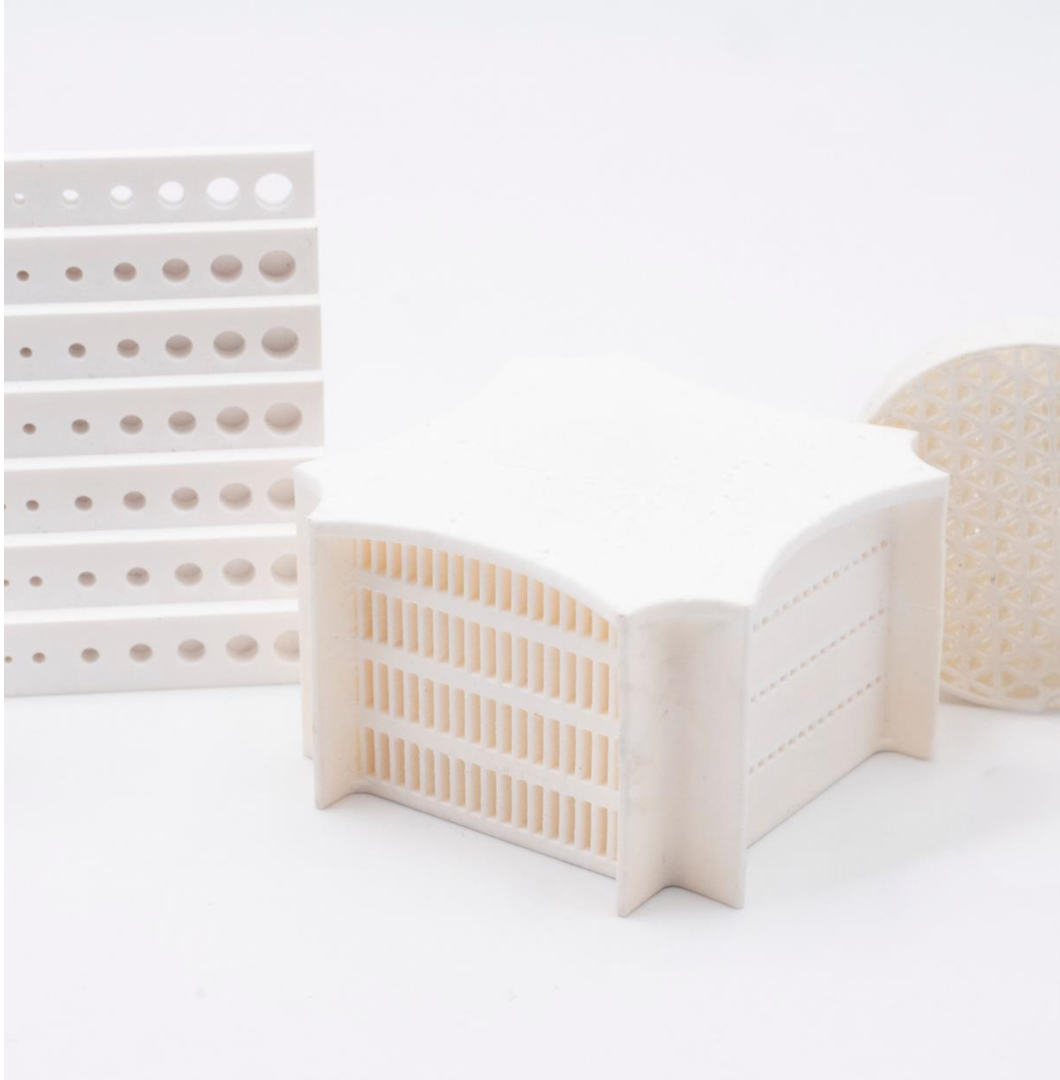
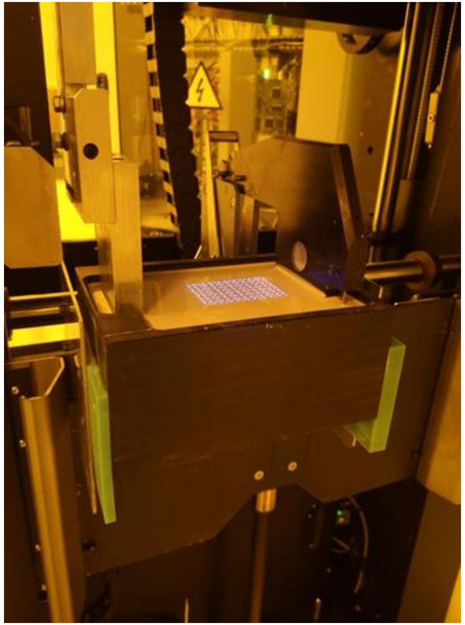
2024 PROJECT PEER REVIEW

