Systems Engineering in Osmotic Membrane Processes

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Outline

I. Introduction/Background
II. Optimization of SEC in SWRO
III. Comparison between SWRO and BWRO
IV. Hydrodynamics and Concentration Polarization
V. Power Generation by Pressure Retarded Osmosis
VI. An Industrial Case Study
Section I
Introduction/Background
Industrial Water Desalination

**Pretreatment**
- Chemical addition
- Cartridge filter

**RO Purification**
- RO membrane to remove dissolved solids

**Post Treatment**
- CO₂ removal, pH adjustment
- Disinfection
- Distribution

RO is the most versatile industrial technology to produce drinking water, consuming approximately 0.5 kWh/m³ and 3.5 kWh/m³ energy.
Reverse Osmosis: How it Works

Controlled variables:
- permeate rate
- water recovery

Manipulated variables:
- pump speed
- retentate valve opening ratio
Sustainability Issues in RO

- Water recovery can never be close to 100% because of skyrocketing energy consumption required to drive the pump.
- In inland areas, any unrecovered water, or brine, is considered as an industrial waste. The brine disposal cost of brackish water RO is approximately $900/mega gallon.
- A higher recovery would require a higher energy consumption and/or capital investment in membrane elements.
Section II
Optimization of SEC in Seawater RO (SWRO)

Seawater RO Characteristic Equation

\[-dQ = dA \cdot L_p \cdot (\Delta P - \Delta \pi) = dA \cdot L_p \cdot (\Delta P - \frac{Q_f}{Q} \Delta \pi_0)\]

\[\frac{Q_p}{\Delta P} + \frac{\Delta \pi_0 Q_f}{(\Delta P)^2} \ln \left(1 - \frac{\Delta \pi_0}{\Delta P} \frac{Q_p}{Q_f} \right) = AL_p\]

Assumptions:
* Negligible pressure drop
* Negligible concentration polarization
* Negligible permeate osmotic pressure
* Negligible salt across membrane

\(\Delta P\) – transmembrane hydraulic membrane
\(\Delta \pi\) – transmembrane osmotic pressure
\(\Delta \pi_0\) – transmembrane osmotic pressure at entrance
\(L_p\) – hydraulic permeability
\(Q\) – retentate flow rate
\(Q_f\) – feed flow rate
\(Q_p\) – permeate flow rate
\(A\) – membrane area
Dimensionless Form

Coupled relationship among membrane properties, operating parameter and process performance

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

\[
\beta = \alpha \left[ 1 + \frac{\alpha}{Y} \ln \frac{1 - \alpha}{1 - Y - \alpha} \right]
\]

\(\alpha = (\Delta \pi_0)/\Delta P\): dimensionless pressure

\(Y = Q_p/Q_f\): recovery

\(\beta = (AL_p\Delta \pi_0)/Q_p\): membrane capacity production ratio

\(\gamma = (AL_p\Delta \pi_0)/Q_f\): membrane capacity intake ratio
Energy Consumption in RO

- Specific Energy Consumption

\[ SEC = \frac{Q_f \Delta P}{\eta_{pump} Q_p} = \frac{1}{\eta_{pump}} \frac{\Delta \pi_0}{\alpha Y} \]

- Normalized Specific Energy Consumption

\[ NSEC = \frac{SEC}{\Delta \pi_0} = \frac{1}{\eta_{pump}} \frac{1}{\alpha Y} \]

- Pump efficiency is usually assumed to be constant for simplified analysis
Constrained Optimization Model

Contour of NSEC ignoring pump efficiency

Optimization of NSEC

\[\min_{\alpha, z} NSEC_m = \frac{1}{\alpha y}\]
\[s.t.\]
\[y = (1 - \alpha)(1 - e^{-z})\]
\[\gamma = \alpha(y + \alpha z)\]

The constrained nonlinear optimization may be solved by various computational tools, e.g., Excel, Matlab (fmincon), Lingo and GAMS etc.
Optimization Results

