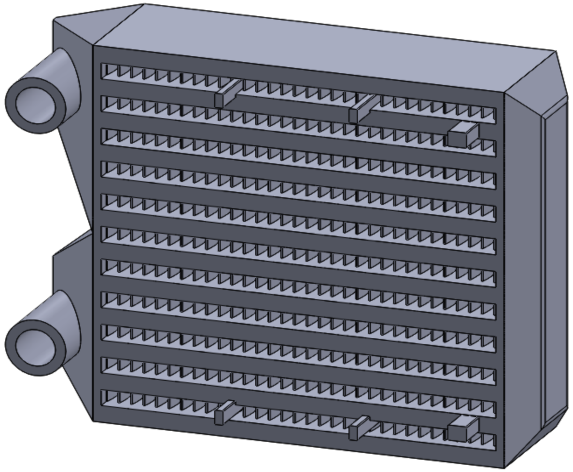
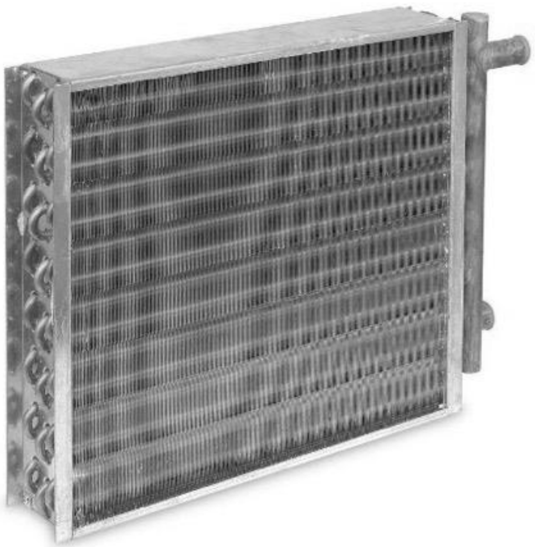
Low Cost, High Performance Polymer Composite Heat Exchangers Manufactured by Additive Manufacturing





Oak Ridge National Laboratory
Kashif Nawaz
865-241-0972

Project Summary

Timeline:

Start date: October 01, 2018

Planned end date: September 30, 2021

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:

Total Project $ to Date:

- DOE: $450,000
- Cost Share: $50,000

Total Project $:

- DOE: $1,350,000
- Cost Share: $150,000

Key Partners:

OAK RIDGE National Laboratory

Johnson Controls

TCPOLY

UNIVERSITY OF MARYLAND 18 56

Project Outcome:

Next generation heat exchanger for air-to-refrigerant heat transfer applications with

- Development of cost effective manufacturing process
- Deployment of corrosion resistant materials
- Improved condensate drainage
- Two time compact design due to
  - higher heat transfer coefficient
  - Improved thermal conductivity

Project Team

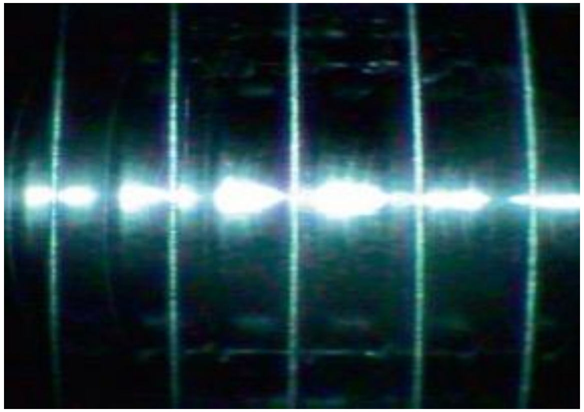
- Oak Ridge National Laboratory
  - Kashif Nawaz (R&D staff)
  - Brian Fricke (R&D staff)
  - Ayyoub Momen (R&D staff)
  - Vlastimil Kunc(R&D staff)
  - Edgar Lara-Curzio (R&D staff)
  - Matthew Sandlin (Post-doc associate)

- University of Oklahoma
  - M. Cengiz Altan (Professor)

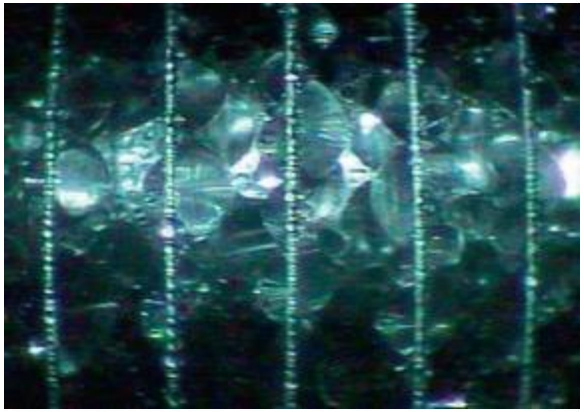
- Johnson Controls Inc.
  - Roy Crawford (Director Advanced R&D)
- TC Poly (A small business)
  - Matthew Smith (Research Director)

Background

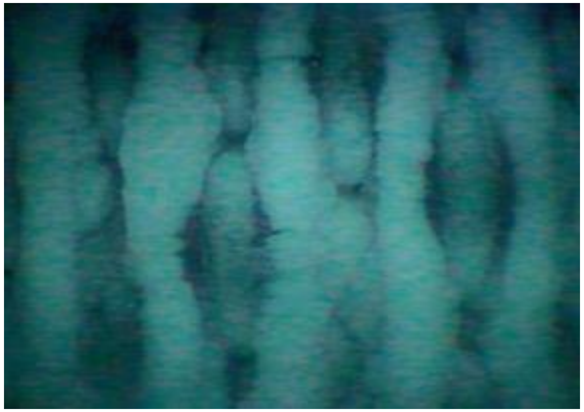
- Air-to-refrigerant heat exchanger are essential component of any heating, cooling and dehumidifying application.
- Heat exchangers account for more than **50%** of the energy consumption in a typical HVAC&R system.
- Operating conditions can significantly impact the performance of heat exchanger.



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.

Background

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.

