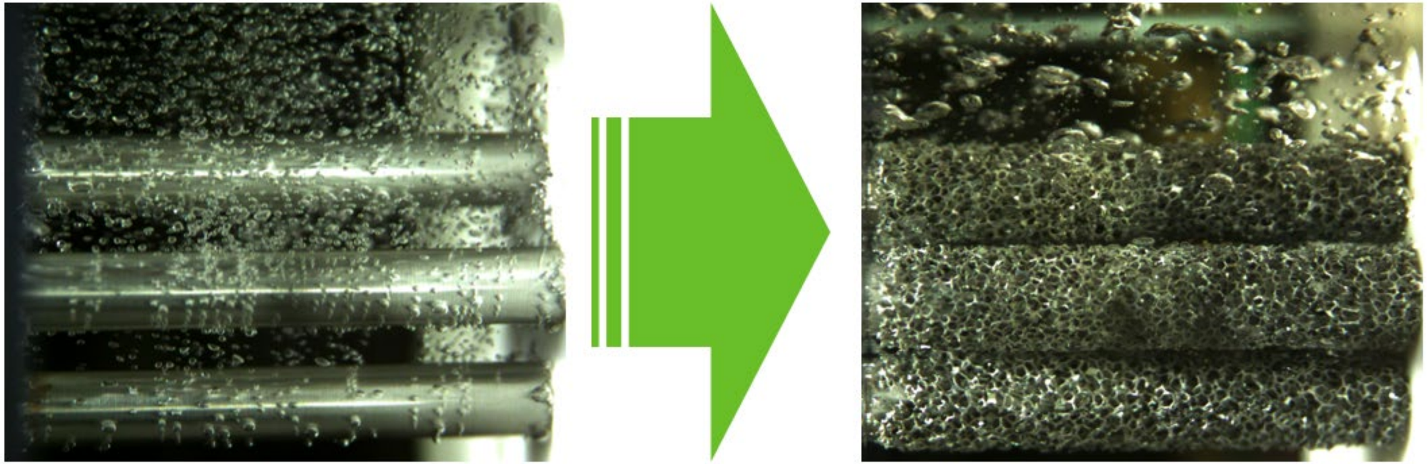
2024 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Novel Compact Flooded Evaporators for Commercial Refrigeration

Novel Compact Flooded Evaporators for Commercial Refrigeration

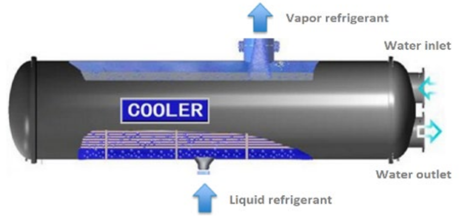


Oak Ridge National Laboratory
Kashif Nawaz, Section Head, Building Technologies Research
865-241-0972, nawazk@ornl.gov
WBS 03.02.02.79.02

Project Summary

OBJECTIVE, OUTCOME, AND IMPACT

- Design and demonstrate a next-generation flooded evaporator with more than 40% reduction in refrigerant charge for commercial and process cooling use.
- Evaluate the performance of equipment for ultra-low GWP (<10) refrigerants and identify the performance improvement opportunities.



TEAM AND PARTNERS

Oak Ridge National Laboratory: Kashif Nawaz, Cheng-Min Yang, Muneeshwaran M., Brian Fricke

Johnson Controls: Patrick Marks

Isotherm Inc.: Zahid Ayub

Copeland: Drew Welch

STATS

Performance Period: Oct. 2022–Sept. 2025

DOE Budget: $250k, Cost Share: $100k

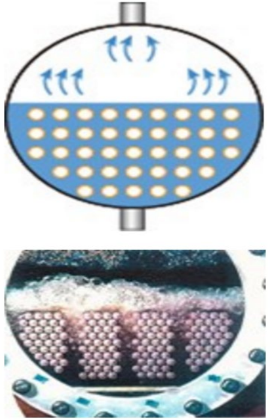
Milestone 1: Single tube and bundle experiments (completed)

Milestone 2: Fabrication of large-scale metal foam tubes (completed)

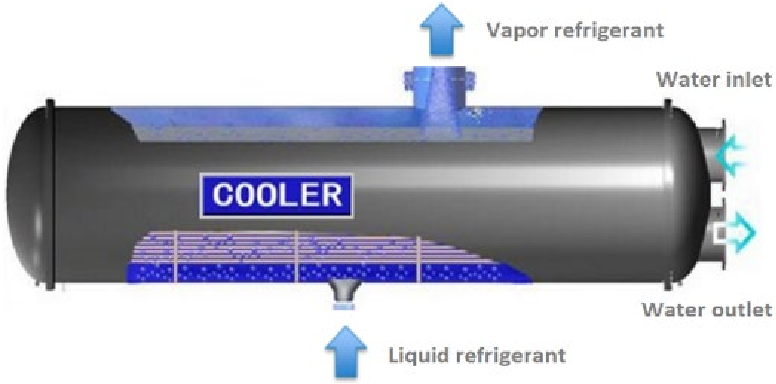
Milestone 3: Testing of large-scale tubes with low-GWP refrigerants (in progress)

