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FWP-FEAA130

Additively Manufactured Intensified Device for Enhanced Carbon Capture

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U.S. DEPARTMENT OF ENERGY

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

Complex fluid passages

Conformal, non-circular internal passages

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

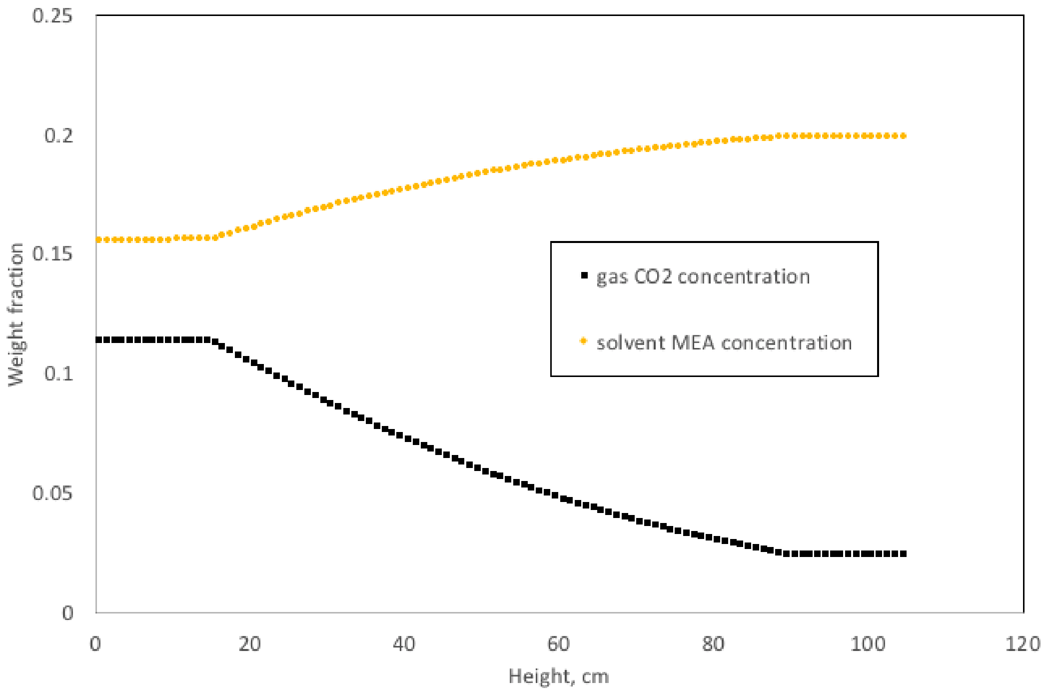
- Goals
  - Utilize CCSI-developed CFD model (at different scales) to enable optimization of additively manufactured carbon capture device for enhanced capture efficiency
- Approach
  - Evaluate and use the most appropriate CCSI-developed computational tool for design realization
  - Perform parametric study on key design and operational parameters

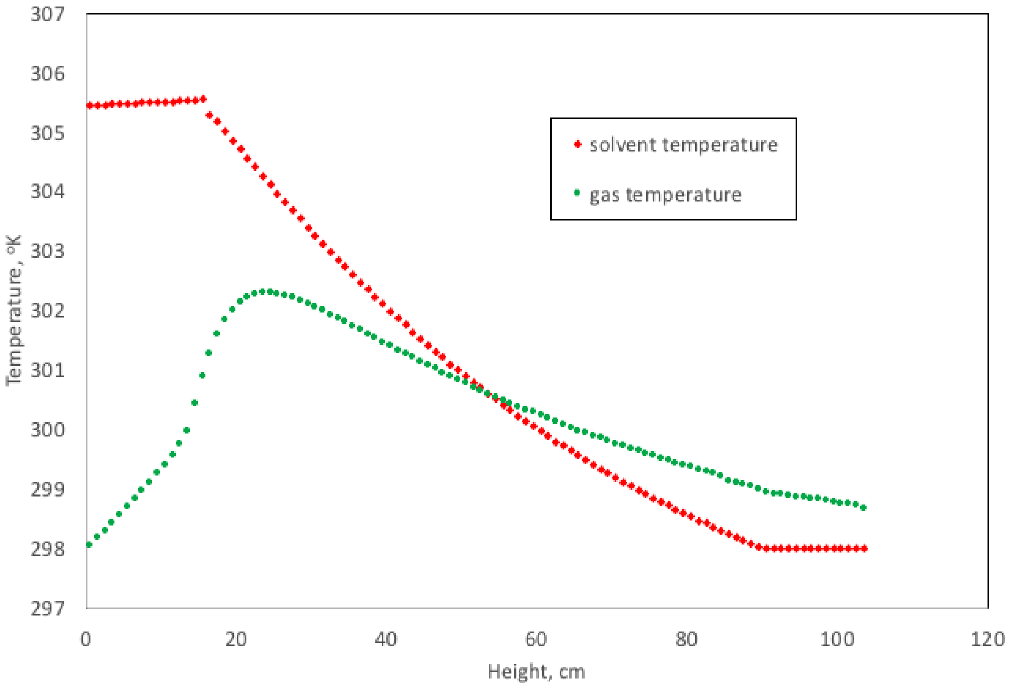
Leveraging CCSI-developed Tools - Status

- 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

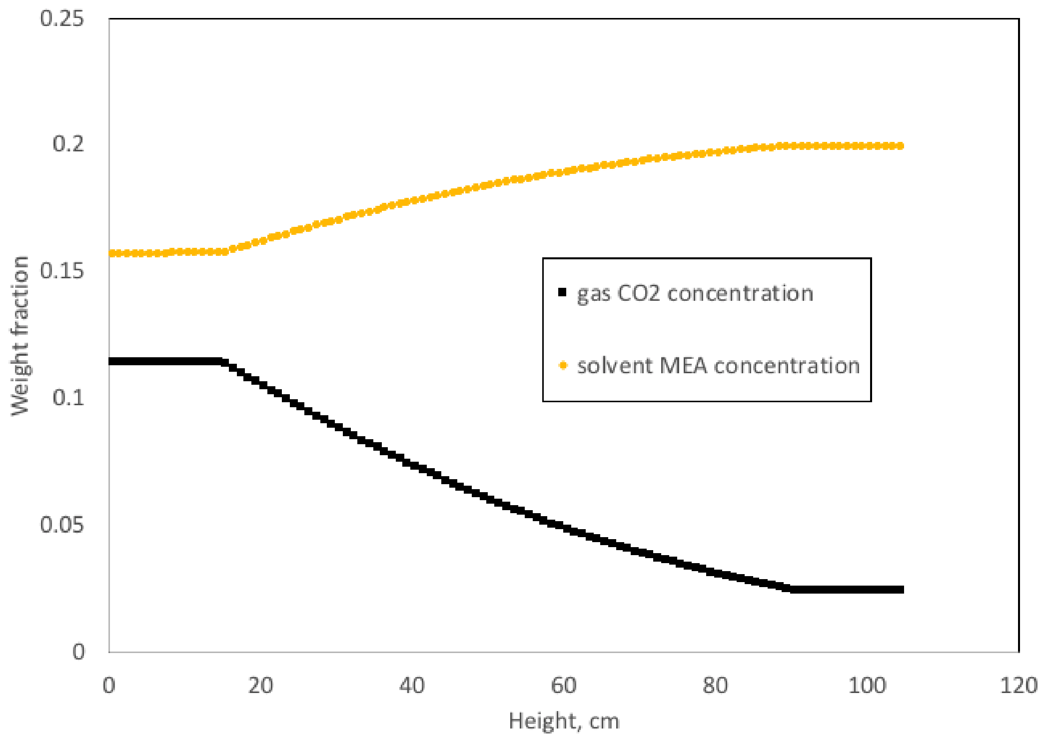
- Reasonable 2-D solution obtained
  - Mass balance achieved for both liquid and gas
  - CO_2 absorption and temperature rise approaching the realistic range

