INVERTER-SCALE, PASSIVE TWO-PHASE COOLING SYSTEM FOR AUTOMOTIVE POWER ELECTRONICS

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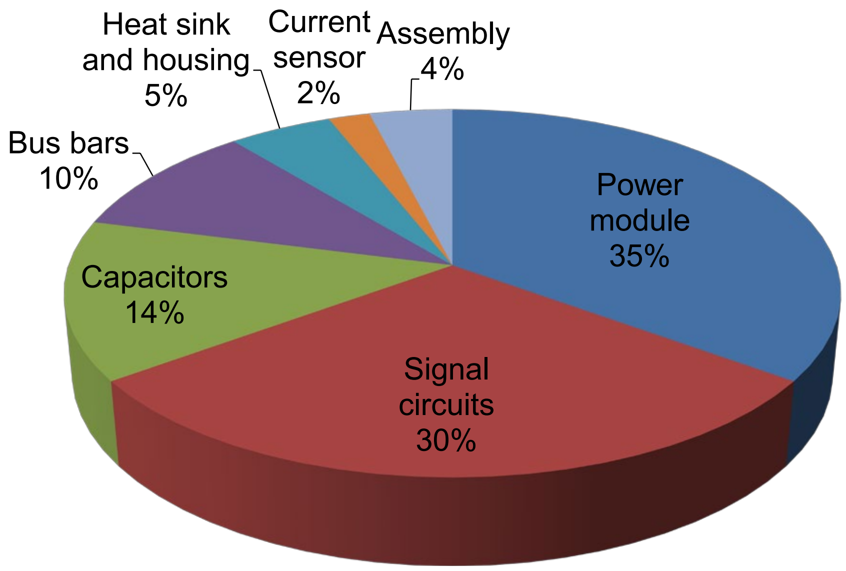
Outline

Motivation

On-road 80 kW Manufactured Cost: $1,092



Source: Susan Rogers (U.S. DOE) 2013 AMR Presentation

Accelerate the adoption of electric-drive vehicles to reduce our nation's dependence on oil

The Problem: High cost of electric-drive vehicles

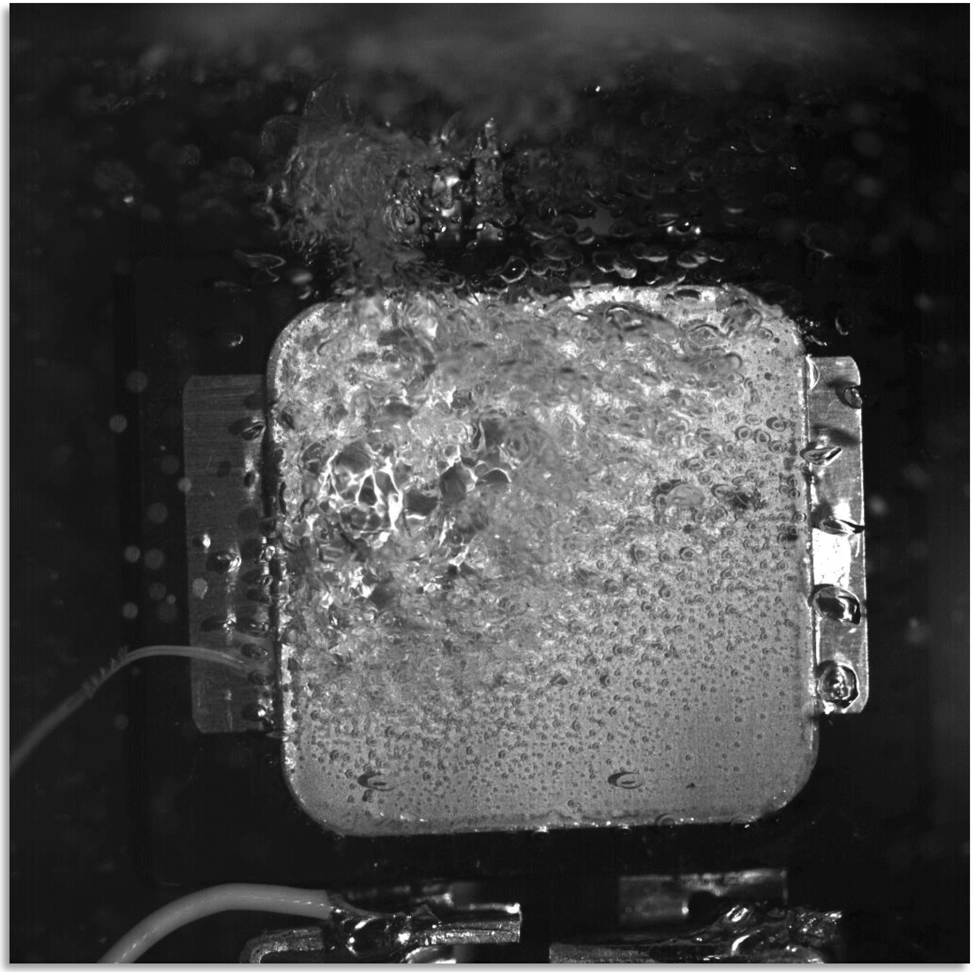
- Power electronics are a big contributor to the overall cost