Problem

- Development of energy-efficient equipment is critical to enhancing national energy security
  - Commercial processes such as refrigeration/process cooling (~2.67 Quads/year) are major energy users
- A flooded evaporator configuration is more common than a direct expansion configuration because of improved system efficiency
- The large flooded evaporator in such systems is a major disadvantage
  - Results in excessive refrigerant charge and increases pumping work



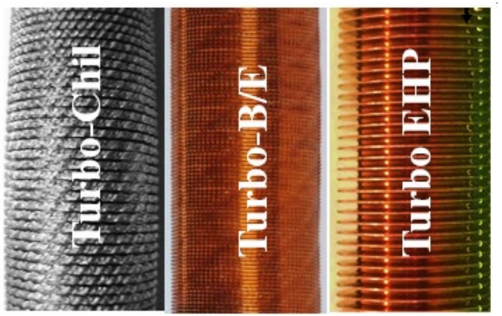
Flooded evaporator operation for water cooling



60%–70% of charge inventory, ~800–1,200 lb for 60 tons

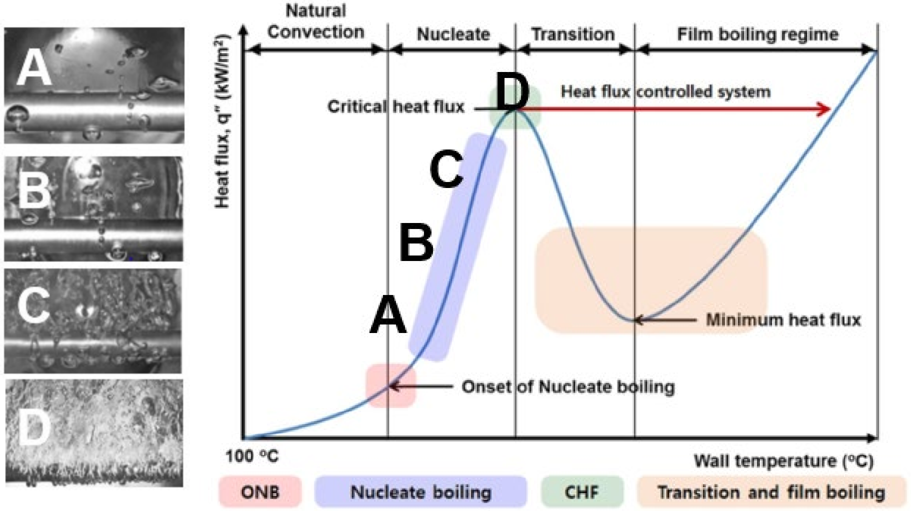
Problem

- Evaporator size depends on rate of heat transfer from fluid flowing through tubes to the refrigerant; heat transfer rate, in turn, is a function of heat transfer surface area and nucleation site density
- Most existing tubes in flooded evaporators have surface enhancements; however, these enhancements are not cost effective and provide limited advantages



Existing enhanced tubes

$$q_s'' = \mu_l h_{fg}\left[\frac{g(\rho_l-\rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f}h_{fg}Pr_l^n}\right)^3$$

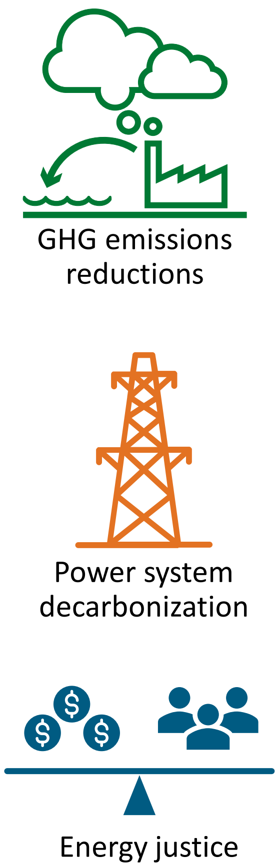


Rohsenow, *ASME Transactions*, 74, 969, 1952.

Alignment and Impact

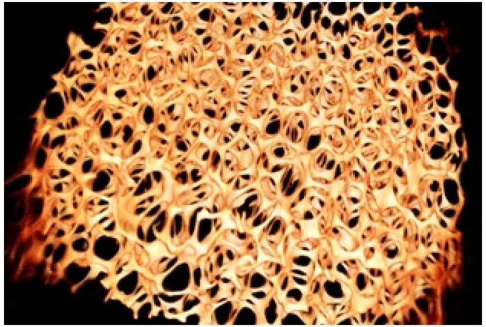
Aligned with BTO goal to develop energy-efficient technology to achieve net-zero GHG emissions by 2050 (~400 Mton CO_2 emission reduction)

- **An improved refrigeration/commercial cooling technology**
  - Unprecedented thermal-hydraulic performance (demonstrated 291% improvement)
  - Reduced footprints (~40% smaller equipment size)
  - Reduced manufacturing cost (20%–30%)
  - Reduced CO_2 footprints (20%–30%)
- **Enables development for deployment of A2L and A3 refrigerants**
  - Reduction in refrigerant charge (at least 40%)
  - Reduced maintenance owing to improved superheat
- **Implications for additional processes**
  - Power generation, waste heat recovery, electronics cooling