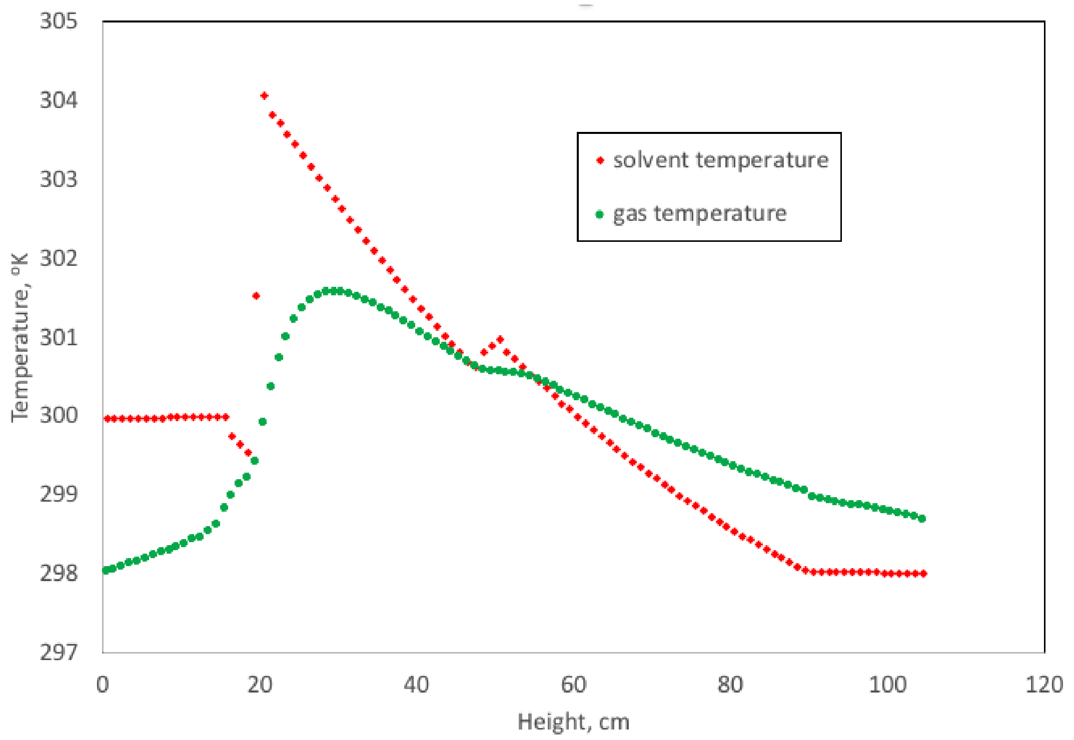




MFIX solvent model: recent improvement

- 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





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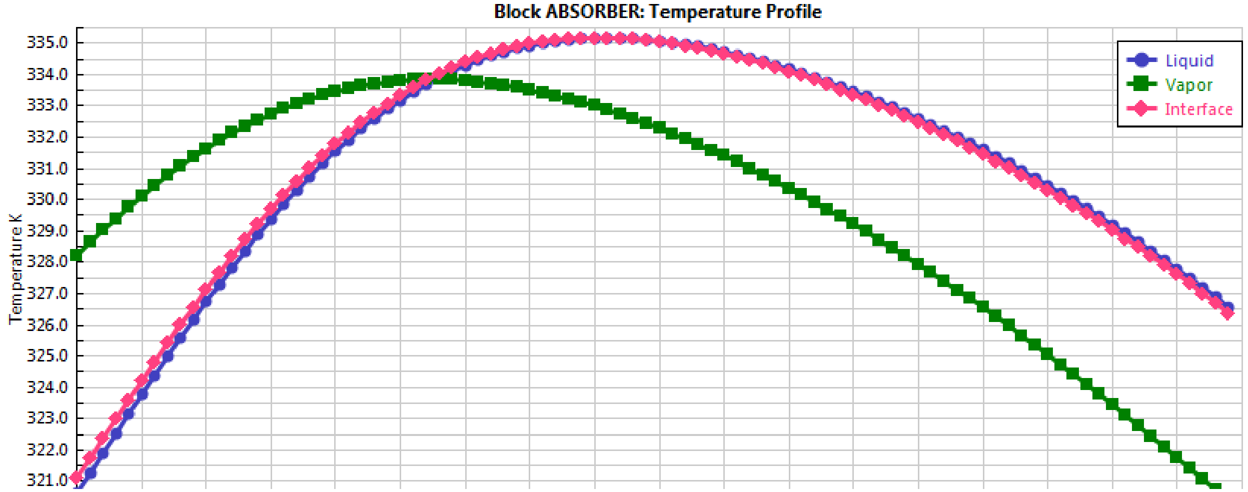
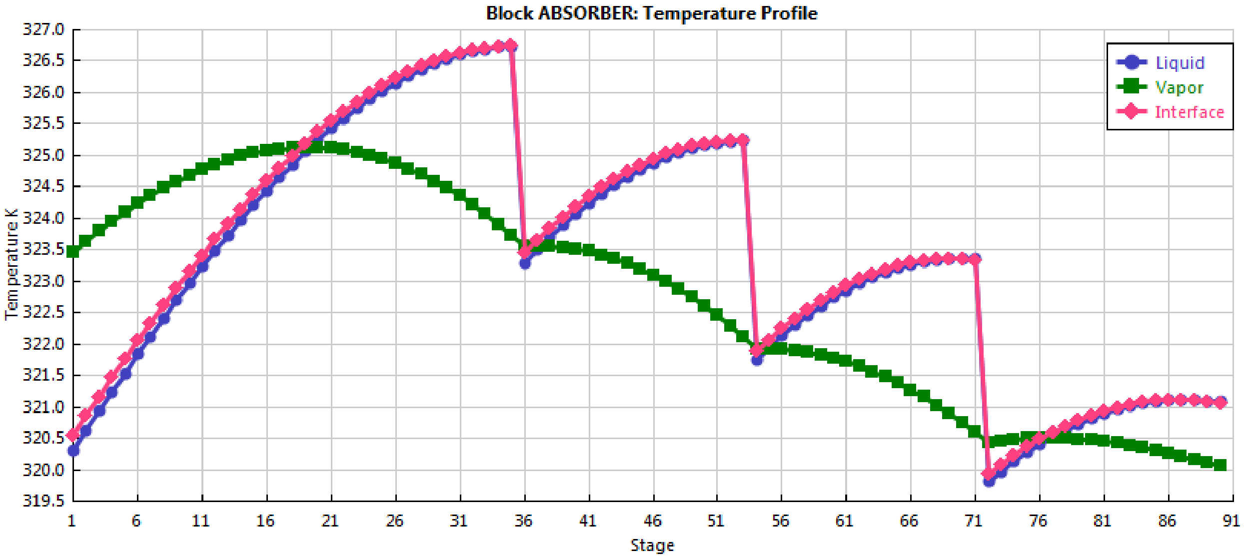
Process Model: Cooling Effects -- WVU

