Two-Phase Cooling of Power Electronics

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Project #: APE037

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Overview

Timeline

Project Start Date: FY11
Project End Date: FY13
Percent Complete: 70%

Budget

Total Project Funding: $1,500K
DOE Share: $1,500K

Funding Received in FY12: $550K

Funding for FY13: $400K

Barriers

- Weight, cost, and efficiency

Partners

- Delphi
- 3M
- DuPont
- University of Colorado-Boulder
- Project lead: National Renewable Energy Laboratory

Relevance

Project Objective

- Significantly improve thermal management of automotive power electronics by utilizing the high heat transfer rates of two-phase cooling
  - Design a passive, two-phase cooling system for automotive power modules (cool six Delphi discrete power switches)
  - Demonstrate improved thermal performance over existing state-of-the-art automotive cooling systems
  - Demonstrate system can dissipate automotive power electronics heat loads
  - Quantify key program metrics (power density and specific power)

Relevance

- Improved thermal management is an enabler to achieving the DOE APEEM targets
  - Reduce **cost** and increase **power density, specific power**, and **efficiency**

Milestones

Month / Year	Milestone or Go/No-Go Decision
July 2012	**Milestone:** Characterized the pool boiling performance of R-245fa. Submitted a conference paper (2013 ASME Heat Transfer Conference) that reported the results
September 2012	**Milestone:** Designed and fabricated a prototype/proof-of-concept passive two-phase cooling system
February 2013	**Go/No-Go Decision:** Demonstrated that the passive two-phase cooling system can dissipate at least 2.5 kW of heat using 250 ml of refrigerant
February 2013	**Milestone**: Identified techniques to improve cooling system performance; submitted a record of invention (ROI)
March 2013	**Milestone:** Initiated experiments to evaluate the long-term reliability of boiling enhancement coatings

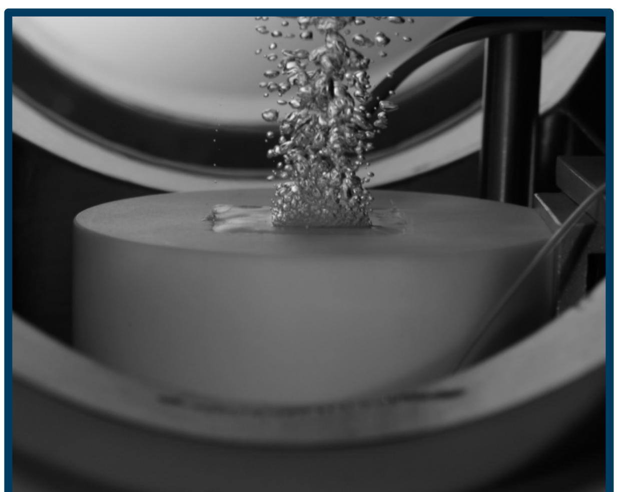
Approach/Strategy

Characterize performance of new, candidate refrigerants → Two-phase heat transfer enhancement → Develop passive, two-phase cooling system for automotive power electronics

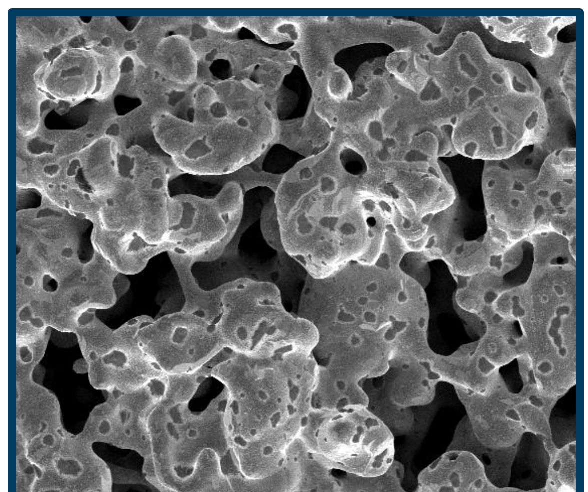
- Heat transfer coefficients
- Critical heat flux
- Temperature effect on performance
- ***Complete***

