



**Thermal
Management
Expo**
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Next Generation Heat Exchangers Technologies: Breaking the Size-Performance Barrier

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Acknowledgements

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Partners:

GE Global Research

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Oak Ridge National Laboratory

National Science Foundation

Next-Gen Heat Exchanger Research Team at UMD-CEEE, 15+ years

CEEE* Vision

Transforming the way thermal systems are conceived, designed, optimized, and operated.

Precompetitive Research

Creativity and Innovation in Energy Systems

Educating Engineering Professionals

Development and Deployment of ML&AI Design & Optimization Tools

Expert Knowledge Supporting Strategic Technology Decisions

MEET OUR TEAM



35+ Years of contributions to HVAC&R and thermal management
Diverse group of colleagues, representing 13 countries

CONSORTIA

University of Maryland
A. James Clark School of Engineering
Department of Mechanical Engineering



CENTER FOR
ENVIRONMENTAL
ENERGY ENGINEERING

BOARD OF VISITORS

SPONSORS

AHXPI

ADVANCED HEAT EXCHANGERS & PROCESS INTENSIFICATION

Michael Ohadi

- Cooling of Electronics (chips, racks, and systems)
- Heat and Mass Transfer and Heat Exchanger Solutions
- Process Control & Intensification
- Data-Driven Energy Audit & Forecasting

EEHP

ENERGY EFFICIENCY & HEAT PUMPS

Yunho Hwang

- “Not-in-kind” Technologies
- Low-GWP Refrigerants
- Applied Heat Pumps
- Heat Transfer Enhancement
- Advanced Compression
- Advanced Energy Storage
- Decarbonization
- Net Zero Energy • Field Tests
- Enhanced Dehumidification & Water Harvesting

MOC

MODELING & OPTIMIZATION

Vikrant Aute

- CoilDesigner • PHESim
- VapCyc • Modelica Library
- Numerical Solvers • DAEX
- Refrigerant Properties
- CFD & LBM Methods
- Optimization Algorithms
- HX Innovation Frameworks
- AI & Machine Learning

Supported by 40+ industry and government organizations
250+ MS and PhD students ; 1000+ Journal and Conference articles; 130+ inventions



CENTER FOR
ENVIRONMENTAL
ENERGY ENGINEERING

Cooling, Heating, and Refrigeration

- **Cooling**
 - Space conditioning (residential, commercial), mobile AC
 - Data centers
 - Industrial processes
- **Heating**
 - Space conditioning, domestic use
 - Industrial processes
- **Refrigeration**
 - Food processing, storage, and transport, cold-chain
 - Warehouses
 - Vaccine storage (esp. remote areas, no reliable power)

**Necessary to preserve and improve
quality of life**

Projected number of air conditioning units

Figures from 2017 onwards are projections from the International Energy Agency, based on estimated changes in population and income.



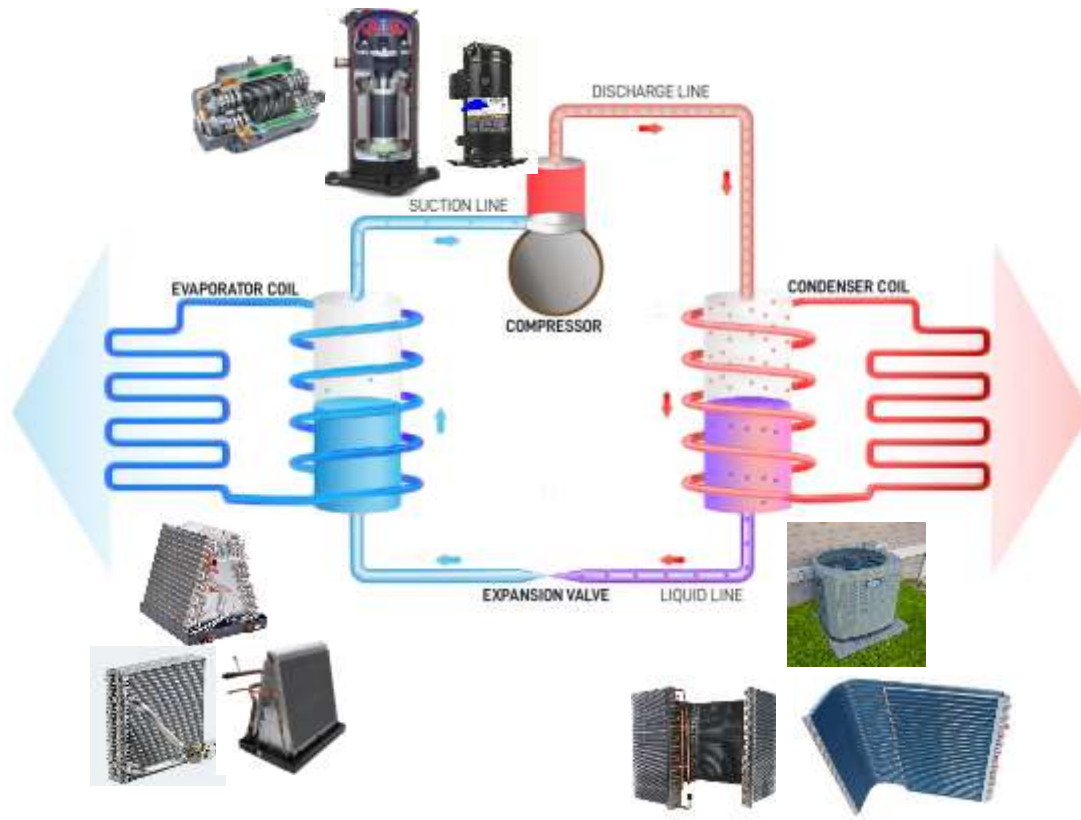
1990 2000 2010 2020 2030 2040 2050

Data source: International Energy Agency (IEA). Future of Cooling.
Rack Density: “The Megawatt Rack” Workshop, Mar-2026, University of Maryland

OurWorldInData.com



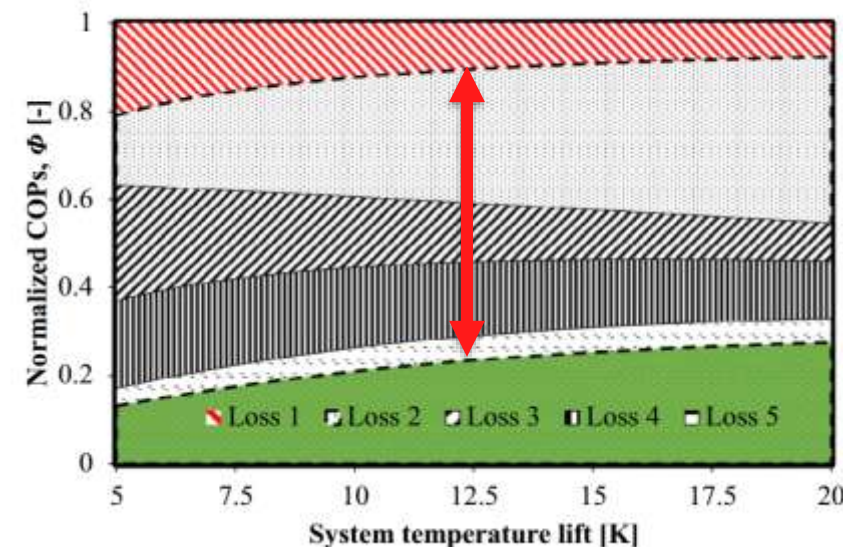
The Basic Vapor Compression System



System Type	COP ^[2]
Window	2.5 – 4.0
Split	2.5 – 5.0
Variable Refrigerant Flow Multi-Split	3.0 – 8.0
Packaged AC	3.0 – 5.5

Key Considerations

- Performance/efficiency, Cost, Affordability
- **Refrigerant** choice & amount
- Size and weight, Installation, Reliability



Loss 1: material hysteresis

Loss 2: compressor efficiency and expansion loss

Loss 3: pressure drop in two heat exchangers

Loss 4: external heat transfer irreversibility

Loss 5: parasitic power (pump, fan, etc.)

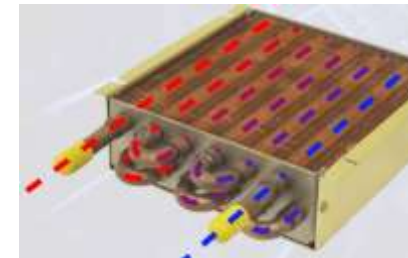
[1] Qian et al. (2016) <https://www.sciencedirect.com/science/article/pii/S014070071500314X#bib0260>

[2] OECD/IEA (2018). The Future of Cooling: Opportunities for energy-efficient air-conditioning

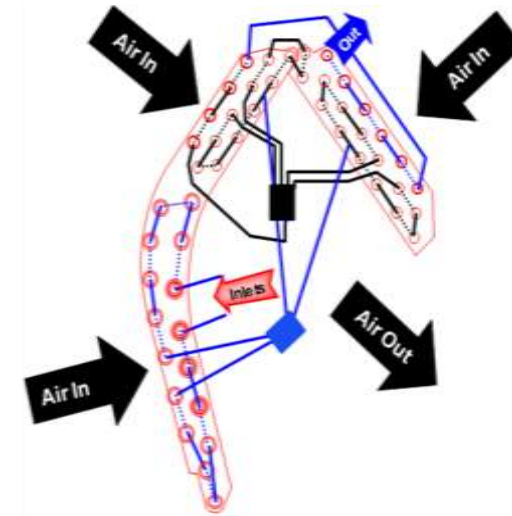
Image: Mitsubishi Website, Basic Cooling System

Heat Exchangers

- Equipment efficiency improvement is a key enabler for decarbonization of buildings
- Heat eXchangers (HX) are key components in thermal systems
 - Account for 20%+ losses
 - Generally 2 or more in each system
 - Cross-cutting technology across domains
- Improved HXs lead to:
 - Lower energy consumption, grid reliability
 - Size/weight reduction (retrofit!), lower costs
 - Lower refrigerant charge, environmental impact



PCM-HX
Paraffin + CENG

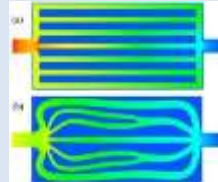


HX Optimization Challenges

- **Physics**
 - Heat Transfer, Pressure drop
 - Phase Change
 - Thermal Storage
 - ...
- **Design evolution**
 - Feasibility
 - Thermal short-circuits
 - Flow path collisions
- **On-the-fly CFD/FEM evaluation**
- **Computational Efficiency**
- **Flow path optimization**
- **Constraints**

