Reliability of Copper Inverse Opal Surfaces for Extreme-Heat-Flux Micro-Coolers in Low-Global-Warming-Potential Refrigerant R-1233zd Pool Boiling Experiments

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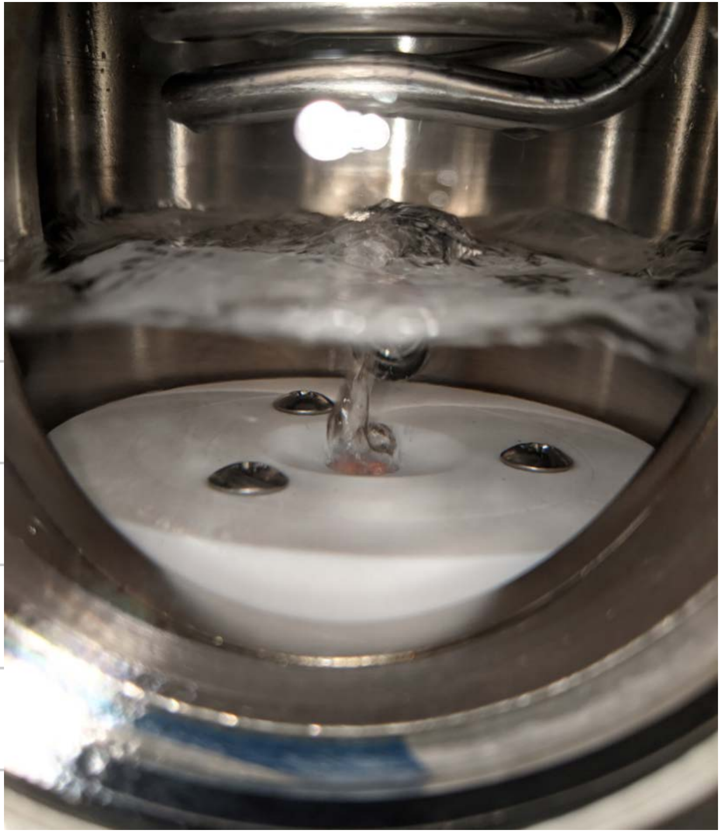


Project Framework

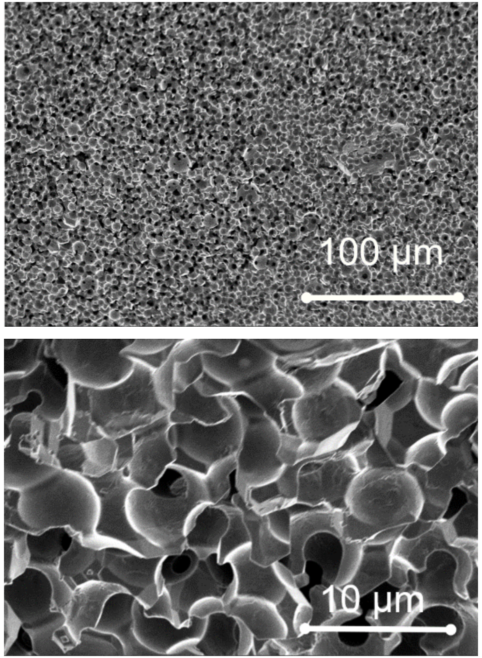
Project funded by the U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E):

- Exploring the Limits of Cooling for Extreme Heat Flux Applications: Data Centers and Power Electronics (2019–2022)
    - Stanford University
    - University of California, Merced
    - National Renewable Energy Laboratory (NREL)
    - Toyota Research Institute of North America
    - Chung-Ang University (2022).
- Development of extreme-heat-flux (≈1,000 W/cm^2) micro-coolers using copper inverse opal (CIO) porous surfaces, wicking/capillary fluid feed, and two-phase heat transfer.

Copper Inverse Opal Surfaces

- Top boiling surface area = 0.785 cm^2 (at 10-mm copper stem diameter)
- 25-µm-thick layer of CIOs with pore diameters ≈ 5 µm
- Neck-to-pore ratio (ratio of the diameter of the connecting opening between pores to the pore diameter) ≈ 0.393

- CIO porous surface enhancement for maximizing two-phase heat transfer [1].
- CIO surfaces were deposited on copper samples at Stanford University.
- NREL performed long-term structural and reliability evaluation of CIO surfaces.

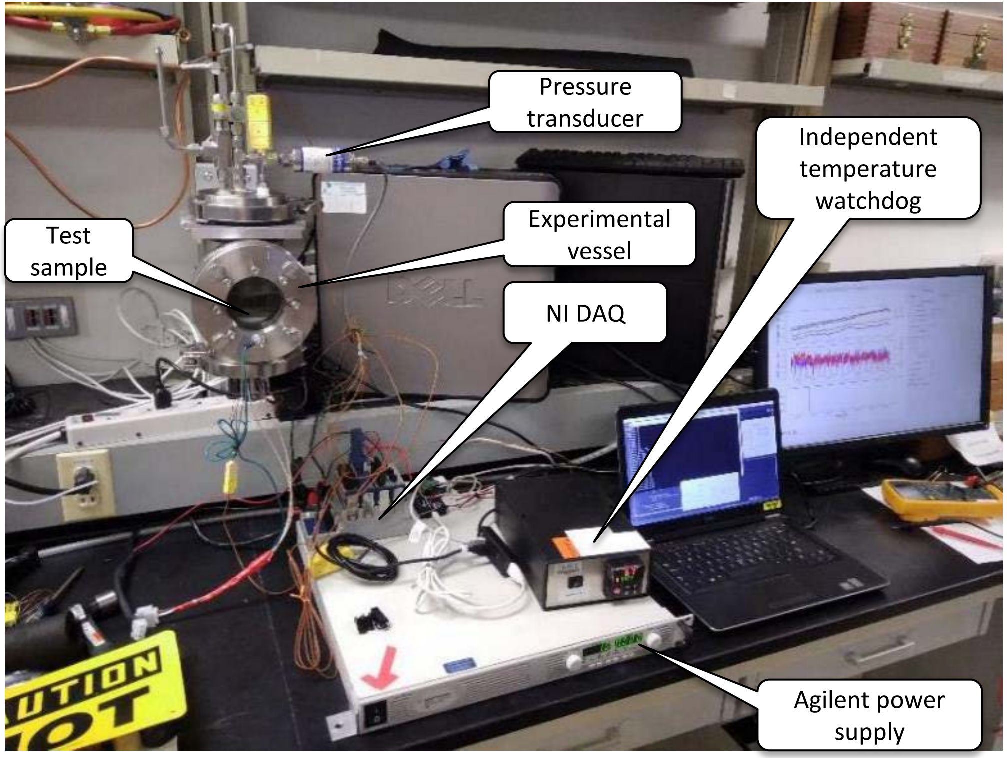


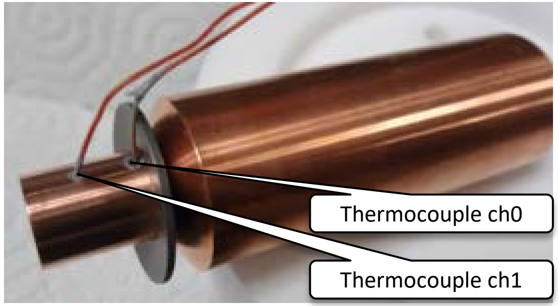
Scanning electron microscope (SEM) images by Qianying Wu, Stanford University.

