A Multi-Objective Evaluation of PC Plants with Aqueous Amine Carbon Capture Systems

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CO₂ Summit: Technology and Opportunity
7 June 2010

Outline

- Motivation – CO₂ and Water
- Approach – Design & Optimization
- Model details
  - PC Plant
  - MEA system
  - Compression system
- Results & Discussion
  - Capital cost
  - Water use
  - Power generation
- Summary
U.S. CO₂ Emissions from Coal Plants

Previous study indicated that in 2030 80% of emissions will be from plants existing in 2010.

Post- and Oxy-combustion CO₂ Capture
Increase in COE

Basis:
- Bituminous Coal
- No capture = 64 mills/kWh
- 90% Capture

Capital + O&M

Parasitic Energy

Advanced CO₂ Capture

Goal

Sources:
Freshwater Use in Thermoelectric Power Plant

Approximately 3% of U.S. freshwater consumption used for thermoelectric power generation

Approximately 39% of U.S. freshwater withdrawal used for thermoelectric power generation
Expected Cooling Water Shortage in 2025


Power Plant Water Withdrawal Requirements with and without CO₂ capture

Source: Water Requirements for Existing and Emerging Thermoelectric Plant Technologies; NETL, August 2008
DOE/NETL Goals: CO₂ Capture

Minimum CO₂ Captured | Maximum Increase in COE
----------------------|---------------------
90%                  | 35% for PC
                      | 10% for IGCC

DOE/NETL Goals: Freshwater Minimization

- **Short-term goals (ready for commercial demonstration by 2015)**
  - Reduce freshwater withdrawal and consumption by > 50% for thermoelectric power plants equipped with wet recirculating cooling technology
  - Levelized cost savings > 25% compared to state-of-the-art dry cooling

- **Long-term goals (ready for commercial demonstration by 2020)**
  - Reduce freshwater withdrawal and consumption by > 70% for thermoelectric power plants equipped with wet recirculating cooling technology
  - Levelized cost savings > 50% compared to state-of-the-art dry cooling

**Challenges**

- **Large-scale problem**
  - 2 billion tons CO₂ from coal by 2020 in US
  - Flue gas: 5 million lb/hr for 550MW PC plant

- **No existing economical solution**
- **No framework for developing & evaluating optimized designs**
- **Difficulty re-using existing models/simulations**

**Approach**

- Process synthesis & design
- Process integration & optimization
- Simulation-based optimization approaches
- Water resource considerations
- Interaction and potential synergy among subsections
- Address multiple (conflicting) goals
Integrated research program with multiple, significant research activities
Simulation Interface

- Set simulation variables
- Supports structural changes
  - Feed stage
  - Number of stages
  - (not supported internally)
- Retrieves results
- Perform post-processing
  - Cost estimation
  - Objective function calculations

Generalized Plantwide Optimization Framework

“Black Box” Derivative-Free Optimization Algorithms (simulation-based)

Algebraic Optimization Codes (GAMS/BARON)

Library of Derived Algebraic Models

Superstructure Development

Process Synthesis (HEN)

Algorithms to Develop Surrogates Models from Simulations
### Steam Cycle Summary

<table>
<thead>
<tr>
<th></th>
<th>P (psia)</th>
<th>T (°F)</th>
<th>Power Generated (W/lb steam)</th>
<th>Power Lost extracting here (W/lb steam)</th>
<th>Heat Available Q (Btu/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP</td>
<td>2415.0</td>
<td>1050</td>
<td>43.70</td>
<td>195.20</td>
<td>773</td>
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<tr>
<td>IP-01</td>
<td>559.0</td>
<td>1000</td>
<td>16.26</td>
<td>151.50</td>
<td>1056</td>
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<tr>
<td>IP-02</td>
<td>363.0</td>
<td>885</td>
<td>23.47</td>
<td>135.24</td>
<td>1050</td>
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<tr>
<td>LP-01</td>
<td>182.0</td>
<td>705</td>
<td>29.58</td>
<td>111.77</td>
<td>1029</td>
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<tr>
<td>LP-02</td>
<td>65.4</td>
<td>500</td>
<td>24.08</td>
<td>82.19</td>
<td>1014</td>
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<td>LP-03</td>
<td>24.0</td>
<td>320</td>
<td>19.71</td>
<td>58.11</td>
<td>993</td>
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<tr>
<td>LP-04</td>
<td>8.5</td>
<td>190</td>
<td>38.41</td>
<td>38.41</td>
<td>991</td>
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</table>

Q calculated for condensation at inlet pressure.
Stripper: 5-10 Stages, based on previous sensitivity
Fraction of max working capacity: 0.30 – 0.65
• RR, D:F ratio, MEA flowrate
Recycled MEA temp: 90°F – 140°F

• 5 stage compression
• Intercoolers 285°F to 100°F
• Water returned to process
• Final pressure 2000 psia
Pareto Curves

Normalized Capital Cost of Carbon Capture ($/MWnet)

Evaporative Water Loss (gpm/MWnet)

90% Capture
70% Capture

6.95 gpm/MWnet base

90% capture, 90°F absorbent, 10 stripper stages

Normalized Capital Cost of Capture System ($/MWnet)

Absorptive Water Loss (gpm/MWnet)

Reflux Ratio = 0.25
Reflux Ratio = 0.40
Reflux Ratio = 0.60

Absorptive Fraction Max. Working Cap.
90% capture, 90°F absorbent, 10 stripper stages

Absorbent Flow Rate (MM lb/hr)

Absorbent Fraction Max. Working Cap.

