What To Do With Produced Water When Its Reuse for Hydraulic Fracturing Is No Longer Feasible?

Omkar Lokare, Sakineh Tavakkoli, Vikas Khanna and Radisav Vidic

Department of Civil and Environmental Engineering
University of Pittsburgh
Treatment and Disposal Strategies

- **Deep well injection**
  - Linked with seismic activities
  - Viable as long as Class II injection wells are available

- **Reverse Osmosis**
  - Not feasible for wastewater with TDS> 40,000 mg/l

- **Evaporation/Crystallization**
  - Above 90% water recovery
  - High energy intensity and cost

- **Recycling water for subsequent fracking**
  - TDS interferences with hydraulic fracturing chemicals (e.g., friction reducers)
  - Water hardness and bacteria are a concern
  - Works only as long as we have new wells to fracture
Total Water Balance Within a Gas Field

(Kujivenhoven et al., 2011)
Direct Contact Membrane Distillation (DCMD)

- Vapor pressure driven process
- Hydrophobic membranes
- Pore size – 0.2 to 1 μm
- Membranes material – PTFE, PVDF, PP, AC
- Permeate flux is proportional to vapor pressure difference
Direct Contact Membrane Distillation (DCMD)

- **Advantages**
  - Operates at low temperature (<100°C)
  - Low quality heat energy can be used
  - Ambient pressures
  - Not highly affected by salinity
  - Produces high quality water

- **Disadvantages**
  - Conduction heat losses
  - Energy consumption (up to 3.5 MWh/m³)\(^1\)

---

Experimental Setup

(a) Schematic diagram of experimental setup,  (b) Picture of the DCMD module
## Membranes Properties

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Mean pore radius (μm)</th>
<th>Thickness (μm)</th>
<th>Contact angle (active layer)</th>
<th>Membrane Porosity (%)</th>
<th>Thermal Conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>Active layer</td>
<td>Bulk</td>
<td>Active Layer</td>
</tr>
<tr>
<td>AC</td>
<td>0.23</td>
<td>215</td>
<td>-</td>
<td>135</td>
<td>30</td>
</tr>
<tr>
<td>PP</td>
<td>0.38</td>
<td>135</td>
<td>-</td>
<td>136</td>
<td>79</td>
</tr>
<tr>
<td>PTFE 1</td>
<td>0.21</td>
<td>112</td>
<td>20</td>
<td>142</td>
<td>42</td>
</tr>
<tr>
<td>PTFE 2</td>
<td>0.25</td>
<td>210</td>
<td>22</td>
<td>147</td>
<td>37</td>
</tr>
<tr>
<td>PTFE 3</td>
<td>0.24</td>
<td>148</td>
<td>60</td>
<td>149</td>
<td>60</td>
</tr>
<tr>
<td>PVDF</td>
<td>0.19</td>
<td>145</td>
<td>-</td>
<td>107</td>
<td>68</td>
</tr>
</tbody>
</table>
Performance of different membranes

Operating conditions:
• Feed and permeate velocity = 0.6 m/s
• Feed - pure water
• Permeate temperature = 30°C

Flux unit – LMH (l/m²/hr)

<table>
<thead>
<tr>
<th>Membrane</th>
<th>MD coefficient (LMH/kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>2.2</td>
</tr>
<tr>
<td>PP</td>
<td>5.6</td>
</tr>
<tr>
<td>PTFE 1</td>
<td>4.4</td>
</tr>
<tr>
<td>PTFE 2</td>
<td>2.8</td>
</tr>
<tr>
<td>PTFE 3</td>
<td>5.6</td>
</tr>
<tr>
<td>PVDF</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Flux (LMH) vs Vapor pressure difference (kPa)
## Produced water characterization

<table>
<thead>
<tr>
<th>Component (mg/l)</th>
<th>Site 1</th>
<th>Site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl⁻</td>
<td>188,728</td>
<td>63,588</td>
</tr>
<tr>
<td>Na⁺</td>
<td>81,442</td>
<td>26,427</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>1,002</td>
<td>279</td>
</tr>
<tr>
<td>K⁺</td>
<td>786</td>
<td>258</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>2,664</td>
<td>675</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>32,901</td>
<td>6,523</td>
</tr>
<tr>
<td>Sr²⁺</td>
<td>11,910</td>
<td>1,620</td>
</tr>
<tr>
<td>Ba²⁺</td>
<td>6,256</td>
<td>3,743</td>
</tr>
<tr>
<td>Fe total</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>TDS</td>
<td>308,334</td>
<td>92,800</td>
</tr>
<tr>
<td>TOC</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>*Ra²²⁶</td>
<td>$17,980 \pm 1,100$</td>
<td>$753 \pm 60$</td>
</tr>
</tbody>
</table>

* Ra 226 activity is shown in pCi/l
DCMD - Constant concentration - Site 1

- Constant flux over time
- Negligible scaling even at a high TDS

- Constant concentration
- TDS = 308,334 mg/l
- Feed temperature = 60 °C
- Permeate temperature = 30°C
- Feed and permeate velocity=0.6 m/s
## Permeate Quality

