Two-Phase Cooling Technology for Power Electronics

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Project ID #: **APE037**

Overview

Timeline

Project Start Date: FY11
Project End Date: FY13
Percent Complete: 50%

Budget

Total Project Funding: $975k
DOE Share: $975k

Funding Received in FY11: $550k

Funding for FY12: $425k

Barriers and Targets

- Weight, Cost, and Efficiency

Partners

- Delphi
- 3M
- DuPont
- University of Colorado-Boulder
- Iowa State University
- University of Illinois-Chicago
- Project lead: NREL

Relevance/Objectives

Project Objective

- Demonstrate a compact, passive two-phase cooling system capable of meeting automotive power electronics heat dissipation requirements.
  - Cooling system will be designed to cool advanced power modules (Delphi's discrete power switches)
  - Demonstrate improved thermal performance
  - Qualitatively demonstrate cost reductions

Relevance

- Potential application to increasing heat dissipation requirements in automotive power electronics
- Efficient heat transfer technologies can:
  - ➢ Reduce **cost** and increase **power density, specific power**, and **efficiency**

Milestones

Date	Milestone or Go/No-Go Decision
October 2011	Characterized the pool boiling performance of a new refrigerant, HFO-1234yf
February 2012	Designed, fabricated, and tested a passive two-phase cooling system (condenser and evaporator) • Working to optimize evaporator performance
March 2012	Designed and fabricated an experimental apparatus to test the reliability of boiling enhancement coatings
June 2012	Initiate the design of a passive two-phase system to cool Delphi's discrete power switches
September 2012	**Go/No-Go:** Can we demonstrate ~1 kW (one inverter leg) of heat dissipation and improved performance with a passive two-phase cooling system?

Approach/Strategy

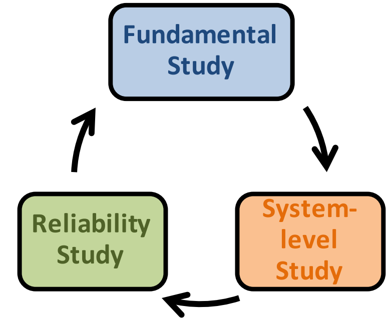
Utilize the high heat-transfer rates and isothermal characteristics of two-phase heat transfer to:

1. Decrease the size, weight, and cost of the cooling system
2. Increase efficiency through a passive (no pumping requirement) two-phase approach
3. Allow for a reduction in the insulated gate bipolar transistor (IGBT) device count and/or size (cost and size reduction)

