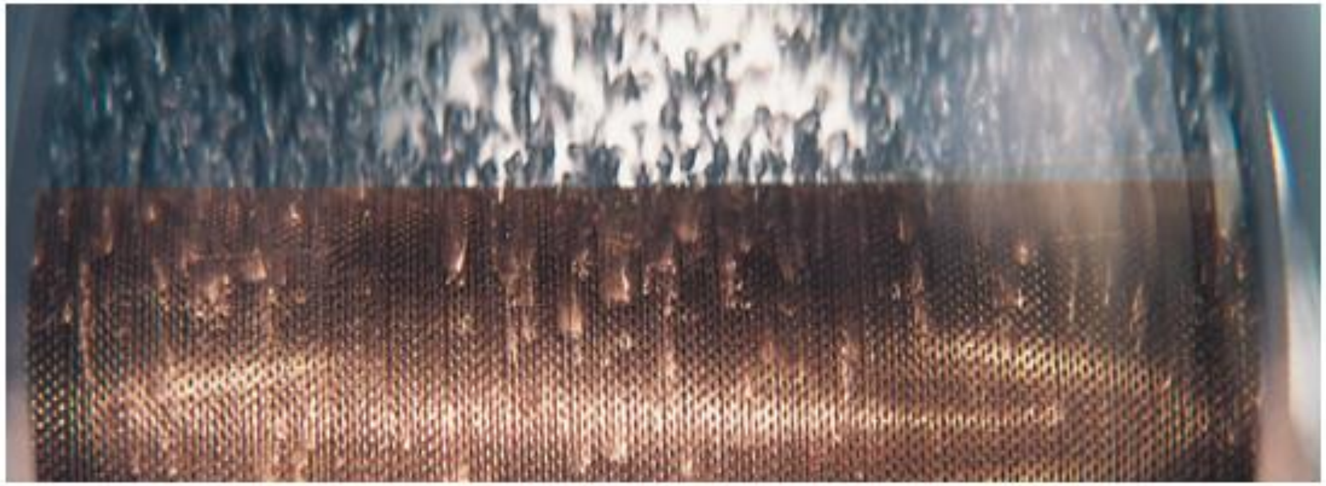
Novel Compact Flooded Evaporators for Commercial Refrigeration

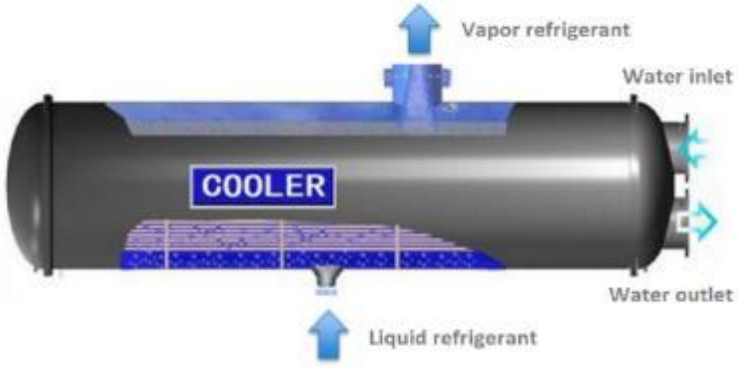


Oak Ridge National Laboratory
Kashif Nawaz (Research Staff)
865-241-0792, nawazk@ornl.gov

Project Summary

Objective and outcome

The objective of the project is to design and demonstrate the next-generation flooded evaporator with more than 40% reduction in refrigerant charge while deploying refrigerants with low GWP for commercial refrigeration and process cooling.



Team and Partners

Kashif N., Cheng-Min Y., Muneeshwaran M., Brian F. (ORNL)

Jay Kohler (JCI), Zahid Ayub (Isotherm Inc.), Drew Welch (Emerson)

Stats

Performance Period: January 2021 –March 2024

DOE budget: $200k/year, Cost Share: $25k/year

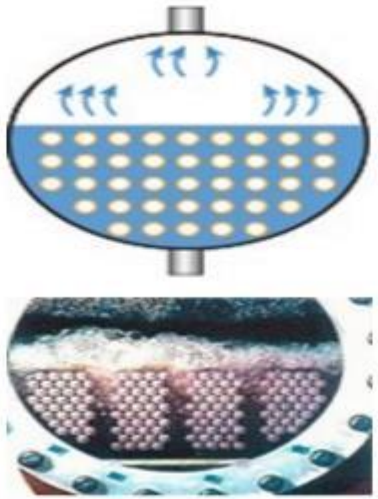
Milestone 1: Flat surfaces analysis (completed)

Milestone 2: Single tube and bundle experiments (completed)

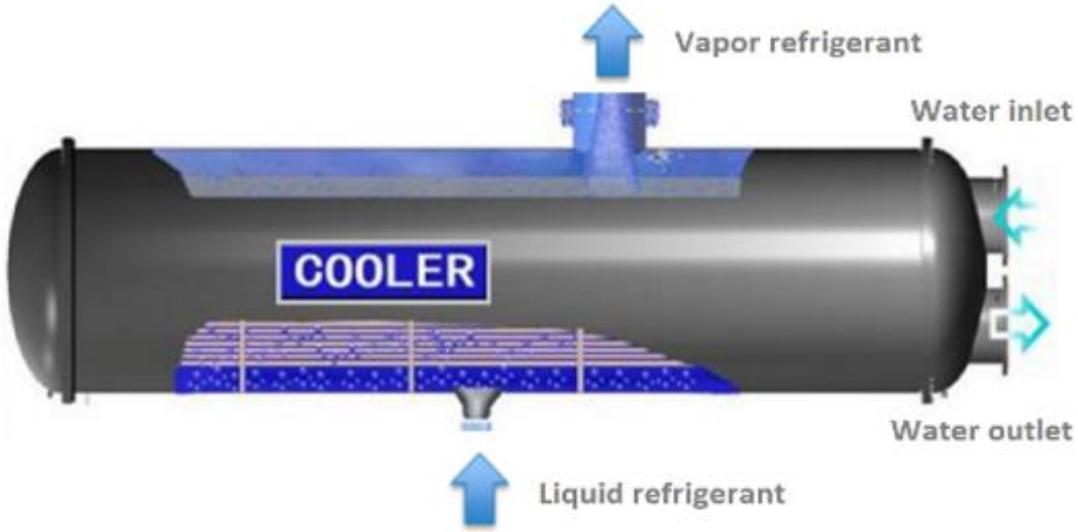
Milestone 3: Demonstration of 40% reduction in refrigerant charge (GWP<150) (in progress)

Problem

- Development of energy-efficient equipment is critical to enhancing national energy security. A major energy user is commercial processes such as refrigeration/process cooling (~2.67 Quads/year).
- A flooded evaporator configuration is more common compared with direct expansion configuration because of improved system efficiency.
- However, the major disadvantages of large flooded evaporators include excessive refrigerant charge and increased pumping work.



Operation of a flooded evaporator for water cooling



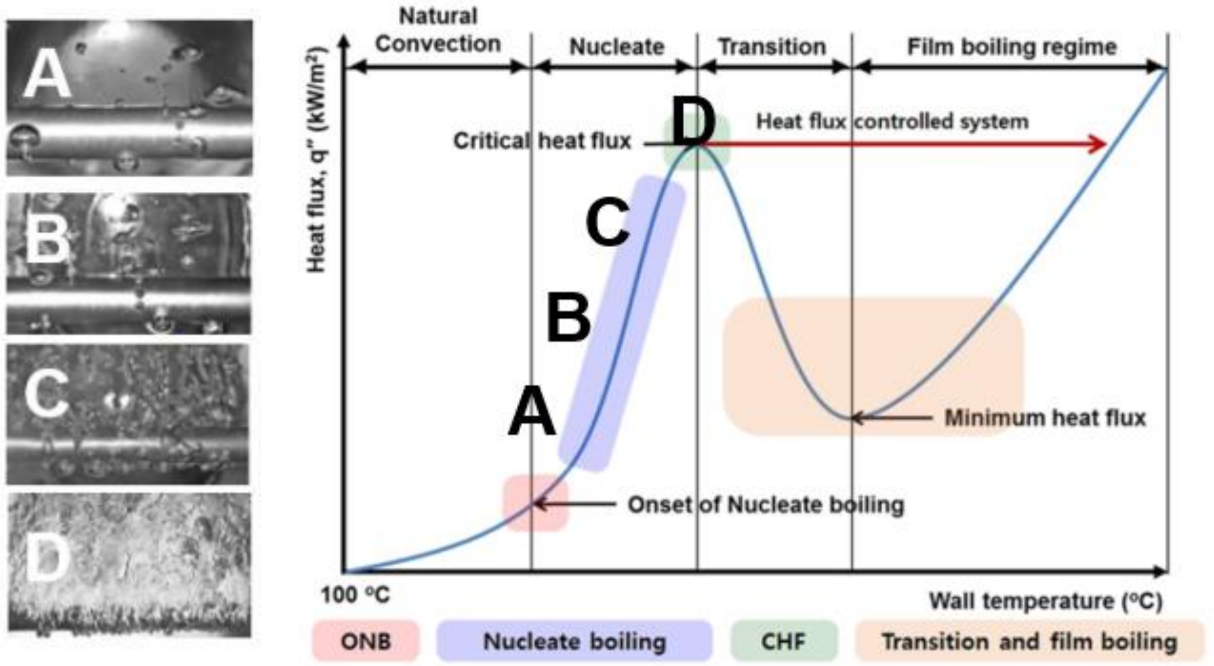
60-70% of charge inventory, ~800-1200 lbs for 60 tons