*Should be compared for same application & working fluids

** Per run: 5min@4 Cores to 6hr@128 cores

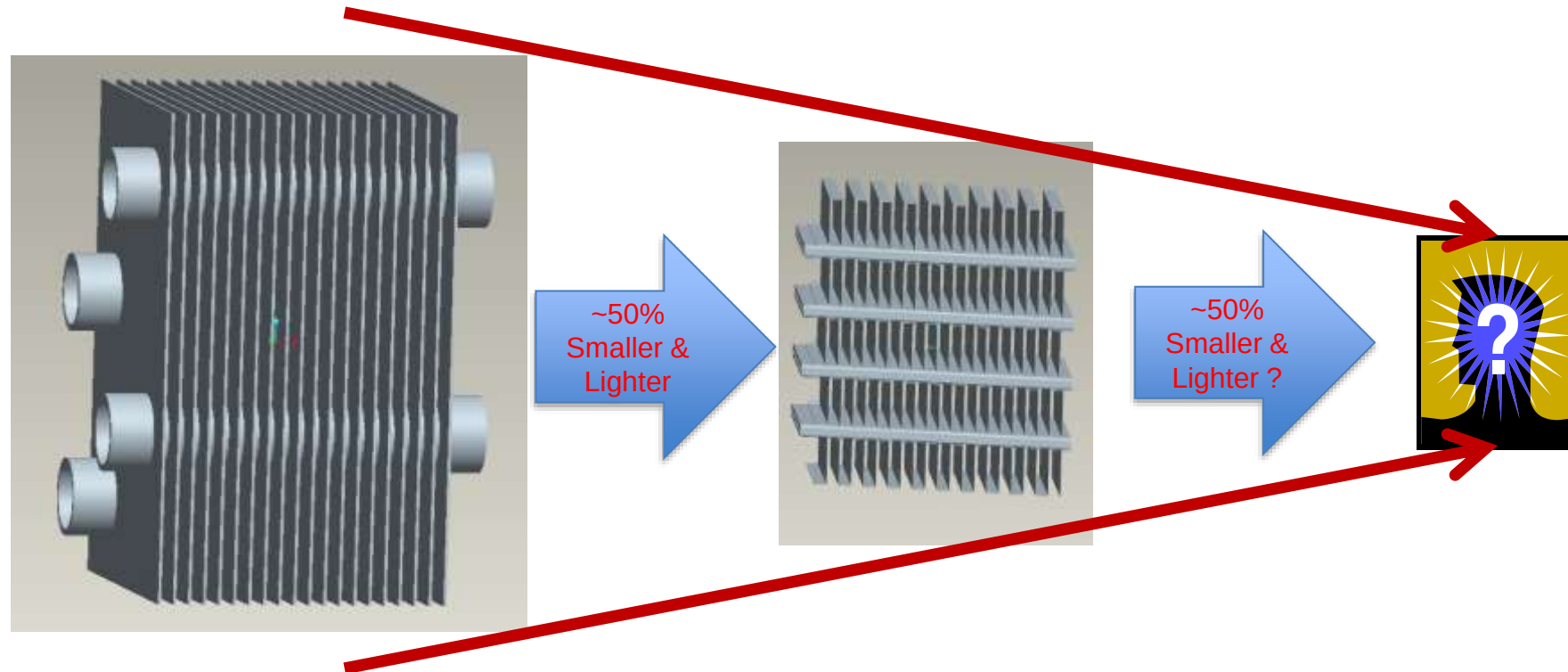
Type	Example	Fluids Contained	Typical Metrics* (to beat!!!)
Heat Sink	 	0 – Normally 1 – if fin is a heat pipe	Annual IEEE/ASME Heat Sink Competition
Cold Plate	 	1 Can also have fins on the outside	0.02 K-cm ² /W
Air (or PCM) -to-Refrigerant (fluid) Heat Exchanger (forced or natural convection)	 	1 (Air or PCM-indirectly) Multiple flow channels for same fluid Internal flow can be optimized	2-6 MW/m ³ ~200-800 W/K 400 W/m ² K (air-side)
Plate Heat Exchanger; Fluid to Fluid Heat Exchanger	  	2, Multiple flow channels for same fluid	1-50 MW/m ³
Generalized Fluid-to-Fluid HX Potential for monolithic HX to reduce total HXs in a system	 	N Fluids; One or more flow channels per fluid (← 2 fluid designs shown)	3kW/kg; 10MW/m ³

Air-to-Refrigerant Heat Exchangers

- Tube-Fin (Dh: 4-12+ mm), Microchannels (Dh: 0.6-3mm)
- Extended Surfaces
 - Plain/enhanced fins
 - Bare tubes
- Refrigerant side
 - Fluid Classes: HFCs/HFOs, NH₃, CO₂, Water, HCs
 - Mass flux: 10 – 1500 kg/s.m²
 - HTC: 500-10,000+ W/m²K
- Air side
 - Face velocity: 0 – 5 m/s
 - HTC: 10 – 300+ W/m²K
- Air-side is the dominant resistance!



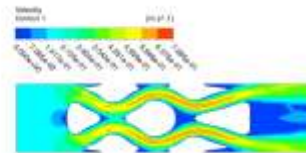
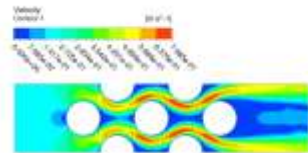
Research Goal: Next Gen Air-to-Ref. HX



HX Innovation Challenges

How to innovate?

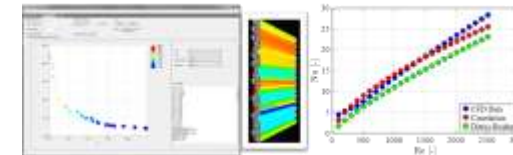
- Incremental improvements
- *Novel Surfaces*, e.g. TPMS
- **Shape & Topology optimization (Computer algorithms inventing new surfaces!)**



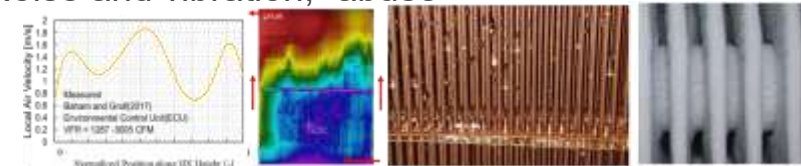
- How to develop predictive capabilities to get the first prototype 95% right!!!
- How to leverage multidisciplinary advances such as Machine Learning/AI; Additive Manufacturing (materials and processes); Digital Twins?

How to make an impact (T2M)?

- **Novelty**
 - Novel designs must be at least 20% better with significant reductions in refrigerant charge
 - **Lack of thermohydraulic characterization and reliable design tools**
 - **Design modularity**

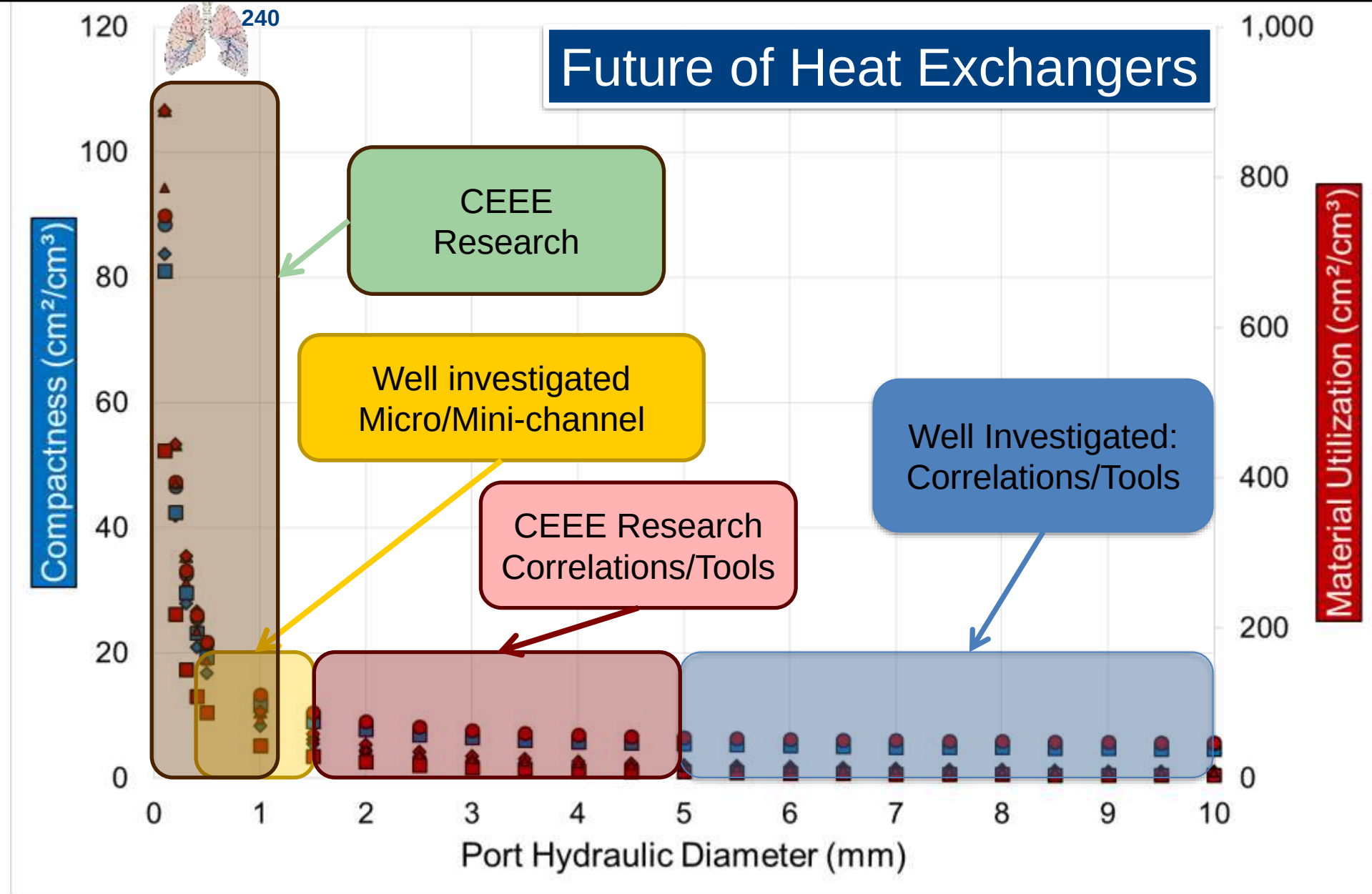


- **Manufacturing aspects**
 - Component availability
 - Joining / manufacturing techniques
 - Process scalability
- **Operational aspects**
 - Fouling, Wetting, and Frosting
 - Flow maldistribution
 - Corrosion
 - Noise and vibration, “abuse”