- Microporous coatings
- Nano-structured surfaces
- ***Complete***

- Demonstrate improved thermal performance via passive, two-phase cooling



Credit: Gilbert Moreno, NREL



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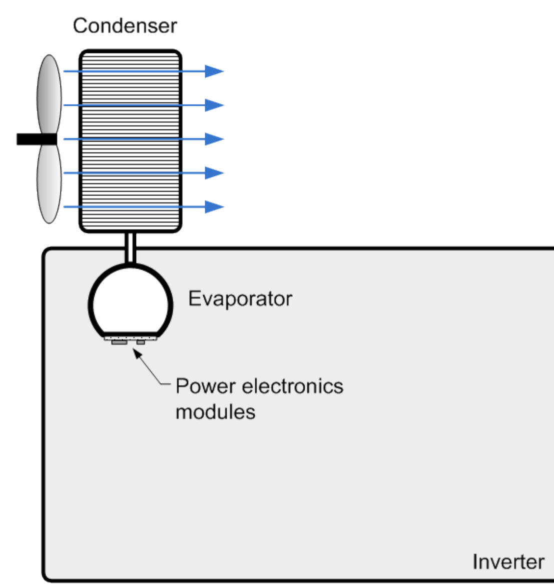


Approach/Strategy

Impacts

The high heat-transfer rates and isothermal characteristics of two-phase cooling can:

- Allow for a reduction in the insulated gate bipolar transistor (IGBT) device count and/or size (cost and size reduction) through an increase in power density
- Increase efficiency through a passive (no pumping requirement) two-phase cooling approach

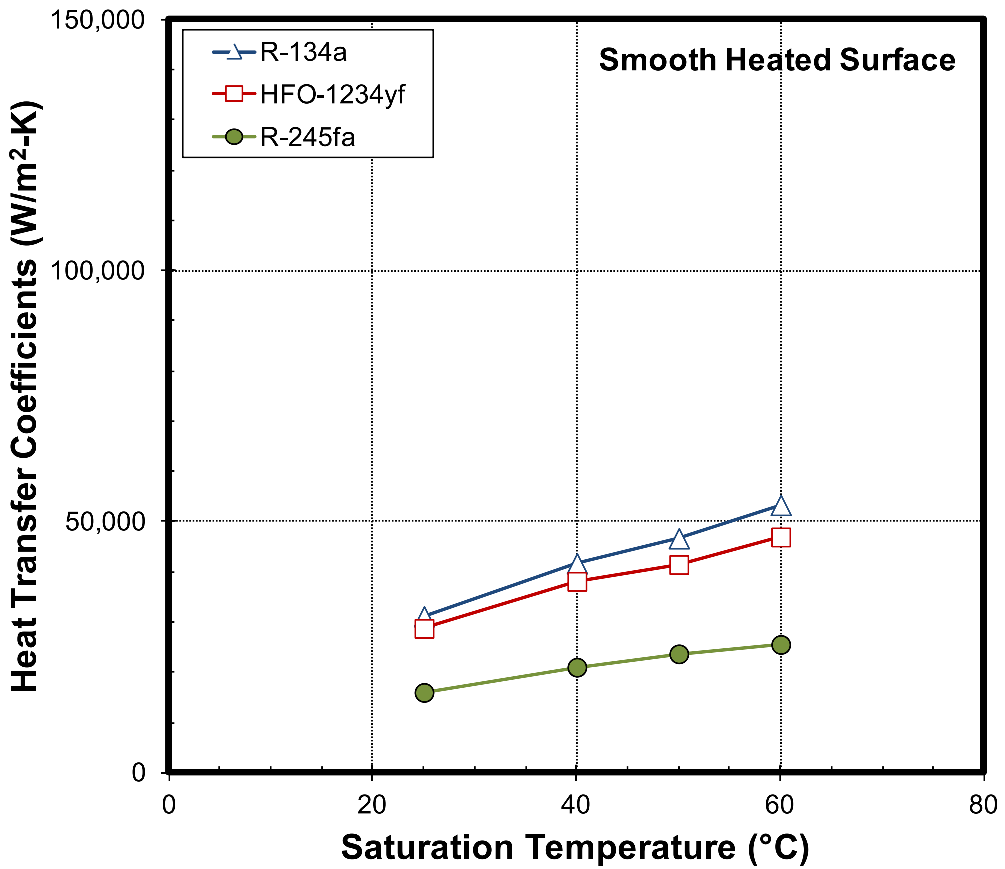
Uniqueness

- New refrigerants: HFO-1234yf is a new, environmentally friendly refrigerant that may replace R-134a in automotive air conditioning systems
- New boiling enhancement techniques

