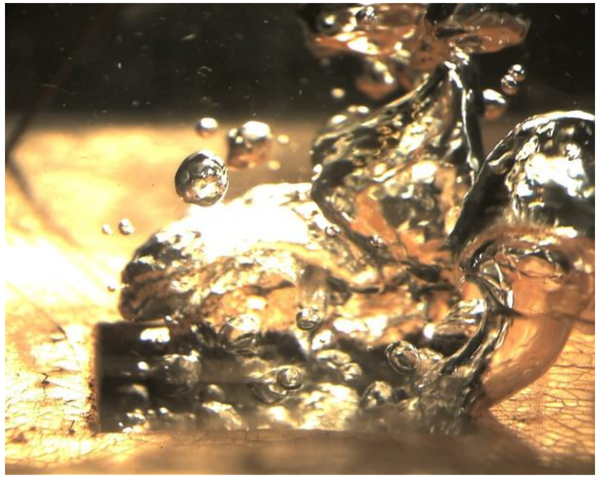
# PoolHT150 – Pool Boiling Heat Transfer for Refrigerants with GWP < 150


Low-GWP refrigerants



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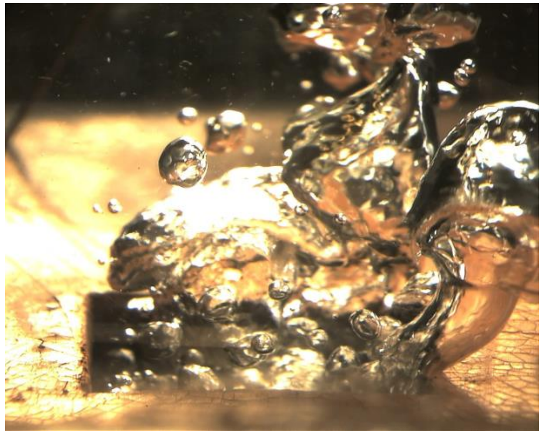
WBS 03.02.02.38.NS04b

# Project Summary

## Objective and outcome

Pool boiling is the primary mode of heat transfer that occurs in heat exchangers used for HVAC and refrigeration applications. This project will evaluate the pool boiling heat transfer of new low-GWP refrigerants (GWP<150), which is critical for designing next-generation heat exchangers with enhanced performance and reduced refrigerant charge.




Low-GWP refrigerants

## Team and Partners

***Oak Ridge National Laboratory***

-Cheng-Min Yang (R&D Staff)

-Muneeshwaran M. (Postdoctoral associate)

-Kashif Nawaz (Sr. R&D Staff)

-Tony Gehl (Sr. Technical Staff )

***Honeywell***

-Ankit Sethi (Sr. R&D manager)

OAK RIDGE National Laboratory

Honeywell

## Stats

Performance Period: May 2022 to April 2024

DOE budget: $750k/yr.

Milestone 1: Development of pool boiling facility for refrigerants (3/31/2023)

Milestone 2: Heat transfer measurement for various low-GWP refrigerants (9/30/2023)

Milestone 3: Evaulation of the enhanced surface (3/31/2024)

# Problem

- Support DOE BTO to accelerate the transition to next-generation low GWP refrigerants
- Widely used nucleate boiling correlations for flat surfaces are developed for narrow range of fluids, which is a critical portion of flow boiling correlations and
- Particularly, there is no correlation to predict the nucleate boiling behavior of low GWP refrigerants such as R-1234yf, R-1234ze(E), and R-1233zd(E)

**Rohsenow (1952)**

$$h_{nb} = \mu_l h_{fg} \left[ \frac{g(\rho_l - \rho_v)}{\sigma} \right]^{\frac{1}{2}} \mathrm{Pr}_l^{\frac{-s}{r}} \left( \frac{c_{p,l}}{c_{s,f} h_{fg}} \right) (\Delta T_{sat})^{\frac{1-r}{r}}$$

**Cooper (1984)**

$$h_{nb} = 55 \left( q''_{nb} \right)^{0.67} P^{*(0.12-0.2\log(R_a))} \left( -\log P^* \right)^{-0.55} M^{-0.5}$$

**Stephan & Abdelsalam (1980)**

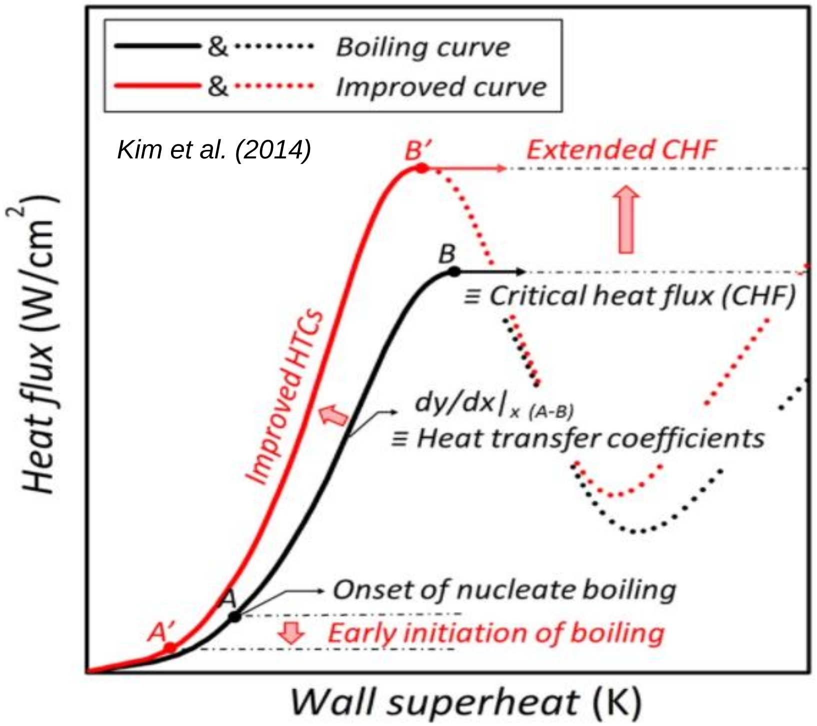
$$h_{nb} = 0.243 \frac{k_l}{D_d} \left( \frac{q''_{nb} D_d}{k_l T_v} \right)^{0.673} \left( \frac{c_p T_v D_d^2}{\alpha^2} \right)^{1.26} \left( \frac{h_{fg} D_d^2}{\alpha^2} \right)^{-1.58} \left( \frac{\rho_l - \rho_v}{\rho_l} \right)^{5.22}$$

