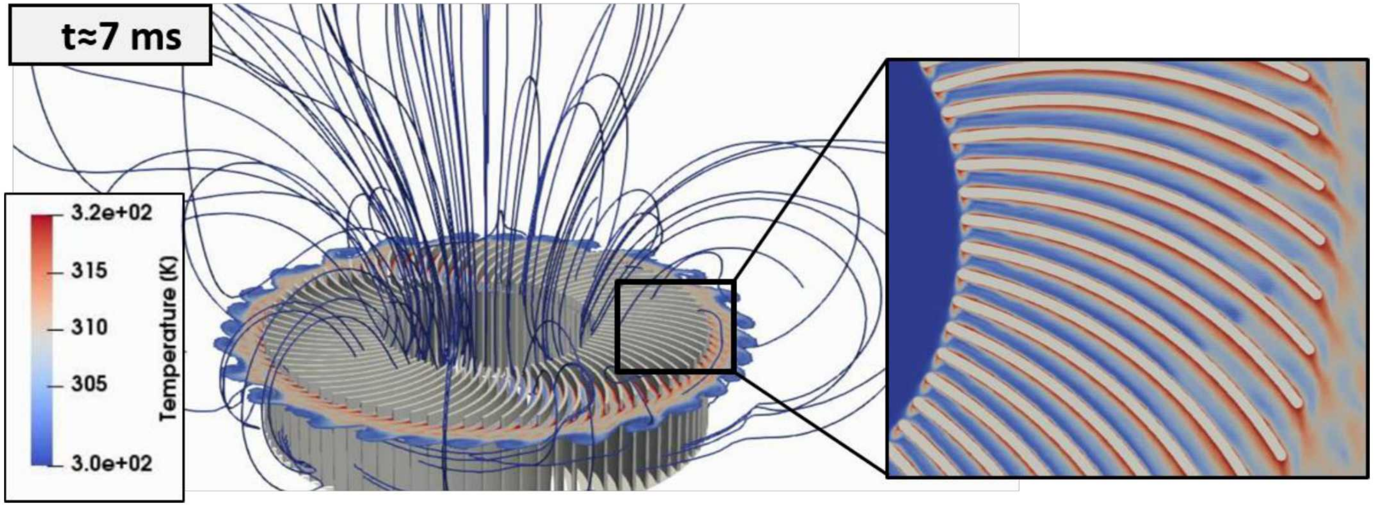
SAND2019-3769C

Fundamental heat transfer physics of rotating heat exchangers and practical realization of non-vapor compression refrigeration



Sandia National Laboratories

Wayne L. Staats, PhD (PI); Rainer Dahms, PhD; Jeff Koplow, PhD

wstaats@sandia.gov

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Project Summary

Timeline:

Start date: October 1, 2018 (early stage)

Planned end date: September 30, 2021

Key Milestones

Project Milestone (M8): Demonstrate operation of rotating IR camera

Go/No-Go Decision Point 1 (M12): Demonstrate agreement between computational model and experimental results

Go/No-Go Decision Point 2 (M24): Demonstrate at least 1 RHX design that exceeds thermal performance of baseline RHX design.

Project Milestone (M36): Demonstrate TRL 4 RHX-based thermoelectric refrigerator having a COP within 10% of a VCC refrigerator.

Budget:

Total Project $ to Date:

- DOE: $450k (FY19)
- Cost Share: N/A (FFRDC)

Total Project $:

- DOE: $1,350k
- Cost Share: N/A (FFRDC)

Key Partners: TBD

Year 1	Complete experimental setup and design hybrid DNS-LES CFD framework
Year 2	Develop high-performance RHX designs and publish a design methodology for RHX technology Develop fundamental understanding of heat transfer in rotating heat exchangers and identify hierarchy of mechanisms
Year 3	Demonstrate a high-COP RHX-based thermoelectric refrigerator, developed to TRL 4

Project Outcome:

- Conduct a combined experimental (rotating IR thermography boundary layer imaging) and computational (hybrid LES-DNS simulation with relevant boundary layer physics) campaign to uncover RHX heat transfer enhancement mechanisms.
- Based on this understanding, develop optimized RHX designs and systematic framework for applying RHX technology to practical applications.
- Use optimized RHX design to demonstrate high-COP, cost-effective thermoelectric refrigeration, which eliminates high-GWP refrigerants without any efficiency compromise. Develop TRL 4 prototype with the intent to stimulate further R&D in the area of non-vapor compression heat pump technology.