- NSEC gradually reduces as $\gamma$ increases.
- The lowest NSEC occurs at the thermodynamic limit where driving force is zero.
- For single-stage without ERD, as $\gamma \to \infty$, the minimum of NSEC is 4 and the corresponding recovery is 50%.
Trade-off between Capital Investment and Energy Consumption

\[
\begin{align*}
\min_{\alpha, z} J &= i \frac{1}{\alpha Y} + j \beta \\
\text{s.t.} & \quad Y = (1 - \alpha)(1 - e^{-z}) \\
\gamma &= \alpha(Y + \alpha z) \\
\beta &= \gamma / Y
\end{align*}
\]
Effect of Staged Operation and ERD

- Retentate from a RO stage is pressurized by a booster pump and sent as feed to the next stage.
- An energy recovery device (ERD) is used to recover the hydraulic energy of the high pressure brine reject, thus reducing feed pump power consumption.
Optimization Model

\[ \min_{\alpha_j, Y_j} \frac{SEC_m}{\Delta \pi_0} = \sum_{j=1}^{N-1} \frac{Y_j}{\alpha_j} + \frac{1}{\alpha_N} - \eta_{era} \frac{(1 - Y_N)}{\alpha_N} \left[ 1 - \prod_{j=1}^{N} (1 - Y_j) \right] \]

s.t.

\[ 0 = \gamma_j - \alpha_j \left[ Y_j + \alpha_j \ln \frac{1 - \alpha_j}{1 - Y_j - \alpha_j} \right] (j = 1, \ldots, N) \]

\[ 0 = \gamma_{total} - \left[ \gamma_1 + \sum_{j=2}^{N-1} \gamma_j \prod_{k=1}^{j-1} (1 - Y_k)^2 \right] \]

\[ 0 = \gamma_j - \gamma_{j+1} (1 - Y_j)^2 (j = 1, \ldots, N - 1) \]

\[ 0 \leq \alpha_j (j = 1, \ldots, N) \]

\[ 0 \leq 1 - \alpha_j (j = 1, \ldots, N) \]

\[ 0 \leq \alpha_{j+1} - \alpha_j / (1 - Y_j) (j = 1, \ldots, N - 1) \]

\[ 0 \leq \left[ 1 - \prod_{j=1}^{N} (1 - Y_j) \right] - Y_{min} \]
Optimization Results – without ERD
Optimization Results – with ERD ($\eta_{ERD} = 90\%$)
Optimization Results – with ERD ($\eta_{\text{ERD}} = 90\%, Y_{\text{min}} = 80\%)
Observations of Optimization Results

• A larger $\gamma$ allows SWRO to be operated closer to the thermodynamic limit, thus reducing NSEC. However, The NSEC flattens out when $\gamma$ becomes sufficiently large.

• Using more stages not only reduces NSEC, but also improves overall recovery. The NSEC flattens out when the number of stages increases.

• ERD can significantly reduce NSEC, theoretically to 1, while the corresponding recovery approaches 0.

• It is possible to obtain an NSEC below 3 while maintaining 80% recovery using all three strategies (e.g., 3-stage, ERD with an efficiency of 90% and a $\gamma_{total}$ of 2).
NSEC of RO at Thermodynamic Limit

NSEC for multi-stage RO with booster pumps and ERD:

\[
NSEC = \frac{\sum_{j=1}^{N-1} \frac{Y_j}{\alpha_j} + \frac{1}{\alpha_N} - \eta_{erd}(1 - Y_N)}{1 - \prod_{j=1}^{N} (1 - Y_j)}
\]

At thermodynamic limit, \(\alpha_j + Y_j = 1\)

\[
NSEC = \frac{\sum_{j=1}^{N} \frac{1}{\alpha_j} - N + (1 - \eta_{erd})}{1 - \prod_{j=1}^{N} \alpha_j}
\]

Optimal solution:

\[
\alpha_1 = \alpha_2 = \ldots = \alpha_N = (1 - Y_o)^{1/N}
\]

\[
NSEC = \frac{N[(1 - Y_o)^{-1/N} - 1] + (1 - \eta_{erd})}{Y_o}
\]
Theoretical Value of NSEC at Thermodynamic Limit

• For single- or multi-stage spiral wound RO, the reduction in NSEC due to an ERD at the thermodynamic limit is $\eta_{erd}/Y_o$.

• Infinite number of RO stages with booster pumps and a 100% ERD is equivalent to an ideal theoretically reversible RO process, or

$$NSEC = \frac{-\ln(1-Y_o)}{Y_o}$$

• Multi-stage design works better at high recoveries. ERD works better at low recoveries.