Problem

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

Existing enhanced tubes

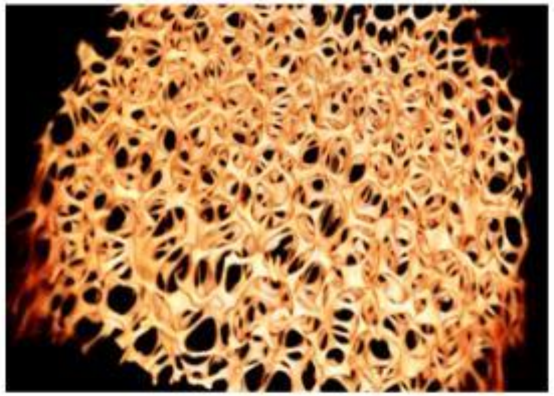
$$q_s'' = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \left(\frac{c_{p,l} \Delta T_e}{C_{s,f} h_{fg} Pr_l^n}\right)^3$$



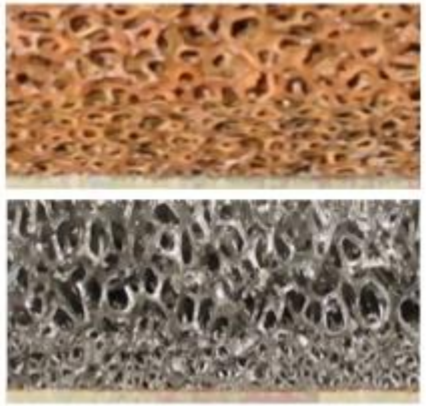
Rohsenow, ASME Transactions, 74, 969, 1952.

Solution Approach

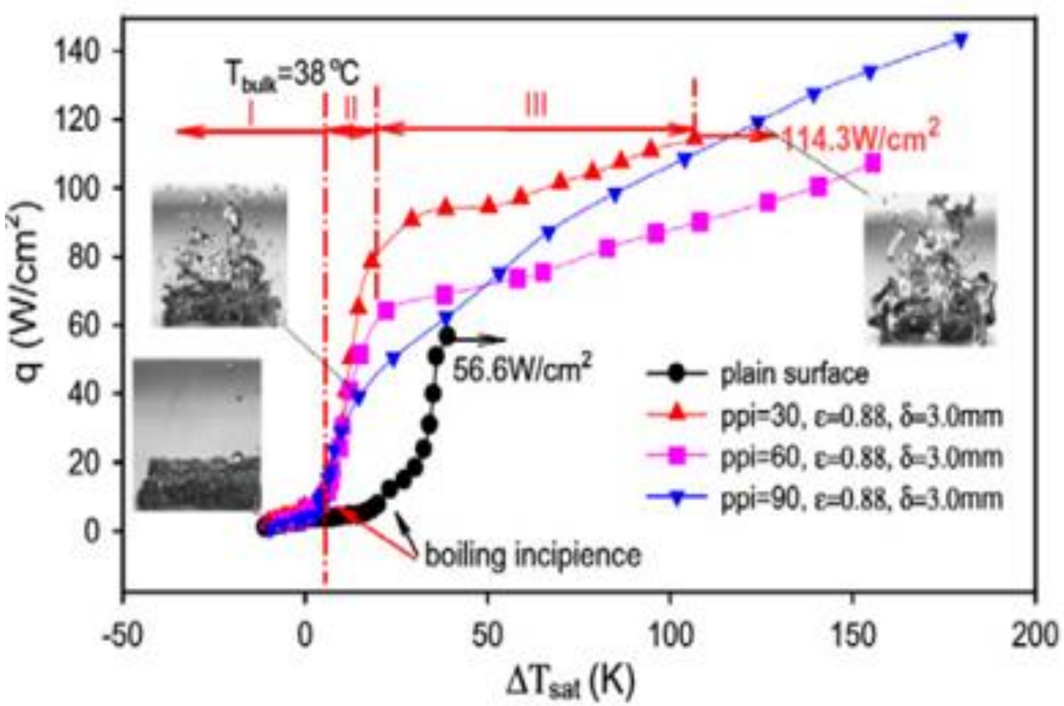
- Metal foam has shown promising results for thermal applications
- The greater surface area (~2,500 m^2/m^3) and tortuous structure provide higher nucleation site density
- The variable porosity achieved through an appropriate compression process is another obvious advantage



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



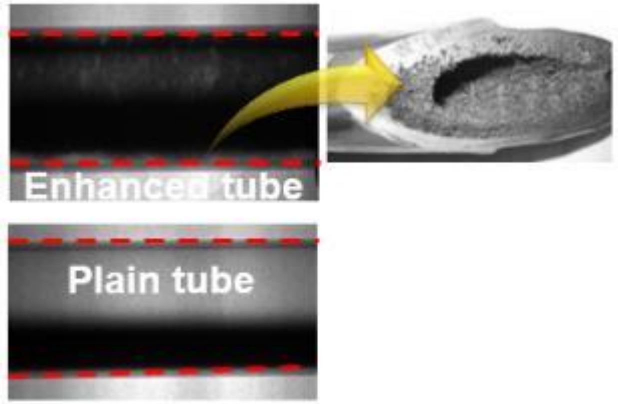
Metal foam with variable pore size.



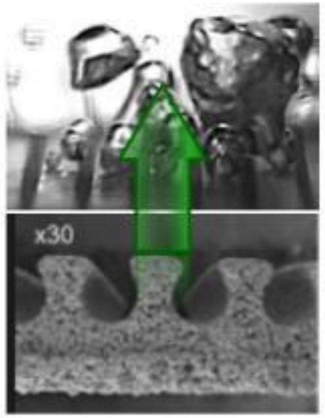
Metal foam can provide a ~35–45% enhancement in heat transfer coefficient, higher surface-area-to-volume ratio, and higher heat transfer coefficient lead to 40% higher heat transfer rate

Solution Approach

- Deployment of metal foam–enhanced tubes can lead to ≥40% reduction in the size of the flooded evaporator due to the improved heat transfer rate
- The volume occupied by foam material can further reduce the refrigerant charge by 30–40%. The design allows easy substitution of A2L and A3 refrigerants
- The wicking effect accommodates a larger heat flux to keep liquid always in contact with the boiling surface → *No dry-out*



Neutron radiograph of flow boiling for enhanced and plane tube.

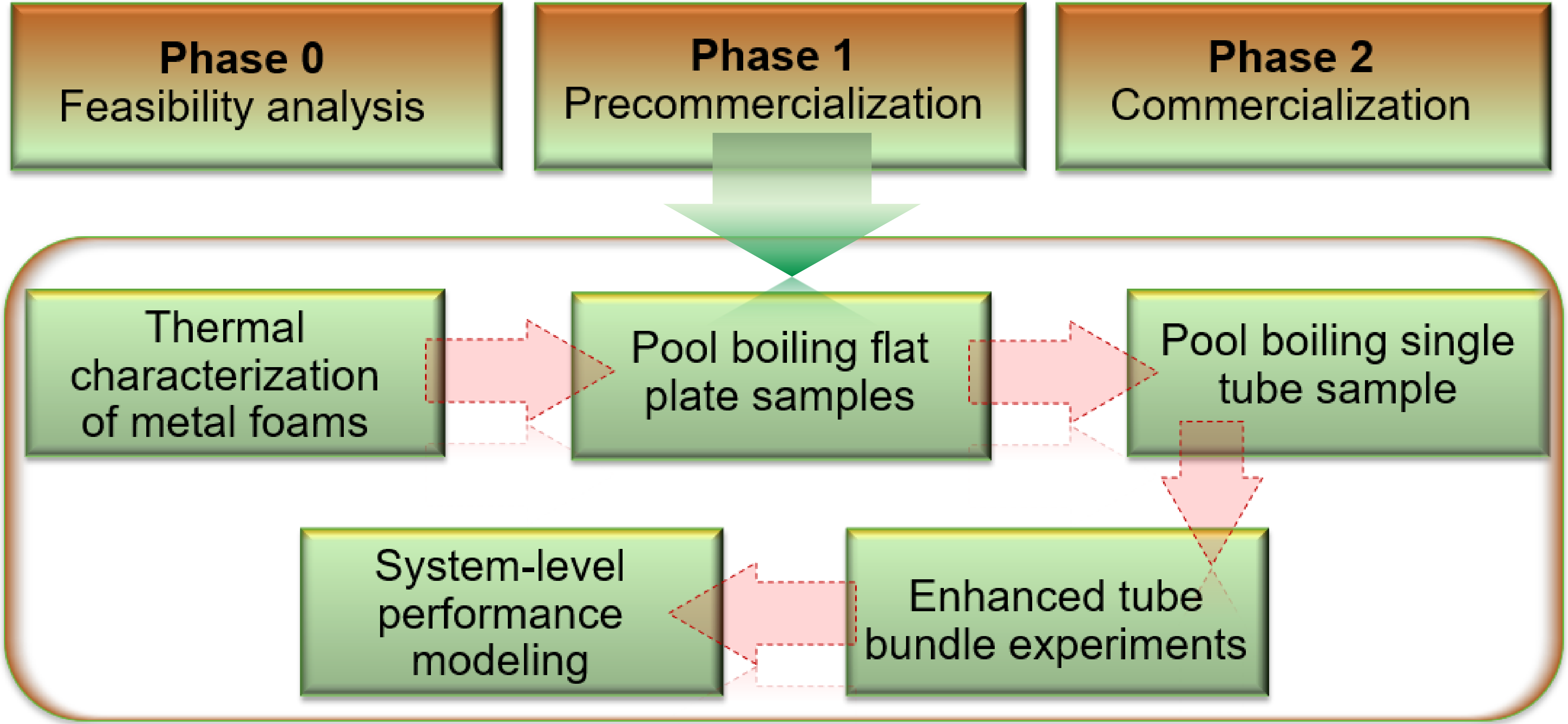


Wicking structures assist in avoiding dry-out.