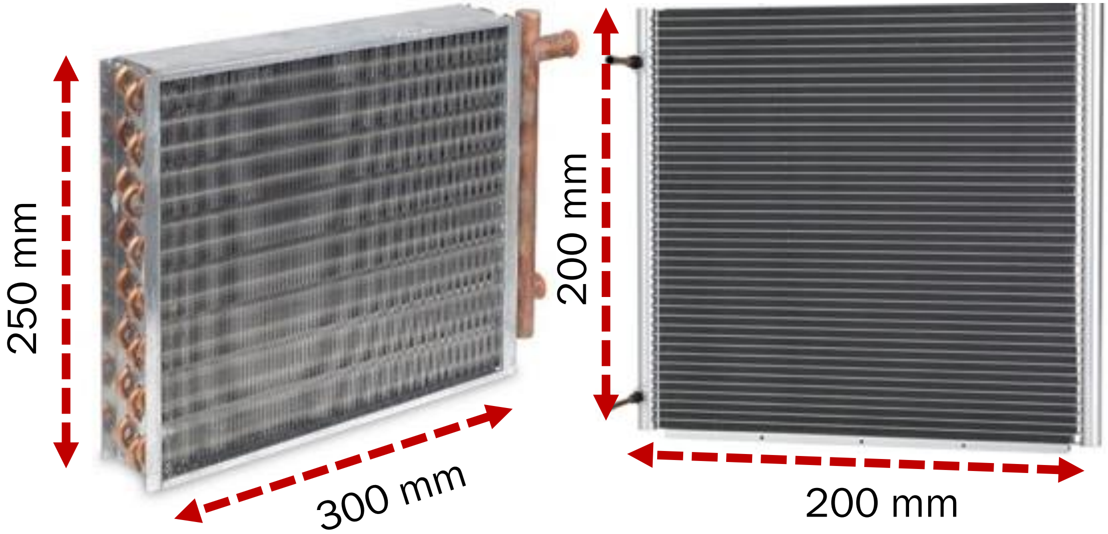
Louver fin

Wavy fin

Staggered fin

Plain fin

Capacity= 5 kW



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

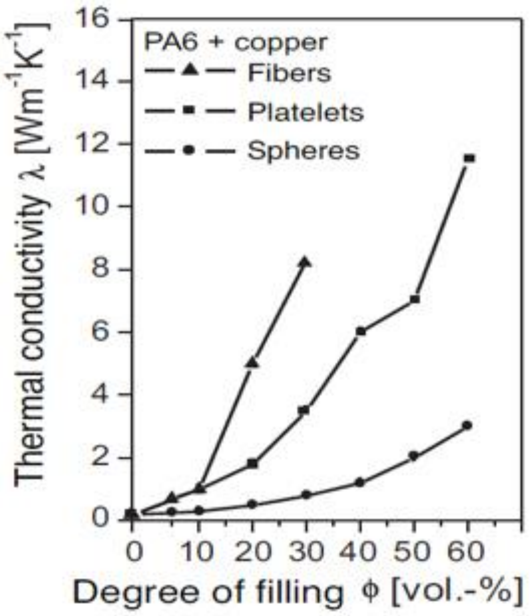
Coil weight= 1.2 kg
Pressure drop= 2.5 bars
Thickness= 18 mm
Manf Cost=~$40

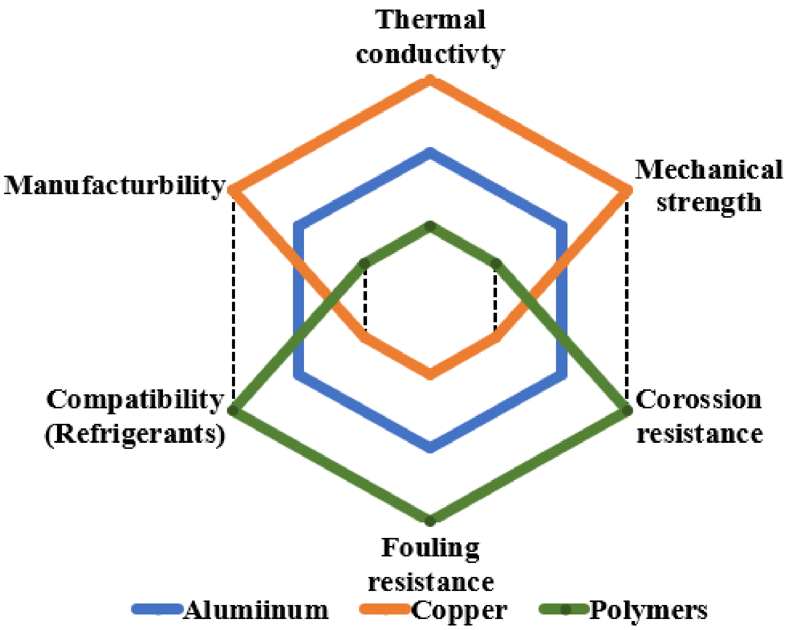
https://www.cantas.com/urunpdf/sanhua_microchannel_cat.pdf

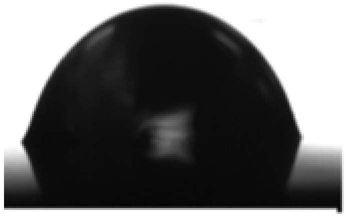
Solution Approach

What about polymer heat exchangers??

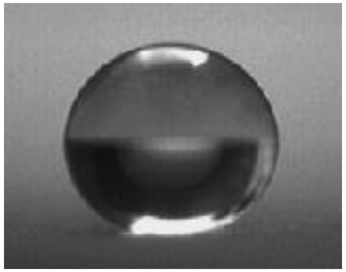
- Low thermal conductivity → Hybrid materials (composites)
- Failure at high operating pressure → Hybrid materials (composites)
- Compatibility with working fluids → Appropriate treatment
- Manufacturability → Advanced manufacturing
- Condensate drainage/self cleaning → 3x better