- 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 CO_2 absorption by 3.5%

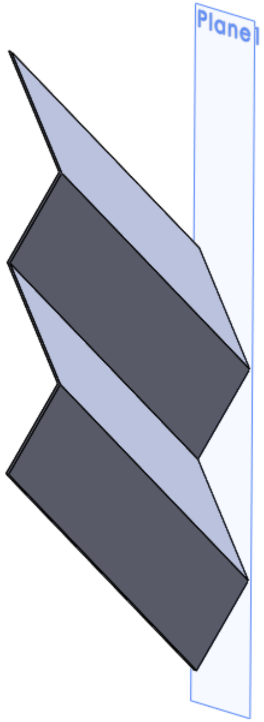
Height (m)	1.5
Diam. (m)	0.424
Lean Flow (lb/hr)	500
Lean Temp (K)	320
Lean Comp. (mass frac)	
MEA	0.285
CO2	0.07
H2O	0.635
Gas Flow (lb/hr)	140
Gas Temp (K)	320
Gas Comp (mass frac)	
CO2	0.135
H2O	0.055
N2	0.81
Lean Loading (mol CO2/mol MEA)	0.340879
Nominal MEA wt perc.	30.65%
Liquid-to-Gas Ratio (mass)	3.571429
No Cooling	
CO_2 Capture Percentage	61.68%
Rich Loading	0.453
Cooling at Y= 0.3m, 0.6m, 0.9m	
CO_2 Capture Percentage	65.14%
Rich Loading	0.459



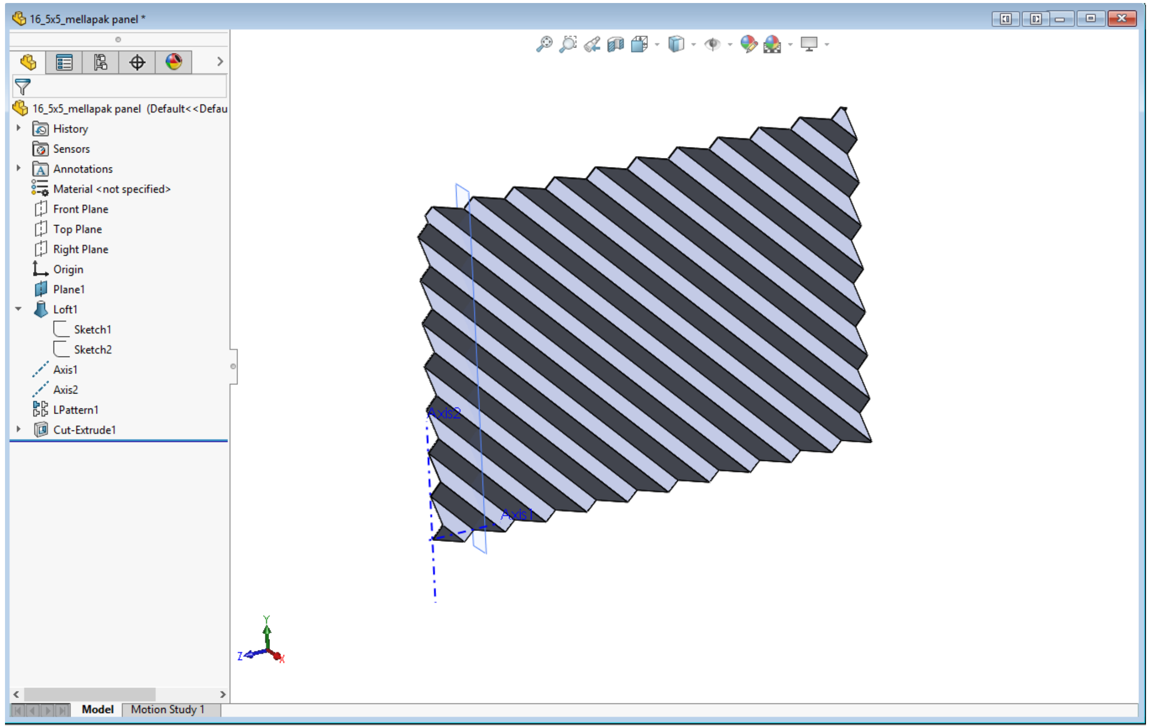


Task 3.0 – Manufacturability (3D Printability) Study

- 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)