Technical Accomplishments and Progress

Characterized the pool boiling performance of refrigerant R-245fa

- Measured heat transfer coefficients and critical heat flux at various temperatures
- Compared its performance with other viable refrigerants

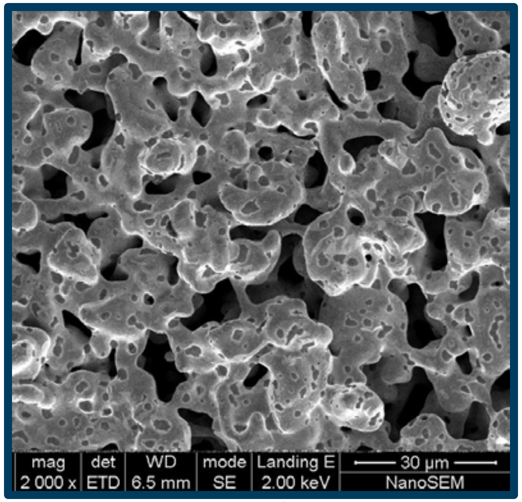


Heat transfer coefficients at ~20 W/cm²

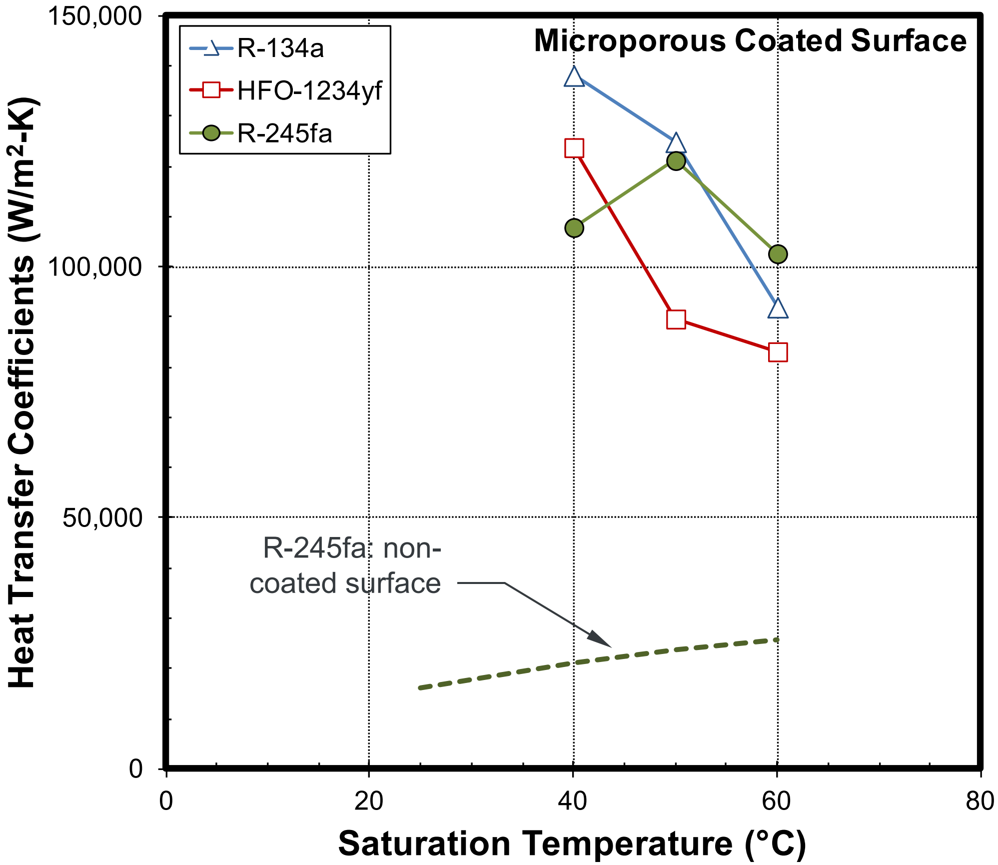
Technical Accomplishments and Progress

Characterized the pool boiling performance of refrigerant R-245fa

- Enhanced R-245fa heat transfer coefficients by as much as 500% and critical heat flux by 50% using the 3M microporous coating
- Higher heat transfer allows for greater power density
- Less variation in performance using the microporous coating



Credit: Bobby To, NREL

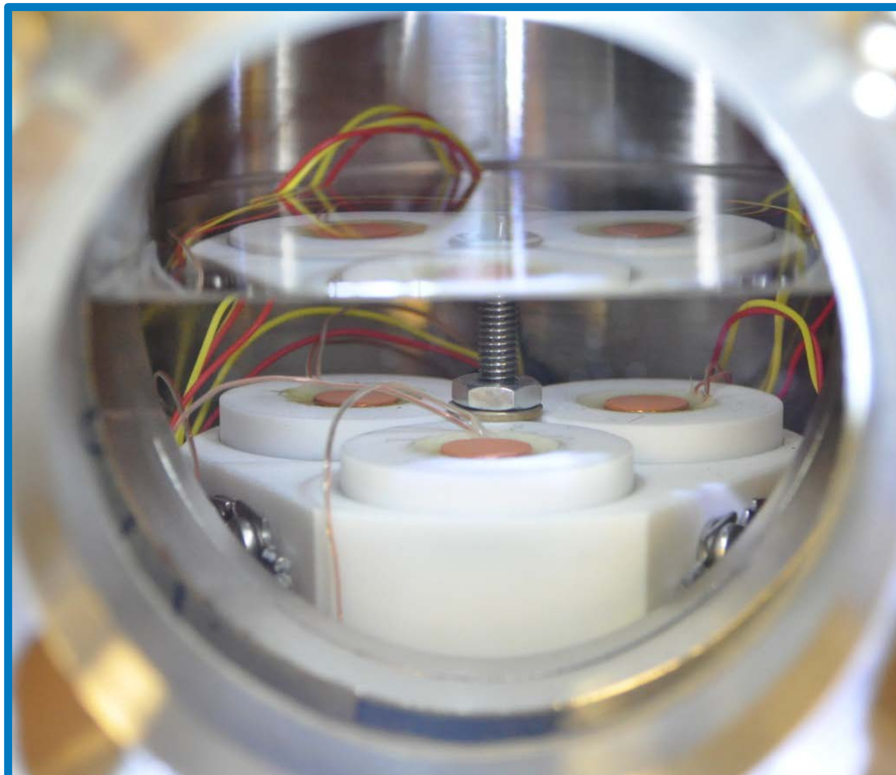


Heat transfer coefficients at ~20 W/cm^2

Technical Accomplishments and Progress

Reliability of boiling enhancement coatings

- Initiated experiments to evaluate the long-term reliability of boiling enhancement coatings
- System will thermally stress coated samples by subjecting them to power/temperature (~50% CHF) cycling for a year
- System will characterize the thermal performance over time and evaluate for changes in performance



Test samples within the reliability vessel

Credit: Gilbert Moreno, NREL

Technical Accomplishments and Progress

Characterize performance of new, candidate refrigerants → Two-phase heat transfer enhancement → **Develop passive, two-phase cooling system for automotive power electronics**

Phase I
Small-scale passive two-phase cooling system experiments

- Focus on improving evaporator performance: finned structures and boiling enhancement coatings
- Define refrigerant quantity requirements

Phase II
Inverter-scale two-phase cooling system experiments

- Cooling system design: evaporator and air-cooled condenser
- Designed to cool automotive power modules (six Delphi discrete power switches)
- Demonstrate systems can dissipate power electronic heat loads
- Quantify performance metrics and compare to state-of-the-art cooling systems

