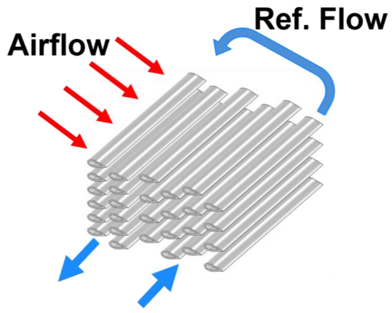
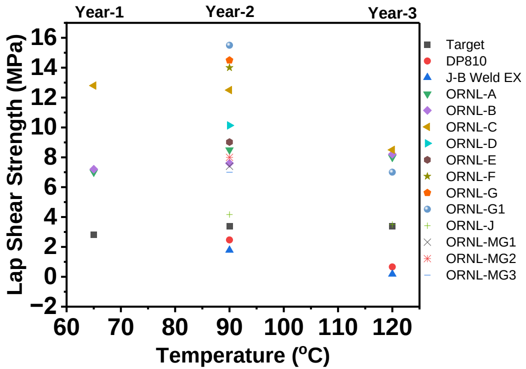
2024 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

Hybrid Manufacturing for High Performance Air-to-Refrigerant Heat Exchangers (DE-EE0009677)



Next Generation Heat Exchangers



High Performance Adhesives

Novel Fabrication Methods

Team:

University of Maryland (Lead), Heat Transfer Technologies, LLC., Oak Ridge National Laboratory

Prof. Reinhard Radermacher (PI), Prof. Vikrant Aute (Co-PI, UMD), Yoram Shabtay (HTT)

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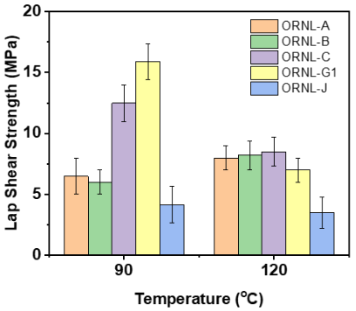
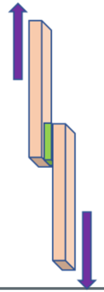
CENTER FOR ENVIRONMENTAL ENERGY ENGINEERING
Heat Transfer Technologies
OAK RIDGE National Laboratory

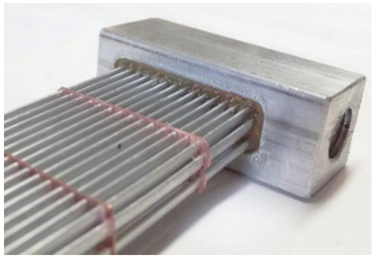
Project Summary

OBJECTIVE, OUTCOME, & IMPACT

- Develop novel air-to-refrigerant variable geometry HXs with higher compactness, improved frost / maldistribution resilience, & lower refrigerant charge
- Develop adhesive-based hybrid manufacturing method for air-to-refrigerant HXs which is >50% cheaper & >36% less energy in manufacturing
- Validation through laboratory and industry partner testing







TEAM & PARTNERS

CENTER FOR ENVIRONMENTAL ENERGY ENGINEERING

Heat Transfer Technologies

OAK RIDGE National Laboratory

STATS

Performance Period: Oct. 2021 – Sept. 2024

DOE budget*: $1400K, Cost Share: $350K

Milestone 1: 1st adhesive; HX design framework + proof-of-concept prototypes

Milestone 2: 2nd adhesive; Lab-scale HXs + testing

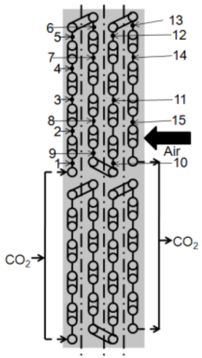
Milestone 3: Final adhesive; System-scale HXs + testing

Industry Partners / Advisors: 3M, Carrier, Daikin Comfort Tech., Honeywell, Small Tube Products

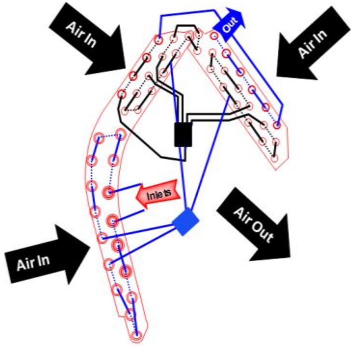
Problem

- **Heat eXchangers (HX) are key components in HVAC&R systems**
  - Contain refrigerant charge; impact system efficiency, cost, installation options
- **Improved HXs can lead to**
  - Lower refrigerant charge
  - Reduced size, weight, and material use
  - Lower energy consumption, emissions, and costs
- **Challenges in bringing new HX technology to market**
  - Novel designs must be at least 20% better
  - Lack of basic heat transfer and flow fundamentals, correlations to assist in modeling and design optimization
  - Field aspects: Flow maldistribution, Frost accumulation, fouling, wetting, noise etc.
  - Component availability
  - Joining/manufacturing techniques
- **Air-side is the dominant resistance**

Approach & Alignment



- **Novel air-to-refrigerant variable geometry heat exchangers (VGHX)**
  - Leverage shape & topology optimization to yield more compact and lighter heat exchangers
  - Contain less refrigerant, facilitate transition to lower-charge systems
  - Are more resilient to frost growth and refrigerant maldistribution
  - Necessary design tools and knowhow for industry (thermohydraulic and flow characteristics)

