Water Management At Coal Power Systems

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2019 Crosscutting Technologies Review Meeting
April 11, 2019
Effluent water from coal-fired power plants are regulated by U.S. EPA

- September 30, 2015, EPA finalized a rule revising the regulations for the **Steam Electric Power Generating** Effluent Guidelines

- Sources of effluent streams include:
  - Fly & Bottom Ash
  - Flue Gas Desulfurization (FGD)
  - Ash Pond
  - Flue Gas Mercury Control Water

- 5 regulated species
  - As, Cl (TDS), Hg, NO$_2$&$_3$, Se

https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines-2015-final-rule
Flue gas desulfurization (FGD) wastewater has a complex array of constituents

- ELGs regulate arsenic, TDS, mercury, and selenium from ZLD

- Wastewater slip stream to maintain low Cl concentration in FGD slurry

- Composition is highly variable and depends on source coal and air pollution control devices installed

- ELGs provide two compliance pathways:
  - Chemical precipitation and biological treatment
  - Zero Liquid Discharge (ZLD)

Gingerich, Grol, and Mauter Env. Sci: Water Res & Technol, 2018
Stable Immobilized Amine Sorbents for REE and Heavy Metals Recovery from Liquid Sources

Patent Application 16N-10 (US patent #: 15/782315)

- Existing licensing agreement with PQ cooperation for: Pb and As
- Potential new licensing agreement under discussion PQ for: Se, Hg, Cd and Cr

- Sorbents are made from inexpensive feedstock materials (silica, polyamines) using a low-cost production method (Pan Drying)
- Sorbents can be tailored for individual applications
Comparison of Alternate Formulations of 181D in FGD Water Metal Uptake Testing

FGD Effluent Water used in this study was collected by AquaTech®
Synergies with other current and future plant water treatment requirements

- Conventional technologies include:
  - softening for hardness removal
  - MVC for ZLD

- Emerging technologies include membrane processes (RO, FO, MD) and electrocoagulation

- High recovery will minimize concentrate disposal costs

E.g. recirculating cooling water blowdown is high in silica, hardness, TDS, bacteria
Grand challenge for concentrating effluent streams

![Graph showing treatment cost per theoretical min work and salinity in g/L.]

- **Salinity, g/L**
  - Brackish Water: 0-35
  - Sea Water: 75
  - RO Conc.: 180
  - NaCl Precipitation: 290
  - Crystallization: 312

- **Treatment cost [$ / kWh]**
  - Reverse Osmosis: 0-1
  - Mechanical vapor recompression: 0-3

- **Commercially available route for ZLD & brine concentration**

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*Image credits: National Energy Technology Laboratory (NETL)*
Project Objective: Reduce cost of concentrating effluent streams by 50% compared with MVR.

<table>
<thead>
<tr>
<th>Treatment cost [$/kWh]</th>
<th>$ per theoretical min work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity, g/L</td>
<td></td>
</tr>
<tr>
<td>Sea Water</td>
<td>75</td>
</tr>
<tr>
<td>NaCl</td>
<td>35</td>
</tr>
<tr>
<td>Reverse Osmosis</td>
<td>0</td>
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<tr>
<td>Goal for Break Even w/ Alternative Disposal Options</td>
<td>1</td>
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<tr>
<td>Mechanical vapor recompression</td>
<td>2</td>
</tr>
<tr>
<td>Crystallization</td>
<td>312</td>
</tr>
</tbody>
</table>

- Brackish Water
- Sea Water
- RO Conc.
- NaCl Precipitation

0-35  35  75  180  290  312

Graph showing comparison of treatment cost [$/kWh] with salinity in g/L.
Recovery in RO is limited by membrane burst pressure.
OARO uses a saline sweep to reduce the pressure difference across membrane.
OARO uses multiple stages to desalinate a high salinity feed

- **High salinity brine**
  - 75 g/L
  - Pressure = 65 bar
  - Concentrated Waste

