Water Purification by the Dewvaporation Technique

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Overview

- Motivation
- Status Quo Technology
  - Thermal processes
  - Membrane processes
- DEWVAP Research
  - Design
  - Theoretical development
  - Experimental work
- Experimental Observations
- Cost Summary
Motivation

- Decrease in fresh water supply
- Increase of water cost by desalination due to high demand
- Seawater, Brackish water, Evap Pond Waters
  - Salinity is defined as g of salt per kg of solution
  - Seawater
    - Salinity of the world oceans varies from 30-50 g/kg
  - Brackish water
    - Waters with salinity of 5 g/kg or less
  - Evaporative Pond Waters
    - Saturated salt solutions of 300 g/kg crystallized
Background - MED

GOR = 0.8*Number of Effects

Background - MSF

Stage N
Low Pressure
Low Temperature

Stage 1
High Pressure
High Temperature

Saline Waters

Distillate

Brine

GOR values range from 4-12

Howe, Everett D. Fundamentals of Water Desalination. New York, 1974
Dewvaporation - Theory

Vapor loading
\[ V = \frac{P_w}{P - P_w} = \frac{\text{RH} \cdot P^0}{P - \text{RH} \cdot P^0} \]

Energy reuse factor
\[ f = \frac{V_{dh} - V_{d0}}{V_{dh} - V_{eh}} \]

Molar production density
\[ P_f = \frac{G}{A} \cdot (V_{dh} - V_{d0}) \]

Z = h

Z = 0
Dewvaporation at ASU

- Uses air as a carrier gas in a contact tower
- Operates at atmospheric pressure and below boiling point
- Air Fan and Feed Pump
- Towers are composed of
  - Polypropylene and nylon plastic materials
  - evaporation and dewformation side separated by thin inexpensive non-corrosive plastic heat transfer walls
Objective I
- Minimum Gamma
- Design a tower for the Dewvaporation technique

Objective II
- Develop a mathematical model for the Dewvaporation
- Develop an approximate solution of the theory

Objective III
- Scaling phenomena
- Different runs on few of the potential designs
### Surface wetting

- **Minimum gamma** (lb of feed liquid/hr. /ft of width)

<table>
<thead>
<tr>
<th>Percent Coverage</th>
<th>Without gauze</th>
<th>With gauze*</th>
</tr>
</thead>
<tbody>
<tr>
<td>REXAM</td>
<td>12</td>
<td>~1</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>&gt;12</td>
<td>~1</td>
</tr>
<tr>
<td>Polypropylene twin wall</td>
<td>&gt;12</td>
<td>~1</td>
</tr>
</tbody>
</table>

- Nylon
Plastic Design Choices

- Plastic material
  - Mylar (3 mil)
    - Design 1
      - Vertical spacers
    - Design 2
      - Horizontal spacers
  - Polypropylene (1 mil)
    - Design 3
      - Horizontal spacers
    - Design 4
      - Reticulated foam
  - Twin walls (9 mil)
    - Design 5
      - Vertical flow
    - Design 6
      - W.E.S.T
    - Design 7
      - N.E.W.T
Dewvaporation - Tower Assembly

Composite (Gauze covered plastic)

Feed heat exchanger
Dewformation side frame
Dewformation side frame
Dewformation side frame
Dewformation side frame
Dewformation side frame
Wall
Evaporation side frame
Evaporation side frame
Evaporation side frame
Evaporation side frame
Evaporation side frame
Dewvaporation tower – Design 1

- 20 ft² effective total heat transfer area
- 12 evaporation and 12 dewformation sides
- REXAM water wettable sheet
Design 2 - Spacers

Spacer for the Evaporation side

Spacer for the Dewformation side
Dewvaporation tower – Design 2

- Total area ~ 55 ft²
- 5 evaporation sides
- 4 dewformation sides
- 1 liquid heat exchanger
- 19 passes per side
Dewvaporation tower – Design 3

- 5 evaporation chambers
- 6 dewformation chambers
- 1 liquid heat exchanger
- 10 passes per side on evaporation and dewformation
- Thin plastic (1 mil) polypropylene
- Foam spacers
- Issues
  - Support
Dewvaporation tower – Design 4

- Thin plastic (1 mil)
- Reticulated foam
- Filled dew formation side (no collapsing)

Issues

- Pressure drop increase with wetting
Dewvaporation tower – Design 5

- 9 mil wall thickness
- No horizontal/vertical spacers
- Issues
  - None
Horizontal spacers on the evaporation side only
Dewvaporation Tower-Design 7

- 850 square Feet
- W.E.S.T. Twin Design
- 45 lb/hr
- 1ftx2ftx7ft

PROJECTED FACILITY
100,000 gallon/day Plant
Footprint: 780 square feet
20 feet high
Dewvaporation - Theory

Energy reuse factor

\[ f = \frac{V_{dh} - V_{d0}}{V_{dh} - V_{eh}} \]

Molar production density

\[ P_f = \frac{G}{A} \cdot (V_{dh} - V_{d0}) \]

Vapor loading

\[ V = \frac{P_w}{P - P_w} = \frac{RH \cdot P^o}{P - RH \cdot P^o} \]