- **Integration of Storage**
- **Costs / ROI / Markets & Regulations**

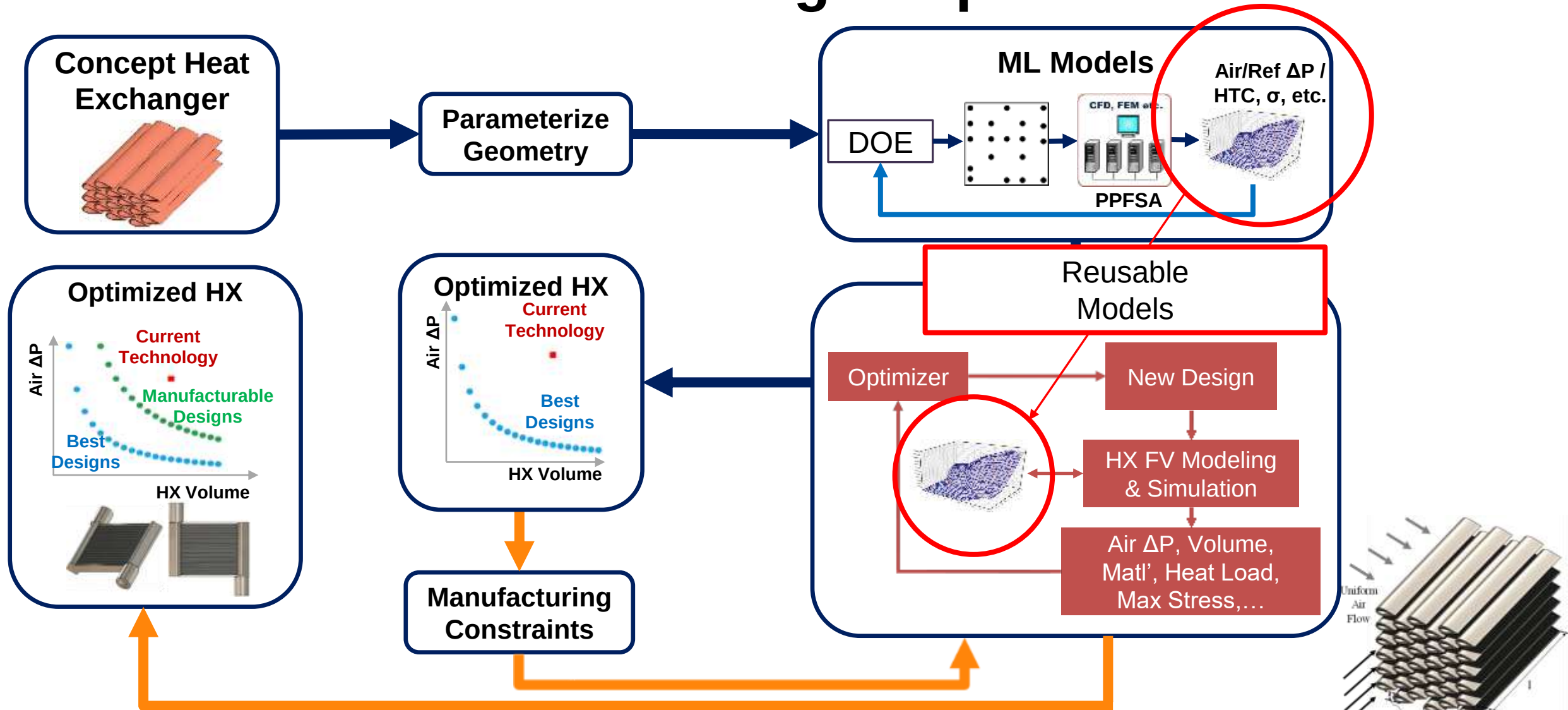
Future of Heat Exchangers



Bacellar et al., 2014



Multiscale Modeling & Optimization

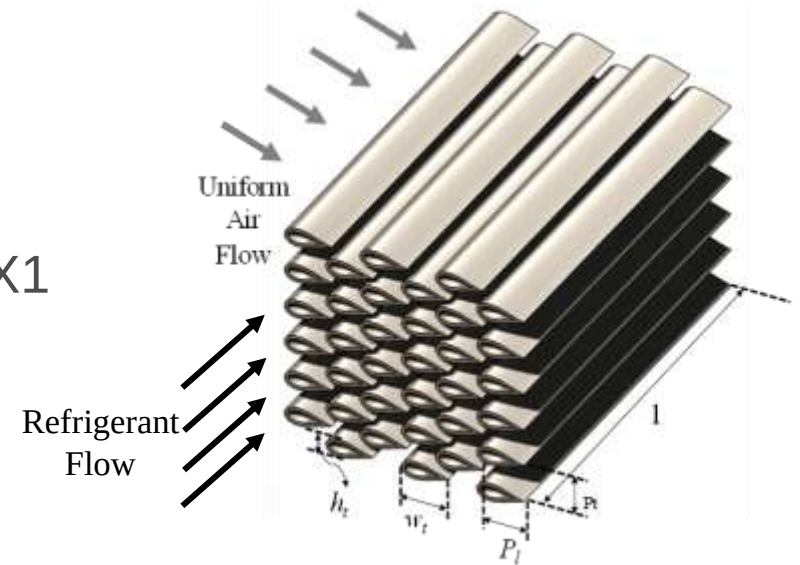


PPFSA = Parallel Parameterized Fluid & Structural Analysis; MOGA = Multi-Objective Genetic Algorithm; FV: Finite Volume
Contributors (since 2006): Drs Aute, Abdelaziz, Saleh, Bacellar, Huang, Eldeeb, Tancabel, Klein

Lower-GWP Nominal 5.28 kW Condenser Optimization

• Optimization Problem Formulation

- Cross-flow HX with fixed inlet conditions^[30]
- Fixed, non-round, conventionally-manufacturable NTHX1 tube shape^[6]
- Baseline refrigerant: R410A
- Lower-GWP alternatives: R32, R454B



$$\min \Delta P_{air}, V_{HX}$$

s.t.

$$\Delta P_{air} \leq 2.0 \cdot \Delta P_{air,BL} \quad V_{HX} \leq V_{HX,BL}$$

$$0.5 \leq \frac{H_{HX}}{L_{HX}} \leq 2.0 \quad A_f \leq A_{f,BL}$$

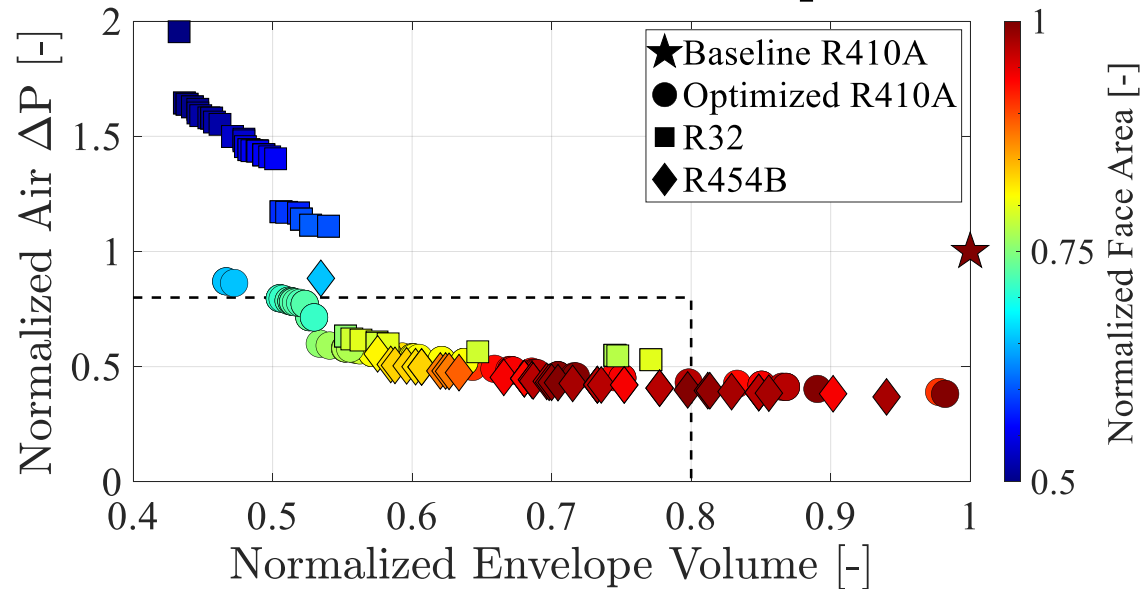
$$\Delta T_{SC,BL} - 1.0 \text{ K} \leq \Delta T_{SC} \leq \Delta T_{SC,BL}$$

*Cu tube showed no deformation up to 20 MPa internal pressure^[30]

**Al tube showed no deformation up to 7.5 MPa internal pressure^[30]

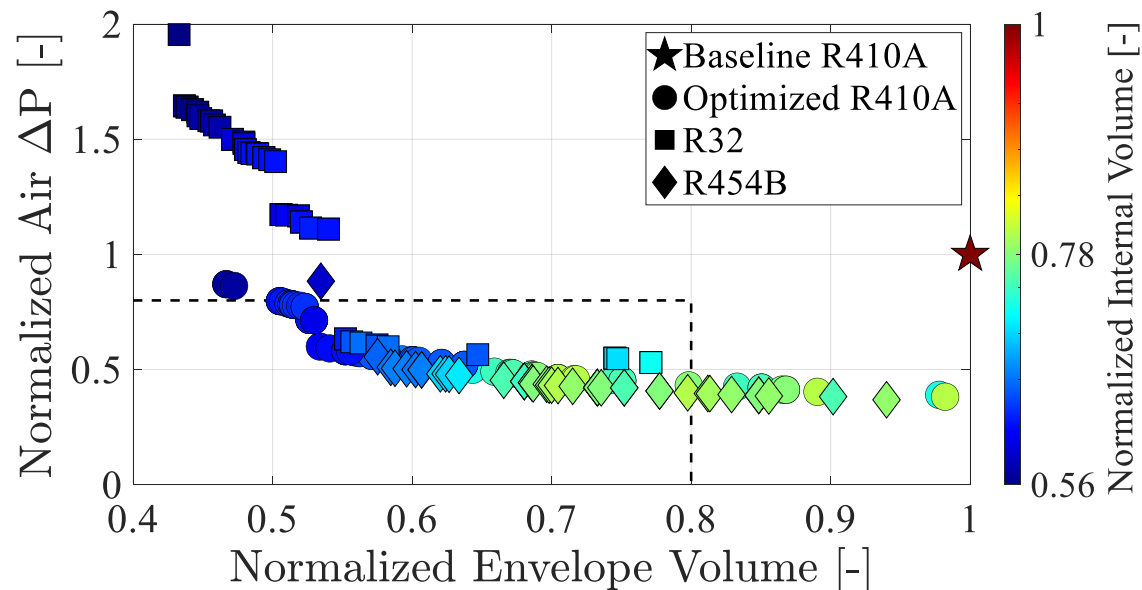
Variables	Parameters
Tube pitches (HS, VS)	Air inlet state (T, RH, $\dot{V}$)
# Tube Banks	Fluid inlet state (T, P, $\dot{m}$)
# Tubes per Bank	NTHX1 tube shape
Inlet Air Velocity	Two fluid passes (60% / 40%)

Optimization Results



Up to 40% reduction in heat exchanger size

30% reduction in internal volume (~ refrigerant charge)



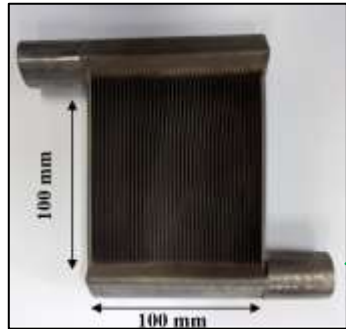
Framework implementation: 2-4 months (one-time effort)

Optimization Time: < 30 mins per run, can use for decades!!!

Tancabel et al., CLIMA-2022, Application: Residential AC, R410A Condenser

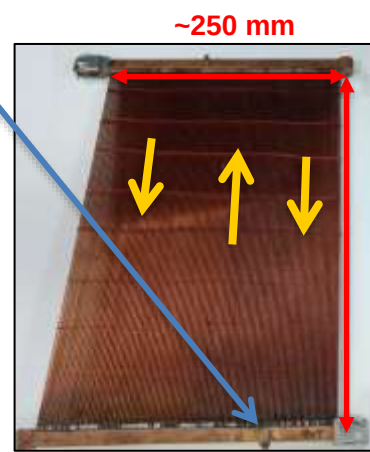
Baffle Location
Based on Flow
Path Optimization

Prototyping



NTHX-1, Ti
(2016)

Conventionally
Manufactured



1.5TR-3B-001
(2019)



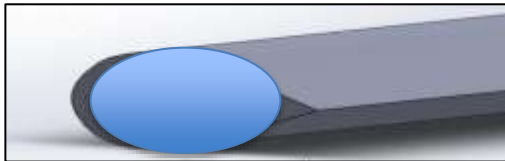
1.5TR-E-11B-001
(2021)



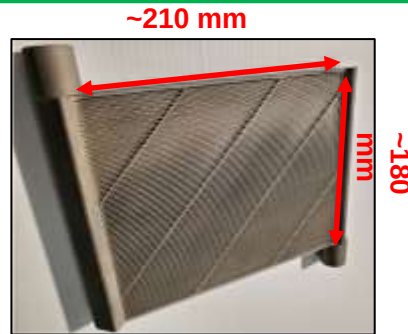
1.5TR-C-4B-002 (x2)
(2021)



Tube Representative
Cross Section



Additively
Manufactured



ENTHX1, Ti
(2019)



1.5TR-E-11B: 1.5TR Nominal capacity evaporator with 11 rows

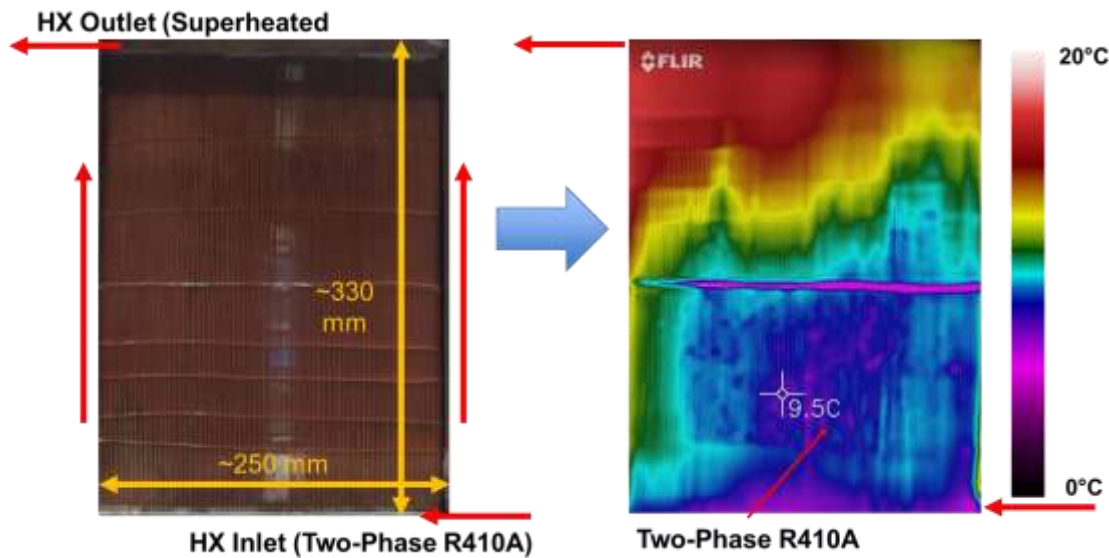
Conventional Materials: Copper, Aluminum; Additive Materials: Titanium, Plastics, other proprietary alloys