Team

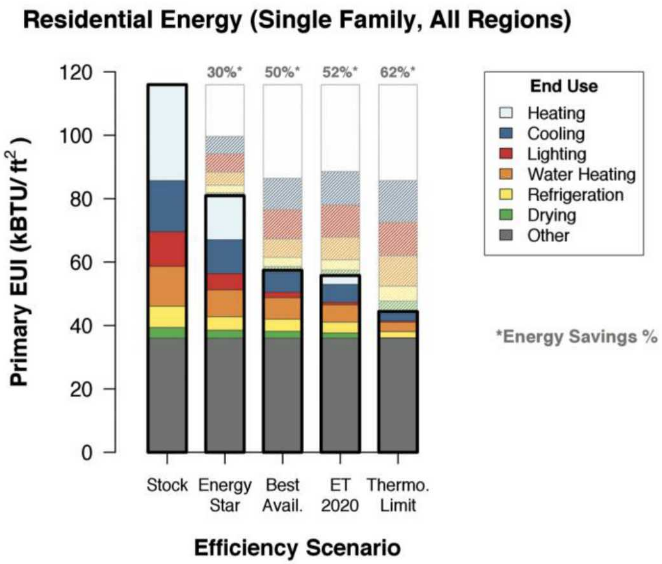
Wayne Staats, PhD (PI), Sandia National Laboratories
- Heat transfer measurements, thermoelectric system design
- Background in thermal-fluids engineering, active convection enhancement, RHX design

Rainer Dahms, PhD, Sandia National Laboratories
- Computational modeling
- Background in combustion modeling, multi-scale simulation, advanced multiphysics CFD

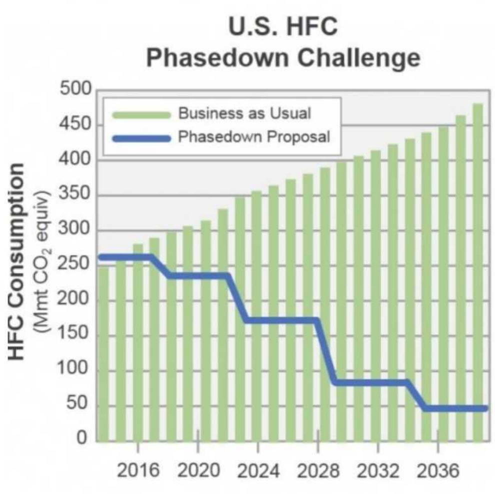
Jeff Koplow, PhD, Sandia National Laboratories
- Thermoelectric system design, electrical engineering
- Background in RHX development (inventor), power electronics, tech transfer and commercialization, multidisciplinary innovation

Challenge

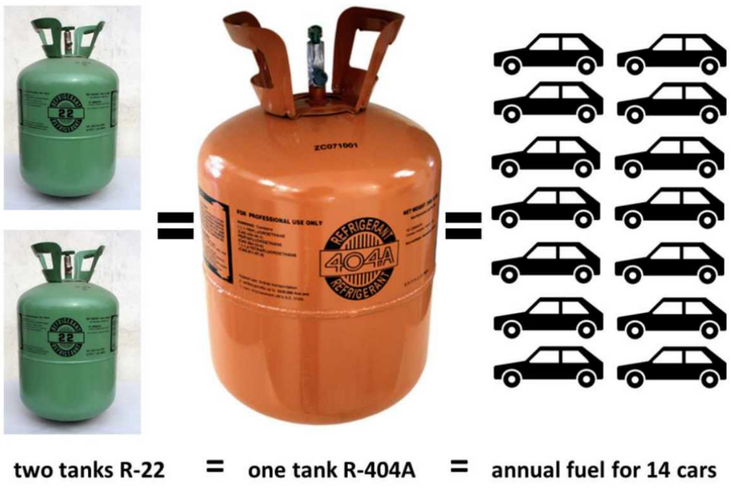
- Heat exchangers (HXs) affect the performance and energy use of many building technologies
- Non-vapor compression (non-VCC) refrigeration is not currently competitive with VCC refrigeration due to HX performance limitations
- Improved HX performance contributes directly to BTO goals
  - Develop cost-effective technologies to reducing a building's energy use per square foot by 45% by 2030
  - Road to "Low": high-GWP refrigerant phasedown (HX performance gains can enable non-VCC refrigeration technology)



