Additively Manufactured Intensified Device for Enhanced Carbon Capture

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Additively Manufactured Intensified Device for Enhanced Carbon Capture

• Background:
  - Traditional solvent-based capture process and equipment:
    • Mass exchange reaction column
    • Exothermic reaction leads to thermal bulge in column, lower capture efficiency
  - Decoupled stages with external cooling:
    • High equipment and space cost

• Objective:
  - Design, rapid prototyping, demonstration and validation of enhanced CO₂ capture with intensified devices
    • Unified devices combining multiple thermodynamic operations into one unit: heat exchanger + mass exchanger
• **Printed heat exchangers** - Heat exchanger is one of the main applications of additive manufacturing

• **Complex fluid passages, not limited to tubular structures**
Project Overview – Two-year effort ending 9/30/2019

• Task 1.0 – Project Management and Planning
• Task 2.0 – Design Realization of Intensified Device
• Task 3.0 – Manufacturability (3D Printability) Study
• Task 4.0 – Experimental Validation of Device Core Metrics
• Task 5.0 - Advanced Manufacturing of Device-scale Prototype
• Task 6.0 - Device-scale Validation through Design of Experiments
  - Set up an experimental facility that can be used to test the heat- and mass-transfer behavior of the intensified device
  - Obtain pressure-drop data for the intensified packing device
  - Obtain heat-transfer data and compare with modeling results for a nonreactive system (water-air)
  - Obtain heat- and mass-transfer data for the CO2-MEA reactive system; experiments guided by modeling
Manufacturability (3D Printability) of 2nd Gen Int. Device

2nd generation intensified devices printed in 2019

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Baffle area (m²)</td>
<td>10.23</td>
</tr>
<tr>
<td>Cylinder area (m²)</td>
<td>0.406</td>
</tr>
<tr>
<td>Total area (m²)</td>
<td>9.824</td>
</tr>
<tr>
<td>Material volume (m³)</td>
<td>0.004365</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>0.424</td>
</tr>
<tr>
<td>Height (m)</td>
<td>0.3048</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>0.043015</td>
</tr>
<tr>
<td>Area/volume</td>
<td>228.3873</td>
</tr>
<tr>
<td>Volume/volume</td>
<td>0.101477</td>
</tr>
</tbody>
</table>
The Printed Aluminum and Sulzer Metal Packing Devices Shows Similar Water Mass Retained

![Graph showing mass of water retained per unit area for different sample treatments. The graph compares Sulzer metal, Sulzer plastic, nominal plastic printed, and half nominal intensified treatments. The data shows that Sulzer metal retains the most water, followed by Sulzer plastic, and then nominal plastic printed. The half nominal intensified treatment retains the least amount of water.]
A column was first set up to compare the hydraulic performance of commercial packing materials with 3D printed packing devices manufactured in this project. Stainless-steel and plastic Sulzer Mellapak 16-inch diameter packing elements (Thanks to Dr. Gary Rochelle)
Column for Testing 8-inch Diameter Packing Elements

Air pump providing over 4,000 LPM

Stephen Bolton
Chemical Engineer Student
University of Delaware
Measured dry Pressure Drop for 8” Printed Packings

Gas Flow Rate (LPM)

Pressure Drop (Pa)

Element #3 (Most Dense)

Element #2

Element #1

Measured
Predicted
Measured
Predicted
Measured
Predicted
Pressure Drop Measurements vs Gas Velocity for the Irrigated System with the Intensified Device

• 3D printed device behaves similarly to commercial devices for pressure drop
Column Scale Validation of Intensified Device

• **Overview**
  - The system’s primary task is to deliver a gas mixture of adjustable CO$_2$ concentration and aqueous MEA in counter-current flow to an absorption column comprised by packing elements at controlled temperatures.

• **Mass Flow Control**
  - Required composition is achieved by controlling flowrates of constituent gases.

• **Temperature Control**
  - Gas and solvent will be heated to between 30 and 80 °C.
  - Gas will be heated with a 3.6 kW in-line air heater.
  - Solvent will be heated using a 11kW tankless water heater.

Schematic of experimental system
There are 7 commercial packing elements in the column in addition to the intensified device.