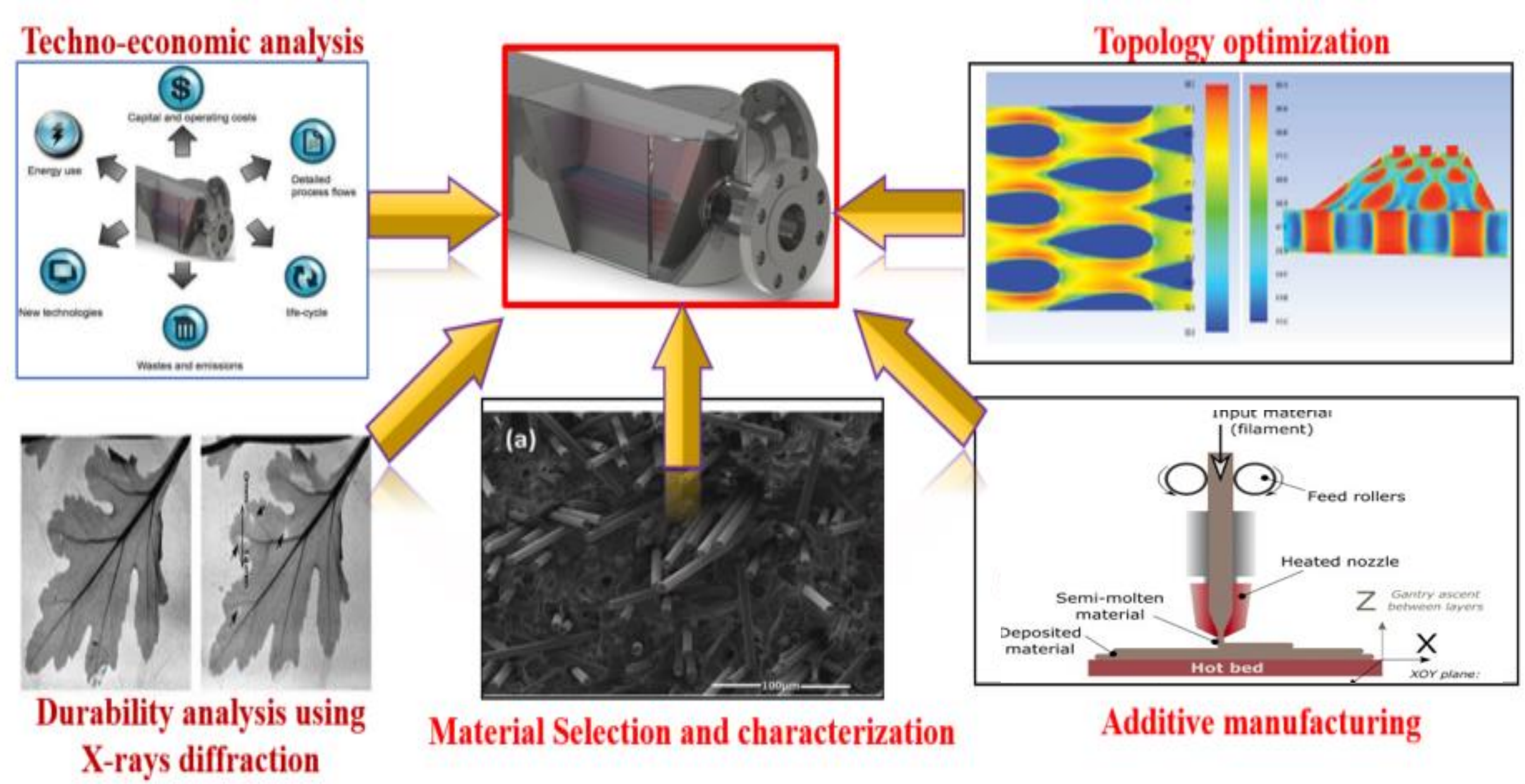


Bare aluminum surface



Teflon surface

Solution Approach

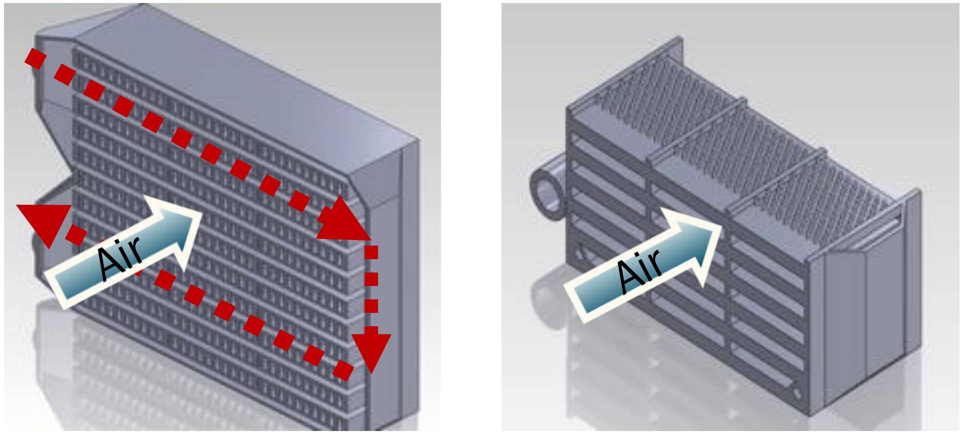


Impact

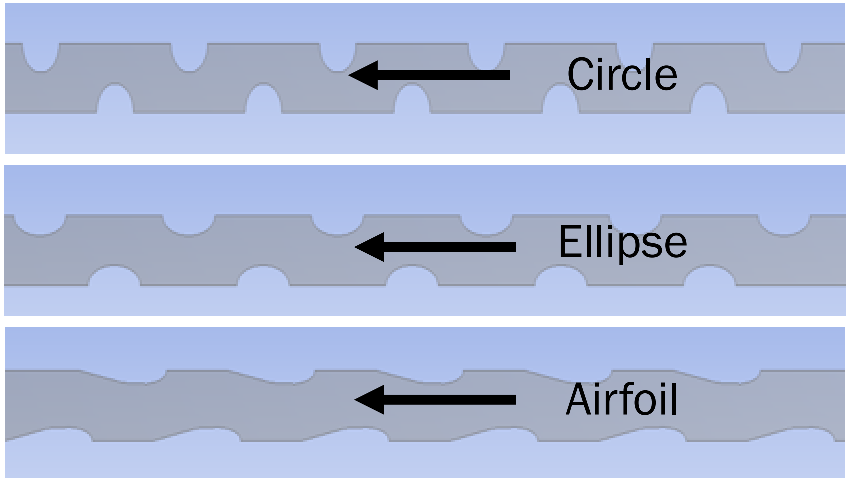
- **Development of next generation heat exchanger with**
  - Unprecedented thermal-hydraulic performance
  - 50% reduction in manufacturing cost
  - Expanded operational life
  - 3-4 times more compact compared to state of the art
- **Enabling development for deployment of A2L and A3 refrigerants**
  - Reduction in refrigerant charge
  - 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 develop energy efficient technology to cause 45% energy saving by 2030 compared to 2010 technologies.
  - Opportunities to create more than 5000 new jobs
  - Paving the path for US manufacturer to expand to international markets