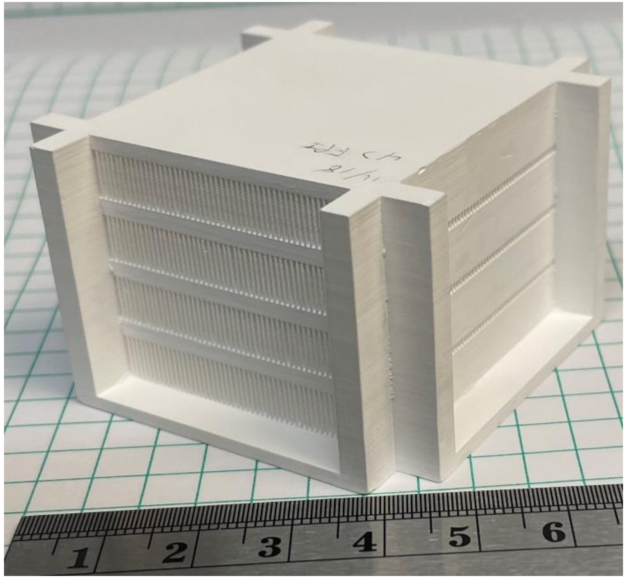
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review: High Payoff 3D Printed Ceramic Heat Exchangers for HVAC



High Payoff 3D Printed Ceramic Heat Exchangers for HVAC





Technology Assessment and Transfer, Inc.
W. Taylor Shoulders, PhD, Director of Technology
Email: tshoulders@techassess.com
Project # **DE-SC0021882**

Project Summary

OBJECTIVE, OUTCOME, & IMPACT

Development of 3D printing technology to evaluate experimental air-to-liquid heat exchanger designs with performance far exceeding conventional designs.

TEAM & PARTNERS

Technology Assessment and Transfer
Dr. Taylor Shoulders (PI)
Mrs. Ann Kutsch (contracting and 3D printing support)
Mr. Mark Kauf (design and engineering for 3D printing)

University of Cincinnati
Prof. Raj Manglik (modelling and characterization)

STATS

Performance Period: 8-22-2022 to 8-21-2024

(NCE to 12-31-2024)

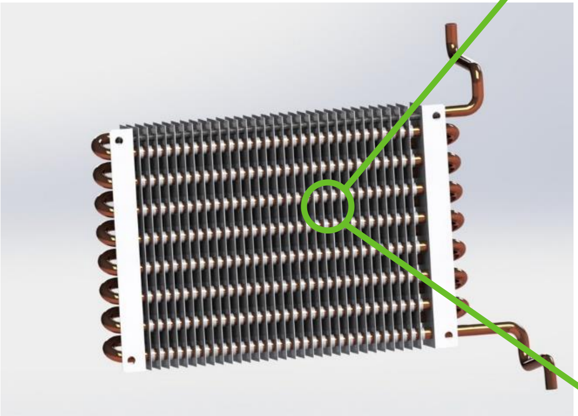
DOE Budget: $1,298k, Cost Share: $0

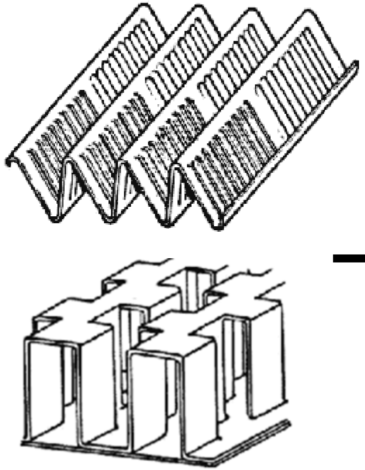
Milestone 1: 3D print 3 in x 3 in x 0.5in fin sections with novel designs

Milestone 2: 3D print air-to-liquid heat exchanger incorporating novel fin design

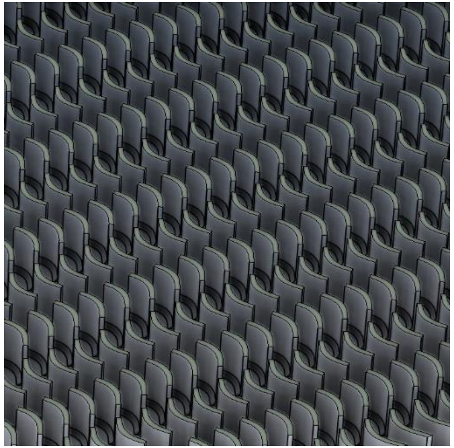
Milestone 3: over 200% heat exchange performance over conventional design

