Intensified, Flexible, and Modular Carbon Capture Demonstration with Additively Manufactured Multi-Functional Device

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National Energy Technology Laboratory
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Program Overview

- **Funding provided by DOE-FE**: $1.5M

- **Overall Project Performance Dates**:  
  January 1, 2021 – December 31, 2022

- **Project Participants**:  
  Costas Tsouris, Josh Thompson, Gyoung Jang, Jim Parks

- **Previous Project: FWP-FEAA375**  
  January 1, 2020 – December 31, 2020  
  Objective: Test intensified process with low-aqueous solvent
Overall Project Objectives

- Design, and construct a larger-scale column (Column B) than the one previously tested at ORNL to:
  
  • Further demonstrate enhanced CO$_2$ capture with 3D printed intensified devices for aqueous amine-based capture at realistic operating conditions
  
  • Demonstrate that Column B can be modularized with segmented packing elements and intensified devices for low-aqueous-solvent based capture
  
  • Demonstrate that Column B can be used to effectively capture CO$_2$ from different CO$_2$ gas compositions and during process transients (i.e., capacity ramping up and down anticipating the intermittent nature of renewable generations).
Technology Background
How the technology is envisioned to work in operation:

Absorption/Desorption System at the National Carbon Capture Center NCCC

\[ 2\text{MEA} + \text{CO}_2 \rightleftharpoons \text{MEAH}^+ + \text{MEACOO}^- (+79-100 \text{ KJ/mol}) \text{ (Exothermic)} \]

Intensified packing device to allow \textit{in situ} cooling
Technology Background

Technology development efforts prior to current project:

- System tested for hydraulic and heat transfer performance with favorable results

Technology Background
Tests for CO₂ capture enhancement:

Schematic of testing facility and absorption column
CPE: Commercial Packing Element
Technology Background

Testing of intrastage cooling with aqueous MEA:

<table>
<thead>
<tr>
<th>Air Flow Rate (LPM)</th>
<th>CO₂ Flow Rate (LPM)</th>
<th>CO₂ Conc. (%)</th>
<th>Molar Capture Rate Before Cooling (mol/min)</th>
<th>Molar Capture Rate After Cooling (mol/min)</th>
<th>Fractional Increase (%)</th>
<th>Capture Efficiency (%) (Before → After Cooling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>810</td>
<td>90</td>
<td>10</td>
<td>2.24</td>
<td>2.30</td>
<td>2.7</td>
<td>59.9 → 61.2</td>
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<tr>
<td>510</td>
<td>90</td>
<td>15</td>
<td>2.75</td>
<td>2.90</td>
<td>5.5</td>
<td>73 → 77</td>
</tr>
<tr>
<td>360</td>
<td>90</td>
<td>20</td>
<td>2.95</td>
<td>3.29</td>
<td>11.5</td>
<td>78 → 88</td>
</tr>
<tr>
<td>264</td>
<td>90</td>
<td>25</td>
<td>3.52</td>
<td>3.57</td>
<td>4.3</td>
<td>94 → 98</td>
</tr>
<tr>
<td>360</td>
<td>40</td>
<td>10</td>
<td>1.38</td>
<td>1.45</td>
<td>5.1</td>
<td>83 → 87</td>
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<tr>
<td>360</td>
<td>63.5</td>
<td>15</td>
<td>1.53</td>
<td>1.77</td>
<td>15.7</td>
<td>58 → 67</td>
</tr>
<tr>
<td>360</td>
<td>90</td>
<td>20</td>
<td>2.95</td>
<td>3.29</td>
<td>11.5</td>
<td>78 → 88</td>
</tr>
<tr>
<td>360</td>
<td>120</td>
<td>25</td>
<td>3.07</td>
<td>3.28</td>
<td>6.9</td>
<td>62 → 66</td>
</tr>
</tbody>
</table>