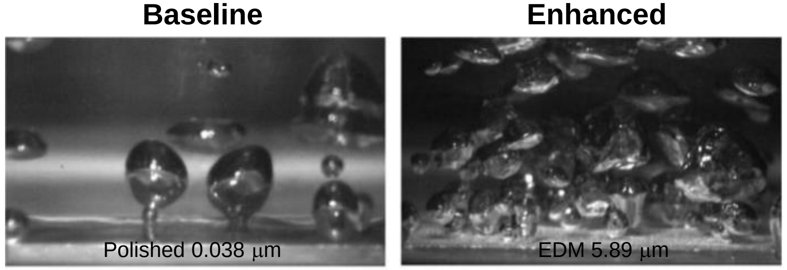
Developed based on the following fluids:

- Water
- Hydrocarbons (e.g., Benzene, n-Pentane)
- Cryogenic liquids (e.g., Hydrogen, Oxygen, Nitrogen)
- Refrigerants: R11, R12, R113, R114, R21, R22, RC318, R744

# Problem

- Development of energy-efficient evaporators is critical to enhancing national energy security.
- The evaporator size depends on the rate of heat transfer.
- The overall target is to maximize the permissible ***critical heat flux (CHF)*** limit and ***rising heat transfer coefficient*** that is defined by a local difference on the slope of the curve.
- The surface modification will be deployed to increase the nucleation sites and wetted surface area.




Pool boiling of water at q=50 kW/m2 *(Jones et al. (2009))*


*Sources:*
*B. Kim, S. Shin, D. Lee, G. Choi, H. Lee, K. Kim, and H. Cho. "Stable and uniform heat dissipation by nucleate-catalytic nanowires for boiling heat transfer." International Journal of Heat and Mass Transfer 70 (2014): 23-32*
*B. Jones, J. P. McHale, and S. V. Garimella. "The influence of surface roughness on nucleate pool boiling heat transfer." Journal of Heat Transfer 131, no. 12 (2009).*

# Alignment and Impact

- Support the nation's ambitious climate mitigation goals by reducing greenhouse gas emissions 50-52% by 2030 vs. 2005 levels.
  - Actionable results for HVAC industry to allow for transitioning from high GWP refrigerants to low GWP refrigerants (<150), which help reducing at lease 96% in direct GHG emissions
  - Ensure the US competitiveness in HVAC market
- Support DOE BTO's goal to reduce onsite use intensity in buildings 30% by 2035 and 45% by 2050, compared to 2005.
  - At least 10% energy efficiency improvement and 250TBTu energy saving in air conditioning and refrigeration systems
- Support the Department of Energy's (DOE) Building Technologies Office (DOE BTO) to decarbonize the US building stock in line with economywide net-zero emissions by 2050.