A metal foam enhanced tube bundle.

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

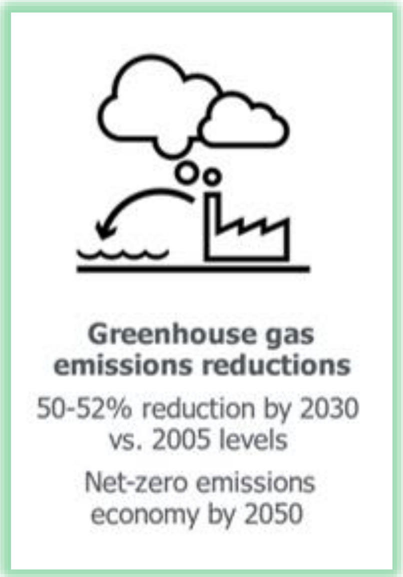
Solution Approach

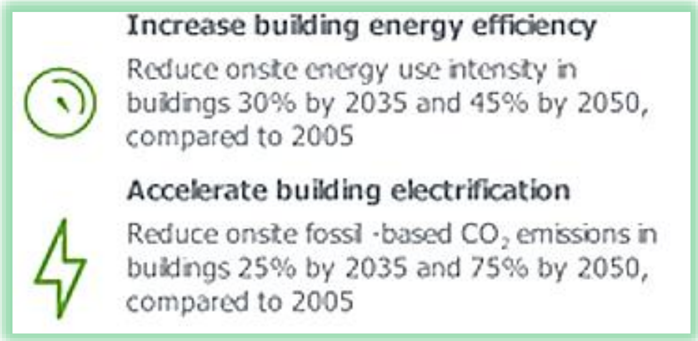


Design, demonstrate, and analyze the performance of an ultracompact flooded evaporator that can lead to an increased efficiency by at least 20%, with a 40% reduction in total system refrigerant charge.

Project Impact

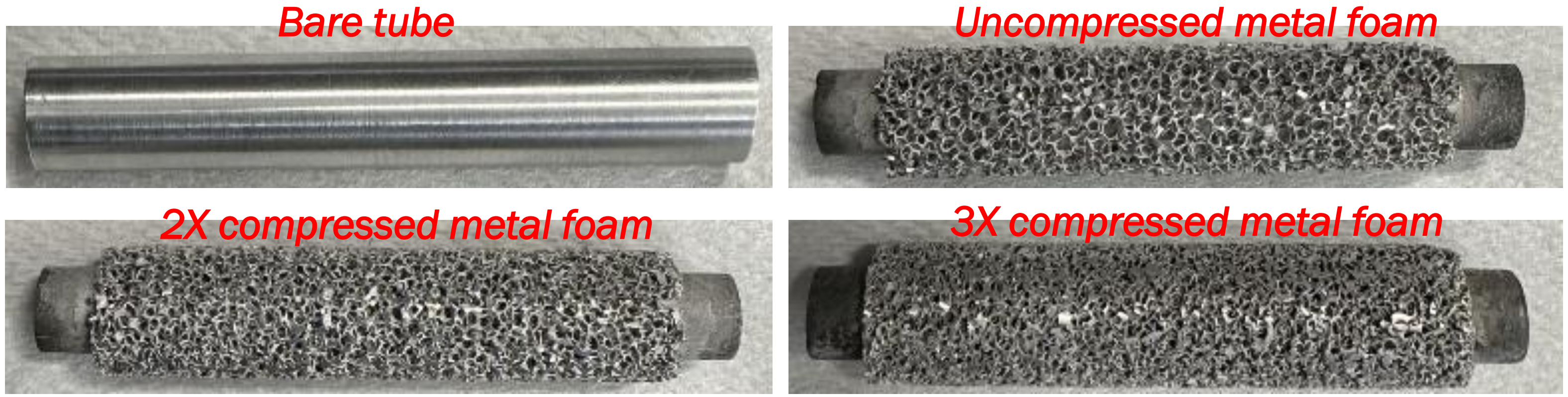
- At least 800 TBtu of energy savings in commercial refrigeration sector
- At least 200 Mton GHG emissions reduction
- An improved refrigeration/commercial cooling technology
  - Unprecedented thermal-hydraulic performance
  - Reduced manufacturing cost
- Enables development for deployment of A2L and A3 refrigerants
  - Reduction in refrigerant charge
  - Reduced required maintenance due to improved superheat
- Implications for additional processes
  - Power generation, waste heat recovery, electronics cooling