Technical Accomplishments and Progress

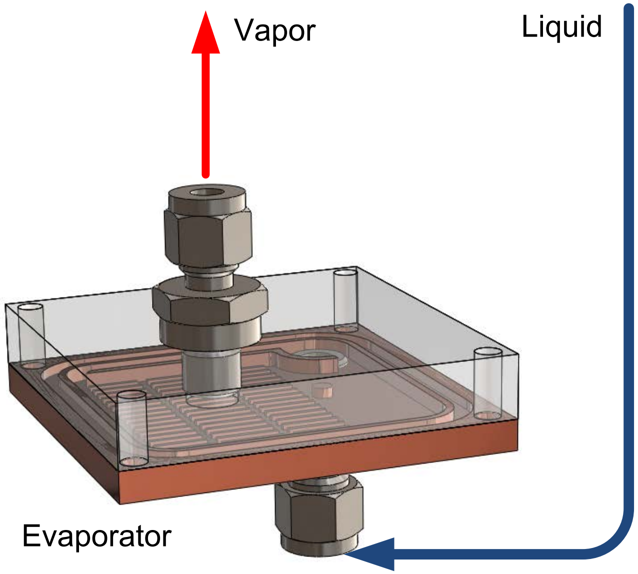
Phase I

Fabricated a compact two-phase cooling system

- Indirect cooling (ease of implementation)
- Passive (increase efficiency)

Experiments conducted to:

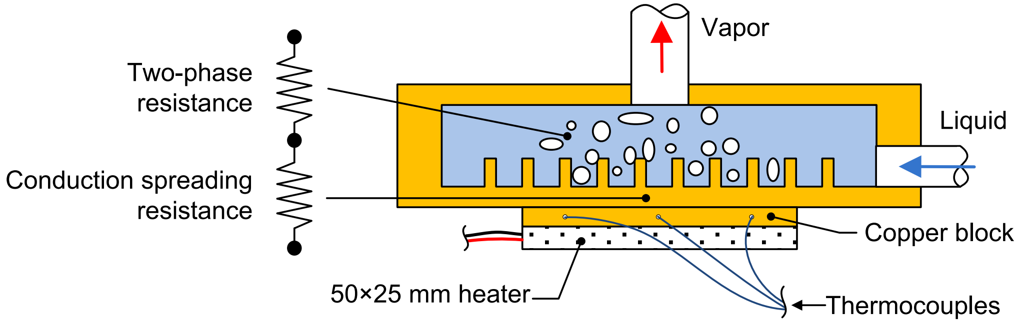
- Improve evaporator performance: finned structures and boiling enhancement coatings
- Define refrigerant quantity requirements: how much fluid is required to dissipate automotive power electronic heat loads
- Implications for using two-phase heat transfer for power electronics cooling



Technical Accomplishments and Progress

Phase I (cont'd)

- Reduced evaporator thermal resistance by about 60% using boiling enhancement coatings
- Estimate it would require ≤ 250 ml of refrigerant (HFO-1234yf or R-245fa) to dissipate 3.5 kW of heat with a passive two-phase configuration



Evaporator resistance: heater to liquid		
	Smooth	Boiling enhancement coating
R"th (mm^2-K/W)	51.9	21.4

Technical Accomplishments and Progress

Phase II

Designed and fabricated a proof-of-concept passive, two-phase cooling system

- System will be charged and tested with refrigerants HFO-1234yf or R-245fa. Operation with other refrigerants is possible.
- Extensive thermal and structural finite element analysis was conducted
- Designed to cool automotive power modules (six Delphi discrete power switches)
- Fan-cooled condenser
- Indirect cooling scheme: electronics are not in contact with refrigerants
- Passive system: no pump or compressor