Uniqueness and Impacts

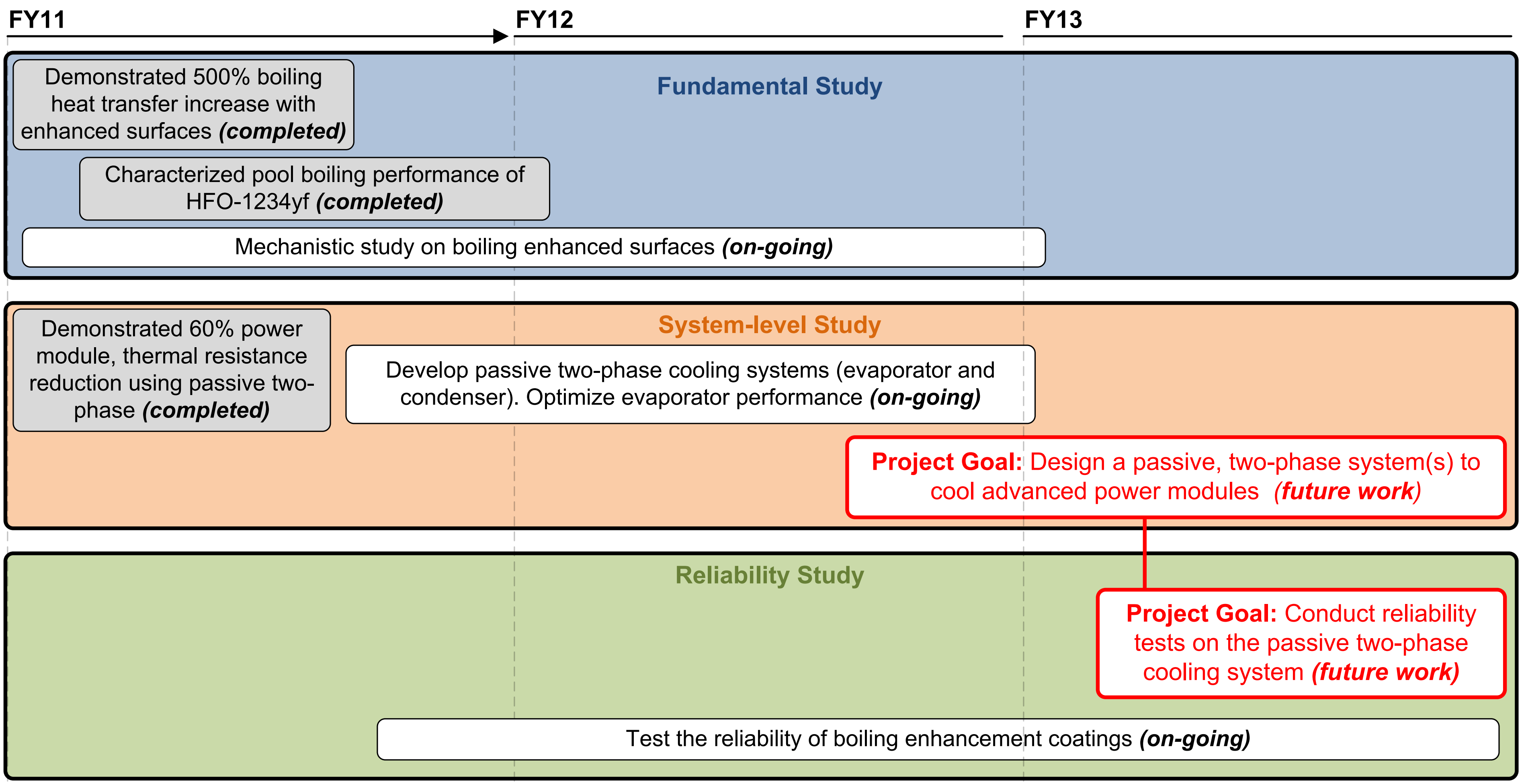
- New refrigerants:
  - HF0-1234yf is a new, environmentally friendly refrigerant likely to replace R-134a in automotive air conditioning systems
  - R-245fa is a somewhat new refrigerant with better thermal properties and lower operation pressures (compared to HFO-1234yf)
- New boiling enhancement techniques
- Provide a cooling solution for high heat-flux applications

Approach/Strategy



Project approach, timeline, and accomplishments

Working towards the end goal of demonstrating a passive two-phase power electronics cooling solution



Technical Accomplishments and Progress

- NREL first to characterized the pool boiling performance of a new refrigerant, HFO-1234yf
  - Saturation temperatures tested: 25°C (P_{sat} = 0.7 MPa) to 60°C (P_{sat} = 1.7 MPa)
- Quantified the thermal enhancements provided by a boiling enhancement coating
- Compared HFO-1234yf performance to R-134a performance

Relevance:

