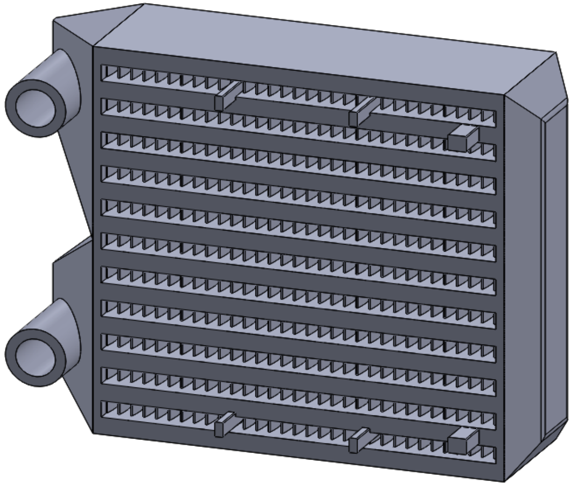
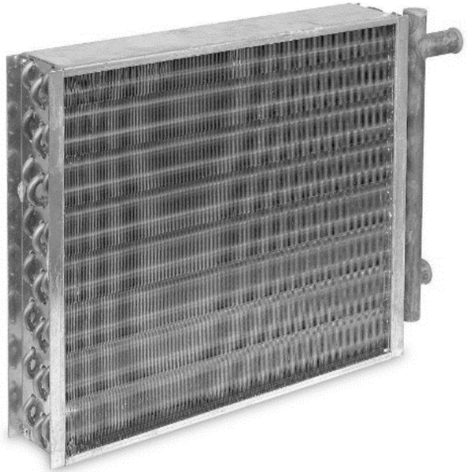
Low-cost, high-performance polymer composite heat exchangers manufactured by additive manufacturing





Oak Ridge National Laboratory

Kashif Nawaz (Group Leader- Multifunctional Equipment Integration)

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Project Summary

Timeline:

Start date: October 2018

Planned end date: March 2022

Key Milestones

1. Development of appropriate manufacturing process to accommodate desired operating pressure (>100 psi)
2. Design, development and demonstration of ultra-efficient heat exchanger (200% higher UA compared to existing technology)

Budget:

	DOE funds	Cost share
FY19	450K	50K
FY20	450K	50K
FY21	450K	50K

Key Partners:

Oak Ridge National Laboratory

Johnson Controls

Mitsubishi Chemical

Mitsubishi Chemical America

TC

Project Outcome:

- Next generation heat exchanger for air-to-refrigerant heat transfer applications
  - Development of cost-effective manufacturing process
  - Deployment of higher durability solution compatible to high operating pressure

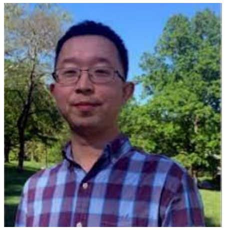
Next generation heat exchangers enabled by advanced manufacturing and novel materials

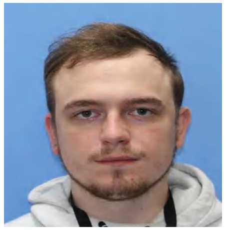
Project Team

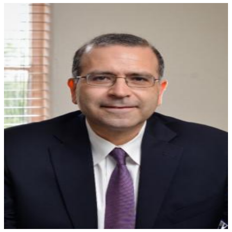
- **Oak Ridge National Laboratory**
  - Kashif Nawaz (Sr. R&D staff)
  - Brian Fricke (Sr. R&D staff)
  - Kai Li (R&D staff)
  - Vlastimil Kunc(Sr. R&D staff)
  - Ahmed Hassan(R&D staff)
  - Edgar Lara-Curzio (Sr. R&D staff)
  - Tyler Smith (Tech Staff)
- **University of Oklahoma**
  - M. Cengiz Altan (Professor)
- **Johnson Controls Inc.**
  - Roy Crawford (Director Advanced R&D)
- **TC Poly Inc.**
  - Matthew Smith (Research Director)