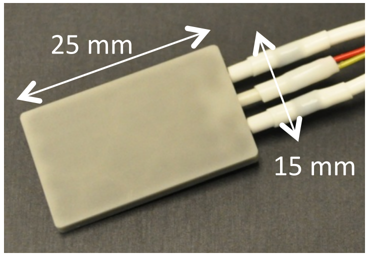
Technical Accomplishments and Progress

Passive two-phase cooling system results

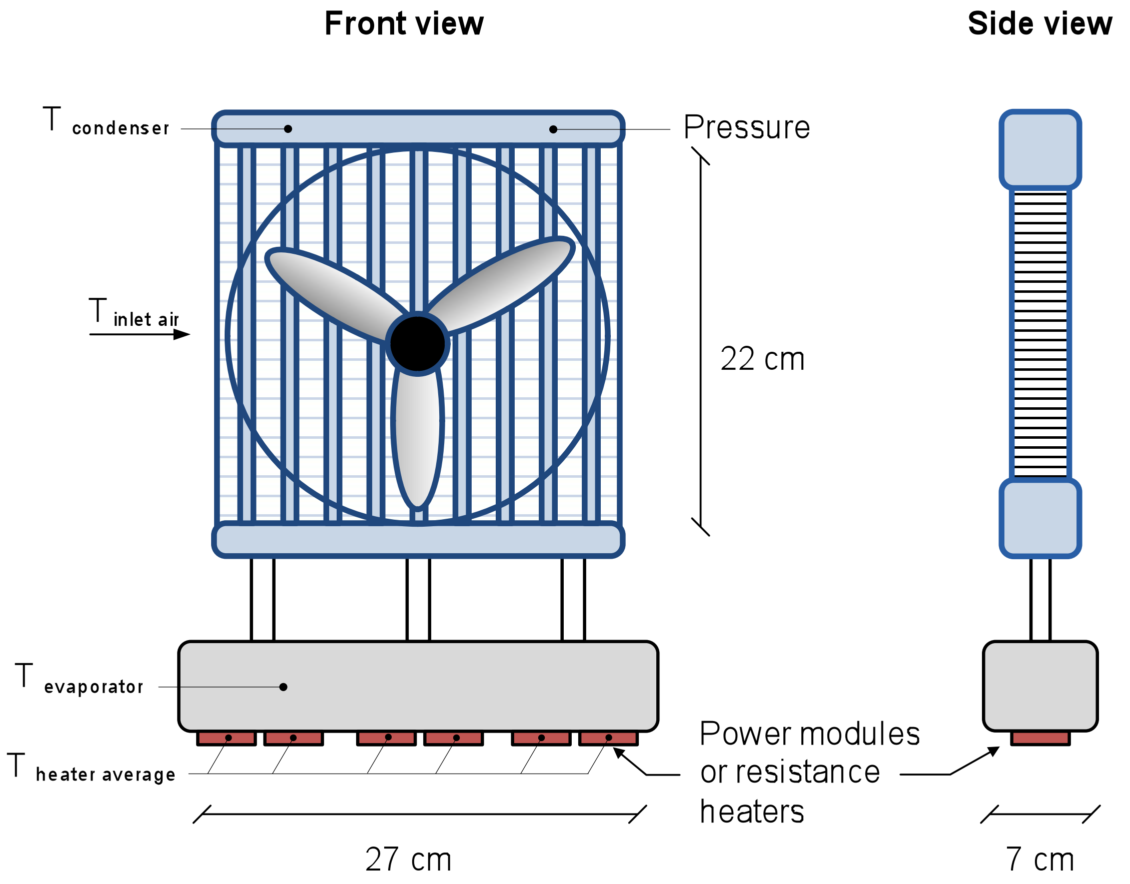
Phase II (cont'd)

Initial test conditions:

- Total system charge: 250 ml of R-245fa
- Non-coated evaporator (i.e., no boiling enhancement coating)
- Conducted experiments using six electric heaters to simulate six power modules. Heaters mounted to evaporator/two-phase cold plate using thermal interface material



