Water for Energy
and
Energy for Water

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Water-Energy-Sustainability

Water for Energy
- Extraction & Refining
- Fuel Production
- Hydropower
- Thermo Electric Cooling

Sustainability
- Extraction and Transmission
- Drinking Water Treatment
- Wastewater Treatment
- Energy Associated with Uses of Water

Energy for Water

Membrane Contact Processes
Membrane Contactor Processes

Mass transfer across the membrane is due to properties of the two fluids and the membrane characteristics.

Salinity gradients – Temperature gradients
Salinity Gradients

Osmosis
Osmosis in Biological Systems

Isotonic solution

\[ \text{H}_2\text{O} \quad \text{H}_2\text{O} \]

\[ \text{H}_2\text{O} \quad \text{H}_2\text{O} \]

Campbell, 1999
Osmosis in Engineered Systems

Semi-permeable membrane

Osmosis

Low salinity solution

High salinity solution

Δπ

Equilibrium

Forward Osmosis (FO)
Pressure Retarded Osmosis

An osmotically driven membrane process similar to RO and FO

Semi-permeable membrane

Pressure Retarded Osmosis

- **FO** (Pressure (ΔP > Δπ))
  - Low salinity solution
  - High salinity solution
- **RO** (Pressure (ΔP = Δπ))
- **PRO** (Pressure (ΔP < Δπ))
Pressure Retarded Osmosis

- An osmotically driven membrane process similar to RO and FO

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

\[ W = -J\Delta P \]

\[ W_{\text{max}} = \frac{\Delta\pi}{2} \]

\[ \Delta P = \Delta\pi/2, \quad \Delta P = \Delta\pi \]

Global energy production from mixing in estuaries: 2,000 TWh/y
Current global energy production from all renewable sources: 10,000 TWh/y

Pressure Retarded Osmosis

- An osmotically driven membrane process similar to RO and FO
- A means for capturing solar energy from the mixing of freshwater with saltwater

Resource Utilization: Specific Energy

\[
\text{PRO Dilution} = \frac{V_{\text{feed}}}{V_{\text{draw solution out}}}
\]

V_{\text{feed}} \text{ (River Water)}

V_{\text{draw in}} \text{ (Seawater)}

V_{\text{draw out}}

\text{System Specific Energy (kWh/m}^3\text{)}

\text{Volumetric Fraction of Feed Solution to the Feed and Draw Solutions}
River-to-Sea PRO Resource Utilization

Promising PRO Applications?

Hybrid Desalination Systems
Urban Water Cycle

Seawater

Desalination Facility (RO)

Drinking Water

High-Salinity Brine

Wastewater

Treated Wastewater

Wastewater Treatment Facility
“California Model” of Desalination
How can we maximize the benefits from this resource?

Seawater
Drinking Water
High-Salinity Brine
Treated Wastewater
Wastewater Treatment Facility
Wastewater

Forward Osmosis & Pressure Retarded Osmosis

Why Forward Osmosis or Pressure Retarded Osmosis?

- Low fouling and high rejection of forward osmosis
- Energy recovery of pressure retarded osmosis

Hybrid Desalination Systems

Drinking water

Brine

RO

PX

Seawater
Forward Osmosis - Reverse Osmosis

Reverse Osmosis - Pressure Retarded Osmosis

Drinking water
Concentrated Wastewater

Pressurized Feed
Diluted Brine

Feed
PX

### Specific Energy Consumption Summary

<table>
<thead>
<tr>
<th></th>
<th>20% Recovery</th>
<th>30% Recovery</th>
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</thead>
<tbody>
<tr>
<td><strong>RO Alone</strong></td>
<td>6.51</td>
<td>5.25</td>
</tr>
<tr>
<td><strong>RO-PX</strong></td>
<td>3.80</td>
<td>3.38</td>
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<tr>
<td><strong>RO-PRO with 2nd PX</strong></td>
<td>3.08</td>
<td>2.64</td>
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≅36% ≅22%
Gen II RO-PRO System and FO-RO

- Projects funded by California Department of Water Resources and NSF-EPRI
- Larger system to operate at 40-50% RO recovery
- Long-term operation utilizing seawater and impaired water sources
- Directly compare RO-PRO with FO-RO experimentally and at the system level
- Develop a computational fluid dynamics model of the FO and PRO processes to describe the membrane module geometry
Temperature Gradients

Distillation
Membrane Distillation

Heated Feed Stream

Cooler Distillate Stream

Hydrophobic, Microporous Membrane

Driving force: vapor pressure gradient
Driving force not significantly reduced at high salt concentrations
Membrane Distillation Modeling

Specific Energy Consumption

Feed → Membrane Module → Distillate

Membrane Area ($m^2$)

Temperature (°C)

Membrane Length (m)

Specific Energy Consumption (KWhL$^{-1}$)

Production (L hr$^{-1}$)

Heat Recovery

10 Membranes
HOT Water: A Hybrid Optical Technology for Water
(Achilli, Hickenbottom, Norwood, and Li)
Thank you!

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