• Brine recirculation would not reduce NSEC.

• Without ERD, the minimum of NSEC with infinite stages and inter-stage booster pumps is 3.1462.
Section III
Differences and Similarities between SWRO and BWRO

Difference in Seawater and Groundwater RO

Process model accounting for pressure drop in feed channel

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

\[-\frac{dp(x)}{dx} = -k \cdot Q^2\]

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

\[Q(x) = \left. Q_0 \right|_{x=0}\]

\[\Delta P(x) = \left. \Delta P_0 \right|_{x=0}\]

\[\alpha = \frac{\Delta \pi_0}{\Delta P_0}, \gamma = A L_p \Delta \pi_0 / Q_0, \kappa = k Q_0^2 / \Delta \pi_0, q = Q / Q_0, p = \Delta P / \Delta P_0\]

\[\kappa = k Q_0^2 / \Delta \pi_0 = 2 f (L_{pv} / D_H) \rho (Q_0 / A_c)^2 / \Delta \pi_0\]
Plant Design Parameters

Two important parameters show the difference between SWRO and BWRO:

\[ \gamma = \frac{A L_p \Delta \pi_0}{Q_0} \]
\[ \kappa = \frac{k Q_0^2}{\Delta \pi_0} \]

- \( \Delta \pi_0 = 390 \) psi for seawater RO and 10-20 psi for brackish water RO.
- Current BWRO plants are not built to have a large \( \gamma \).
- Effect of retentate pressure drop may not be ignored in BWRO because of a large \( \kappa \).

Correlation of \( \gamma \) and \( \kappa \) based on literature data from various plants
Optimization Model

Left: Single- or multi-stage without booster pump
Right: Two-stage (2:1 layout) with booster pump

\[
\begin{align*}
\min_{\alpha_1} J &= \frac{1}{\alpha_1 - (P_{bp} - P_p)/\Delta \pi_0} \\
&= \eta_{pump} \left( 1 - \prod_{i=1}^{N} q_i(i) \right)
\end{align*}
\]

s.t.
\[
\begin{align*}
\frac{dp_i(x)}{dx} &= -\kappa_i \alpha_i q_i^2(x), i = 1,2,\ldots,N \\
\frac{dq_i(x)}{dx} &= -\gamma_i \left( \frac{p_i(x)}{\alpha_i} - \frac{1}{q_i(x)} \right), i = 1,2,\ldots,N \\
p_i(x) &= 1, @x = i - 1, i = 1,2,\ldots,N \\
q_i(x) &= 1, @x = i - 1, i = 1,2,\ldots,N
\end{align*}
\]

\[
\begin{align*}
\min_{\alpha_1, \alpha_2} J &= \frac{1/\alpha_1 + 1/\alpha_2 - p_1(1)q_1(1)}{1 - q_1(1)q_2(2)} \\
s.t. \\
\frac{dp_i(x)}{dx} &= -\kappa_i \alpha_i q_i^2(x), i = 1,2 \\
\frac{dq_i(x)}{dx} &= -\gamma_i \left( \frac{p_i(x)}{\alpha_i} - \frac{1}{q_i(x)} \right), i = 1,2 \\
p_i(x) &= 1, @x = i - 1, i = 1,2 \\
q_i(x) &= 1, @x = i - 1, i = 1,2
\end{align*}
\]

\[
\begin{align*}
\gamma_1 &= (2/3)\gamma_{total} \\
\gamma_2 &= \gamma_1/2q_1^2(1) \\
\kappa_2 &= 4\kappa_1q_1^3(1) \\
\alpha_2 &\leq \alpha_1/p_1 (1)/q_1 (1) \\
-\alpha_i &\leq \alpha_i &\leq 0, i = 1,2 \\
1, i = 1,2
\end{align*}
\]
Optimization of Single-Stage RO

- Pressure drop effect may be ignored in SWRO but not in BWRO.
- The optimal recovery for BWRO is much higher mainly because of a smaller $\gamma$.
- Operation near thermodynamic limit is only valid for SWRO but not for BWRO.
Effect of RO Stage Configuration

a) One stage
b) Two stage without booster pump
c) Two stage with booster pump
d) One stage with brine recirculation
Optimization Results for Two Cases

\( \kappa = 1 \) (based on the first-stage in a two-stage RO)

\( \kappa = 0.1 \) (based on the first-stage in a two-stage RO)
Observations of Optimization Results

• For BWRO, single-stage is better than two-stage in terms of NSEC (However, industrial design employs two-stage to achieve a more uniform flow). Using booster pump does not improve NSEC under optimal conditions because of a very small $\gamma$.