Resistance heater



Cooling system schematic

Credit: Gilbert Moreno, NREL

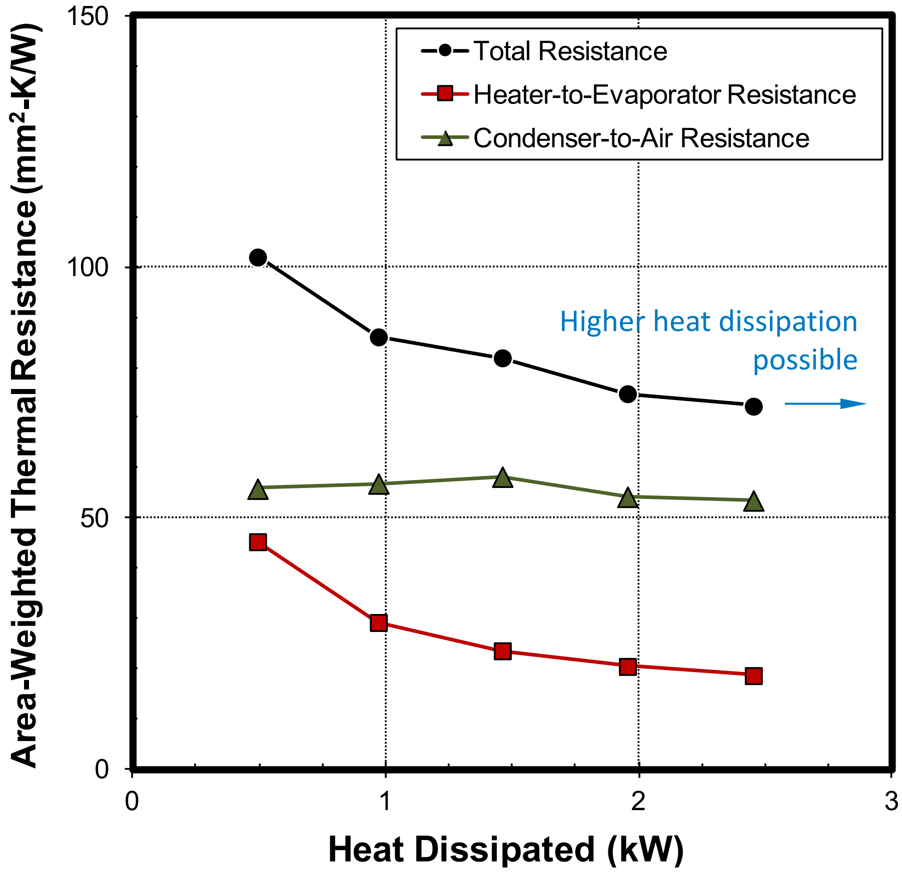
Technical Accomplishments and Progress

Passive two-phase cooling system results

Phase II (cont'd)

Preliminary results:

- Cooling system can dissipate at least 2.5 kW of heat
- Decreasing thermal resistance trend indicates system can dissipate more heat
- System thermal performance will be increased and its size will be reduced through the use of:
  - Enhanced-surfaces: prior results indicate that evaporator thermal resistance can be reduced by 60%
  - Bonded interfaces between heater and evaporator
  - Folded-fin design condenser