Patent Pending

Experimental Validation

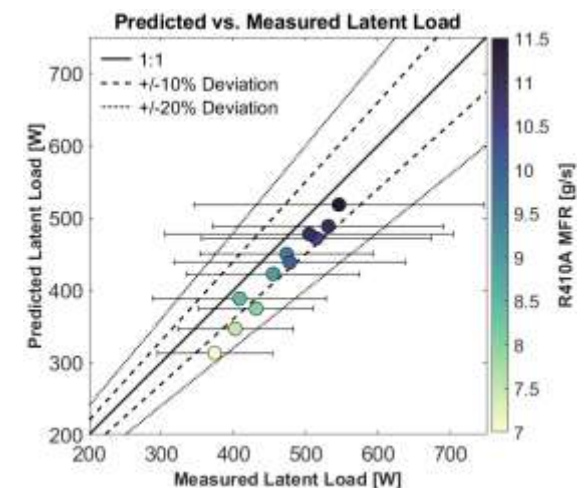
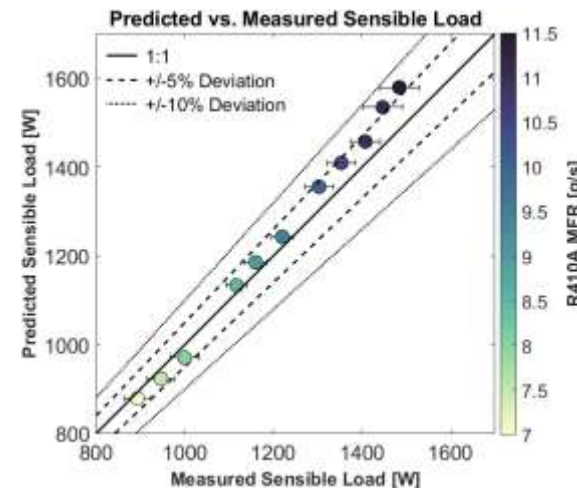
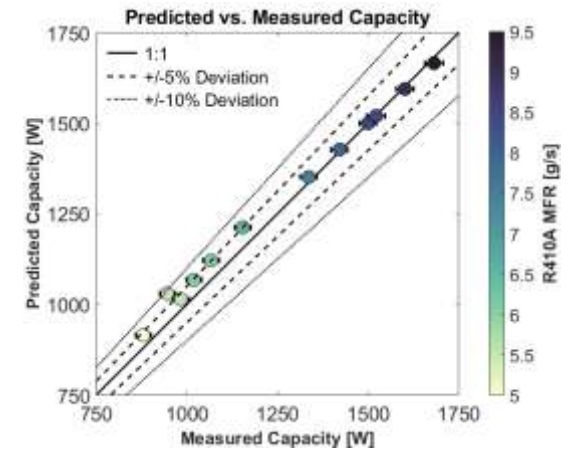
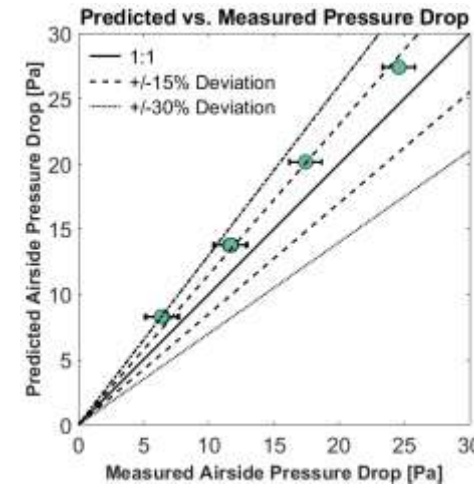


Bar	Pressure	I (base) [mm]	II (mid) [mm]	III (tip) [mm]
up to 200 bar		No Measurable Deformation		

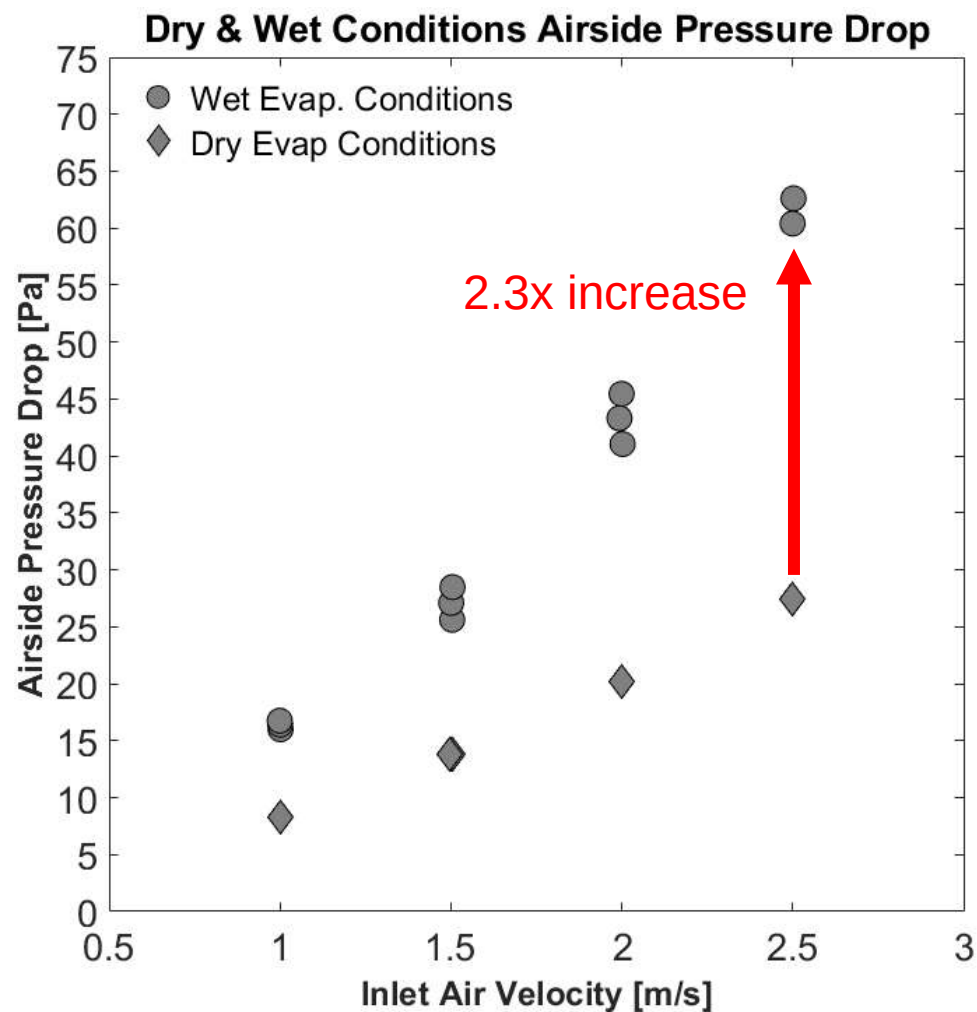


- Comprehensive validation across 11+ radiator, condenser, and evaporator prototypes^[11-12]
- Predictions within $\pm 15\%$ for capacity and pressure drop
- Successful independent lab validations

Courtesy: Zhiwei Huang, Ellery Klien, Jan Muehlbauer, Yunho Hwang, HTT



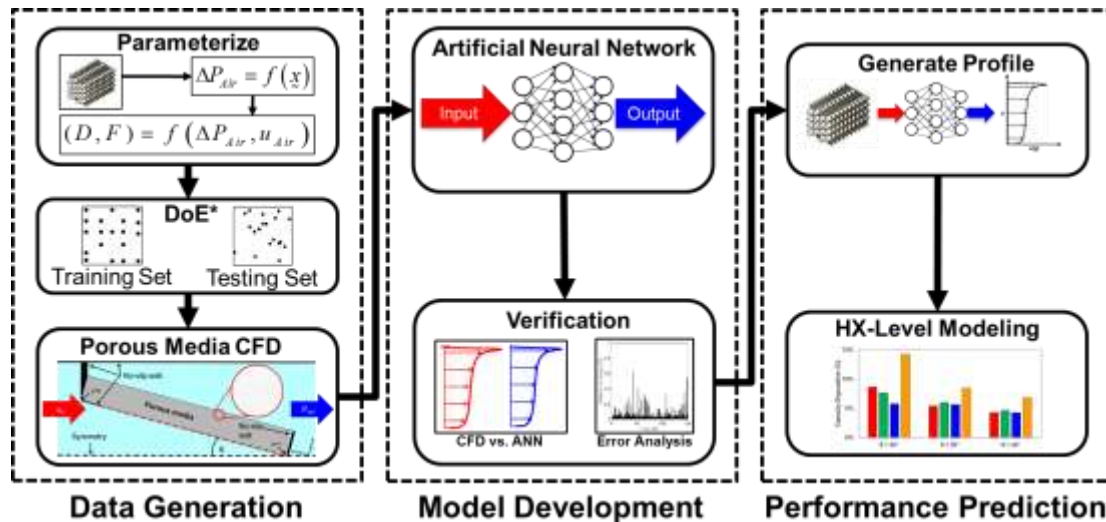
Challenges: Water Bridging



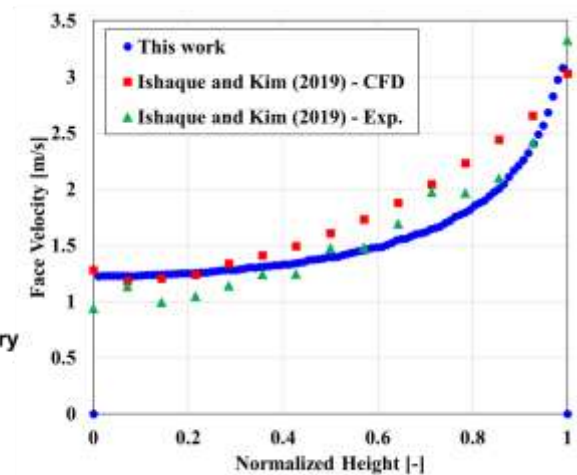
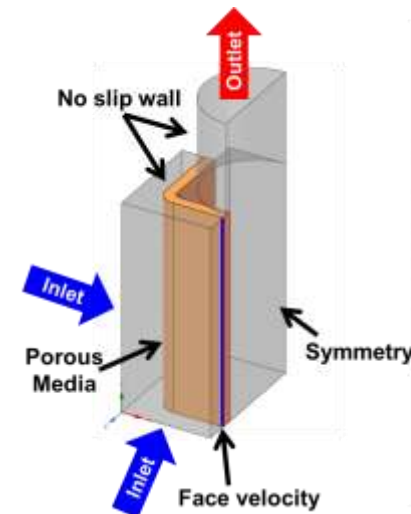
Prototype C1 Wet Evaporator Tests

Some Enabling Capabilities

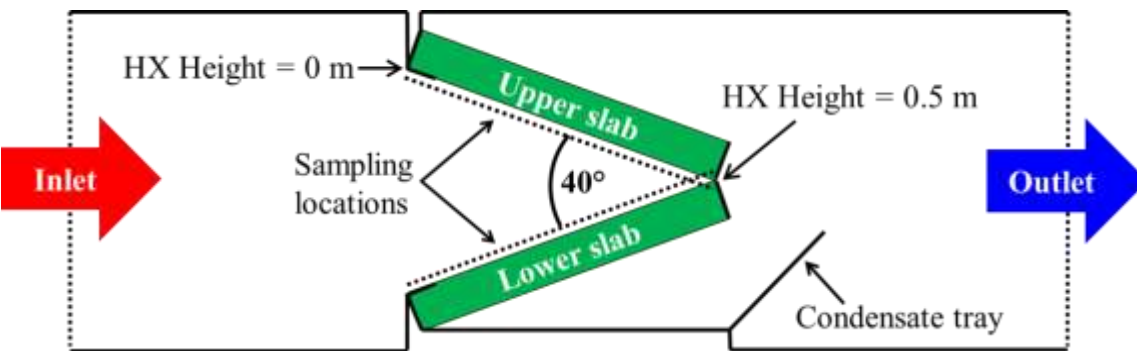
ML-Based Flow Profile Prediction



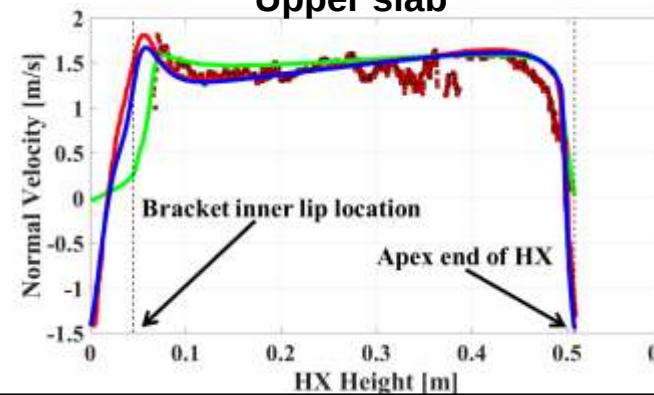
Prediction Framework – Independent of Fin Type