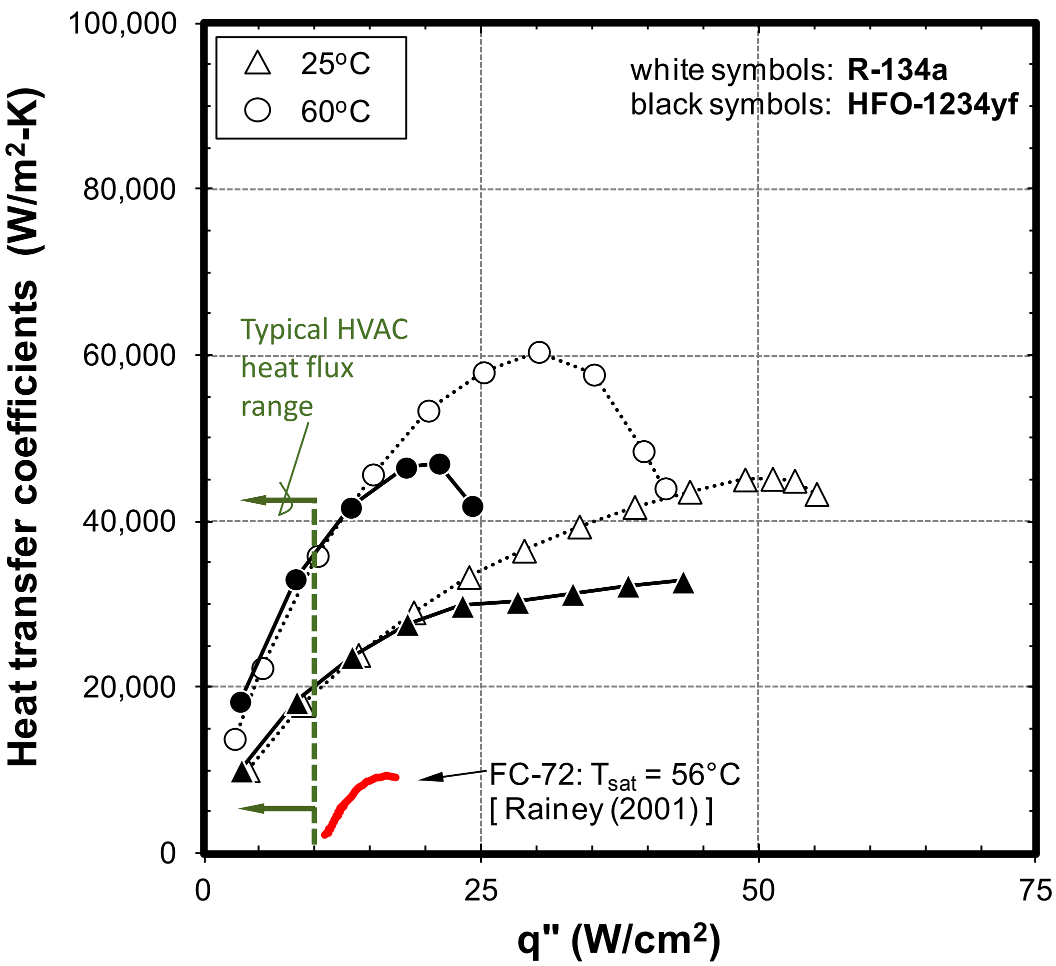
- Potential use of HFO-1234yf for two-phase cooling of power electronics
- Potential for consolidating automotive cooling systems (*potential cost and weight reductions*)

Experimental chamber

Credit: Gilbert Moreno, NREL

Technical Accomplishments and Progress

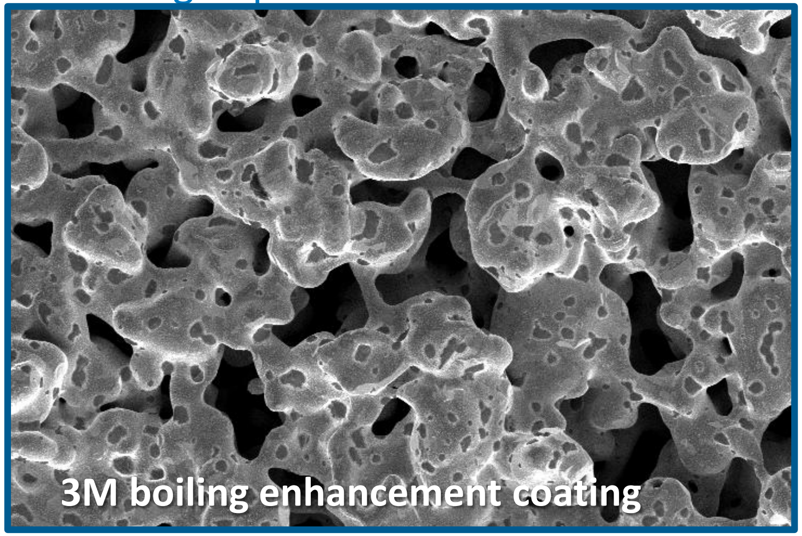
- HFO-1234yf and R-134a had similar performance at lower heat fluxes
- At higher heat fluxes HFO-1234yf produces lower heat transfer coefficients
- HFO-1234yf's lower performance is due in part to its lower latent heat and thermal conductivity
- Both refrigerants provide higher heat-transfer rates as compared with FC-72 (a coolant used in immersion cooling applications)

