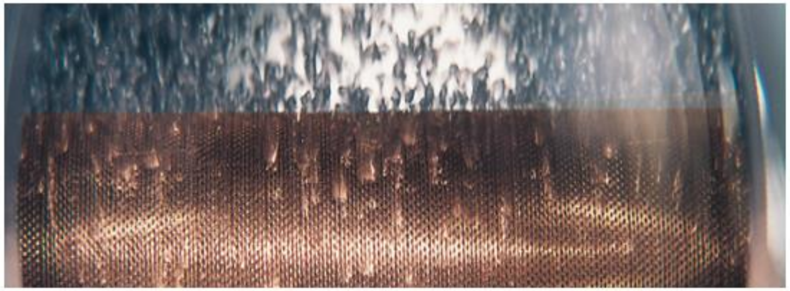
Novel Compact Flooded Evaporators for Commercial Refrigeration



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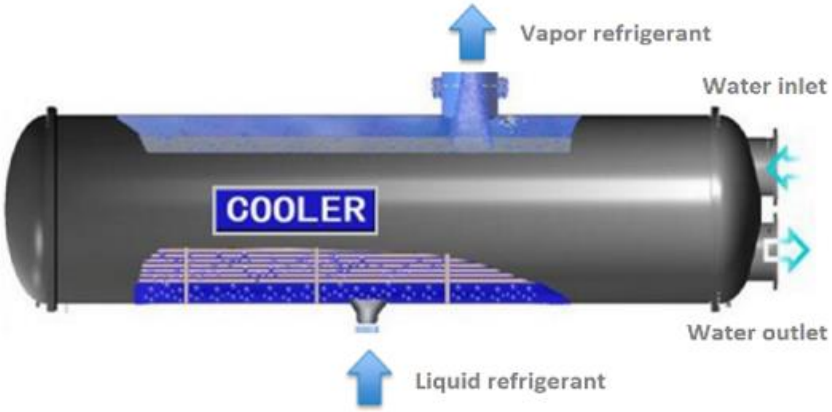


Project Summary

Timeline:

Start date: October 2017

Planned end date: October 2020

Key Milestones

1. Pool boiling of refrigerants on surfaces, single tube performance, October 2019
2. Performance of an enhanced tube bundle, enhanced flooded evaporator, October 2020

Key Partners:

ISOTHERM, INC. ENHANCED HEAT TRANSFER

Johnson Controls

Carrier United Technologies

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Michigan Technological University 1885

Budget:

Total Project $ to Date:

- DOE: $658K
- Cost share: $150K

Total Project $:

- DOE: $900K
- Cost share: $200K

Project Outcome:

- The project has the potential to revolutionize the commercial refrigeration and cooling industry
- The highly compact design not only will improve overall system performance by reducing power consumption (pumping power) but also will lead to a substantial reduction in total refrigerant charge requirements
- Since a total system charge reduction is an important factor (safety and cost aspects), the proposed design will assist with easy substitution of emerging refrigerants

Project Team

- **Oak Ridge National Laboratory**
  - Kashif Nawaz (R&D staff)
  - Brian Fricke (R&D staff)
  - Mingkan Zhang (R&D staff)
  - Matthew Sandlin (Postdoctoral associate)
  - Viral Patel (R&D staff)
  - Ayyoub Momen (R&D staff)
- **Isotherm Inc.**
  - Zahid Ayub
- **Johnson Controls Inc.**
  - Jay Kohler (Director R&D)
- **Carrier Corporation**
  - Satyam Bandapudi
- **University of Illinois, Michigan Technological University**
  - Nenad Miljkovic, Sajjad Bigham, James Carpenter





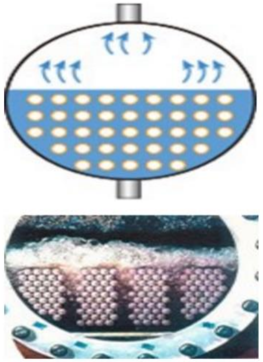




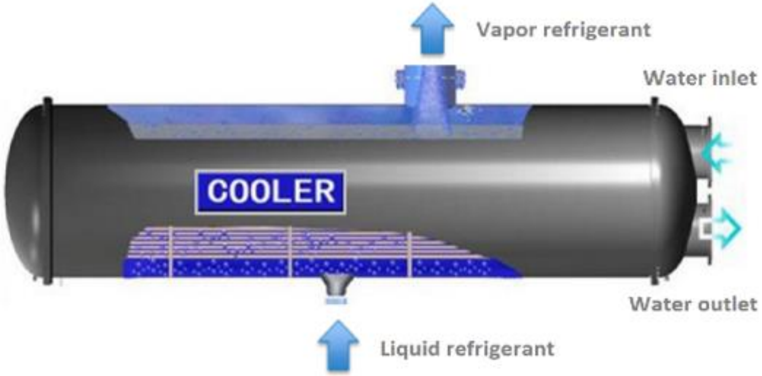



Background

- Development of energy-efficient equipment is critical to enhancing national energy security. A major energy user is commercial processes such as refrigeration/process cooling (>300 TBtu/year as per Scout)
- A flooded evaporator configuration is more common compared with direct expansion configuration because of improved system efficiency
- The large flooded evaporator in such systems is a major disadvantage that not only results in excessive refrigerant charge but also increases the pumping work.