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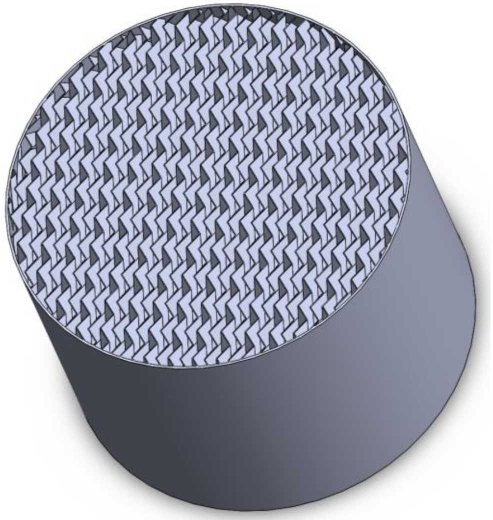
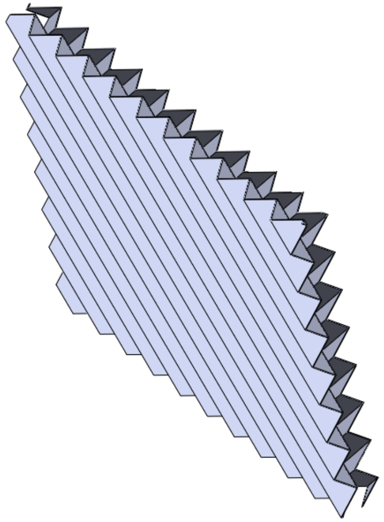
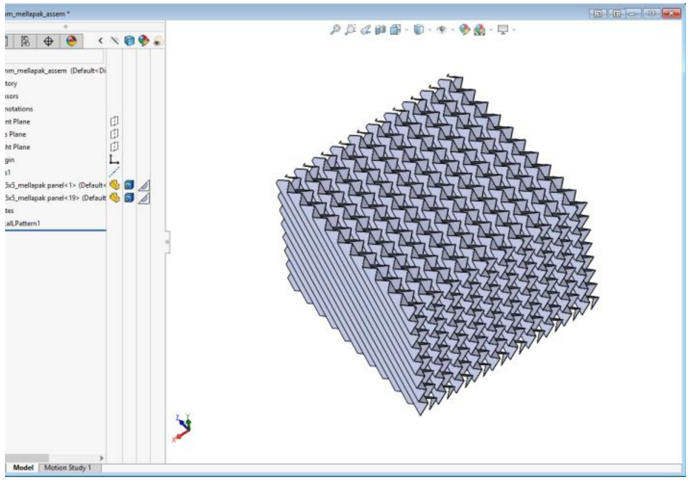
3.1 -- Printing the 16.5”D/12”H BaselinePack

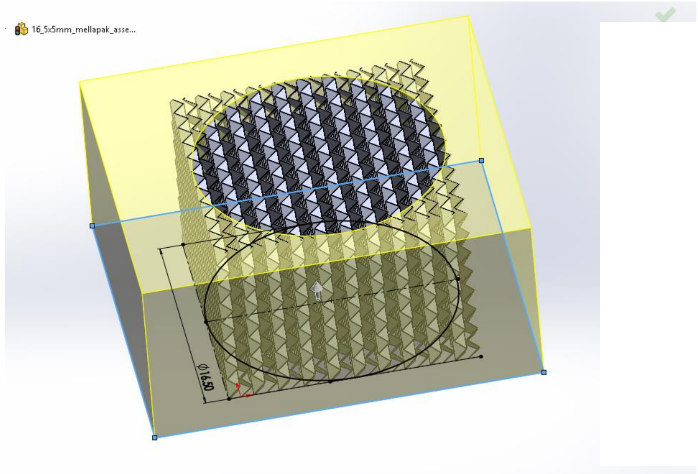
- Use assembly to create the pack
  - Mate two surfaces, oppositely facing each other
  - Use linear pattern to repeat
  - Save as part so we can make it into a cylinder with cylinder cut
  - Install a sleeve around the perimeter
  - Area to volume: 228:1
  - Volume percentage: 10.1%

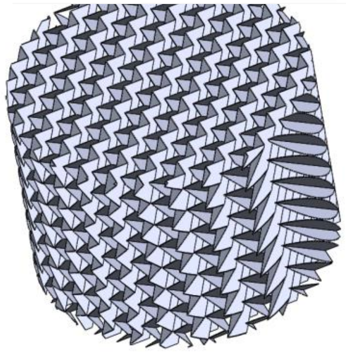
Total Baffle area (m2)	10.23
Cylinder area (m2)	0.406
Total area (m2)	9.824
Material volume (m3)	0.004365
Diameter (m)	0.424
Height (m)	0.3048
volume (m3)	0.043015
Area/volume	228.3873
Volume/volume	0.101477











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

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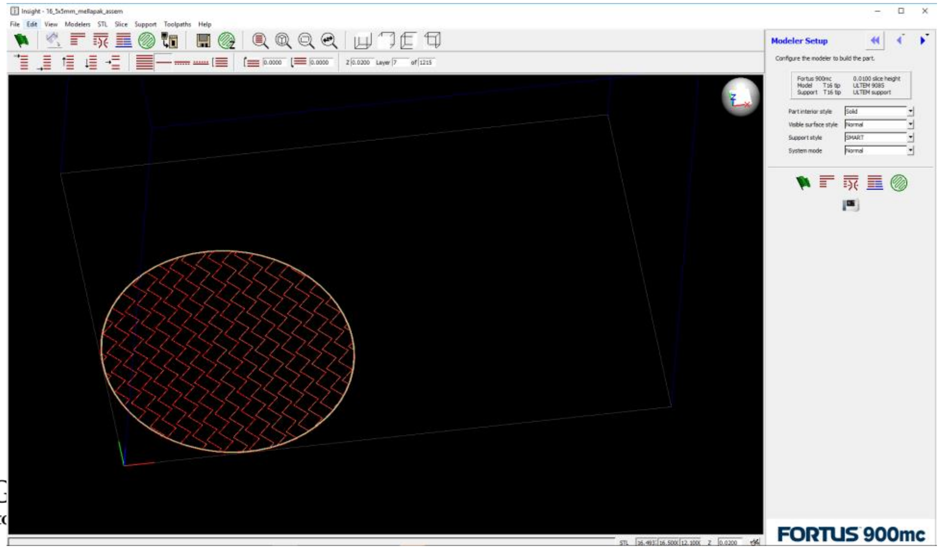
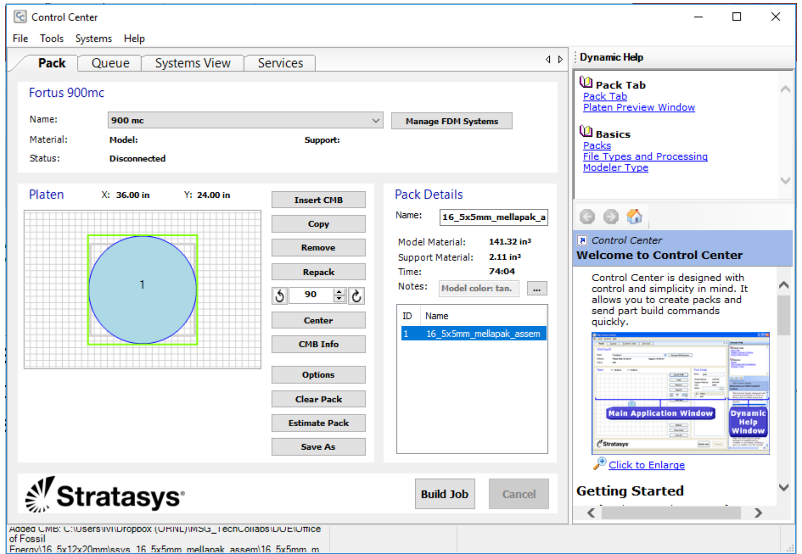


