Pulsed-Power Electromagnetic Effects on Crystallization During Desalination

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Overview

- **Background**
  - Reverse osmosis (RO) Desalination and Scaling
  - Electromagnetic Field Effects on Electrolyte Crystallization
  - Electromagnetic field generator

- **Initial Study Results**
  - Pilot-scale plant
  - Bench-scale cross-flow system

- **Crystallization Characterization**
  - Acoustic Spectroscopy

- **Significance and Future Work**
Background

- Reverse osmosis (RO) membrane desalination is a well-known pressure-driven water purification process.
- Scaling due to crystallization of sparingly soluble salts on the membrane surface causes flux decline, low water recovery rate, and short membrane lifetime.

Strategies for scaling mitigation:

- Chemical methods: antiscalant, pH adjustment, ion exchange: solution chemistry, expensive
- Non-chemical methods
  - Mechanical cleaning: down time, membrane lifetime
  - Electronic or magnetic pretreatment
Electromagnetic (EM) Mechanism

- EM affects crystallization kinetics and morphology of various electrolytes.
- EM field treatment prevents or eliminates chemical scale.
- Incorporation of an EM field in a RO desalination system could be an feasible approach to prevent membrane scaling.

Electromagnetic Field Benefit

- Simple device setup
- Minimal energy input
- Eliminate chemical usage
- Eliminate disposal costs, pollution possibility
EM Field Generator

Dolphin System – Clearwater System Corporation

Operating Status
External Mounting Flange
Lock
Fan Inlet/Filter
Ventilation
Serial No.
Signal Generator

Treatment Module
Water in
Water out

http://www.clearwater-dolphin.com/operating_principles.htm
Dolphin System

- Dolphin system removes the static electric charge on the small suspended particle surface.
- The suspended particles act as seeds for precipitation of sparingly soluble salts.
- The aggregation occurs in bulk solution instead of scaling on the membrane surface.

Typical Surface Scale
Chemical Treatment

Bulk Solution Precipitation
Pulsed EM Treatment

http://www.clearwater-dolphin.com/operating_principles.htm
Dolphin System Application

- Significant cleaning of the plate-and-frame heat exchanger
- Consistently low bacteria levels
- Less corrosion results
- Eliminate of nearly all chemical treatment

Dolphin Water Treatment Study Report prepared by BWI Solutions Inc. 2004
http://www.clearwater-dolphin.com/cooling_towers.htm
Initial Study - Pilot Scale

Full scale pilot plant in Northport, Florida by Carollo Engineering
The membrane is not fouled from sparingly soluble salts
Pressure difference was caused by the back pressure created by concentrate blockage
Concentrate blockage initiates at the intersections of spacer fibers
Initial Study - semi-pilot scale

2.5” element pilot scale plant in Bureau of Reclamation, Denver

K: Conductivity meter
P: Pressure transducer
Flow: Flow meter
T: Thermal couple

<table>
<thead>
<tr>
<th>Species</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>1 kg</td>
</tr>
<tr>
<td>NaOH</td>
<td>0.4 mg</td>
</tr>
<tr>
<td>NaHCO₃</td>
<td>100 mg</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>0.475 g</td>
</tr>
<tr>
<td>Mg SO₄</td>
<td>0.12 mg</td>
</tr>
<tr>
<td>KCl</td>
<td>1.0 g</td>
</tr>
<tr>
<td>FeCl₂</td>
<td>0.38 mg</td>
</tr>
<tr>
<td>NaCl</td>
<td>20.6 g</td>
</tr>
</tbody>
</table>

Concentration: ~11000 ppm
Initial Study - semi-pilot Scale

2.5” element pilot scale plant in Bureau of Reclamation, Denver

<table>
<thead>
<tr>
<th>Productivity (m³/m²)</th>
<th>With Dolphin</th>
<th>Without Dolphin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st – 4th cycle</td>
<td>575</td>
<td>676</td>
</tr>
<tr>
<td>5th-7th cycle</td>
<td>421</td>
<td>360</td>
</tr>
</tbody>
</table>

Interpretation:
- With Dolphin: smaller colloidal crystals may be formed that do not settle easily in the feed tank, instead, they precipitated on the membrane surface.