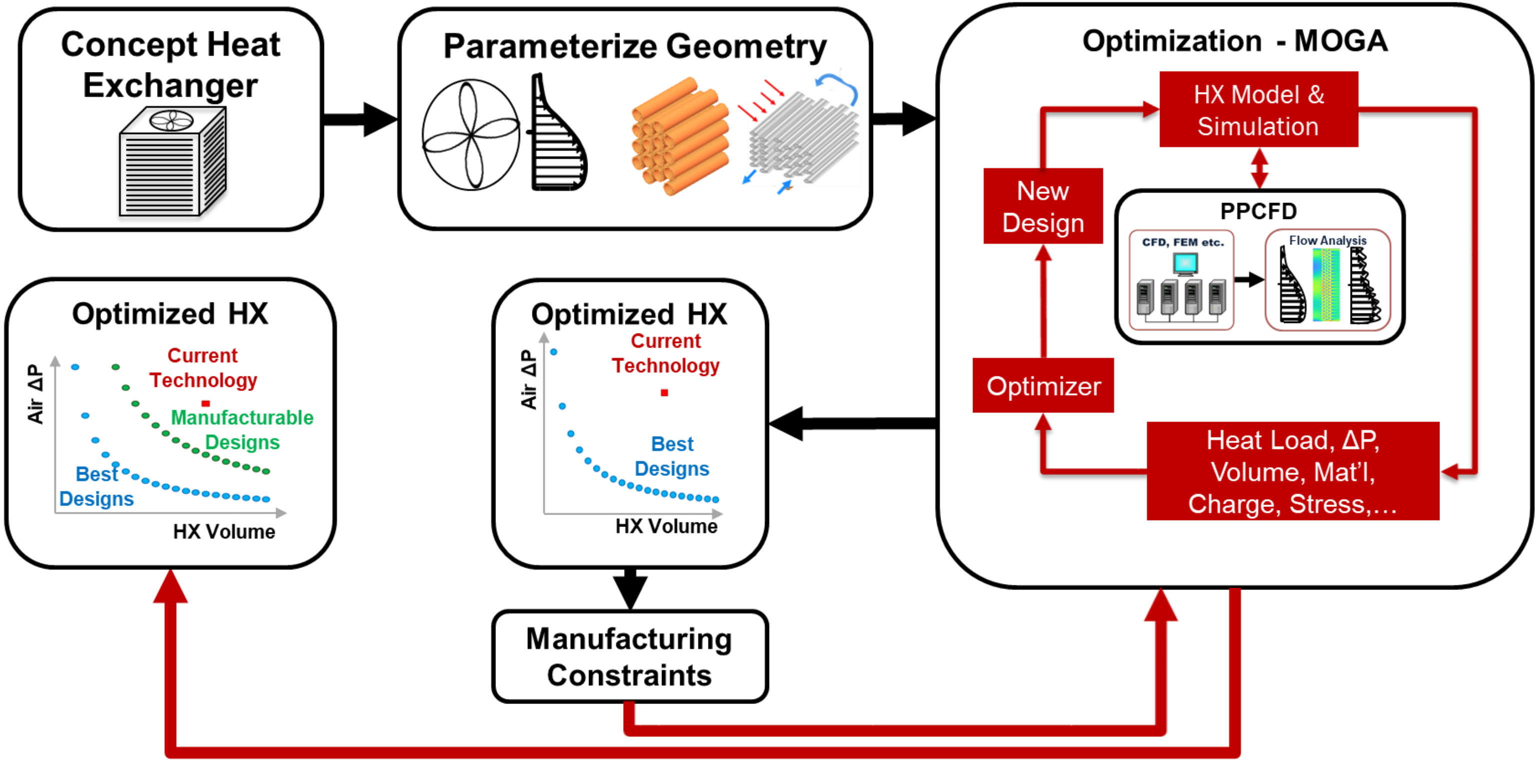


- **Adhesive based hybrid manufacturing method for air-to-refrigerant heat exchangers (HX)**
  - ≥36% less energy in manufacturing; more reliable than existing solder-based methods
  - Strive to be at least 30% lower cost compared to current designs
  - Collaboration with OEMs involved in HX supply chain
- **Conduct frost accumulation tests**
  - Reduce refrigerant maldistribution from frost growth
- **Deliver HX prototypes to partner OEMs for independent performance testing; facilitate T2M**

Target Market & Impact

- **Target Market**
  - Residential and commercial air conditioners and heat pumps
  - New construction and retrofit applications
- **Novel HX designs**
  - 20 to 40% reduction in size and refrigerant charge, demonstrated via lab and independent OEM testing
  - ≥10% longer operation time during frost accumulation conditions
  - ≥20% improvement in uniformity of evaporator mass flow rate
- **New manufacturing method expected to be 30% cheaper and consume 36% less energy than existing solder-based methods**
  - Adhesive based approach has potential to reduce production barriers for next generation HXs
  - Improved reliability over solder-based methods to reduce refrigerant leakage (1.5-2.0% of total emissions)

Approach: Design & Optimization Framework

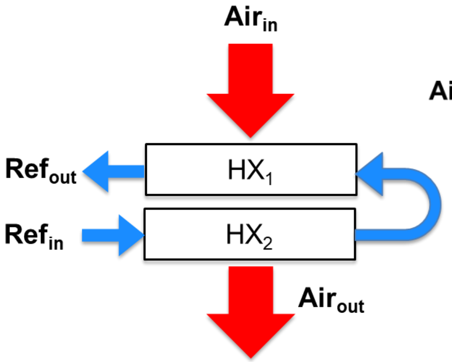


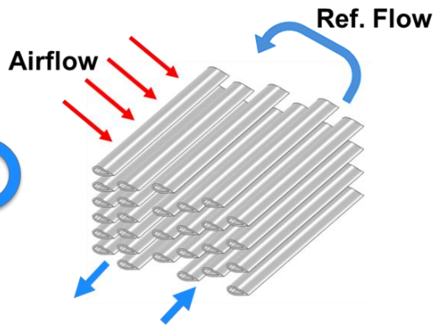
PPCFD = Parallel Parameterized Computational Fluid Dynamics | MOGA = Multi-Objective Genetic Algorithm

ML-based Approximation for thermohydraulic performance;

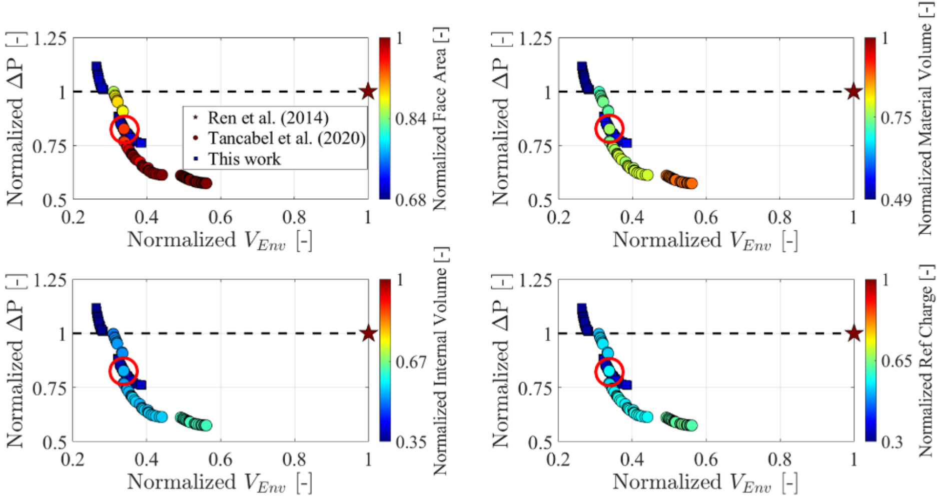
Flow Path Optimization, System Analyses (2 HX), and LCCP Evaluation not shown for brevity

