappa \) in the first stage of a two-stage RO, it becomes \( (2/3)^2\kappa \) in a single-stage RO because of increased cross-sectional channel area for retentate flow (based on eq 3).

The optimized NSECs and corresponding recoveries for BWRO and SWRO are shown in Figures 9 and 10. For BWRO, the optimal NSECs with/without a booster pump are almost the same. Both two-stage designs have a higher NSEC than the one in single-stage design at their optimal conditions. Therefore, installing a booster pump would not help reduce SEC in BWRO. In SWRO, the two-stage with booster pump
design outperforms the other two designs at a large $\gamma_{\text{total}}$ (e.g., 0.8 or greater in this case). However, the single-stage may be the most energy efficient at a $\gamma_{\text{total}}$ smaller than 0.8. Calculation also shows that this critical $\gamma_{\text{total}}$ reduces from 0.8 to 0.7 when $\kappa$ decreases from 0.1 to 0.05. In both BWRO and SWRO studied here, the two-stage RO without booster pump is always no better than the other two configurations from a viewpoint of SEC.

The above comparisons among three RO configurations are made at their best operating conditions. It is possible that one design at its optimal condition is more energy-effective than another at a nonoptimal condition. Moreover, because the two-stage designs (with/without booster pumps) have higher recoveries at its optimal condition than the one in the single-stage, adding a constraint of maximum recovery may also change the comparison results.

**Effect of Brine Recirculation on SEC in BWRO.** The use of ERD is a proven technology to reduce SEC in SWRO.\textsuperscript{20,21,39} It has also been recently demonstrated in BWRO.\textsuperscript{29} However, in some cases there is leakage of brine into the feed in the ERD, which may increase the feed salinity and reduce the driving force for separation. The same issue exists in brine recirculation systems where energy contained in the brine is recovered. In this subsection, an example is used to quantify the effect of brine feed mixing on SEC in BWRO.

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Figure 11 shows an example in which an ERD (PX by Energy Recovery Inc.) is intentionally unbalanced in a BWRO system which yields an overall system recovery (F divided by A) of 85% and 2000 TDS feedwater, whereas the membrane recovery (F divided by E) is at 65% and 4886 TDS feedwater.\textsuperscript{40}

The pressures and flows in all locations are shown in Table 3. Based on these data, it can be derived that $\alpha = 0.232$, $\gamma = 0.268$, and $\kappa = 0.426$. If RO properties are the same when ERD is used, $\alpha = 0.092$, $\gamma = 0.138$, and $\kappa = 0.638$ because $\gamma \propto \Delta p_0 / Q_0$.
and \( \alpha \Delta \pi_0 / \Delta P \), The model-predicted pressures and flow rates based on the new values of \( \alpha \), \( \gamma \), and \( \kappa \) are shown in Table 3 for a comparison.

Without ERD, the recovery predicted by the model is 90% (see Figure 12), implying that the pump power may be reduced to maintain the same production. Without blending the fresh feed with the highly concentrated brine stream, a lower osmotic pressure is maintained in the retentate. Moreover, a smaller feed with the highly concentrated brine stream, a lower osmotic pressure drop is maintained in the retentate. However, with an interstage booster pump, two-stage may be more energy efficient than single-stage in SWRO. In both BWRO and SWRO studied in this paper, the two-stage RO without booster pump is always no better than the other two configurations from a viewpoint of SEC.

- In brine recirculation and/or ERD, mixing of brine and feed may increase salinity, adversely affecting SEC. A trade-off between increased feed salinity and increased energy recovery should be carefully evaluated.

**Table 3. Comparison of Single-Stage BWRO with/without ERD**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
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<td>2000</td>
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<td>4886</td>
<td>92</td>
<td>14000</td>
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</tr>
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</table>

![Figure 12. Effect of brine leakage in ERD on retentate pressure drop and recovery.](image)

The following conclusions are drawn based on the computational studies of RO desalination in this work:

- Even though BWRO and SWRO may be described by the same mathematical model, their process characteristics are different because they are in completely different regions in the \( \gamma \) vs. \( \kappa \) map. The pressure drop effect on RO performance cannot be ignored for BWRO.
- In current RO plants, SWRO may be operated near the thermodynamic limit to reduce SEC. However, BWRO is operated far away from the thermodynamic limit because of a small \( \gamma \).
- Without interstage booster pumps, single-stage is more energy efficient than two-stage in BWRO because of less retentate pressure drop. However, with an interstage booster pump, two-stage may be more energy efficient than single-stage in SWRO.

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