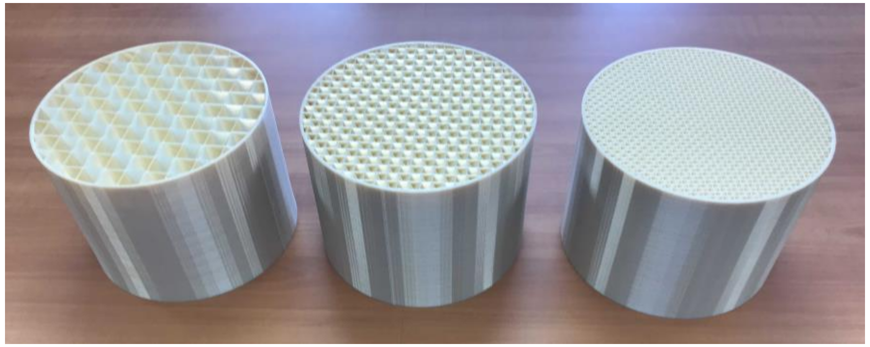


3.1 Print Baseline Packing with Varying Cell Density

- 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

Test Pack	
Diameter (m)	0.2032
Length (m)	0.14605
Cylinder Volume (m3)	0.004734

	Pack 1	**Pack 2**	**Pack 3**
Cell size (m)	0.0254	0.0127	0.00635
Total Baffle Area (m2)	1.325	2.671	6.303
Material Volume (m3)	0.00059	0.00097	0.00171
Area/Volume	**279.930**	**564.221**	**1331.507**
Material Volume/Cyl Volume	**0.125**	**0.205**	**0.361**



25.4 mm Cell

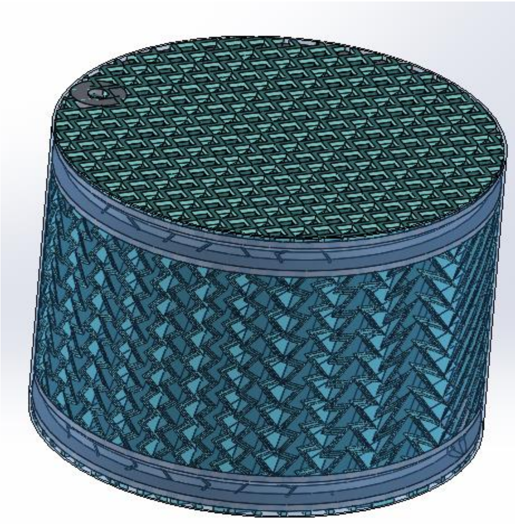

12.7 mm Cell

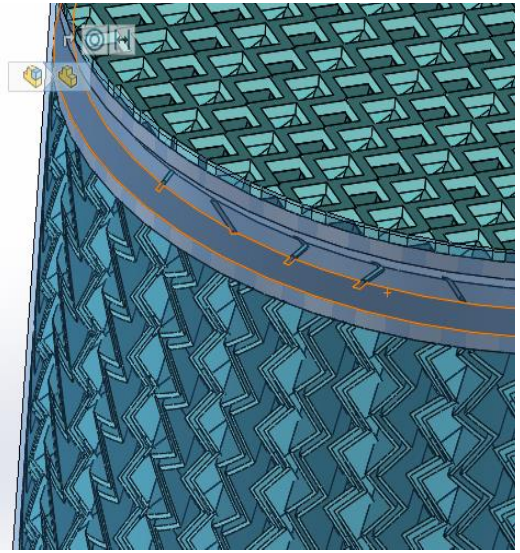

6.35 mm Cell

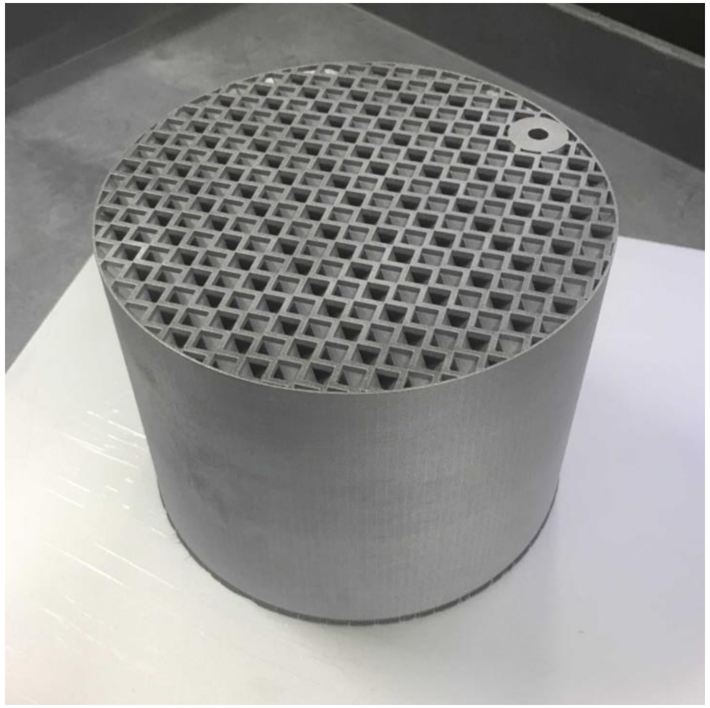
3.2 Printability of Intensified Device

- 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)