• For SWRO, two-stage with booster pump could be better than one-stage in terms of NSEC if $\gamma$ is sufficiently large. Using booster pump does improve NSEC under optimal conditions.

• Brine recirculation does not improve NSEC in BWRO due to increase in feed salinity and retentate pressure drop.
Section IV
Hydrodynamics and Concentration Polarization in Industrial RO Feed Channel

Concentration Polarization

\[ J_w c + D \frac{\partial c}{\partial z} = J_w c_p \]
\[ c = c_r, \text{at } z = \delta_D \]
\[ c = c_w, \text{at } z = 0 \]

Concentration Polarization Modulus:
\[ \frac{\Delta \pi_{eff}}{\Delta \pi} \approx \frac{c_w - c_p}{c_r - c_p} = \exp \left( \frac{J_w}{D/\delta_D} \right) \]

Mass transfer boundary layer in narrow flat channel:
\[ \delta_D = 1.475x \left( \frac{H}{2x} \right)^{2/3} \left( \frac{2D}{u_{\max} H} \right)^{1/3} \]

It is discussed extensively in literature that concentration polarization has a strong adverse effect on water flux. However, we argue that its effect may not be so significant in commercial RO under realistic industrial operating conditions.
Commercial RO Feed Channel with Spacer Filaments

courtesy of M. Busch and J. Johnson, Dow Chemical

Geometry construction using COMSOL
Comparison of Hydrodynamics between Flat and Spacer-Filled Channels
Comparison of Salt Concentration and Water Flux between Flat and Spacer-Filled Channels
Comparison of Mass Transfer between Flat and Spacer-Filled Channels
Observations of the Effect of Feed Spacer Filaments

• The pressure drop v.s. average longitudinal velocity can be approximated by \( \Delta P_c \propto \bar{u}^{1.67} \) and the trend matches an empirical correlation previously derived from plant data.

• Substantial wall-parallel velocity near the membrane surface is observed, which helps suppress boundary layer development. Rolling cells are formed in the center of the feed channel, which promote transverse mixing.

• Different from concentration polarization phenomenon in flat, narrow channels, concentrated islands are isolated in regions near spacer filaments where flow is relatively stagnant. The local mass transfer coefficient \( k_m \) oscillates longitudinally but the cell-average \( \bar{k}_m \) appears fairly constant in cells adjacent to each other. It is shown that \( \bar{k}_m \propto \bar{u}^{0.40} \) under plant operating conditions.

• Concentration polarization is not very significant in modeling industrial BRWO.
Section V
Power Generation from Seawater or SWRO Brine by Pressure Retarded Osmosis
Pressure Retarded Osmosis

• PRO may be used to generate power from seawater or brine from SWRO.

• There are discussions in literature about integration of PRO with RO to reduce the energy consumption of RO.

• Flux: \( J_w = L_p (\Delta \pi - \Delta P) \) is usually assumed to be constant in literature, which may not be true.

• Power Density: \( PD = L_p (\Delta \pi - \Delta P) \Delta P \)
  Maximum occurs at \( \Delta P_{opt} = \Delta \pi / 2 \) based on literature.
Basic Definitions in PRO

• Specific Energy Production (SEP)

\[ SEP = Q_0(q_d - 1)\Delta P / Q_0 = (q_d - 1)\Delta P \]

- \( q_d \): dilution ratio at the end of the membrane
- \( \Delta P \): applied pressure

• Normalized SEP or Osmotic to Hydraulic Efficiency

\[ NSEP = SEP / \pi_0^D = (Q_0SEP)/(Q_0\pi_0^D) = \eta_{O2H} \]