Problem





‘advanced’ sheet metal fin designs

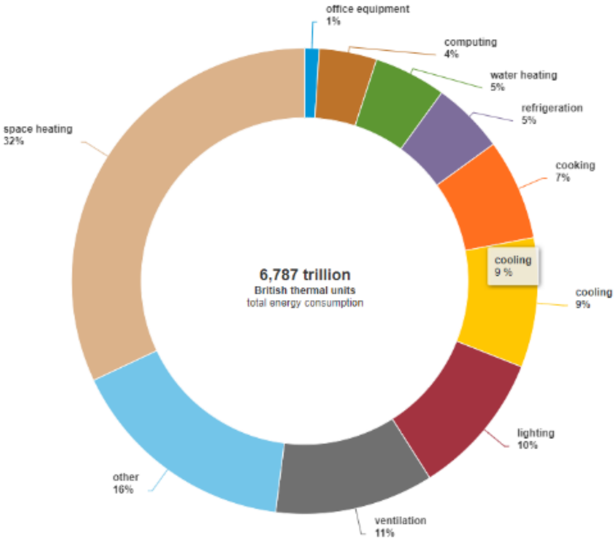


3D printed designs with segmented fins of smaller minimum width

Commercial heating and cooling applications depend heavily on plate tube heat exchangers. Efficiency is stagnated in part by the limited design space allowed by traditional sheet metal processing for fins. Additive manufacturing by DLP technology can broaden the design space leading to significant improvements in efficiency and performance. We present a demonstration of novel designs as a proof of concept for the performance payoff of 3D printed ceramic heat exchangers in air to water cross flow configuration.

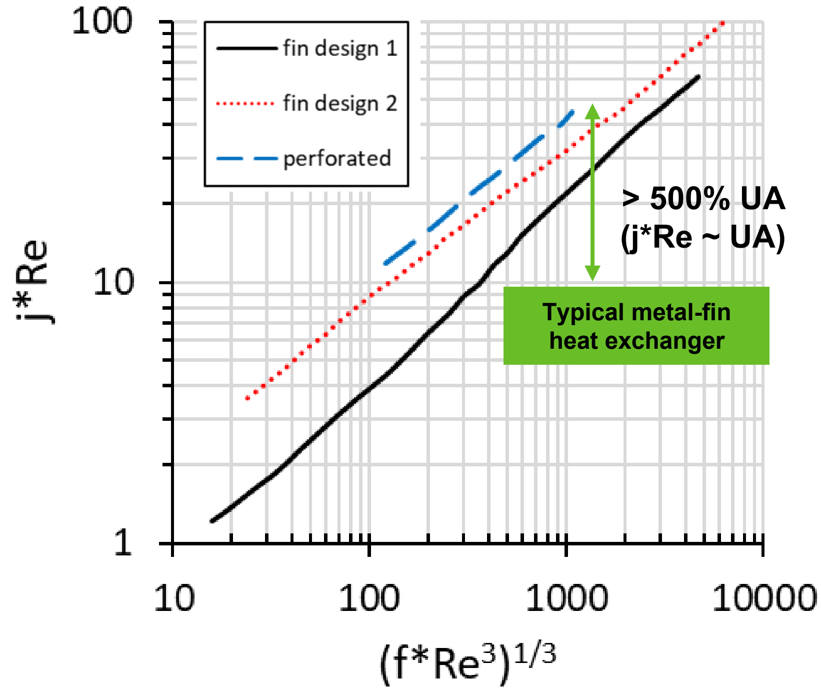
Alignment and Impact

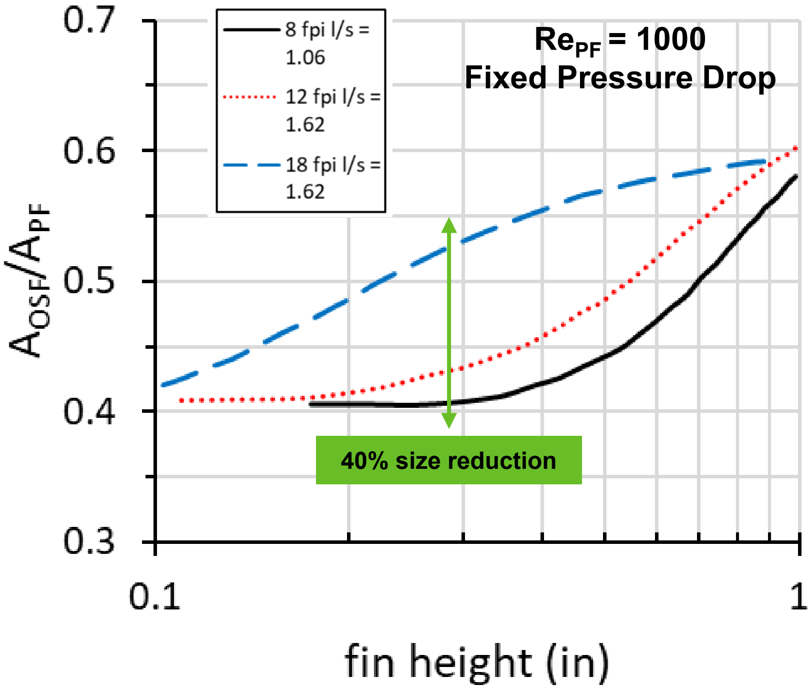
- Almost 40% of commercial building energy consumption is driven by heating and cooling
- More efficient heat exchangers have the potential to significantly cut into this number
- This program focuses on demonstrating designs that have the potential to **increase heat transfer by 500%** and **reduce size by 40%** compared to conventional designs.