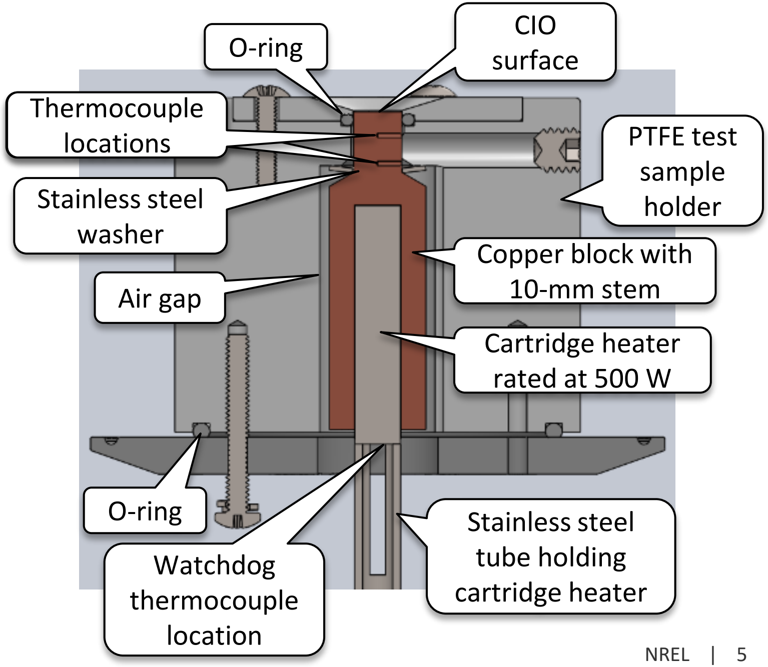

Photos by Bidzina Kekelia, NREL.

1 Q. Wu, C. Zhang, M. Asheghi, and K. Goodson. 2020. "Design and Fabrication of Graded Copper Inverse Opals (g-CIOs) for Capillary-Fed Boiling in High Heat Flux Cooling Applications." *Proceedings of the ASME 2020 InterPACK.* October 27–29, 2020. V001T07A011. ASME. https://doi.org/10.1115/IPACK2020-2603

Experimental Setup for Pool Boiling Tests at NREL

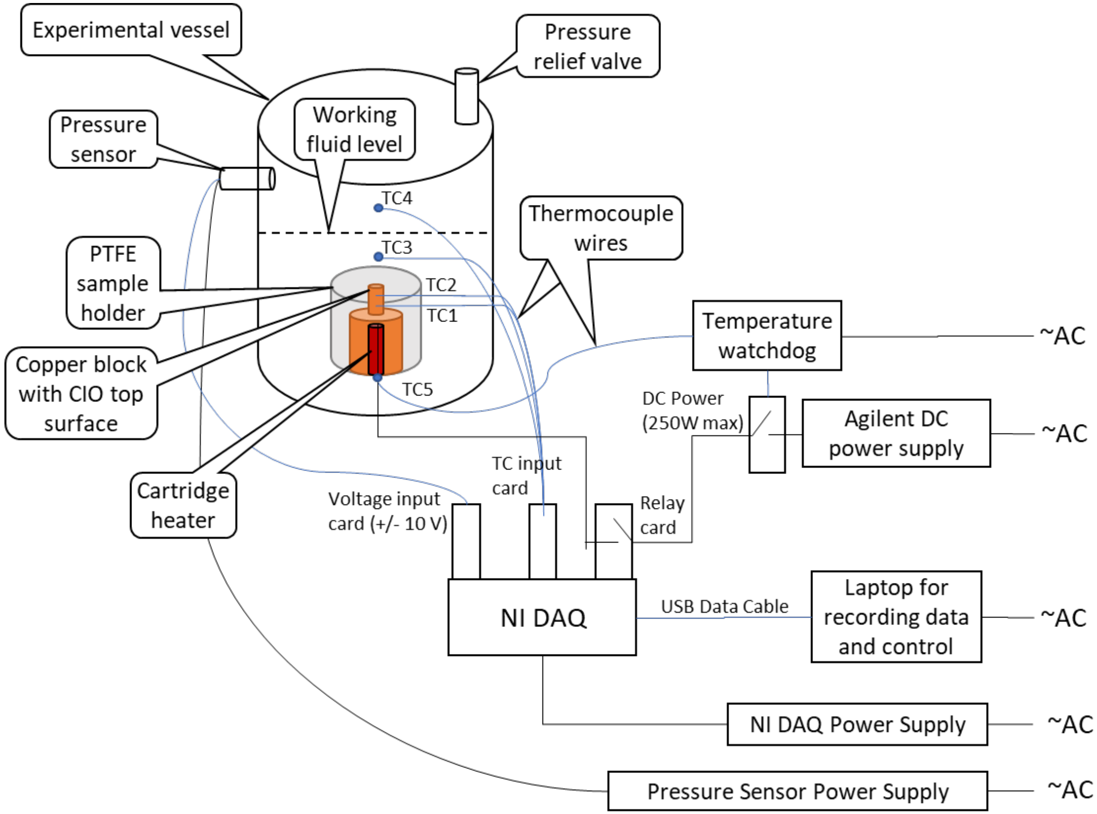






Photos and figure by Bidzina Kekelia, NREL

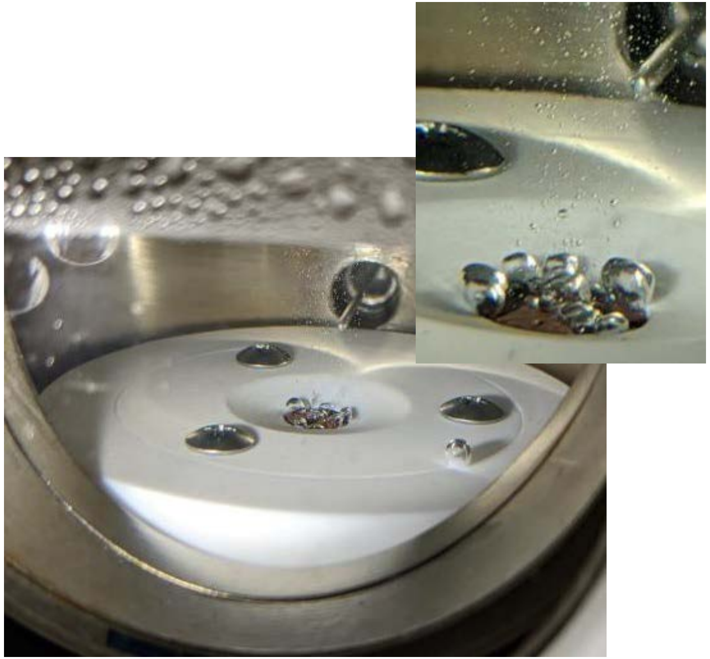
Experimental Setup – Single Line Diagram for Control and Data Acquisition



Test # 2 – CIO Sample 1: 47 Hours in Water at 50% CHF

- Copper block stem D = 10 mm
- Top surface area A = 0.785 cm^2
- Working fluid: deionized water
- Power input = 91 W
- q''_{CHF} = 225.6 W/cm^2 (previous pool boiling tests [1])