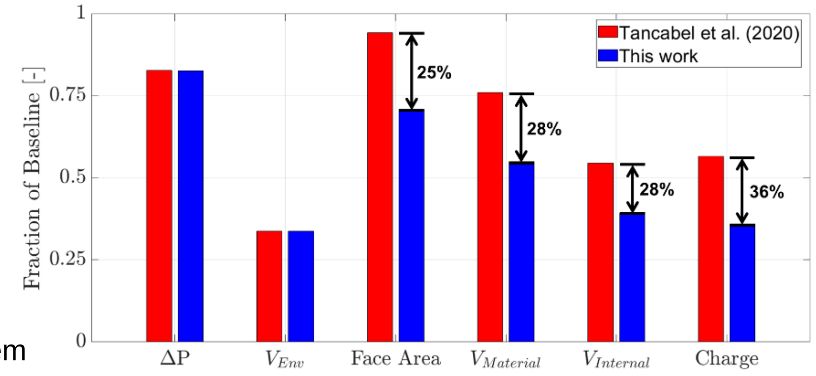
Progress: Air-to-R290 Variable Geometry HXs





HX$_1$ (2nd pass)	HX$_2$ (1st pass)
$\min \Delta P_{air}; \min V_{env}$ $s.t.$ $\Delta T_{SC,BL} - 1\,K \le \Delta T_{SC,HX_1} \le \Delta T_{SC,BL}\ K$ $0.98 \cdot H_{HX_1} \le H_{HX_2} \le 1.02 \cdot H_{HX_1}$ $0.98 \cdot L_{HX_1} \le L_{HX_2} \le 1.02 \cdot L_{HX_1}$	$\min \Delta P_{air}; \min V_{env}$ $s.t.$ $0.50 \cdot Q_{BL} \le Q_{HX_2} \le 0.55 \cdot Q_{BL}$ $0.5 \le \frac{H_{HX_{1,2}}}{L_{HX_{1,2}}} \le 2.0$

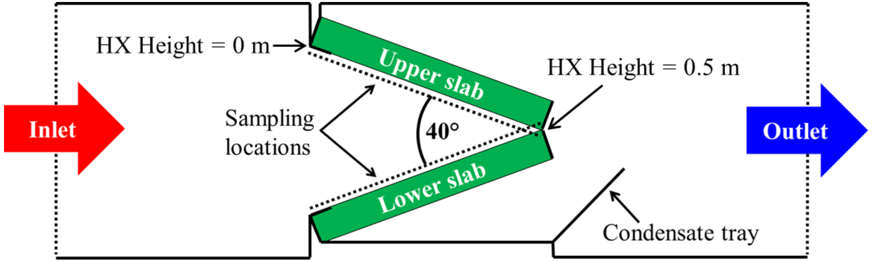


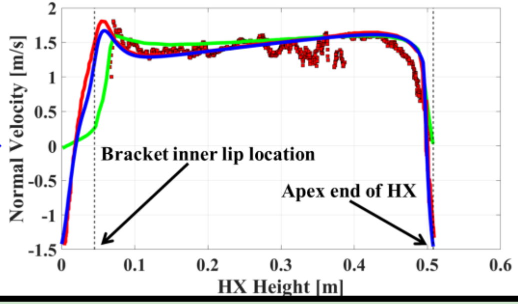


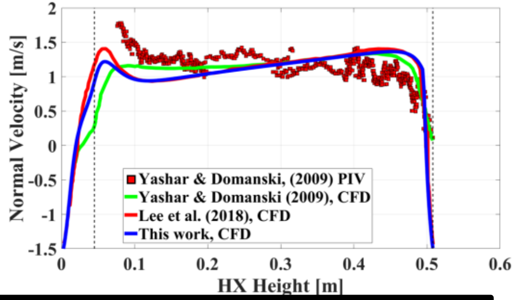
Baseline : 5mm tube-fin condenser, propane AC system

Progress: Flow Profile Prediction Framework

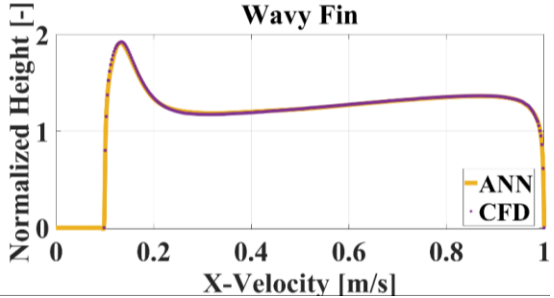
Validated against PIV and verified against CFD (average VFR within 1.1%)

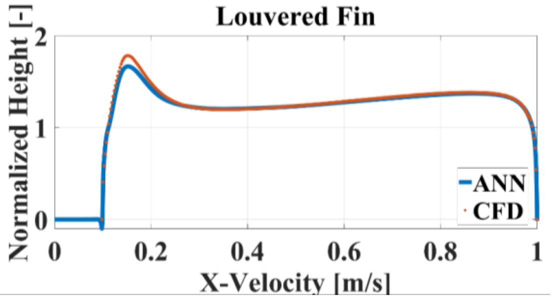


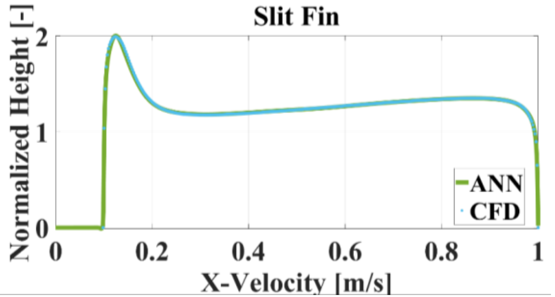




ML model is independent of fin type





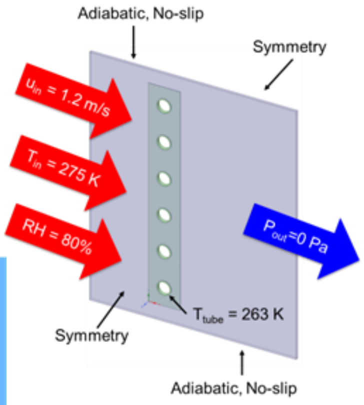


Average prediction time = 3 ms → 2.4x10^5 times faster than CFD

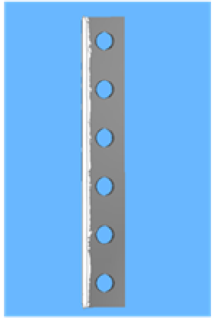
Details: O'Malley et al., 2024 Purdue Conferences, July 2024

Progress: NTHX with Variable Tube-Tube Spacing

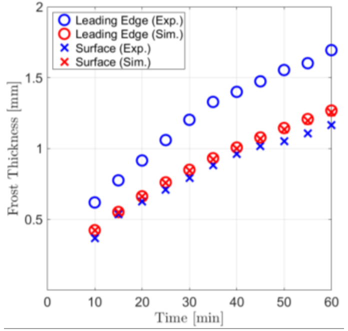
Computational domain



Frost growth

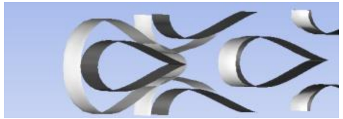


Fin-tube HX validation



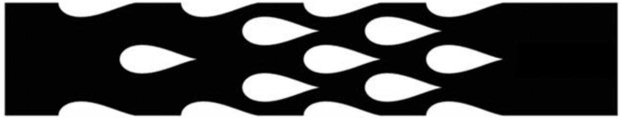
Uniform Spacing

T = 6 minutes



Frost Model

Variable Spacing



T = 21 minutes

	Uniform Spacing	Variable Spacing
Q/V [MW/m³]	2.9	2.4 (↓ 17%)
Time to blockage [min]	6	21 (↑ 320%)