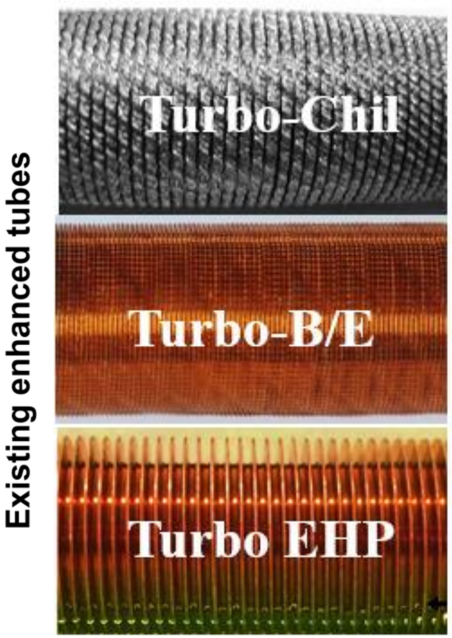
Boiling on a tube bundle

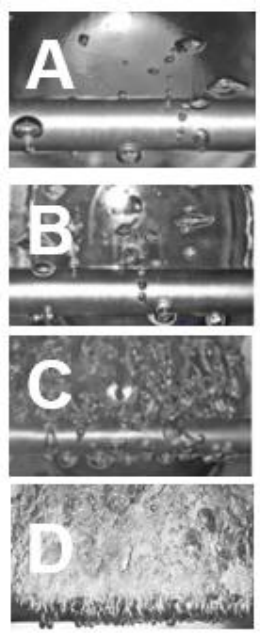


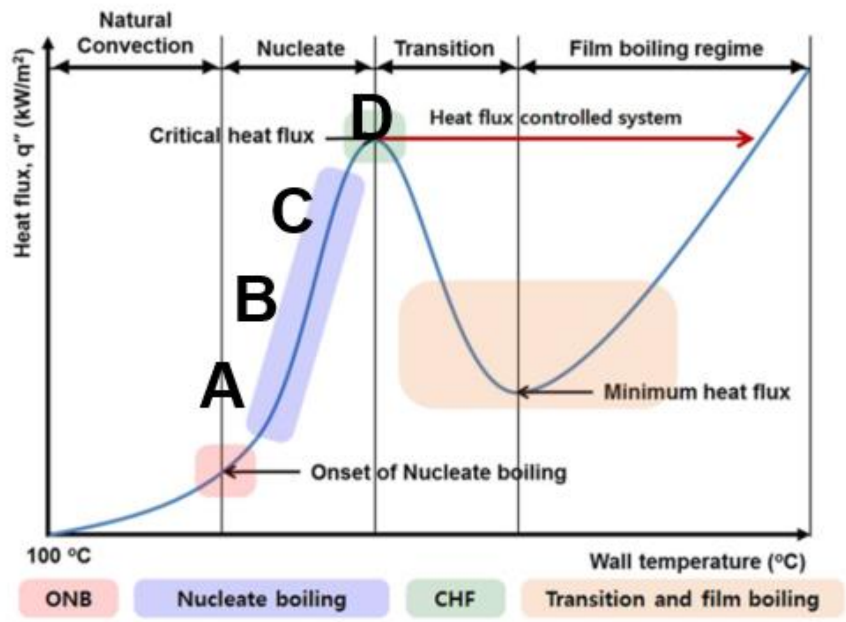
Operation of a flooded evaporator for water cooling

Background

- 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





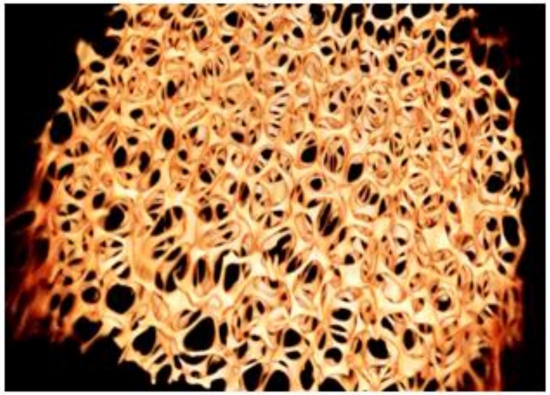


$$q_s'' = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f} h_{fg} Pr_l^n}\right)^3$$

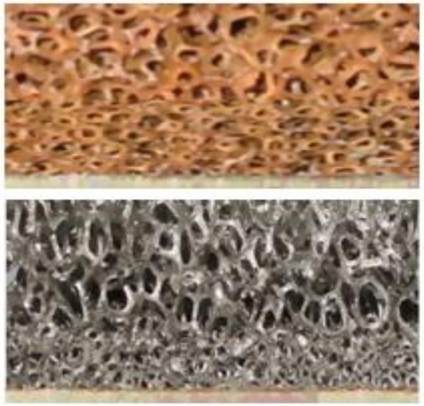
Rohsenow, ASME Transactions, 74, 969, 1952.

Solution Approach

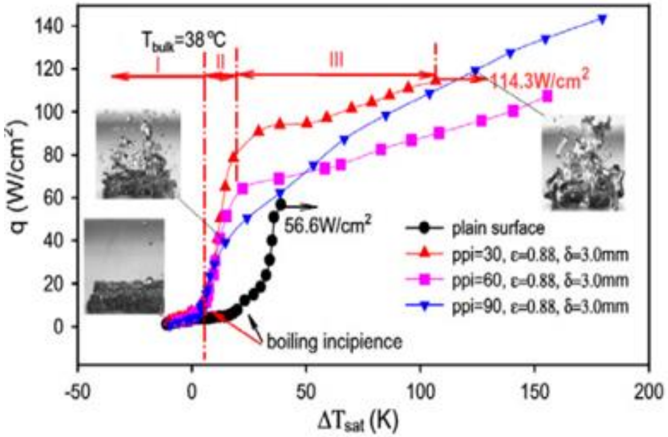
- Metal foam has shown promising results for thermal applications
- The greater surface area (~2,500 m^2/m^3) and tortuous structure provide higher nucleation site density
- The variable porosity achieved through an appropriate compression process is another obvious advantage
- Metal foam can provide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



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



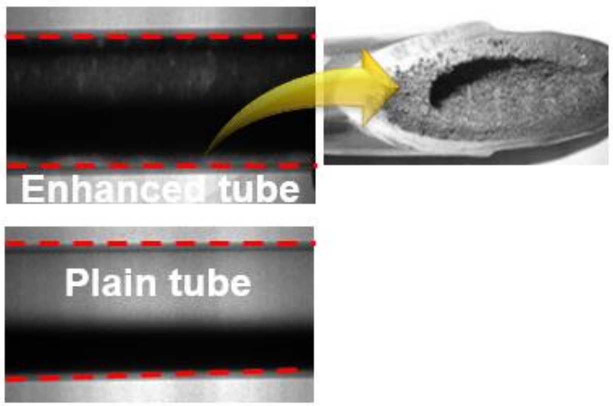
Metal foam with variable pore size.



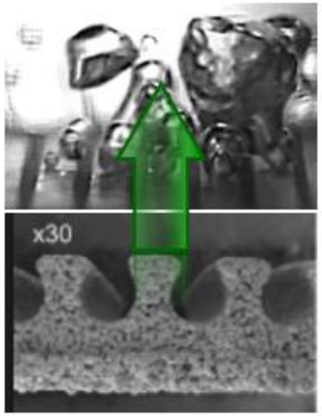
The metal foam's enhanced surface can accommodate higher heat flux.

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.