- Without Dolphin: larger sized crystals may be formed that could act as seeds for precipitating salt in the feed tank.
Bench-scale RO setup
Experimental design

- **Controlled Parameters**
  - Concentration: 1.85 gL⁻¹ CaSO₄
  - Temperature: 23°C

- **Experimental Variable:**
  - Pressure: 50 - 300 psi
  - Cross-flow velocity: 10 - 21 cm/s
  - Control experiments: without PP-EM field

- **Real-Time Response Variables**
  - Permeate flow-rate
  - Conductivity
  - Membrane salt rejection

- **Post-Mortem Characterization**
  - Gravimetric measurements
  - Light microscopy image: surface area coverage
  - Scanning electronic microscope (SEM)
Experimental results

Transmembrane Pressure

Permeate Flow-rate

Feed Solution Conductivity
## Experimental results

<table>
<thead>
<tr>
<th>Tests (PP-EM on/off)</th>
<th>Test 1/Test 2</th>
<th>Test 3/Test 4</th>
<th>Test 5/Test 6</th>
<th>Test 7/Test 8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pump Speed</strong></td>
<td>327 rpm</td>
<td>89 rpm</td>
<td>327 rpm</td>
<td>89 rpm</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>300 psi</td>
<td>110 psi</td>
<td>50 psi</td>
<td>300 psi</td>
</tr>
<tr>
<td><strong>Test Period</strong></td>
<td>1.5 HR</td>
<td>3 HR</td>
<td>4.5 HR</td>
<td>11 HR</td>
</tr>
<tr>
<td><strong>Flow Velocity</strong></td>
<td>32 cm/s</td>
<td>10 cm/s</td>
<td>32 cm/s</td>
<td>10 cm/s</td>
</tr>
<tr>
<td><strong>Permeate Flow-rate</strong></td>
<td>21 - 8 ml/min</td>
<td>9 - 6 ml/min</td>
<td>5 - 4 ml/min</td>
<td>17 - ~0 ml/min</td>
</tr>
<tr>
<td><strong>Post-mortem Gravimetric</strong></td>
<td>Test 1: 12.8%</td>
<td>Test 3: 5.7%</td>
<td>Test 5: 7.7%</td>
<td>Test 7: 13.8%</td>
</tr>
<tr>
<td></td>
<td>Test 2: 13.5%</td>
<td>Test 4: 9.4%</td>
<td>Test 6: ~0%</td>
<td>Test 8: 16.7%</td>
</tr>
<tr>
<td><strong>Visual Observation</strong></td>
<td>Test 1: trace amount of precipitation</td>
<td>Test 3: Clear precipitation in bulk solution</td>
<td>Test 5: small amount of precipitation</td>
<td>Test 7: trace amount of precipitation</td>
</tr>
<tr>
<td></td>
<td>Test 2: small amount of precipitation</td>
<td>Test 4: small amount of precipitation</td>
<td>Test 6: trace amount of precipitation</td>
<td>Test 8: trace amount of precipitation</td>
</tr>
</tbody>
</table>
Experimental results

- The bulk solutions treated with PP-EM field showed significant more precipitation than the one without utilizing PP-EM field.
- More scaling on the membrane surface when not utilizing PP-EM.
Feed solution modification

As a sparingly soluble salt, utilizing CaSO₄ directly may cause nucleation easily

\[ \text{CaCl}_2 + \text{Na}_2\text{SO}_4 \rightarrow 2 \text{NaCl} + \text{CaSO}_4 \]

<table>
<thead>
<tr>
<th>Tests (PP-EM on/off)</th>
<th>Test 9/Test 10</th>
<th>Test 3/Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pump Speed</strong></td>
<td>89 rpm</td>
<td>89 rpm</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>110 psi</td>
<td>110 psi</td>
</tr>
<tr>
<td><strong>Test Period</strong></td>
<td>3 h</td>
<td>3 h</td>
</tr>
<tr>
<td><strong>Flow Velocity</strong></td>
<td>10 cm/s</td>
<td>10 cm/s</td>
</tr>
<tr>
<td><strong>Permeate Flow-rate</strong></td>
<td>9 – 8 (11%) ml/min</td>
<td>9 – 6 (33%) ml/min</td>
</tr>
<tr>
<td><strong>Post-mortem Gravimetric</strong></td>
<td>Test 9: 0.4% Test 10: /</td>
<td>Test 3: 5.7% Test 4: 9.4%</td>
</tr>
<tr>
<td><strong>Visual Observation</strong></td>
<td>Test 9: trace amount of precipitation Test 10: trace amount of precipitation</td>
<td>Test 3: clear precipitation in bulk solution Test 4: small amount of precipitation</td>
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Acoustic spectroscopy has been applied as a non-destructive method in characterization of particle size distribution in aqueous suspensions by measurement of the ultrasonic signal attenuation coefficient as a function of frequency.