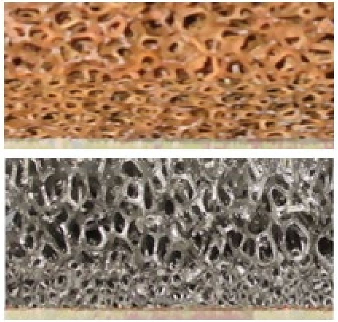


Approach

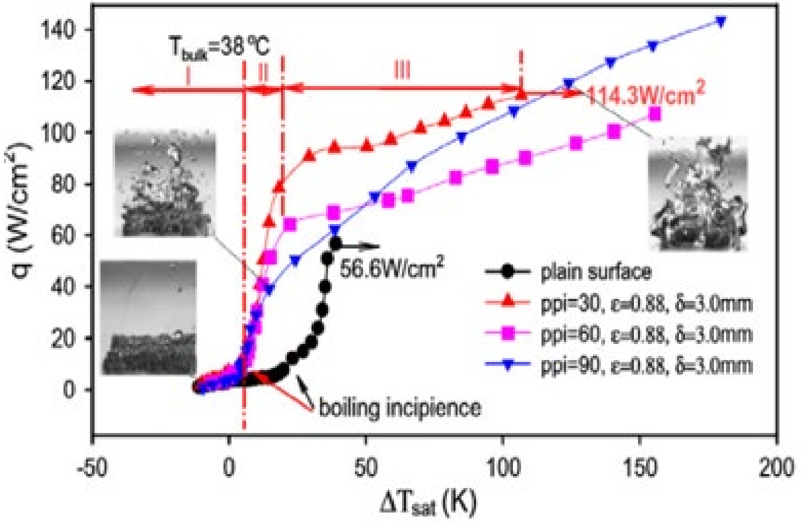
- Metal foam has shown promising results for thermal applications
- Greater surface area (~2,500 m^2/m^3) and tortuous structure provide higher nucleation site density
- Variable porosity achieved through appropriate compression process is another obvious advantage



Complex structure of a metal foam (x-ray TC image)



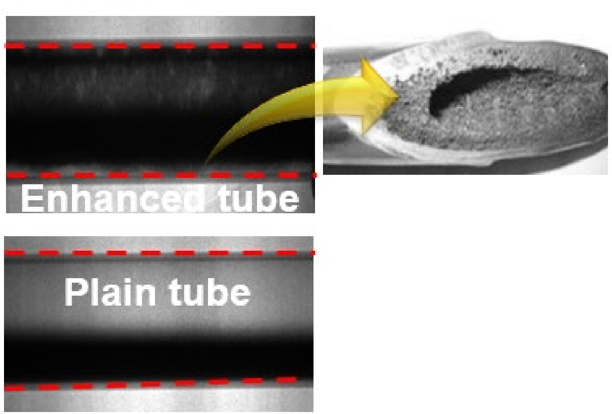
Metal foam with variable pore size



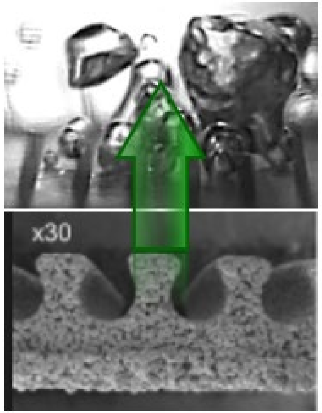
Metal foam can provide a ~35%–45% enhancement in heat transfer coefficient, higher surface-area-to-volume ratio, and higher heat transfer coefficient leading to 40% higher heat transfer rate

Approach

- Deployment of metal foam–enhanced tubes can lead to ≥40% reduction in flooded evaporator size owing to improved heat transfer rate
- Volume occupied by foam material can further reduce refrigerant charge by 30%–40%; the design allows easy substitution of A2L and A3 refrigerants
- Wicking effect accommodates a larger heat flux to keep liquid always in contact with boiling surface → ***Delayed dry-out***