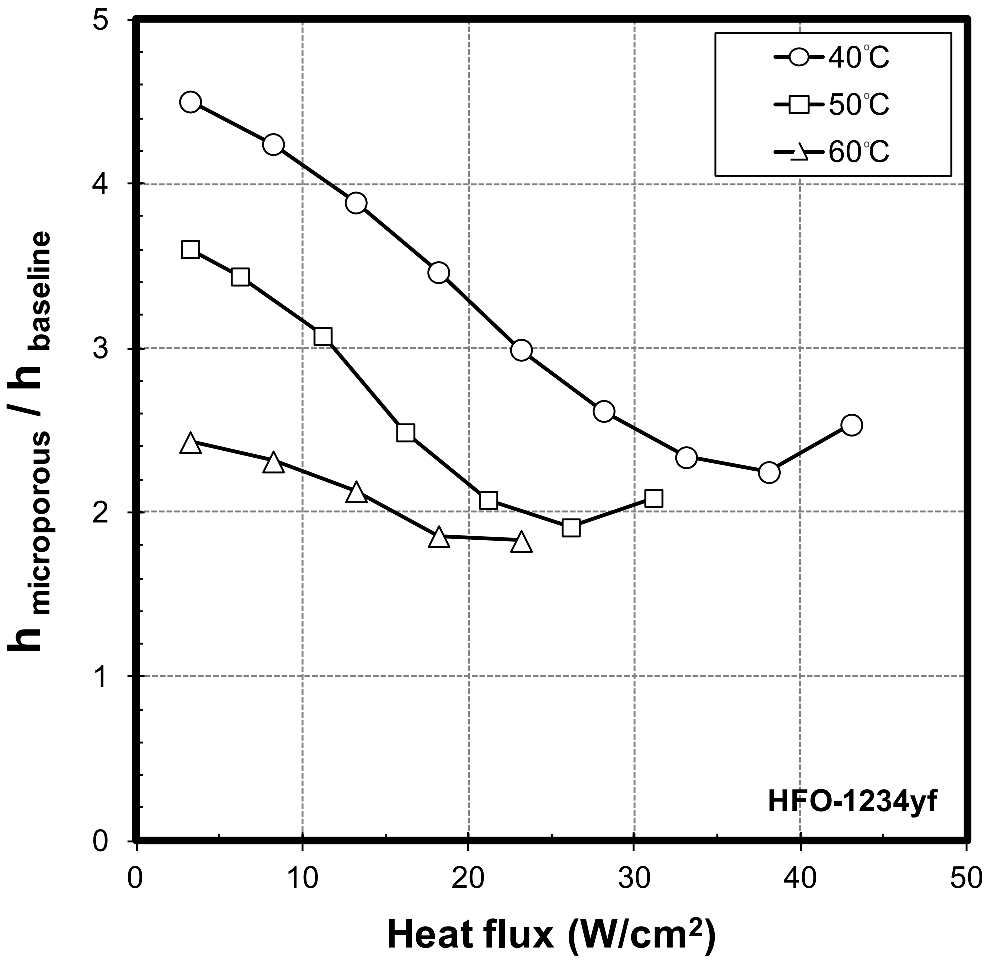


Rainey, K. N., 2001, "Pool and Flow Boiling Heat Transfer from Microporous Flat and Finned Surfaces in FC-72," Ph.D. Dissertation, The University of Texas at Arlington

