Modeling and Optimization of Reverse Osmosis Desalination: An Industrial Case Study

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US Desalination Capacity

Economic Considerations

Energy Consumption
Economic Considerations

- Energy Consumption
- Capital Investment
Economic Considerations

- Energy Consumption
- Capital Investment
- Brine Disposal
Background
What is Reverse Osmosis?

- Osmotic pressure is the minimum amount of pressure needed to stop water from flowing across the membrane.

- Water flow will be reversed by applying pressure greater than osmotic pressure.

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Factors Affecting Driving Force in RO Module

\[ J = L_p (\Delta P - \Delta \pi) \]

- Pressure drop
- Concentration polarization

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Objective
Chino I Desalter

Wells 1-4 → VOC

Wells 5-15 → RO

Final Blended Product
14 MGD

Product Quality Requirement
TDS: 350 mg/L
Nitrate: 25 mg/L

Ion Exchange
5 MGD

2 MGD
Methodology
Computational Fluid Dynamic (CFD) Simulations → System Model → Model Validation and Optimization of Operating Conditions
Geometry

- Platform: COMSOL™ Multiphysics
- Filmtec™ BW30-400 RO element
- Fully developed inlet velocity profile

4 Johnson and Busch, Engineering Aspects of Reverse Osmosis Module Design, http://www.lenntech.com
Governing Equations

- Navier Stokes Equation (Hydrodynamics)

\[ \rho (u \cdot \nabla) u = \nabla \cdot \left[ -p I + \mu (\nabla u + (\nabla u)^T) \right] \]
\[ \rho \nabla \cdot u = 0 \]

- Diffusion-Convection Equation (Salt transport)

\[ \nabla \cdot (D \nabla c) = u \cdot \nabla c \]
\[ n \cdot (-D \nabla c + cu) = 0 \]

- Water Flux (Boundary condition)

\[ J_w = L_p (P - P_p - f_{os} c) \]
Results
Pressure Drop

Concentrate Pressure Drop $-\frac{dP}{dx}$ (kPa/m)

- Spacer-filled channel
- Open channel

Avg Interstitial Velocity $\bar{u}$ (m/s)

Mingheng Li
Reverse Osmosis Water Desalination
AIChE Annual Meeting 2016
Average Mass Transfer Coefficient

![Graph showing the relationship between Average Interstitial Fluid Velocity ($\bar{u}$) and Average Mass Transfer Coefficient ($k_m$). The graph compares two conditions: Spacer-filled channel (red circles) and Open channel (blue circles). The $k_m$ values increase with $\bar{u}$ for both conditions.]
System Level Model

\[
\frac{dQ}{dx} = -J_w A; \quad Q = Q_0 \text{ at } x = 0
\]

\[
\frac{d(\Delta P)}{dx} = -kQ^{1.67}; \quad \Delta P = \Delta P_0 \text{ at } x = 0
\]

\[
J_w = L_p [\Delta P - \Delta \pi \exp(J_w/(\bar{k}Q^{0.40}))]
\]

\[
\Delta \pi = Q_0 \Delta \pi_0 / Q
\]
Production rate kept constant at 1235 GPM

Adjusted simultaneously
  ⇒ Intake Flow
  ⇒ Valve Position
Normalized Energy Consumption

- Plant data
- Model

Normalized pump energy consumption vs Recovery

Recovery range: 0.75 to 1
Conclusions

- By increasing recovery from 80% to 90% while maintaining production rate:
  - 10% electricity reduction ($40k/year in savings)
  - Reduction in waste volume by 50% ($360k/year in savings for disposal)

- Making incremental changes so that operating cost is reduced without substantially shortening membrane life.
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Li, M.; Bui, T.; Chao, S. Three-dimensional CFD analysis of hydrodynamics and concentration polarization in an industrial RO feed channel, Desalination, 397, 194-204, 2016.