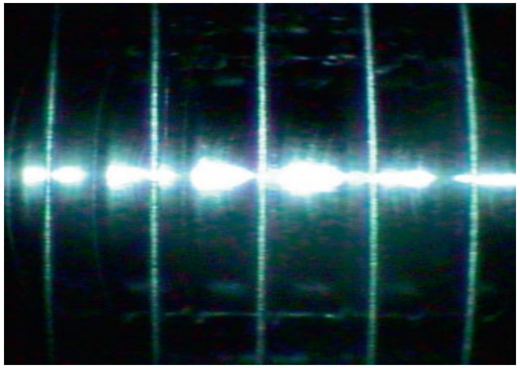




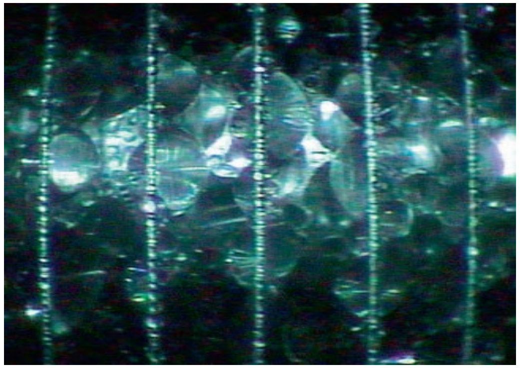



Challenge

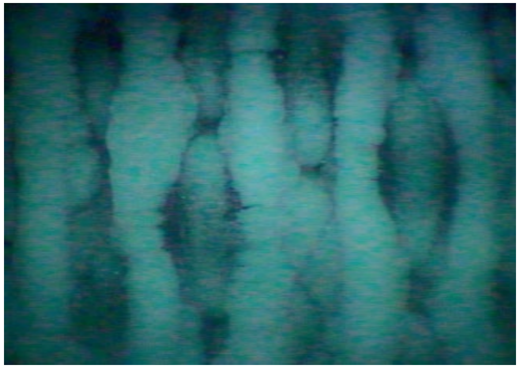
- Air-to-refrigerant heat exchanger are essential component of any heating, cooling and dehumidifying application.
- Heat exchangers account for more than **50%** of the energy consumption in a typical HVAC&R system.
- Operating conditions can significantly impact the performance of heat exchanger.



Dry operation



Wet operation



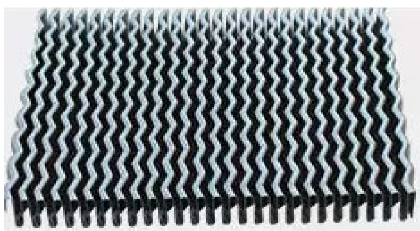
Frosted operation

The development of an effective air-to-refrigerant heat exchanger can lead to at least **500 TBtu/year** of U.S. primary energy savings, due to merely **20-25%** improvement in heat exchanger efficiency.

Challenge

- Depending on the operation, 60-80% of thermal resistance to heat transfer lies on the air-side ⟶ often times extended surfaces are deployed.
- Conventionally metals (aluminum and copper) have been used to manufacture the heat exchanger.

Louver fin

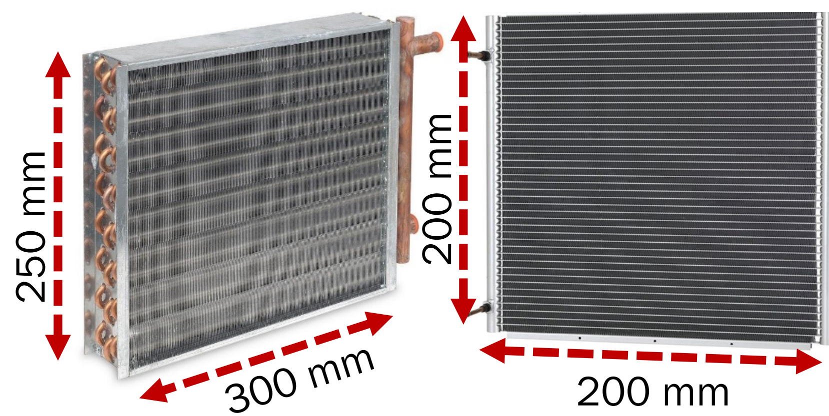


Wavy fin

Staggered fin

Plain fin

Capacity= 5 kW



Coil weight= 6 kg
Pressure drop= 3.5 bars
Thickness= 36 mm
Manf Cost=>$55

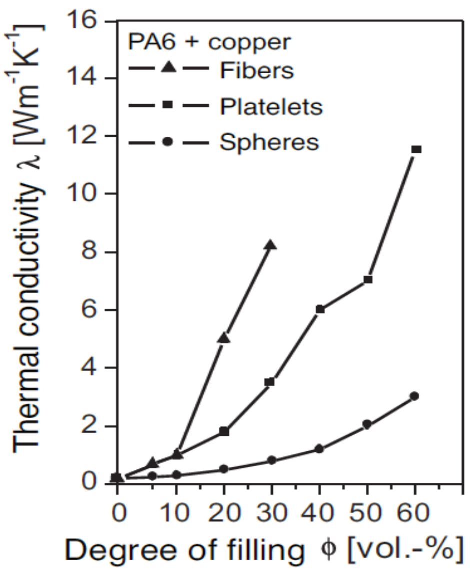
Coil weight= 1.2 kg
Pressure drop= 2.5 bars
Thickness= 18 mm
Manf Cost=~$40

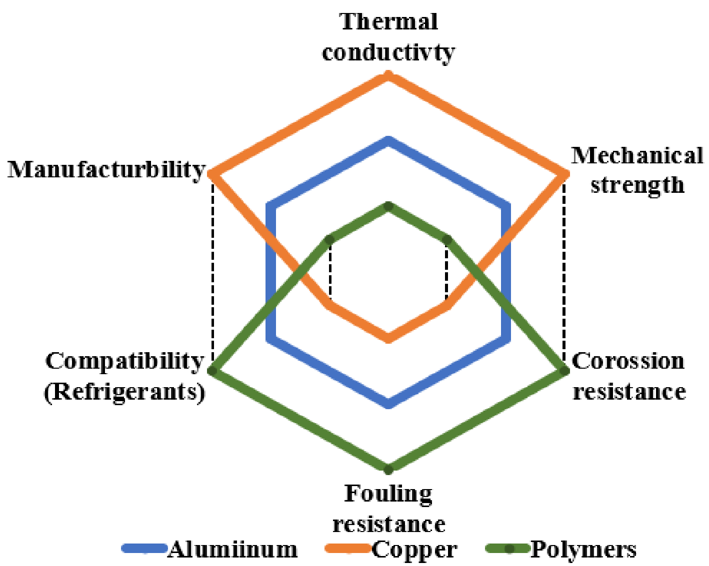
https://www.cantas.com/urunpdf/sanhua_microchannel_cat.pdf