Improved thermal management enables cost reductions

Project Objective

Significantly improve thermal management of automotive power electronics by utilizing the high heat transfer rates of two-phase cooling

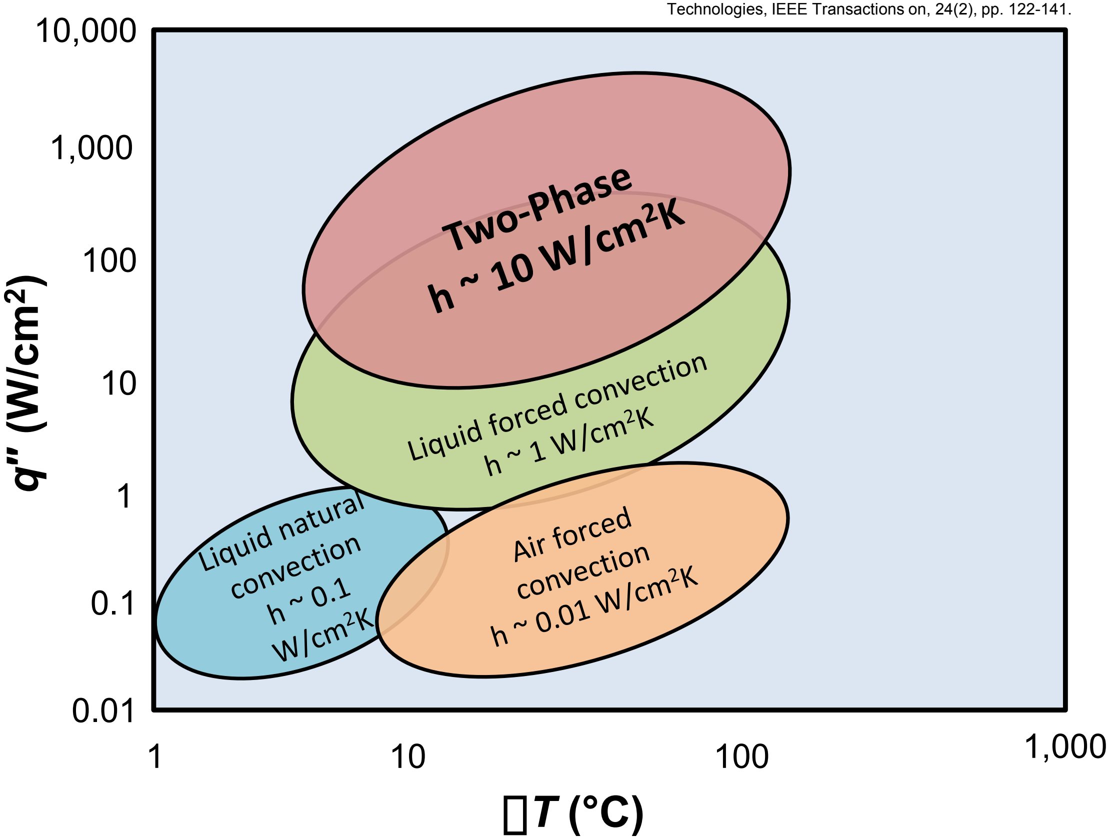
- Design and build an inverter-scale passive two-phase cooling system
- Demonstrate that the system dissipates automotive heat loads and provides superior thermal performance