Neutron radiograph of flow boiling for enhanced and plain tube

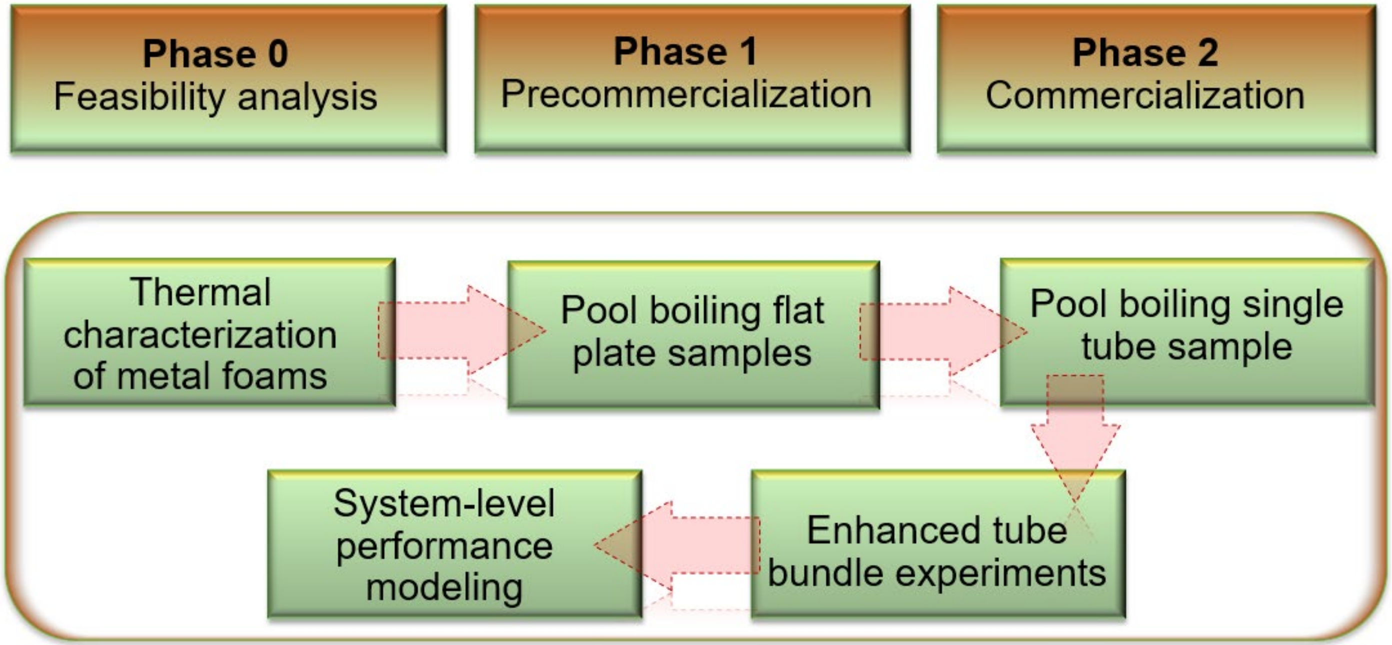


Wicking structures assist in delaying dry-out

Metal foam–enhanced tube bundle

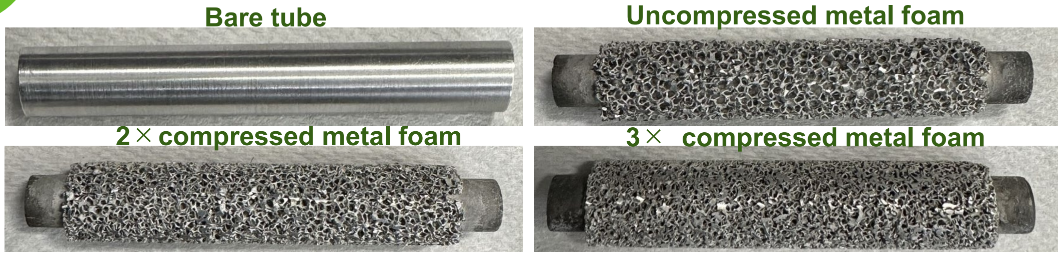
Intellectual property, 2021, "High efficiency compact boilers/evaporators and condensers."

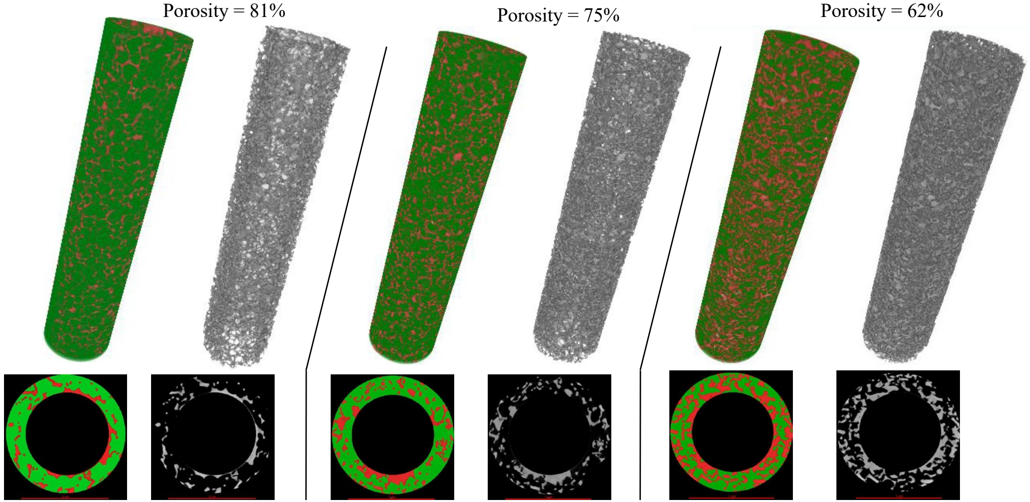
Approach



Design, demonstrate, and analyze performance of ultracompact flooded evaporator that can lead to at least 20% increased efficiency with 40% reduction in total system refrigerant charge