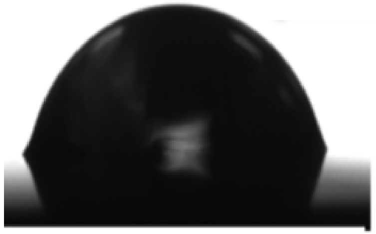
Solution Approach

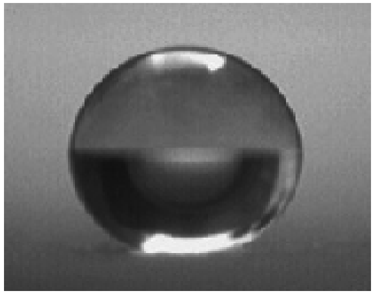
What about polymer heat exchangers??

- Low thermal conductivity Hybrid materials (composites)
- Failure at high operating pressure Hybrid materials (composites)
- Compatibility with working fluids Appropriate treatment
- Manufacturability Advanced manufacturing
- Condensate drainage/self cleaning 3x better

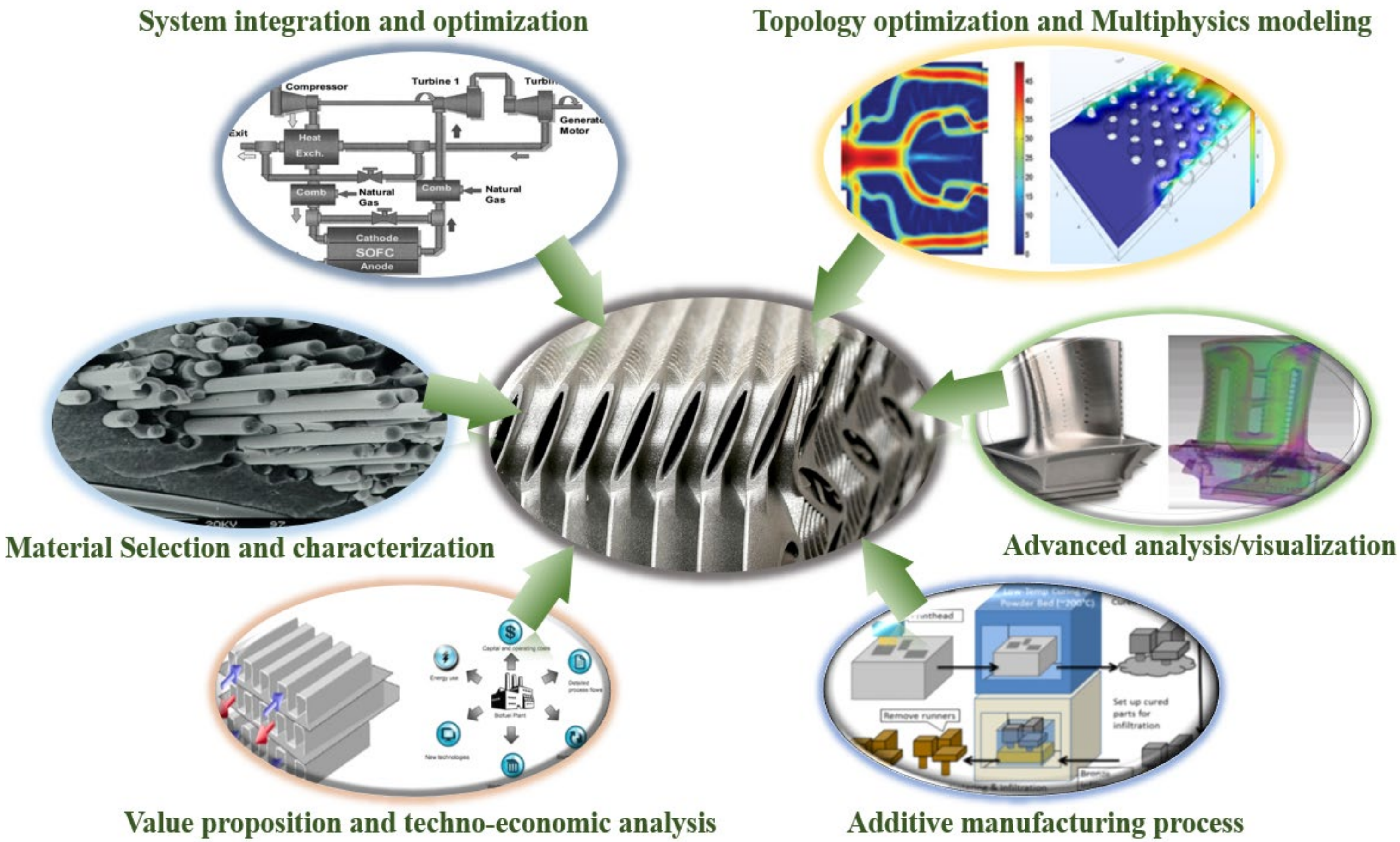





Bare aluminum surface


Teflon surface

Solution Approach

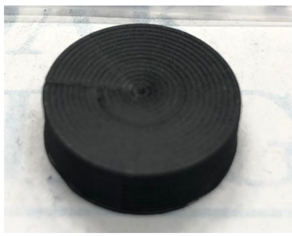


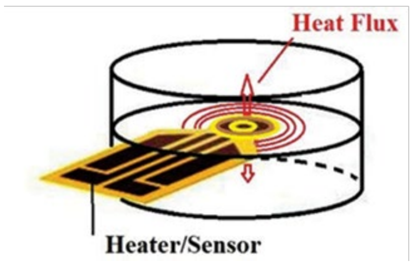
Project Impact

- Development of next generation heat exchanger with
  - Unprecedented thermal-hydraulic performance (Indirect GHG emission reduction)
  - 50% reduction in manufacturing cost
  - Expanded operational life
  - 3-4 times more compact compared to state of the art