Progress - Numerical Analysis

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

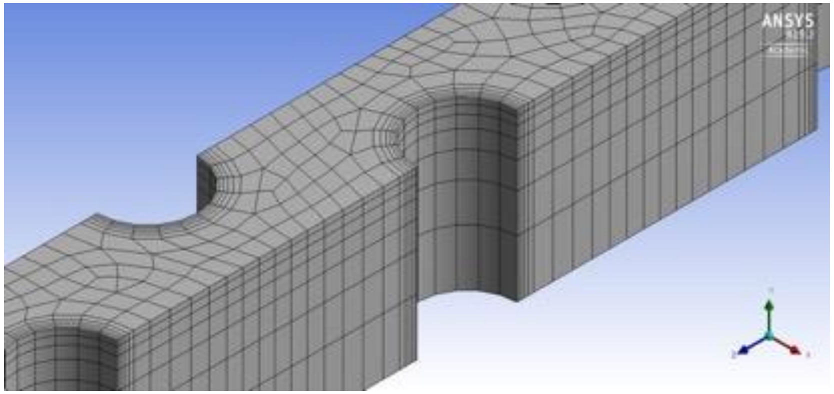


Fluid flow configuration



Different fin profiles considered in the study

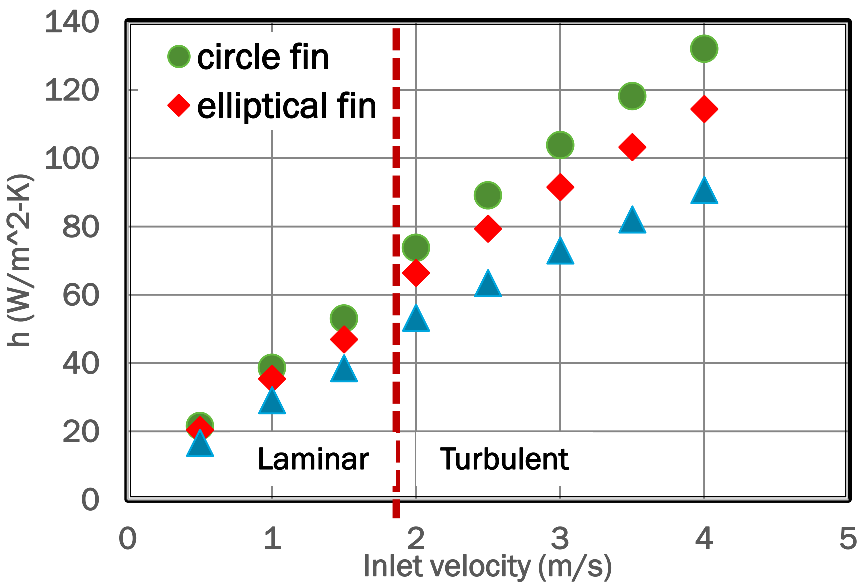
Mesh detail showing inflation layers around fins. Final element count ~30000 elements

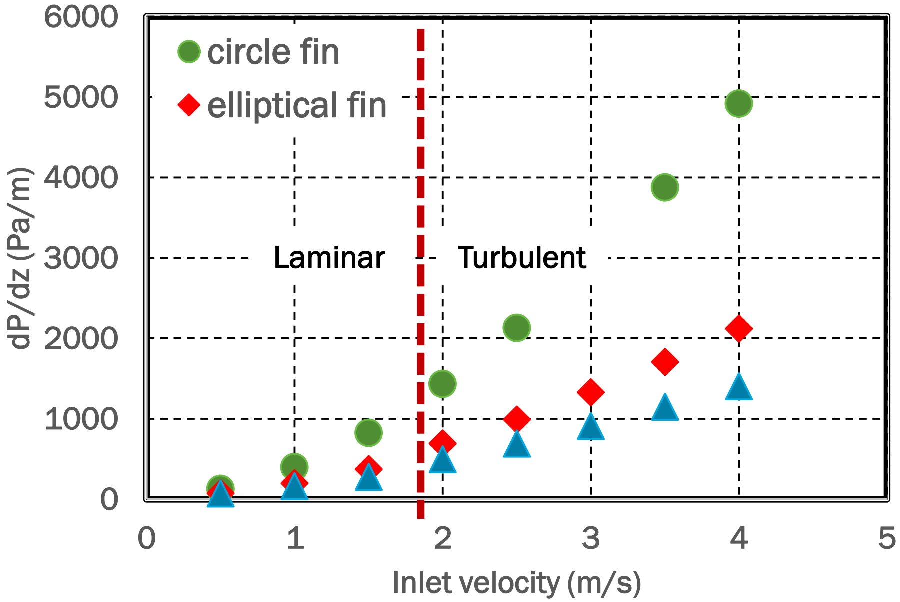


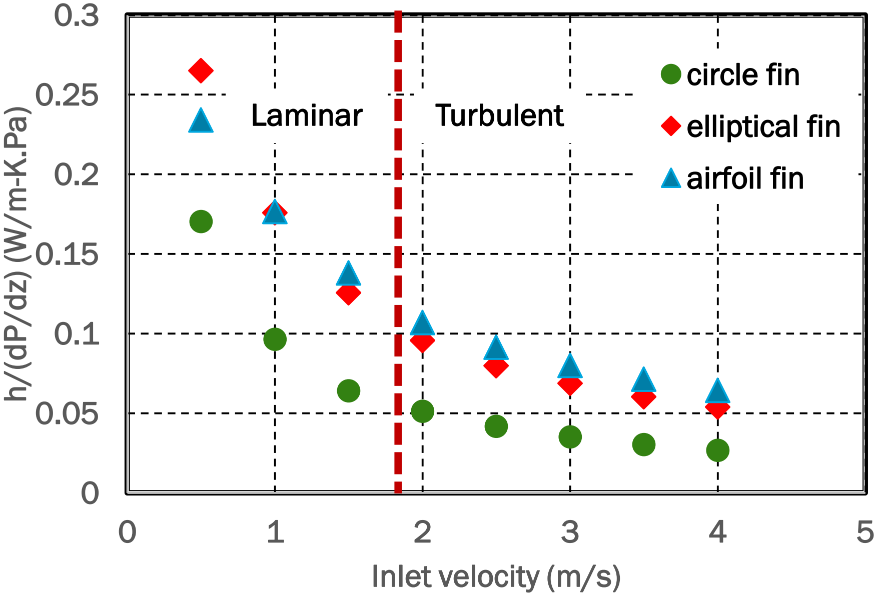
Boundary conditions:

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

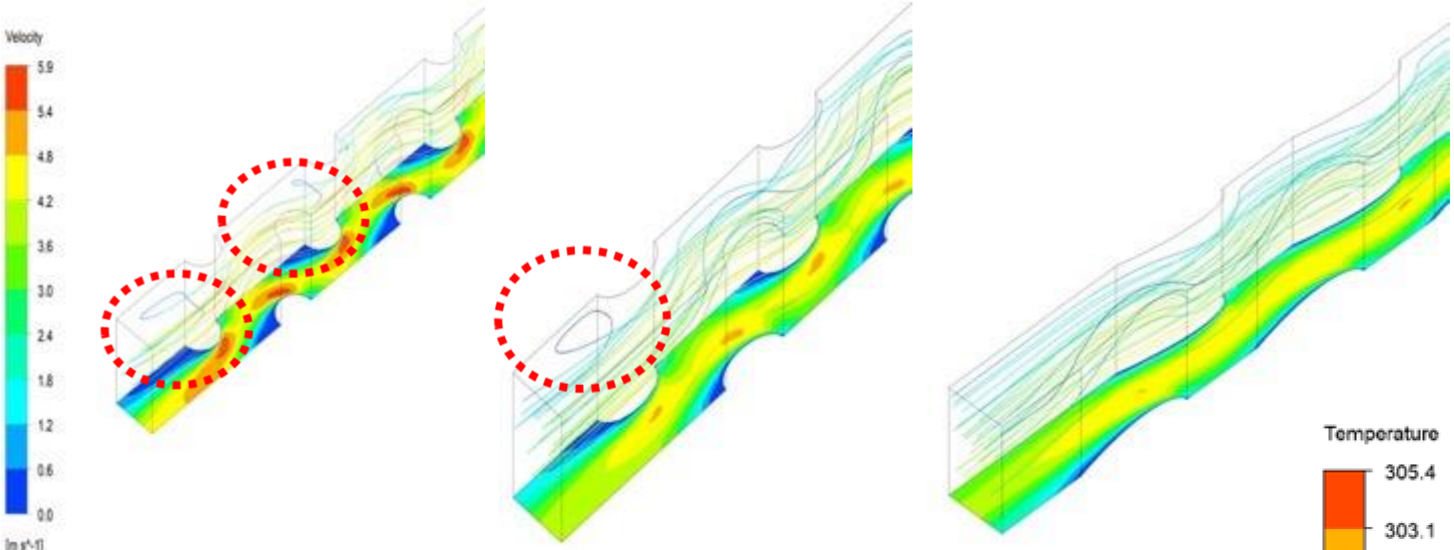
Progress - Numerical Analysis







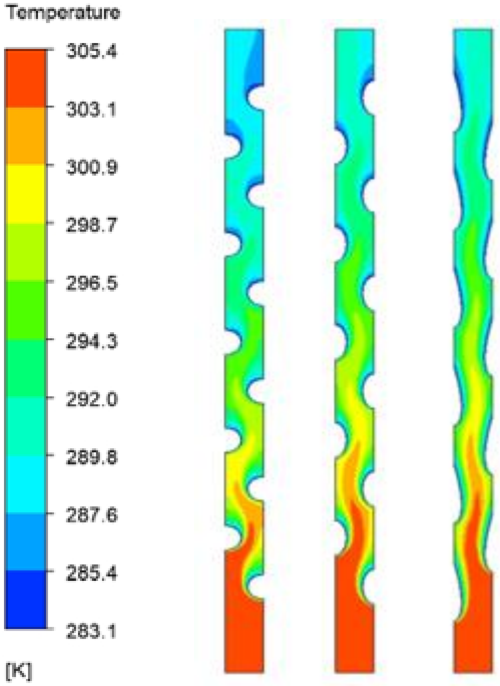
Progress - Numerical Analysis



Circular fin

Elliptical fin

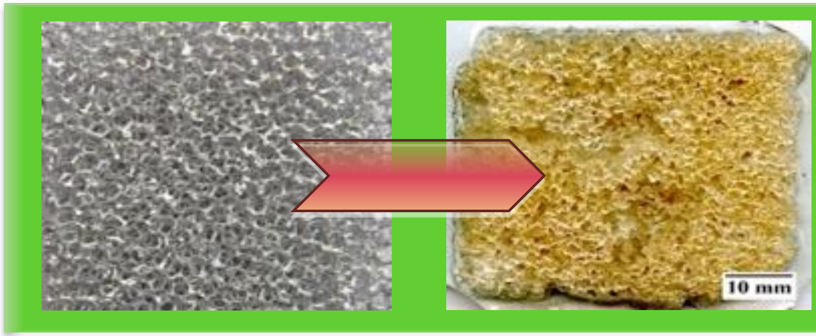
Airfoil fin



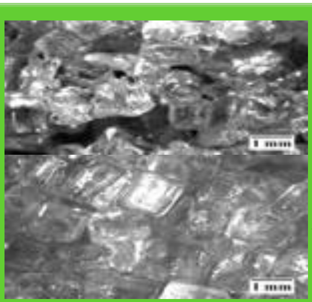
- Recirculation can impact the mixing and hence the heat transfer coefficient.
- The implication is obvious from the temperature contours for three fin profiles.