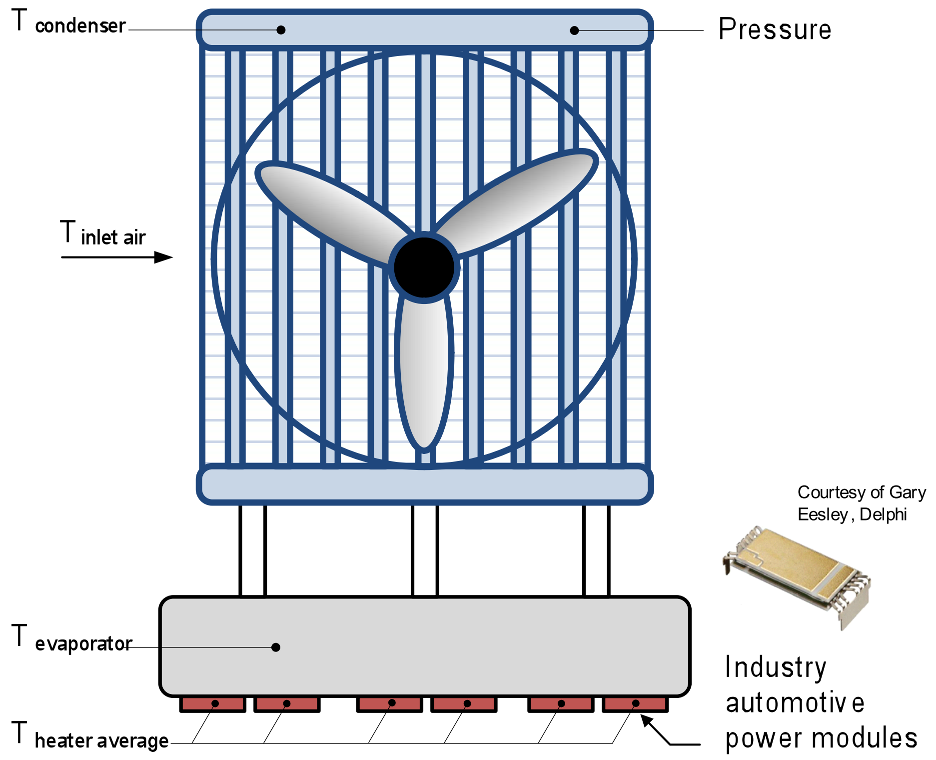


Technical Accomplishments and Progress

Next Steps

- Test to higher power levels
- Implement boiling enhancement coatings within evaporator
- Experiments using refrigerant HFO-1234yf
- Understand effect of inclination on performance
- Cool Delphi power module: measure junction-to-air resistance

Techniques to further improving evaporator performance and reduce manufacturing cost have been identified. ROI has been submitted



Collaboration and Coordination with Other Institutions

University Partners

- University of Colorado-Boulder (graduate student)
- Iowa State University (provided enhanced surfaces)
- University of Illinois-Chicago (provided enhanced surfaces)

Industry Partners

- Delphi (supplied power modules)
- 3M Electronics Markets Materials Division (supplied boiling enhancement coating)
- DuPont (supplied HFO-1234yf refrigerant)

Proposed Future Work

FY13

Characterize thermal performance of the proof-of-concept two-phase power electronics cooling system

- Measure thermal resistance (junction-to-air) while cooling Delphi's discrete power switch
- Measure maximum heat dissipated
- Understand effects of inclination on thermal performance
- Characterize performance under transient heat loads (drive cycle power profile)
- Compare against performance of conventional water-glycol cooling systems

Proposed Future Work

FY13 (cont'd)

- **Improve two-phase cooling system design to improve performance and decrease size and manufacturing cost**
  - Improve evaporator design
  - Work with industry partner to fabricate a custom-made condenser
- **Evaluate the long-term reliability of boiling enhancement coatings**
- **Develop industry partnership to demonstrate a two-phase cooled inverter system**

Summary

DOE Mission Support

- Enable meeting the DOE APEEM cost, power density, and specific power targets to be achieved via improved thermal management

Approach

- Utilize the high heat transfer rates of two-phase cooling to improve performance
- Demonstrate a passive, two-phase cooling solution for automotive power electronics

Accomplishments

- Characterized the pool boiling performance of R-245fa on plain and microporous-enhanced surfaces
- Demonstrated that a passive, two-phase cooling system can dissipate at least 2.5 kW of heat with 250 ml of refrigerant
- Identified means to enhance passive, two-phase cooling system performance and submitted an ROI
- Initiated experiments to evaluate the long-term reliability of boiling enhancement coatings

Summary

Future work

- Characterize the thermal performance of the proof-of-concept passive, two-phase cooling system
- Further reduce the size and increase the thermal performance of the two-phase cooling system
- Quantify performance metrics (i.e., power density, specific power, and efficiency) for the cooling system. Compare values to those of existing state-of-the-art cooling systems
- Seek collaboration with industry partner to further demonstrate this technology

Collaborations

- Delphi
- 3M
- DuPont
- University of Colorado-Boulder
- Iowa State University
- University of Illinois-Chicago

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