Additively Manufactured Intensified Device for Enhanced Carbon Capture

Xin Sun, Lonnie Love, Kevin Lai, Costas Tsouris, Stephen Bolton

Energy and Transportation Science Division

August 14, 2018
Additively Manufactured Intensified Device for Enhanced Carbon Capture

• Background:
  – Current capture equipment design: Decoupled unit operations with mass transfer and heat transfer
  – Decoupled stages with external cooling

• Objective:
  – Design, rapid prototyping, demonstration and validation of enhanced CO$_2$ capture with intensified devices
    • Unified devices combining multiple thermodynamic operations into one unit
  – Demonstrate key strength of additive manufacturing for process intensification
Printed heat exchangers – One of the main applications of additive manufacturing

- Printed heat exchangers with complex fluid passages, not limited to tubular structures
Technical Approach

• Six multi-disciplinary tasks involving three physical disciplines
  – Design and optimization of heat/mass exchanger/location
  – Additive manufacturing
  – Core and device-scale experimental validation

• Two-year effort
Project Structure Overview

- 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
Task 2 -- Design Realization of Intensified Device

• Goals
  – Utilize CCSI-developed CFD model (at different scales) to enable optimization of additively manufactured carbon capture device for enhanced capture efficiency

• Approach
  – Evaluate and use the most appropriate CCSI-developed computational tool for design realization
  – Perform parametric study on key design and operational parameters
Leveraging CCSI-developed Tools - Status

• MFIX-TFM device scale solvent model
  – Many challenges in earlier versions
  – Major improvements made recently – Thank you, Janine

• OpenFOAM-based wetted wall column model
  – Limited to small scale, best for solving mass transfer coefficient, challenging in thermal equations and upscaling -- Thank you, Jay and Chao

• 1D process model
  – Although lack of resolution in 2D, it is the most mature in solving the multi-phase and multi-physics phenomenon
  – Chosen for the current task -- Thank you Debangsu
MFIX solvent model with recent improvements – NETL

• Reasonable 2-D solution obtained
  – Mass balance achieved for both liquid and gas
  – CO$_2$ absorption and temperature rise approaching the realistic range
MFIX solvent model: recent improvement

• Thermal sinks have been implemented in the tool to model cooling tubes
  – Two cooling tubes are introduced in the simulation, one at height=48cm with a small heat transfer coefficient and one at height=20cm with a large heat transfer coefficient
  – Change in CO2 absorption rate is not significant due to the limited temperature rise in the simulation
Process Model: Cooling Effects -- WVU

- Three heat sinks representing cooling stages at three different locations
  - Without cooling, gas and solvent temperatures rise due to exothermic CO2 absorption
  - With cooling, solvent peak temperature reduced by 8 degrees
  - Improving CO₂ absorption by 3.5%

| Height (m) | 1.5 |
| Diam. (m)  | 0.424 |
| Lean Flow (lb/hr) | 500 |
| Lean Temp (K) | 320 |
| Lean Comp. (mass frac) |
  | MEA | 0.285 |
  | CO2 | 0.07 |
  | H2O | 0.635 |
| Gas Flow (lb/hr) | 140 |
| Gas Temp (K) | 320 |
| Gas Comp (mass frac) |
  | CO2 | 0.135 |
  | H2O | 0.055 |
  | N2 | 0.81 |
| Lean Loading (mol CO₂/mol MEA) | 0.34087 |
| Nominal MEA wt perc. | 30.65% |
| Liquid-to-Gas Ratio (mass) | 3.57142 |

No Cooling

- CO₂ Capture Percentage: 61.68%
- Rich Loading: 0.453

Cooling at Y= 0.3m, 0.6m, 0.9m

- CO₂ Capture Percentage: 65.14%
- Rich Loading: 0.459
Task 3.0 – Manufacturability (3D Printability) Study

• Task 3.1: Printability of baseline
• Task 3.2: Printability of intensified device
• Develop parametric model
  – Vary cell packing, cellular structure
  – Manufacture as one part

- Thanks, Rajesh (PNNL)
3.1 -- Printing the 16.5”D/12”H BaselinePack

- Use assembly to create the pack
  - Mate two surfaces, oppositely facing each other
  - Use linear pattern to repeat
  - Save as part so we can make it into a cylinder with cylinder cut
  - Install a sleeve around the perimeter
- Area to volume: 228:1
- Volume percentage: 10.1%
3.1 Printing Baseline Pack

- Material compatible with MEA -- Ultem 9085
  - Use Stratasys 900 mc (3 ft x 2 ft x 3 ft build volume) for size and resolution
  - Use Insight for slicing (toolpath generation)
    - Use smart supports to eliminate support material usage in the structure
  - Load resulting cmb file into Control Center
    - 141.32 ci of Ultem, 2.11 ci of support, 74.04 hours to print.
    - $984 in material cost, $1480 in machine time for total cost of $2464
    - No assembly required. Whole pack is one piece.
  - Note: material cost is $6/ci for wire. Pellets are approximately $0.50/ci. Manufacturing time is approximately 10X faster with pellet fed systems. These are still in development but are becoming commercial
3.1 Print Baseline Packing with Varying Cell Density