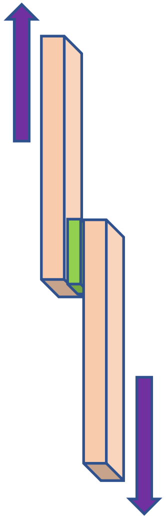
NURBS: Non-Uniform Rational B-Splines; NTHX: NURBS-Tube Heat Exchanger

Approach: HX Manufacturing – State of the Art

- **Metal cast based method**
  - High energy consumption to cast metals
  - Requires corrosive fluxes to clean metals
  - Costly EDM cutting of tube ends
  - Requires tanks and gasket seals
  - High-pressure and temp. capable

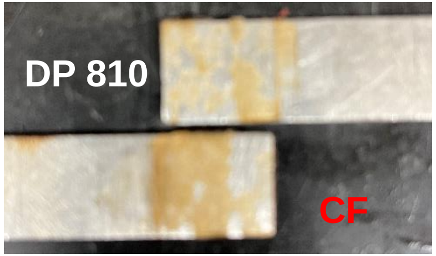
Solder cast in Brass header with Aluminum tank and gasket

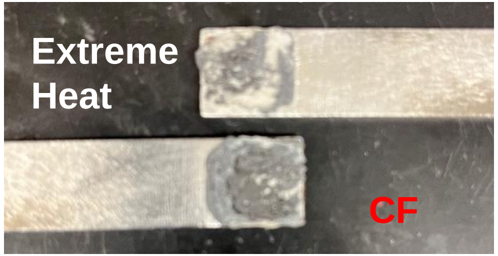
Approach: State-of-the-art Commercial Adhesives

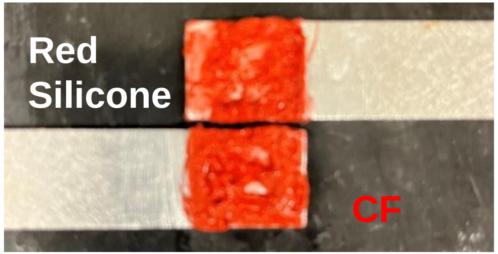


Lap Shear Test

Commercial adhesives	Tested substrate	Temperature (ºC)	Lap shear strength (MPa)
3M DP 810 (Acrylate)	Aluminum	90	3.47
J-B Weld Extreme Heat (Epoxy)	Aluminum	90	1.78
J-B Weld Hi-temp RTV (Silicone)	Aluminum	90	0.34



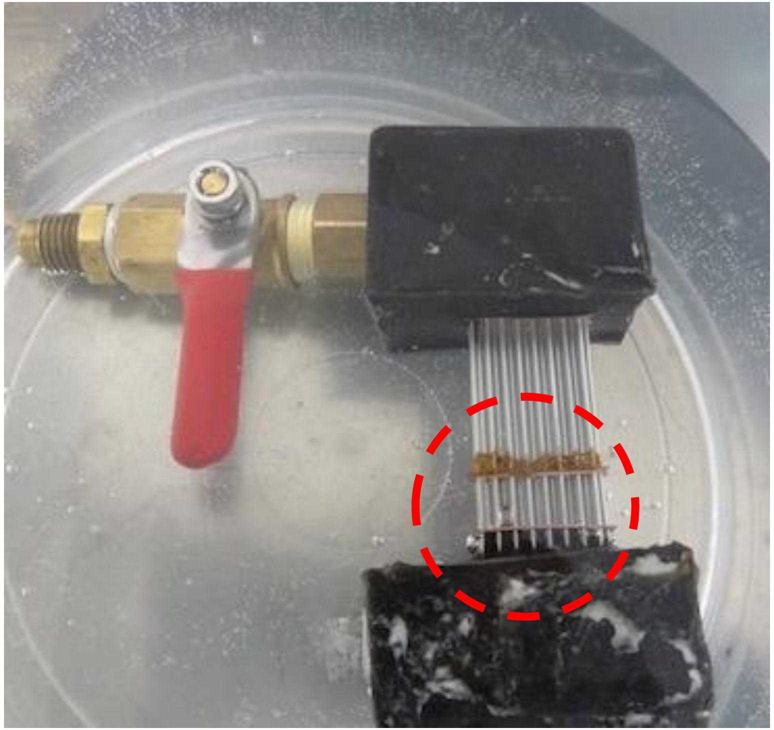




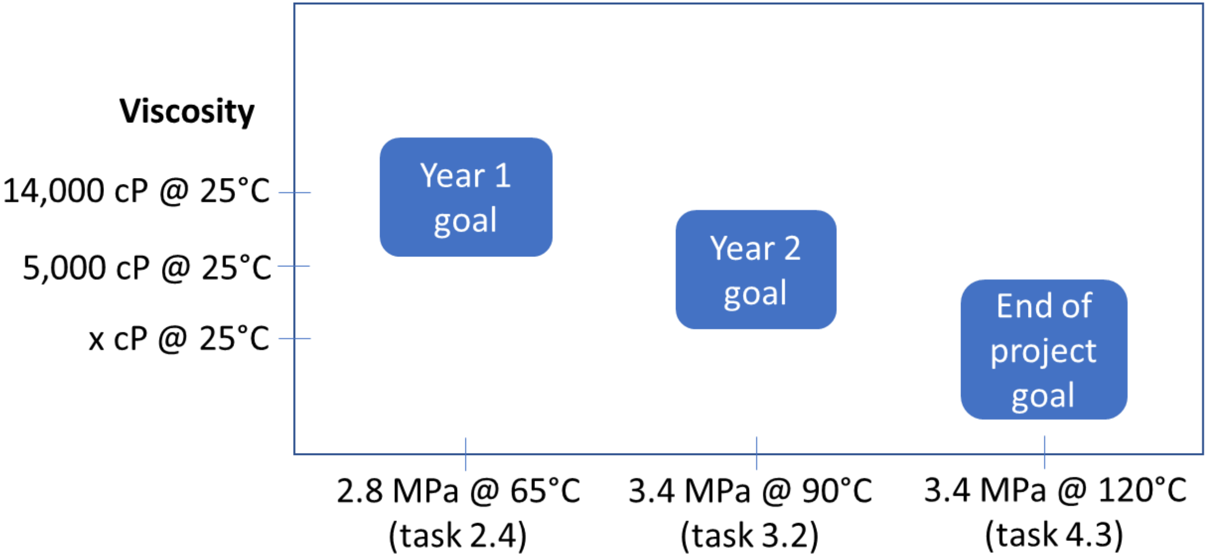
Cohesive Failure (CF): Failure occurs within the adhesive. Most get soft @ 90°C