- Enabling development for deployment of A2L and A3 refrigerants
  - Reduction in refrigerant charge (Direct GHG emission reduction)
  - Compatibility with emerging fluids over wide operating range
- Implications for additional processes
  - Power generation, waste heat recovery, electronics cooling
- At least 500TBtu energy saving in air cooling and heating processes
- Aligned with BTO goal to reduce the GHG emissions (direct and indirect).

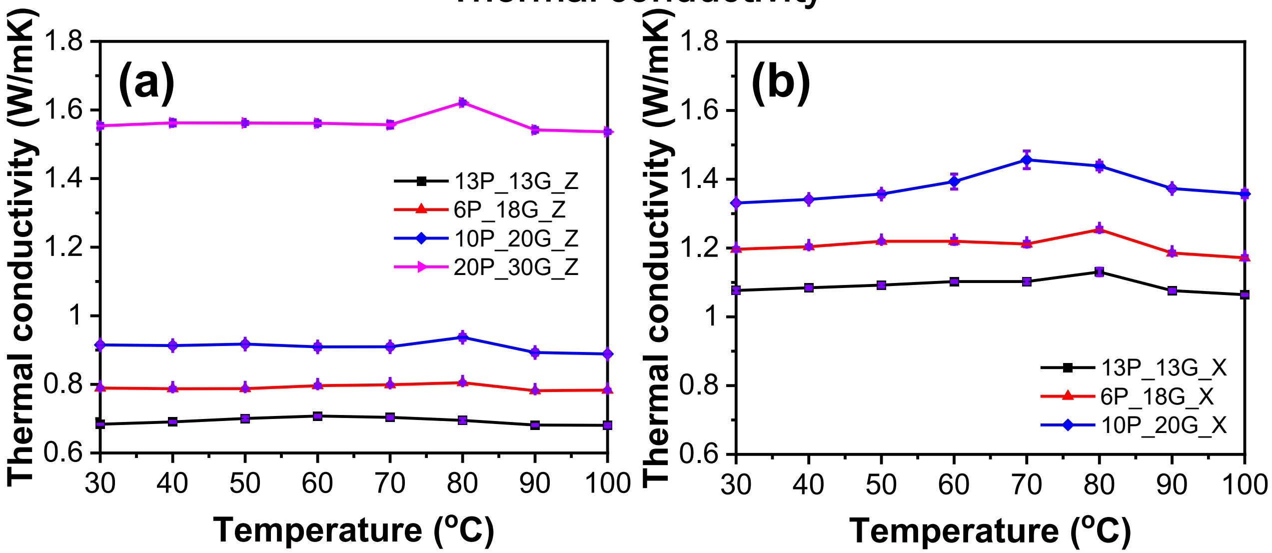
Progress Overview

Transient plane source (TPS) technique (Hot Disk technique)





Thermal conductivity



Formulations	Pitch fiber (%)	Graphite (%)	PETG (%)
6P_18G[a]	6	18	76
10P_20G	10	20	70
13P_13G	13	14	73
20P_30G	20	30	50

Push Plastic

MITSUBISHI CHEMICAL

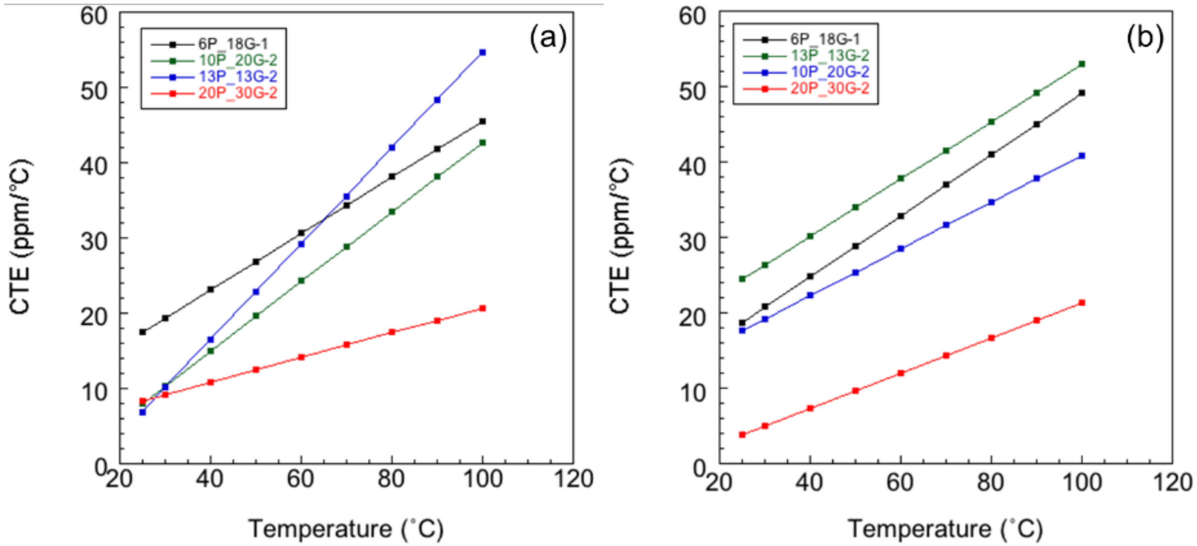
Mitsubishi Chemical America

Progress Overview

Thermomechanical analyzer (TMA)