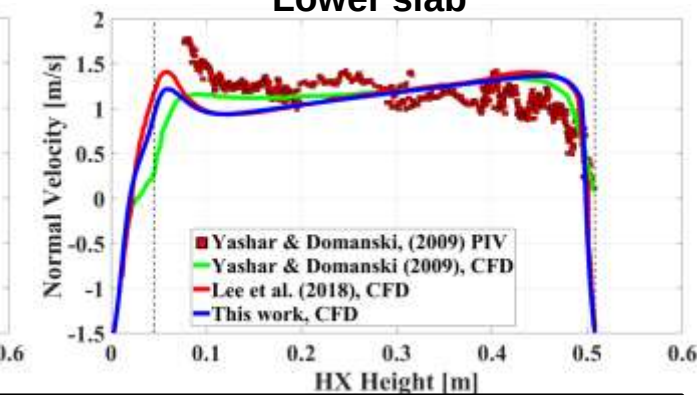
Outdoor Unit Analyses



Upper slab

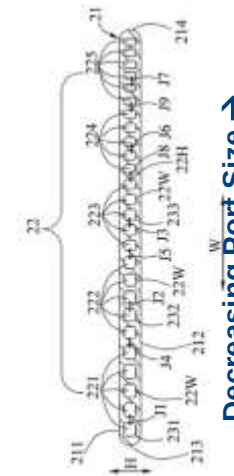
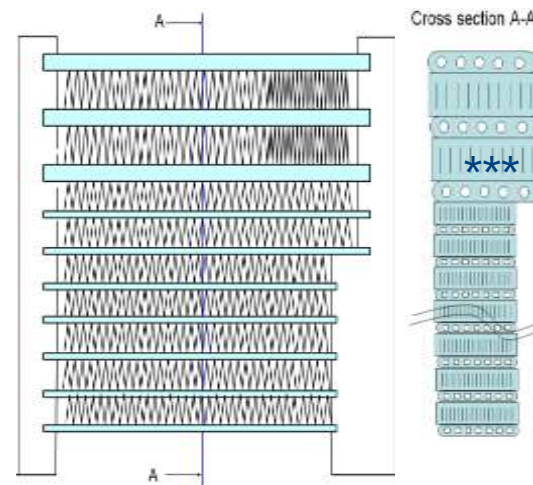
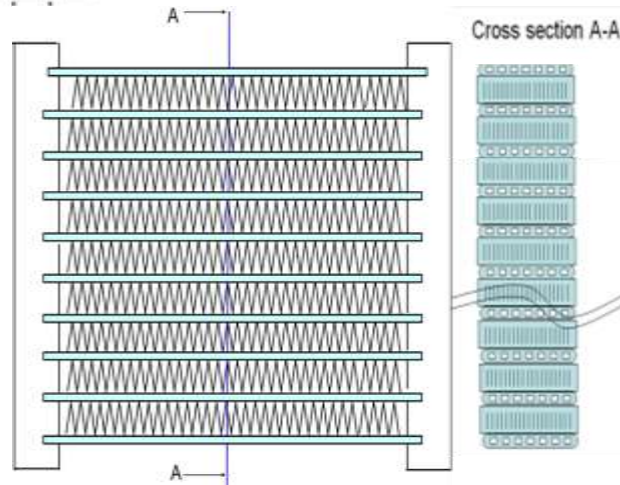
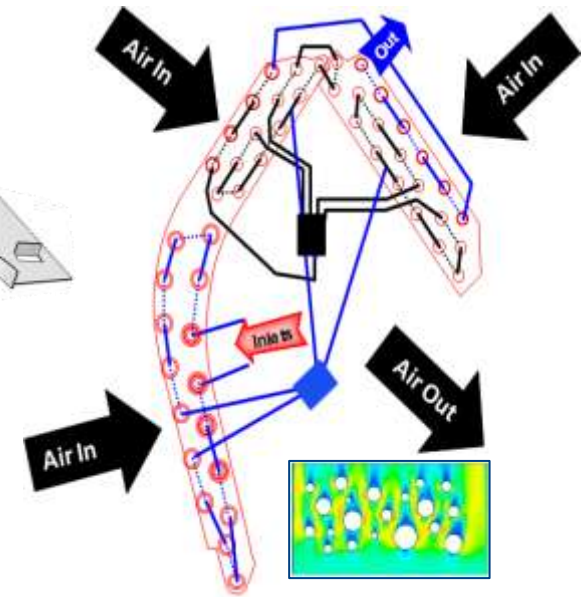
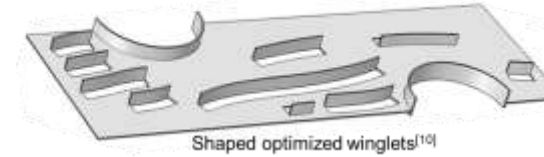
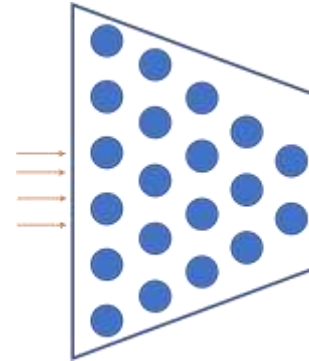
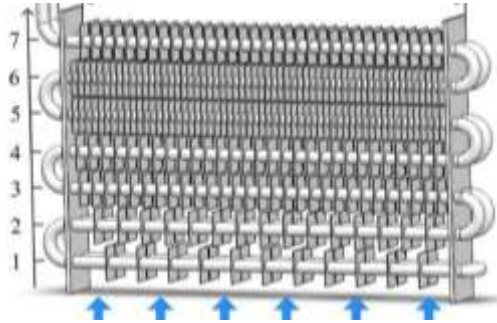
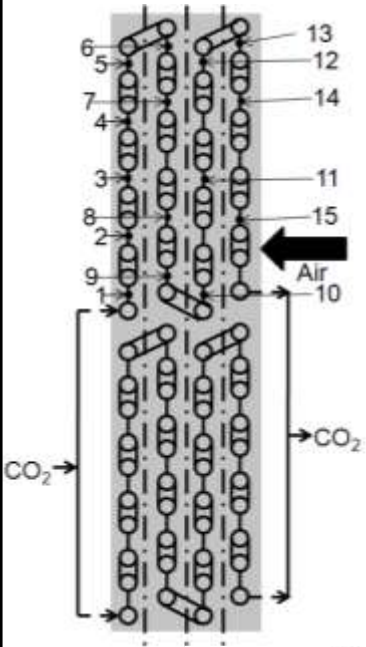


Lower slab



Indoor Unit (A-Configuration): CFD model validated against PIV and ML model verified against CFD (average VFR within 1.1%)
ML Models are 10^5 times faster than CFD

Variable Geometry Heat Exchangers



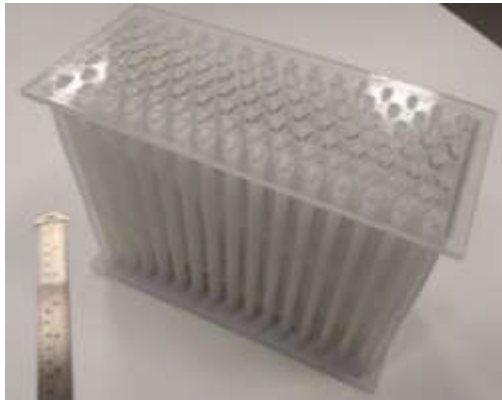
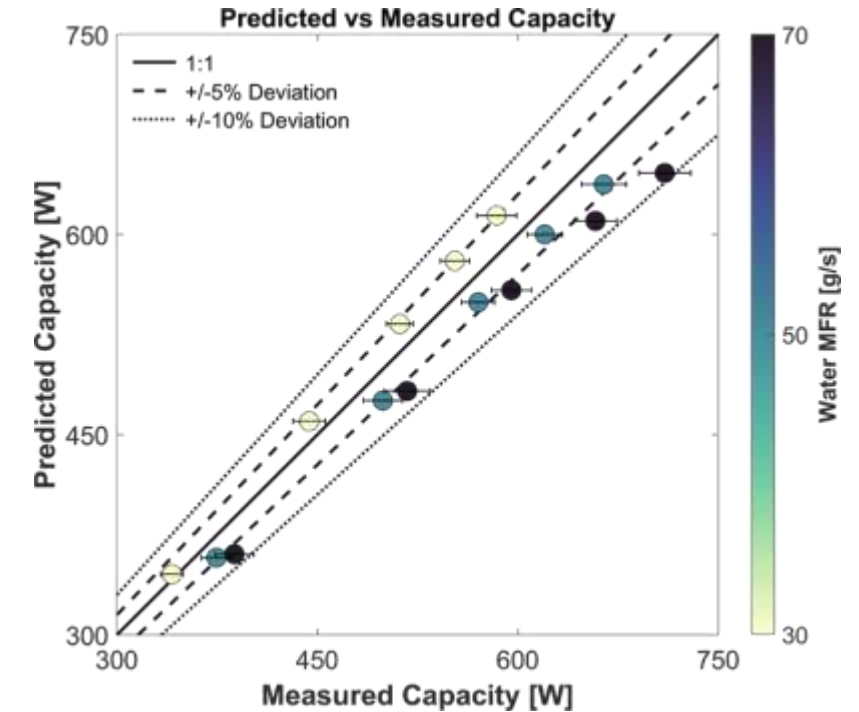
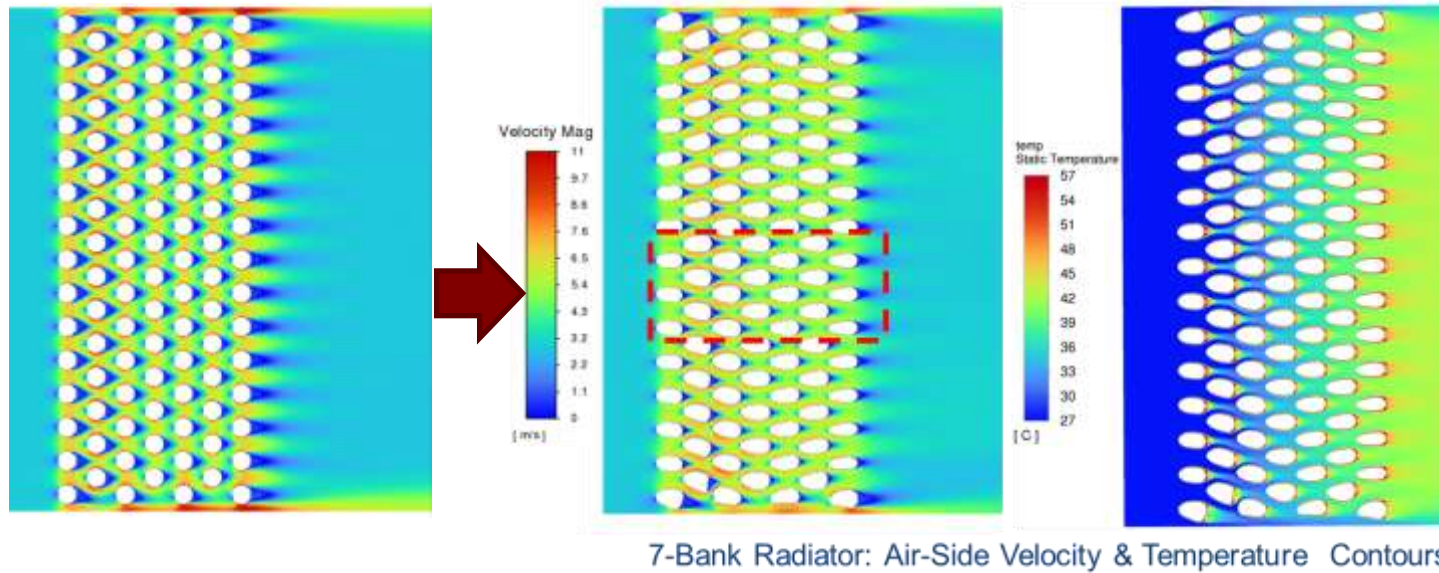
Decreasing Port Size →

Today, we can model and optimize the geometry for these designs. What's next?