Demonstrate more than 60% reduction in thermal resistance via two-phase immersion cooling. (*Credit: Gilbert Moreno, NREL)*

Why Two-Phase Cooling?

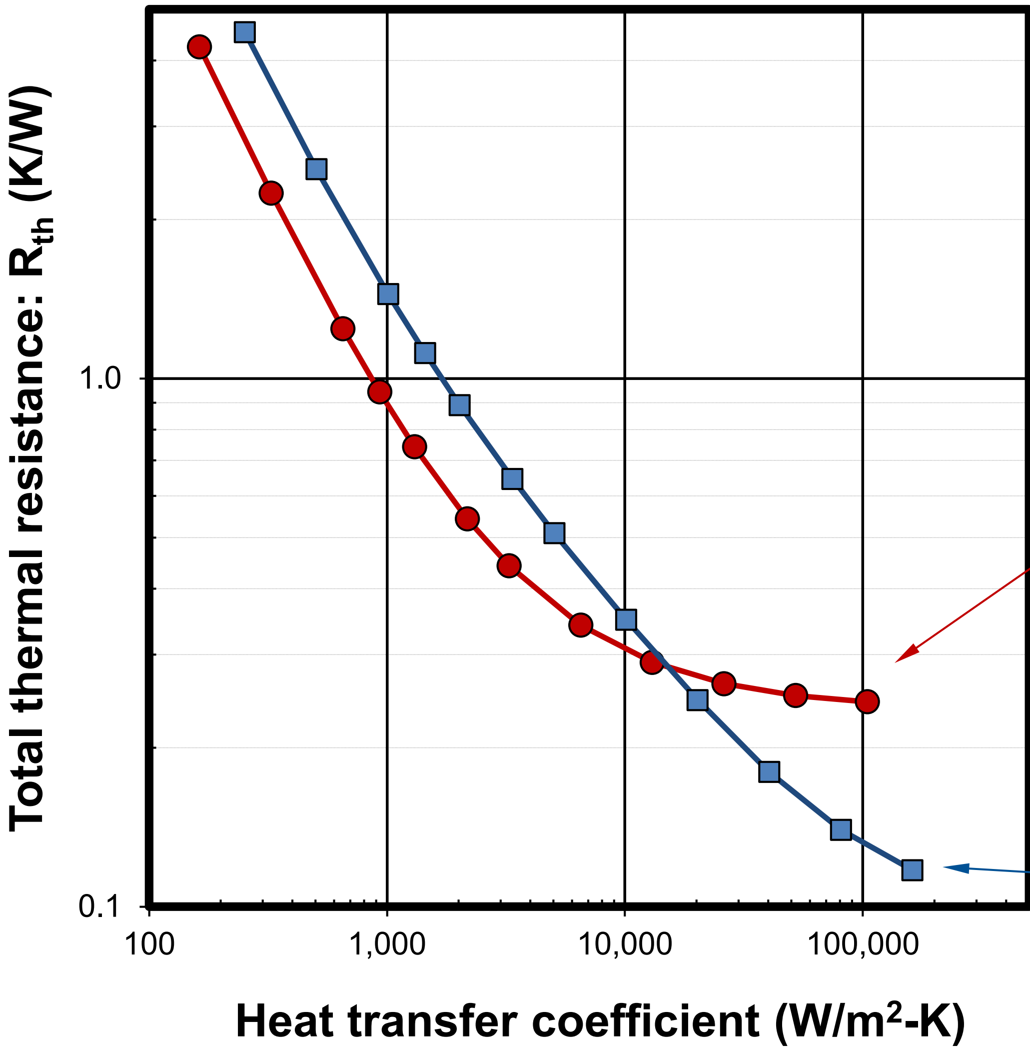
Adapted from: Mudawar, I., 2001, "Assessment of High-Heat-flux Thermal Management Schemes," Components and Packaging Technologies, IEEE Transactions on, 24(2), pp. 122-141.