Approach: Initial Fabrication

- **Commercially available adhesives**
  - Evaluated 23 adhesives
  - Acrylic-Based DP810 → most promising
  - Withstood 2.8 MPa (406 PSI) at room temperature but leaked at >50°C
- **Issues:**
  - Shrinkage
  - Too high viscosity for tight tube gaps
  - Low temp. capability



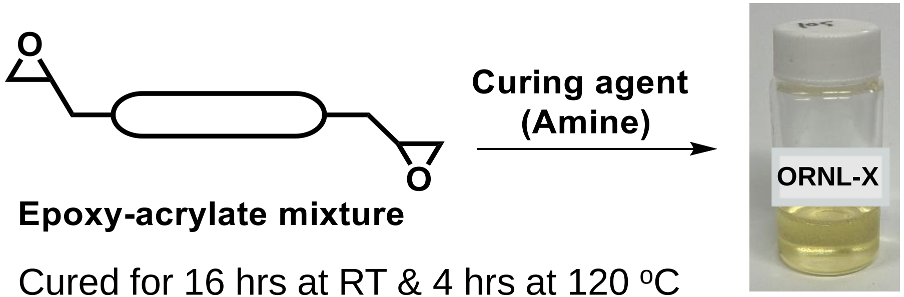
Approach: High Temp Adhesives for HX



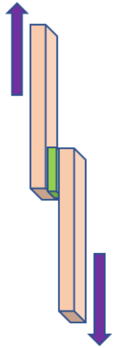
Adhesive target requirements:

3.4MPa pressure, 90°C and viscosity in the range of 2000-5000 cP.

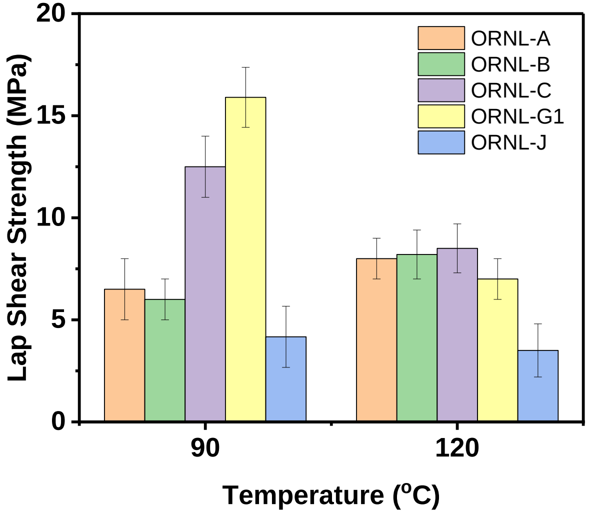
Progress: Adhesive Development



Cured for 16 hrs at RT & 4 hrs at 120 ^oC



Lap Shear Test



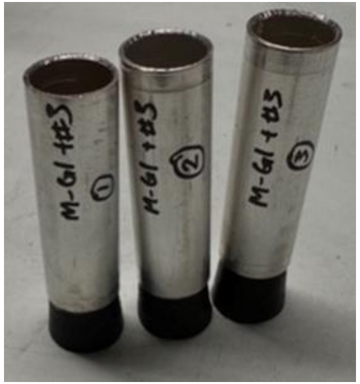
Adhesive	Epoxy viscosity at 25°C	Adhesive viscosity at 25°C	Curing condition	Lap Shear Strength at 90°C	Lap Shear Strength at 120°C
ORNL-A	3000-6000 cP	2000 cP	RT 16 hrs & 120°C for 4 hrs	6.5 MPa	8.0 MPa
ORNL-B	550-950 cP	500-600 cP	RT 16 hrs & 120°C for 4 hrs	6 MPa	8.2 MPa
ORNL-C	1550 cP	1550 cP	RT 16 hrs & 120°C for 4 hrs	12.5 MPa	8.5 MPa
ORNL-G1	800-1100 cP	700-800 cP	RT 16 hrs & 120°C for 4 hrs	15.5 MPa	7 MPa
ORNL-J	800-1100 cP	600-700 cP	RT 16 hrs & 120°C for 4 hrs	4.17 MPa	3.5 MPa

Progress: Adhesive Enhancement

- A Tube Plug test better simulates the adhesive conditions in the HX
- 132 tests were run to date
- Test includes Low and Hi pressure, ambient to 90C cycles, x 3

Plug tests – No filler

Sample	High Pressure 3.4MPa (500 psi Reduced Temperature (70°C)
#1	Failed at 475 psi
#2	Held 3 cycles
#3	Failed at 460 psi

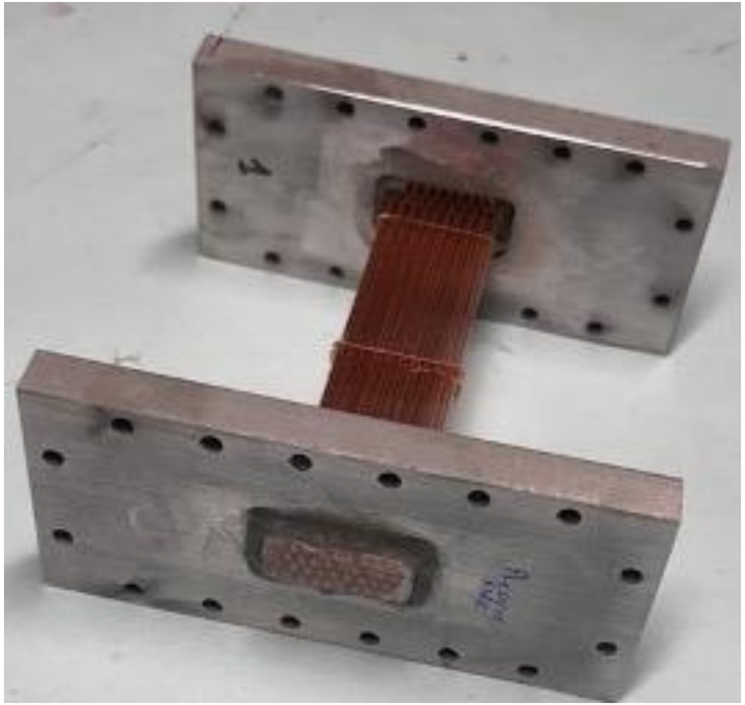


Plug tests <u>with</u> filler

Sample	High Pressure 3.4MPa 500 psi) High Temperature (90°C)
#1	Held 3 cycles
#2	Held 3 cycles
#3	Held 3 cycles