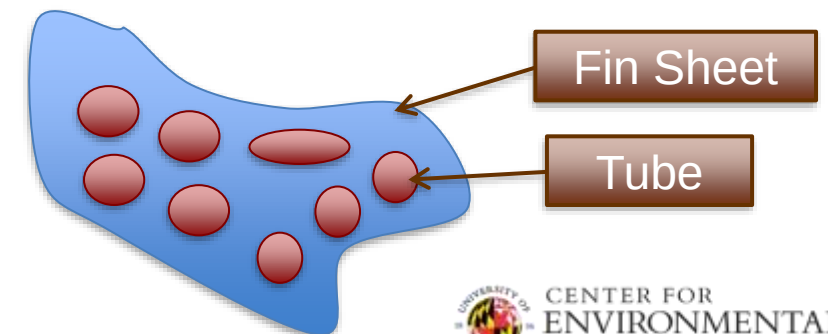
***Variable fin structure in direction of air flow

O'Malley et al., 2023, Review of. Variable. Geometry. Air-to-Refrigerant Heat Exchangers, Int. Congress of Refrigeration
 Jiang, Aute, and Rademacher, 2006, Intl. J. of Refrigeration, Singh, Aute, and Rademacher, 2009, Intl. J. of Refrigeration
 Huang, Aute, and Rademacher, 2014, Intl. J. of Refrigeration

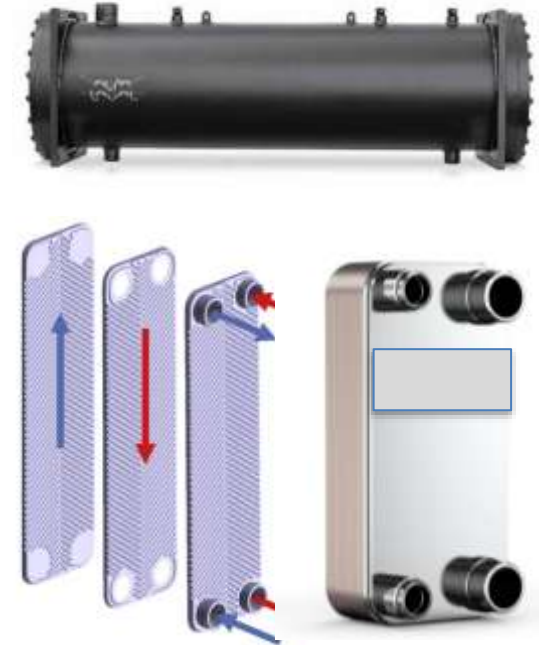
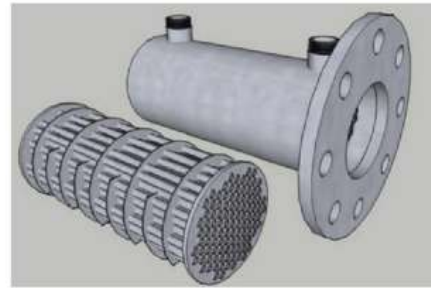
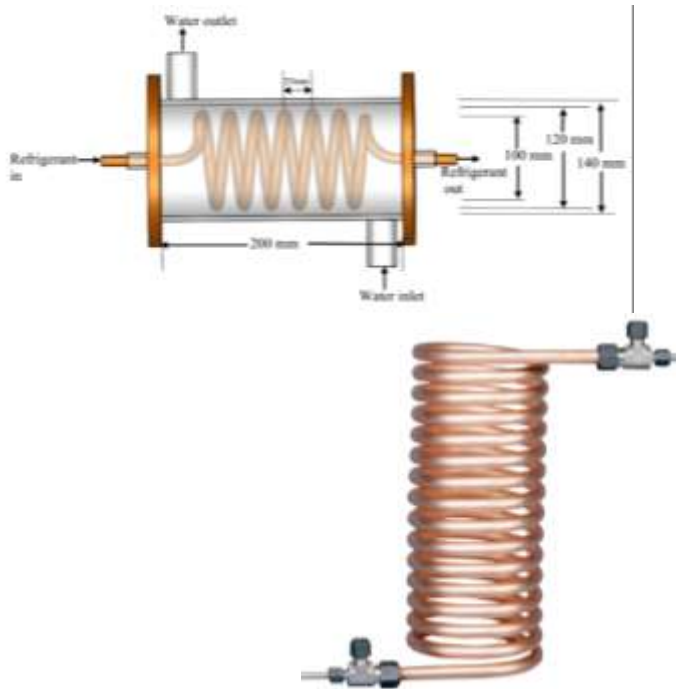
The Ultimate Air-to-Refrigerant Heat Exchanger



Research: Develop predictive capabilities and design tools to recommend best designs to the user for a given application.

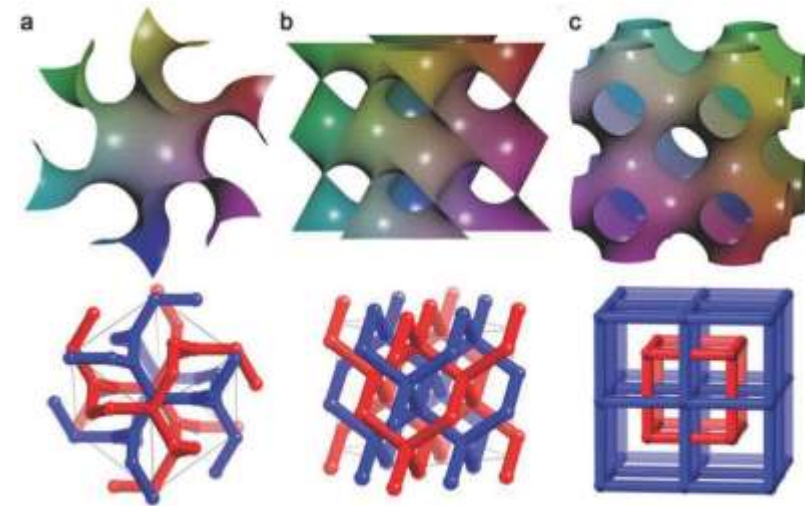


Liquid-to-Refrigerant Heat Exchangers

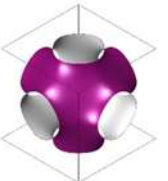


Triply Periodic Minimal Surfaces (TPMS)

- TPMS^[10] can pack significant surface area in a given volume
- **Balanced Bi-continuous TPMS** divide 3D Euclidean space into “two” domains that are:
 - Congruent
 - Interpenetrating – close contact
 - Intersection-free – avoid flow collisions
 - Infinitely repeating – highly scalable
- **Benefits of TPMS**
 - High compactness (surface area / volume ratio)
 - Can prevent adverse pressure drops due to continuous flexures
 - Simple representation using Level-Sets
 - Small solid model file sizes
- **Literature:** Many papers on mechanical & unit-cell analysis; small fraction of papers focusing on complete heat exchangers

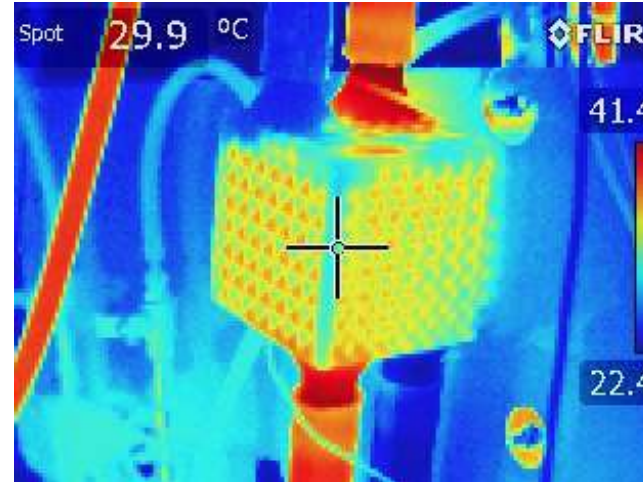
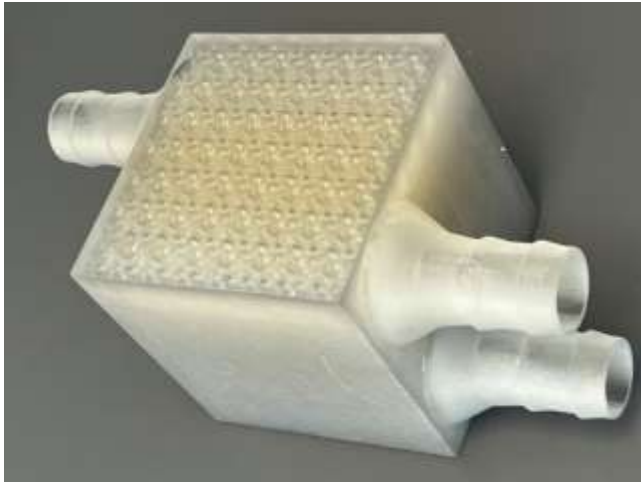
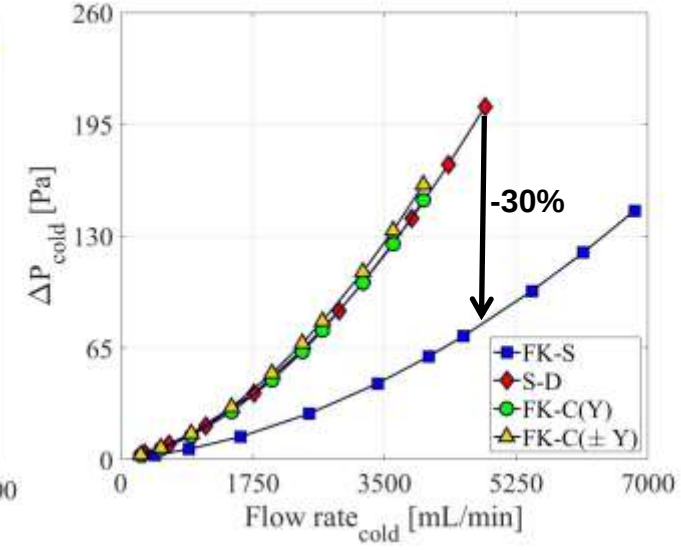
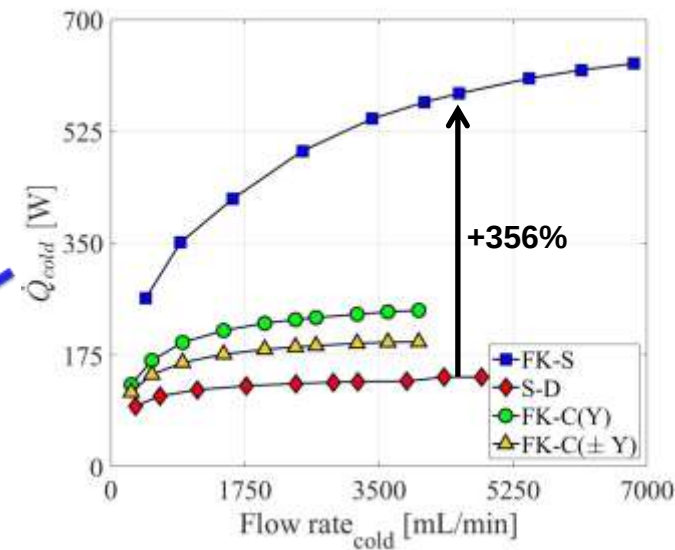
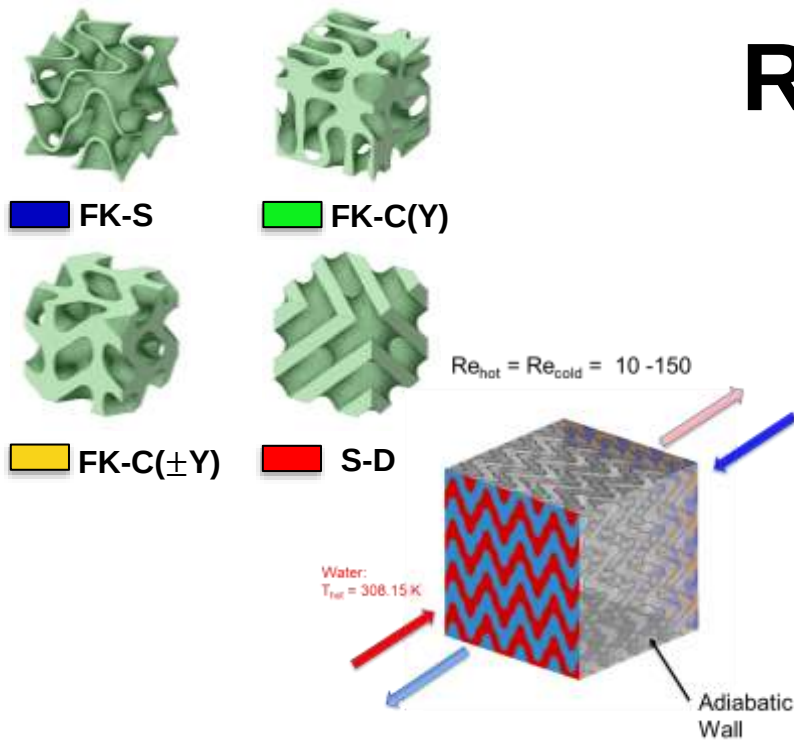