Technical Accomplishments and Progress

- Microporous coating enhanced HFO-1234yf heat transfer coefficients by as much as **350%** and produced heat transfer coefficients as high as **120,000 W/m²-K**
- Coating heat transfer enhancements decrease with increasing saturation temperature and heat flux
- The high heat-transfer rates of HFO-1234yf with microporous coatings makes it a viable refrigerant for two-phase cooling of power electronics

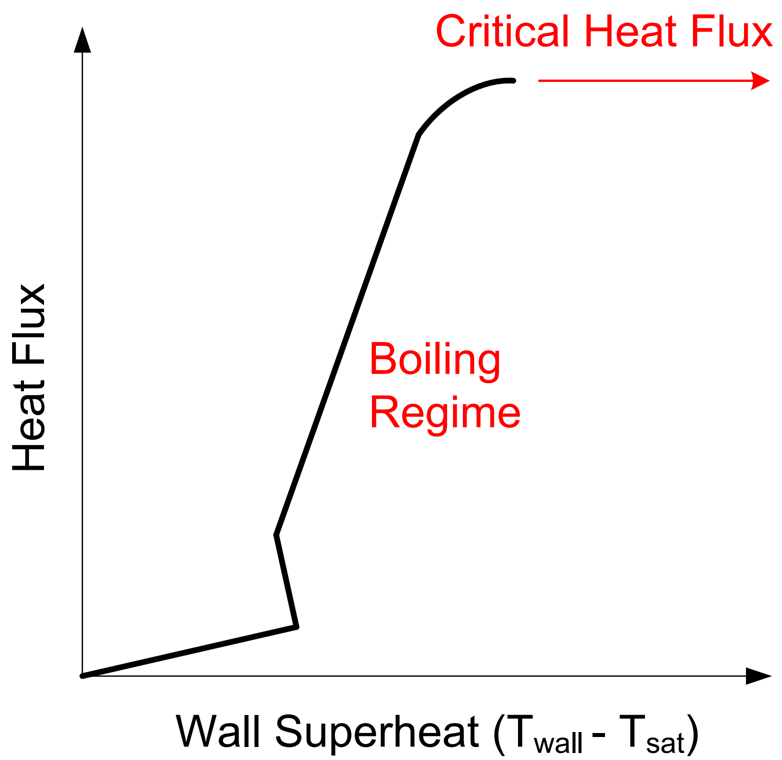


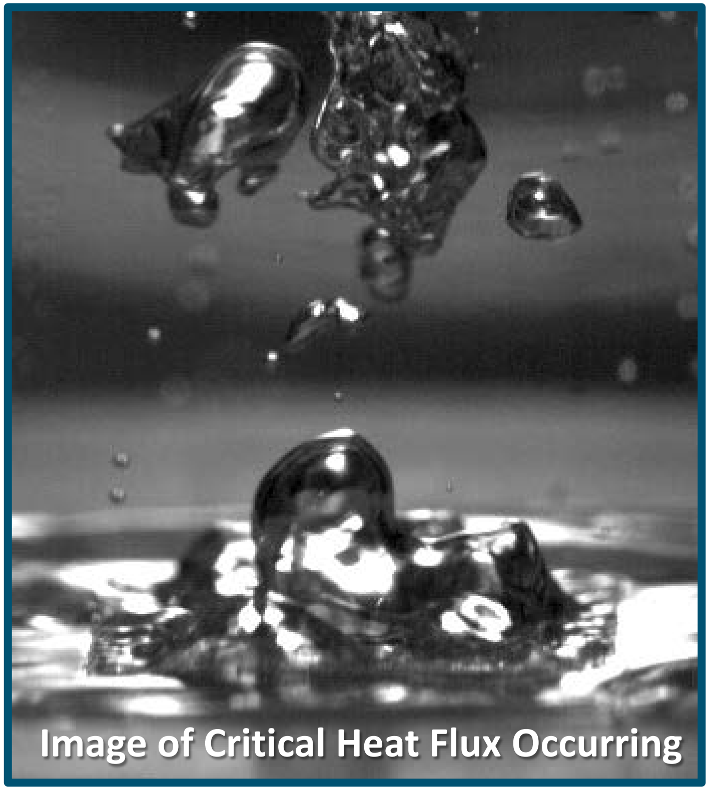


Credit: Bobby To, NREL

Technical Accomplishments and Progress

- Critical heat flux (CHF) is the maximum heat flux that can be dissipated through boiling heat transfer
- It is important to know the CHF for a refrigerant
- Exceeding CHF results in sudden and drastic temperatures increases (i.e., damage to electronics)
- Operating near CHF should be avoided