[1]



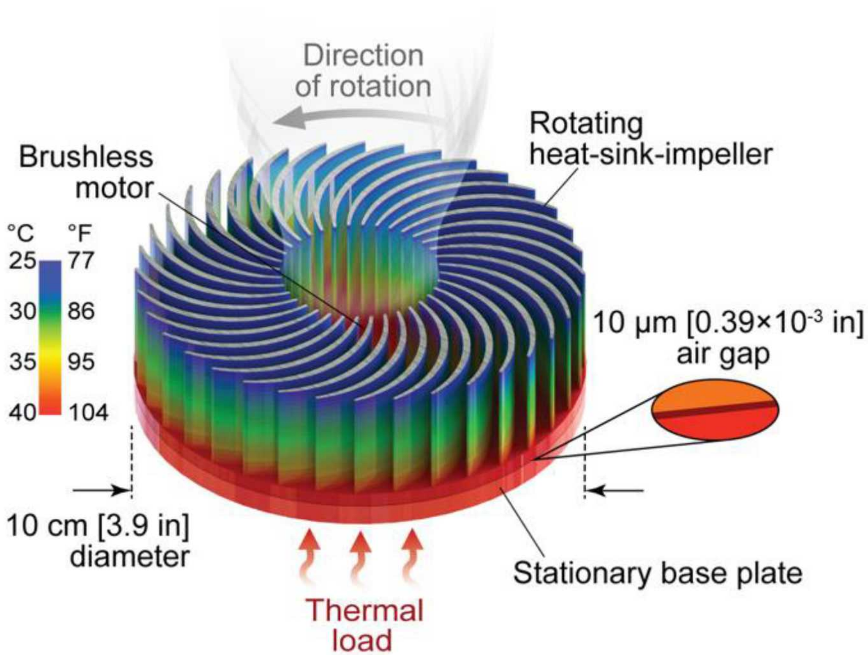
[2]