Bi-continuous TPMS surfaces and their skeletal graphs: a) Gyroid, b) Diamond, and c) Primitive^[11]

TPMS Name	Level set function	Surface
Schwarz Primitive [P]	$\cos(X) + \cos(Y) + \cos(Z) = 0$	
Schwarz Diamond [D]	$\cos(X) \cdot \cos(Y) \cdot \cos(Z) + \sin(X) \cdot \sin(Y) \cdot \cos(Z) + \sin(X) \cdot \cos(Y) \cdot \sin(Z) + \cos(X) \cdot \sin(Y) \cdot \sin(Z) = 0$	

200+ other equations/surfaces

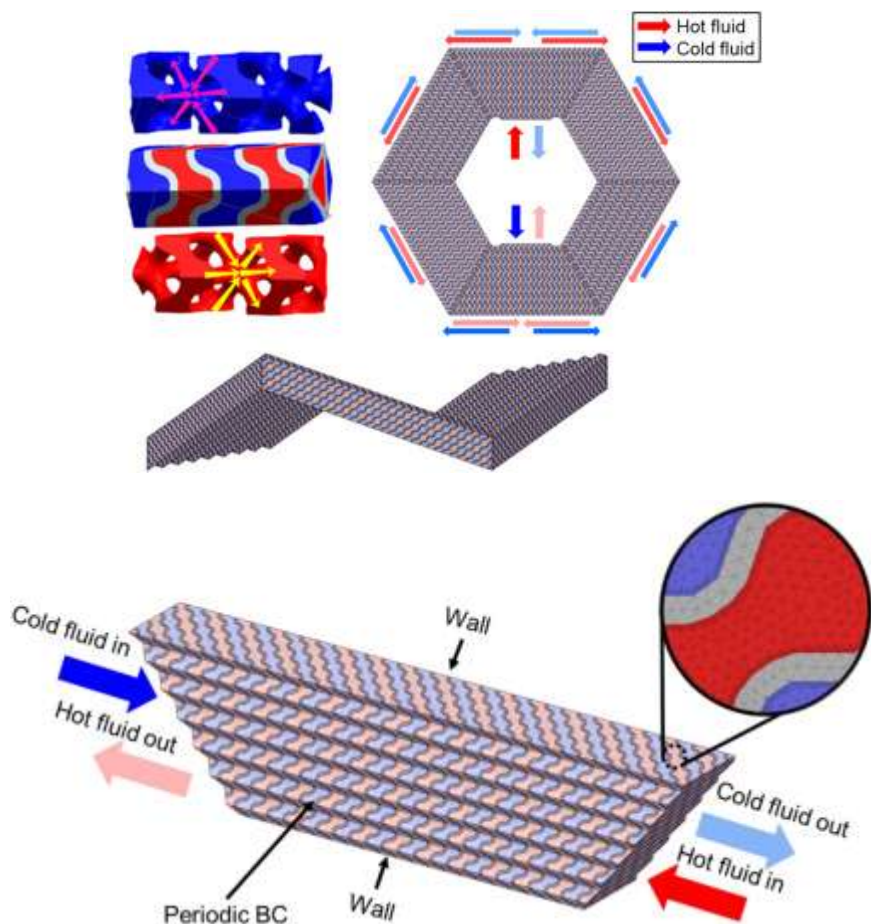
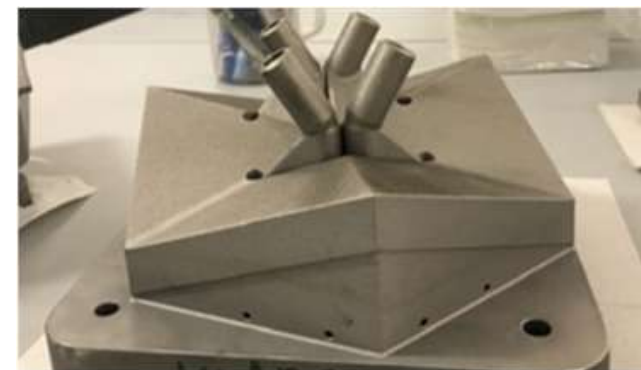
Results & Discussion



TPMS are promising designs for heat exchangers with “similar” fluids, and equal areas on both sides

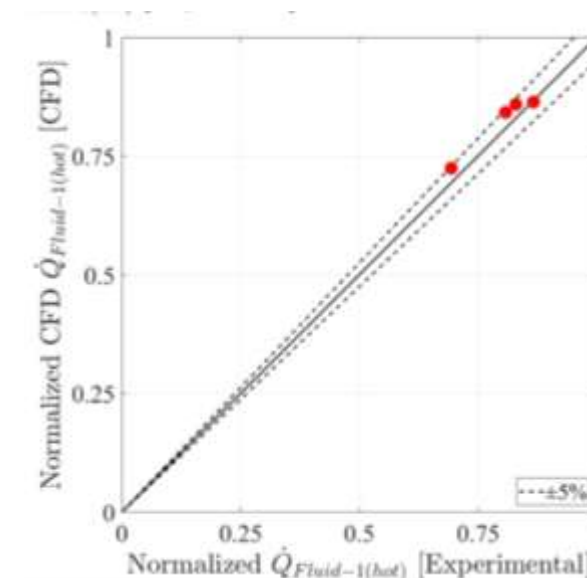
Application – Extreme Conditions

- CFD-based unit-cell characterization
- Developed SEWT-based approach for predicting performance of arbitrary unit cell aggregates, i.e., Slice Solver
- Conducted Multiobjective optimization



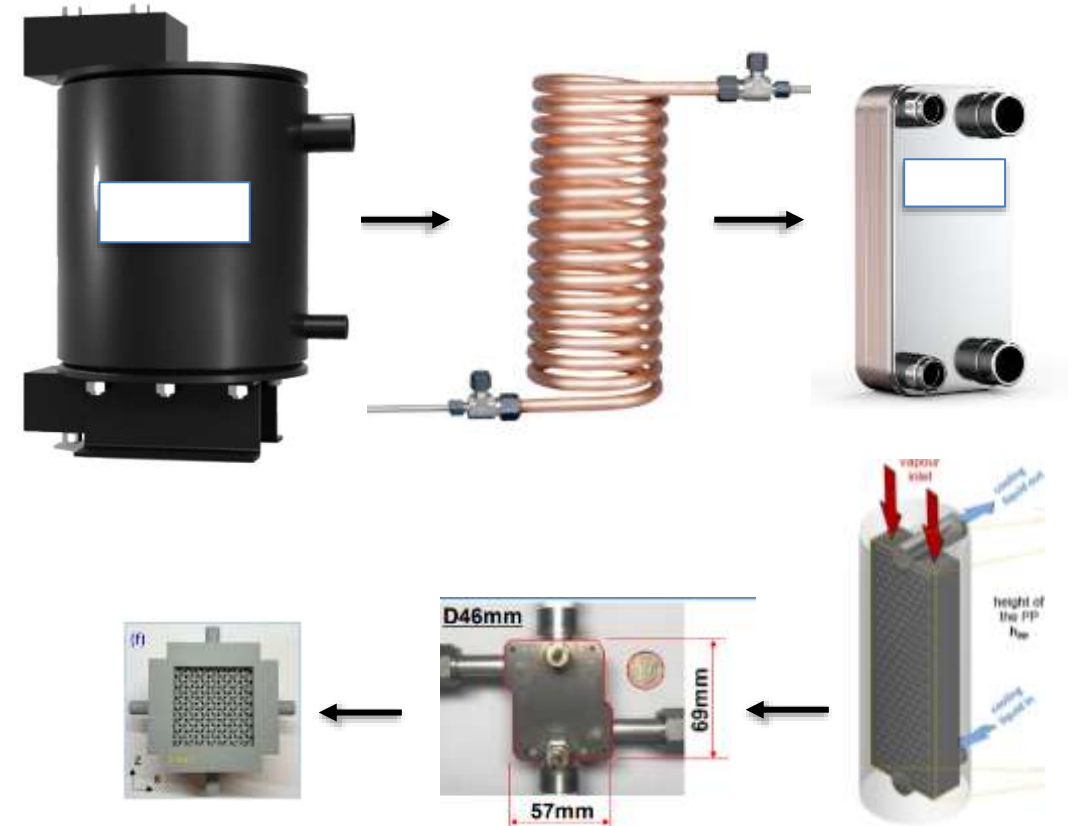
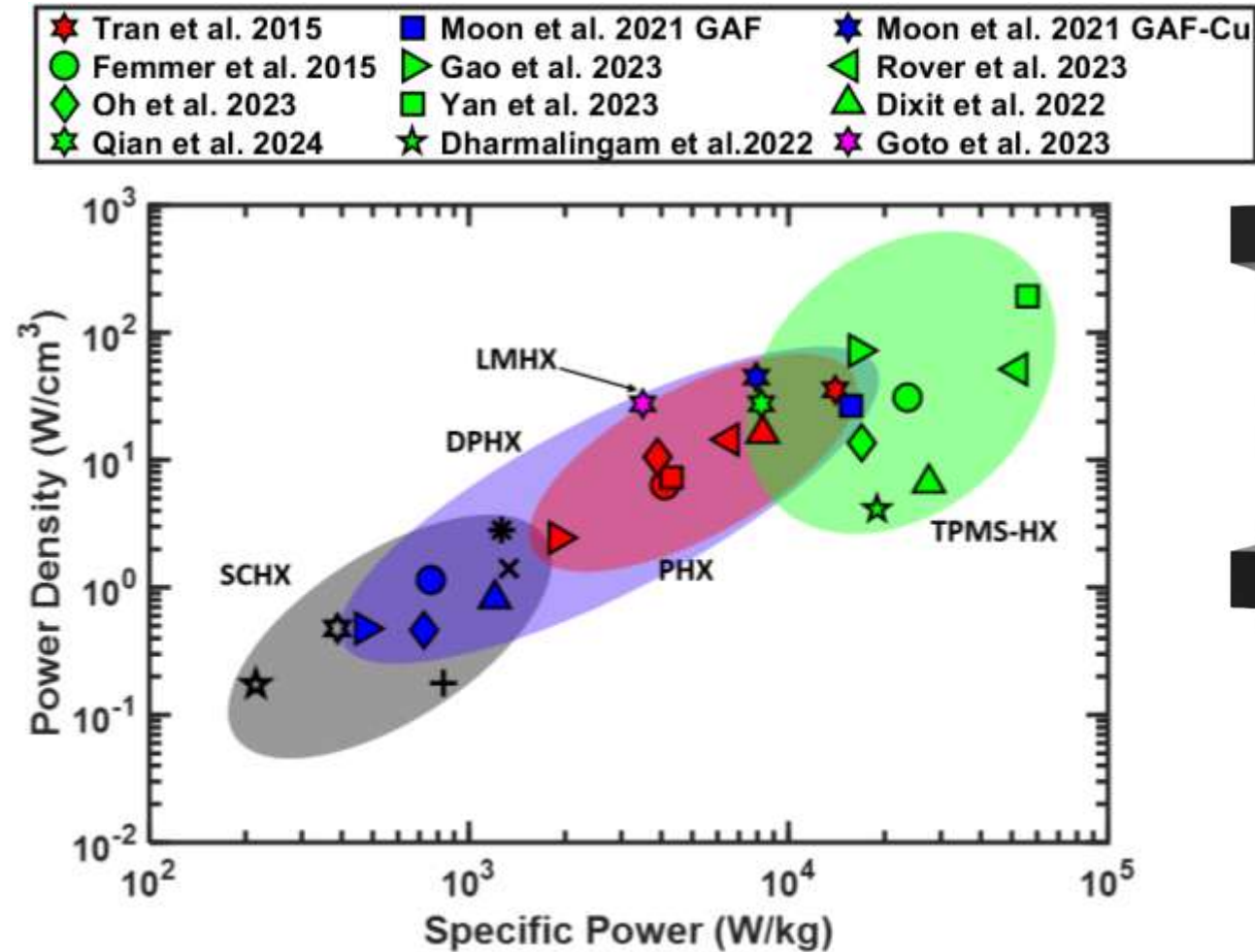
High temperature & pressure sCO₂ cycles Metrics: 3.76 kW/kg (vs. 1.6), 10MW/m³ (vs. 2);