Carrier Gas
Saline Feed
Brine

Evaporation
Dewformation

Z = h

Q_{Feed}
Q_{Top}

Z = 0

Carrier Gas
Distillate
Dewvaporation - Theory

Overall Heat Transfer Coefficient

\[
\frac{1}{U_z} = \frac{1}{h_{fe,z}} + \frac{1}{h_{fd,z}} + \frac{t_{\text{plastic}}}{k_{\text{plastic}}} + \frac{\delta_e}{k_{\text{water}}} + \frac{\delta_d}{k_{\text{water}}}
\]

Resistances

Heat Transfer Coefficient

\[
h_{f,z} = h_{g,z} \cdot (1 + M_z \cdot (1 + M_z))
\]

Plastic Thickness

\[
M = \left( \frac{\lambda}{RT} \right)^2 \cdot \left( \frac{R}{c_p} \right) \cdot V
\]

Liquid Film Thickness

\[
\delta = \left( \frac{3 \cdot \mu \cdot \Gamma}{\rho^2 \cdot g} \right)^{1/3}
\]
Assumption: Energy terms of liquid and air are small compared to latent heat of vaporization

\[
P_f \cdot f = \left( \frac{\lambda}{B \cdot R \cdot T} \right)^2 \cdot \left( \frac{h_g}{c_p} \right) \cdot \left( \frac{V_{eh}}{2 + V_{eh}} \right) \cdot \sum \frac{k}{t}
\]

\[
F = \frac{1}{1 + F_{RH} + F_{\epsilon} + F_{RH} \cdot F_{\epsilon} \cdot \left( \frac{6 + 3 \cdot V_{eh}}{3 + 2 \cdot V_{eh}} \right)}
\]
Cross flow Reduction Effect

Number of passes

Energy Factor, f

- 5.3
- 13.06
- 14.26
- 10.65
- 9.56
- 11.46
- 14.6
- 15.43
- 15.43
- 15.72
- 15.61

0 5 10 15 20 25 30 35 40 45 50

0 5 10 15 20 25
Scale

- Defined as a deposit that forms on solid surfaces by enhanced species concentration
- Problem: Reduction of heat transfer coefficient
Preliminary Data - Scale

- 85% recovery
- Solids were observed but did **NOT** adhere to the surface
- No potential scaling problem
- 85% recovery
- Crystals formed at the gas/liquid interface
- Crystals did NOT adhere to the heat transfer wall
Preliminary Data based on Design 1

\[ \frac{fP_f}{\text{lb mole/hr ft}^2} \]

193°F, \( f = 15 \)
## Sea & Brackish Water Data: Design 2

<table>
<thead>
<tr>
<th>Run #</th>
<th>Distillate (lb/hr)</th>
<th>Steam (lb/hr)</th>
<th>GOR</th>
<th>GOR (no heat loss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>729</td>
<td>3.04</td>
<td>0.37</td>
<td>8.96</td>
<td>17.74</td>
</tr>
<tr>
<td>805c</td>
<td>2.22</td>
<td>0.29</td>
<td>7.69</td>
<td>19.34</td>
</tr>
<tr>
<td>806*</td>
<td>2.60</td>
<td>0.27</td>
<td>9.46</td>
<td>28.25</td>
</tr>
<tr>
<td>809*</td>
<td>1.98</td>
<td>0.37</td>
<td>5.29</td>
<td>13.34</td>
</tr>
</tbody>
</table>

* seawater with 42000 ppm
<table>
<thead>
<tr>
<th>Run #</th>
<th>Feed* (lb/hr)</th>
<th>Distillate (lb/hr)</th>
<th>% Reclaimed</th>
<th>f Reuse** Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.0</td>
<td>3.30</td>
<td>41</td>
<td>20.0</td>
</tr>
<tr>
<td>2</td>
<td>8.0</td>
<td>3.63</td>
<td>45</td>
<td>14.1</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>3.30</td>
<td>55</td>
<td>20.8</td>
</tr>
<tr>
<td>4</td>
<td>4.0</td>
<td>3.52</td>
<td>88</td>
<td>7.3</td>
</tr>
</tbody>
</table>

* CMP Slurry 1 wt% solids
** Behaves Like Brackish Water but some gel in tower
PVA will Prevent Gel Formation in the Dewvaporation Towers
Air flow correction - Design 7

- Improved design (N.E.W.T) where cross flow occurs on the dewformation side instead of the evaporation side
- Eliminates spacers on Dew formation side
## Economics (100,000 gallons per day)

<table>
<thead>
<tr>
<th>Design Heat Source</th>
<th>Capital Cost ($)</th>
<th>Operating Cost ($/1000 gallons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas @ $0.36/therm</td>
<td>$100,900</td>
<td>3.67</td>
</tr>
<tr>
<td>Desiccant Enhanced</td>
<td>$97,400</td>
<td>2.67</td>
</tr>
<tr>
<td>Waste Heat @ $1/1000 lb steam</td>
<td>$85,900</td>
<td>1.39</td>
</tr>
</tbody>
</table>
Summary

✓ No potential scaling
✓ Operated at atmospheric pressure and below boiling point
✓ No clogging of membranes (no additional cost for cleaning / replacing membranes)
✓ Demonstrated CMP water reclamation
  • (at least 90% more with PVA)
✓ Potential Ultra-Pure Water Preparation
  • (leaks 10 ppm less with manufactured units)
✓ Potential Plating & Post etch Clean Reclamation
  • (like evaporation Pond Waters)
Acknowledgements

- United States Department of Interior, Bureau of Reclamation (Brackish & Sea Water)
- Salt River Project (Evap Ponds Crystallizer)