Progress Characterization of metal foam tubes





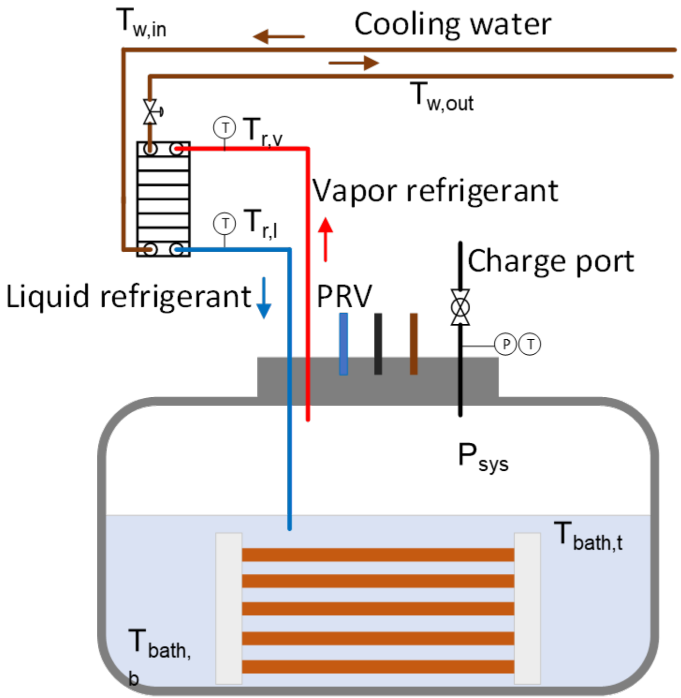
X-ray computed tomography (3D scanning) for metal foam–enhanced tubes

- Material of tube: aluminum (6101)
- Outer diameter of tube: 9.52 mm
- Length of tube: 76.5 mm
- Aluminum (6101) metal foam with 40 PPI was brazed around tube's outer surface
- Metal foam thickness: 2.54 mm
- Porosity of metal foam quantified using x-ray computed tomography

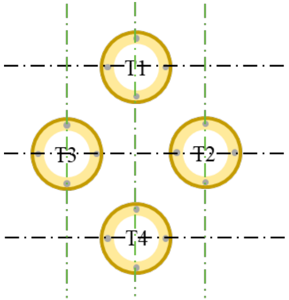
Metal foam porosities

Metal foam enhanced tube	Porosity
Uncompressed metal foam	81%
2× compressed metal foam	75%
3× compressed metal foam	62%

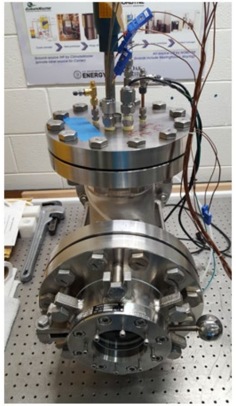
Progress Development of experimental facility



Schematic of tube bundle setup

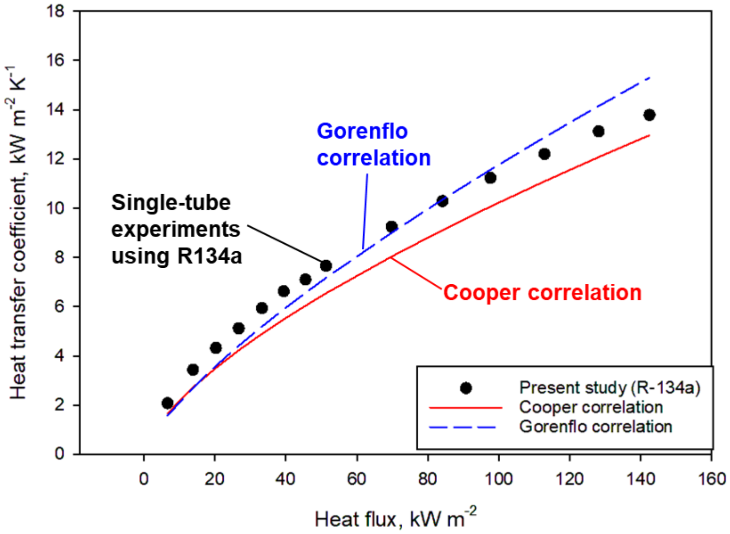


Thermocouple locations



Pressure vessel

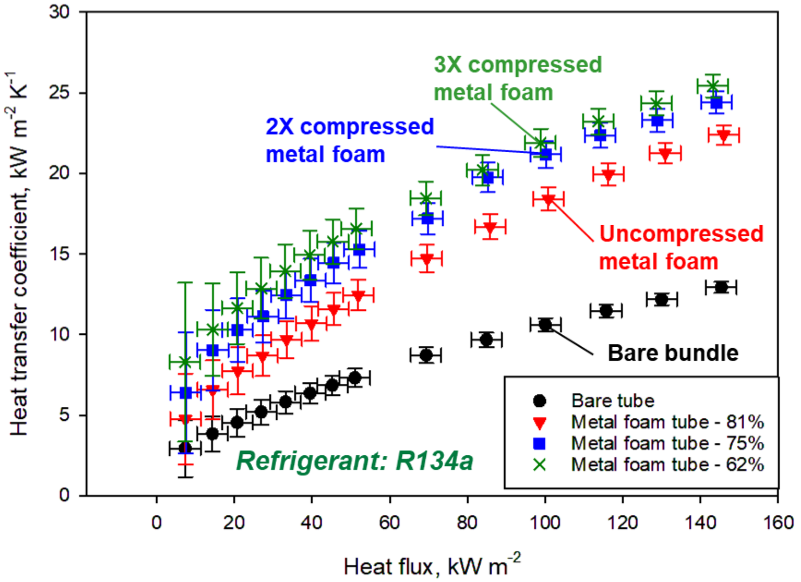
Heat transfer coefficient of plain single tube