US Energy Information Administration 2018 Commercial Buildings Energy Survey, December 2022

Alignment and Impact



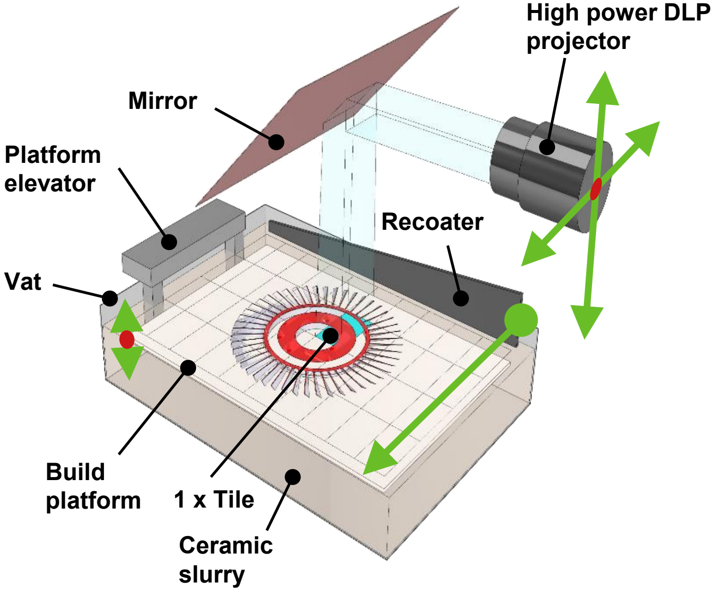


Based on UC modelling efforts, 500% increase in heat exchange and 40% reduction in size over conventional designs is possible

Approach

DLP 3D Printing of Ceramic Heat Exchangers

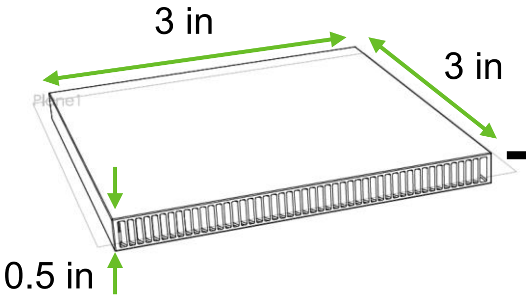
- Material feedstock is a particulate-filled (~50 v%) photocurable acrylate resin
- Ceramics offer advantages over metals in terms of corrosion resistance and temperature resistance while still offering good thermal conductivity
- Printed parts are debound and sintered to yield fully dense ceramics (no filled polymers)
- Minimum achievable fin thickness and gaps on the order of 300 μm
- Continuous tool paths not necessary as with extrusion-based 3D printing methods
- Large print bed (up to 300 x 445 x 300 mm)



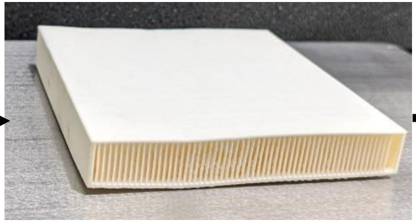
Approach

Design, Fabrication, and Evaluation of Advanced Fin Designs

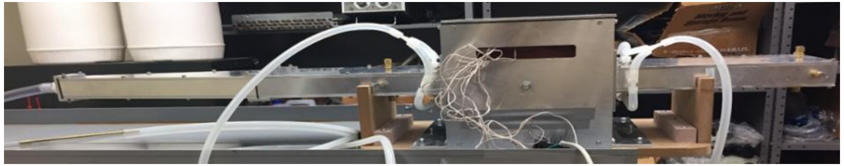
- Draw on past work at UC to prove-out advanced designs first as single-layerd fin coupons
- Print and sinter these fin coupons at TA&T
- Test these fin coupons at UC to experimentally determine fin effectiveness parameters

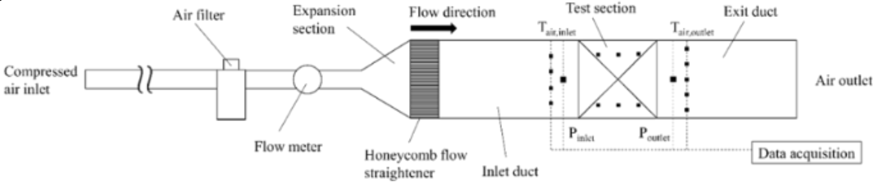


design



fabricate



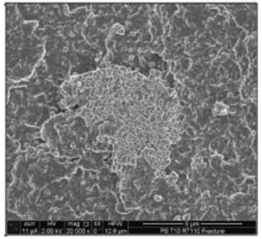


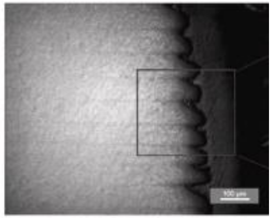
characterize

Approach

Refinement of Ceramic Fabrication Process

- DLP 3D printing of ceramics encompasses many steps, each of which can result in critical part failures (complete destruction of part, deviation from ideal dimension)
- For the geometries targeted in this study, cleaning parts which are completely submerged in the vat upon the completion of printing is the most critical
- Process refinement around the use of TA&T's new low-viscosity Al_2O_3-loaded resin to promote cleaning of long micro-channels