➢ Test was run with q'' = 91 W/0.785 cm^2 ≈ **116 W/cm^2** ≈ 51% of expected pool boiling critical heat flux (CHF)



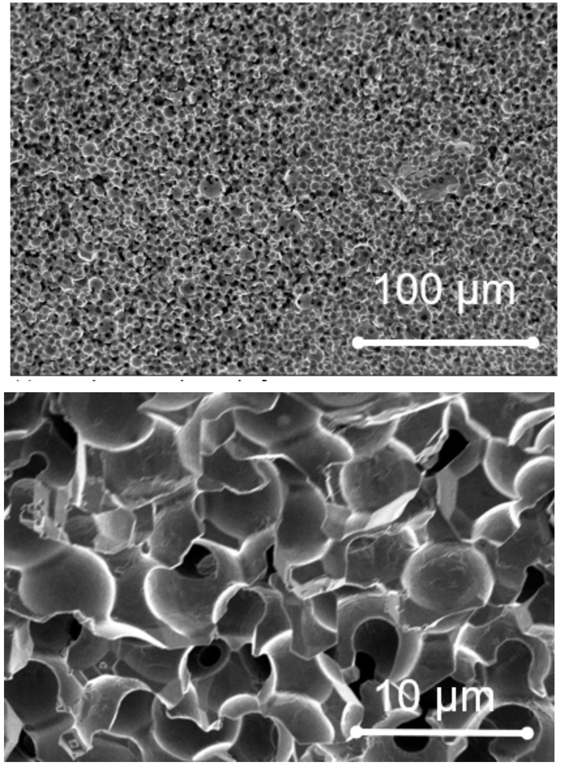
Before test

After test: Noticeable oxidation/deposits

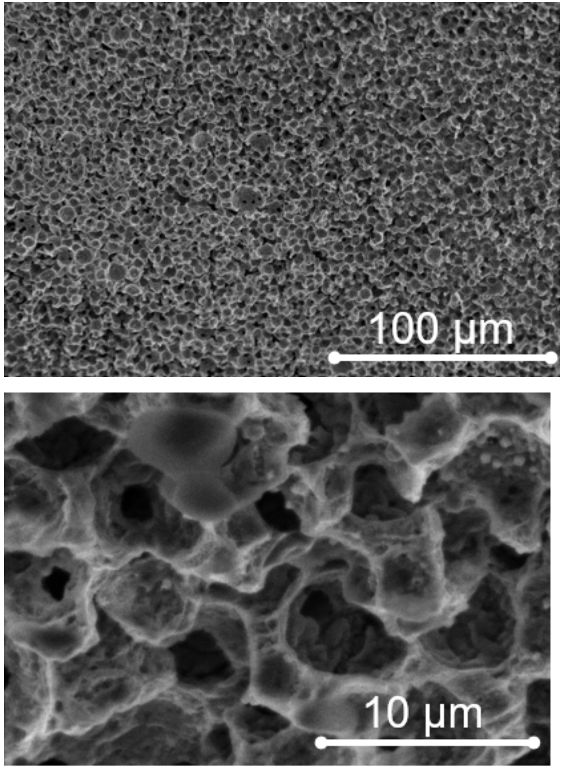
Photos by Bidzina Kekelia, NREL

[1] H. Lee, T. Maitra, J. Palko, D. Kong, C. Zhang, M. T. Barako, Y. Won, M. Asheghi, and K. E. Goodson. 2018. "Enhanced Heat Transfer Using Microporous Copper Inverse Opals." *J. Electron. Packag.* 140 (2): 020906. https://doi.org/10.1115/1.4040088

Test # 2 – SEM Images



Sample 1 SEM images before test



Sample 1 SEM images after test

- SEM images of CIO surface Sample 1 at various magnifications after 47-hour pool boiling test in deionized water at 50% of CHF.
- Oxidation of the CIO surface, but no observable damage to overall CIO structure, including connecting necks.

Images by Qianying Wu, Stanford University

Modified Experimental Setup for R-1233zd Refrigerant Tests

- The experimental setup was modified for refrigerant (HFO-1233zd) charging and recovery from the test vessel.
- CHF tests were targeted at 45°C of HFO-1233zd fluid temperature.
- Due to lower power input (lower CHF) in refrigerant pool boiling tests (compared to water tests), chiller for circulating cold water in the condenser coil was not used.