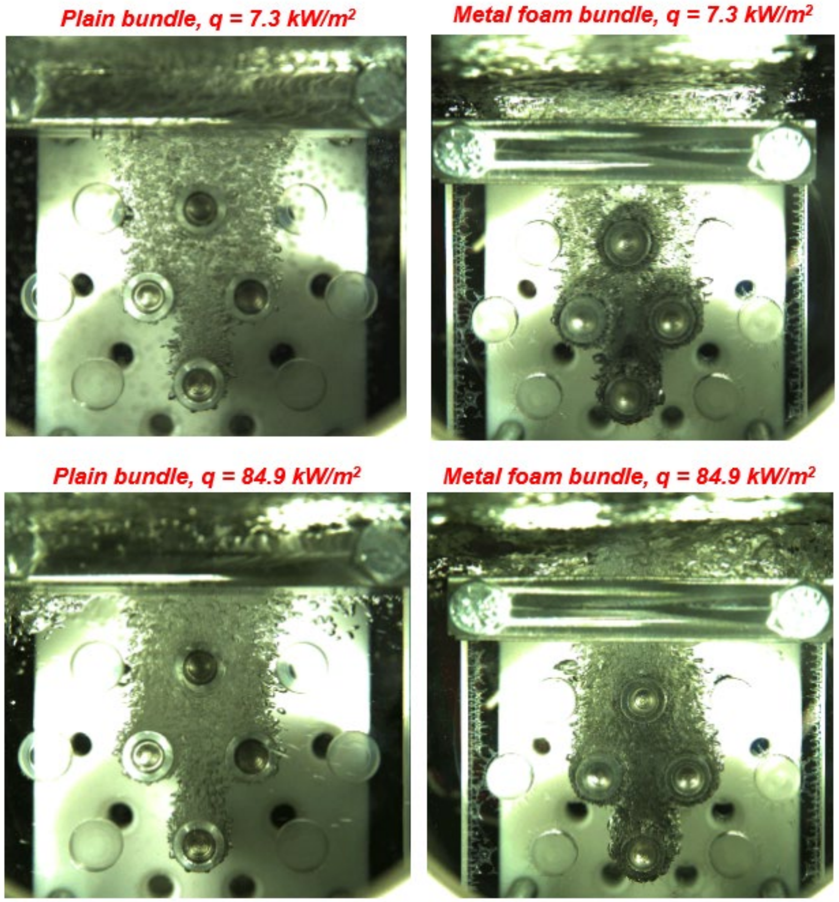
- Single-tube experiments using R-134a were conducted for facility validation
- Results show good agreement with Cooper (5%–20% deviation) and Gorenflo (1%–20% deviation) correlations

Progress

Performance of metal foam tubes

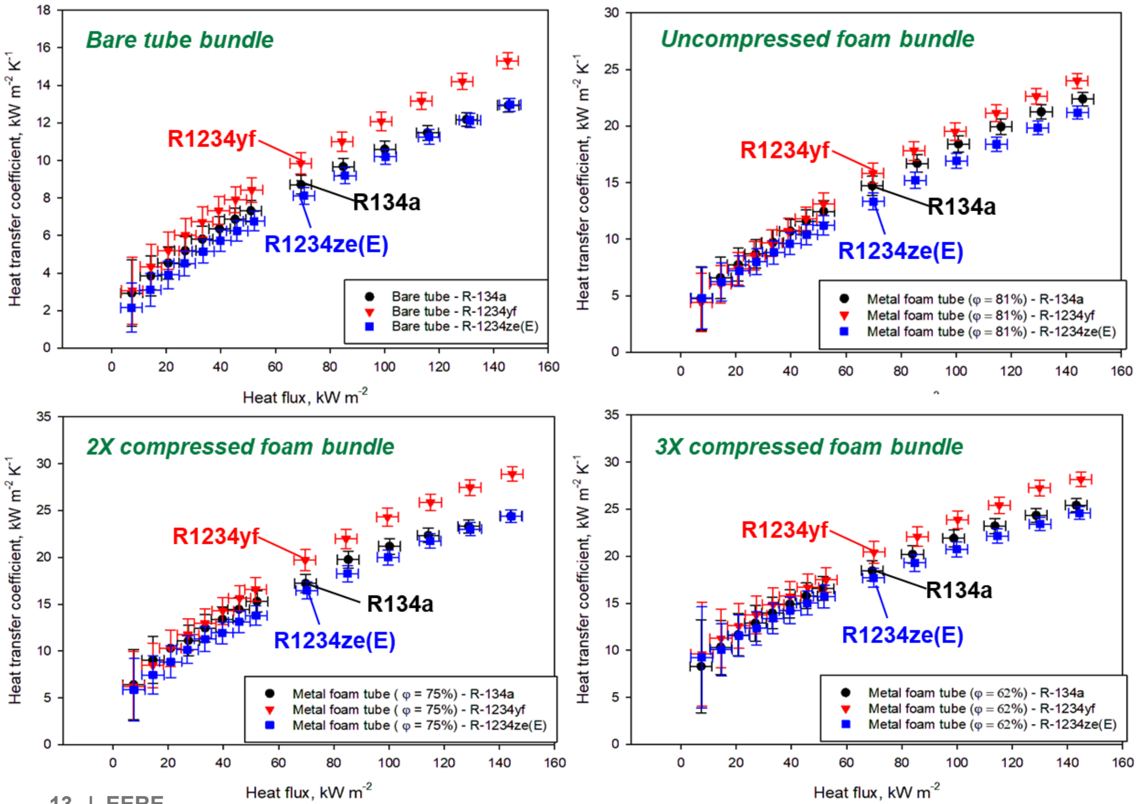


- Metal foam tube bundles provide a maximum of 291% enhancement in HTC compared with bare tube bundle
- HTC increases with decreasing porosity
- Larger surface area and greater number of nucleation sites cause increased HTC in metal foam tubes