\[ X_0 (\omega) = \exp \left[ - \alpha_0 (\omega) d \right] \]

- **Acoustic spectroscopy** has been applied as a non-destructive method in characterization of particle size distribution in aqueous suspensions by measurement of the ultrasonic signal attenuation coefficient as a function of frequency.

Challis et al., IEEE transactions on ultrasonic, ferroelectrics, and frequency control, 52 (10), 1754-1768, 2005
Acoustic system setup

- The two transducers are held with kinematic mounts so their tilting angle can be adjusted.
- The distance between two transducers is measured precisely under an optical microscope.
- A short pulse is generated by the pulser/receiver, and the acoustic signal is recorded by the oscilloscope.
Theoretical function

\[ S(\omega) = H(\omega) X(\omega) \]

- \( S(\omega) \): detected acoustic signal in the frequency domain
- \( H(\omega) \): the system transfer function
- \( X(\omega) \): frequency response of the test liquid

- Calibration of the system to obtain \( H(\omega) \): liquid with known acoustic properties
  
  \[ X_0(\omega) = \exp[-\alpha_0(\omega)d] \]

  - \( \alpha_0(\omega) \): attenuation coefficient of aqueous solution
  - \( d \): distance between two transducers surfaces

  \[ H(\omega) = S_0(\omega)/X_0(\omega) \]

- Measurement of attenuation spectrum to obtain \( X(\omega) \)
Acoustic Study Results

**Graph 1:**
- **d=10.496mm**
- Detected signal
- System transfer function
- Attenuation in water

**Graph 2:**
- **d=10.387mm, 1.36% volume fraction**
- TiO$_2$ measurement
- TiO$_2$ simulation
Acoustic study results

\[
\text{CaCl}_2 + \text{Na}_2\text{CO}_3 \rightarrow 2 \text{NaCl} + \text{CaCO}_3
\]

The solubility of \(\text{CaCO}_3\) in DI water at ambient temperature: 0.0147 g L\(^{-1}\)
Acoustic study results

\[ \text{CaCl}_2 + \text{Na}_2\text{CO}_3 \rightarrow 2 \text{NaCl} + \text{CaCO}_3 \]

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>pH</th>
<th>Conductivity (µs/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.2</td>
<td>2290</td>
</tr>
<tr>
<td>5</td>
<td>8.4</td>
<td>1900</td>
</tr>
<tr>
<td>10</td>
<td>8.2</td>
<td>1900</td>
</tr>
<tr>
<td>20</td>
<td>8.2</td>
<td>1900</td>
</tr>
<tr>
<td>30</td>
<td>8.2</td>
<td>1870</td>
</tr>
<tr>
<td>120</td>
<td>7.9</td>
<td>1840</td>
</tr>
<tr>
<td>1200</td>
<td>7.9</td>
<td>1840</td>
</tr>
</tbody>
</table>

The solubility of \( \text{CaCO}_3 \) in DI water at ambient temperature: 0.0147 g L\(^{-1}\)
Significance

➤ Initial study in both pilot and bench scale RO desalination system utilizing PP-EM field verified possible effects of electromagnetic field on precipitation of scarcely soluble salts crystallization in bulk solution.

➤ Initial study indicated possibility to mitigate scaling during RO process by utilizing PP-EM field.

➤ A possible real-time crystallization characterization methodology, acoustic spectroscopy, has been developed.
Future Work

- Replicates of the current tests
- More systematic tests with the bench-scale cross-flow RO system with variable testing conditions and complex feed solutions
- Install acoustic spectroscopy system into the RO flow system for real-time solution property monitoring
Acknowledgements

The authors gratefully acknowledge support of this work by the Bureau of Reclamation and Clearwater System LLC.