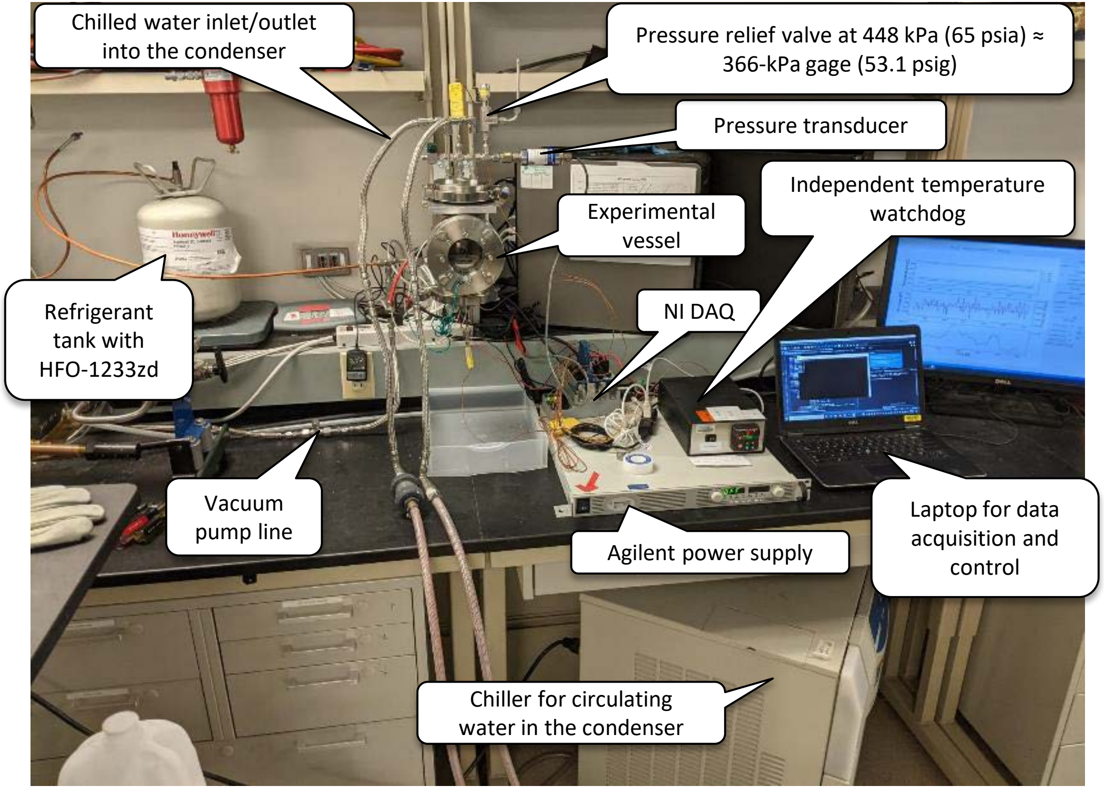


Photo by Bidzina Kekelia, NREL

Conditions for Pool Boiling Tests in R-1233zd Refrigerant

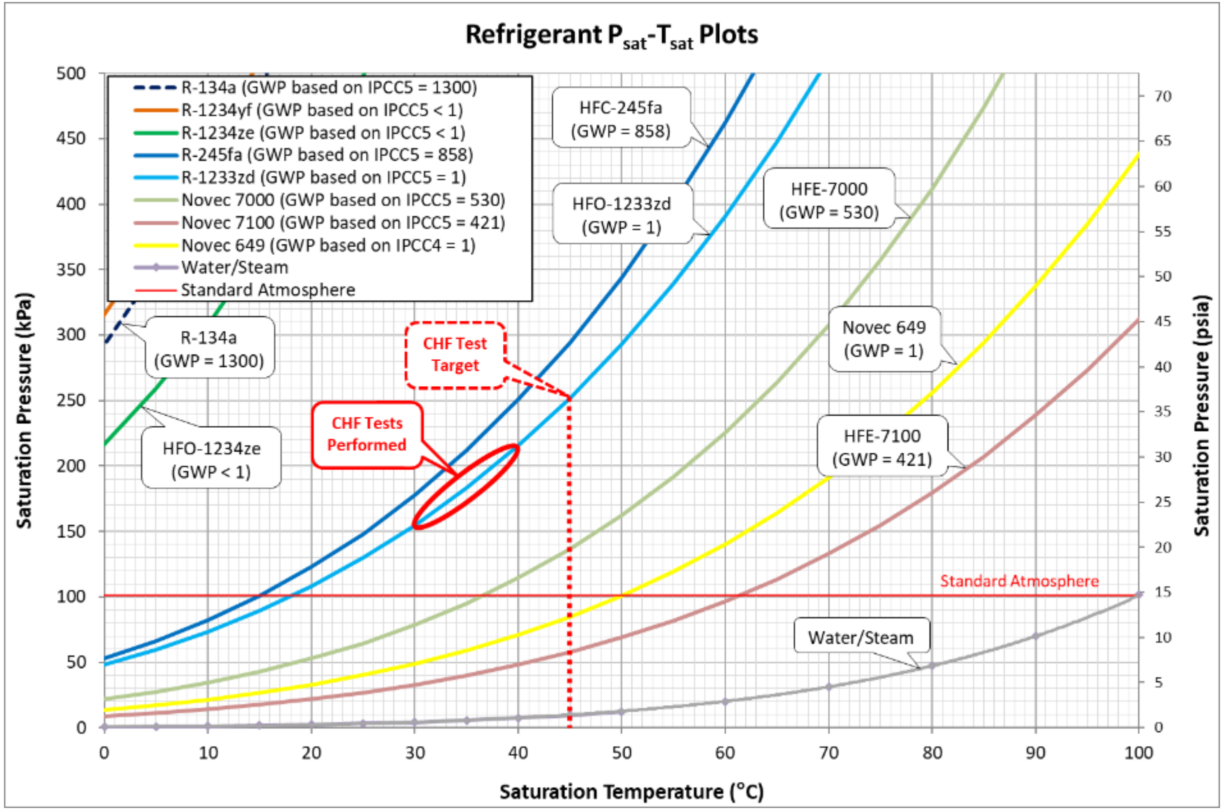
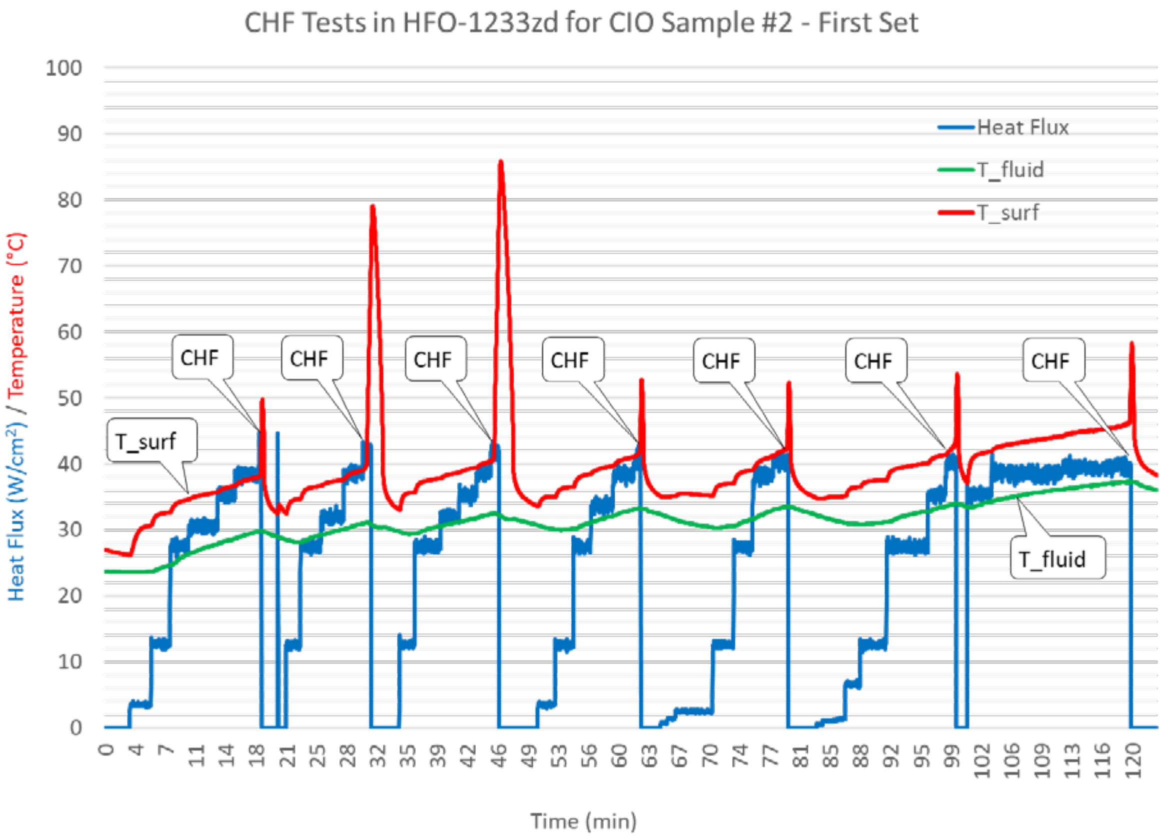


Figure by Bidzina Kekelia, NREL

- CHF tests were targeted at 45°C of HFO-1233zd fluid temperature.
- Due to low power input (low CHF) and heat dissipation from experimental vessel to the ambient, tests were performed at 30°C–40°C fluid temperature.
- Experimental vessel insulation is planned for subsequent tests. Lower heat losses to ambient should enable higher (45°C–50°C) fluid temperature tests.

Test #3 – CHF for Pool Boiling in R-1233zd Refrigerant, First Set

- First set of CHF tests were performed at 30°C–37°C of HFO-1233zd fluid temperature.