# Approach

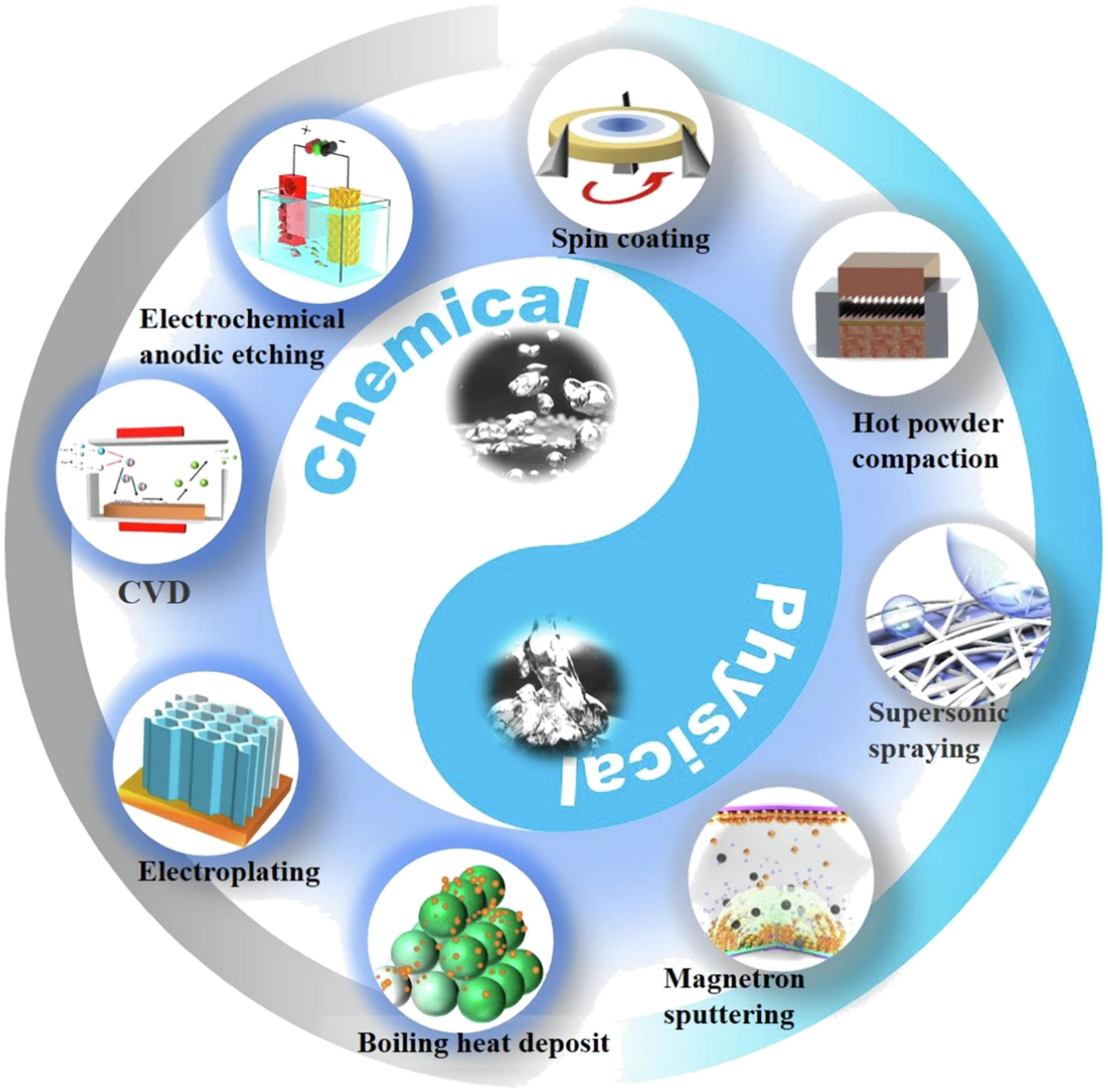
*Pool boiling performance of low GWP refrigerants*

- Evaluate various refrigerants with GWP<150
- Measure the heat transfer coefficient and generate pool boiling curve
- Develop an empirical model or correlation that will be suitable for new low GWP refrigerants

| Refrigerant | Composition (blends) | Regulatory GWP (IPCC AR4) | ASHRAE Class |
|---|---|---|---|
| R-1336mzz(E) | | 2 | A1 |
| R-1336mzz(Z) | | 2 | A1 |
| R-1233zd(E) | | 1 | A1 |
| R-1234yf | | 4 | A2L |
| R-1234ze(E) | | 7 | A2L |
| R-514A | R-1336mzz(Z)/R-1130(E) (74.7/25.3) | 2 | B1 |
| R-516A | R-1234yf/R-134a/R-152a (77.5/8.5/14.0) | 142 | A2L |

# Approach

## *Enhanced surfaces for pool boiling heat transfer*




Commonly used surface modification techniques *(Chu et al. (2022))*

- Factors that affect pool boiling performance
  - Bubble dynamics/surface roughness/ wick ability/surface wettability…
- Fundamental studies of the heat transfer mechanisms for pool boiling
  - Nucleation/bubble growing and detaching/rewetting/surface area…
- Evaluation of enhanced surfaces that can improve the pool boiling heater or delay the critical heat flux for low GWP refrigerants

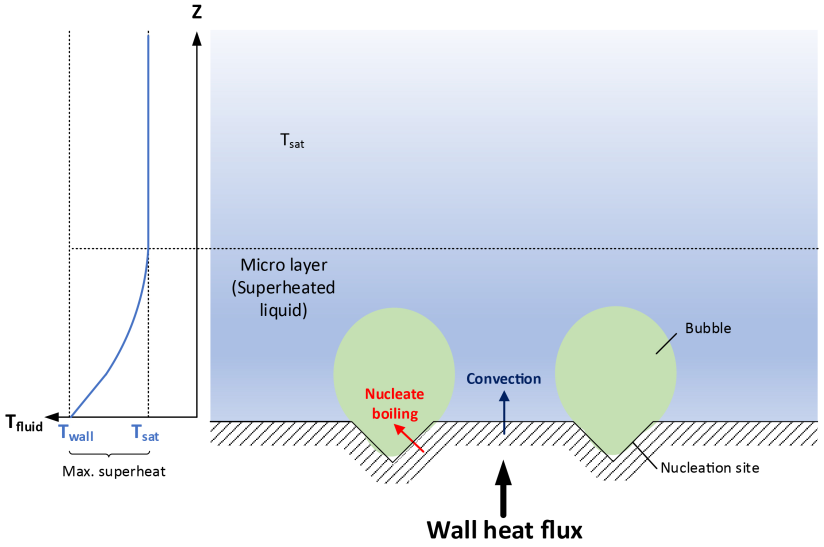
*Source:*
*H. Chu, N. Xu, X. Yu, H. Jiang, W. Ma, and F. Qiao. "Review of surface modification in pool boiling application: Coating manufacturing process and heat transfer enhancement mechanism." Applied Thermal Engineering (2022): 119041.*