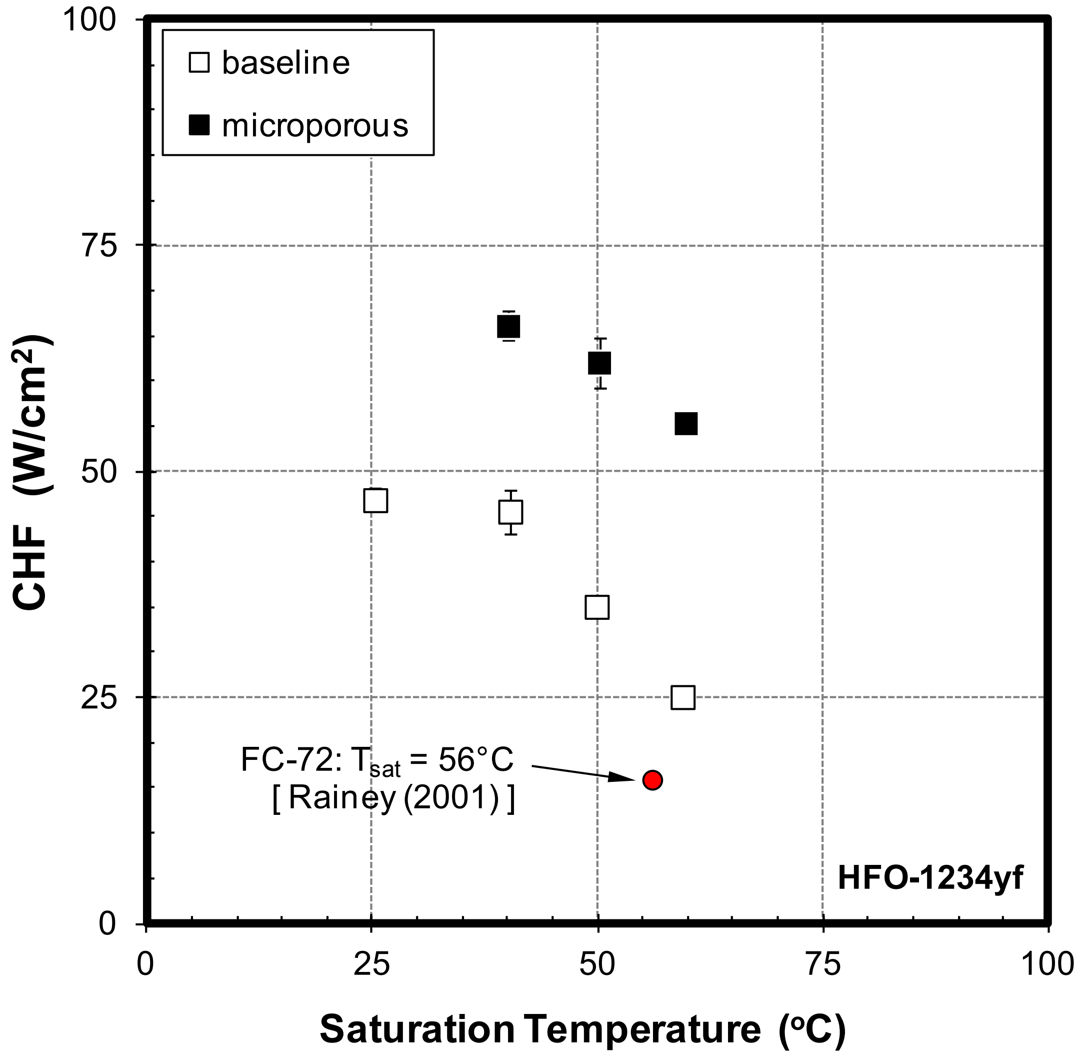




Credit: Gilbert Moreno and Charlie King, NREL

Technical Accomplishments and Progress

- Microporous coating increases CHF by as much as **120%**
- Coating CHF enhancements increase with increasing saturation pressure