Cooling passages in fins

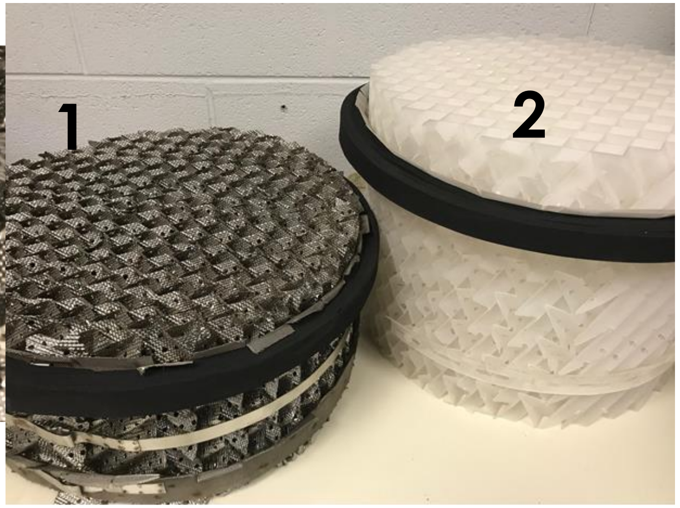


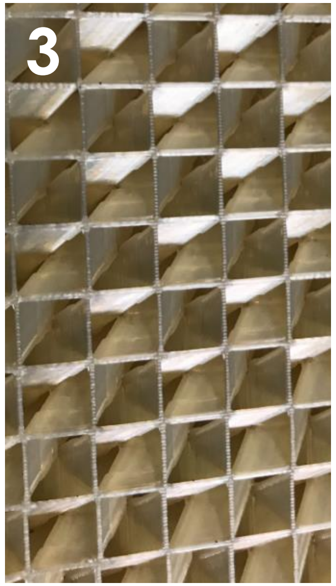


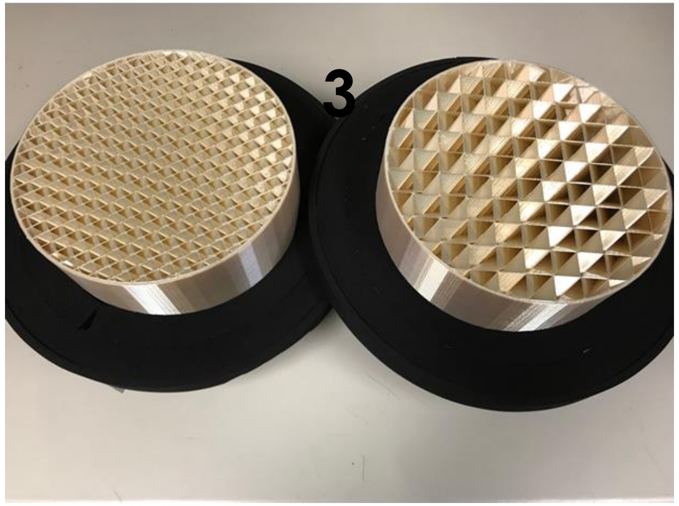


4.1 Experimental Validation of Device Core Metrics

- 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







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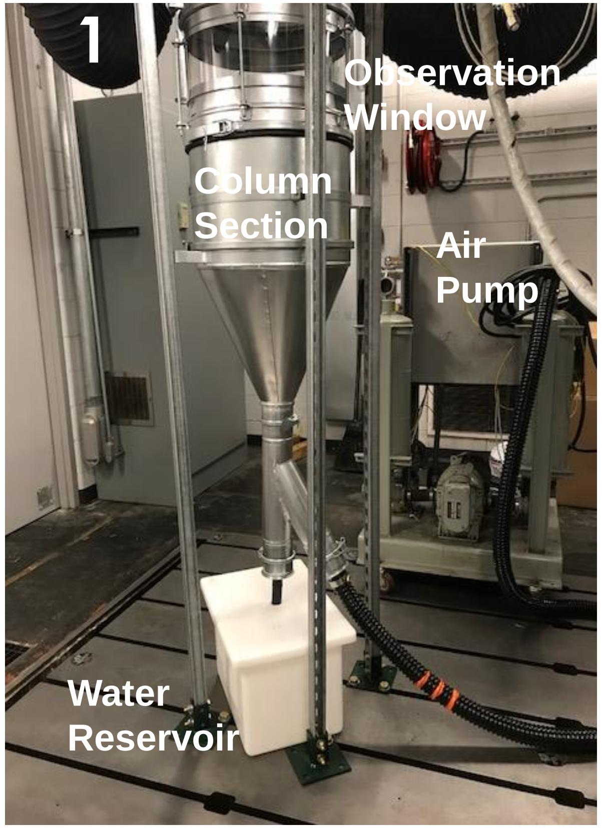
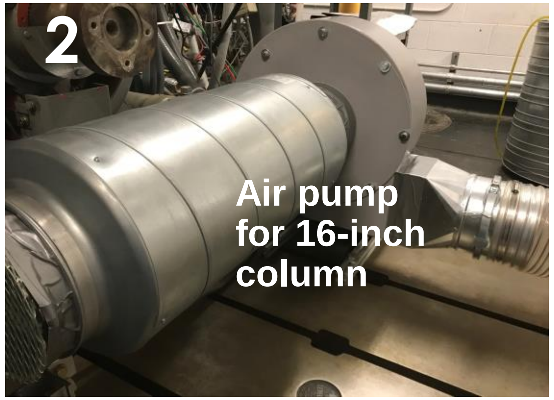
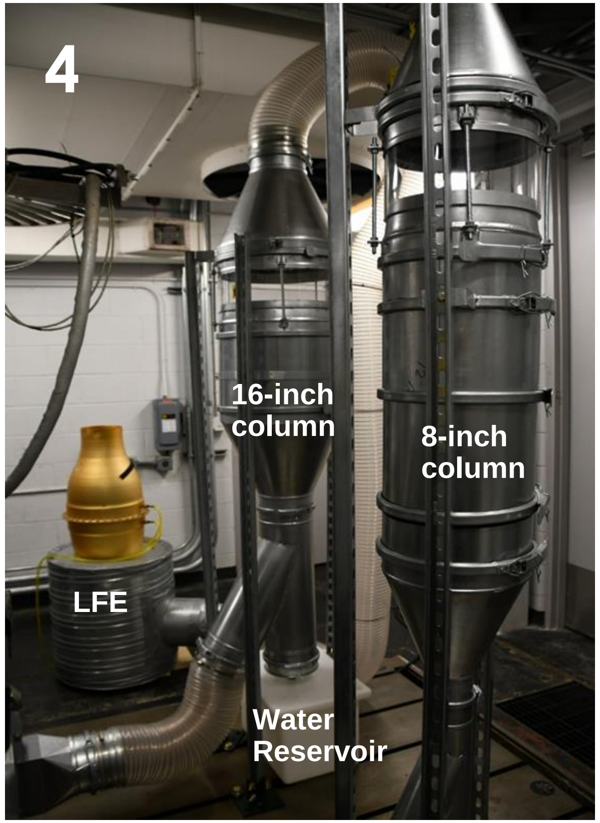
4.1 Laboratory Setup for Hydrodynamic Testing