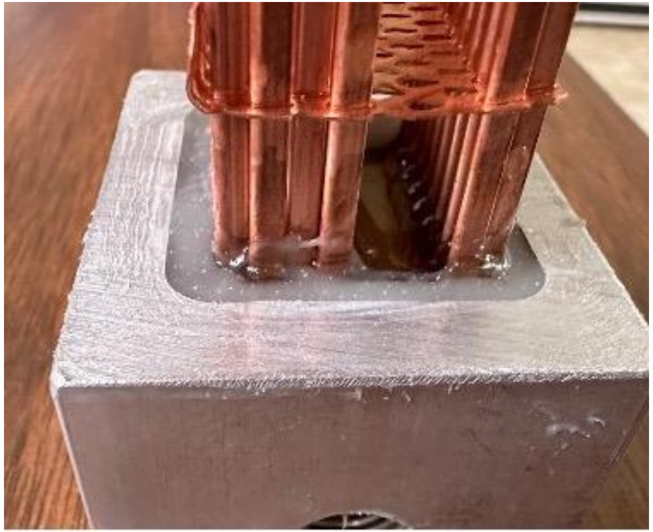
Progress: Manufacturing

- **Type 1: Header plate and tank design**
  - Tube bank is attached to headers by means of adhesive
  - A manufacturing method was developed to allow the use of either low or high viscosity adhesives

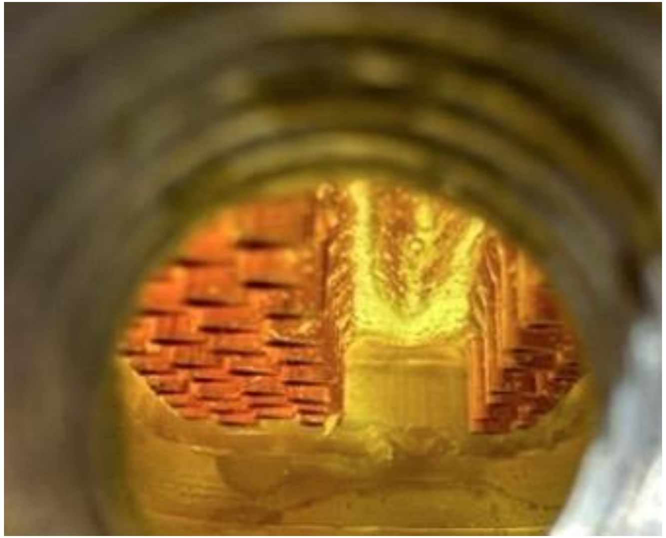


Progress: Manufacturing

- **Type 2: Single piece header design**
  - 2-pass HX - Adhesive cast into header
  - In total, 26 HXs were made to date



2-pass HX part



View through port

3.2MPa (468 PSI) 25°C

Future Work

- **Design and Analysis**
  - Simulation and optimization for larger capacity heat exchangers
  - Extend flow profile prediction to other HX packages (e.g., outdoor units)
- **Fabrication**
  - Finalize fabrication methods
  - HX prototyping
- **Testing**
  - Lab and industry partner testing & model validation
- **Report and Publications**

Team

- University of Maryland
  - 30+ years of experience in R&D of heat pumps, refrigerant, HVAC&R components and systems, modeling and optimization software development; system and component test facilities; funded by industry and government

- ORNL
  - Experimental studies of synthesis and manufacturing novel polymeric materials; developing a fundamental understanding of physical and chemical phenomena in soft matters and applying this knowledge to the design of novel materials and technologies for different applications

- Heat Transfer Technologies
  - 25+ years of experience in design and mfg. of heat exchangers for pre-production evaluation; development of innovative joining techniques for small diameter tubes and manifolds

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Thank you

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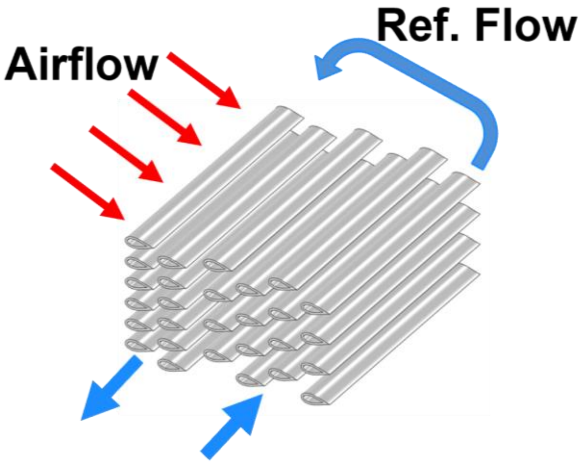
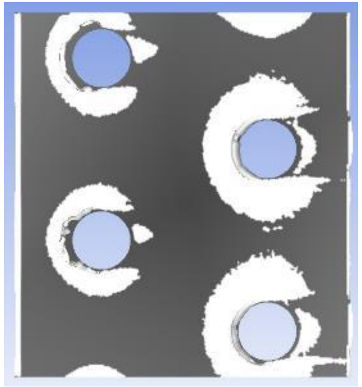
Heat Transfer Technologies