19.2 mm × 5.6 mm × 3.5mm

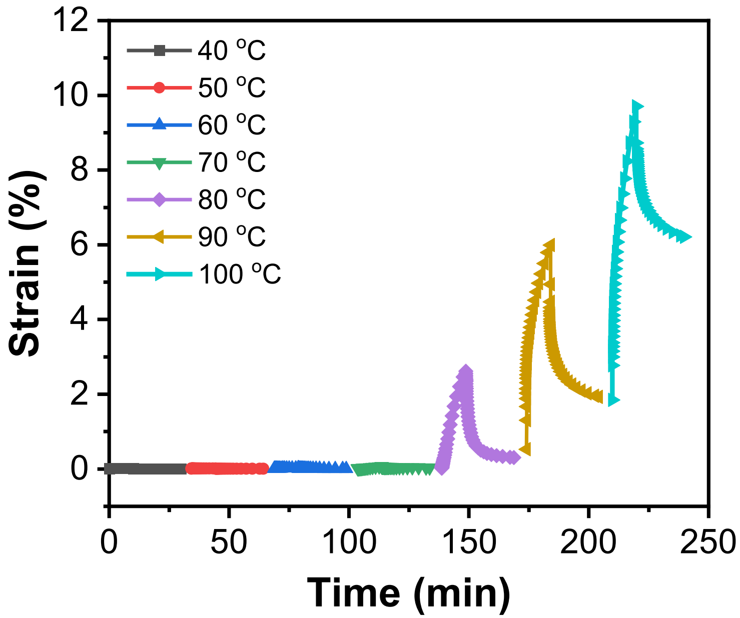
Coefficient of Thermal Expansion (CTE)

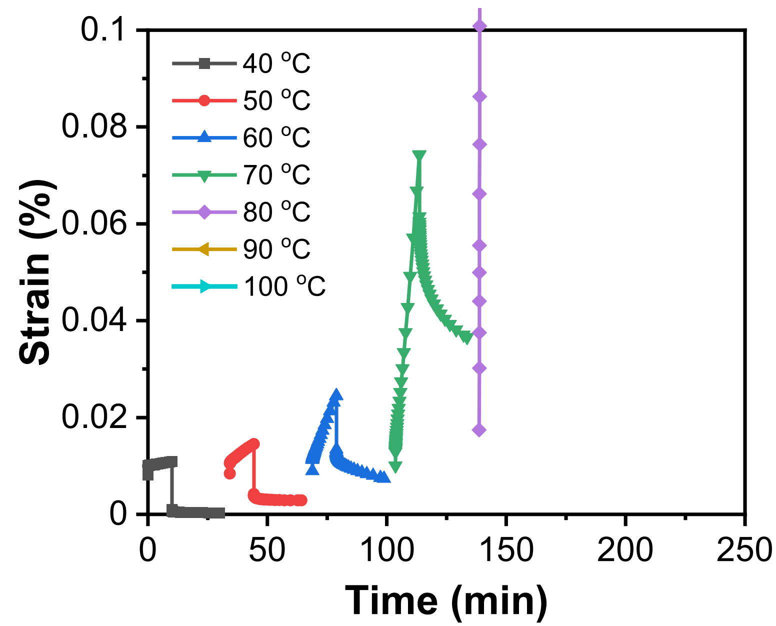


- CTE of printed part increase with the temperature linearly during heating and cooling
- 20P_30G has lower CTE among the samples tested
- At 100 °C, the CTE is 20.7 ppm/°C, suggesting the printed part has a good thermal stability

Progress Overview

Creep test



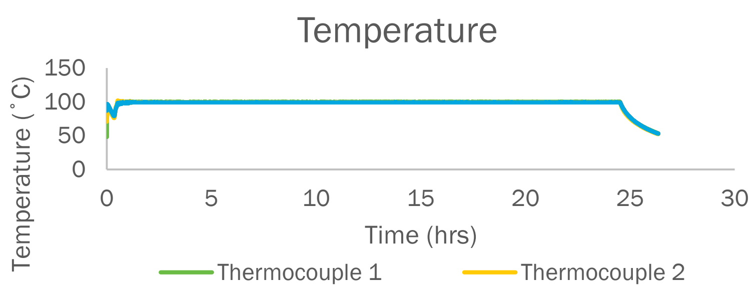


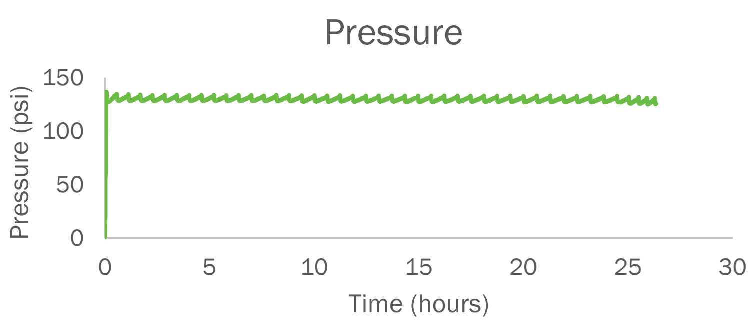
- The creep behavior of exhibited a strong temperature dependence due to the glass transition (ca. 70 °C)
- At low temperatures (40-70 °C), the material exhibited low and almost a constant creep strain value of 0.08% due to the restricted mobility of the polymer chain
- At high temperature (>70 °C), creep strain increased