-Rainey, K. N., 2001, "Pool and Flow Boiling Heat Transfer from Microporous Flat and Finned Surfaces in FC-72," Ph.D. Dissertation, The University of Texas at Arlington

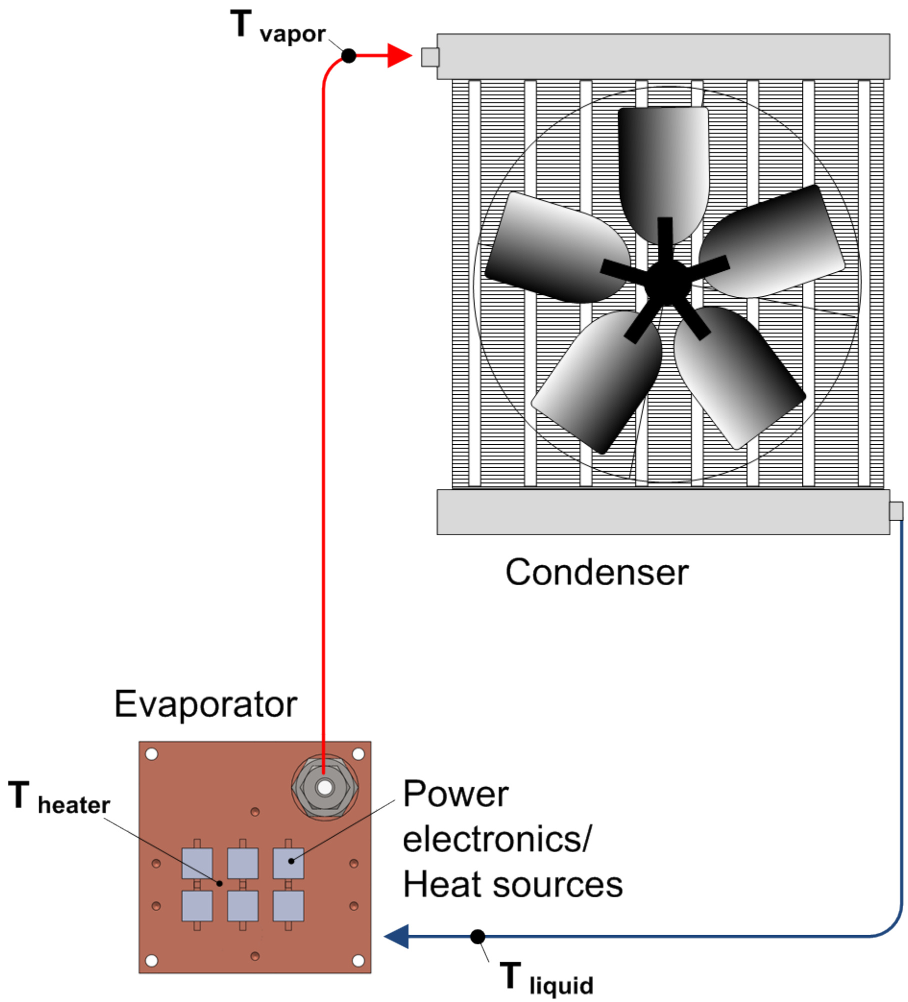
Technical Accomplishments and Progress

Passive two-phase cooling system prototype development

Objective: Design a passive two-phase cooling system for power electronics cooling. Demonstrate improved thermal performance within a compact and reliable system.