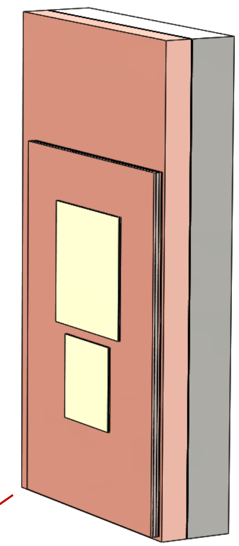


Experimentally measured heat transfer coefficients of ~20 W/cm^2-K using passive two-phase cooling (R-134a)

- Two-phase cooling provides the highest heat transfer rates compared to other methods of cooling
- Near-isothermal system characteristics reduce temperature gradients

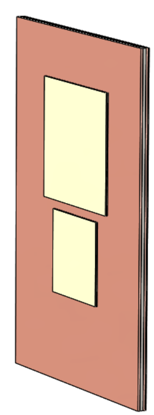
When Does Two-Phase Cooling Make Sense?





Cold-plate cooled

- Package resistance dominates
- Thermal grease is a major contributor to resistance



Direct-bond-copper substrate cooled

- Lower package resistance, more suited for high performance cooling strategies (i.e., two-phase)

Challenges and Barriers

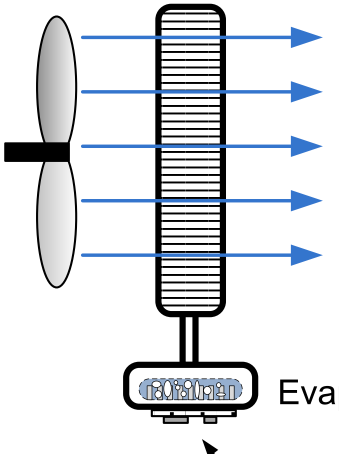
Two-phase cooling is not used to cool automotive power electronics. There are reliability and cost concerns associated with the technology.

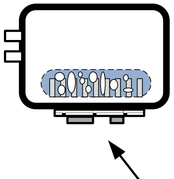
Strategy:

- Propose a simple two-phase cooling solution (indirect cooling, passive, low-cost materials, minimize refrigerant requirements)
- Propose solution with pressures equivalent or lower than those used in vehicle air-conditioning systems
- Two-phase cooling technology is used in the vehicle air-conditioning systems. Technology is available to develop reliable refrigerant-based cooling systems.

Two-Phase Cooling Concept

- Indirect-cooled: Easier to implement, electronics not in contact with refrigerant
- Passive: Increased efficiency through a passive (no pump or compressor) two-phase cooling approach
- Decrease the condenser size using a liquid-cooled condenser. Liquid-cooled condenser may allow use of waste heat for cabin heating (integrated thermal management)