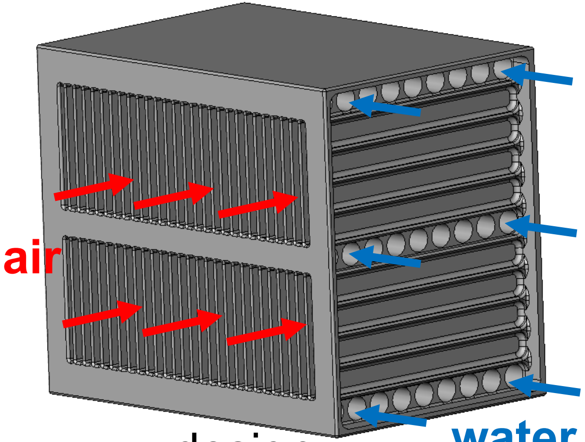


Resin mixing → Printing → Cleaning → Solvent extraction / burn out → Sintering

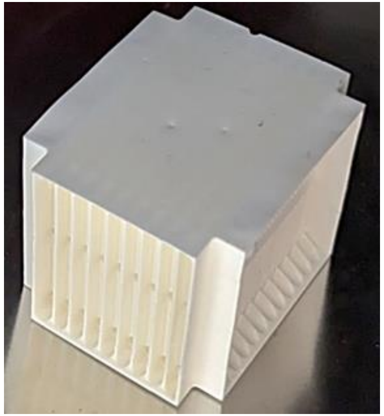
Approach

Demonstration of advanced fin designs in air-to-liquid cross-flow configuration

- Design of test elements with circular micro-channels in one direction and advanced fin designs in the orthogonal direction
- Print and sinter these cross-flow designs
- Experimentally determine the heat exchange capacity for advanced ceramic air-to-liquid test elements



design



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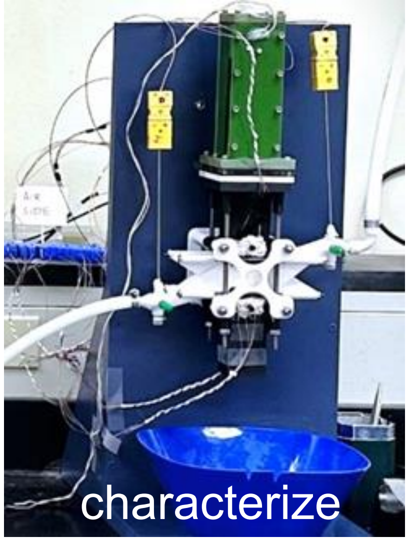
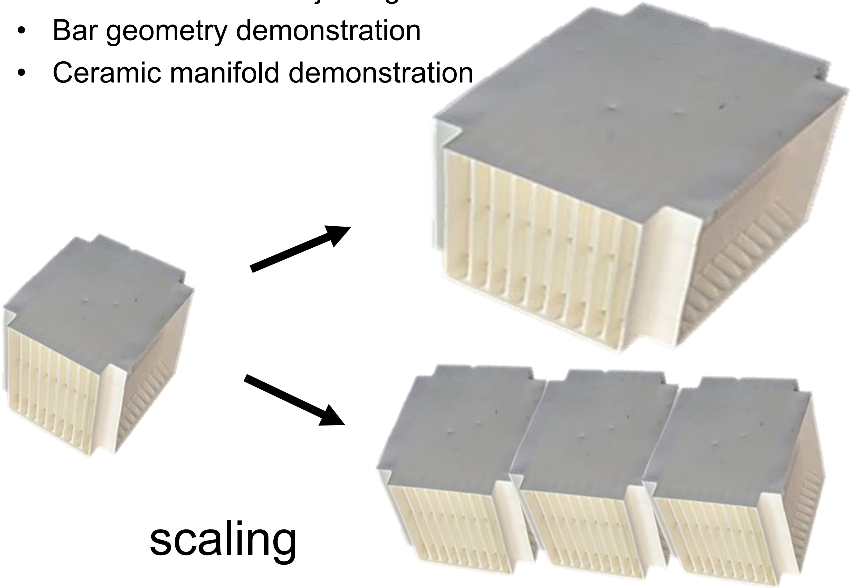