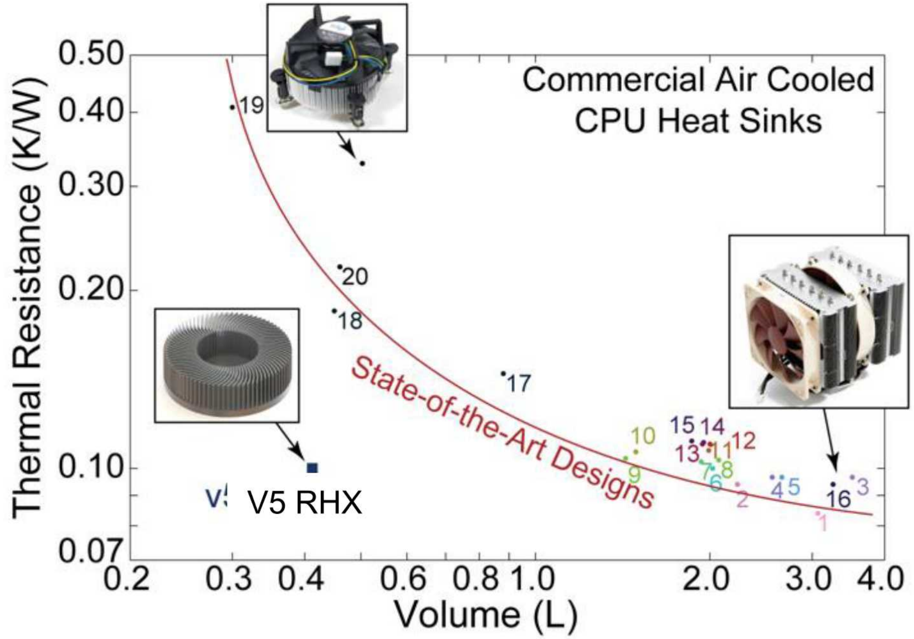


[3]

Challenge

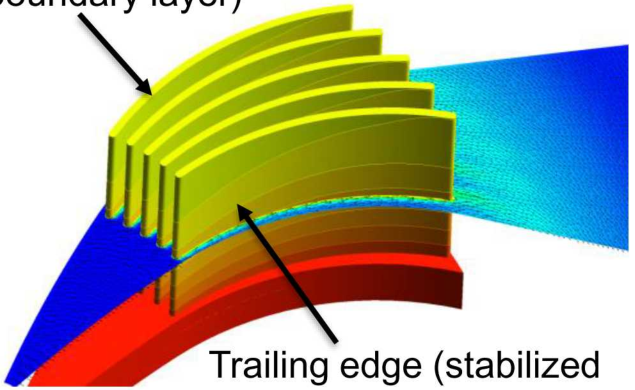
- **Rotating heat exchangers (RHXs) represent a new lever to attack the HX performance optimization problem**
- **RHXs offer significant performance improvements for some applications, especially when cooling a solid (e.g. a semiconductor)**
  - Up to 10x volume reduction, low power consumption, intrinsic fouling resistance, quiet operation
  - Building technology applications: non-VCC refrigeration, solid-state lighting cooling, appliance thermal management, and rooftop solar PV inverter thermal management