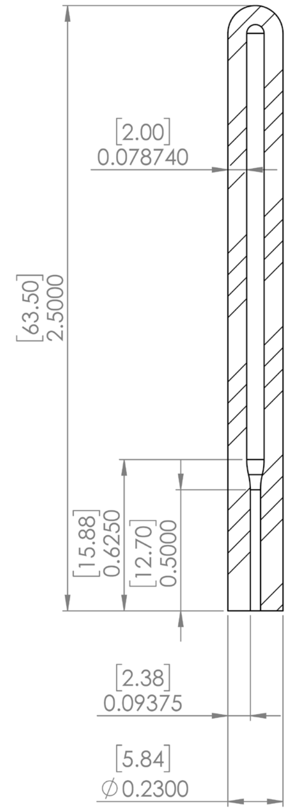
Progress Overview

Pressure and temperature testing

- Polymer tubes printed to test strength of printed parts at elevated pressures and temperatures
  - Wall thickness varied from 0.5 mm to 2.0 mm
- Tube dimensions measured in 5 locations to compare deformation before and after testing



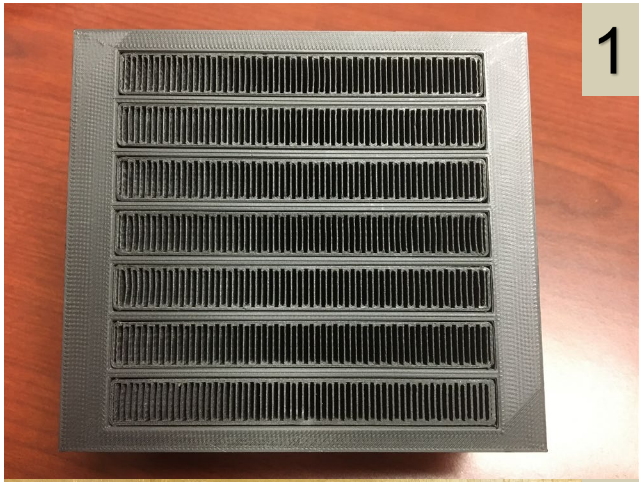




Progress Overview

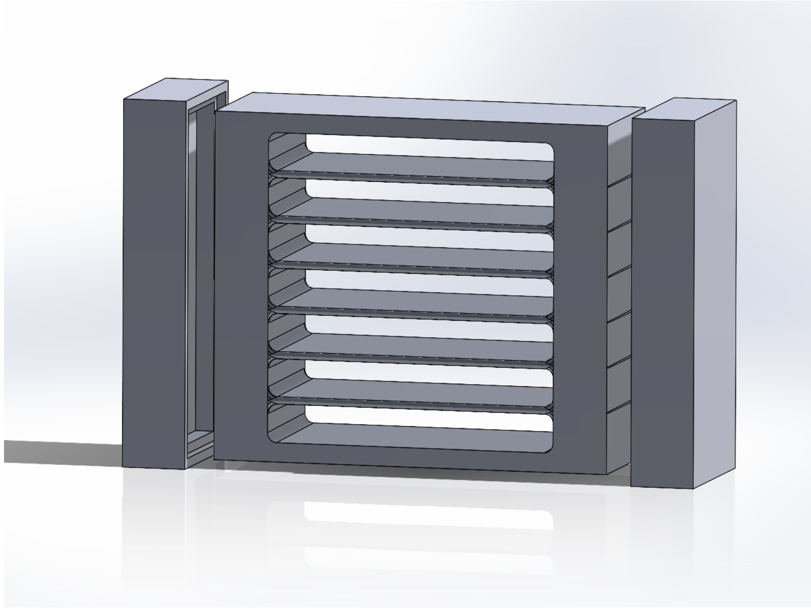
Manufacturing Process

- A variety of methods have been employed to create a polymer heat exchanger:
  - One-piece build
  - Multi-component designs:
    - Body with fluid passages and cartridge-style fin inserts (1)
    - Manifolds, fins, and tubes printed separately and combined with epoxy (2)
    - Variations on these two designs
- Difficulties in leak-proofing
  - High thermal conductivity produces stresses in parts while printing due to thermal stress (rapid heating and cooling). This causes splits between layers.
  - Nozzle start and stop locations also create possible leak paths within a layer
  - Post-process sealing may help