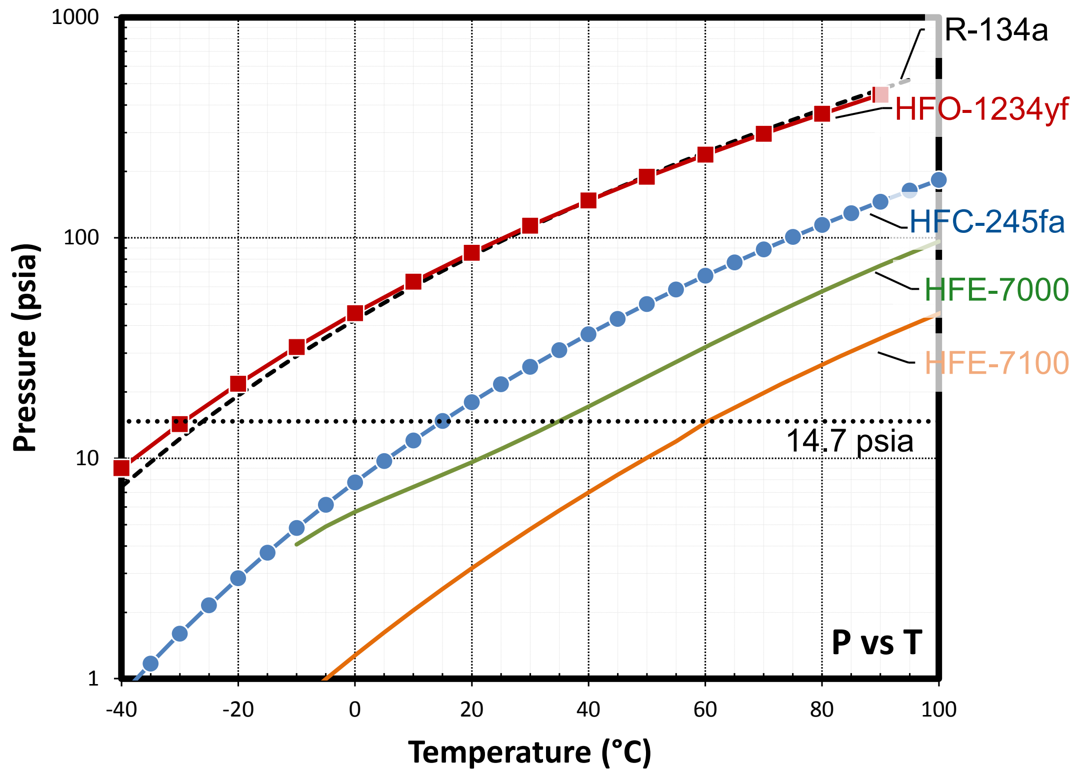
Refrigerant Selection

HFO-1234yf: Potential next generation air-conditioning refrigerant

- ✓ Qualified for automotive use
- ✓ Environmentally friendly (GWP = 4)
- ○ Lower critical temperature (95 °C)
- ○ Mildly flammable

HFC-245fa:

- ✓ Higher critical temperature (150 °C)
- ✓ Non-flammable
- ✓ Lower pressure as compared with HFO-1234yf
- ○ Higher GWP = 985
- ○ Not used in automotive applications



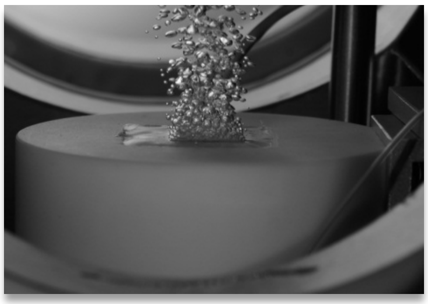
– Evaluating two refrigerants, but the cooling concept can work with other refrigerants

GWP = global warming potential

Approach

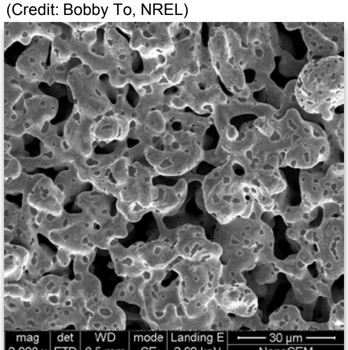
Fundamental Research

(Credit: Gilbert Moreno, NREL)



Characterized performance of HFO-1234yf and HFC-245fa

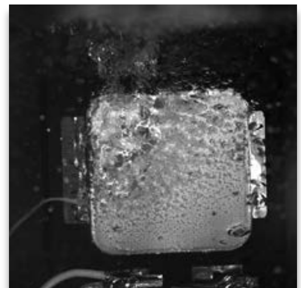
(Credit: Bobby To, NREL)



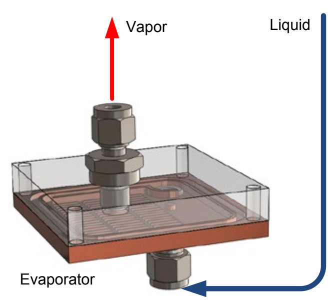
Evaluate techniques to enhance two-phase cooling