Solvent flowrate: 3.2 LPM  Solvent input temperature: 70 °C

## Technology Background – Testing with RTI’s low-aqueous solvent

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Solvent Condition</th>
<th>Solvent Flowrate (LPM)</th>
<th>Air Flowrate (SLPM)</th>
<th>CO₂ Flowrate (SLPM)</th>
<th>CO₂ Amount (%)</th>
<th>CO₂ output before cooling (%)</th>
<th>CO₂ output after cooling (%)</th>
<th>Capture efficiency (%) (before → after)</th>
<th>Fractional Improvement (%)*</th>
<th>Feed temp. (℃)</th>
<th>Average Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pristine</td>
<td>3.26</td>
<td>510</td>
<td>90</td>
<td>13.8</td>
<td>2.21</td>
<td>0.64</td>
<td>84 → 95.4 (11.4↑)</td>
<td>13.5</td>
<td>59</td>
<td>60.7</td>
</tr>
<tr>
<td>2</td>
<td>Pristine</td>
<td>3.26</td>
<td>510</td>
<td>90</td>
<td>14.0</td>
<td>1.95</td>
<td>0.47</td>
<td>86 → 96.6 (10.6↑)</td>
<td>12.3</td>
<td>52</td>
<td>59.6</td>
</tr>
<tr>
<td>3</td>
<td>Pristine</td>
<td>3.26</td>
<td>510</td>
<td>90</td>
<td>13.8</td>
<td>1.61</td>
<td>0.64</td>
<td>88.3 → 95.4 (7.1↑)</td>
<td>8.0</td>
<td>45</td>
<td>58.6</td>
</tr>
<tr>
<td>4</td>
<td>1st Regen.</td>
<td>3.26</td>
<td>510</td>
<td>90</td>
<td>14.7</td>
<td>3.18</td>
<td>1.57</td>
<td>78.4 → 89.4 (11.0↑)</td>
<td>14.0</td>
<td>41</td>
<td>54.5</td>
</tr>
<tr>
<td>5</td>
<td>2nd Regen</td>
<td>3.26</td>
<td>608</td>
<td>107</td>
<td>13.1</td>
<td>3.75</td>
<td>2.23</td>
<td>71.3 → 82.9 (11.6↑)</td>
<td>16.3</td>
<td>44</td>
<td>55.2</td>
</tr>
<tr>
<td>6</td>
<td>2nd Regen + DI H₂O(5L)</td>
<td>3.26</td>
<td>608</td>
<td>107</td>
<td>13.0</td>
<td>2.94</td>
<td>2.08</td>
<td>77.4 → 84.0 (6.6↑)</td>
<td>8.5</td>
<td>44</td>
<td>55.4</td>
</tr>
<tr>
<td>7</td>
<td>3rd Regen</td>
<td>3.26</td>
<td>425</td>
<td>75</td>
<td>13.3</td>
<td>1.19</td>
<td>0.67</td>
<td>91.1 → 95.0 (3.9↑)</td>
<td>4.3</td>
<td>41</td>
<td>52.8</td>
</tr>
<tr>
<td>8</td>
<td>3rd Regen</td>
<td>2.82</td>
<td>510</td>
<td>90</td>
<td>13.1</td>
<td>2.75</td>
<td>1.75</td>
<td>79.1 → 86.7 (7.6↑)</td>
<td>9.7</td>
<td>41</td>
<td>53.8</td>
</tr>
<tr>
<td>9</td>
<td>4th Regen</td>
<td>3.26</td>
<td>353</td>
<td>62</td>
<td>13.3</td>
<td>0.79</td>
<td>0.44</td>
<td>94.0 → 96.6 (2.6↑)</td>
<td>2.8</td>
<td>41</td>
<td>49.8</td>
</tr>
<tr>
<td>10</td>
<td>4th Regen</td>
<td>3.65</td>
<td>510</td>
<td>90</td>
<td>12.8</td>
<td>2.16</td>
<td>1.13</td>
<td>83.2 → 91.2 (8.0↑)</td>
<td>9.7</td>
<td>41</td>
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<td>11</td>
<td>5th Regen</td>
<td>2.39</td>
<td>510</td>
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<td>13.1</td>
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<td>4.71</td>
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<td>90</td>
<td>13.0</td>
<td>4.92</td>
<td>3.25</td>
<td>62.2 → 75.0 (12.8↑)</td>
<td>20.7</td>
<td>41</td>
<td>54.2</td>
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<tr>
<td>13</td>
<td>6th Regen</td>
<td>3.26</td>
<td>510</td>
<td>90</td>
<td>13.2</td>
<td>5.74</td>
<td>3.86</td>
<td>56.7 → 70.9 (14.2↑)</td>
<td>25.1</td>
<td>41</td>
<td>53.5</td>
</tr>
<tr>
<td>14</td>
<td>6th Regen + DI H₂O(5L)</td>
<td>3.26</td>
<td>510</td>
<td>90</td>
<td>13.1</td>
<td>5.33</td>
<td>4.73</td>
<td>59.3 → 63.9 (4.6↑)</td>
<td>7.8</td>
<td>41</td>
<td>52.1</td>
</tr>
</tbody>
</table>

## Comparison of MEA and LAS Performance

<table>
<thead>
<tr>
<th></th>
<th>MEA</th>
<th>LAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed temperature (°C)</td>
<td>70</td>
<td>40</td>
</tr>
<tr>
<td>Avg. Temperature before cooling</td>
<td>72.0 ± 9.9</td>
<td>54.5 ± 5.5</td>
</tr>
<tr>
<td>Avg. Temperature after cooling</td>
<td>60.5 ± 13.9</td>
<td>45.3 ± 6.8</td>
</tr>
</tbody>
</table>

### LAS is more heat-sensitive compared to aqueous MEA

Technical Approach/Project Scope

- Scale up CO₂ capture rate by a factor of 10 from Column A to Column B
  - Construct Column B
- Scale up intensified device
- Demonstrate enhanced capture by aqueous MEA using intrastage cooling
- Demonstrate enhanced capture by LAS using intrastage cooling
- Demonstrate modularization with one or more packing elements for each module
- Demonstrate smooth operation with variable gas feed flow rate and CO₂ concentration