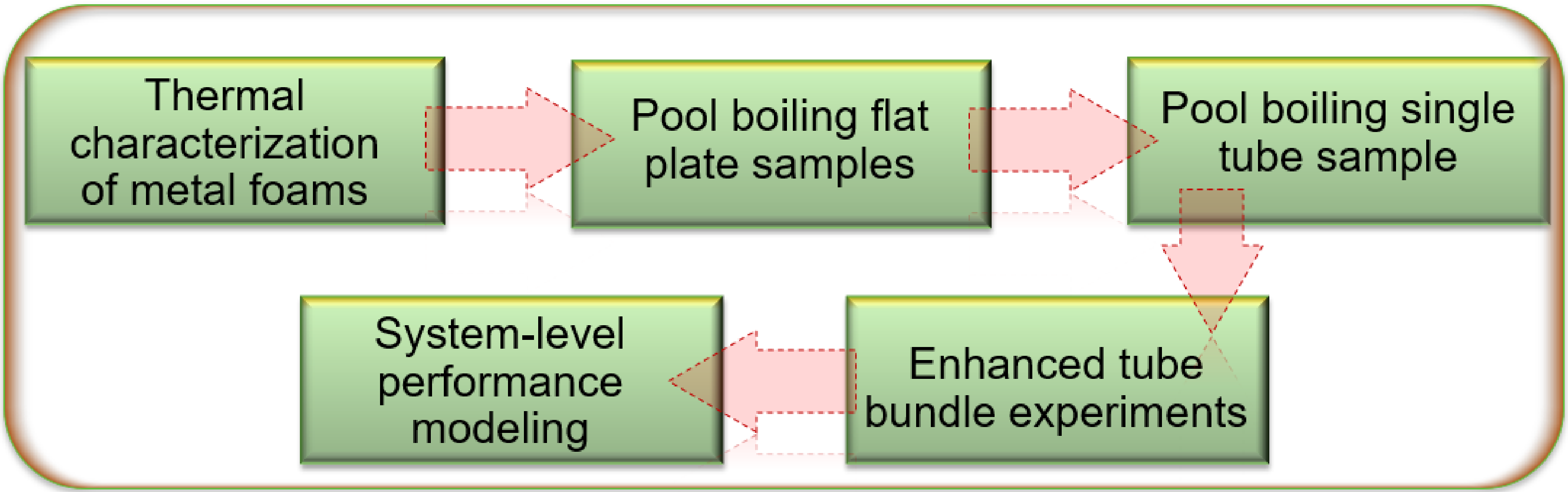


Wicking structures assist in avoiding dry-out.

A metal foam enhanced tube bundle.

Solution Approach

Phase 0	Phase 1	Phase 2
Feasibility analysis	Precommercialization	Commercialization



Design, demonstrate, and analyze the performance of a, ultracompact flooded evaporator that can lead to an increased efficiency by at least 20%, with a 35% reduction in total system refrigerant charge.

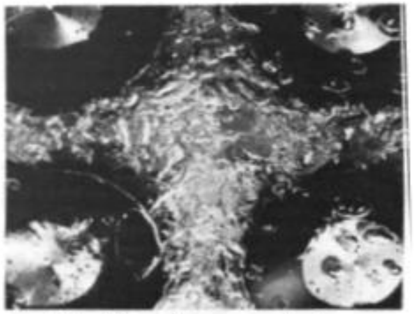
Project Impact

- **An improved refrigeration/commercial cooling technology**
  - Unprecedented thermal-hydraulic performance
  - Reduced footprints
  - Reduced manufacturing cost
- **Enables development for deployment of A2L and A3 refrigerants**
  - Reduction in refrigerant charge
  - Reduced cost of working fluid
  - Reduced required maintenance due to improved superheat
- **Implications for additional processes**
  - Power generation, waste heat recovery, electronics cooling
- **At least 200 TBtu of energy savings in commercial refrigeration sector**
  - Aligned with BTO goal to develop energy-efficient technology to effect 45% energy saving by 2030 compared with 2010 technologies
  - Opportunities to create more than 3,000 new jobs
  - Enabling US manufacturers to expand to international markets

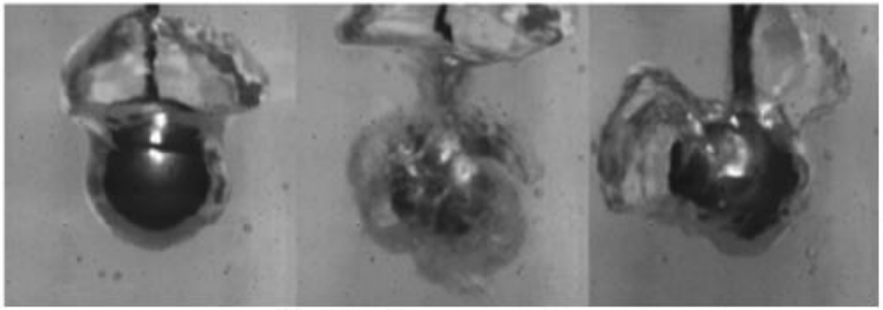
Progress — Overview of State of the Art

- Pool boiling on both smooth and enhanced tubes
- Pool boiling on spheres
- Pool boiling on downward-facing curved surfaces

Boiling on a single tube.



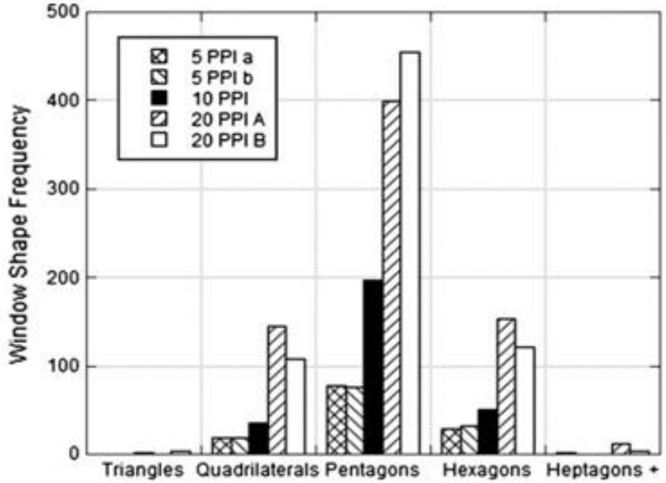
Boiling on a tube Bundle.