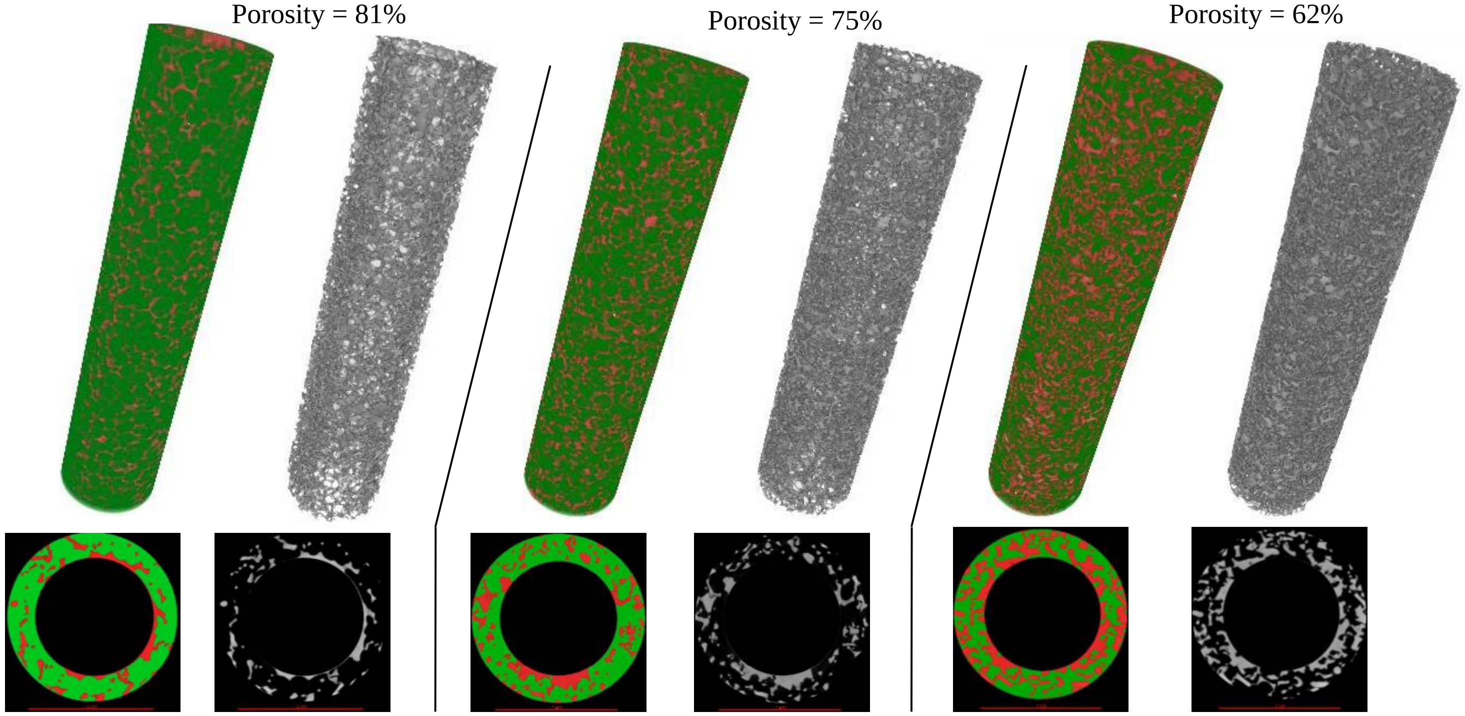




Progress

Characterization of metal foam enhanced tubes





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

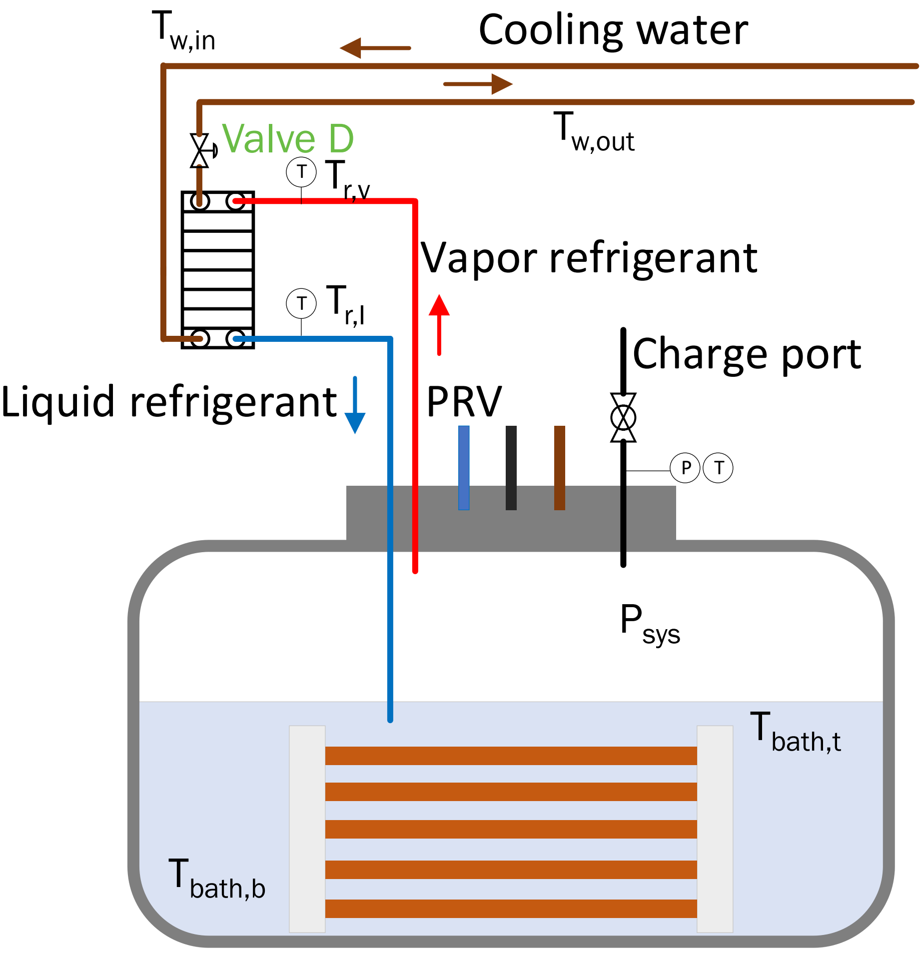
- Tube material: Aluminum (6101)
- Outer diameter of tube: 9.52 mm
- Length of tube: 76.5 mm
- Aluminum (6101) metal foam with 40 PPI was brazed around the outer surface of the tube.
- Metal foam thickness: 2.54 mm
- The porosity of metal foam was quantified using X-ray computed tomography technique.

Metal foam porosities

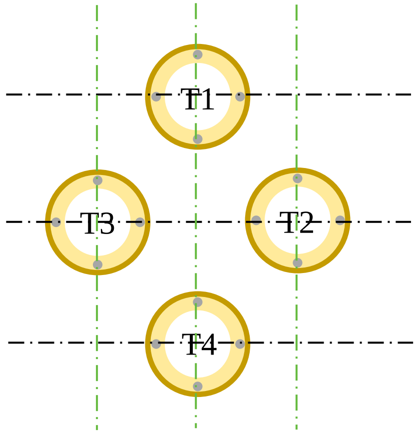
Metal foam enhaced tube	Porosity
Uncompressed metal foam	81%
2X compressed metal foam	75%
3X compressed metal foam	62%

Progress

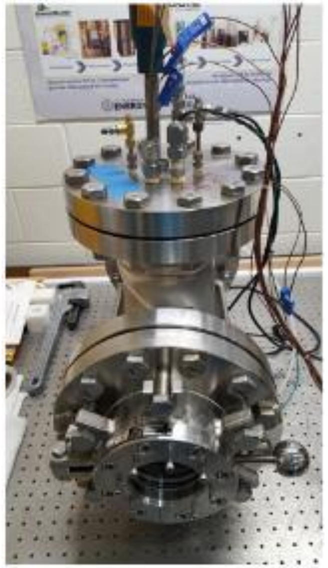
Development and validation of tube bundle facility for refrigerant tests



Schematic of tube bundle setup

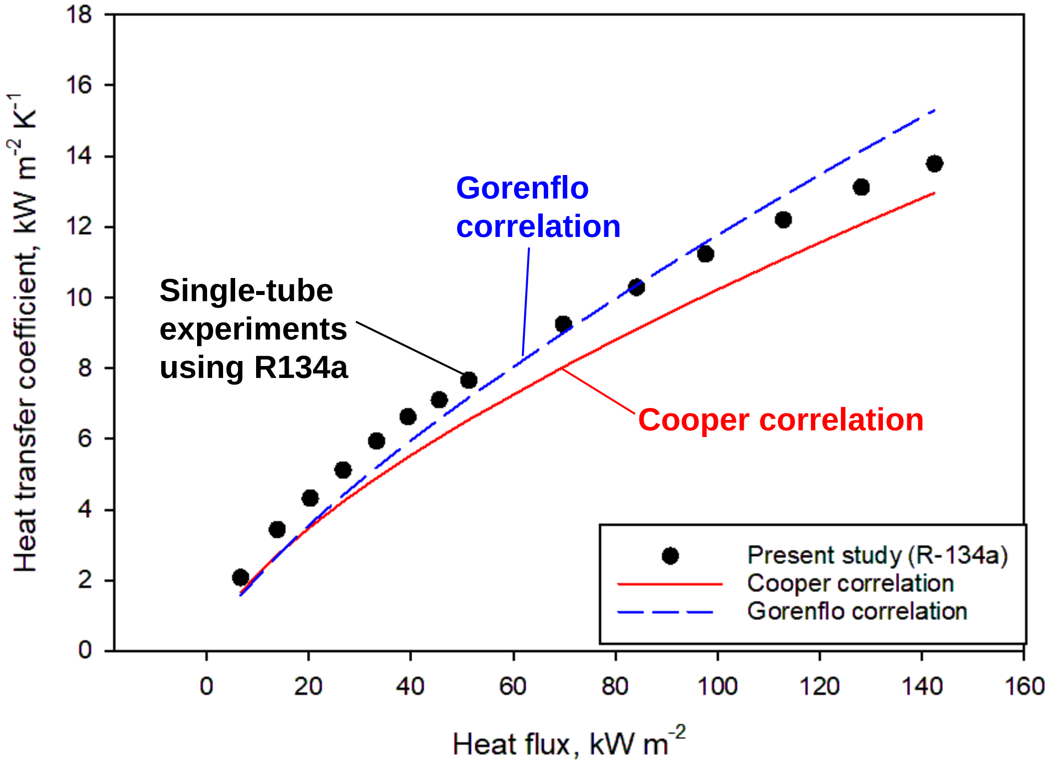


Thermocouple locations



Pressure vessel

Heat transfer coefficient of bare single-tube for R134a

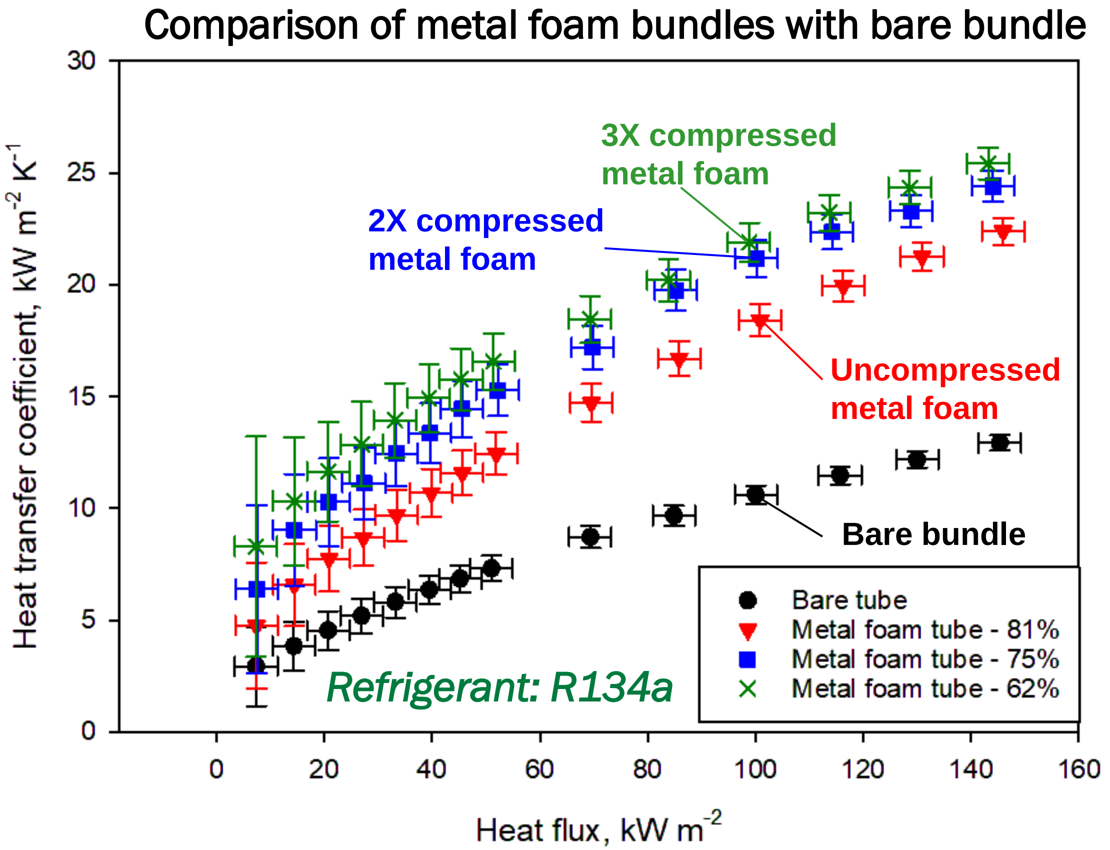


- To validate the facility, single-tube experiments using R134a were conducted.
- The results show good agreement with Cooper (5-20% deviation) and Gorenflo (1-20% deviation) correlations.

