2.500 Desalination & Water Purification

Slides to accompany reverse osmosis discussion

3 March 2009
Professor John H. Lienhard V
Spiral-wound element
20 cm diam by 1 m length

Source. This image and many of the subsequent images are from:
<table>
<thead>
<tr>
<th>Year</th>
<th>Element Price</th>
<th>Price ft²</th>
<th>Normalized Price/Area</th>
<th>CPI</th>
<th>1978=1 CPI</th>
<th>Norm 78 Price/Area</th>
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<tbody>
<tr>
<td>1978</td>
<td>$950</td>
<td>$6.33</td>
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<td>71</td>
<td>1</td>
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<tr>
<td>1989</td>
<td>$875</td>
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<td>1.75</td>
<td>0.26</td>
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<tr>
<td>1995</td>
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<td>$0.36</td>
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<td>2.14</td>
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<td>$1.38</td>
<td>$0.22</td>
<td>200</td>
<td>2.82</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Source: Leon Awerbuch, desalination lecture at MIT, 23 Feb 2009

Courtesy of Leon Awerbuch. Used with permission.

J. Birkett & R Truby, 2007

LET Proprietary
Configuration of a pressure vessel assembly

Water flow in a pressure vessel assembly

Vertical centrifugal pumps & Membrane pressure vessels
Recovery per element is limited to about 18% to prevent excessive concentration polarization

Relative concentration polarization factor vs. membrane element recovery rate. \( \beta = \exp \left( 0.75 \cdot \frac{2R}{2 - R} \right) \)

Recovery rate of individual elements in a pressure vessel. 
Seawater RO, $R = 50\%$

<table>
<thead>
<tr>
<th>Element position</th>
<th>6 elements/vess. Recovery, %</th>
<th>7 elements/vess. Recovery, %</th>
<th>8 elements/vess. Recovery, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.1</td>
<td>15.1</td>
<td>13.2</td>
</tr>
<tr>
<td>2</td>
<td>15.3</td>
<td>12.9</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>11.3</td>
<td>11.0</td>
<td>11.1</td>
</tr>
<tr>
<td>4</td>
<td>10.2</td>
<td>8.3</td>
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</tr>
<tr>
<td>5</td>
<td>8.5</td>
<td>6.8</td>
<td>7.8</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>4.9</td>
<td>6.3</td>
</tr>
<tr>
<td>7</td>
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<td>4.5</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>2.3</td>
</tr>
</tbody>
</table>

Seawater system, salinity distribution

Feed salinity 40,000 ppm TDS
Recovery rate 45%
Permeate flux 13.7 l/mh

RO elements in a pressure vessel.

Concentrate may be staged in order to achieve high recovery without excessive concentration polarization, e.g., in brackish water RO (BWRO)

\[ R_{p,1 \text{ stage}} \leq 60\% \quad \text{and} \quad R_{p,2 \text{ stage}} \leq 75-85\% \]

First stage has 32 pressure vessels; second stage has 14

Two-stage brackish unit, 32:14 (7M) array
4.0 × 2.9 × 8 m, 8000 m³/d
13.1 × 9.5 × 26', 2.1 mgd

Concentrate staging in a high-salinity brackish RO system with 80% recovery. Note turbine assisted booster pump.
Pumping power = (Volume flow rate) * (pressure rise)

The high pressure concentrate accounts for a large part of the pumping power

High pressure pump with Pelton wheel

100 m$^3$/h, 60 bar
440 gpm, 870 psi

50 m$^3$/h, 58 bar
220 gpm, 840 psi

50 m$^3$/h, 1 bar
220 gpm, 14.5 psi

50 m$^3$/h, 0 bar
220 gpm, 0 psi

Power recovery

34% reduction of energy consumption

Energy consumption of RO process: 2.60 kWh/m$^3$ (9.84 kWh/kgallon)

Pumping system at Larnaca plant. (Cyprus)


Pelton Wheel
Energy recovery device

Turbine impeller
Shaft bearing
Pump impeller

Turbocharger applied as interstage booster pump

Permeate blending in a low-salinity brackish RO system with 89% recovery
Permeate may be blended to lower feed salinity in SWRO

<table>
<thead>
<tr>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow, m³/h (gpm)</td>
<td>979.0 (4308)</td>
<td>992.2 (2159)</td>
<td>992.2 (4369)</td>
<td>575.5 (2534)</td>
<td>138.9 (611)</td>
<td>138.9 (611)</td>
<td>13.9 (61)</td>
<td>125 (550)</td>
<td>277.8 (1222)</td>
<td>402.8 (1772)</td>
</tr>
<tr>
<td>Pressure, bar (psi)</td>
<td>64.4 (934)</td>
<td>62.8 (911)</td>
<td>10.7 (155)</td>
<td>7.1 (103)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>TDS, ppm</td>
<td>45199</td>
<td>44695</td>
<td>44695</td>
<td>76707</td>
<td>977</td>
<td>977</td>
<td>9153</td>
<td>68</td>
<td>245</td>
<td>190</td>
</tr>
</tbody>
</table>

Figure by MIT OpenCourseWare.
Ocean surface temperatures in July and January

Source: R.H. Stewart, *OceanWorld* website, TAMU.

Courtesy of Robert H. Stewart. Used with permission.
Correction for temperature change

Membrane permeability (for both water and salt) rises with temperature: \( P = P_0 \exp(-E/RT) \)

Temperature correction factor (representative):

\[
TCF = \exp[-2700(1/T-1/298)] \text{ for } T \text{ in kelvin.}
\]

Both \( A \) and \( B \) in solution-diffusion model are multiplied by the TCF.

\( TFC = 1 \text{ at } T=298 \text{ K. TCF rises with increasing temperature.} \)
Effect of feed water temperature on required feed pressure in a seawater RO unit, recovery 50%, flux 14 l/m²-h.

Feedwater preheating can be beneficial, especially if supply is relatively cold.

This 10,000 gpd (38 m³/day) system costs ~$40K. With ancillary hardware, it is ~$60K, plus site preparation and related costs.

A 100,000 gpd (380 m³/day) system is ~$600K, with ancillary systems.

Typical applications include Caribbean resorts and hotels.
Representative Seawater RO Intake

Intake 10 to 15 m below surface at low tide.

Seawater pretreatment.

Disinfect with chlorine

Add ferric chloride to coagulate small particulates

Filter, adjust pH to protect membranes, add scale inhibitor
dechlorination (by sodium bisulfate), cartridge filtration (5-15 μm porosity)
Cartridge filter housing in a horizontal configuration

Seawater RO Post-treatment.

Add alkalinity and hardness via: \( \text{CO}_2 + \text{Ca(OH)} \rightarrow \text{Ca(HCO}_3\text{)}_2 \)

Disinfect with additional chlorine, control pH
Diffuser for concentrate discharge

- Effluent volume: 67,000 m³/d
- Discharging velocity: 6.0 m/s
- Concentrated seawater: 5.8%
- Raw seawater: 3.5%