These images will be replaced by videos

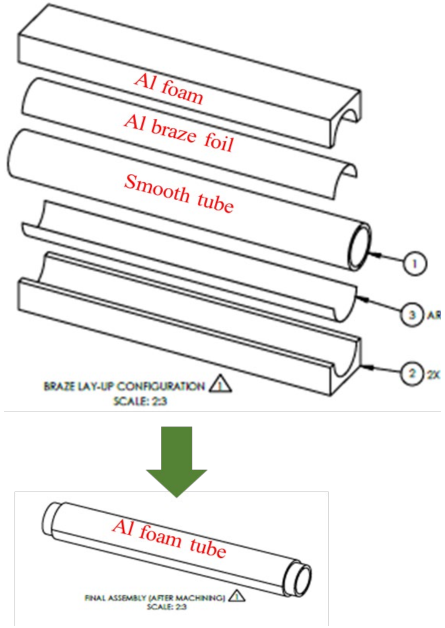
Progress R-134a vs. R-1234yf vs. R-1234ze(E)



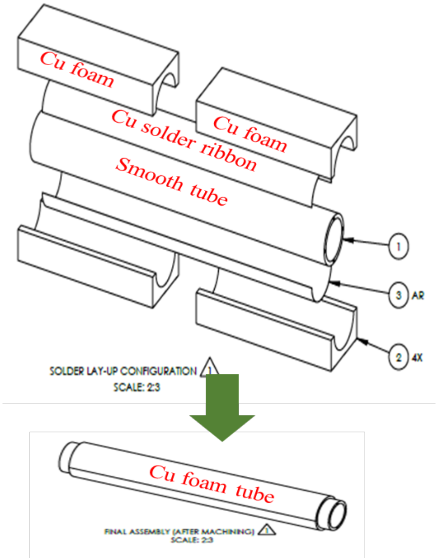
- Both bare and metal foam–enhanced tube bundles were tested using three refrigerants:
  - R-134a (GWP = 1,430)
  - R-1234yf (GWP = 4)
  - R-1234ze(E) (GWP = 7)
- R-1234yf performance is nearly 10% higher than that of R-134a for both bare and metal foam tubes, whereas R-1234ze(E) performance is nearly 5% lower than that of R-134a
- In summary:
  - ✓ R-1234yf > R-134a > R-1234ze(E)
  - ✓ 3× compressed ≈ 2× compressed > uncompressed

Progress Scaling up development of large specimens

Aluminum metal foam tubes—Fabrication



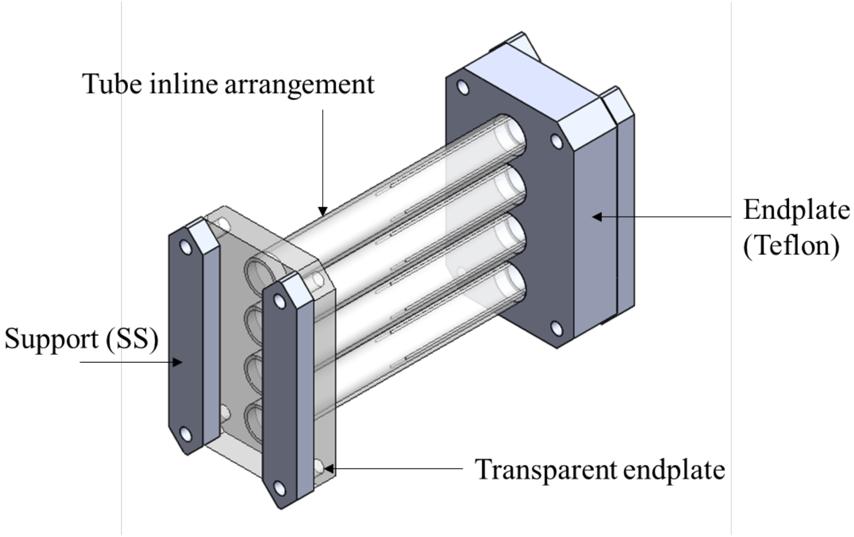
Copper metal foam tubes—Fabrication



Parameters	Values
Tube outer diameter	3/4 in.
Total length	6 in.
Metal foam thickness	1.5 mm
Metal foam PPI	40 PPI (3× compressed)

Future Work

- FY25 will focus on testing commercial scale tube size (3/4 in.)
- Inline tube arrangement with P/D ratio of 1.3 selected
- Tests will be conducted on ultra low-GWP refrigerants (e.g., R-290, R-1234yf, R-1234ze(E), and R-1233zd)
- Four tubes will be tested
    - Smooth
    - Aluminum foam
    - Copper foam
    - Commercial (e.g., GEWA, Turbo)



Publications Two journal and four conference articles

Applied Thermal Engineering 236 (2024) 121812

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Augmentation of pool boiling heat transfer on tube bundles using metal foam