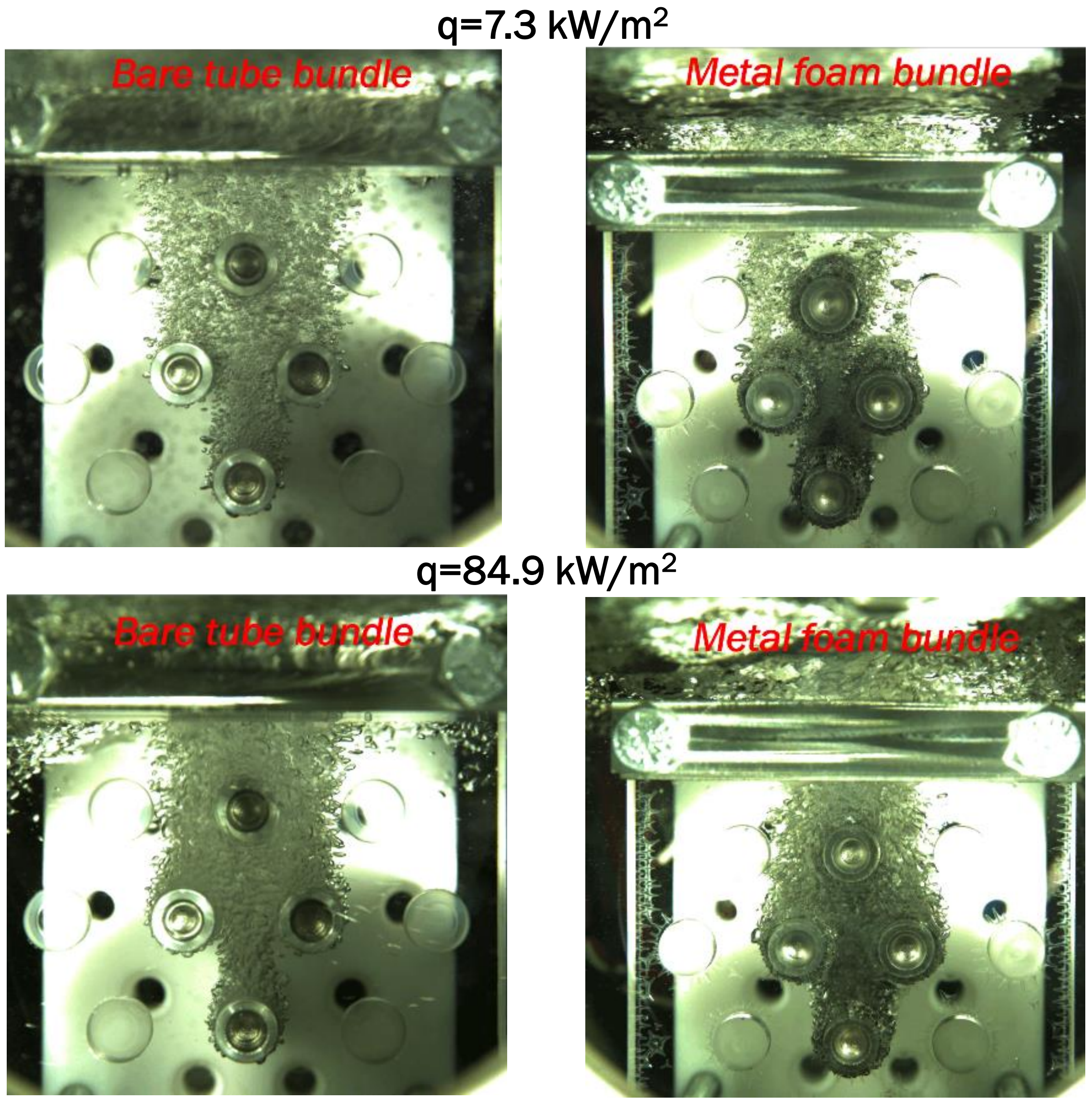
The facility for testing bundle performance of refrigerants has been validated with single tube experiments.

Progress

Comparison of heat transfer performance of various tube bundles



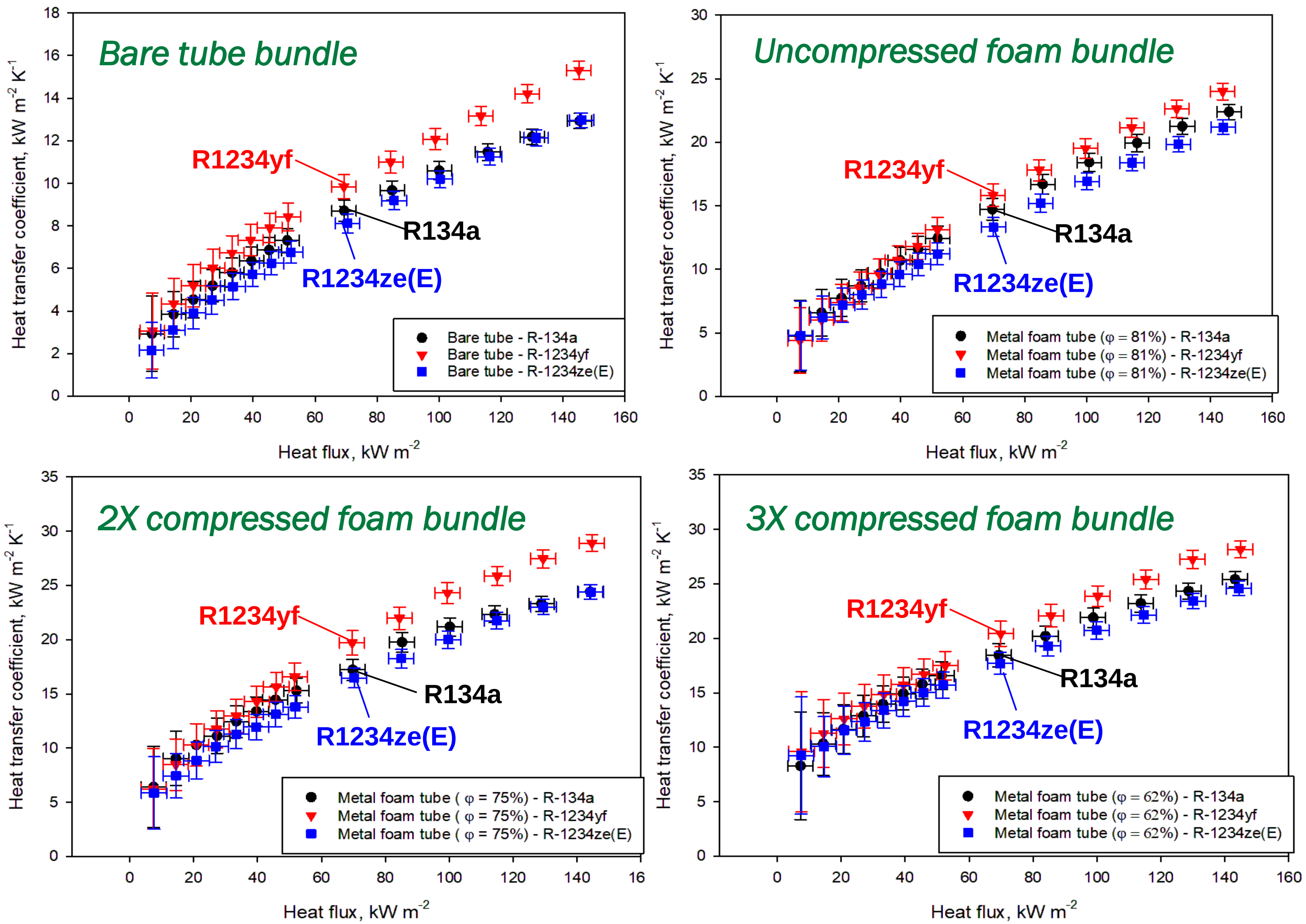
- Metal foam tube bundles provide a maximum of 120% enhancement in HTC compared with bare tube bundle.
- HTC increases with decreasing porosity.
- Larger surface area and a greater number of nucleation sites causes an increased HTC in metal foam tubes.



Visualization of R134a pool boiling processes over tube bundles

Progress

Effect of refrigerant on bundle performance



Average heat transfer coefficient of tube bundles for various refrigerants

Both bare and metal foam enhanced tube bundles were tested using three refrigerants: R134a (GWP=1430), R1234yf (GWP=4), and R1234ze(E) (GWP=7).