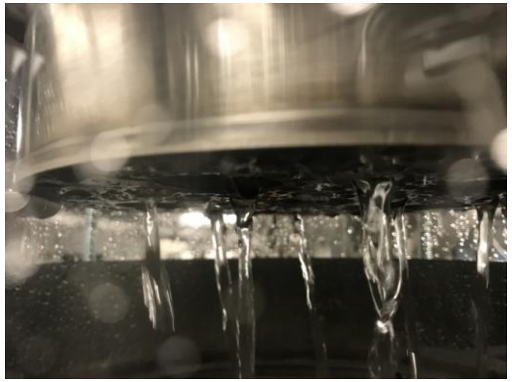


1. Initial Lab setup (air pump too weak for 16-inch column)
2. New pump for 16-inch column (43,500 LPM)
3. Smaller pump works for 8-inch column
4. Entire Lab Set-up
5. Easy-Load Liquid Pump

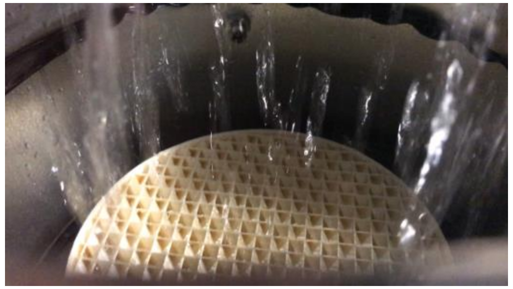
4.1 Testing Facility for 3D Printed Packing Elements

