Novel Compact Flooded Evaporators for Commercial Refrigeration

Oak Ridge National Laboratory
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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

Budget:
Total Project $ to Date:
- DOE: $658K
- Cost share: $150K

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

Key Partners:

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.
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.

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

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.
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.
Design, demonstrate, and analyze the performance of an 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

- 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).

<table>
<thead>
<tr>
<th>Foam type</th>
<th>Measured minimum flow area to front area ratio ($A_{min}/A_{fr}$)</th>
<th>Pore diameter, $D_p$ (mm)</th>
<th>Ligament diameter, $D_f$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 PPI</td>
<td>0.988</td>
<td>4.02</td>
<td>0.50</td>
</tr>
<tr>
<td>10 PPI</td>
<td>0.977</td>
<td>3.28</td>
<td>0.45</td>
</tr>
<tr>
<td>20 PPI</td>
<td>0.971</td>
<td>2.58</td>
<td>0.35</td>
</tr>
<tr>
<td>40 PPI</td>
<td>0.957</td>
<td>1.80</td>
<td>0.20</td>
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</tbody>
</table>
Progress — Water Pool Boiling

Boiling water apparatus.

Schematic of water boiling apparatus.

Placement of test specimens.

Metal foam

AM surface

Open to atm.

Aux. heater

Sample 1” x 1”

T7

T6

Q_{gen} provided by cartridge heaters (max 1600 W)

T5

T4

T3

T2

T1

Insulation
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

- Plane surface
- 80 PPI foam
- 20 PPI foam
- H13-531
- 40 PPI foam
- 10 PPI foam
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_{\text{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

#### Factors

<table>
<thead>
<tr>
<th></th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bubble diameter/ Frequency:</strong></td>
<td>1 mm / 5 Hz</td>
<td>0.7 mm / 10 Hz</td>
</tr>
<tr>
<td><strong>Tube diameter</strong></td>
<td>12 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td><strong>horizontal/vertical distance</strong></td>
<td>9 mm / 15.6 mm</td>
<td>7 mm / 12.1 mm</td>
</tr>
</tbody>
</table>

- 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)

Simulation setup for tube bundle optimization.
- 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

- **Zone 1**: $D_b = 1$ mm, $D_t = 12$ mm, $f = 5$, $d_h = 9$ mm, $d_v = 15.6$ mm
- **Zone 2**: $D_b = 0.75$ mm, $D_t = 12$ mm, $f = 10$, $d_h = 9$ mm, $d_v = 15.6$ mm
- **Zone 3**: $D_b = 1$ mm, $D_t = 12$ mm, $f = 5$, $d_h = 7$ mm, $d_v = 12.1$ mm
- **Zone 4**: $D_b = 1$ mm, $D_t = 12$ mm, $f = 5$, $d_h = 7$ mm, $d_v = 12.1$ mm
- **Zone 5**: $D_b = 1$ mm, $D_t = 12$ mm, $f = 5$, $d_h = 7$ mm, $d_v = 12.1$ mm
- **Zone 6**: $D_b = 1$ mm, $D_t = 12$ mm, $f = 5$, $d_h = 7$ mm, $d_v = 12.1$ mm
- **Zone 7**: $D_b = 1$ mm, $D_t = 12$ mm, $f = 5$, $d_h = 7$ mm, $d_v = 12.1$ mm
- **Zone 8**: $D_b = 1$ 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

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

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REFERENCE SLIDES
Project Budget

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

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<th>Budget History</th>
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<tr>
<td>FY 2018 (past)</td>
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<tr>
<td>DOE</td>
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<td>$508K</td>
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## Project Plan and Schedule

### Project Schedule

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<tr>
<th>Project Start: 10-01-2017</th>
<th>Completed Work</th>
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<tr>
<td>Projected End: 09-30-2020</td>
<td>Active Task (in progress work)</td>
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- **Milestone/Deliverable (Originally Planned)**
- **Milestone/Deliverable (Actual)**

### FY2018

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<th>Task</th>
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