The performance of R-1234yf is nearly 10% higher than that of R-134a for both bare and metal foam tubes, while the performance of R-1234ze(E) is nearly 5% lower than that of R-134a.

In summary,

- R1234yf >R134a>R1234ze(E)
- 3X compressed≈2X compressed >uncompressed foam>bare bundle

Enhancement ratio	R1234yf	R134a	R1234ze(E)
Uncompressed	52%	70%	72%
2X compressed	97%	108%	107%
3X compressed	112%	120%	125%

Progress

Name	Description	Status
Establishment of thermal conductivity of metal foams	Develop a model to determine the thermal conductivity of metal foams (various PPI)	Completed
Establish the geometry of metal foams	X-ray imaging to evaluate the key geometrical characteristics of metal foams	Completed
Water boiling on enhanced surfaces	Conduct detailed analysis of water boiling performance on metal foams and enhanced surfaces	Completed
Pool boiling of refrigerants	Conduct detailed analysis of pool boiling performance of various refrigerants	Completed
Development and performance evaluation of single enhanced tubes	Based on the preliminary evaluation, design and fabricate an enhanced tube that can be used for single tube performance evaluation; conduct experiments and develop the performance model	Completed
Development of enhanced tube bundle	Design and fabricate an enhanced tube bundle that can be used as a prototype to demonstrate the technology	Completed
Performance evaluation of tube bundle	Conduct detailed parametric analysis of tube bundle using various refrigerants and develop the performance models	Completed
Commercialization plan	Develop reports and advertisements to facilitate the commercialization of the proposed technology. Identify and mitigate the market risks	In-progress

Publications

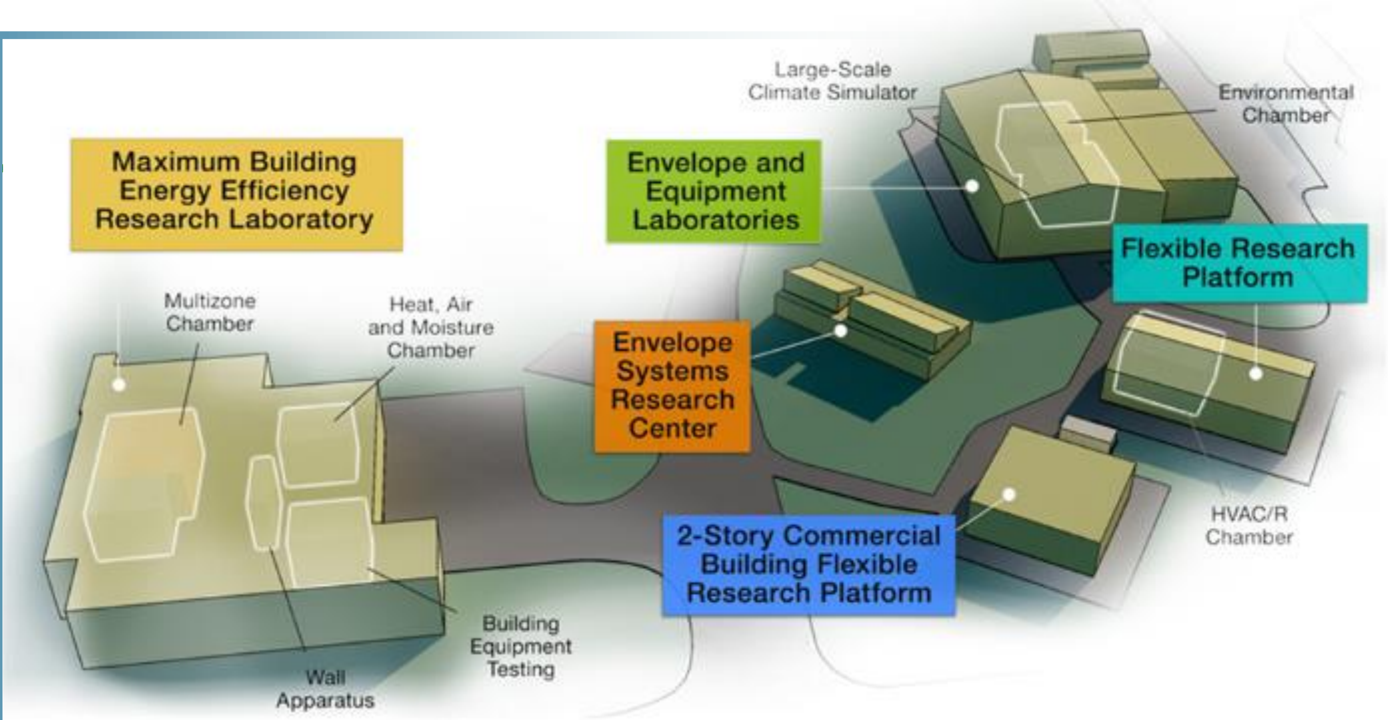
1. Zhang, Mingkan; Nawaz, Kashif; Yang, Cheng-Min; Sandlin, Matthew; Asher, William; Fricke, Brian; and Gehl, Anthony, "A Numerical Study on the Pool Boiling with Foam Surface Enhancement Using Different Refrigerants" (2021). International Refrigeration and Air Conditioning Conference. Paper 2179.
2. 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.
3. 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.
4. 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. ***Under review***.
5. Yang, Cheng-Min; Asher, William; Sandlin, Matthew; and Nawaz, Kashif, " Investigating the effect of metal foam on the pool boiling heat transfer of dielectric fluid over a horizontal tube". *Target journal: International Journal of Heat and Mass Transfer.* ***Under preparation.***
6. Muneeshwaran, M.; Yang, Cheng-Min; and Nawaz, Kashif, " Augmentation of pool boiling heat transfer on tube bundles using metal foam". *Target journal: Thermal Science and Engineering Progress.* ***Under preparation***.
7. Muneeshwaran, M.; Yang, Cheng-Min; and Nawaz, Kashif, " Performance assessment of low GWP refrigerants, R-1234yf and R-1234ze(E) on flooded evaporators". *Target journal: Applied Thermal Engineering.* ***Under preparation***.

Thank you

Oak Ridge National Laboratory

Kashif Nawaz, Section Head of Building Technologies Research; Group Leader of Multifunctional Equipment

865-241-0972 | nawazk@ornl.gov



ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

Project Execution

	FY2021				FY2022				FY2023				FY2024			
Planned budget	$200,000				$200,000				$200,000				$200,000			
Spent budget	$175,000				$200,000											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Market assessment																
Characterization of metal foams																
Flat surfaces analysis (low and high pressure fluids)																
Single tubes analysis (low and high pressure fluids)																
Tubes bundle analysis (low and high pressure fluids)																
Data analysis and correlation development																
Parametric analysis																
CRADA partnership																