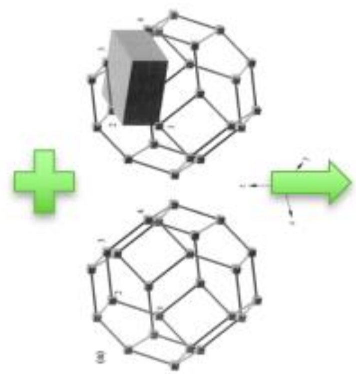


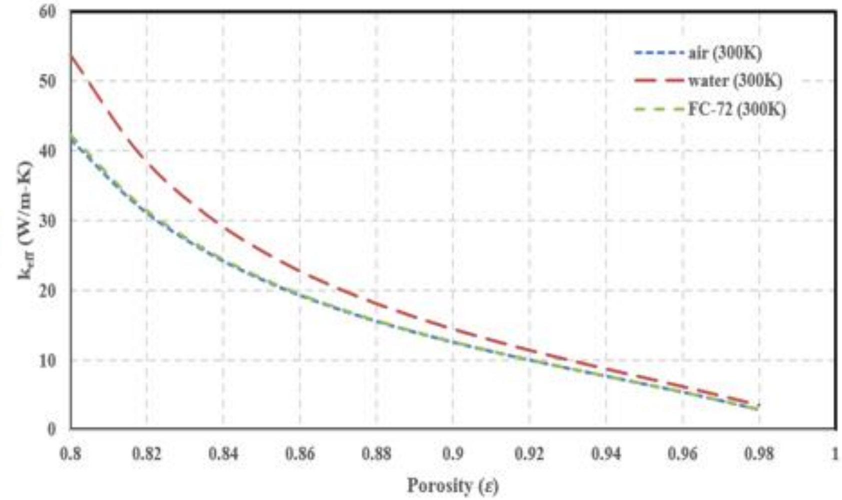
Boiling on a sphere (nuclear application).

- Most of the literature is focused on water (high surface tension fluid) and some on obsolete/conventional fluids
- Literature on metal foam or other porous structures is rare
- Most of the enhanced studies do not address durability and scalability

Progress — Characterization of Metal Foams



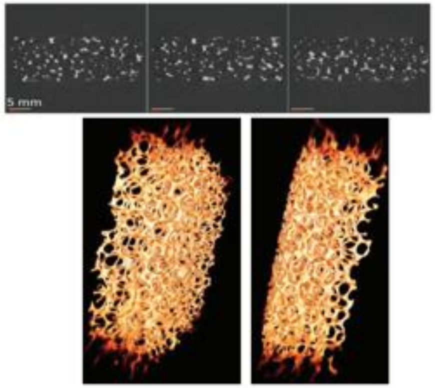




Development of thermal conductivity model.

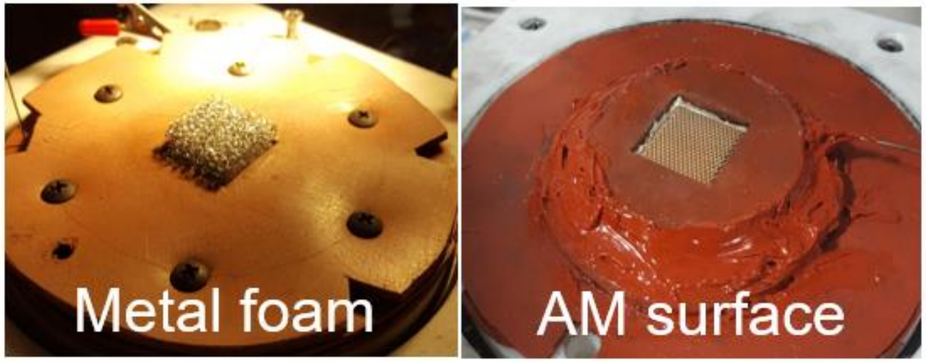
Geometric properties of metal foam (x-ray CT analysis).

Foam type	Measured minimum flow area to front area ratio (A_{min}/A_{fr})	Pore diameter, D_p (mm)	Ligament diameter, D_f (mm)
5 PPI	0.988	4.02	0.50
10 PPI	0.977	3.28	0.45
20 PPI	0.971	2.58	0.35
40 PPI	0.957	1.80	0.20

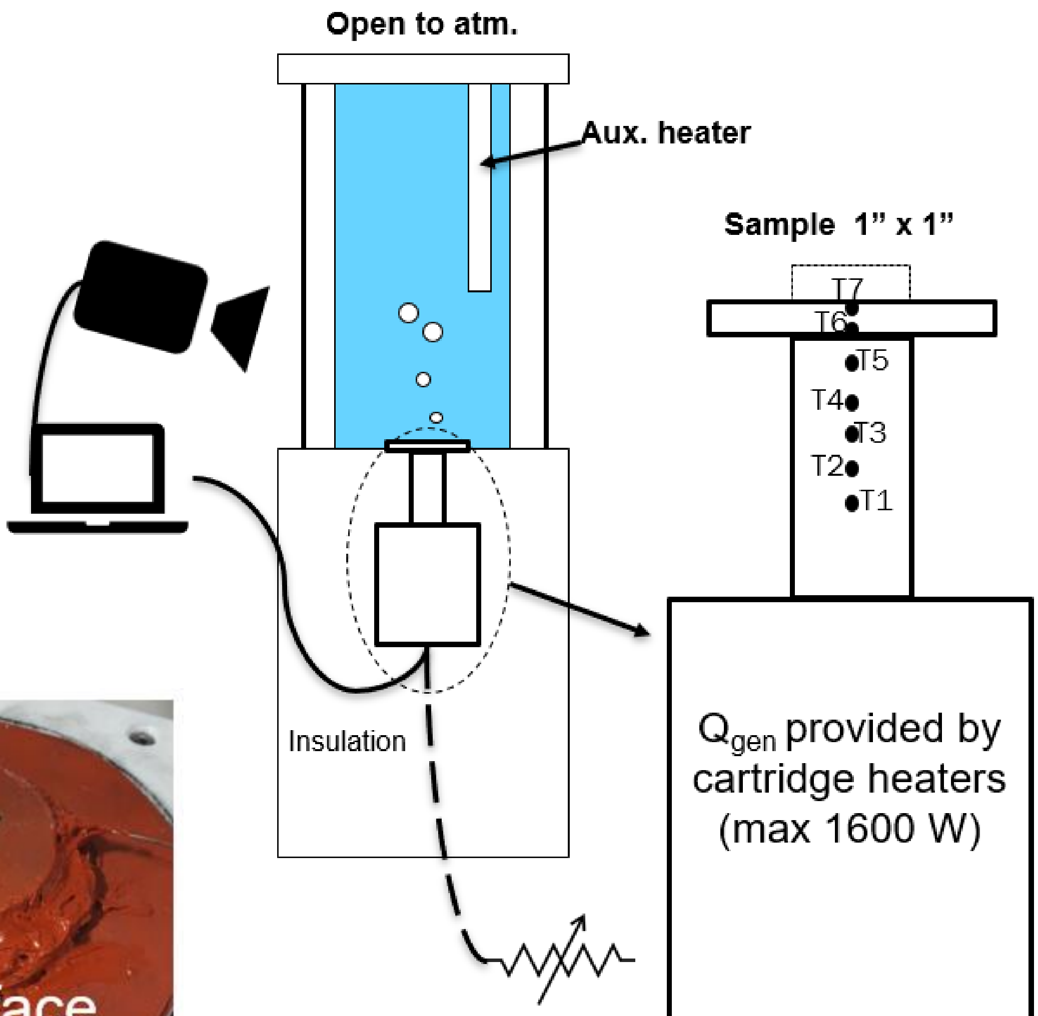


Progress — Water Pool Boiling

Boiling water apparatus.