Sample 2 specs:

Pore diameter ≈ 5 µm

Neck-to-pore ratio = 0.393

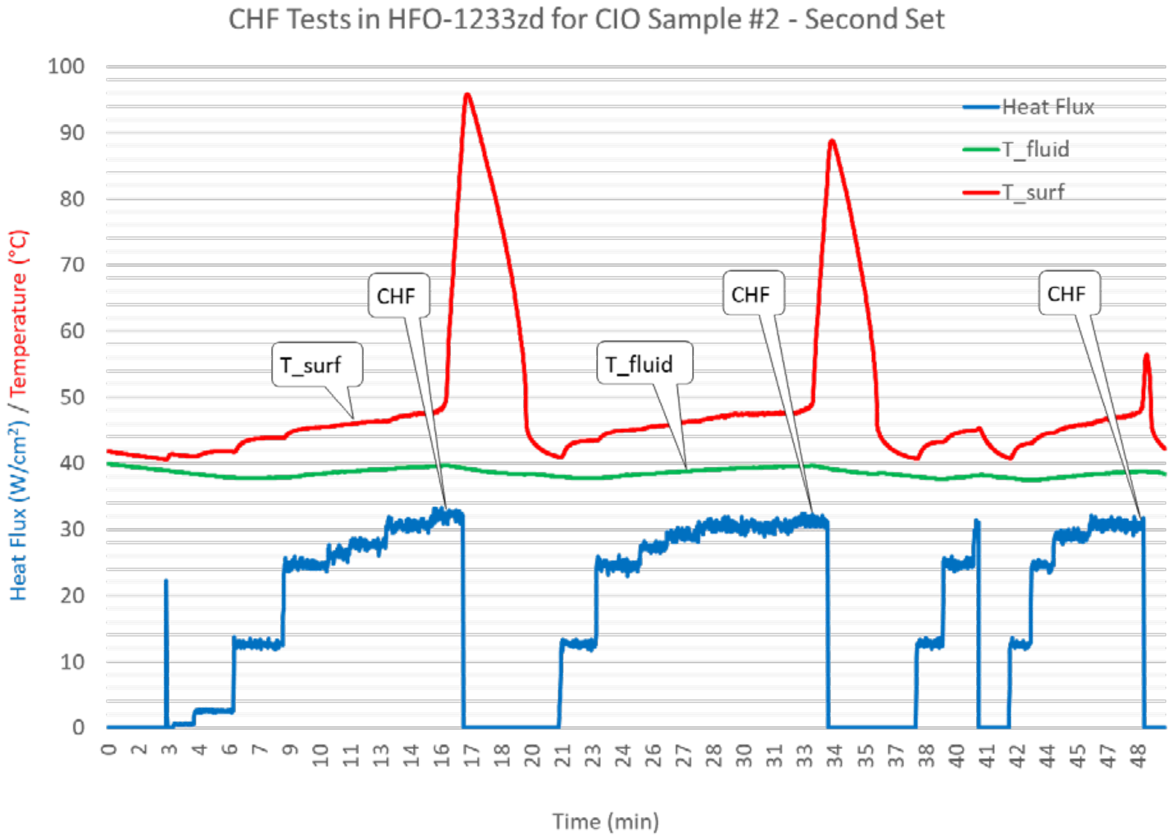
CIO layer thickness ≈ 25 µm

CIOs deposited on the top surface of a copper block

Photo and figure by Bidzina Kekelia, NREL

Test #3 – CHF for Pool Boiling in R-1233zd Refrigerant, Second Set

- Second set of CHF tests were performed at 39°C–40°C of HFO-1233zd fluid temperature.



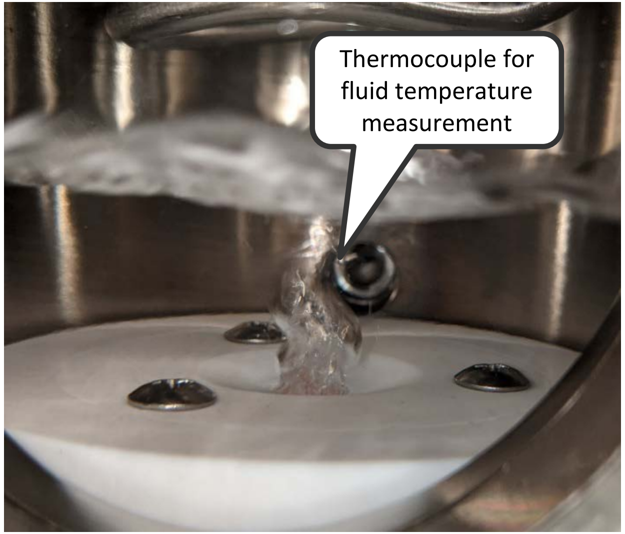
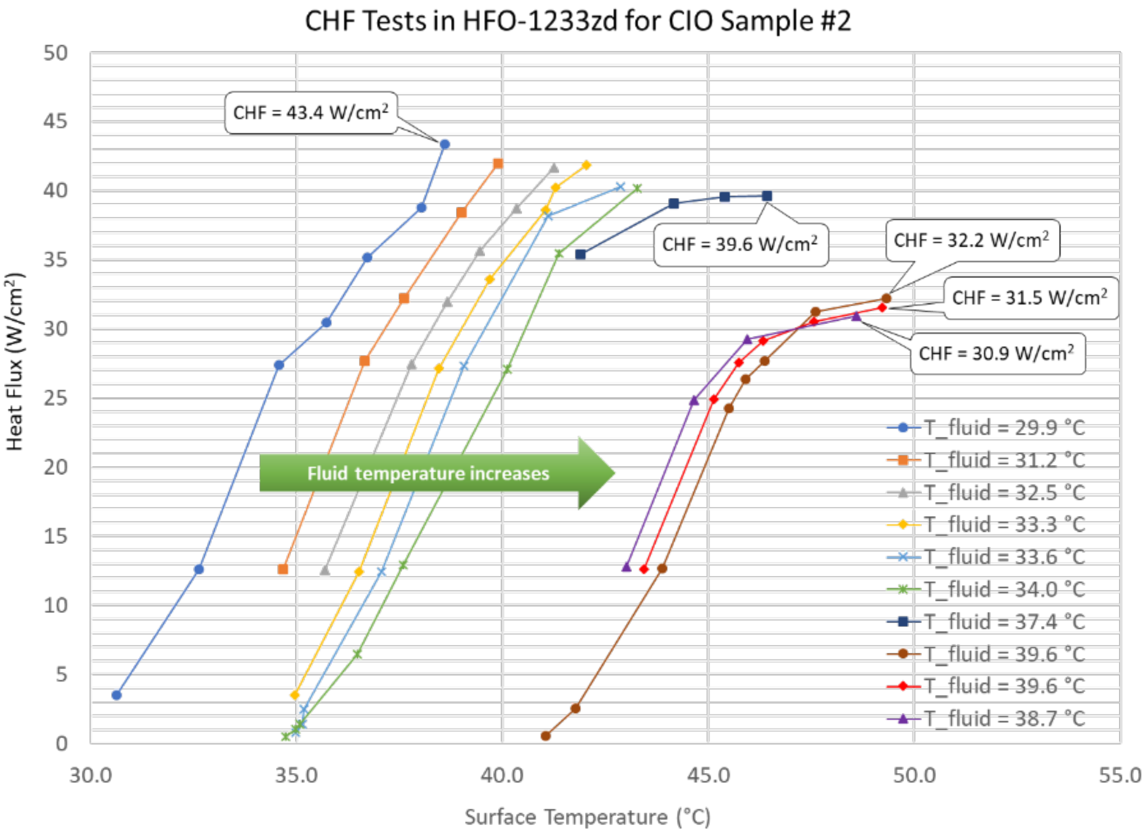
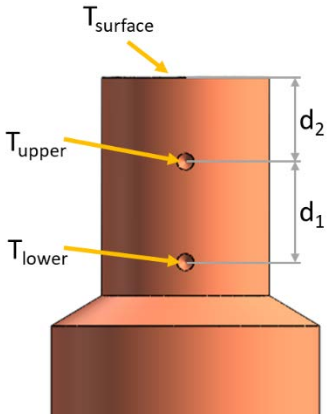