Project Team

Kashif Nawaz
Project management
Protype development

Cheng-Min Yang
Thermodynamic analysis
Instrumentation

Muneesh Murugan
Experimentation
Data analysis

Jay Kohler
Commercialization

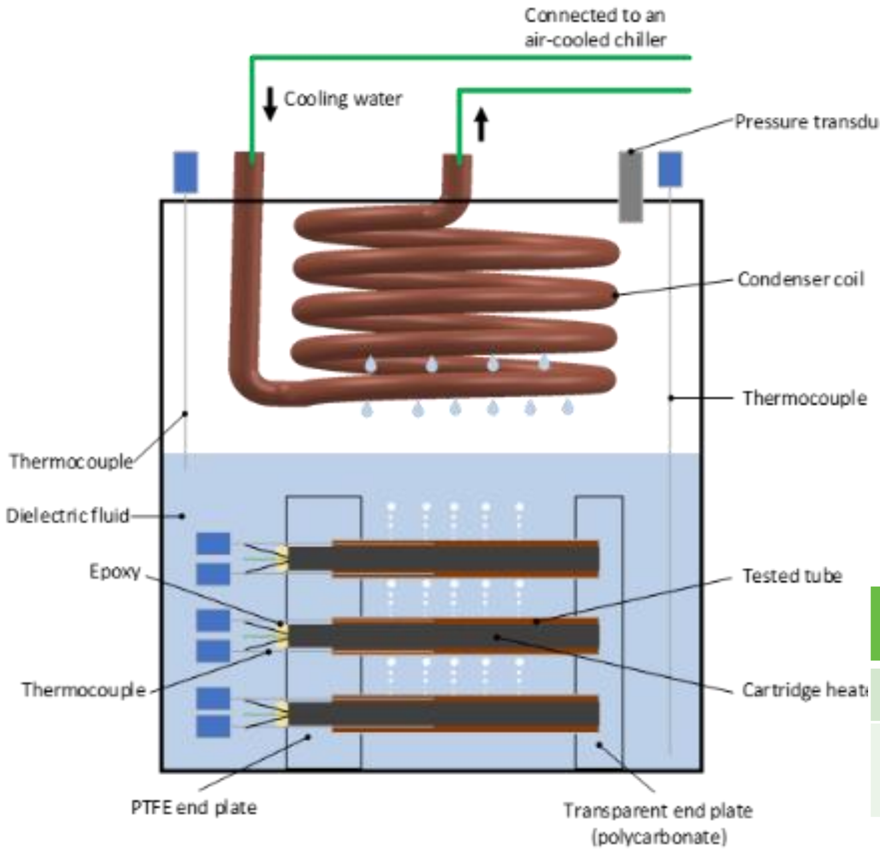
Zahid Ayub
Commercialization

Brian Fricke
Experimentation
Performance modeling

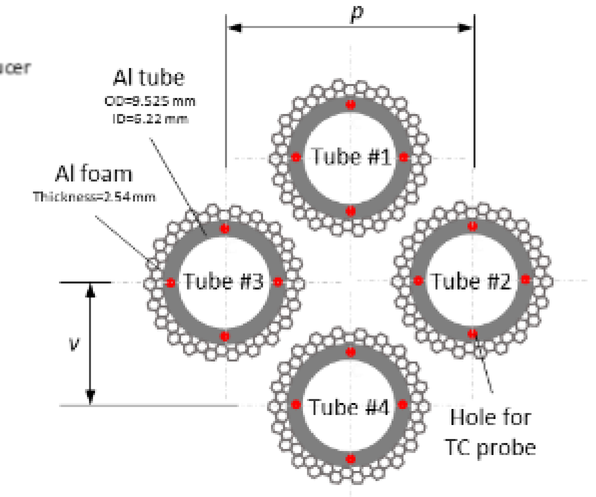
Drew Welch
Commercialization

Progress

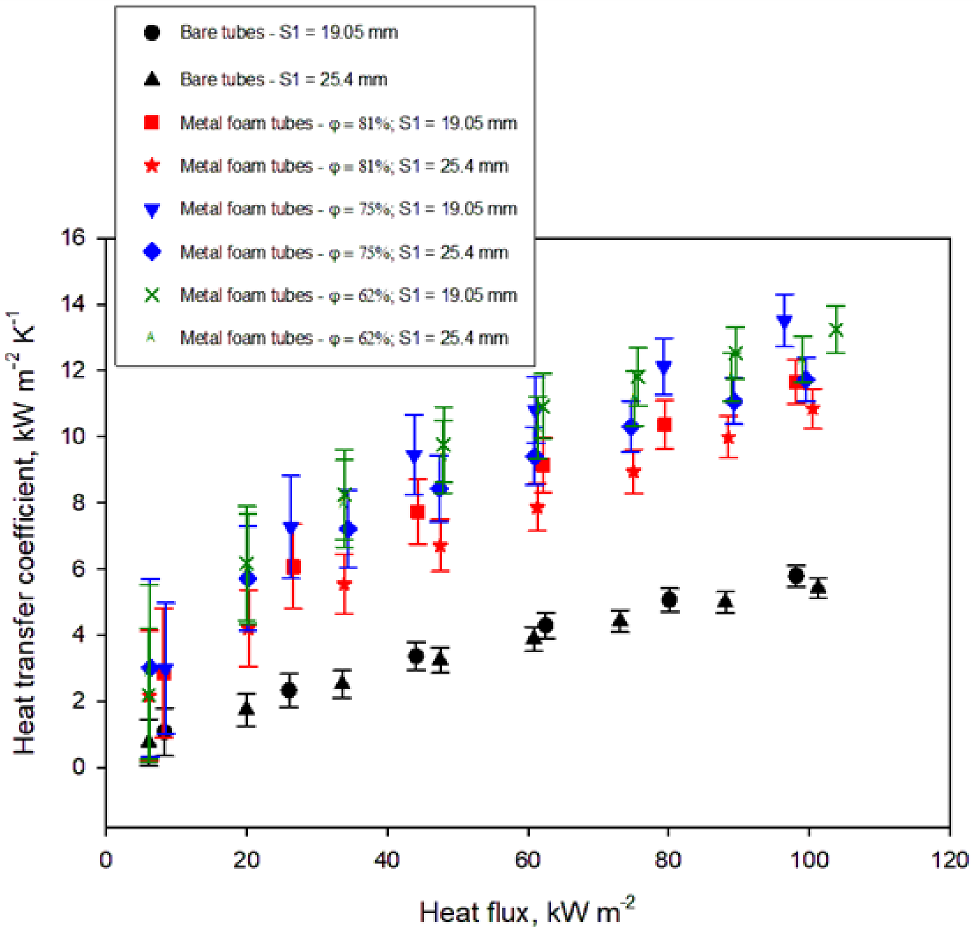
Effect of tube pitch on heat transfer performance of tube bundles



Schematic of tube bundle setup for dielectric fluids

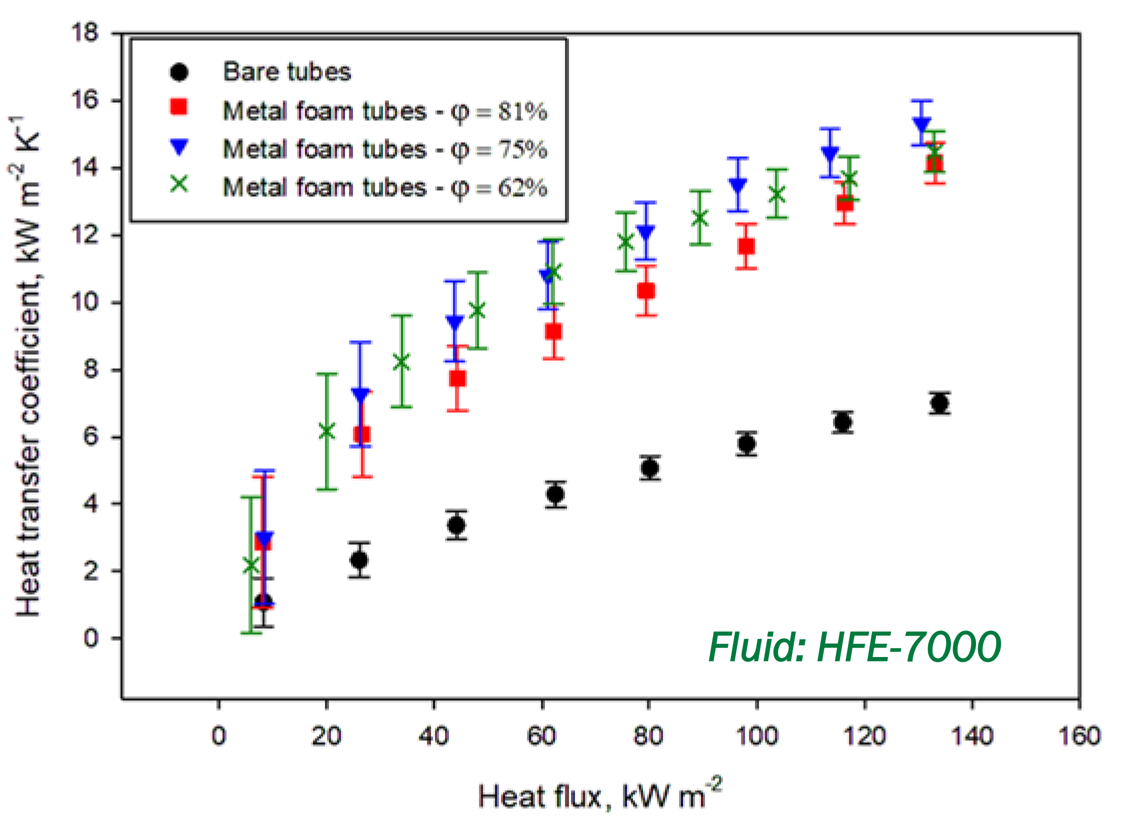


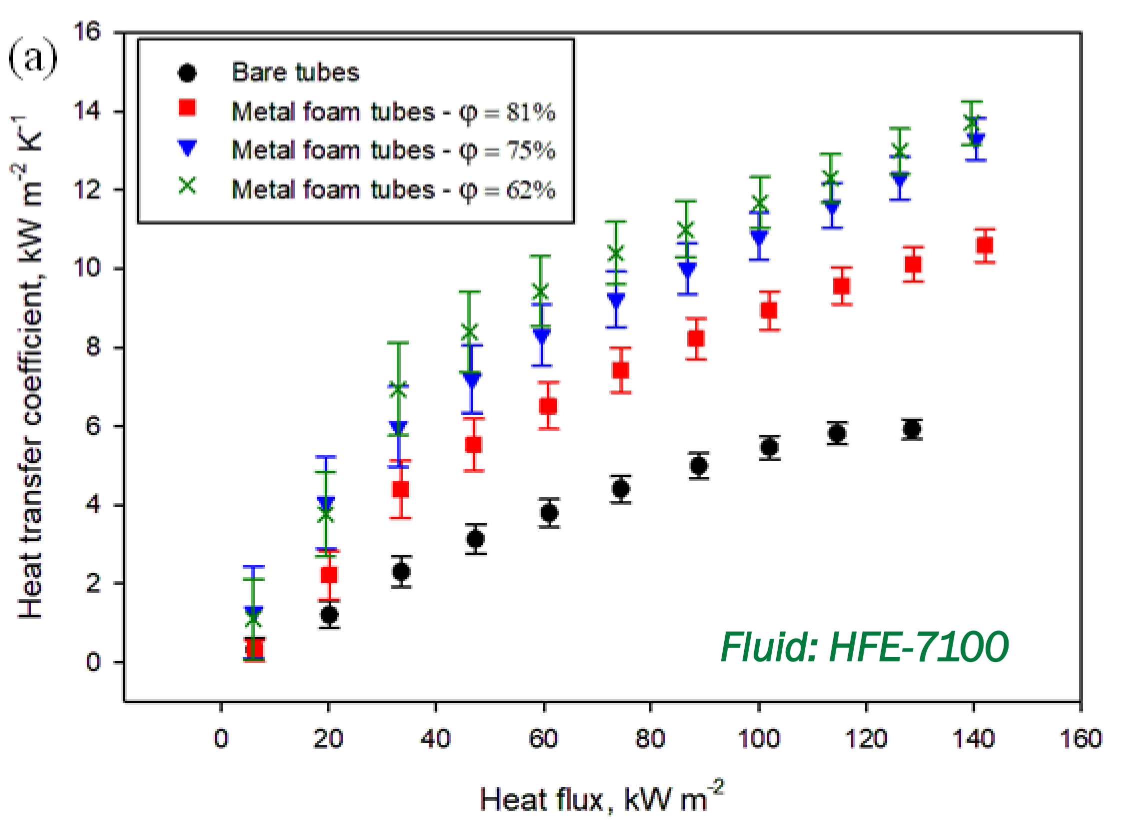
	Case 1	Case 2
Tbe pitch p	19.05 mm	25.4 mm
Veritcal distance between tubes v	16.5 mm	22.0 mm