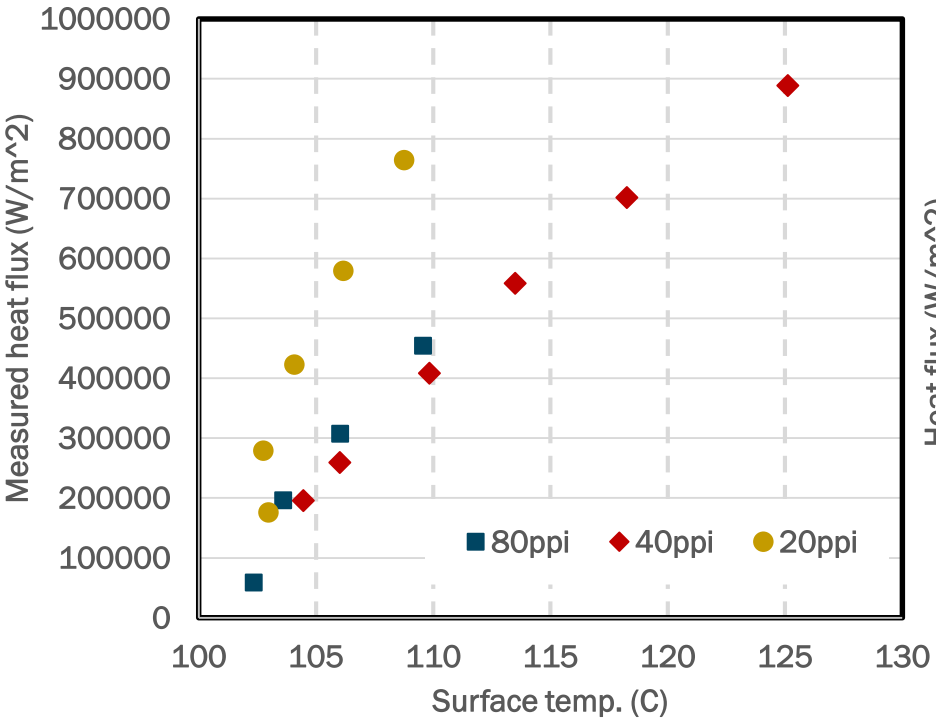


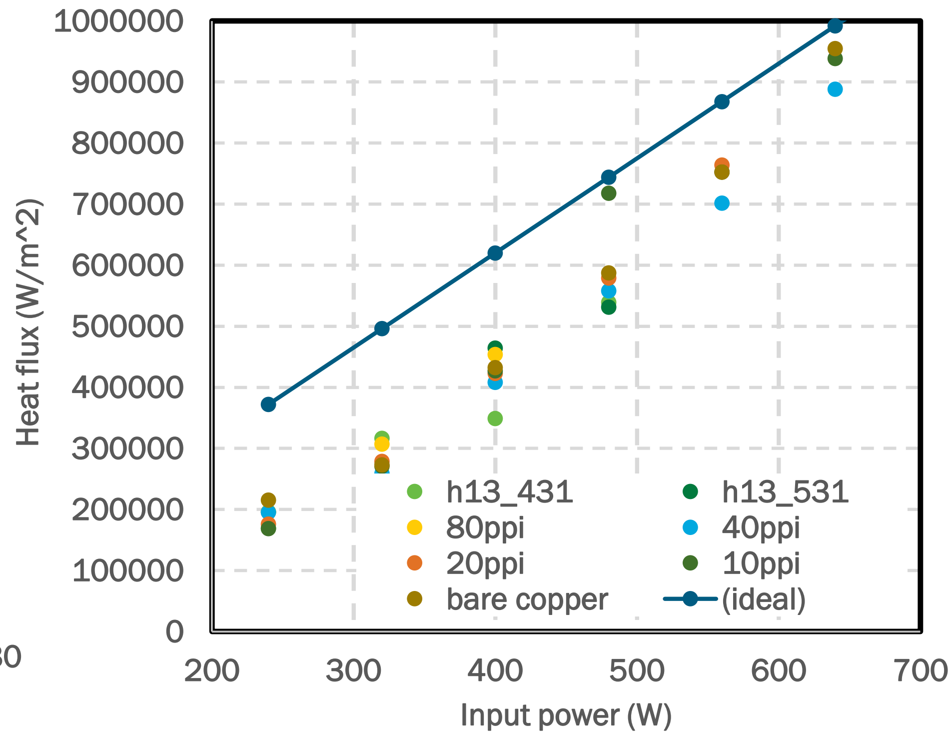
Placement of test specimens.



Schematic of water boiling apparatus.

Progress — Water Pool Boiling

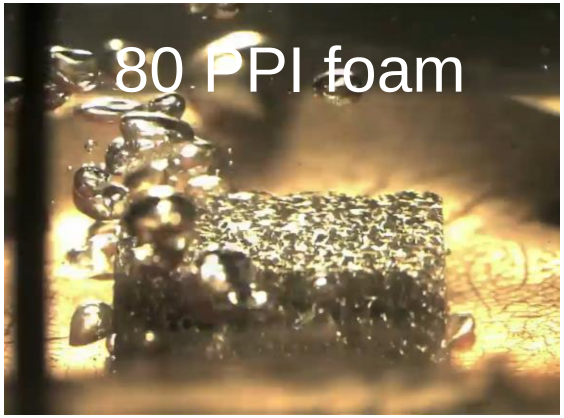


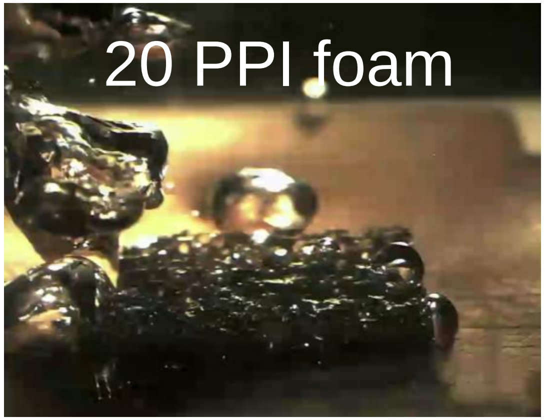


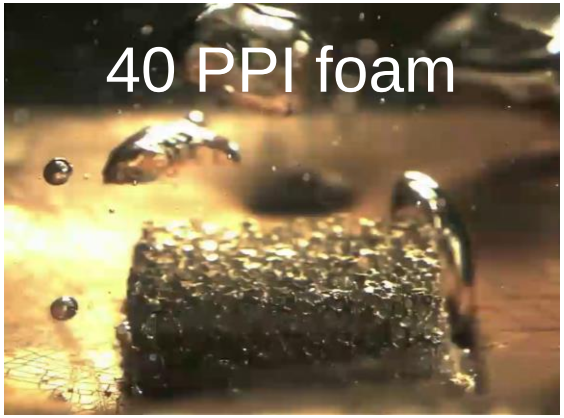
- Preliminary test results indicate the influence of the metal foam on water boiling behavior
- Perfect thermal contact on the surface has been a challenge
- Heat loss from the heaters can lead to inaccurate measurement