Photo and figure by Bidzina Kekelia, NREL

Test #3 Results: Heat Flux vs. Surface Temperature





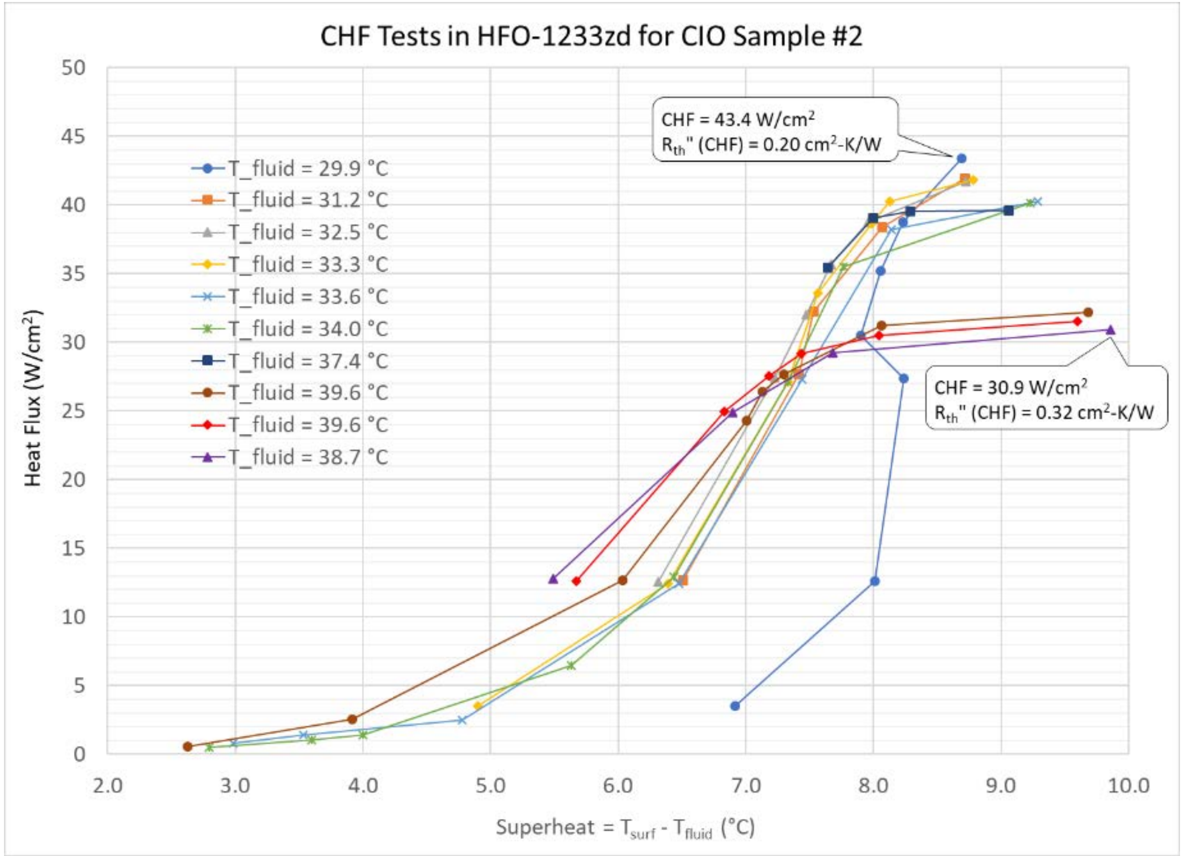
T_{surf} was calculated from T_{lower} and T_{upper} thermocouple measurement data:

$$T_{surface} = T_{upper} + \frac{d_2(T_{upper} - T_{lower})}{d_1}$$

- CHF ranged from 43 to 31 W/cm^2 for 30°C to 40°C fluid (HFO-1233zd) temperature.

Figures by Bidzina Kekelia, NREL

Test #3 Results: Heat Flux vs. Superheat



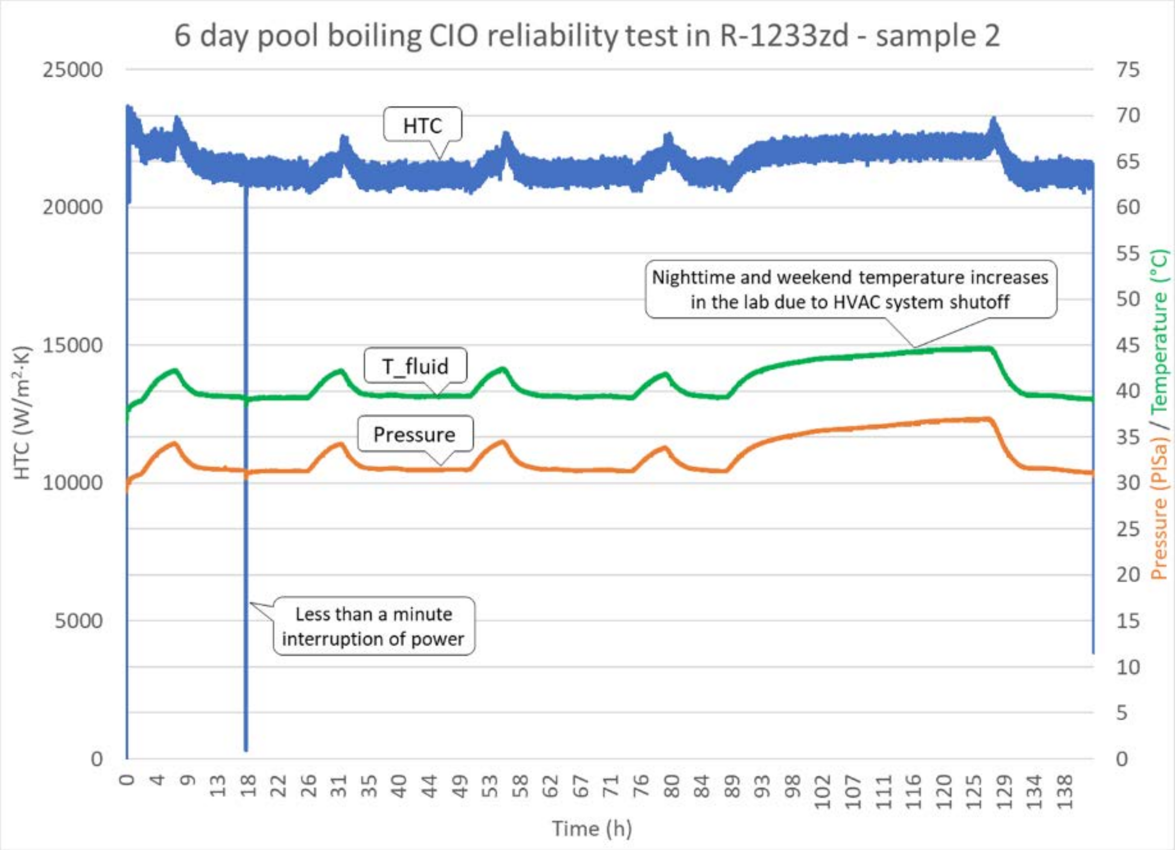
Thermal resistance values:

At T_{fluid} = 29.9°C
CHF = 43.4 W/cm^2
R_{th}" (CHF) = 0.20 $cm^2 \cdot K/W$

At T_{fluid} = 38.7°C
CHF = 30.9 W/cm^2
R_{th}" (CHF) = 0.32 $cm^2 \cdot K/W$

Test #4 – CIO Reliability/Pool Boiling in R-1233zd Refrigerant

HTC: $\bar{h} = \frac{Q}{A(T_{surface} - T_{fluid})}$



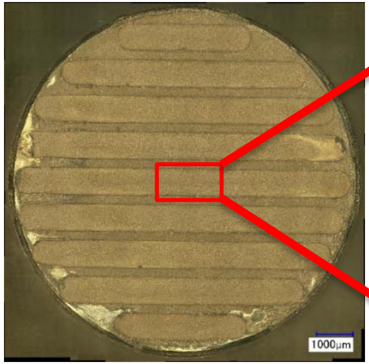
Test conditions:

- Duration: 6 days
- T_{fluid} ≈ 39°C–44°C
- P_{fluid} ≈ 31–36 PSIa
- Power set to ≈ 18 W
- Heat flux q" ≈ 23 W/cm^2 (≈75% of CHF at 39°C)

Observations:

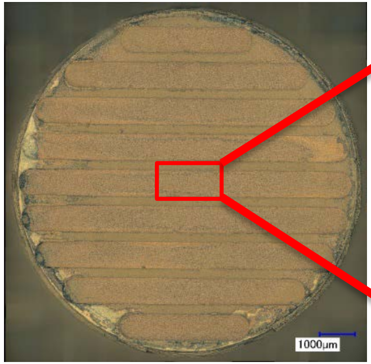
- Ambient lab temperature affects fluid temperature/pressure in the experimental vessel.
- No degradation noticeable in heat transfer coefficient (HTC).

Test #4 – Optical Images



Sample 2: CIO surface before test

Center of Sample 2 at 1,000x magnification



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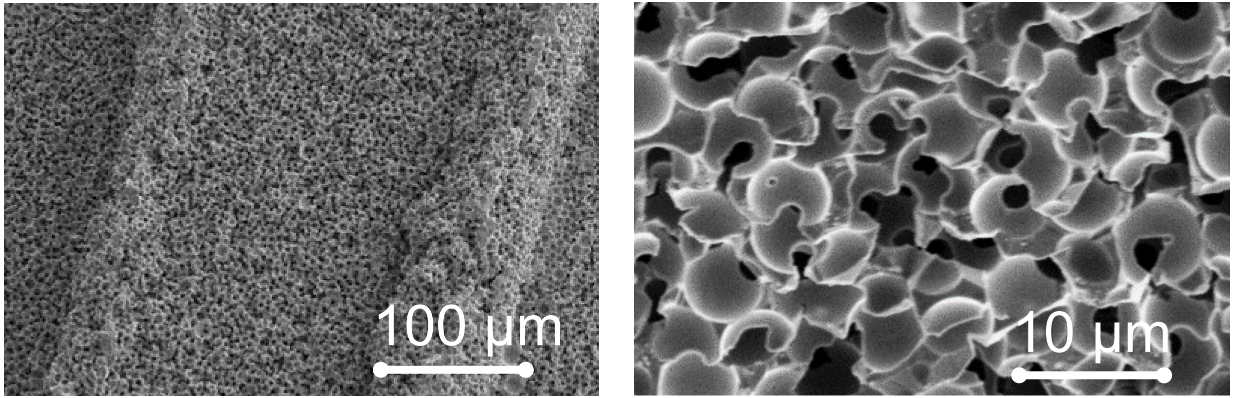
- Power set to ≈ 18 W
- Heat flux q" ≈ 23 W/cm^2 (≈75% of CHF at 39°C)

Observations:

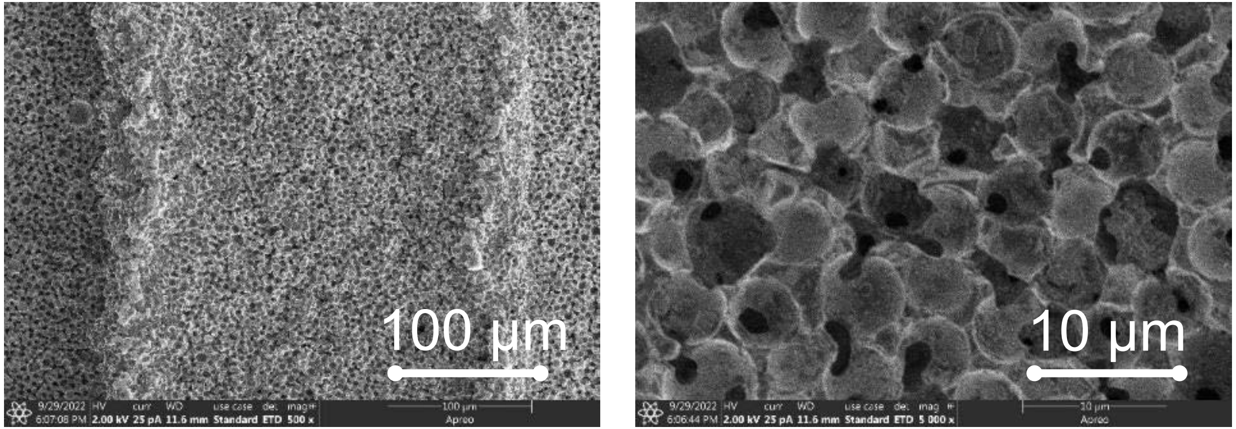
- No structural degradation noticeable in optical microscope images at 1,000x magnification.
- Black deposits of O-ring and gasket material (EPDM) dissolved during the test in the refrigerant.

Figures by Bidzina Kekelia, NREL

Test #4 – SEM Images



Sample 2: SEM images before the test. Images by Qianying Wu, Stanford University



Sample 2: SEM images after the test. Images by Qianying Wu, Stanford University

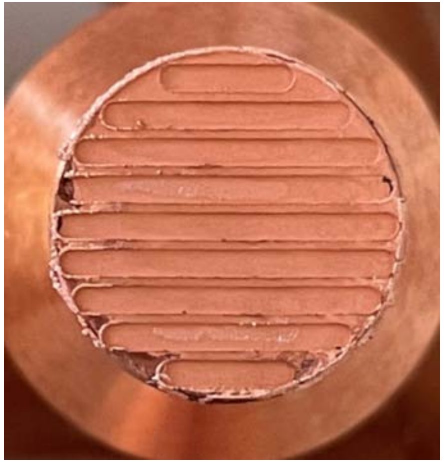


Photo by Bidzina Kekelia, NREL

Observations:

- No structural degradation noticeable in SEM images.
- Deposits and fouling with gasket/O-ring material can be seen in SEM images as well.