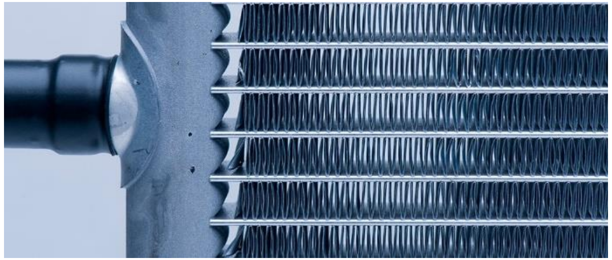
Approach

Scaling and Integration

- Demonstration of improved yield on 3D printed ceramic heat exchangers as well as increased size
- Demonstration of a potential strategy for system integration
  - Ceramic-to-ceramic joining
  - Bar geometry demonstration
  - Ceramic manifold demonstration



scaling

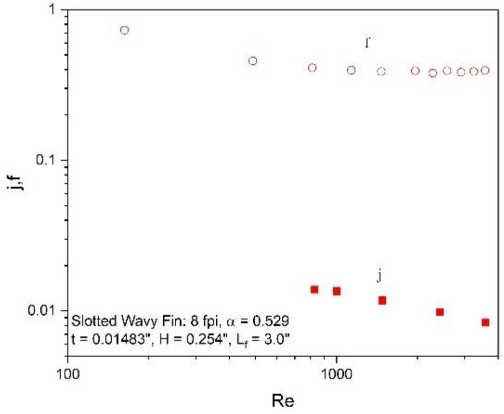


integration

Progress

Design, Fabrication, and Evaluation of Advanced Fin Designs

- Several fin configurations have been printed, sintered and tested in the 3 in x 3 in x 0.5 in coupon geometry
- Impact of fin density and fin geometry on heat transfer and pressure drop has been characterized



y-axis

f = Fanning friction factor

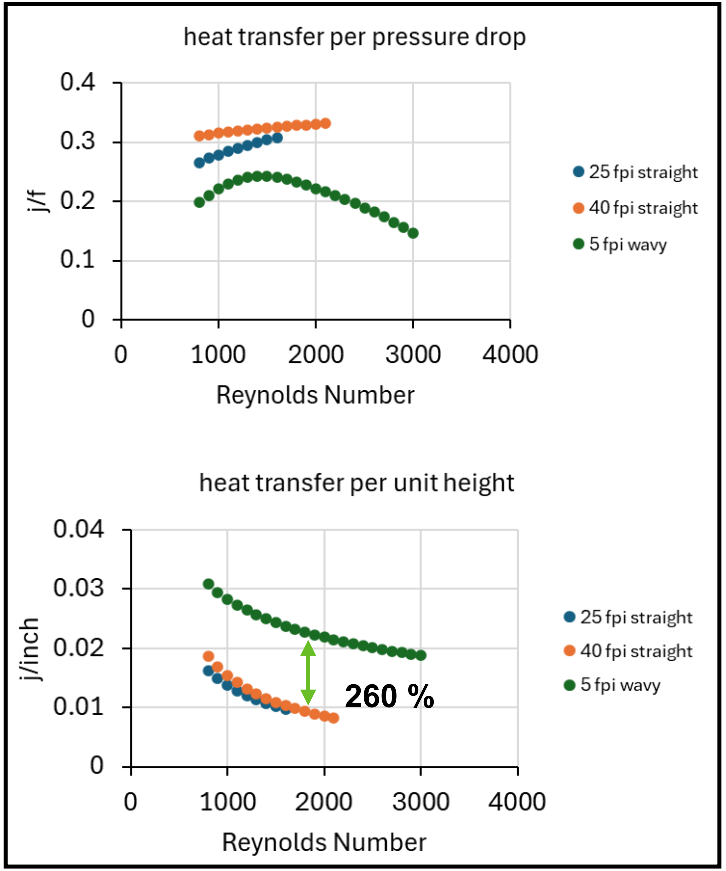
j = Colburn factor (heat transfer)

x-axis

Re= Reynolds Number (fluid flow)

Example of heat transfer and pressure drop data generated from the fin coupon testing at UC