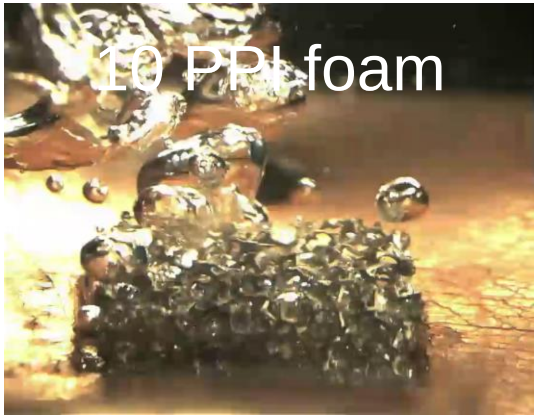
Progress — Water Pool Boiling

High-speed video of various surfaces at same input power



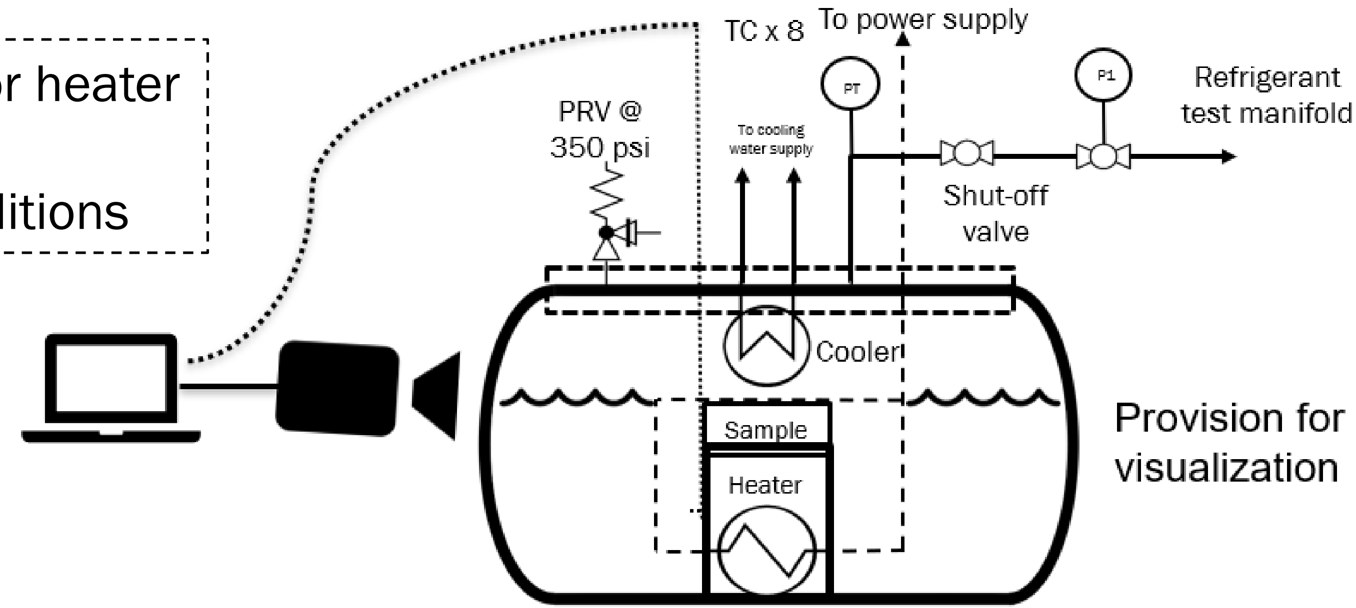


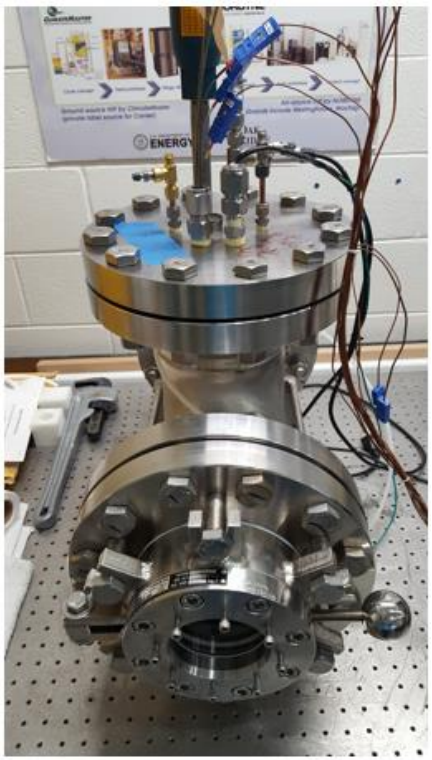


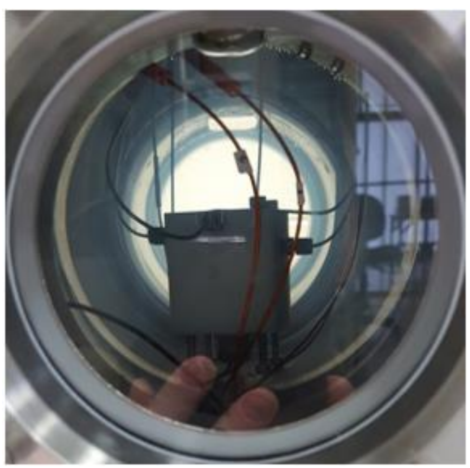


Progress — Refrigerant Pool Boiling

Feedback controller for heater and cooling system to maintain desired conditions

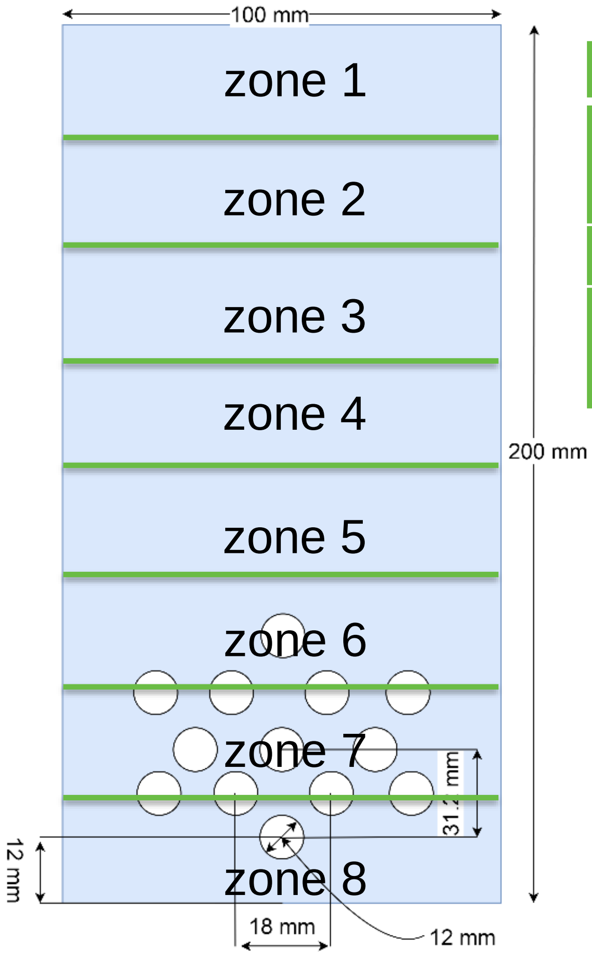






- Expected operating temp: 60° C
- Expected operating pressure: ~300 psig (P_{sat} at 60° C)
- Refrigerants: R134a, R1234yf, R1234ze(E), possible blends
- Can be modified for enhanced tube performance analysis

Progress — Numerical Analysis for Tube Bundle

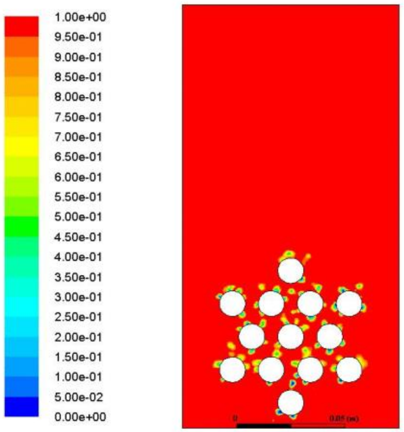


Simulation setup for tube bundle optimization.

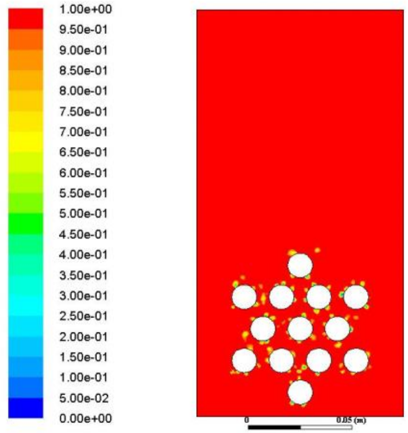