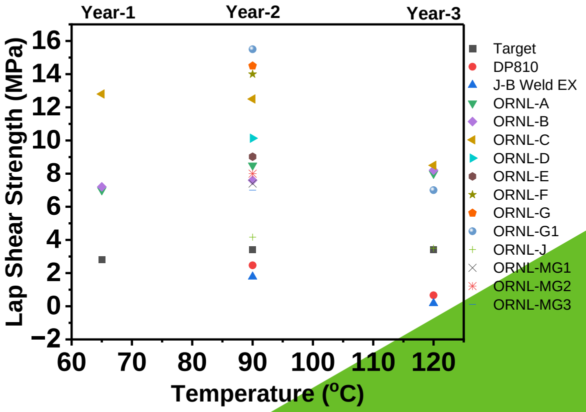
OAK RIDGE National Laboratory



Next generation HXs



HX frost modeling



High performing adhesives

Novel fabrication methods

Reference Slides

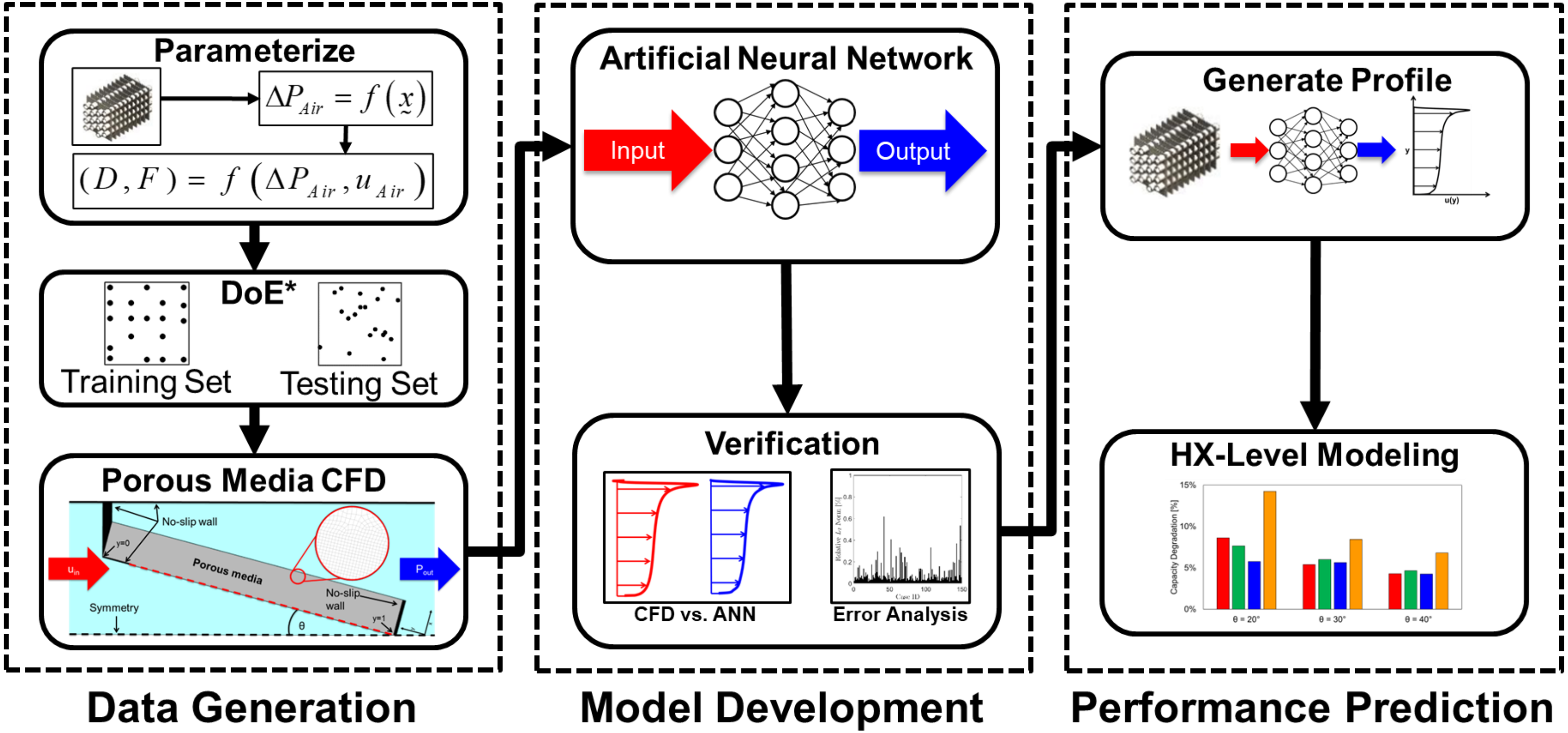
Project Execution

	BP1				BP2				BP3 / NCE							
Planned budget	$xxx				$xxx				$xxx							
Spent budget	$xxx				$xxx				$xxx							
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Milestone 0.1: PMP / IPMP																
Milestone 1.1: Comprehensive literature review																
Milestone 1.2: Determine application for VGHX																
Milestone 1.3: Develop first-cut adhesive material																
Milestone 1.4: Design proof of concept HX																
Milestone 1.5: Improve in-house design & opt. framework																
Milestone 2.1: evaluate results of adhesive / hybrid method																
Milestone 2.2: Further adhesive development																
Milestone 2.3: Design extended operation time HX(s)																
Milestone 2.4: Fabricate heat exchangers from milestone 2.1																
Milestone 2.5: Performance tests and framework validation																
Milestone 2.6: Conduct model validations and calibration																
Milestone 3.1: Evaluate and review progress																
Milestone 3.2: Design a ~5-10 kW heat exchanger																
Milestone 3.3a: Fabricate HXs from milestone 3.2													P			
Milestone 3.3b: Fabricate 3 kW Condensers													F			
Milestone 3.4: Burst pressure testing on milestone 3.3 HX(s)																
Milestone 3.5: Validation and testing of Milestone 3.3 HXs																
Milestone 3.6: Simulated assessment of milestone 4.2 HXs																P
Milestone 3.7: Final technical report																F
Past Work					**Current/Future Work**											

Team

- **University of Maryland (Prime recipient)**
  - Component modeling/design, data analysis, project management
- **Heat Transfer Technologies, LLC (Sub-recipient)**
  - Heat exchanger design, assembly, technical advisor
- **Oak Ridge National Laboratory (Sub-recipient)**
  - Adhesive development, laboratory testing, technical advisor
- **Industry Partners**
  - 3M
  - Carrier
  - Goodman / Daikin Comfort Technologies
  - Honeywell
  - Small Tube Products

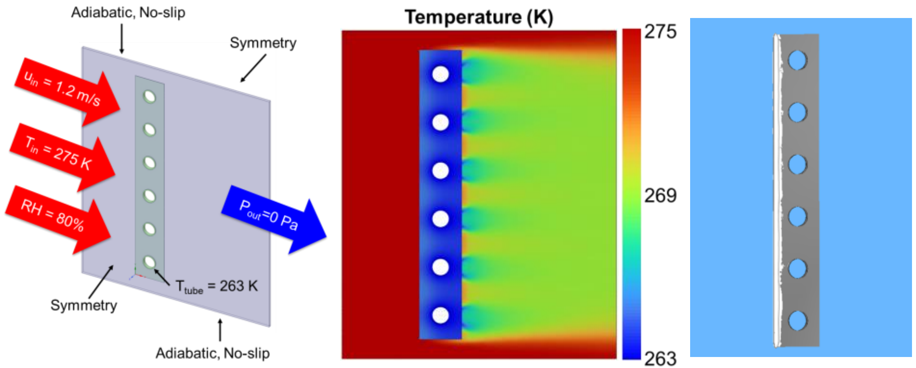
Approach: Flow Profile Prediction Framework

