Desalination Technology and Energy

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Desalination in history

“Salt water when it turns into vapor becomes sweet and the vapor does not form salt water again when it condenses.”

----Aristotle, Meteorologica

Pliny the Elder, Natural History
Water on Earth

2.5% Fresh water but frozen

0.5% Fresh water available

97% Seawater (non-drinkable)

Aquifers
- Rainfall
- Natural lakes
  - Reservoirs
  - Rivers

Water Business Council for Sustainable Development
Numbers about Desalination

- World annual water consumption: 9,087 Gm$^3$/y
- World desalination capacity: 31.7 Gm$^3$/y
  - 0.3% of total consumption
- World energy consumption: $1.1 \times 10^{14}$ kWh/y
- World desalination energy consumption: $\sim 1.8 \times 10^9$ kWh/y
  - 0.002% of total energy consumption
  - Compare to Haber process 1-2%
Desalination plans in the world

MAJOR DESALINATION PLANTS WORLDWIDE
The United States has 2 major municipal seawater-desalination plants — 1 under construction in Tampa and another inactive plant in Santa Barbara, Calif. Other countries with 1 or more major plants are marked with red dots.

Capacity by region
A breakdown of where desalination technology is used on seawater, salty underground water and in other water treatments around the world.

SOURCES: Engineering News-Record; Aqua Resources International Corp.; International Desalination Association

SCOTT HIESTAND/ORLANDO SENTINEL
Energy cost of water supply (Qingdao, China)
Water Price

<table>
<thead>
<tr>
<th>Cost of measure</th>
<th>$/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desalination</td>
<td>0.70 - 0.90</td>
</tr>
<tr>
<td>Typical groundwater supply measures</td>
<td>0.04 - 0.21</td>
</tr>
<tr>
<td>Agricultural measure – Irrigation scheduling</td>
<td>(0.12) - (0.02)</td>
</tr>
<tr>
<td>Industrial measure – paste tailings (mining)</td>
<td>(0.60) - (0.30)</td>
</tr>
</tbody>
</table>

2030 Water Resource Group
Analysis of energy cost of desalination

• Estimate osmotic pressure of seawater

• Thermal dynamic (limit)

• Practical cost
Calculate Seawater Osmotic Pressure

\[ \pi = iMRT = 2,675\text{kPa} = 26.4 \text{ atm} \]

- Osmotic Pressure
- Molarity (mole/L)
- Temperature (K)
- van’t Hoff’s factor (1.8)
- Ideal gas Constant

Pressure of \(~260\text{m}\) high water pillar !!!
Calculate Ideal Energy Cost of Desalination

How much energy is needed to convert 1m$^3$ seawater into pure water?

$$W = \pi V = 2675\text{kJ} = 0.743\text{ kWh}$$

Assumptions:

• Slow conversion
• No osmotic pressure change (0% recovery)
• Ideal ionic membrane
Real Energy Cost of Desalination

- 0% recovery: 0.76 kWh/m³
- 50% recovery: 1.06 kWh/m³
- Practical RO: 1.56 kWh/m³
- Real case RO: 2 kWh/m³
- Real case Overall: 3-4 kWh/m³
Recovery rate selection

![Graph showing the relationship between water recovery and minimum work required. The graph indicates that as water recovery increases, the minimum work required also increases significantly.]
Desalination Technologies

• Phase change technologies
  ▪ Solar still
  ▪ Multi effect distillation (MED)
  ▪ Multi stage flash (MSF)
  ▪ ...

• Membrane based technologies
  ▪ Reverse Osmosis (RO)
  ▪ Electrodialysis
  ▪ ....
Solar Still Desalination

- Simple
- Low cost
- 3-4 L/day
- About 1000kWh/m³

Towards engineering of 21st century
Multi stage flash (MSF) distillation

- High temperature & high pressure
- Energy recovered by heating up seawater

Ali M. El-Nashar
Desalination with Renewable Energy
Multi effect distillation (MED)

- Low temperature & reduced pressure
- Energy recovered by vaporizing sea water
## Comparison between MSF & MED