The intensified device was placed after the fourth element from the bottom.
Location of Temperature Bulge Depends on L/G Ratio

• The magnitude of the bulge is maximized near the center of the column
  - At that location, there is a decrease in CO₂ absorption
  - Hypothesis: Cooling the location of the bulge could promote higher CO₂ absorption

(Kvaamsdal & Rochelle, 2008)

- Input Water: 80°C, 2.26 LPM
  - Coolant: 1.55 LPM
  - Temperature: ~5°C

- Input Water: 80°C, 1.81 LPM
- Input Water: 80°C, 1.36 LPM
Heat Transfer Study: Average Heat-Transfer Coefficient

- Heat transfer coefficient at selected experimental conditions
- Calculated heat transfer coefficient were consistent for all conditions

<table>
<thead>
<tr>
<th>Air Flow Rate (LPM)</th>
<th>Air Temperature (°C)</th>
<th>Water Flow Rate (LPM)</th>
<th>Water Temperature (°C)</th>
<th>Heat-Transfer Coefficient (W/K-m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>80</td>
<td>1.36</td>
<td>80</td>
<td>34.7</td>
</tr>
<tr>
<td>650</td>
<td>80</td>
<td>1.81</td>
<td>80</td>
<td>34.7</td>
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<tr>
<td>650</td>
<td>80</td>
<td>2.26</td>
<td>80</td>
<td>32.8</td>
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<tr>
<td>650</td>
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<td>32.8</td>
</tr>
<tr>
<td>650</td>
<td>80</td>
<td>2.26</td>
<td>40</td>
<td>32.5</td>
</tr>
<tr>
<td>520</td>
<td>80</td>
<td>2.26</td>
<td>80</td>
<td>34.9</td>
</tr>
</tbody>
</table>
Reactive MEA-CO$_2$ System: Identify Tbulge location

**Experimental Conditions:**

- A lower L/G ratio was needed to move the temperature bulge to the middle
Cooling Effect on CO₂ Capture

**Air:** 496 LPM  
CO₂: 84 LPM  
Temperature: 80°C  
MEA concentration: 25%

**Solvent:** 2.9 LPM  
Temperature: 70°C

**Coolant:** 1.55 LPM  
Temperature: ~5°C

**Before cooling, temperature bulge above device**

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**Graphs:**
- CO₂ Concentration (%)
- Temperature (°C)
- CO₂ Concentration Change
- Temperature of Liquid Before and After Cooling
- Temperature Bulge
- Height (in)

**Legend:**
- Before Cooling
- After Cooling
- Cooling Started

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**Temperature Chart:**
- Temperature (°C)
- Height (in)
- Before cooling, temperature bulge above device

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**Packing Elements:**
- Intensified Device
- Packing Element

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Air: 496 LPM  
CO₂: 84 LPM  
Temperature: 80°C  
MEA concentration: 25%

**Solvent:** 2.9 LPM  
Temperature: 70°C
Cooling Effect on CO\textsubscript{2} Capture

Air: 120 LPM  
CO\textsubscript{2}: 51.2 LPM  
Temperature: 80°C  
MEA: 25%

Coolant: 1.55 LPM  
Temperature: ~5°C

Before cooling, temperature bulge below the intensified device

Temperature of Liquid

- Before Cooling

CO\textsubscript{2} Concentration (%)

Temperature (°C)

CO\textsubscript{2} Data

Cooling Started

Temperature (°C)

Air: 120 LPM  
CO\textsubscript{2}: 51.2 LPM  
Temperature: 70°C

Solvent: 3.12 LPM  
Temperature: 70°C

MEA: 25%

Coolant: 1.55 LPM  
Temperature: ~5°C

Air: 120 LPM  
CO\textsubscript{2}: 51.2 LPM  
Temperature: 80°C  
MEA: 25%

Coolant: 1.55 LPM  
Temperature: ~5°C

Before cooling, temperature bulge below the intensified device

CO\textsubscript{2} Data

Cooling Started

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Solvent: 3.12 LPM  
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Coolant: 1.55 LPM  
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Air: 120 LPM  
CO\textsubscript{2}: 51.2 LPM  
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CO\textsubscript{2} Data

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Temperature: 80°C  
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Coolant: 1.55 LPM  
Temperature: ~5°C

Before cooling, temperature bulge below the intensified device

CO\textsubscript{2} Data

Cooling Started

Temperature (°C)
Cooling Effect on CO₂ Capture

Without cooling: 80% capture

With cooling: 90% capture

Coolant: 1.55 LPM
Temperature: ~5°C

Before cooling, temperature bulge below the intensified device

Air: 212 LPM
CO₂: 90 LPM
Temperature: 80°C
MEA concentration: 25%

Solvent: 3.12 LPM
Temperature: 70°C

Without cooling:
80% capture

With cooling:
90% capture
Conclusions and Accomplishments

• Conclusions:
  - Validated the enhanced CO2 capture of intensified device

• Accomplishments:
  - In discussions with Sulzer Chemtech Ltd, which produces packing elements for packed columns, toward commercialization of the intensified device