- Test packing -- 203 mm (8") in diameter, 146 mm (5.75") tall
  - Keeping outside dimensions the same, vary the cell size (25.4 mm, 12.7 mm, 6.3 mm)
  - Results show surface area to volume scales inversely proportional to cell size growing from 280 for 25.4 mm to 1331 for 6.3 mm cell

<table>
<thead>
<tr>
<th>Cell size (m)</th>
<th>Pack 1</th>
<th>Pack 2</th>
<th>Pack 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0254</td>
<td>0.0127</td>
<td>0.00635</td>
<td></td>
</tr>
<tr>
<td>0.0127</td>
<td>0.0097</td>
<td>0.00171</td>
<td></td>
</tr>
<tr>
<td>0.00635</td>
<td>0.0097</td>
<td>0.00171</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Baffle Area (m²)</th>
<th>Pack 1</th>
<th>Pack 2</th>
<th>Pack 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.325</td>
<td>2.671</td>
<td>6.303</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Volume (m³)</th>
<th>Pack 1</th>
<th>Pack 2</th>
<th>Pack 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00059</td>
<td>0.00097</td>
<td>0.00171</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area/Volume</th>
<th>Pack 1</th>
<th>Pack 2</th>
<th>Pack 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>279.930</td>
<td>564.221</td>
<td>1331.507</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Volume/Cyl Volume</th>
<th>Pack 1</th>
<th>Pack 2</th>
<th>Pack 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
<td>0.205</td>
<td>0.361</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Printability of Intensified Device

- **Heat exchanger integrated into pack**
  - Not optimized, demonstration and validation for enhanced capture

- **Conceptual system has fluid flowing within fins (12.7 mm cell)**
  - Outer jacket has cool fluid on the input
  - Complete flexibility on porting of fluid
  - All aluminum (250 W/m-K thermal conductivity)
    - Concept Laser Xline 1000 system
    - Material: Aluminum (Valimet AM103, 15 to 35 micron aluminum powder)
4.1 Experimental Validation of Device Core Metrics

- Two scales of structured packing used:
  - 16” diameter packings for comparison of 3D printed with commercially available structures
    - Steel (1) – Thanks, UTA
    - Plastic (2) – Thanks, UTA
    - 3D printed
    - Flow rate: 43,500 LPM
  - 3D printed 8” packings
    - All 3D printed (3)
    - Different cell densities
    - Varying flow rate: 50-3,000 LPM
1. Initial Lab setup (air pump too weak for 16-inch column)
2. New pump for 16-inch column (43,500 LPM)
3. Smaller pump works for 8-inch column
4. Entire Lab Set-up
5. Easy-Load Liquid Pump
4.1 Testing Facility for 3D Printed Packing Elements

Top of solvent distributor

Bottom of solvent distributor

Top of 3D printed column packing

Stephen Bolton
Chemical Engineering Student from the University of Delaware
4.1 Measured Pressure Drops for 16” (D) Packings -- Printed vs. commercial metal and plastic baselines

Height= 5.88 in

Height= 12.25 in

Height= 12 in

Plastic Measured

Plastic Predicted

Metal Measured

Metal Predicted

3D printed Measured

3D printed Predicted
4.1 Measured Pressure Drop for 8" Printed Packings

- **Element #1**
- **Element #2**
- **Element #3 (Most Dense)**

**Graph Details**
- **Y-axis**: Pressure Drop (Pa)
- **X-axis**: Gas Flow Rate (LPM)
- **Data Points**: Measured and Predicted values for each packing element.
4.1 Preliminary Measurements with Wet System

Pressure Drop (Pa) vs. Gas velocity (m/s)

- 0 LPM
- 5.2 LPM
- 10.4 LPM
- 15.6 LPM
- 20.8 LPM
- 26 LPM

Liquid Flowrate

- 0 LPM Predicted
- 5.2 LPM Predicted
- 10.4 LPM Predicted
- 15.6 LPM Predicted
- 20.8 LPM Predicted
- 26 LPM Predicted
Future Work

• Task 2 Analyses
  – Prepare parameters to model the intensified device made by additive manufacturing
  – Perform the baseline simulation and process the simulation result
  – Establish the methodology of analyzing and optimizing the cooling configurations for more efficient CO2 capture

• Task 5 Advanced manufacturing of device-scale prototype

• Task 6 Solvent experiments with packing at different scales
  – Hydrodynamic performance for water-gas system (liquid volume fraction and pressure drop measurements)
  – Temperature control of water-gas system
  – Separation performance for CO$_2$-MEA system
  – Separation performance enhancement with intensified devices