Module-Level Research

(Credit: Gilbert Moreno, NREL)

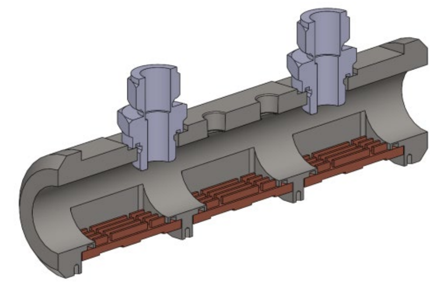


Demonstrate two-phase immersion cooling of a power module



Quantified refrigerant volume requirements

Inverter-Scale Demonstration

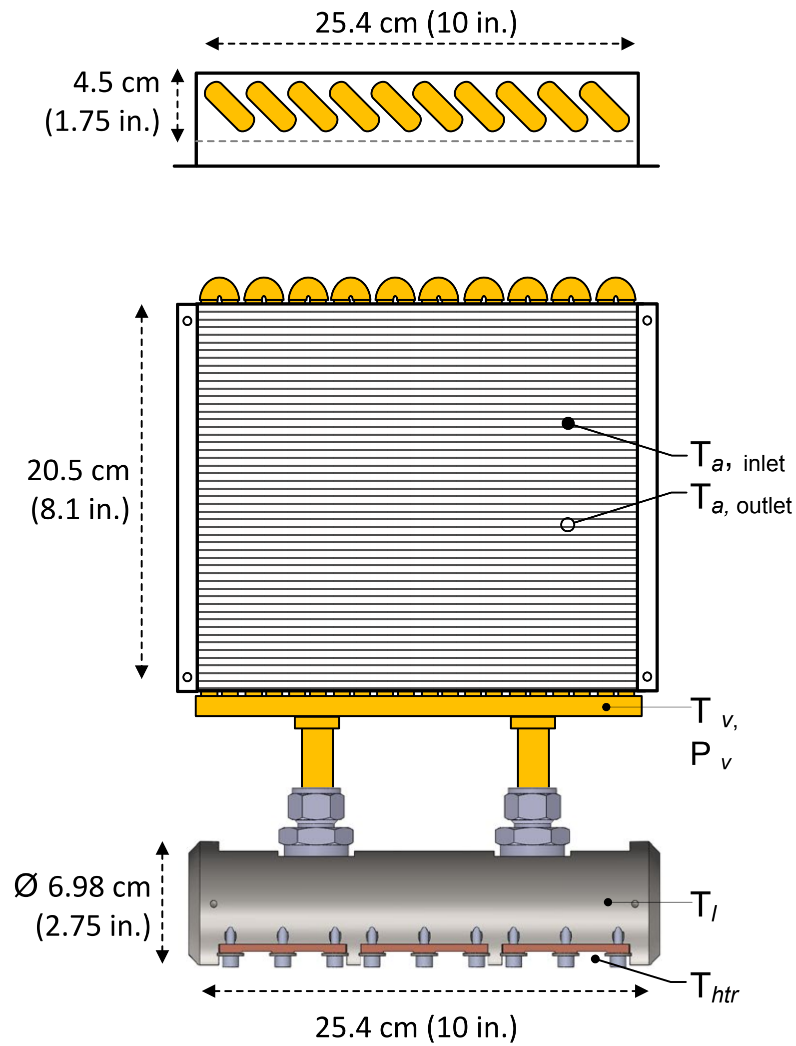


Design a system to dissipate the required heat loads

Demonstrate improvements over conventional cooling systems

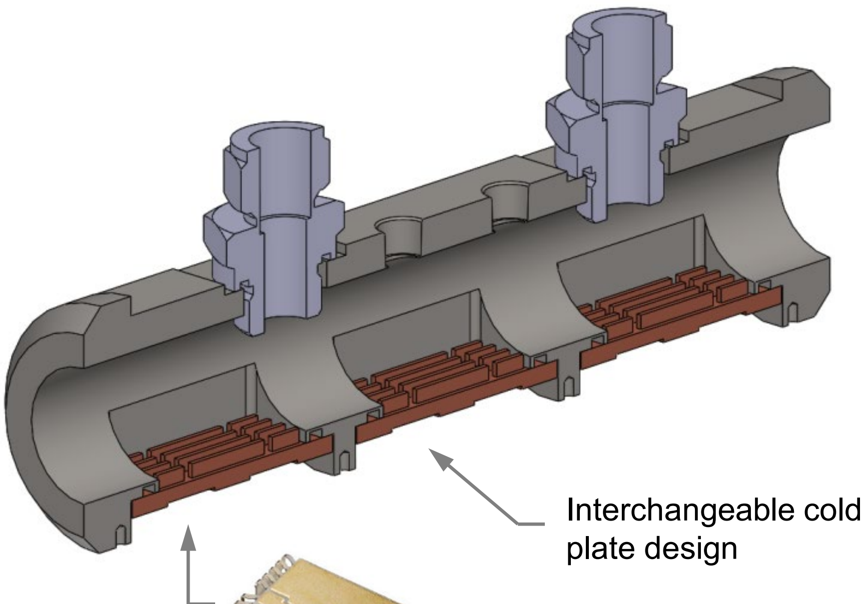