M. Muneeshwaran [a,*], Cheng-Min Yang [a], Ercan Cakmak [b], Kashif Nawaz [a,*]

[a] Building Technologies Research and Integration Center, Oak Ridge National Laboratory, TN, USA
[b] Materials Science and Technology Division, Oak Ridge National Laboratory, TN, USA

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Research Paper

Pool boiling heat transfer characteristics of low-GWP refrigerants in a horizontal tube bundle configuration

M. Muneeshwaran [a,*], Cheng-Min Yang [a], Ercan Cakmak [b], Kashif Nawaz [a,*]

[a] Building Technologies Research and Integration Center, Oak Ridge National Laboratory, TN, USA
[b] Material Science and Technology Division, Oak Ridge National Laboratory, TN, USA

Conference papers

- Zhang, Mingkan; Nawaz, Kashif; Yang, Cheng-Min; Sandlin, Matthew; Asher, William; Fricke, Brian; and Gehl, Anthony, “A Numerical Study on the Pool Boiling with Foam Surface Enhancement Using Different Refrigerants” (2021). International Refrigeration and Air Conditioning Conference. Paper 2179.
- Yang, Cheng-Min; Asher, William; Sandlin, Matthew; and Nawaz, Kashif, “Enhanced Pool Boiling of Low-Pressure Refrigerants on Round Tubes—An Experimental Evaluation” (2022). International Refrigeration and Air Conditioning Conference. Paper 2397.
- Yang, Cheng-Min; Muneeshwaran, M.; Wang, Pengtao; and Nawaz, Kashif, “Pool Boiling On Metal-Foam Enhanced Tube Bundle: Heat Transfer Characteristics and Flow Visualization” (2023). 14th IEA Heat Pump Conference. Paper 1098.
- Yang, Cheng-Min; Muneeshwaran, M.; and Nawaz, Kashif, “Experimental Investigation on Nucleate Boiling Heat Transfer of Low-GWP Refrigerants over Metal-Foam Enhanced Tube Bundles” (2023). ICR2023, 26th International Congress of Refrigeration.

Intellectual property

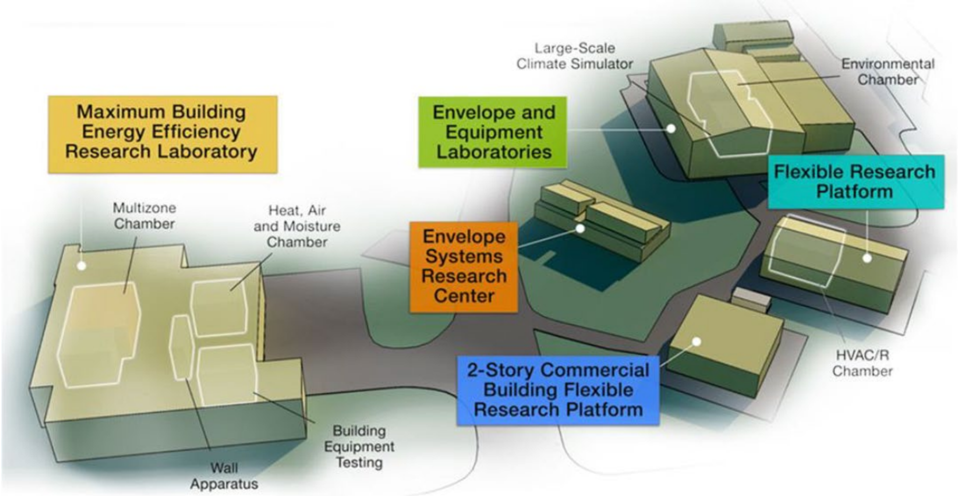
- US nonprovisional patent application, 6321-548, “Enhanced Pool Boiling System and Method.”

Thank you

Oak Ridge National Laboratory

Kashif Nawaz, Section Head, Building Technologies Research
865-241-0972, nawazk@ornl.gov

WBS 03.02.02.79.02



The **Building Technologies Research and Integration Center** (**BTRIC**) at ORNL has supported DOE BTO since 1993. BTRIC is comprised of more than 60,000 square feet of lab facilities conducting RD&D to develop affordable, efficient, and resilient buildings while reducing their greenhouse gas emissions 65% by 2035 and 90% by 2050.

Scientific and Economic Results
139 publications in FY24
140+ industry partners
60+ university partners
16 R&D 100 awards
64 active CRADAs

BTRIC is a DOE-Designated National User Facility

Reference Slides

Project Execution

	FY2023				FY2024				FY2025			
Planned budget ($)	250,000				250,000				250,000			
Spent budget ($)	230,000				260,000							
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: Evaluation of pool boiling on flat surfaces												
Q2 Milestone: Single tube experiments (low pressure fluids)												
Q3 Milestone: Tube bundle experiments (low pressure fluids)												
Q4 Milestone: Single enhanced tube experiments (HFOs)												
Q1 Milestone: Enhanced tube bundle experiments (HFOs)												
Current/Future Work												
Q3 Milestone: Large scale tube bundle preparation												
Q4 Milestone: Experiments using R290 and ammonia												

Team

Kashif Nawaz

Section Head

Muneesh Murugan

Associate Research Staff

Cheng-Min Yang

Associate Research Staff

Brian Fricke

Group Leader