Factors	Value 1	Value 2
Bubble diameter/ Frequency:	1 mm / 5 Hz	0.7 mm / 10 Hz
Tube diameter	12 mm	8 mm
horizontal/vertical distance	9 mm / 15.6 mm	7 mm / 12.1 mm

- Bubble diameter and frequency depends on surface morphology
- Tube bundle configuration can be optimized to maximize vapor departure
- Preliminary simulations include frequent imposition of vapor bubbles (controlled diameter and frequency to represent the boiling process)

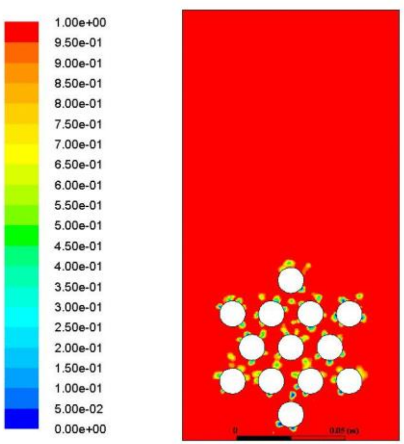
Progress — Numerical Analysis for Tube Bundle



D_b= 1 mm, D_t= 12 mm, f= 5 Hz
d_h= 9 mm, d_v=15.6 mm



D_b= 0.75 mm, D_t= 12 mm, f= 10 Hz
d_h= 9 mm, d_v=15.6 mm



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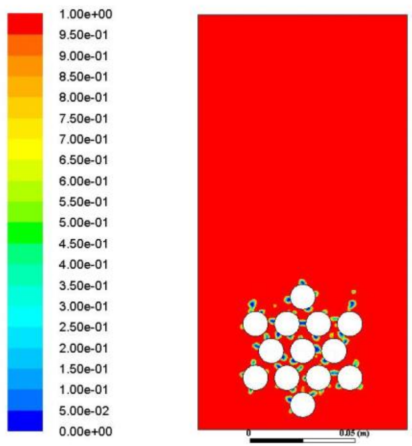
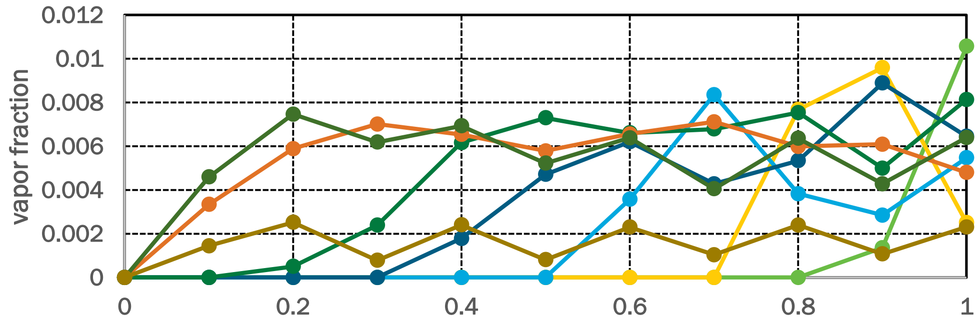