Comparison of Fin Designs

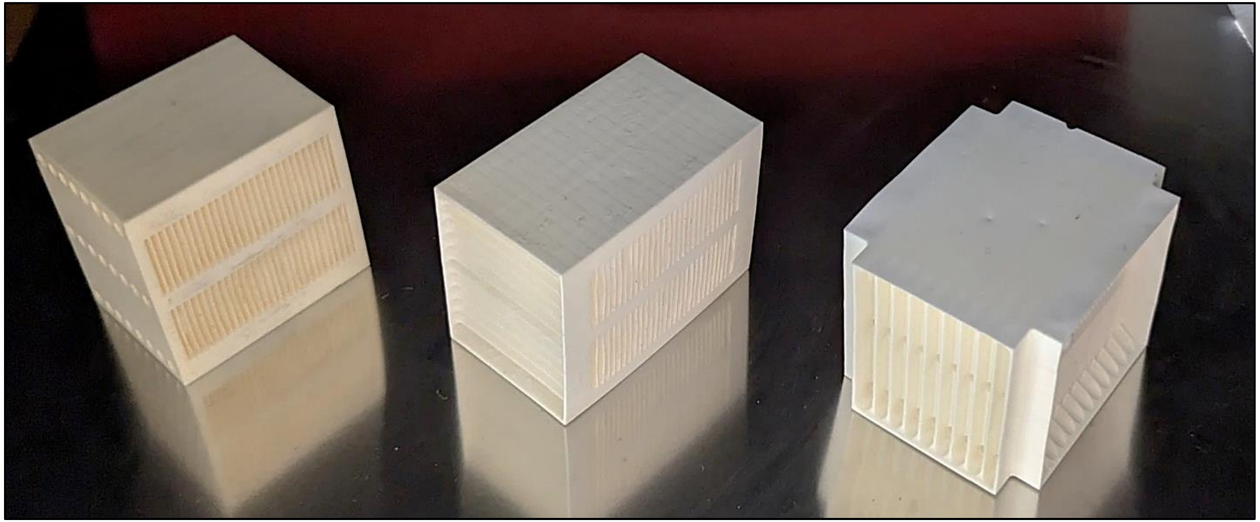


Progress

Printing and Thermal Processing of Ceramic Heat Exchangers

- Overcoming problems with yield due to cracking of parts
- Integration of design changes, especially in cross-flow designs in order to make hermetic attachment to test setup easier

Example of fin coupon which cracked during binder burnout

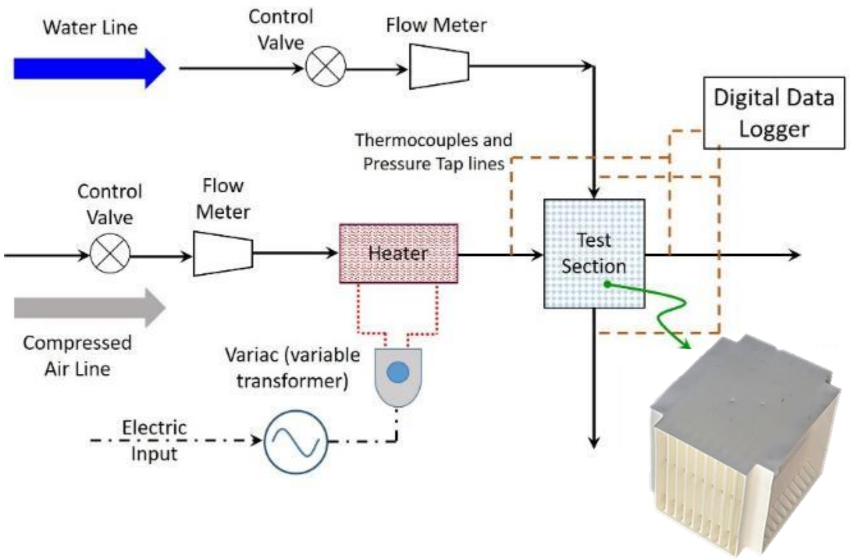


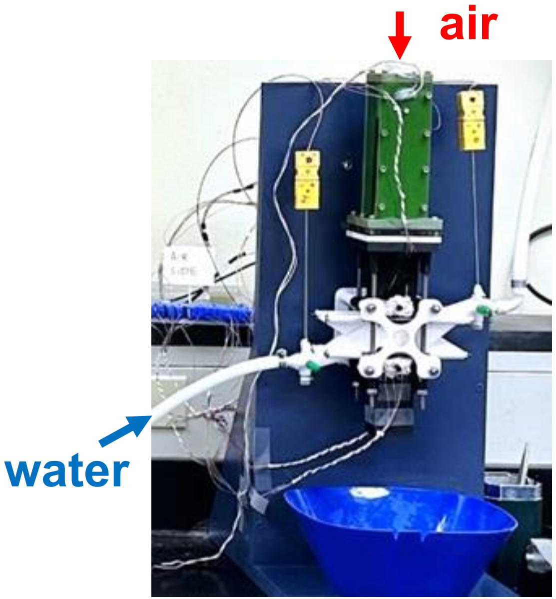
Evolution of attachment features in printed and sintered cross-flow elements

Progress

Evaluation of Ceramic Air-to-Liquid Heat Exchangers

- Setup has been assembled since the start of the program in 2022
- Setup has been used to characterize cross-flow heat exchangers of straight-fin and complex fin designs