# Approach

| Phase I: Facility development | Phase II: Evaluation of low GWP refrigerants | Phase III : Testing enhanced surfaces |
|---|---|---|
| • Review state-of-the-art test facility in literature<br>• Develop pool boiling setups for evaluating medium and low pressure refrigerants<br>• Validate the facility by comparing with open literature<br>• Study heat transfer measurement techniques | • Evaluate pool boiling heat transfer for various low-GWP refrigerants<br>• Compare the results with the existing correlations<br>• Develop a model to predict the performance of new refrigerants<br>• Study heat transfer mechanisms for pool boiling | • Fabricate the enhanced surfaces<br>• Characterize the surface structure of the developed surfaces<br>• Evaluate the pool boiling heat transfer of the enhanced surfaces<br>• Evaluate the effect of orientation<br>• Investigate the physics of the enhanced surface |

# Final outcome of this project

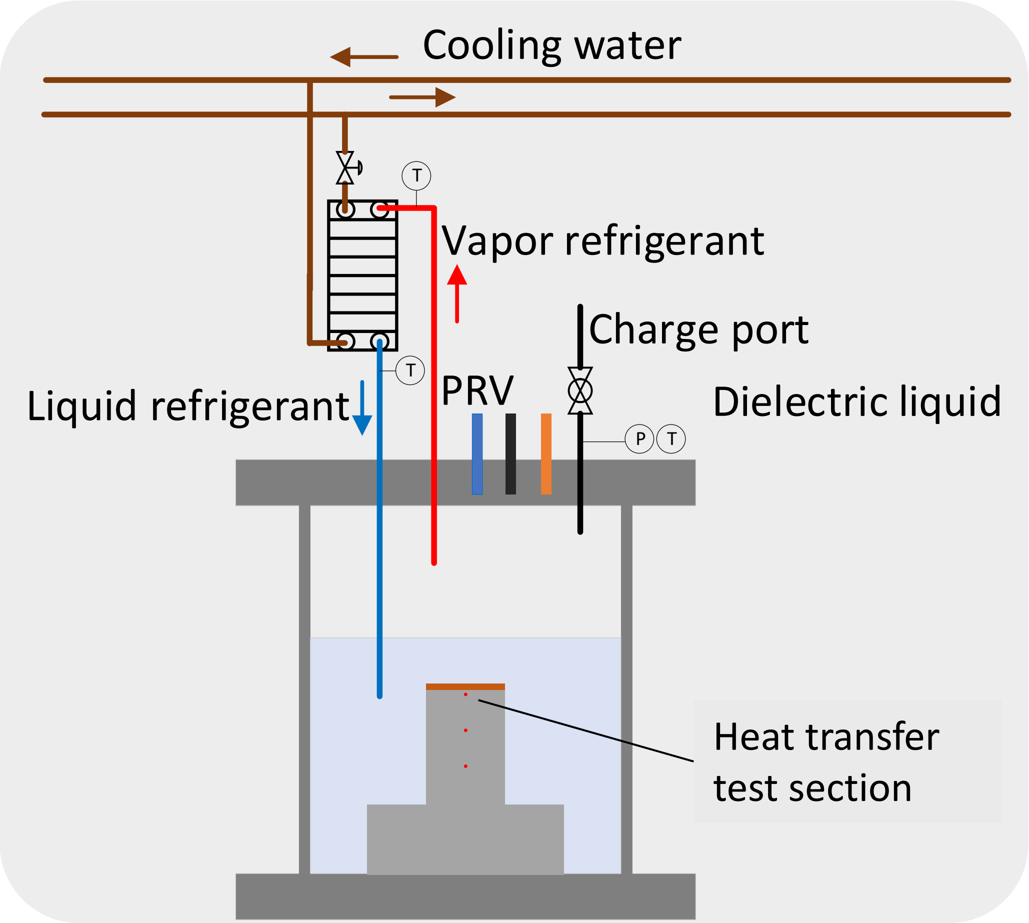
- State-of-the-art infrastructure to evaluate pool boiling heat transfer for both low-pressure and medium-pressure applications
- Extensive experimental data and an empirical model for pool boiling heat transfer of ultra low GWP refrigerants (GWP<150)
- Tested the enhanced surfaces that can improve the heat transfer performance and extend critical heat flux for the target refrigerants
- Insight of pool boiling heat transfer mechanisms on the enhanced surface and the effect of the surface orientation