- **OARO**
  - 60 g/L
  - 65 bar

- **OARO**
  - 45 g/L
  - 85 bar

- **RO**
  - 0.5 g/L
  - Product water

- **Concentrated Waste**
  - 150 g/L
  - 115 g/L

- **Product water**
  - 85 g/L
Modeling OARO process performance

Water and salt flux:

\[ J_w = A \cdot (\Delta P - \Delta \pi) = A \cdot [\Delta P - \pi(C_{fm}) + \pi(C_{sm})] \]
\[ J_s = B \cdot \Delta C = B \cdot (C_{fm} - C_{sm}) \]

Concentration polarization:

\[ C_{fm} = C_{fb} \cdot \exp\left(\frac{J_w}{k_f}\right) + \frac{J_s}{J_w} \cdot \left[1 - \exp\left(\frac{J_w}{k_f}\right)\right] \]
\[ C_{sm} = C_{sb} \cdot \exp\left(-J_w \left(\frac{1}{k_s} + \frac{S}{D}\right)\right) + \frac{J_s}{J_w} \cdot \left[1 - \exp\left(-J_w \left(\frac{1}{k_s} + \frac{S}{D}\right)\right)\right] \]

Notation:

- \( J_w \) – water flux
- \( J_s \) – salt flux
- \( A \) – water permeability coef.
- \( B \) – solute permeability coef.
- \( P \) – hydraulic pressure
- \( \pi \) – osmotic pressure
- \( C \) – solute conc.
- \( C_m \) – interfacial conc.
- \( C_b \) – bulk conc.
- \( k \) – mass transfer coef.
- \( S \) – structural parameter
- \( D \) – diffusion coeff. of solute

Flow

Feed-side

Membrane active layer

Porous support

Boundary layer

Sweep-side

Boundary layer

Cfb

Water & salt flux

Cfm

Csm

A, B

k_f

k_s

S
OARO is cost competitive across a range of water qualities/recovery targets

Wenzlick et al. URTC, 2018
Sensitivity analysis can guide future OARO research

- Doubling the water permeability reduces cost by less than 10%
- Halving the structural parameter reduces cost by 15-25%
- Increasing the maximum applied pressure reduces cost by 35-40%
Experimental work characterizes membranes at OARO conditions

- Estimate A, B, and S for a range of feed pressures, and feed and sweep solute concentrations
Estimating water permeability at varying operating conditions

\[ J_w = A \cdot \left\{ \left[ P_f - P_s \right] - \left[ \pi(c_{f,m}) - \pi(c_{s,m}) \right] \right\} \]

- Permeability decreases with average salinity
- Possible dehydration of CTA membrane surface
- No major effect of pressure
- Further tests to determine how salinity changes membrane

[Graph showing water permeability vs. average membrane concentration for 0 psi, 40 psi, and 60 psi]

Estimating structure parameter at varying operating conditions

\[ c_{s,m} = c_{s,b} \cdot \exp\left( -\frac{J_w S}{D} \right) + \frac{J_s}{J_w} \cdot \left[ 1 - \exp\left( -\frac{J_w S}{D} \right) \right] \]

- Possible compression of support layer and spacers with pressure
- Expected value from literature around 150-300 microns
- SW30 even higher—significant loss of applied pressure
Remaining technical gaps

- Developing membranes with high burst pressure and low structural parameters
- Testing the OARO process at pilot scale
- Modeling the integration of OARO with other technologies (RO, MVR, MD) to minimize the cost/energy of meeting treatment specifications for different effluent streams
  - Accounting for variable water quality
  - Assessing the role for alternative membrane and thermal processes
  - Building a comprehensive decision matrix
Future Work: Developing decision matrix for concentrating effluent

- Identify low cost technology or technology combinations across the broad range of potential treatment needs at power plants
- Assess energy implications of the low cost technology
Conclusions

Key findings
• OARO can potentially lower cost to concentration compared against the baseline MVR technology

Lessons learned:
• Optimization modeling is a critical tool for techno-economic assessment

Remaining Steps:
• Develop hollow fiber membrane modules with high burst pressure, high permeability, and low structural parameter
• Optimize treatment trains that incorporate OARO
• Compare against cost/energy of other membrane processes
References