• Power Density (PD)
Local water flux (assuming $\pi^F = \pi_0^F$):

$$\frac{dQ}{dA} = L_p (\Delta \pi - \Delta P) = L_p (\pi_0^D \frac{Q_0}{Q} - \pi_0^F - \Delta P)$$

Dimensionless form:

$$\frac{dq}{dx} = \gamma \left( \frac{1}{q} - \theta \right)$$

$$\theta = (\Delta P + \pi_0^F)/\pi_0^D, \ q = Q/Q_0, \ \text{and} \ \gamma = A L_p \pi_0^D / Q_0$$

Solution:

$$\gamma = \frac{1}{\theta} \left[ 1 - q_d + \frac{1}{\theta} \ln \frac{1 - \theta}{1 - q_d \theta} \right]$$

$q_d$: dilution ratio at the end of the membrane
Optimization of NSEP

Observations from profiles of $q_d$ and NSEP

- $q_d$ increases as $\Delta P$ reduces and/or $\gamma$ increases.
- At a fixed $\gamma$, there is an optimal $\Delta P$ corresponding the maximum NSEP.

Optimization of NSEP:

$$\max_{\alpha, z} NSEP = (q_d - 1) \left( \frac{1}{\alpha} - r \right)$$

s.t.

$$q_d = \alpha - (\alpha - 1)e^{-z}$$

$$\gamma = \alpha(1 - q_d + \alpha z)$$

$$1 - \alpha \leq 0$$

$$1 - q_d \leq 0$$
Optimization Results

Observations:

- The optimal $\Delta P$ shifts away from $\Delta \pi_0/2$ as $\gamma = A L_p \pi_0^D / Q_0$ increases.
- An increase in $r$ ($r = \pi_0^F / \pi_0^D$) significantly reduces $q_d$ and NSEP.
- When $r = 0$ (or fresh water is used as feed solution), the largest NSEP occurs at forward osmosis conditions, i.e., $\Delta P_{opt} = 0$. 
Optimal Driving Force in PRO

- Similarities between RO and PRO
  - A larger $\gamma$ allows the PRO to be operated closer to its thermodynamic limit, thus improving SEP.
  - A larger $\gamma$ allows the RO to be operated closer to its thermodynamic limit, thus improving SEC.
Optimization of PRO Accounting for Concentration Polarization

\[
\begin{align*}
\max_{\Delta P} PD &= \frac{\Delta P \int_0^A J_w \, dA}{A} \\
\frac{dQ}{dA} &= J_w \\
J_w &= L_p \left[ \pi_b^P \exp \left( -\frac{J_w}{k_m} \right) \frac{1 - \frac{\pi_b^F}{\pi_b^P} \exp (J_w K) \exp \left( \frac{J_w}{k_m} \right)}{1 + \frac{B}{J_w} \left[ \exp (J_w K) - 1 \right]} \right] - \Delta P
\end{align*}
\]

\(J_w\) is in an implicit form.
Short-Cut Optimization Method

- If \( J_w/k_m \ll 1 \) and \( J_w K \ll 1 \), \( J_w \) may be approximated by
  \[
  J_w \approx L'_p (\sigma \Delta \pi - \Delta P),
  \]
  where \( \sigma = 1/(1 + BK) \) and \( L'_p = L_p/(1 + L_p \Delta \pi \sigma / k_m) \).

- The characteristic equation becomes
  \[
  \gamma = \frac{1}{\theta} \left[ (1 - q_d) + \frac{\sigma}{\theta} \ln \frac{\sigma - \theta}{\sigma - q_d \theta} \right],
  \]
  where \( \gamma = AL'_p Q_0 / \pi_0^D \).

- Optimization model:

\[
\begin{align*}
\max_{\alpha, z} NSEP &= (q_d - 1) \left( \frac{1}{\alpha} - r \right) \\
\text{s. t.} \\
q_d &= \alpha \sigma - (\alpha \sigma - 1)e^{-z} \\
\gamma &= \alpha (1 - q_d + \alpha \sigma z) \\
1/\sigma - \alpha &\leq 0 \\
1 - q_d &\leq 0
\end{align*}
\]

**Note:**

It is found that this method provides very accurate solution to \( \Delta P_{opt} \). However, flux profile, NSEP and PD are better calculated using the original concentration polarization model and the derived \( \Delta P_{opt} \).
Optimization Results