Motivation: Intrastage cooling with intensified devices may have economic and operational advantages over interstage cooling
Technical Approach/Project Scope

Project Schedule: Two-year project

- **Task 1.0** – Project Management and Planning (1-24 Months)
- **Task 2.0** – Design Evaluation and Construction of Column B based on Results from FEAA375 (1-12)
  - Model needed
- **Task 3.0** – Advanced Manufacturing and Core Metrics Testing of Intensified Device for Column B (1-15)
- **Task 4.0** – Using NTRC Engine Combustion Exhaust to Simulate Various Flue Gas Compositions (1-15)
- **Task 5.0** – Test Plan Development for Subsequent Tasks (13-15)
- **Task 6.0** – Aqueous Solvent Capture with Simulated Coal-Fired Power Plant Flue Gas (13-16)
- **Task 7.0** – Aqueous Solvent Capture with Simulated Natural Gas-Fired Power Plant Flue Gas (17-19)
- **Task 8.0** – Aqueous Solvent Capture under Process Transients (20-21)
- **Task 9.0** – Column B Modification and Demonstration of Modular Capture with Low-aqueous Solvent (22-24)
- **Task 10** – Collaboration with CCSI\(^2\) on Modeling of Process Intensification with Column B Results (1-24)
Progress and Current Status of Project Modeling Framework:

Thompson, Tsouris, "Rate-Based Absorption Modeling for Post-Combustion CO\textsubscript{2} Capture with Additively-Manufactured Structured Packing", Submitted.
Modeling Framework

- Chemical & Vapor-Liquid Equilibria with Kent-Eisenberg Equations
- Rate-based model utilizes Wang-Song-Rochelle correlations for mass transfer and Enhancement factor models for reaction
- Model validated with published CO$_2$ solubility and pilot data

MEA
30 wt%

Chemical/VLE Model

Thompson, Tsouris, "Rate-Based Absorption Modeling for Post-Combustion CO$_2$ Capture with Additively-Manufactured Structured Packing", Submitted.
Modeling Framework

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MEA 30 wt%
Modeling MEA w/ Intrastage Cooling

- Simulation of intrastage cooling with device shows good agreement with experiments from Miramontes et al.
  - CO₂ Capture difference all ≤ 5%

- CO₂ capture improvement and temperature profile agreement suggests modeling framework for heat transfer is accurate in predicting device performance

\[ E = Ha \]
\[ E = f(Ha,E_\infty) \]

Thompson, Tsouris, "Rate-Based Absorption Modeling for Post-Combustion CO₂ Capture with Additively-Manufactured Structured Packing", Submitted.
Modeling Framework Applied to Other Solvents

- In process of extending modeling framework to other solvents
- Speed up evaluation of alternative solvents and how intensified device may improve CO₂ capture
- Currently applied to aqueous piperazine (PZ) and a low-aqueous solvent (LAS)

![Graph 1: Simulated vs. Experimental CO₂ Capture (Adiabatic)]

![Graph 2: Simulated vs. Experimental CO₂ Capture (Cooling)]

\[ E = \text{Ha} \]

\[ E = f(\text{Ha}, E_\infty) \]
Process flow and equipment is essential to proper design around absorption column.
Modular Column Design

Modular column design provides flexibility in testing packing locations and gas/liquid axial sampling.
Scale-up of Intensified Device from 8” to 12” Diameter

- New unit cell geometry
- Added flanges and hole pattern for system integration
- Added supports for printability
Current Status of Project

- Currently working on Column B construction with significant progress in all supporting subsystems:
  
  • Column B, including modular sections with packing elements
  
  • Intensified devices
  
  • Gas generator and load bank systems
  
  • Gas conditioning systems for the feed and exhaust gases
  
  • Gas and solvent delivery systems
  
  • Solvent storage and regeneration systems
  
  • Sensors and controls for the column and data acquisition systems
Plans for Future Testing/Development/Commercialization

- Construction of Column B and hydraulic testing expected to be completed by end of Quarter 1 of FY 2022
- Testing with aqueous MEA will be initiated in Quarter 2 of FY 2022
- The geometry of the intensified device, as well as location of intensified devices along the column, are being optimized under a TCF project
- Under the TCF project, a surface coating has been successfully tested to prevent corrosion of the intensified device in aqueous MEA
- The partners on the TCF project including Volunteer Aerospace, RTI International, Oxford PM, and AristoSys are actively engaged and are willing to help toward commercialization
Summary

- Work in all tasks of the project has progressed well so far
- Spending rate has been slow because equipment purchasing has been slow, but it is expected to increase this Quarter
- Quotes for most of the equipment needed have been obtained
- Modeling work has been very helpful for column design
- Efforts toward commercialization are progressing well
- Previous work under FEAA130 and FEAA375 has been published
- Additional manuscripts supported by FEAA384 and the TCF project have been submitted for publication in July of 2021
Publications