Matrix of Experiments for Pool Boiling Reliability Testing of CIO Surfaces at NREL

- HFC-245fa was substituted with newer, lower GWP=1 HFO-1233zd

Reliability testing of CIO surfaces:

- CIO sample preparation: NREL/Stanford
- Pool boiling CHF [1] in water: q''_{CHF} = 225.6 W/cm^2
- CIO surface degradation assessment (optical/SEM imaging) and performance evaluation (continuous HTC monitoring)

Test #	Sample #	Sample Type/Surface Coating	Surface Area (cm^2)	Working Fluid (Pool Boiling)	Test Duration (hours)	**Test Duration (days)**	Cycling/ Continuous Power	Heat Flux (W/cm^2)	% of Expected CHF	Fluid Temp (°C)	**Fluid Pressure (kPa)**	Comments/Results
1	0	Large copper block, D = 10 mm, plain surface/copper	0.785	Water	1	-	Continuous	153	68%	40–70	78	Initial test run. Transient time measurement.
2	1	Large copper block, D = 10 mm, CIO in 0.1-mm-deep channels/copper	0.785	Water	47	1.96	Continuous	116	51%	60–70	14–34	CIO surface structure was preserved, but significant oxidation was observed.
3	2	Small copper block, D = 10 mm, CIO in 0.1-mm-deep channels/copper	0.785	R-1233zd	1	-	Continuous	0-43	100%	30–40	150–215	CHF measurements for R-1233zd at 30°C–40°C/150–215 kPa.
4	2	Small copper block, D = 10 mm, CIO in 0.1-mm-deep channels/copper	0.785	R-1233zd	144	6.00	Continuous	23	Approx. 75%	39–44	215–245	No noticeable damage to CIO surface structure or HTC degradation.

[1] H. Lee, T. Maitra, J. Palko, D. Kong, C. Zhang, M. T. Barako, Y. Won, M. Asheghi, and K. E. Goodson. 2018. "Enhanced Heat Transfer Using Microporous Copper Inverse Opals." *J. Electron. Packag.* 140 (2): 020906. https://doi.org/10.1115/1.4040088

Summary

- Limited number of CIO surfaces were evaluated at NREL in deionized water and HFO-1233zd refrigerant.
- CHF measurements in new low-global-warming-potential refrigerant HFO-1233zd were performed.
- No structural degradation of CIO surfaces noticeable in optical or SEM images.
- Black deposits of O-ring/gasket material (EPDM) dissolved during the test in the refrigerant can be seen in optical and SEM images. Material compatibility of system components with HFO-1233zd should be verified.
- Development of high-heat-flux coolers is important for reduction of thermal management system size and achieving high system power density for a number of applications, including data centers and power electronics cooling.

Thank You

www.nrel.gov

NREL/PR-5400-87860

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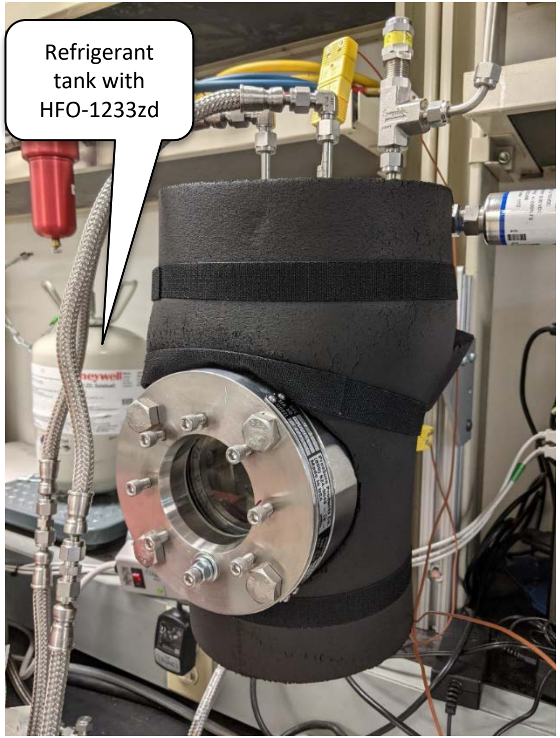
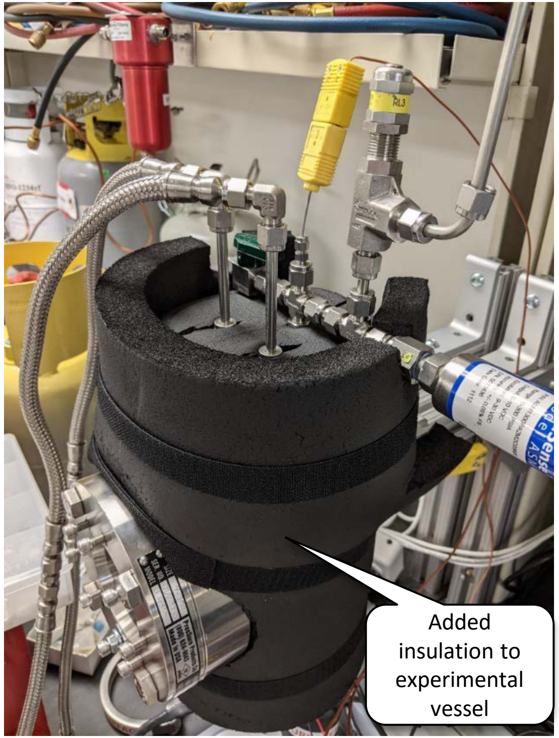
Backup Slides

Modified Experimental Setup for R-1233zd Refrigerant Tests

- Insulation was added to the experimental vessel for reducing heat losses to the ambient lab air.
- This modification should help reach higher fluid temperature target of 45°C.
- CHF tests are targeted at 45°C of HFO-1233zd fluid temperature, but due to low heat input (lower CHF values for the refrigerant compared to water), heat was dissipated to ambient lab air.





Photos by Bidzina Kekelia, NREL

Equations for T_{surf} and $\bar{h}$ Calculation

- Average heat transfer coefficients ($\bar{h}$) for the target surface: $\bar{h} = \frac{Q}{A(T_{surface} - T_{fluid})}$

  where Q is the heat dissipated through the top surface (with surface area of A) of the target, T_{surface} is the target's average impingement surface temperature and T_{fluid} is the fluid temperature at the inlet of the nozzle.

- Due to the highly conductive properties (*k*) of the oxygen-free copper target and the low conductivity of the PTFE holder, one-dimensional heat transfer can be assumed within the cylindrical body of the stem.
- During steady-state conditions, variations in temperature in cross-sectional planes of the stem would be relatively insignificant with T_{surface}, T_{upper} and T_{lower} representing average temperatures in respective cross-sectional planes.
- Neglecting losses to the sides of the stem, heat flow *Q* from the bottom of the target towards the top surface can be calculated as:

$$Q = -kA\frac{T_{upper} - T_{lower}}{d_1} \qquad \text{and as:} \qquad Q = -kA\frac{T_{surface} - T_{upper}}{d_2}$$

- From the above equations the top surface temperature can be expressed as:

$$T_{surface} = T_{upper} + \frac{d_2(T_{upper} - T_{lower})}{d_1}$$

- And average heat transfer coefficient ($\bar{h}$) can be calculated as:

$$\bar{h} = k\frac{T_{lower} - T_{upper}}{d_1(T_{upper} - T_{fluid}) - d_2(T_{lower} - T_{upper})}$$