Progress - Manufacturing Process

Molding using Sugar Template



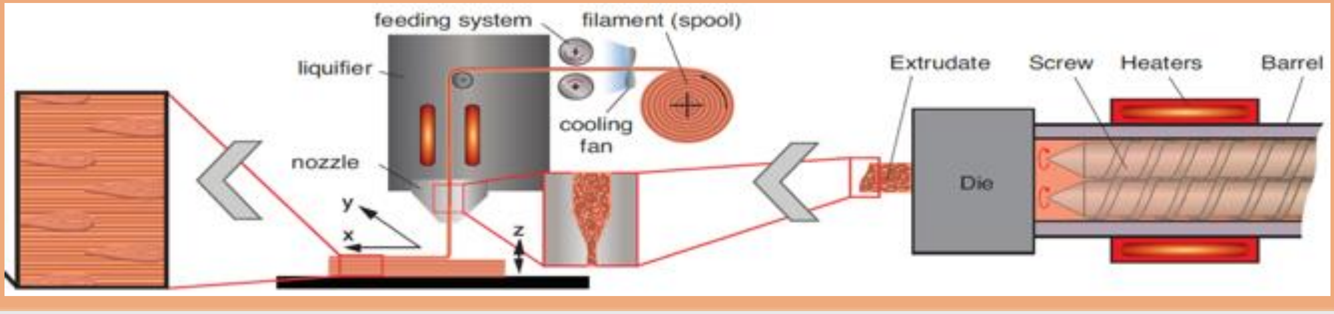

Sugar Template

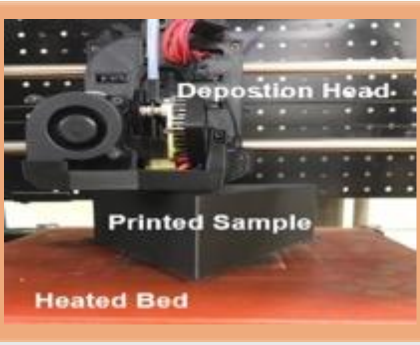


Sugar Template-Top Surface

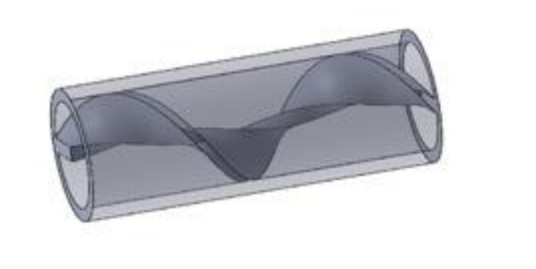
Sugar Template-Bottom Surface

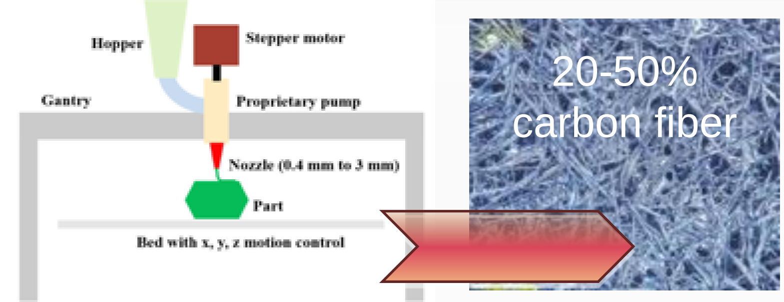
Fused Filament Process





Gel-Slurry Process





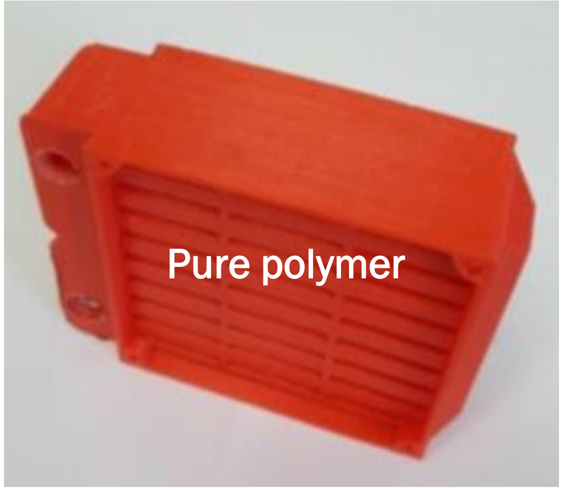
20-50% carbon fiber

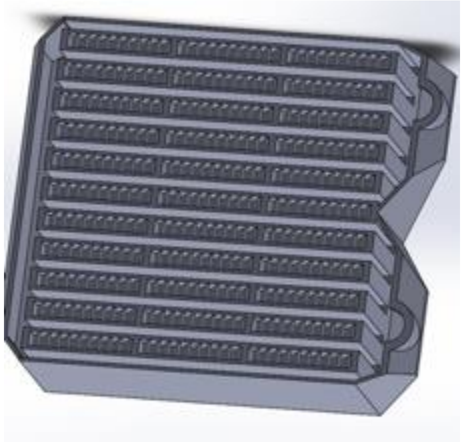

Parts to be infiltrated

Progress - Manufacturing Process

Thermal conductivity

Flexibility




Cross-sectional view

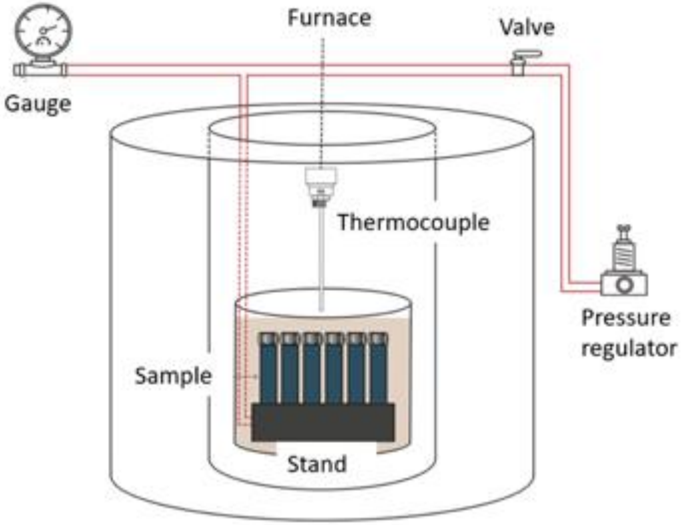
Progress - Materials Development, Characterization

Mechanical Fatigue Test

- Cylindrical test specimens
- Pressurized up to 160 psi
- Isothermal conditions (0ºC, 50ºC, 100ºC)

Thermal Fatigue Test

- Thermal cycling (-60ºC and 100ºC)
- Samples pressurized up to 160 psi.