- Parameters are taken from literature (Achilli, JMS, 2009)
- Comparison between short-cut and rigorous optimization methods (values obtained using the short-cut optimization method, if different from the rigorous method, are presented in parenthesis):

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_m$</td>
<td>$8.48 \times 10^{-5}$ m/s</td>
</tr>
<tr>
<td>$K$</td>
<td>$4.51 \times 10^5$ s/m</td>
</tr>
<tr>
<td>$B$</td>
<td>$1.11 \times 10^{-7}$ m/s</td>
</tr>
<tr>
<td>$L_p$</td>
<td>$1.87 \times 10^{-9}$ m/s/kPa</td>
</tr>
<tr>
<td>$\Delta \pi_0$</td>
<td>2763, 4882 kPa</td>
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</table>

<table>
<thead>
<tr>
<th>$\Delta \pi_0 = 2763$ kPa</th>
<th>$\Delta P$, kPa</th>
<th>$\bar{J}_w$, $\mu$m/s</th>
<th>PD, W/m²</th>
<th>$\gamma$</th>
<th>$q_d$</th>
<th>$\eta_{O2H}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \pi = \Delta \pi_0$</td>
<td>1330 (1316)</td>
<td>2.16 (2.18)</td>
<td>2.87</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$Q_0/A = 8\mu$m/s</td>
<td>1300 (1295)</td>
<td>1.78 (1.79)</td>
<td>2.31</td>
<td>0.65</td>
<td>1.22</td>
<td>10.5</td>
</tr>
<tr>
<td>$Q_0/A = 4\mu$m/s</td>
<td>1260 (1259)</td>
<td>1.56 (1.56)</td>
<td>1.96</td>
<td>1.29</td>
<td>1.39</td>
<td>17.7</td>
</tr>
<tr>
<td>$Q_0/A = 2\mu$m/s</td>
<td>1190 (1186)</td>
<td>1.28 (1.28)</td>
<td>1.52</td>
<td>2.58</td>
<td>1.64</td>
<td>27.6</td>
</tr>
<tr>
<td>$Q_0/A = 1\mu$m/s</td>
<td>1070 (1067)</td>
<td>1.00 (1.01)</td>
<td>1.07</td>
<td>5.17</td>
<td>2.01</td>
<td>38.9</td>
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<tr>
<td>$\Delta \pi_0 = 2763$ kPa</td>
<td>$\Delta P$, kPa</td>
<td>$\bar{J}_w$, $\mu$m/s</td>
<td>PD, W/m²</td>
<td>$\gamma$</td>
<td>$q_d$</td>
<td>$\eta_{O2H}$, %</td>
</tr>
<tr>
<td>$\Delta \pi = \Delta \pi_0$</td>
<td>2390 (2325)</td>
<td>3.38 (3.47)</td>
<td>8.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$Q_0/A = 8\mu$m/s</td>
<td>2260 (2244)</td>
<td>2.64 (2.66)</td>
<td>5.97</td>
<td>1.14</td>
<td>1.33</td>
<td>15.3</td>
</tr>
<tr>
<td>$Q_0/A = 4\mu$m/s</td>
<td>2140 (2133)</td>
<td>2.24 (2.25)</td>
<td>4.79</td>
<td>2.28</td>
<td>1.56</td>
<td>24.6</td>
</tr>
<tr>
<td>$Q_0/A = 2\mu$m/s</td>
<td>1950 (1943)</td>
<td>1.79 (1.80)</td>
<td>3.50</td>
<td>4.56</td>
<td>1.90</td>
<td>35.8</td>
</tr>
<tr>
<td>$Q_0/A = 1\mu$m/s</td>
<td>1680 (1685)</td>
<td>1.38 (1.38)</td>
<td>2.32</td>
<td>9.13</td>
<td>2.37</td>
<td>47.4</td>
</tr>
</tbody>
</table>
Power Density and Flux Profile

Six cases:

Black: $\Delta \pi = \Delta \pi_0$ no CP.
Red: $\Delta \pi = \Delta \pi_0$ with CP.
Magenta: $Q_0/A = 8 \times 10^{-6}$ m/s.
Yellow: $Q_0/A = 4 \times 10^{-6}$ m/s.
Blue: $Q_0/A = 2 \times 10^{-6}$ m/s.
Green: $Q_0/A = 1 \times 10^{-6}$ m/s.
Conclusions from PRO Optimization

• Short-cut optimization yields essentially the same solution as the rigorous solution. Moreover, it provides parameters to explain the effect of ICP, ECP and dilution in DS.