Experimental System: Designed and Fabricated a Proof-of-Concept Two-Phase Cooling System

- Refrigerant charge: 250 mL (280 g – 330 g)
  - **Comparison**: 2010 Toyota Camry air-conditioning system uses 510 g of R-134a
- Maximum operating pressure: 1 MPa (150 psi)
- Automotive fan: 17.8 cm (7 in.) diameter, 38 W, 12 V

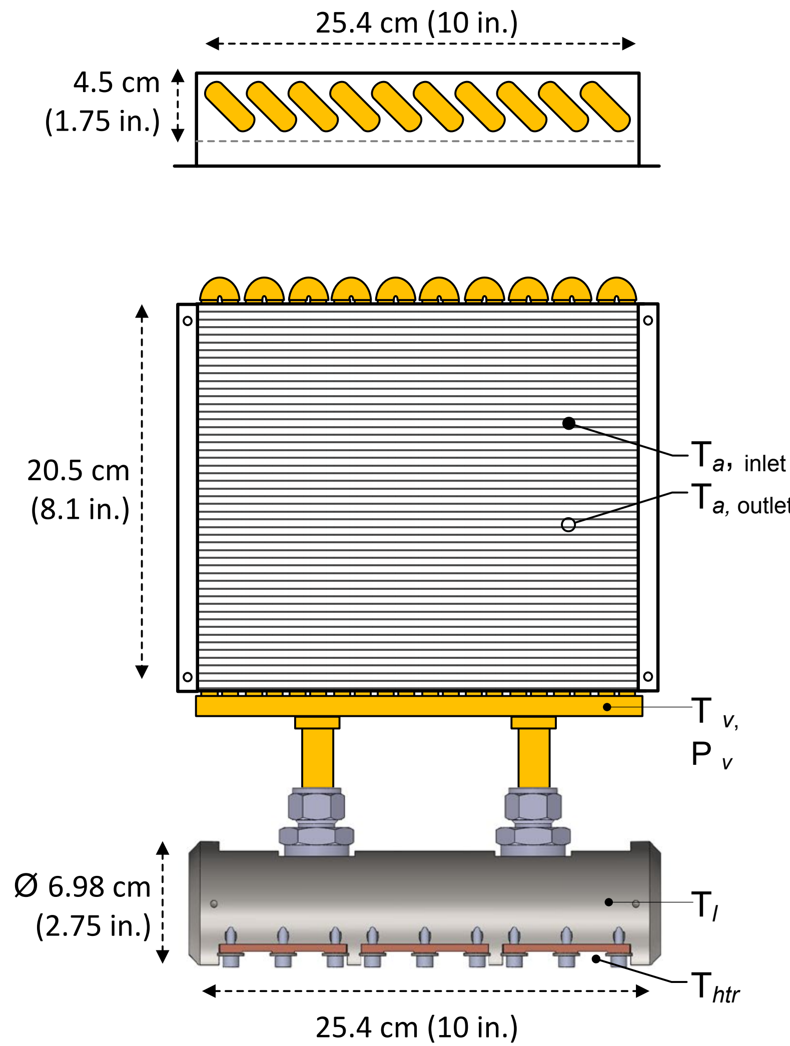


Experimental System: Designed and Fabricated a Proof-of-Concept Two-Phase Cooling System