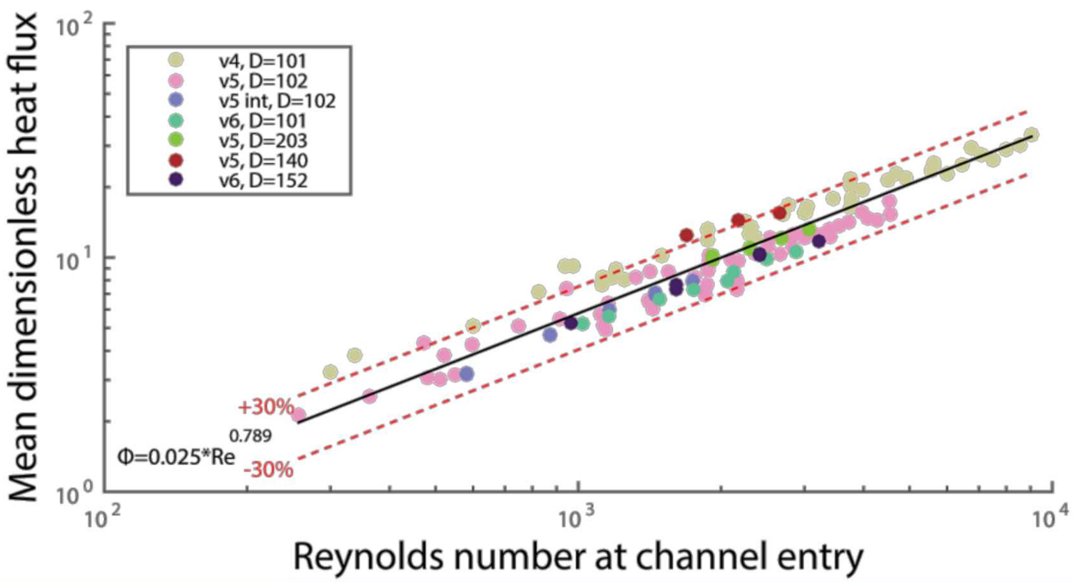


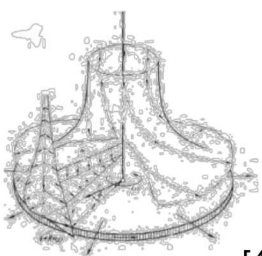


Challenge

- In past work we developed an empirical understanding of RHX performance
- We seek to develop a mechanistic understanding of RHX performance and apply it to non-VCC refrigeration
- Three hypothesized enhancement mechanisms
  - Centrifugal force boundary layer thinning
  - Direct wall-relative-velocity increase
  - Coriolis force boundary layer destabilization
- With a mechanistic understanding, we can develop rationally optimized RHX designs and a systematic framework to apply RHX technology to practical building technology applications

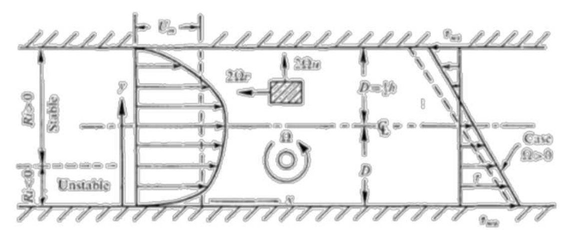






Centrifugal force boundary layer thinning

[4]

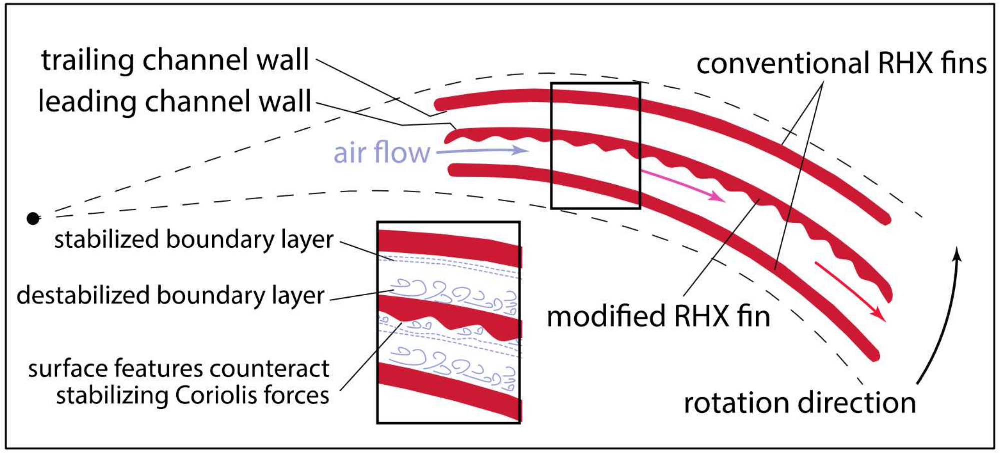


[5]

Coriolis force boundary layer destabilization

Approach

- Combine experimental and computational methods
  - Rotating infrared (IR) thermography to directly probe local boundary layer behavior and wall heat transfer
  - Hybrid Large Eddy Simulation (LES) / Direct Numerical Simulation (DNS) computational study
  - Develop fundamental understanding of physical heat transfer enhancement mechanism
- Develop new RHX designs and design methodology
- Apply optimized RHX design to non-VCC refrigeration
  - Develop TRL 4 prototype refrigeration system



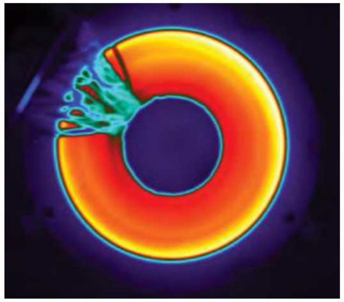
Understanding enhancement mechanism can reveal effective performance improvements

[6]

Example: thin printed circuit board with heater traces

[7]

…viewed with compact IR camera



[6]