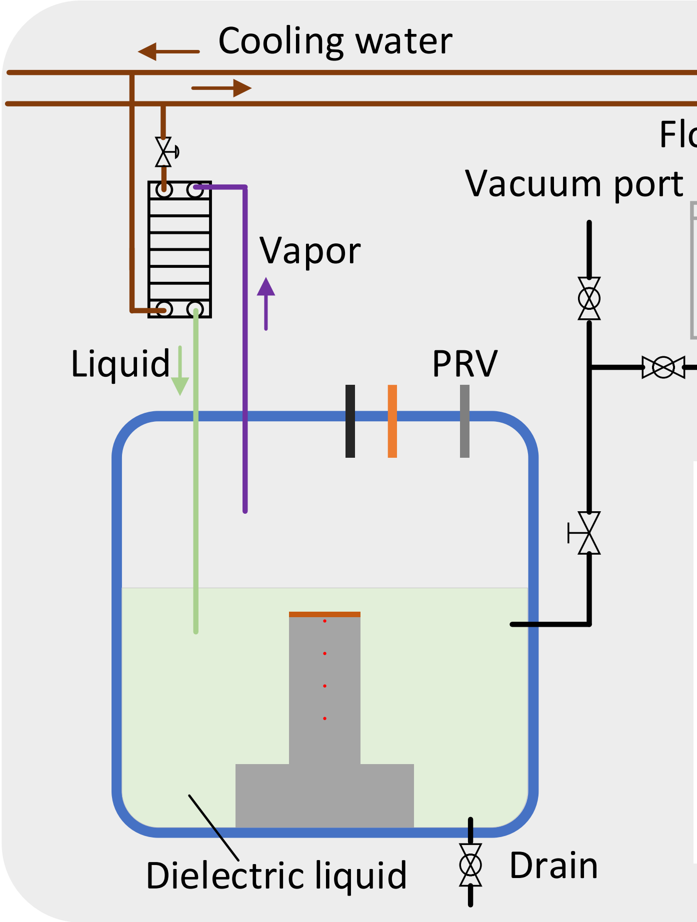
# Progress

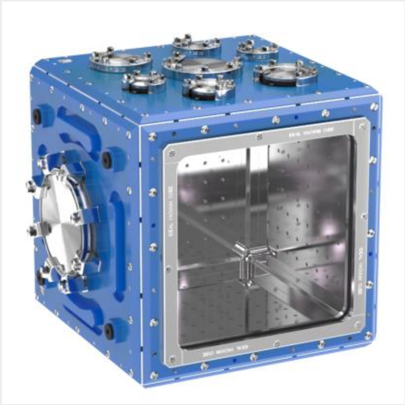
## *Design of pool boiling test facility*

### Pool boiling facility for medium pressure refrigerants




### Pool boiling facility for low pressure refrigerants

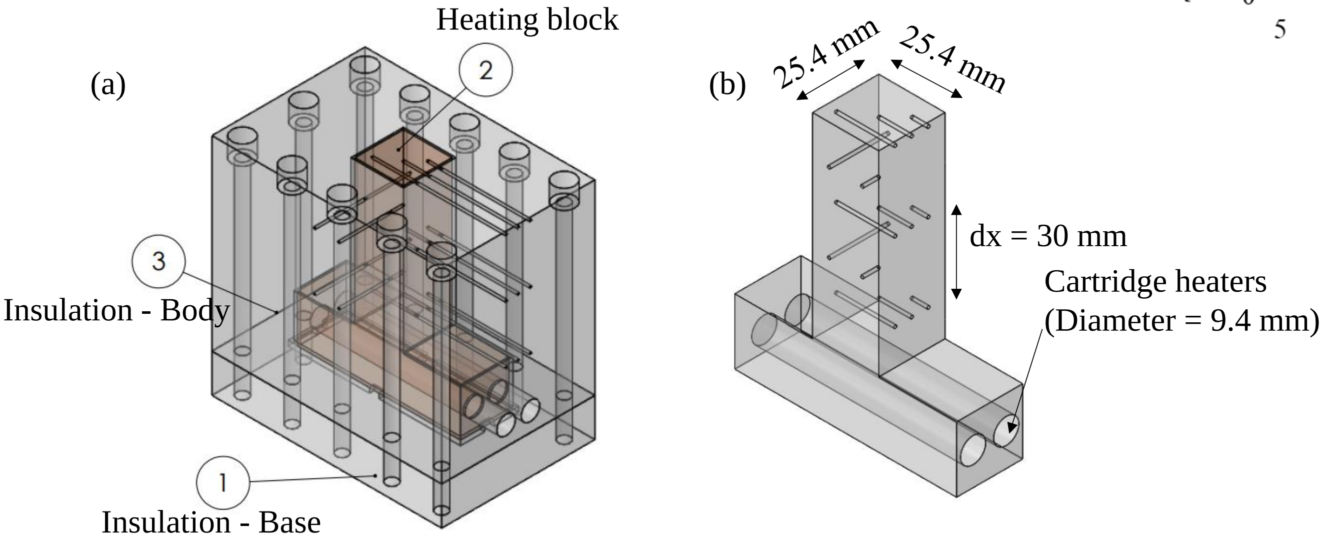


# Progress

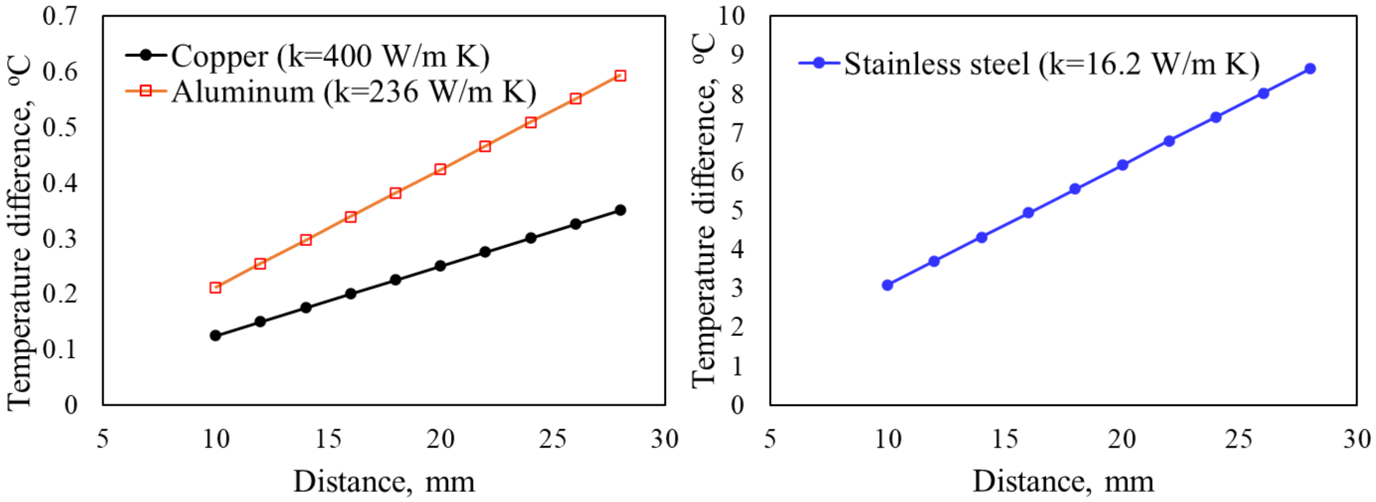
## *Design of heat transfer test section*