Steam Extraction (MM lb/hr)

Absorbent Fraction Max. Working Cap.

90% capture, 90°F absorbent, 10 stripper stages

Water Flow to Compressor (1000 lb/hr)

Absorbent Fraction Max. Working Cap.

NATIONAL ENERGY TECHNOLOGY LABORATORY
### 90% Capture Summary - Design

<table>
<thead>
<tr>
<th></th>
<th>Base 543 MW</th>
<th>Best Water</th>
<th>Best Cost</th>
<th>Worst Case</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Power (MW)</strong></td>
<td>343</td>
<td>347</td>
<td>304</td>
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<tr>
<td><strong>Number of Stripper Stages</strong></td>
<td>10</td>
<td>10</td>
<td>6</td>
<td></td>
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<tr>
<td><strong>Fraction of Max MEA capacity</strong></td>
<td>0.550</td>
<td>0.515</td>
<td>0.543</td>
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<tr>
<td><strong>MEA Circulation (MM lb/hr)</strong></td>
<td>15.6</td>
<td>16.7</td>
<td>15.9</td>
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<tr>
<td><strong>Steam Extraction (MM lb/hr)</strong></td>
<td>1.56</td>
<td>1.55</td>
<td>1.86</td>
<td></td>
</tr>
<tr>
<td><strong>Relative Capital Cost ($/MW_{net})</strong></td>
<td>0.97x</td>
<td>0.94x</td>
<td>1.18x</td>
<td></td>
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</tbody>
</table>

### 90% Capture Summary - Water

<table>
<thead>
<tr>
<th></th>
<th>Base</th>
<th>Best Water</th>
<th>Best Cost</th>
<th>Worst Case</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water Evap (gpm/MW_{net})</strong></td>
<td>7.0</td>
<td>13.1</td>
<td>13.2</td>
<td>15.0</td>
</tr>
<tr>
<td><strong>Base PC Evap (gal/hr)</strong></td>
<td>226,431</td>
<td>115,288</td>
<td>116,406</td>
<td>93,086</td>
</tr>
<tr>
<td><strong>Capture Evap (gal/hr)</strong></td>
<td></td>
<td>124,143</td>
<td>109,092</td>
<td>156,100</td>
</tr>
<tr>
<td><strong>Abs. Evap. (gal/hr)</strong></td>
<td></td>
<td>29,389</td>
<td>50,273</td>
<td>23,910</td>
</tr>
<tr>
<td><strong>Total (gal/hr)</strong></td>
<td>226,431</td>
<td>268,820</td>
<td>275,770</td>
<td>273,096</td>
</tr>
</tbody>
</table>
Conclusions

• Important to consider plant integration
• Optimization needed to find best cases
• Tradeoff: Water use and capital cost

• Future work
  – Dry cooling
  – Additional heat integration
  – Advanced column configurations
  – Nontraditional sources of water

Acknowledgements: Research Team

• Optimization and computational infrastructure
  – ModeFrontier integration & multi-criteria, simulation-based optimization/DOE – NETL
  – Derivative-free “Blackbox” Optimization – CMU (Sahinidis/Cozad)
  – Surrogate model development – CMU (Sahinidis/Rios)
  – Simultaneous Superstructure-based Optimization – CMU (Grossmann/Yang)
  – Synthesis of Integrated IGCC Systems – CMU (Grossmann/Biegler/Kamath)

• Module development
  – Base plant modules
    • Predictive Plant Models (PC/IGCC) – NETL (Miller/Eslick)
    • Development of Predictive Turbine Models – NETL (Liese)
    • Oxycombustion Plant Model – NETL Albany (Summers/Oryshchyn/Harendra)
  – Carbon capture modules
    • Rate-based amine capture – NETL (Miller/Eslick)
    • Solid sorbent capture systems – NETL (Miller/Lees)
    • Membrane-based separation systems – NETL (Miller/Morinelly)
    • Compression system – NETL (Miller/Eslick)
    • Synthesis of Optimal PSA Cycles for CO2 Capture from Flue Gas – CMU (Biegler/Agarwal)
    • Synthesis of Optimal PSA Cycles for Hydrogen/CO2 Separation – CMU (Biegler/Velukuri)
    • Cryogenic separation and hydrate-based separation – NETL (van Osdol)
  – Water-specific activities
    • Development of Predictive Models of Cooling Towers – WVU (Huebsch/Ogretim)
    • Treated Municipal Wastewater for Power Plant Cooling – CMU (Dzombak/Hsieh)
    • Modeling Nontraditional Sources of Power Plant Water – IIT (Abassian/Arastoopour)
    • Water from Oxycombustion – NETL Albany (Summers/Oryshchyn/Harendra)