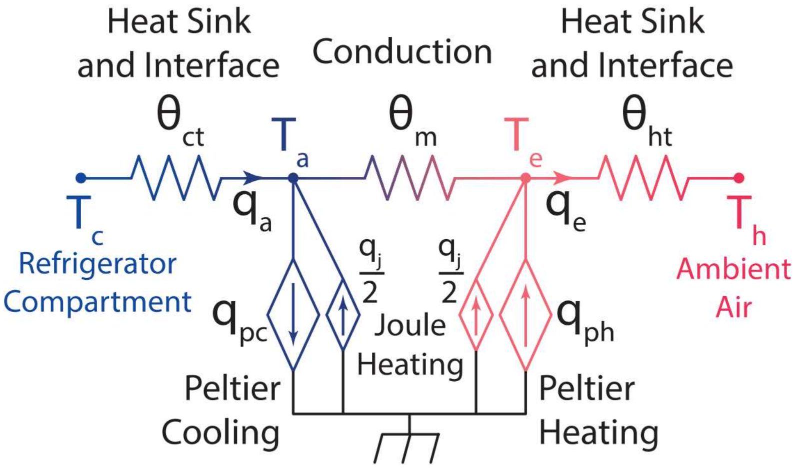
…yields IR image (temperature) → reveals local heat transfer coefficient

Impact

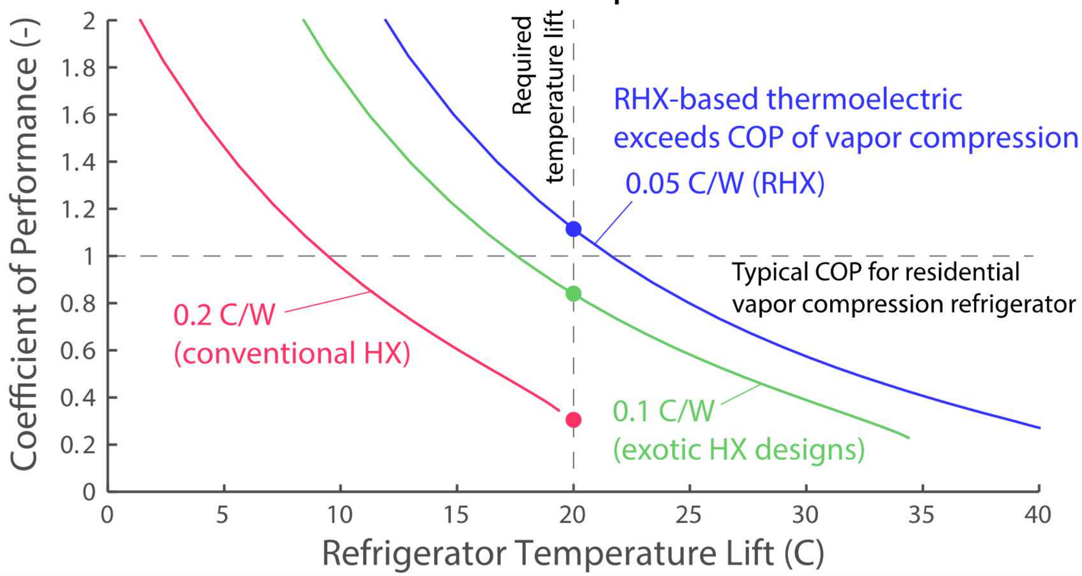
- Understanding the physical mechanisms of RHX heat transfer will reveal the full potential of the technology
- The design tools developed in this project will make RHX technology more accessible to thermal engineers
  - Contributes to BTO ET's goal of reducing building energy use per square foot by 45% by 2030
- High-performance RHX designs enable high-COP, cost-effective thermoelectric residential refrigerators, accelerating phasedown of high-GWP refrigerant use

[8]