- Components of heat transfer test section:
  - One heating block and two insulation units
  - 1” × 1” Al or Cu flat surface sample
  - Two 625 W cartridge heaters
  - Heat flux: 0-193 W/cm$^2$
- Instrumentation:
  - Type T thermocouples and pressure transducer
  - SCR power controller and watt transducer




**Pool boiling heat transfer test section for flat surface**

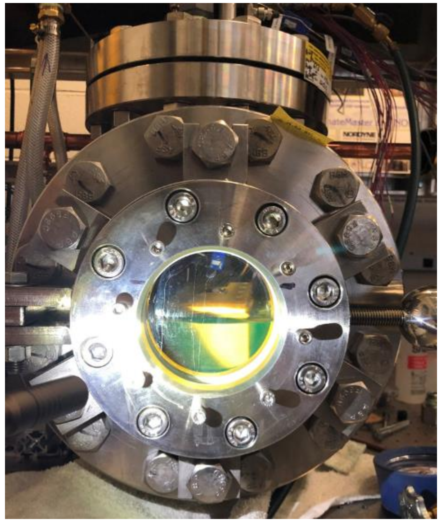
**The variation of temperature difference (ΔT) with distance between thermocouples (dx) for different materials (q = 10 kW/m$^2$)**



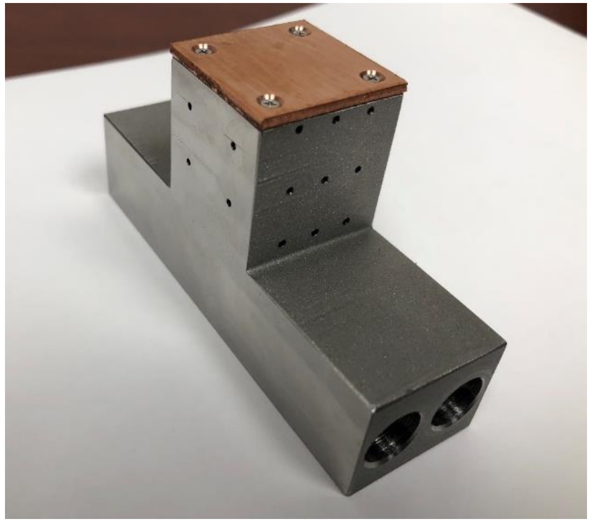

- Material selection of the test section:
  - Material of the heating block influences the uncertainty of the measurement technique
  - Estimation of temperature differences within the heating block
  - PTFE insulation for reducing heat loss

# Progress

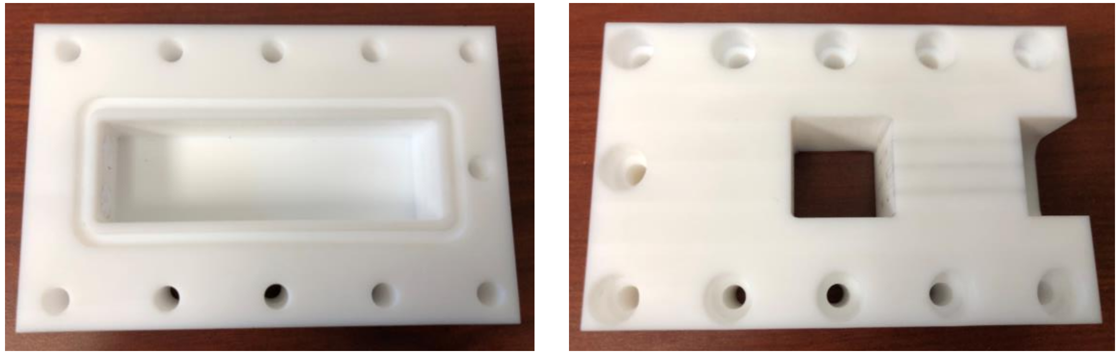
## *Development of pool boiling test facility*