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Cl⁻ (ppm)</th>
<th>Rejection %</th>
<th>Average Flux (LMH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>2</td>
<td>99.9</td>
<td>10.5</td>
</tr>
<tr>
<td>PP</td>
<td>7</td>
<td>99.9</td>
<td>34.7</td>
</tr>
<tr>
<td>PTFE 1</td>
<td>0.5</td>
<td>99.9</td>
<td>32.5</td>
</tr>
<tr>
<td>PTFE 2</td>
<td>1</td>
<td>99.9</td>
<td>20.8</td>
</tr>
<tr>
<td>PTFE 3</td>
<td>2</td>
<td>99.9</td>
<td>37.5</td>
</tr>
<tr>
<td>PVDF</td>
<td>1</td>
<td>99.9</td>
<td>16.3</td>
</tr>
</tbody>
</table>
Feed was concentrated until TDS reached 30%

Permeate quality

<table>
<thead>
<tr>
<th></th>
<th>PTFE 1</th>
<th>PTFE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl- (mg/l)</td>
<td>0.4 (99.9% rejection)</td>
<td>0.5 (99.9% rejection)</td>
</tr>
<tr>
<td>Ra 226 (pCi/l)</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>TOC (mg/l)</td>
<td>1 (90.9% rejection)</td>
<td>0.83 (92.4 % rejection)</td>
</tr>
</tbody>
</table>
Scale Formed on DCMD Membrane

- Scaling is not uniform on membrane surface
- Scale is about 1 micron thick after 8 hours of filtration
Testing of Used Membranes

Gas Permeation Test

Pristine and used membranes exhibited almost identical gas permeability.

Pure water flux with the used membranes was equal to that with pristine membranes.
Systems Level Analysis
Stepwise Modelling

(a) Temperature profile across the membrane
- Divide membrane into ‘n’ parts
- Solve for each part sequentially

(b) Small section of the membrane
Model Calibration and Validation

Flux vs flow rate at 50, 60 and 70 °C for (a) 93 g/l and (b) 308 g/l TDS produced water solutions

- Model was calibrated at 60 °C and 1.9 l/min
Optimizing System Performance

(a) Average flux and percent heat recovery vs Feed Temperature
(b) Energy required per m³ of produced water vs Feed Temperature

- Raising the feed temperature increases flux and heat recovery
- More energy is required at lower feed temperature
Systems Level Flow-sheet

Process flow-sheet for water treatment using waste heat
Waste heat from natural gas compressor stations estimated to be 46 TJ/day in PA.
Quantification of Produced Water in PA

- Total of about 2.7 million m³ produced in six months (2014)
How much produced water can be treated?

- 54% of waste heat from NGCS is required to concentrate produced water in PA to 30% salinity.

- Practical constraints:
  - Water transportation
  - NGCS load factor

![Map showing brine production and treatment capacity](image)
Initial guess:
\[ T_{f,i} = T_{m,f}; \ T_{p,i+1} = T_{m,p} \]

Determine \( p_{m,f} \) and \( p_{m,p} \)

Calculate \( J \) by Eq. (1)

Calculate heat transfer coefficients by Eqn. (8)

Calculate \( T'_{m,f} \) and \( T'_{m,p} \) by Eq. (6) and (7)

Determine \( p'_{m,f} \) and \( p'_{m,p} \)
Calculate \( J' \) by Eq. (1)

Update:
\[ T_{f,i} = T_{f,avg} \]
\[ T_{p,i+1} = T_{p,avg} \]

\[ \left| \frac{J' - J}{J'} \right| < 10^{-3} \]

Yes

Determine \( Q_{m,i} \) by Eq. (3)

Determine \( M_{f,i+1}, \ M_{p,i}, \ E_{f,i+1} \)
and \( E_{p,i} \) by Eq. (10), (11), (12)
and (13) respectively

Evaluate \( T_{f,i+1} \) and \( T_{p,i} \) from \( E_{f,i+1} \) and \( E_{p,i} \) respectively

Calculate:
\[ T_{f,avg} = \frac{T_{f,i} + T_{f,i+1}}{2} \]
\[ T_{p,avg} = \frac{T_{p,i} + T_{p,i+1}}{2} \]

\[ \left| \frac{T_{f,i} - T_{f,avg}}{T_{f,i}} \right| < 10^{-3} \]
\[ \left| \frac{T_{p,i+1} - T_{p,avg}}{T_{p,i+1}} \right| < 10^{-3} \]

Yes

Final values
Simulation Results

Temperature and flux profiles for 12 modules in series

- Assuming 1 module has an area of 0.2 m²
- Minimum temperature difference of 10 °C was selected
- 12 modules in series
• Iron fouling may be a problem in the long run
• Pretreatment should be considered

<table>
<thead>
<tr>
<th>Location</th>
<th>Location</th>
<th>Weight %</th>
<th>Location</th>
<th>Location</th>
<th>Location</th>
<th>Location</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>O Na Mg Cl Ca Fe Sr Ba</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>11 31 0 51 1 5 0 1</td>
<td>2</td>
<td>1</td>
<td>9 31 0 56 1 3 0 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>43 0 1 10 6 37 0 2</td>
<td>3</td>
<td>3</td>
<td>44 1 1 10 6 37 0 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>32 2 0 5 2 11 2 46</td>
<td>5</td>
<td>5</td>
<td>30 2 0 8 4 22 1 34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>30 2 0 8 4 22 1 34</td>
<td>7</td>
<td>7</td>
<td>30 2 0 8 4 22 1 34</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>