• Shift of optimal $\Delta P$ from $\Delta \pi_0 / 2$:
  • Dilution effect (i.e. $\gamma$ is not zero).
  • Internal concentration polarization (i.e., $\sigma < 1$).

• Nonlinearities and conflicting power density and efficiency in process scale-up
  • Realistically, up to 25% of the osmotic energy in SWRO brine may be recovered if similar membranes are invested in PRO (i.e., the capital investment in RO elements will be doubled).
Section VI
An Industrial Case Study

Chino I Desalter

- Draws raw water from 15 groundwater wells
- Processes 14 MGD of drinking water
- 1.7 megawatt (0.5 megawatt is for RO)
- Serves the Chino basin and neighboring areas

**Diagram:**

- Input Wells 1-4: VOC (2 MGD)
- Input Wells 5-15: RO (7 MGD)
- Output: Ion Exchange (5 MGD)
- Final Blended Product: 14 MGD

**Product Quality Requirement:**
- TDS: 350 mg/L
- Nitrate: 25 mg/L
Desalination RO Unit

• Consists of 4 process trains, each equipped with:
  • a dedicated membrane feed pump with VFD – 9 stage vertical turbine pump with 300 hp motor, 1450 gpm, 625 ft TDH at 1785 rpm
RO Stage Configuration and Layout

- Two-stage pressure vessel array \((28+14)\times7\) = 294 RO elements
- No inter-stage booster pump
# Typical Brackish Feedwater Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (Ca), mg/L</td>
<td>174</td>
</tr>
<tr>
<td>Magnesium (Mg), mg/L</td>
<td>40</td>
</tr>
<tr>
<td>Sodium (Na), mg/L</td>
<td>48</td>
</tr>
<tr>
<td>Potassium (K), mg/L</td>
<td>3</td>
</tr>
<tr>
<td>Carbonate (as CO$_3$), mg/L</td>
<td>0</td>
</tr>
<tr>
<td>Bicarbonate (as HCO$_3$), mg/L</td>
<td>490</td>
</tr>
<tr>
<td>Sulfate (SO$_4$), mg/L</td>
<td>55</td>
</tr>
<tr>
<td>Chloride (Cl), mg/L</td>
<td>102</td>
</tr>
<tr>
<td>Nitrate (as NO$_3$), mg/L</td>
<td>170</td>
</tr>
<tr>
<td>Silica (as SiO$_2$), mg/L</td>
<td>37</td>
</tr>
<tr>
<td>Barium (Ba), mg/L</td>
<td>0.20</td>
</tr>
<tr>
<td>Fluoride (F), mg/L</td>
<td>0.20</td>
</tr>
<tr>
<td>Strontium (Sr), mg/L</td>
<td>1.3</td>
</tr>
<tr>
<td>Total Dissolved Solids (TDS), mg/L</td>
<td>924</td>
</tr>
<tr>
<td>pH, units</td>
<td>6.5</td>
</tr>
<tr>
<td>Temperature, degrees C</td>
<td>20</td>
</tr>
</tbody>
</table>
RO Process Model

\[
\frac{dQ(x)}{dx} = -A \cdot L_p \cdot (\Delta P - \Delta \pi)
\]

\[
\Delta \pi = \frac{Q_f}{Q} \Delta \pi_0
\]

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

@ \(x = 0, Q(x) = Q_f\)