Pressure vessel

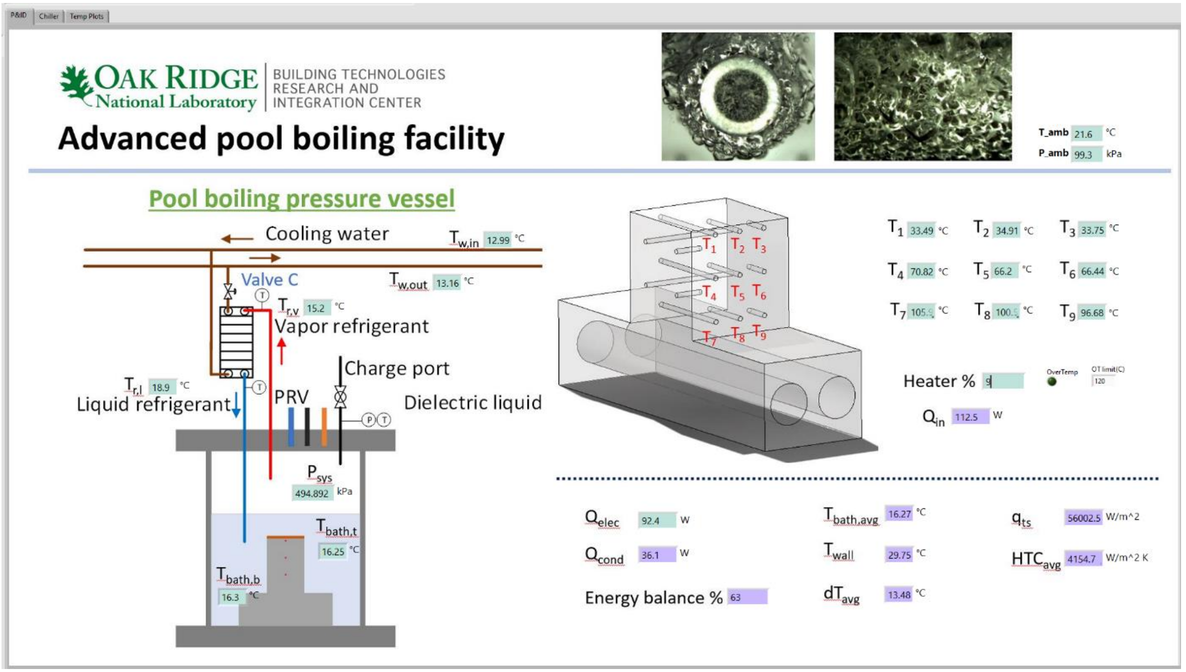


Heat transfer test section



PTFE insulation (base plate and top cover)

- A closed loop setup to measure the pool boiling heat transfer of medium pressure refrigerants has been built.
- A LabVIEW program has been developed to control the operating conditions and record the heat transfer data.




LabView program for pool boiling facility

# Progress

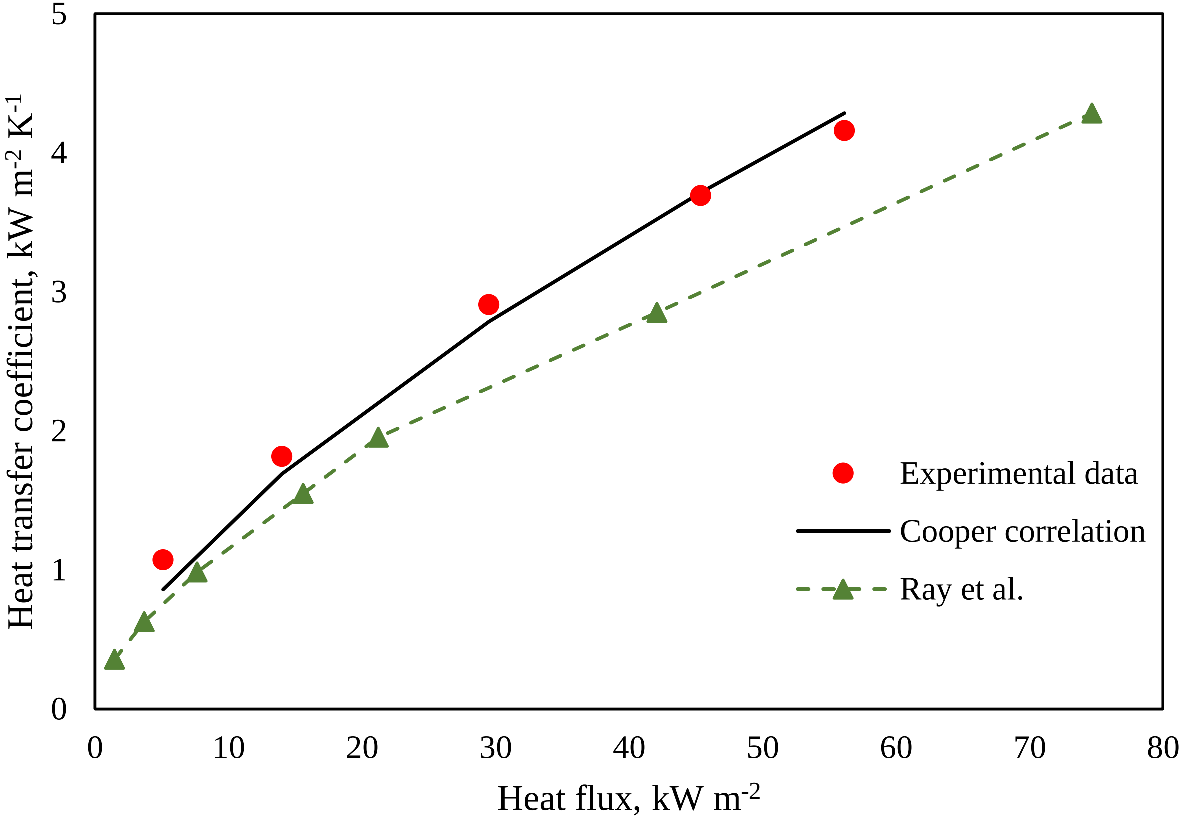
## *Validation of test facility using R134a*

- Experiments for facility validation:
  - Bare copper surface
  - R134a
  - Saturation pressure: 5 bar ($P_r$=0.123)
  - Heat flux: 5-56 kW/m$^2$
- Comparison with literature:
  - Experimental data of R134a pool boiling data from Ray et al.
  - Pool boiling correlation developed by Cooper

$$h_{nb} = 55\left(q''_{nb}\right)^{0.67} P^{*(0.12-0.2\log(R_a))}\left(-\log P^*\right)^{-0.55} M^{-0.5}$$

- Results:
  - A maximum deviation of 7% with Cooper correlation
  - About 23% with the Ray's experimental data
  - $P_r$ of the current study is slightly different from Ray's conditions.