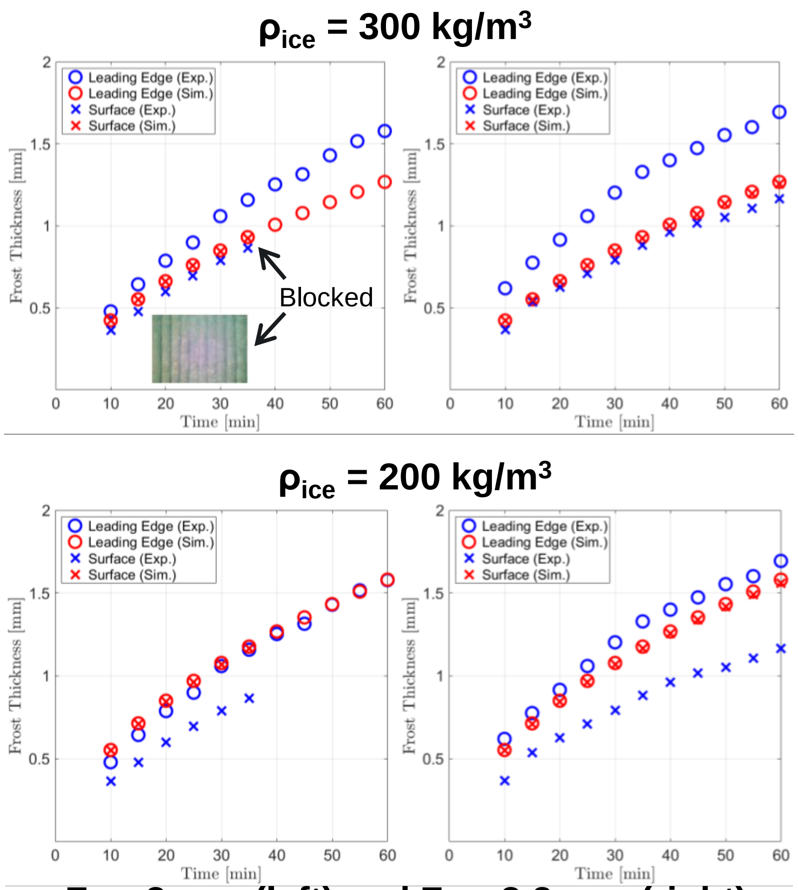


*DoE – Design of Experiments

Approach: Frost Modeling

- **Frost modeling assumptions**
  - Assumes constant ice density
  - Neglects airflow redistribution
- **Compared to experiment (for fin-tube HX)**
  - Good agreement on rate of growth
  - Deviation is consistent between HXs and for different ice densities

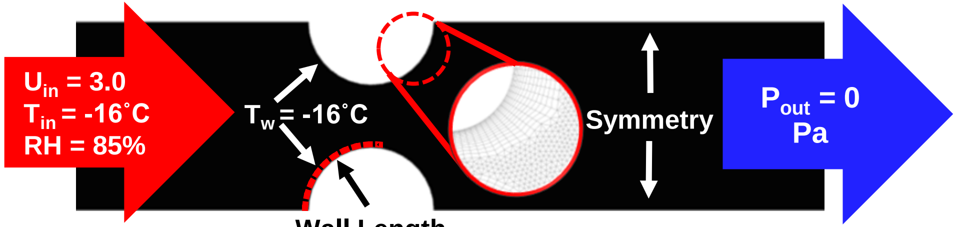




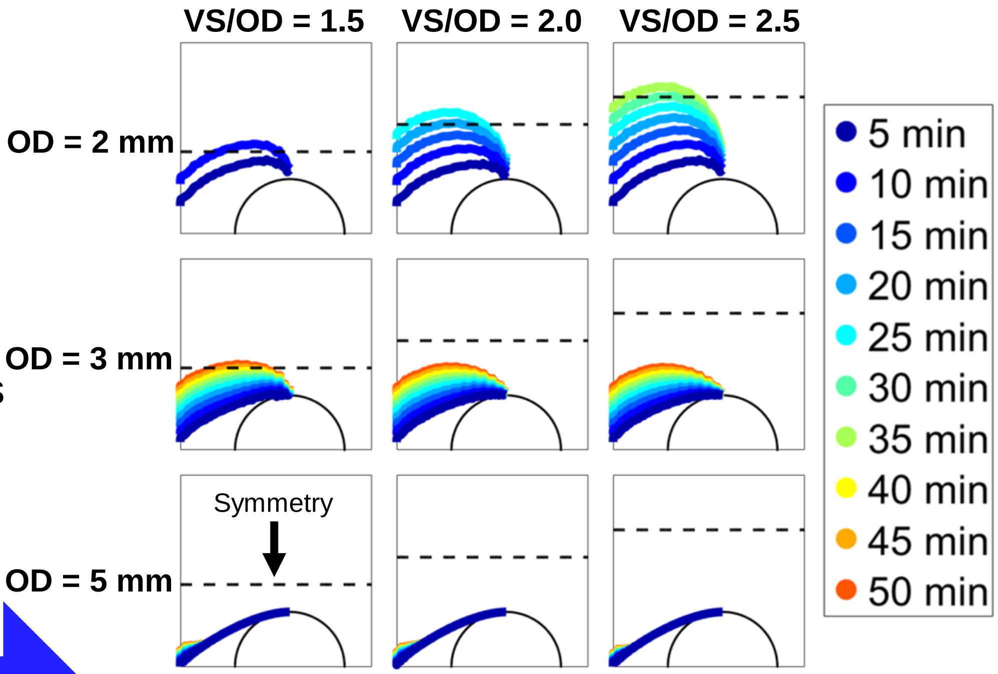
F_p = 2 mm (left) and F_p = 3.2 mm (right)

Approach – Preliminary Analysis

- **Objective**
  - Determine tradeoffs for low temperature operation
- **Conclusions**
  - Larger tubes → longer operation
    - More surface area
    - Greater distance between tubes
  - Primary tradeoff: compactness vs. time between defrost cycles



Computational domain and sample mesh

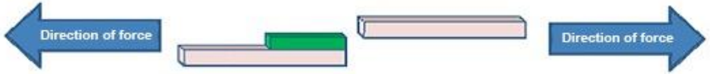


*Figures not to scale

Approach: Adhesive Failure modes

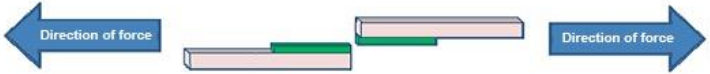
Adhesive

This is the most common failure when bonding dissimilar materials. The adhesive (glue, paint, coating, tape, etc.) has more chemical and/or mechanical attraction to one substrate than the other. When the bonded material is submitted to lap-shear testing (pulled apart by hand), the two pieces come apart and all (or most) of the adhesive remains on one substrate. This is referred to as “delamination.”



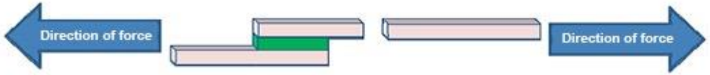
Cohesive

This is most common failure when the adhesive is too weak for the intended application. As shown below, the adhesion to the substrates is greater than the structural integrity of the adhesive. This can occur with “soft” adhesives like certain urethanes and silicones. It can also occur if the adhesive bond-line is applied too thick.



Substrate Failure

This is the best type of failure. It simply indicates that the strength of the adhesive bond and the adhesive itself (and the correct amount applied) is the right formula for the application.



https://www.tstar.com/blog/bid/93991/recognizing-the-three-types-of-bond-failure