<table>
<thead>
<tr>
<th></th>
<th>MSF</th>
<th>MED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High P high T</td>
<td>Reduced P, Low T</td>
</tr>
<tr>
<td></td>
<td>Easy scale up</td>
<td>Difficult to scale up</td>
</tr>
<tr>
<td></td>
<td>Severe corrosion</td>
<td>Less corrosion</td>
</tr>
<tr>
<td></td>
<td>Require high T steam</td>
<td>Recover low T steam</td>
</tr>
<tr>
<td></td>
<td>10-16 kWh/m³</td>
<td>5.5-9 kWh/m³</td>
</tr>
</tbody>
</table>

Hug March Advanced Review 2015
Desalination Technologies

• Phase change technologies
  ▪ Solar still
  ▪ Multi effect distillation (MED)
  ▪ Multi stage flash (MSF)
  ▪ ...

• Membrane based technologies
  ▪ Reverse Osmosis (RO)
  ▪ Electrodialysis
  ▪ ....
Single Stage RO

1. Cold Water Supply Line
2. Pre-Filter
3. Carbon Filter
4. Membrane
5. Shut-Off Valve
6. Flow Restrictor
7. Post Filter
8. Storage Tank
9. Purified Water To RO Faucet
10. Impurities Out To Drain
Two-stage Reverse Osmosis

- 1 Stage: 1.56 kWh/m$^3$
- 2 Stages: 1.28 kWh/m$^3$
- $\infty$ stages: 1.06 kWh/m$^3$
- Best practice: 2kWh/m$^3$
- Overall consumption: 3-4kWh/m$^3$
Towards engineering of 21st century
Thermal process economic comparison

<table>
<thead>
<tr>
<th>Desalination process</th>
<th>Capacity (m³/day)</th>
<th>Desalination cost ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MED</td>
<td>&lt;100</td>
<td>2.5-10</td>
</tr>
<tr>
<td></td>
<td>12,000-55,000</td>
<td>0.95-1.95</td>
</tr>
<tr>
<td></td>
<td>&gt;91,000</td>
<td>0.52-1.01</td>
</tr>
<tr>
<td>MSF</td>
<td>23,000 – 528,000</td>
<td>2.01-2.66</td>
</tr>
<tr>
<td>OS</td>
<td>&lt;1000</td>
<td>1.25-18.75</td>
</tr>
<tr>
<td></td>
<td>60,000 - 15,000</td>
<td>0.48-1.62</td>
</tr>
<tr>
<td></td>
<td>100,000 – 320,000</td>
<td>0.45-0.66</td>
</tr>
</tbody>
</table>

Towards engineering of 21st century
Construction costs of different technologies

• Qingdao Case (RO):
  ▪ $176m construction cost, 100,000m$^3$ capacity
  ▪ about $1760 per day per m$^3$

• Black and Veatch case (MSF):
  ▪ $19m construction cost, 4,000m$^3$ capacity
  ▪ About $4750 per day per m$^3$
Comparison between Major Desalination technologies

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDE</td>
<td>Energy efficient</td>
<td>Smaller in scale</td>
</tr>
<tr>
<td></td>
<td>Couple with Cogen and Solar</td>
<td>Vacuum</td>
</tr>
<tr>
<td></td>
<td>thermal, geothermal</td>
<td></td>
</tr>
<tr>
<td>MSF</td>
<td>Large scale</td>
<td>Less efficient</td>
</tr>
<tr>
<td></td>
<td>Corrosion</td>
<td></td>
</tr>
<tr>
<td>OS</td>
<td>Highly efficient</td>
<td>Use electricity</td>
</tr>
</tbody>
</table>
THANKS
Typical Cost Structure of SWRO
Feed temperature effect

Pumping Energy vs. Feed Temperature

Notes:
- 50% Recovery
- 34,000 mg/L Feedwater TDS

Pumping Energy, kWh/kgal and Temperature, °C
Desalination by Renewable Energy

- PV-RO, 32%
- Wind RO, 19%
- Hybrid, 4%
- Solar MED, 13%
- Solar MSF, 6%
- WMVC, 5%
- Other, 15%
- PV-ED, 6%