Thermoelectric refrigerator system model

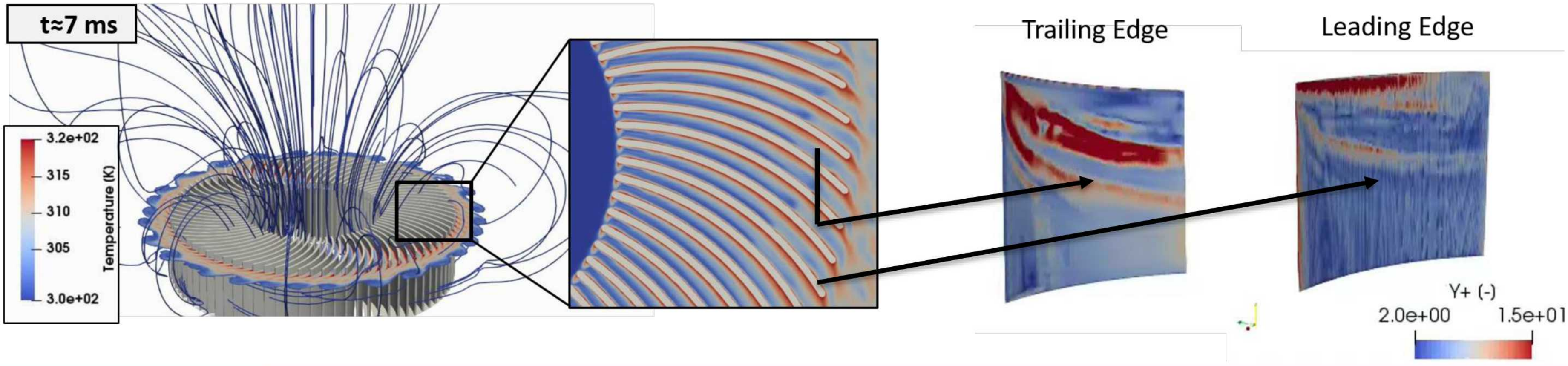


Thermoelectric refrigerator COP is very sensitive to HX performance!



Progress

- Project started in October 2018
- Hybrid LES-DNS flow simulation framework demonstrated
  - Transient simulation of full RHX completed to establish high-fidelity boundary conditions for single channel
  - Boundary layer refinement parameter selected
  - Initial high-fidelity results demonstrated and confirmed to have qualitatively consistent flow behavior
- Design of experimental apparatus completed, fabrication currently underway
  - Conducted literature review of thermographic measurement techniques
  - Selected infrared camera and data acquisition system
  - Rotational platform under construction



Stakeholder Engagement

- Project is in early stage (started in October 2018)
- Key stakeholders include: refrigerator OEMs, thermoelectric device OEMs, research personnel in the field of advanced heat sink design, and DOE personnel responsible for strategic road-mapping and budget allocation on programs related to thermal management, heat pumps, and building efficiency.
- Plan to engage key stakeholders:
  – Year 1: engage Tony Bouza (conduct base research)
  – Year 2 and 3: focus on path forward to engage appropriate OEMs, participate in conferences to share results (e.g. ASME ITherm)
  – Ongoing: assess market and literature to ensure relevancy
  – Future (TBD): develop commercialization strategy

Remaining Project Work

Blue indicates currently in progress

Year	Task	Description
1	**Task 1:** Design experimental apparatus and characterize local heat transfer (M1-M18)	• Design experimental apparatus to accurately determine the local heat transfer characteristics under the range of conditions encountered in RHXs
	Project Milestone (M8): Demonstrate operation of rotating IR camera system and make measurements on a test object.	
	Task 2: Conduct targeted computational study of fundamental RHX heat transfer (M1-M18)	• Test the boundary conditions and setup, assess results by comparison to experiments • Test the dynamic subgrid-scale model to ensure smooth transition between LES and DNS • Perform simulation runs with increasing fidelity and validate against experiments • Analyze and interpret results for novel insights into physical mechanisms
	Go/No-Go Decision Point 1 (M12): Demonstrate that results of computational model agree with average flow and heat transfer measurements of baseline RHX designs under various operating conditions.	
2	**Task 3:** Develop high-performance RHX designs and design methodology (M15-M24)	• Develop high-performance RHX designs that exceed the heat transfer performance of the baseline design and publish a design methodology for RHX technology • Develop fundamental understanding of heat transfer in rotating heat exchangers and identify hierarchy of mechanisms, resulting in a correlation for the local heat transfer coefficient
	Go/No-Go Decision Point 2 (M24): Demonstrate at least 1 RHX design that exceeds thermal performance of baseline RHX design.	
3	**Task 4:** Design and build proof-of-concept RHX-based thermoelectric refrigerator (M22-M36),	• Demonstrate a high-COP RHX-based thermoelectric refrigerator, developed to TRL 4 by the end of year 3 and having a COP comparable to VCC refrigerators.
	Project Milestone (M36): Demonstrate TRL 4 RHX-based thermoelectric refrigerator having a COP within 10% of a vapor compression refrigerator.	