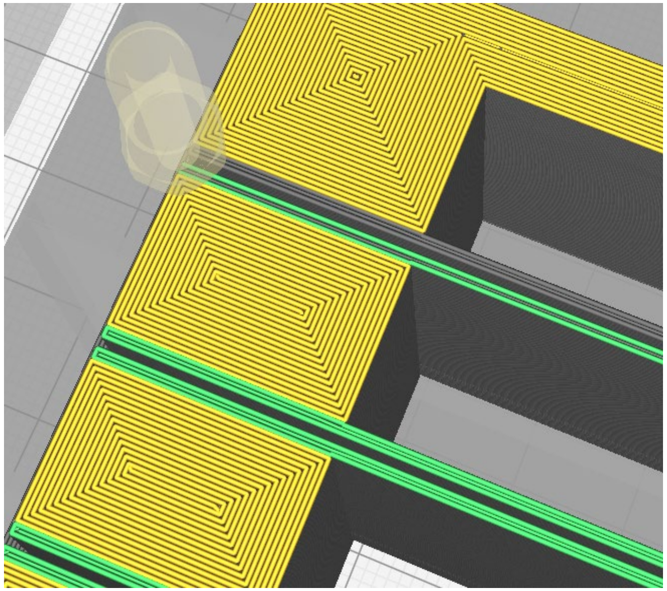


Progress Overview

Manufacturing Process



- Smooth transitions, no sharp corners near fluid passages
- Printing in heated build chamber to reduce thermal stresses



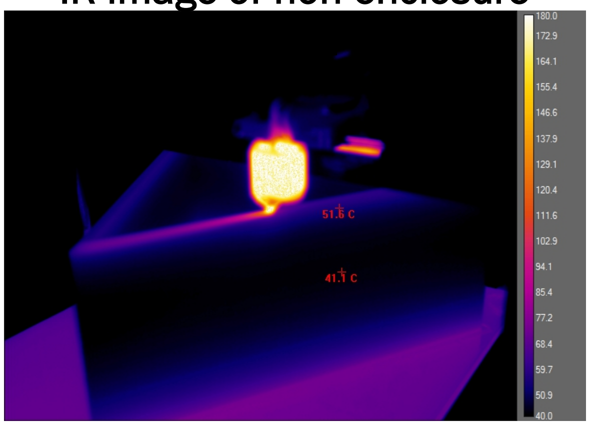
- Print fluid passages in a separate tool path from other structures in a layer
- Post-printing annealing to reduce thermal stresses

Progress Overview

Manufacturing Process

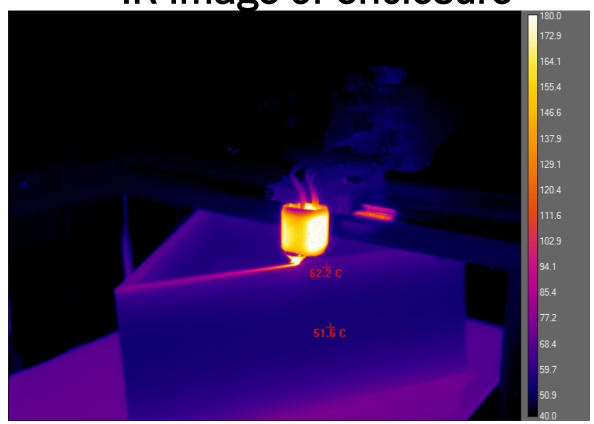
- IR images around the half the print height (~2.75in). Temperature gradients show a significant increase in temperature of the part as the print leaves the influence of the bed temperature.
- Signiant impact on the materials properties

IR image of non-enclosure



Modulus of Elasticity [MPa]	
X-Dir	69
Z-Dir	30

IR image of enclosure



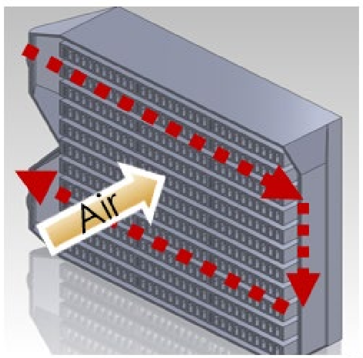
Modulus of Elasticity [MPa]	
X-Dir	224
Z-Dir	101

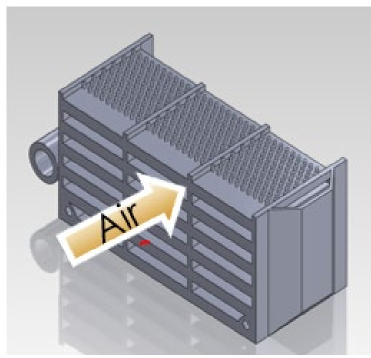
ASTM D638 Type 4

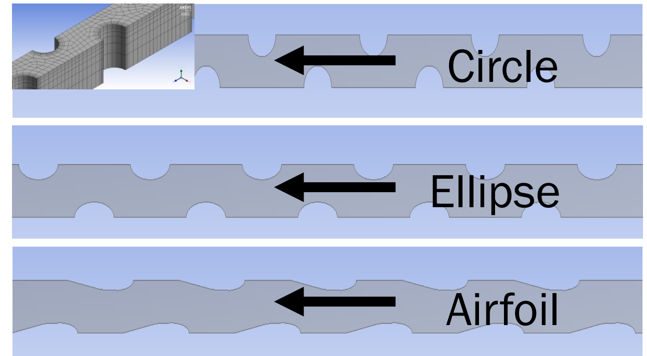
Progress Overview

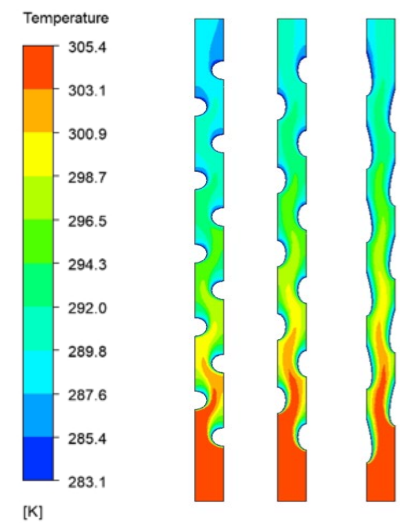
Design Analysis

- 3 different profiles: circle, ellipse, and NACA0020 airfoil
- The same cross-sectional area
- Same amount of material