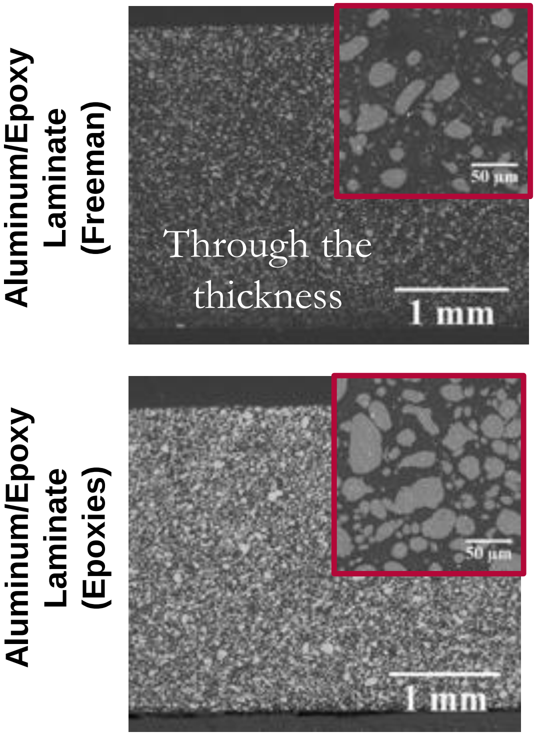


Schematic of thermal and fatigue tester

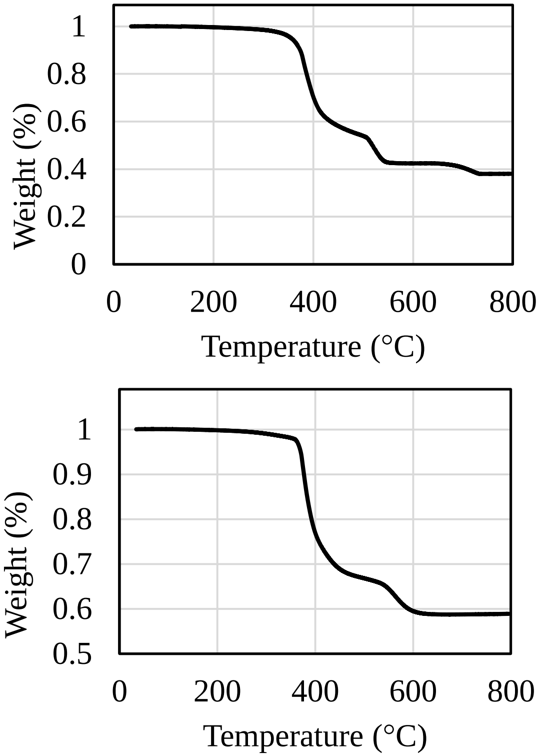
Tube samples placement for thermal and mechanical fatigue tests

Samples placed in psychrometric chamber

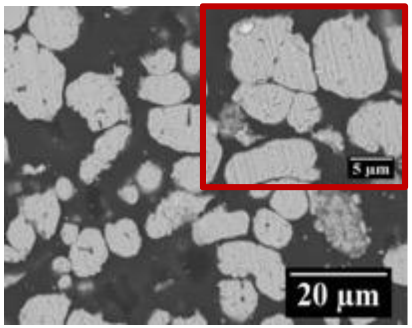
Progress - Materials Development, Characterization



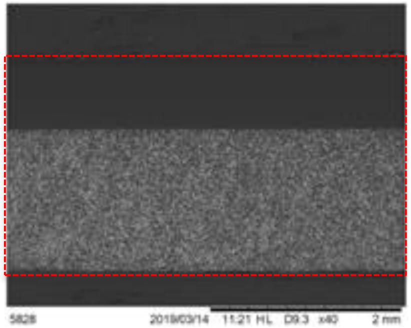
SEM images for the polymer composites



Particle weight fraction test



Copper/Epoxy Laminate
(in house preparation)