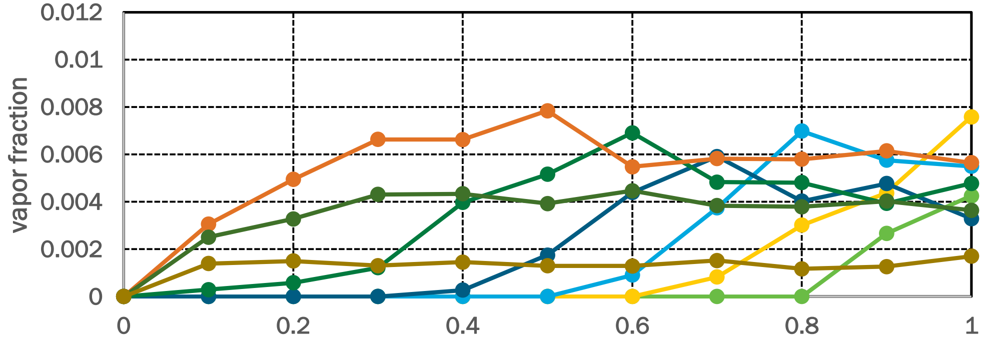
D_b= 1 mm, D_t= 12 mm, f= 5 Hz
d_h= 7 mm, d_v=12.1 mm

- Bubble diameter and frequency depends on surface morphology
- Tube bundle configuration can be optimized to maximize vapor departure
- Preliminary simulations include frequent imposition of vapor bubbles to represent
  - Controlled diameter
  - Frequency

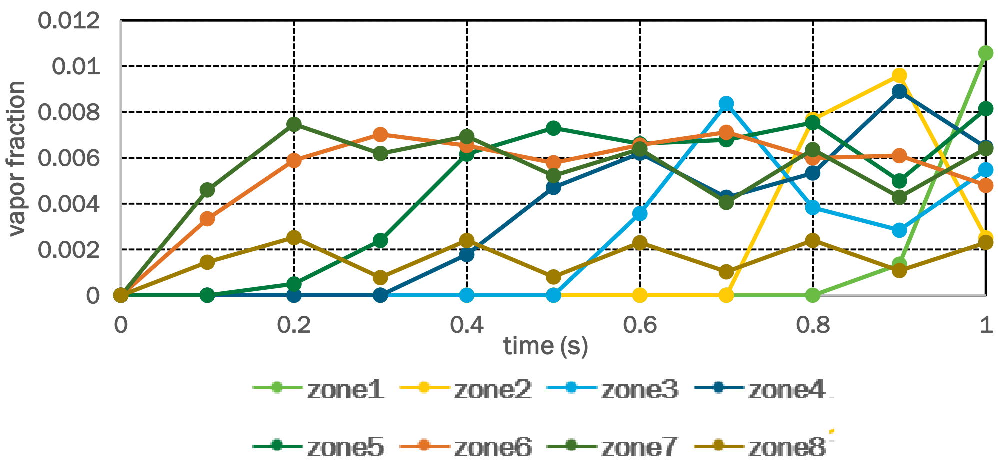
Progress — Numerical Analysis for Tube Bundle



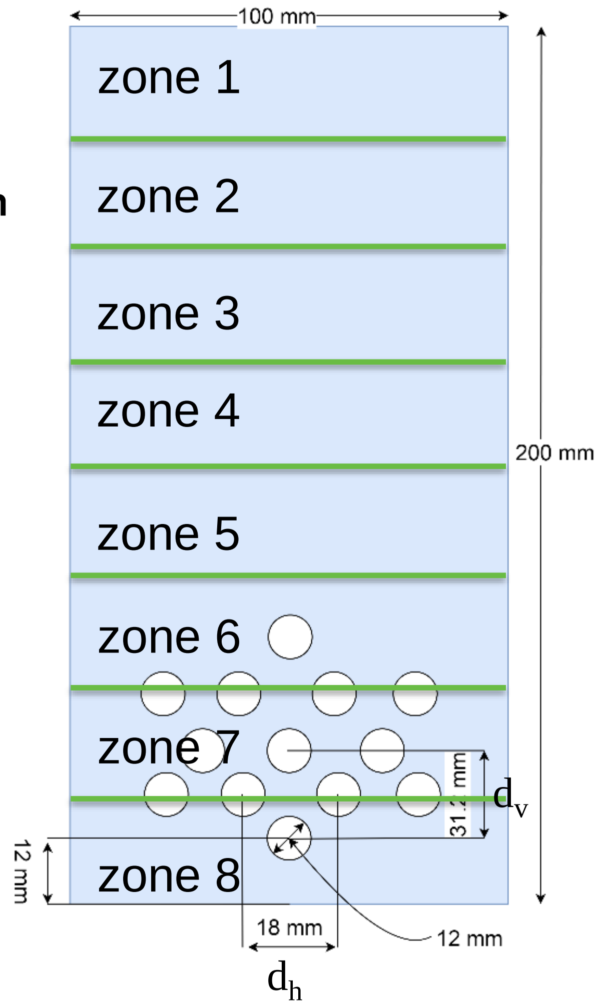
D_b= 1 mm
D_t= 12 mm
f= 5
d_h= 9 mm,
d_v=15.6 mm



D_b= 0.75 mm
D_t= 12 mm
f= 10
d_h= 9 mm
d_v=15.6 mm



D_b= 1 mm
D_t= 12 mm
f= 5
d_h= 7 mm
d_v=12.1 mm



Stakeholder Engagement

- **Development of the technology**
  - Tube bundle arrangement
  - Major challenges (oil management, maintenance)
  - Techno-economic analysis
  - Prototype development and testing (Isotherm & JCI)
- **Meetings with experts at technical platform**
  - ASHRAE (TC 8.4)
  - ASME (IMECE, SHTC)
  - Purdue, Gordon Research Conference
- **Presentations/Conference papers**
  - GRC on enhanced heat transfer 2019
  - ASHRAE (Speaker at 2019 Annual Conference)
  - ASME (Speaker at SHTC 2019)

Remaining Project Work

Name	Description
Establishment of thermal conductivity of metal foams	Develop a model to determine the thermal conductivity of metal foams (various PPI)
Establish the geometry of metal foams	X-ray imaging to evaluate the key geometrical characteristics of metal foams
Water boiling on enhanced surfaces	Conduct detailed analysis of water boiling performance on metal foams and enhanced surfaces
Pool boiling of refrigerants	Conduct detailed analysis of pool boiling performance of various refrigerants
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
Development of enhanced tube bundle	Design and fabricate an enhanced tube bundle that can be used as a prototype to demonstrate the technology
Performance evaluation of tube bundle	Conduct detailed parametric analysis of tube bundle using various refrigerants and develop the performance models
Field study	With the assistance of DOE and Isotherm, initiate and complete a field study deploying the proposed technology at an appropriate site
Commercialization plan	Develop reports and advertisements to facilitate the commercialization of the proposed technology. Identify and mitigate the market risks

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $900K
Variances: None.
Cost to Date: $615K
Additional Funding: None.

Budget History					
FY 2018 (past)		FY 2019 (current)		FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$508K	$100K	$192K	$50K	$200K	$50K

Project Plan and Schedule