Top of solvent distributor

Bottom of solvent distributor

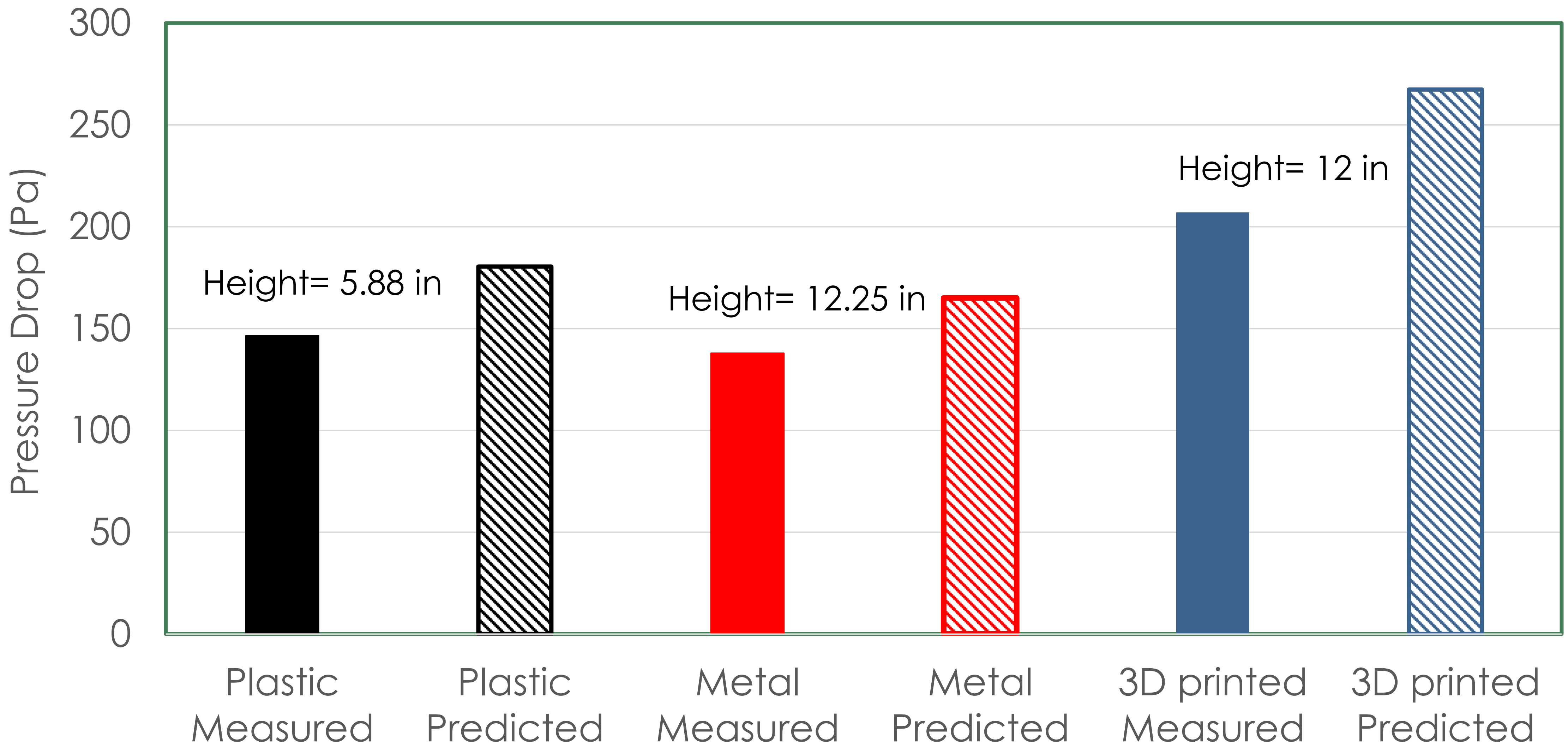


Top of 3D printed column packing

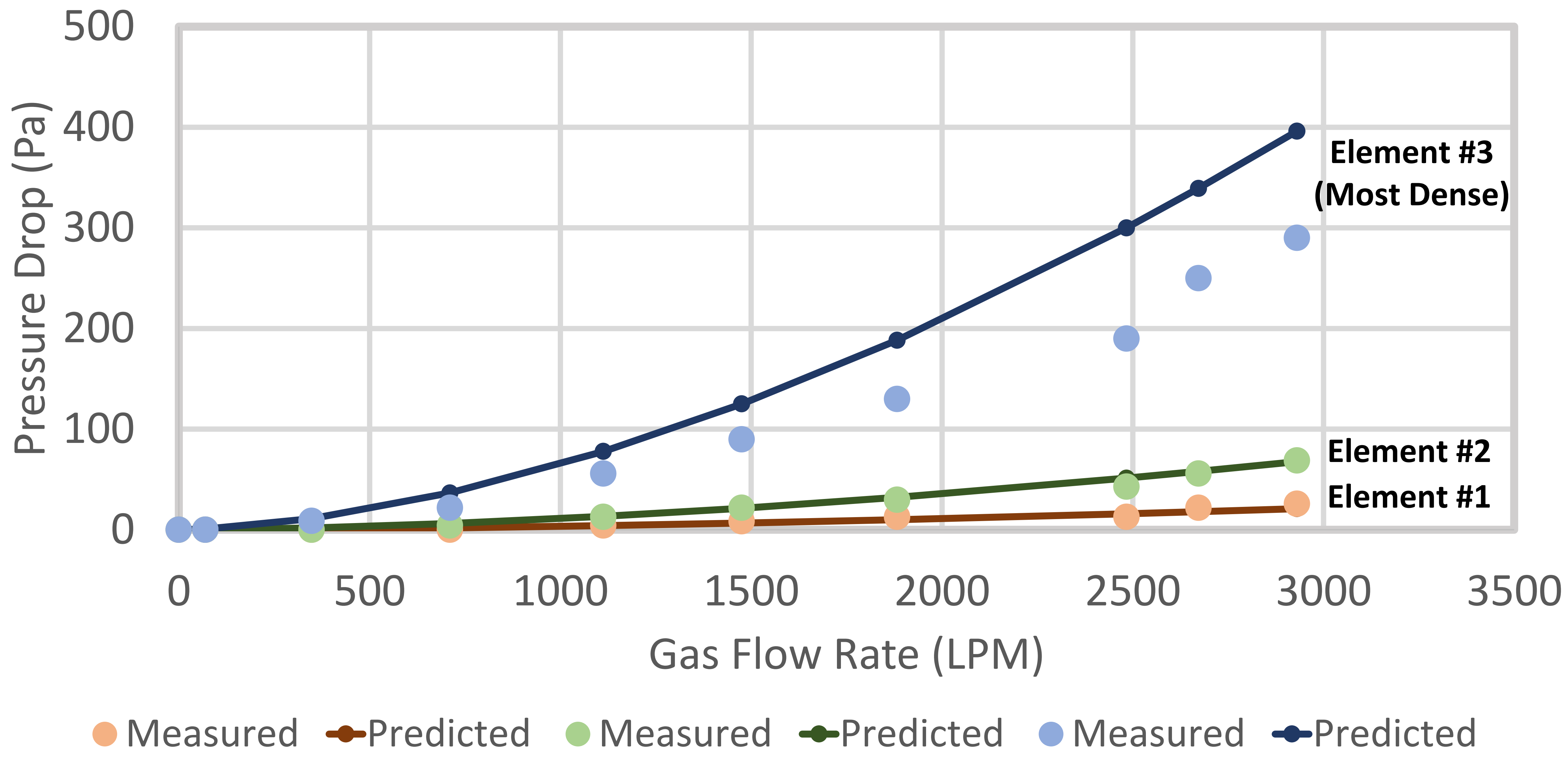


Stephen Bolton
Chemical Engineering Student from the University of Delaware

4.1 Measured Pressure Drops for 16” (D) Packings -- Printed vs. commercial metal and plastic baselines



4.1 Measured Pressure Drop for 8” Printed Packings



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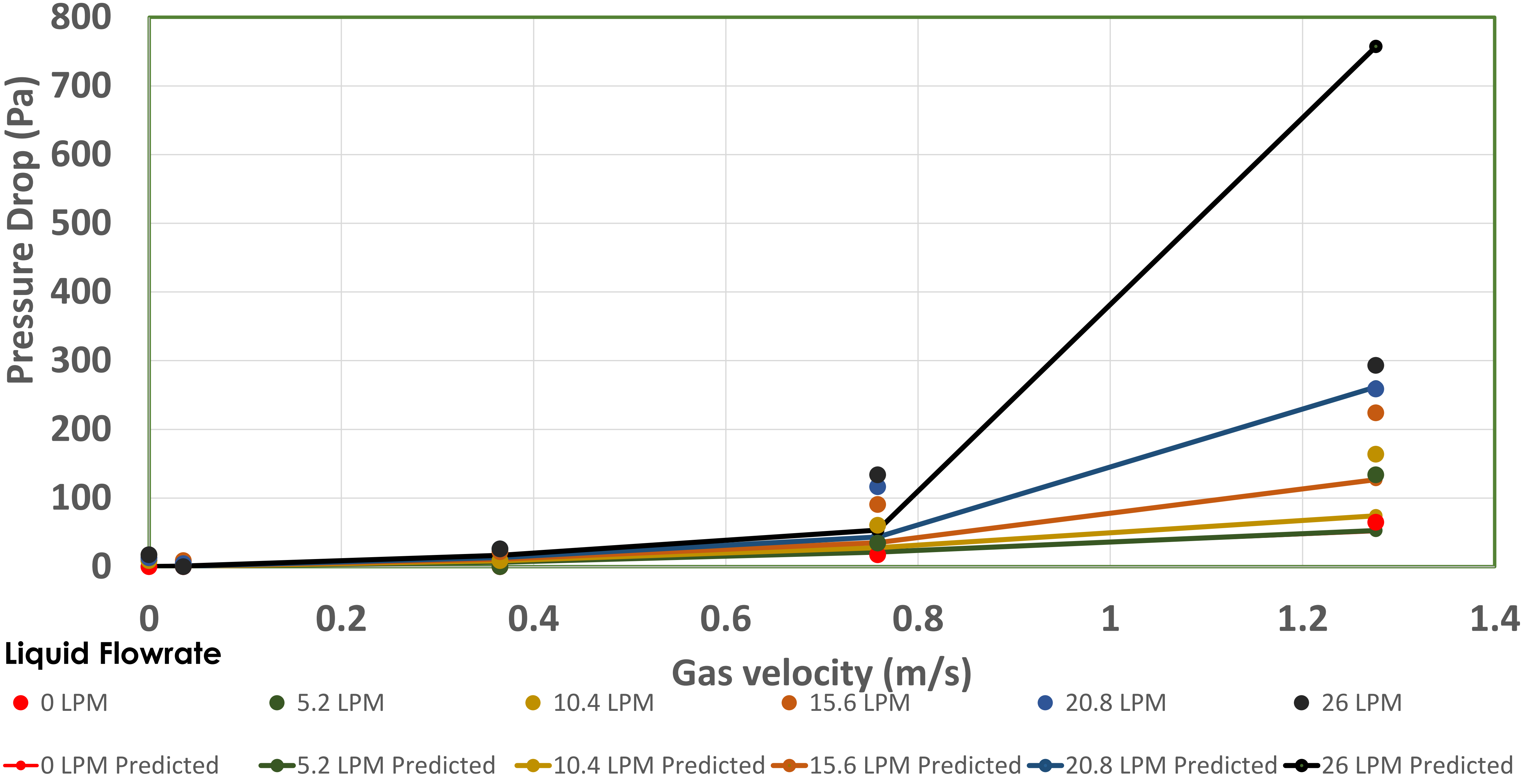
4.1 Preliminary Measurements with Wet System



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