@ \(x = 0, \Delta P(x) = P_o + \Delta P_{pump} - P_p\)

k – pressure drop factor
\(\Delta P\) – pressure difference across the membrane
\(P_o\) – feed pressure prior to pump
\(\Delta P_{pump}\) – pressure increase across pump
\(P_p\) – permeate pressure
\(Q\) – retentate flow rate
\(Q_f\) – feed flow rate
\(\Delta \pi_0\) – osmotic pressure change across the membrane entrance
## Plant Production Data – Train 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pressure vessels per train</td>
<td>42</td>
</tr>
<tr>
<td>Number of 1st stage pressure vessels</td>
<td>28</td>
</tr>
<tr>
<td>Number of 2nd stage pressure vessels</td>
<td>14</td>
</tr>
<tr>
<td>Number of membrane elements per vessel</td>
<td>7</td>
</tr>
<tr>
<td>Area per element, $ft^2$</td>
<td>400</td>
</tr>
<tr>
<td>Feed pressure, $P_0$, psi</td>
<td>40.6</td>
</tr>
<tr>
<td>Feed osmotic pressure, $\Delta \pi_0$, psi</td>
<td>9</td>
</tr>
<tr>
<td>Feed flow, $Q_f$, gpm</td>
<td>1,525</td>
</tr>
<tr>
<td>Permeate pressure, $P_p$, psi</td>
<td>16.4</td>
</tr>
<tr>
<td>Permeate flow, $Q_p$, gpm</td>
<td>1,234</td>
</tr>
<tr>
<td>Recovery, $Y$, %</td>
<td>80.9</td>
</tr>
<tr>
<td>Retentate pressure drop in 1st stage, $\Delta P_{r_1}$, psi</td>
<td>24.9</td>
</tr>
<tr>
<td>Retentate pressure drop in 2nd stage, $\Delta P_{r_2}$, psi</td>
<td>18.2</td>
</tr>
<tr>
<td>Pump head, $H$, ft</td>
<td>360</td>
</tr>
</tbody>
</table>
Parameter Identification from Plant Operation Data

$k = 2.1 \times 10^{-5} \text{ psi/gpm}^2$ (in the first stage)

$L_p = 0.11 \text{ gfd/psi}$
Optimization Model

\[
\begin{align*}
\min & \quad NSEC_{Q_f,Y} \\
\text{s.t.} & \quad \eta_{pump} = \eta_{pump}(Q_f, H) \\
& \quad dQ(x) = -A \cdot L_p \cdot \left(\Delta P - \frac{Q_f}{Q} \Delta \pi_0\right) \\
& \quad d(\Delta P(x)) = -k \cdot Q^2 \\
& \quad Q(x) = Q_f @x = 0 \\
& \quad P(x) = \Delta P_0 + \Delta P_{pump} - P_p @x = 0 \\
& \quad \Delta P_{pump} = 0.4327 \cdot H \\
& \quad Q_p = Q_f - Q(2) \\
& \quad Y = \frac{Q_p}{Q_f} \\
& \quad Y \leq Y_{max} \\
& \quad Y \geq Y_{min} \\
& \quad g_{pump}(Q_f, H) \leq 0
\end{align*}
\]
RO Plant Trial Methodology

• Data was taken from Train 1 over 4 days

• Permeate flow rate kept constant at 1235 GPM

• Recovery rate was varied from 78% to 95% and the resulting field data were recorded for analysis
Recovery = \frac{\text{Permeate flow}}{(\text{Permeate flow} + \text{Retentate flow})} = \frac{1236}{(1236 + 291)} = 81\%
Plant Validation of Model
Improved Model Incorporating CFD Results

\[
\begin{align*}
\frac{dQ}{dx} &= -J_w A_t, \quad @x = 0, Q = Q_0 \\
\frac{d(\Delta P)}{dx} &= -k_2 Q^{1.67}, \quad @x = 0, \Delta P = \Delta P_0 \\
J_w &= L_p [\Delta P - \Delta \pi \exp \left(\frac{J_w}{k_3 Q^{0.40}}\right)] \\
\Delta \pi &= \frac{Q_0 \Delta \pi_0}{Q}
\end{align*}
\]
A desalination plant may have multiple RO trains with RO elements of different service times.

Older membranes tend to have lower $L_p$.

By optimally allocating permeate production rates among all trains based on $L_p$, the SEC of the whole plant may be reduced.
Economic Considerations for Sustainable Production

- Model predicts optimum recovery point
  - Power saving ($40 K/year)
  - Reduction in brine volume (>50%) which leads to less disposal cost ($360 K/year)
  - Faster membrane fouling not quantified ($negative)

- Requires comprehensive optimization study prior to implementation

Precipitation in Brine Line after 13 Years of Service
Related Publications


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