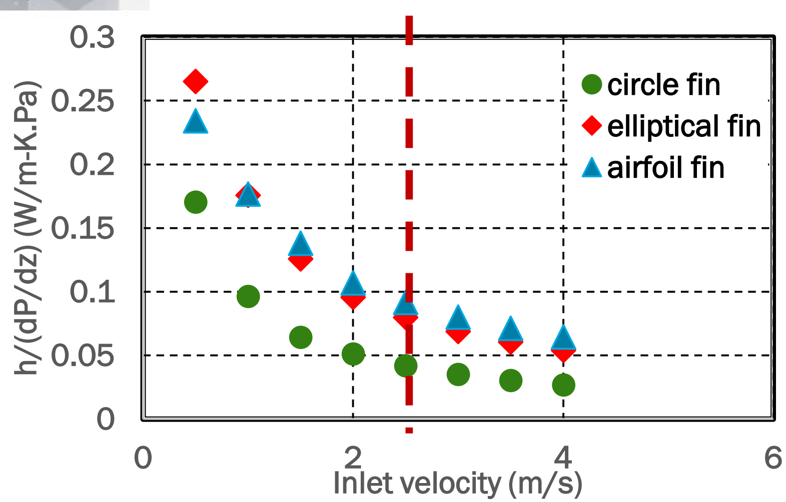






Boundary conditions:

- Inlet velocity: 0.5 – 4 m/s,
- Inlet temp: 90 F
- Wall temp: 50 F



Stakeholder Engagement

- **Industrial participation**
  - Requirement based system specifications
  - Important design constraints
  - Refrigerants replacement
  - Manufacturing process for large scale
- **Meetings with experts at technical platform**
  - ASHRAE (TC 8.5, TC 1.3)
  - Purdue conference
- **Presentations/Conference papers**
  - Review article based on state-of-the-art technology
  - Articles on design, material and manufacturing aspects
- **Advertisement at HVAC&R consortium**
  - ACRC (University of Illinois)
  - CEEE (University of Maryland)
  - Oklahoma State University

Thank you

Oak Ridge National Laboratory
Kashif Nawaz
(Group Leader- Multifunctional Equipment Integration)
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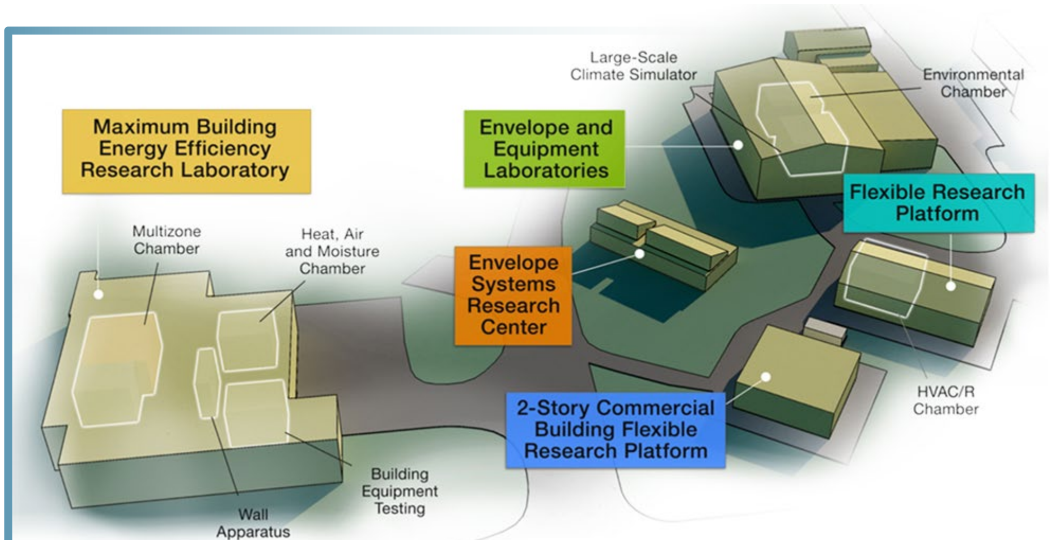

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 50,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

238 publications in FY20
125 industry partners
27 university partners
10 R&D 100 awards
42 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Budget

Project Budget: $1.35M, $150K cost-share
Variances: None
Cost to Date: $47K
Additional Funding: None

Budget History					
FY 2019- FY 2020 (past)		FY 2021 (current)		FY 2022	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$900K	$100K	$450K	$50K		

Project Plan and Schedule

Project Schedule		
Project Start: 10-01-2018		Completed Work
Projected End: 09-30-2021		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned)
		Milestone/Deliverable (Actual)

	FY2019				FY2020				FY2021			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Review of state of the art												
CFD Simulations												
Topology optimization												
Material selection and characteriztaion												
Manufacturing process optimization												
Techno-economic analysis												
Demonstration and Evaluation												
Field validation												