Team: GE-UPHEAT, UMD, ORNL
HX Fabricated by GE-Global Research



Dharmalingam et al., 2025, Intl. J. Heat & Mass Transfer
Supported by ARP Ae-HITEMMP Program
SEWT: Semi-Explicit Wall Temperature based approach

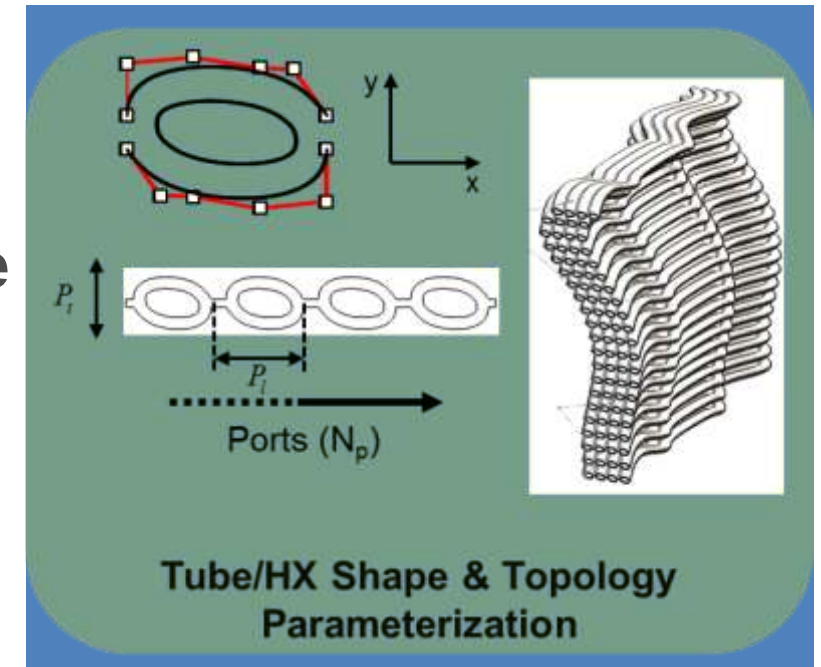
Liquid-to-Refrigerant HX Benchmarking



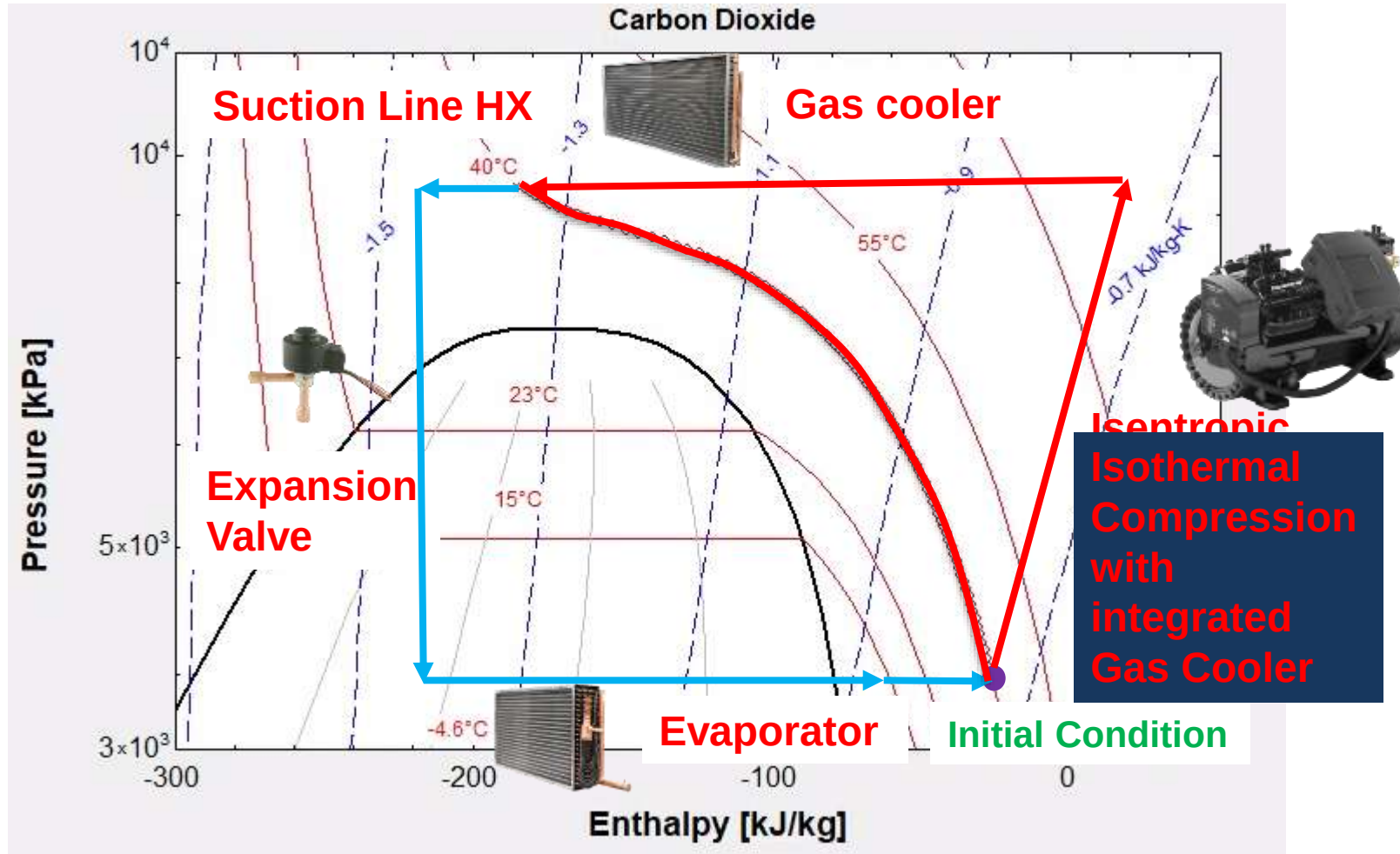
Das et al., 2024, 8th IIR Int. Conf. on Sustainability and the Cold Chain, Japan
Should be interpreted qualitatively.

Opportunities

- HX with unparallelled compactness
- Shape conforming designs
 - HX around battery packs/cells; side panels of a car
 - HX integrated into existing duct
 - HX + Fan integration
- Monolithic HX, with multiple working fluids in the same core; e.g., EV thermal management, multi-circuit systems in HVAC
- Hybrid Manufacturing & trade-offs
 - Conventional Core and AM manifolds
 - Performance trade-off
- Aesthetically pleasing



Isothermal Compression of CO₂



Achieved using a liquid piston compressor

~ 30% COP Improvement

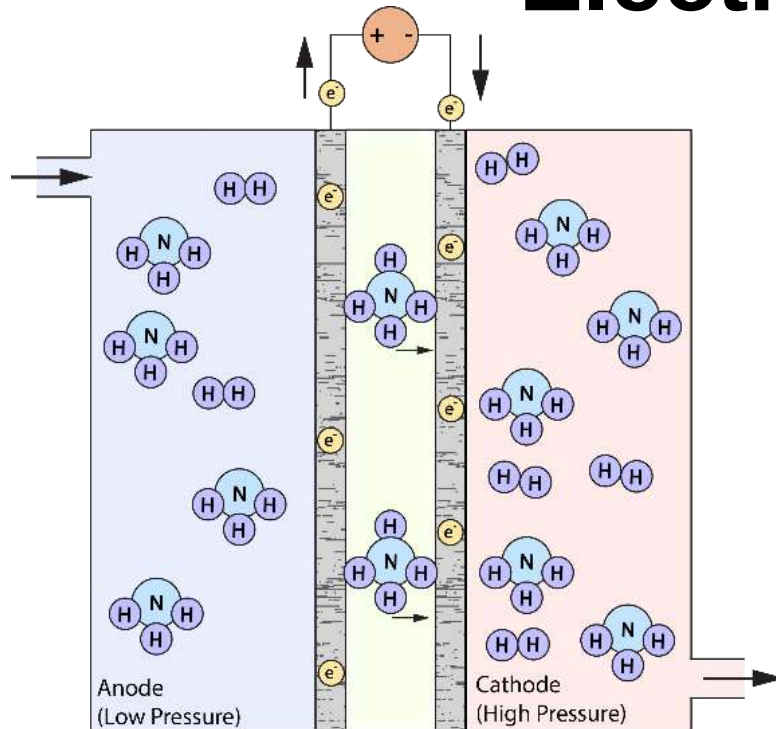
Compressor & condenser are the same device!!!

Demonstrated 27% improvement for CO₂

Timothy Kim, Cheng-Yi Lee, Yunho Hwang, Reinhard Rademacher, 2022, A review on nearly isothermal compression technology, International Journal of Refrigeration, Volume 144, 2022, Pages 145-162

Liu, Haopeng and Lee, Cheng-Yi and Muehlbauer, Jan and Hwang, Yunho and Aute, Vikrant, 2026, Dynamic Modeling of Near Isothermal Compressor for Transcritical Carbon Dioxide Cycle to Support Efficiency Improvement. <http://dx.doi.org/10.2139/ssrn.6206528>

Electrochemical Compression



Pressure lift: 4-9

No moving parts

Oil free!!!

Challenges:

- Presence of external electric field
- Increase pressure via electrochemical reaction
- Coupled mass and charge transfer
- Concept demonstrated for CO₂ as well

- Membrane durability
- Mass throughput

Tao, Y., H. Lee, Y. Hwang, R. Radermacher, C. Wang, 2015, Electrochemical Compressor Driven Metal Hydride Heat Pump, Int. J. of Refrigeration, V.60, pp. 278-288, 08/2015.

Tao, Y., Y. Hwang, R. Radermacher, C. Wang, 2019, Experimental Study on Electrochemical Compression of Ammonia and Carbon Dioxide for Vapor Compression Refrigeration System, Int. J. of Ref., 104, 180-188.

Conclusions

- Space conditioning, food preservation, and data centers will continue to drive the growth and innovation in thermal systems
- Advances in computational methods, computing hardware, and AI/ML is transforming the way thermal systems are conceived, designed, optimized, and operated
- Novel heat exchanger and compressor technologies are around the corner that can yield up to 30% improvement in energy efficiency and 2-5X improvements in heat densities
- Cost is still the primary consideration in introducing novel HX technologies to market
 - Affordability is an important step between innovation and sustainability
 - Need aircraft quality, at automotive scale, for bicycle pricing!
- Incredible room for creativity and collaboration

Thank You for your Attention!