Designed and fabricated a compact two-phase cooling system

- The system consists of an evaporator and a condenser and operates on only 50 mL of coolant
- Passive (no pump or compressor)→ high system efficiency and reliability
- Indirect cooling approach decreases potential for coolant leakage



Technical Accomplishments and Progress

Passive two-phase cooling system prototype development

Phase 1: Optimize evaporator performance using the current two-phase system (*current work)*

- Obtained initial experimental results using an evaporator module incorporating finned geometries, have not implemented boiling enhancement coatings
- Work continues to improve performance using boiling enhancement coatings and refrigerants with better thermal properties (e.g., HFO-1234yf, R-245fa)
- System allows for visualization of the fluid flow, which aids in understanding and optimizing performance

Technical Accomplishments and Progress

Passive two-phase cooling system prototype development

Phase 2: Demonstrate a compact, passive two-phase cooling solution on an advanced power module *(future work)*

- The two-phase system will be designed to cool multiple Delphi discrete power switches. The system will consist of an evaporator cold plate and an air-cooled condenser.

Courtesy of Gary Eesley, Delphi

- Demonstrate the system can dissipate automotive power electronic heat loads
- Characterize the junction-to-air thermal resistance of the system. We will compare this performance to that of conventional water– ethylene glycol cooling systems.
- Conduct experiments to characterize the system performance at elevated temperatures and under transient heat loads (impose a typical drive cycle heating profile)

Technical Accomplishments and Progress

Reliability of boiling enhancement coatings

- Designed and fabricated a reliability test system (*pressure vessel and control/monitoring system*)
- System will subject coated samples to power/temperature (~50% CHF) cycling operation for months or years to stress the coatings
- System will characterize the thermal performance over time and evaluate for potential coating delamination


Test samples within the reliability vessel

Credit: Gilbert Moreno, NREL

Collaboration and Coordination

UNIVERSITY PARTNERS

- University of Colorado-Boulder
- Iowa State University
- University of Illinois-Chicago

INDUSTRY PARTNERS

- Delphi
- 3M Electronics Markets Materials Division
- DuPont

Proposed Future Work

FY12

- Optimize the two-phase system evaporator to improve thermal performance
- Design a passive two-phase system capable of cooling ~1 kW (one inverter leg). This system will be scaled up in FY13 to dissipate higher heat loads typical of automotive power electronic systems (see first item in FY13 plan below).
- Initiate boiling enhancement coating reliability experiments

FY13

- Design a compact, passive two-phase system to cool advanced power modules (Delphi's discrete power switches). Demonstrate the system can dissipate automotive power electronic heat loads (2-3 kW) while providing superior thermal performance.
- Operate two-phase cooling systems under extreme temperature conditions
- Understand the performance of the two-phase cooling system under transient heat loads
- Initiate cooling system reliability study
- We will seek to collaborate with an industry partner (e.g., Delphi) to develop an inverter designed specifically for two-phase cooling

Summary

Objectives / Relevance

- Demonstrate a compact, passive two-phase cooling system capable of meeting automotive power electronics heat dissipation requirements. The cooling system will be designed to cool advanced power electronics modules.
- Efficient heat transfer technologies (two-phase) can reduce **cost** and increase **power density, specific power**, and **efficiency**

Approach / Strategy

- Conduct fundamental research to characterize the performance of new candidate refrigerants and boiling enhancement techniques
- Conduct system-level research to develop compact, passive two-phase cooling systems for power electronics cooling
- Conduct research to analyze the reliability aspects of two-phase systems

Summary

Technical Accomplishments

- NREL was first to fully characterize and publish the pool boiling characteristics of a new automotive air conditioning refrigerant, HFO-1234yf
  - A boiling enhancement coating was found to increase HFO-1234yf heat transfer coefficients by 350% and achieve values of 120,000 W/m^2-K.
  - The high heat transfer rates of HFO-1234yf make it a viable refrigerant for two-phase cooling of power electronics.
- Fabricated and tested a passive two-phase cooling system. Work currently underway to optimize evaporator performance
- Completed design and fabrication of a system intended to test the reliability of boiling enhancement coatings

Collaborations

- University of Colorado-Boulder, Iowa State University, University of Illinois-Chicago, Delphi, 3M Electronics Markets Materials Division, and DuPont

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