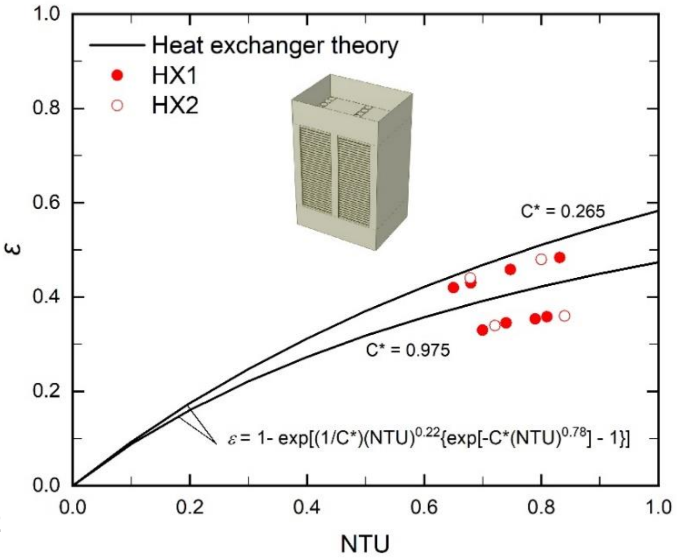


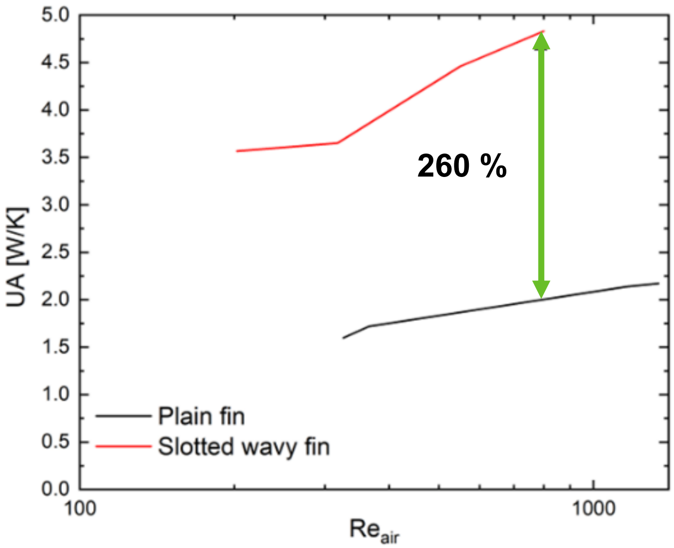


Progress

Evaluation of Ceramic Air-to-Liquid Heat Exchangers

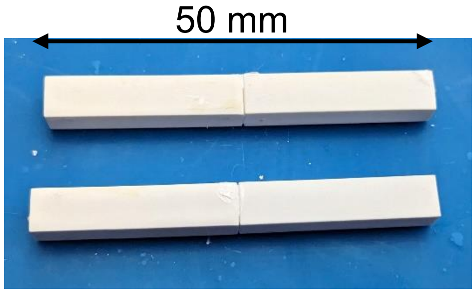
- For multiple 3D printed ceramic straight-fin cross-flow heat exchangers, the UC team has demonstrated good agreement between theory and experiment
- A comparison of performance between ‘straight’ fin and ‘slotted wavy fin’ shows 225% improvement in heat exchange for the complex fin design





Future Work

- Full evaluation of the heat exchangers by the ε-NTU method is pending final complex fin coupon testing and testing of additional replicates of ceramic heat exchangers
- Results on scaling and integration are also being finalized
- In a follow-on or extension of this effort, the team plans to demonstrate the same or similar designs in Si_3N_4 and/or AlN



Bend bars printed at half-size, joined in green state and co-sintered (top) and the load frame used for evaluation (right)

Thermal conductivity data for candidate materials

Material	κ (W/mK)	Limitations
Aluminum 1050	227	Temperature, mechanical properties
Copper	400	Temperature, mechanical properties
Aluminum Oxide	30	Thermal conductivity, thermal shock
Aluminum Nitride	150-250	Manufacturing of complex geometries, integration
Silicon Nitride	80-170	Manufacturing of complex geometries, integration

Thank you

Technology Assessment and Transfer, Inc.
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Director of Technology
Email: tshoulders@techassess.com
Project # **DE-SC0021882**

Reference Slides

Project Execution

	FY2023				FY2024				FY2025			
Planned budget	549,463				548,618							
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Delivery of Complex Fin Designs to TA&T												
Successful Printing and Sintering of Fin Couopns												
Completion of Cross-Flow Test Setup at UC												
Delivery of Complex Cross-Flow Designs to TA&T												
Successful Printing and Sintering of Cross-Flow Hxers												
Current/Future Work												
Fabrication Additional Fin Coupons and HXers												
Testing Additional Fin Coupons and Hxers												
Ceramic to Ceramic Bonding												

- Printing and thermal processing delays were encountered throughout 2024 due to facility relocation and changeover in technical staff

Team

Dr. Taylor Shoulders

Director of Technology

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Mrs. Ann Kutsch

General Manager

Technology Assessment and Transfer, Inc.

Prof. Raj Manglik

Director

Thermal-Fluids Processing Laboratory

University of Cincinnati