Thank You

Sandia National Laboratories

Wayne Staats, PhD

wstaats@sandia.gov

REFERENCE SLIDES

Project Budget

Project Budget: Federal funds: $1350k Cost-Share: N/A (FFRDC) Total: $1350k
Variances:
Cost to Date: $260k
Additional Funding:

Budget History					
10/1/2019– FY 2019 (current)		FY 2020 (planned)		FY 2021 – 9/30/2021 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$450k	N/A	$450k	N/A	$450k	N/A

Project Plan and Schedule

Blue indicates currently in progress

Year	Task	Description
1	**Task 1:** Design experimental apparatus and characterize local heat transfer (M1-M18)	• Design experimental apparatus to accurately determine the local heat transfer characteristics under the range of conditions encountered in RHXs
	Project Milestone (M8): Demonstrate operation of rotating IR camera system and make measurements on a test object.	
	Task 2: Conduct targeted computational study of fundamental RHX heat transfer (M1-M18)	• Test the boundary conditions and setup, assess results by comparison to experiments • Test the dynamic subgrid-scale model to ensure smooth transition between LES and DNS • Perform simulation runs with increasing fidelity and validate against experiments • Analyze and interpret results for novel insights into physical mechanisms
	Go/No-Go Decision Point 1 (M12): Demonstrate that results of computational model agree with average flow and heat transfer measurements of baseline RHX designs under various operating conditions.	
2	**Task 3:** Develop high-performance RHX designs and design methodology (M15-M24)	• Develop high-performance RHX designs that exceed the heat transfer performance of the baseline design and publish a design methodology for RHX technology • Develop fundamental understanding of heat transfer in rotating heat exchangers and identify hierarchy of mechanisms, resulting in a correlation for the local heat transfer coefficient
	Go/No-Go Decision Point 2 (M24): Demonstrate at least 1 RHX design that exceeds thermal performance of baseline RHX design.	
3	**Task 4:** Design and build proof-of-concept RHX-based thermoelectric refrigerator (M22-M36),	• Demonstrate a high-COP RHX-based thermoelectric refrigerator, developed to TRL 4 by the end of year 3 and having a COP comparable to VCC refrigerators.
	Project Milestone (M36): Demonstrate TRL 4 RHX-based thermoelectric refrigerator having a COP within 10% of a vapor compression refrigerator.	

References

[1] https://www.energy.gov/sites/prod/files/2015/10/f27/Ch5-SI-building-technologies-potential-savings-analysis-10-6-15.pdf

[2] https://www.energy.gov/eere/buildings/road-zero-does-next-generation-heating-and-cooling-rd-strategy

[3] https://ww2.arb.ca.gov/resources/documents/high-gwp-refrigerants

[4] Schlichting, H. “Boundary-layer theory,” Seventh edition, McGraw-Hill series in mechanical engineering, pp. 102-107, 1979.

[5] Benton, G., & Boyer, D. (1966). Flow through a rapidly rotating conduit of arbitrary cross-section. Journal of Fluid Mechanics, 26(1), 69-79. doi:10.1017/S0022112066001095

[6] Staats, W.L., Active heat transfer enhancement in integrated fan heat sinks, doctoral dissertation, Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/80414, 2012.

[7] http://www.optovision.fr/IMG/pdf/flir_quark2_brochure.pdf

[8] https://products.geappliances.com/appliance/gea-specs/GCE06GSHSB