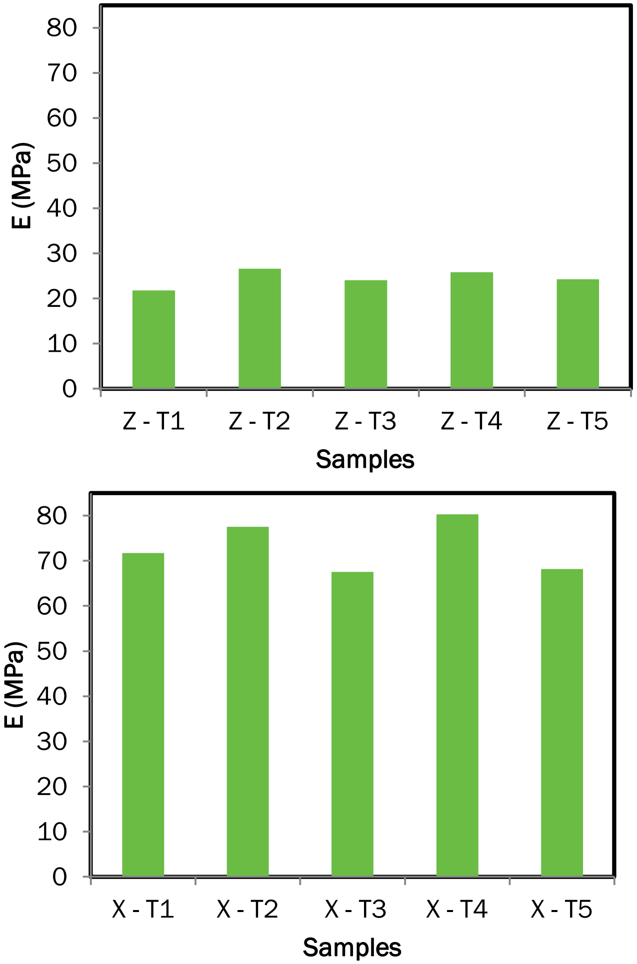


Sedimentation cause a non-uniform particle distribution

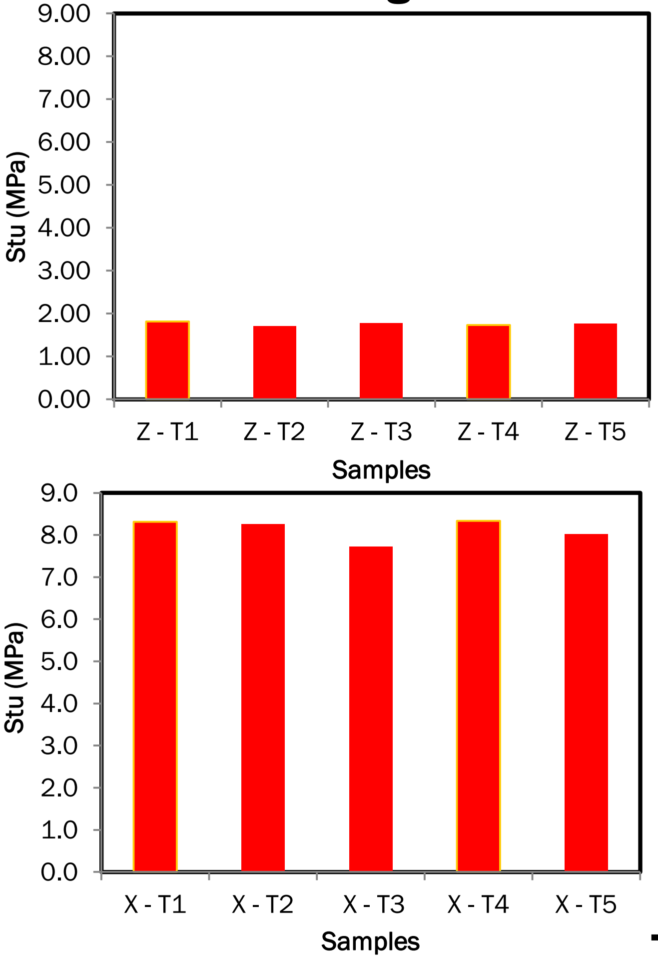
Sample	Thickness (mm)	Laminate density (g/cm^3)	Particle weigh/volume fraction (%)	Tg by tan delta (°C)
Sample 1	2.40 ± 0.18	1.495 ± 0.014	38/21	72.3
Sample 2	2.53 ± 0.08	1.710 ± 0.001	59/37.4	63.2

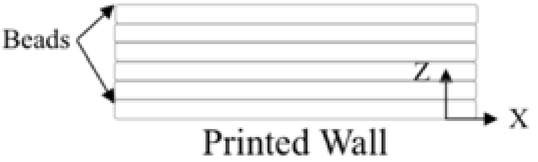
Progress - Materials Development, Characterization

Modulus



Strength





- Anisotropic nature of the material impact
  - Thermal characteristics
  - Mechanical characteristics

Thermal conductivity

K_x= 2.075 W/mK

K_z= 1.913 W/mK

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

Remaining Project Work

- **Review of existing state of the art**
  - Heat Exchanger Design
  - Materials and processes
- **Computational Fluid Dynamics modeling**
  - Model development
  - Validation and optimization
- **Materials and Manufacturing Processes**
  - Characterization of materials and appropriate manufacturing
  - Scale up analysis and durability
- **Pre-commercialization**
  - Lab scale evaluation
  - Field evaluation
  - Comparison to other technologies
  - Techno-economic analysis

Thank You

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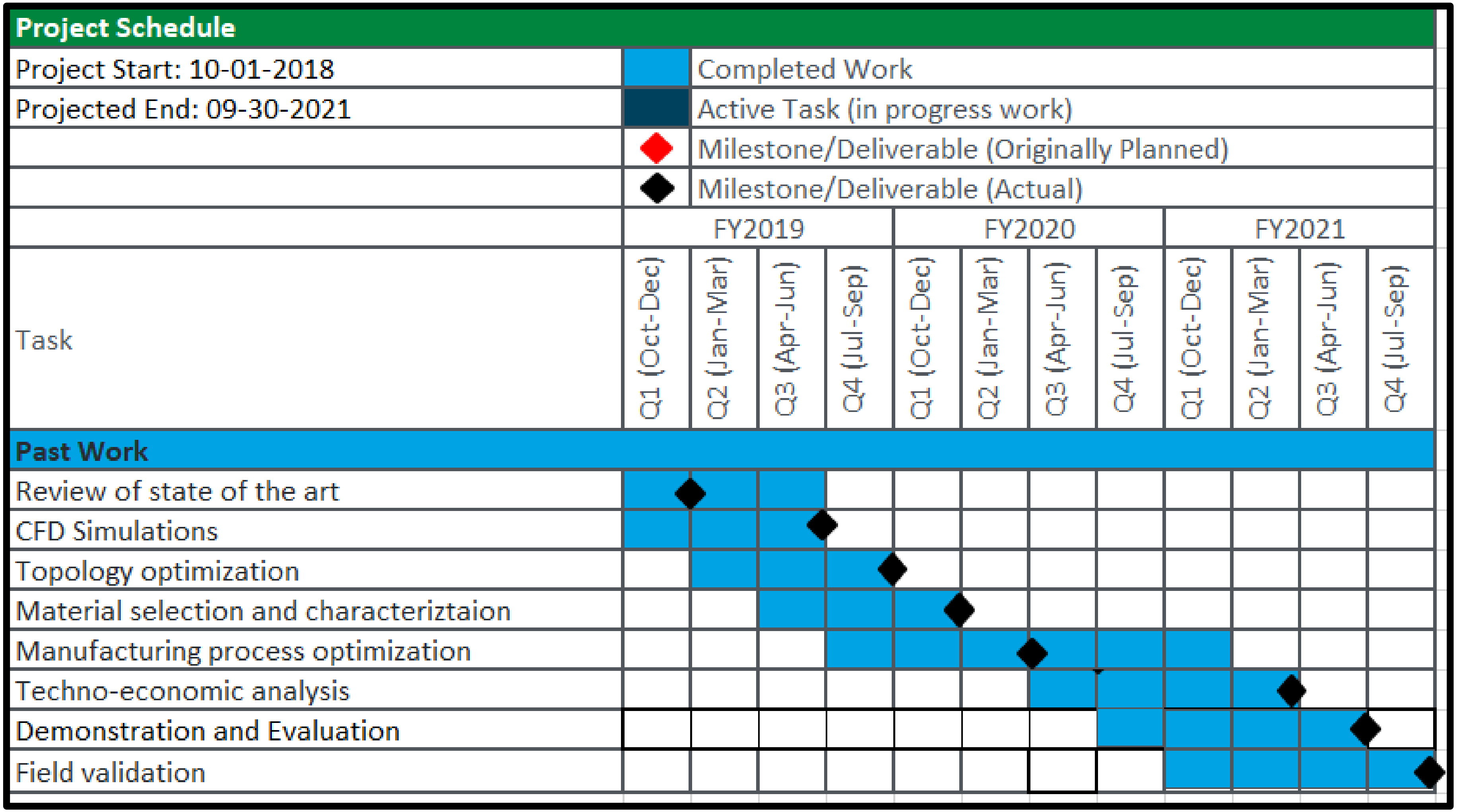
REFERENCE SLIDES

Project Budget

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

Budget History					
FY 2018 (past)		FY 2019 (current)		FY 2020 – (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$451K	$50K	$448K	$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									🟦	🟦	🟦	🟦 ◆