Progress

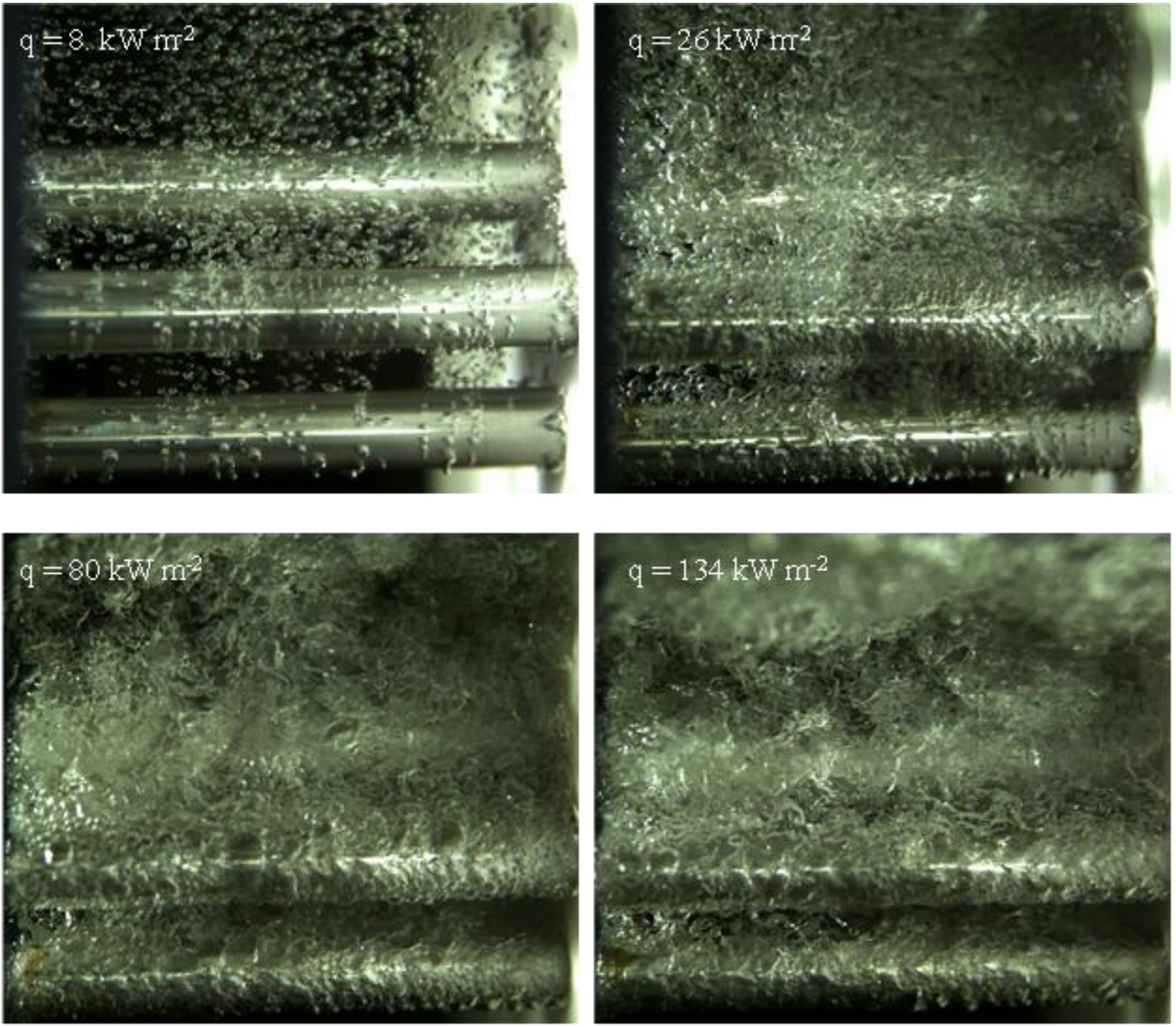
Comparison of metal foam bundles with bare bundle (dielectric fluids)



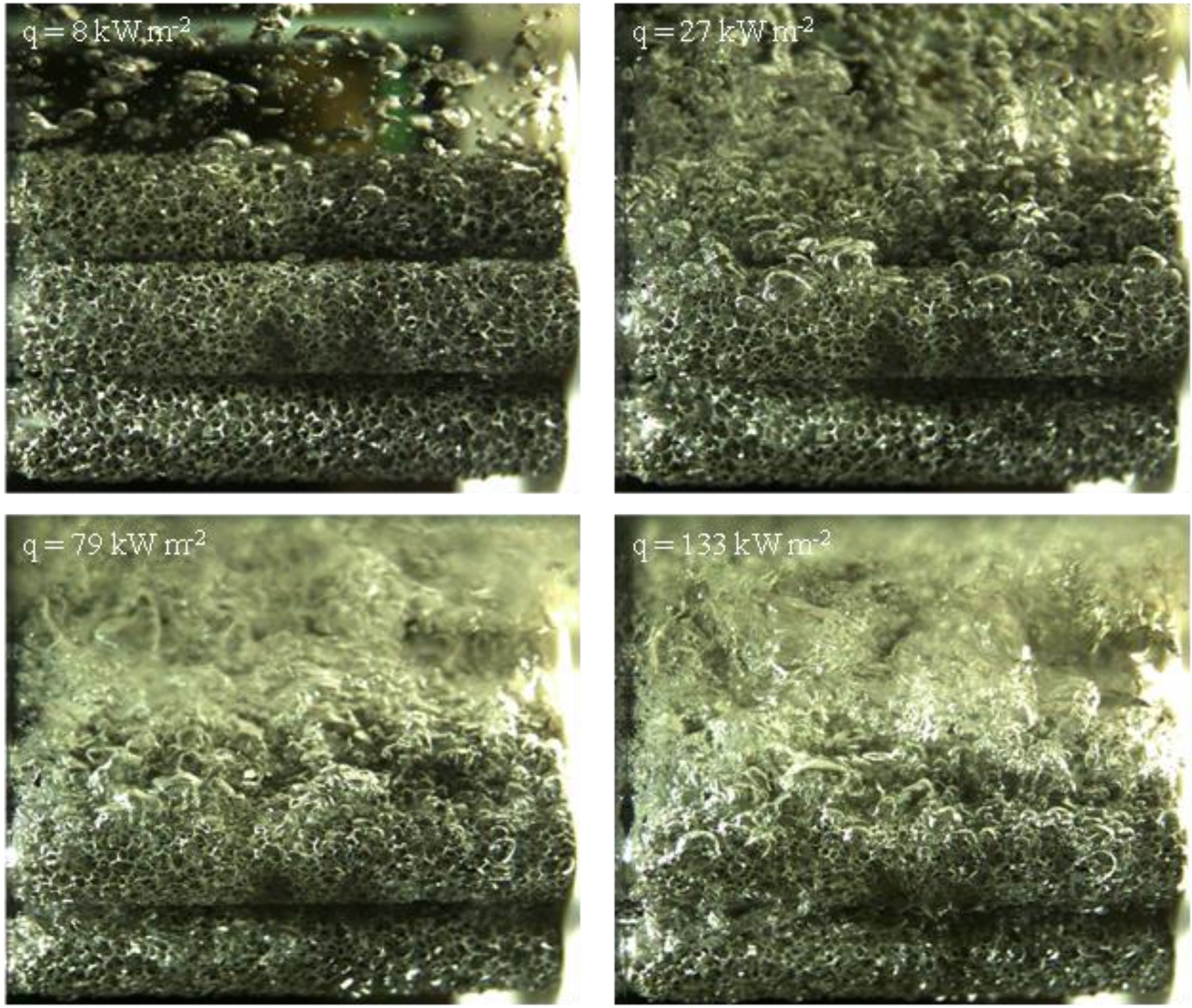


Progress

Visualization of pool boiling across tube bundles (HFE-7000, side view)



Bare tube bundle



Uncompressed metal tube bundle