Comparison of measured heat transfer coefficient with Cooper correlation and Ray's experimental data




*Sources:*
*M. Cooper, "Saturation Nucleate Pool Boiling: A Simple Correlation, Department of Engineering Science," Oxford University, England, vol. 86, pp. 785-793, 1984.*
*M. Ray, S. Deb, and S. Bhaumik, "Pool boiling heat transfer of refrigerant R-134a on TiO2 nano wire arrays surface," Applied Thermal Engineering, vol. 107, pp. 1294-1303, 2016.*

***The facility has been validated and the results of HTC showed a reasonable agreement with Cooper correlation.***

# Future work

- **Work in progress:**
  - Review low-GWP refrigerant pool boiling heat transfer on enhanced surfaces
  - Design a closed loop apparatus to evaluate pool boiling heat transfer for low pressure refrigerants
  - Validate the facility using known commercial refrigerants with heat transfer data available in the open literature
  - Conduct pool boiling experiments under different operating conditions
  - Visualize the pool boiling process to understand the heat transfer mechanisms for future model development
- **Future tasks:**
  - Test various refrigerants with GWP lower than 150
  - Develop a modelling strategy to predict pool boiling heat transfer performance of new low GWP refrigerants
  - Fabricate and characterize the enhanced surfaces
  - Modify the test section to evaluate the effect of enhanced surfaces
  - Investigate the effect of orientation on pool boiling heat transfer
  - Summarize the project activities

# Thank you

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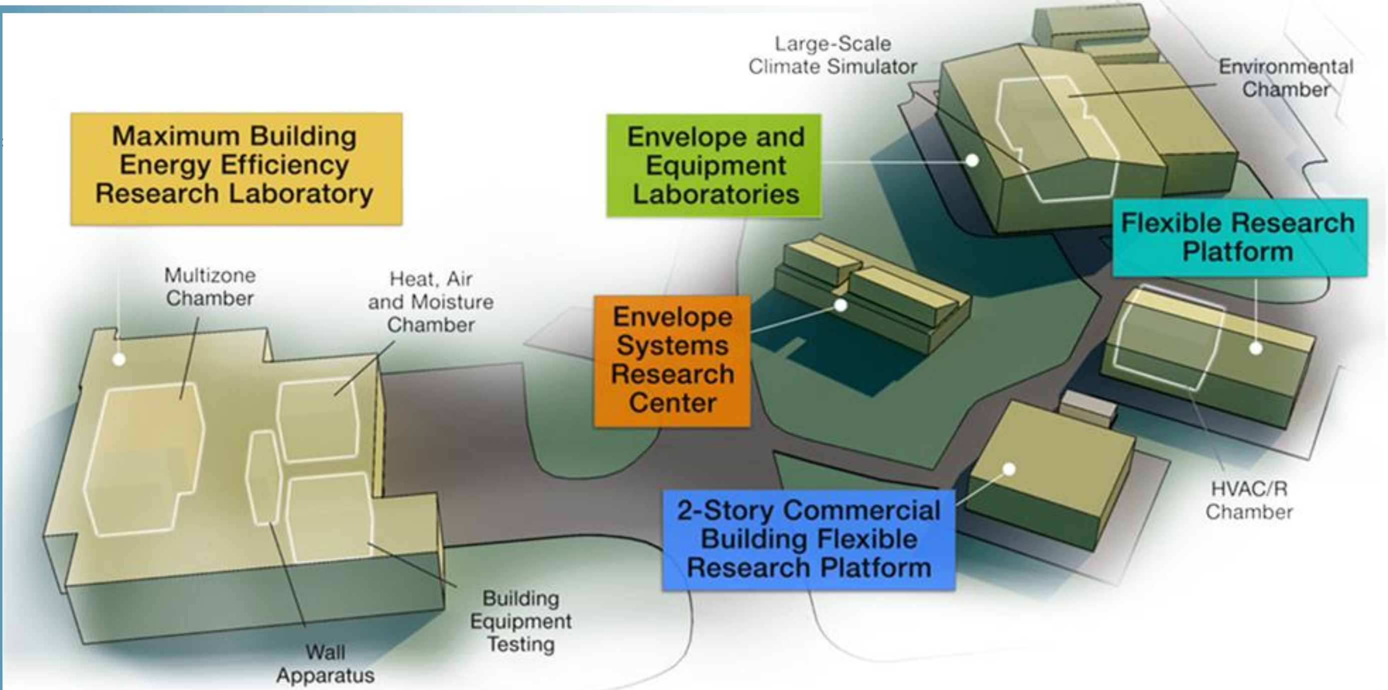


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**Scientific and Economic Results**

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***

# REFERENCE SLIDES

# Project Execution

| | FY22 | | FY23 | | | | FY24 | |
|---|---|---|---|---|---|---|---|---|
| | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 |
| **Past Work** | | | | | | | | |
| Q4 Milestone: Develop a closed loop pool boiling apparatus for refrigerants | | ◆ | | | | | | |
| Q1 Milestone: Validate the facility using known commercial refrigerants | | | ◆ | | | | | |
| Q2 Milestone: Complete the baseline study of pool boiling experiments | | | | ★ | | | | |
| **Current/Future Work** | | | | | | | | |
| Q4 Milestone: Measure heat transfer performance of various low GWP refrigerants | | | | | | ◆ | | |
| Q1 Milestone: Develop enhanced surfaces and evaulate the pool boiling heat transfer | | | | | | | ★ | |
| Q2 Milestone: Summarize the project activities | | | | | | | | ◆ |