Evaporator cross-sectional view



Delphi discrete power module:
Image courtesy of Delphi



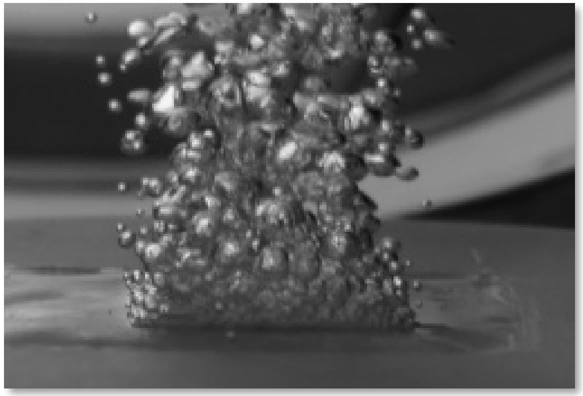
Experimental System: Designed and Fabricated a Proof-of-Concept Two-Phase Cooling System

Objectives

- Dissipate inverter-scale (< 3.5 kW for a 55-kW system) heat loads with a small amount of refrigerant without reaching critical heat flux (dry-out)

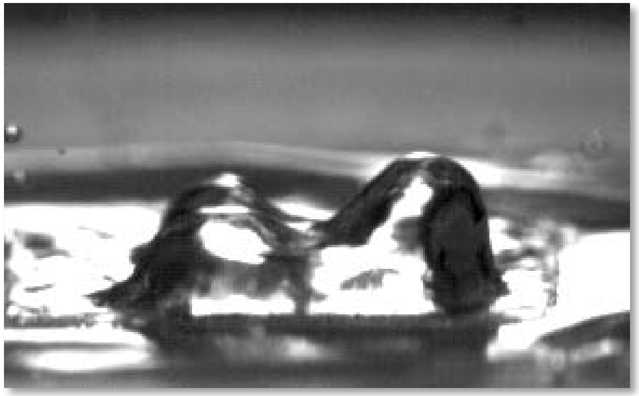
R-134a

(Credit: Gilbert Moreno, NREL)



Nucleate boiling

(Credit: Gilbert Moreno, NREL)



Critical heat flux
(low heat transfer)

- Measure the condenser thermal resistance to size the condenser for automotive applications

Test Procedures

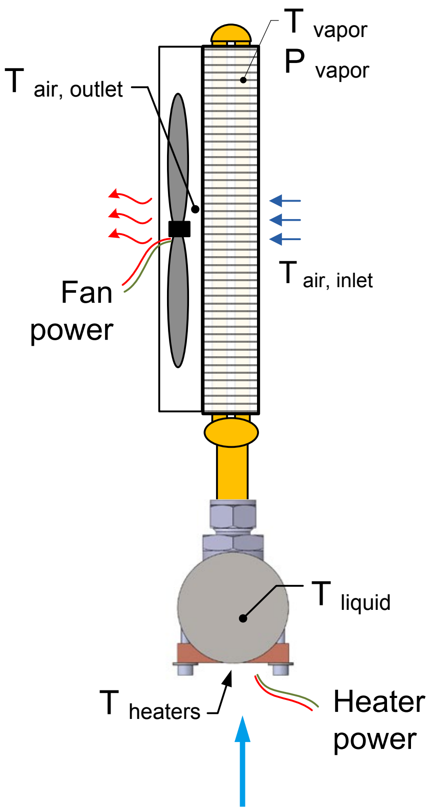
- Initial test conducted using six ceramic heaters attached to evaporator using thermal grease
- Six heaters represent six power switches (inverter-scale).

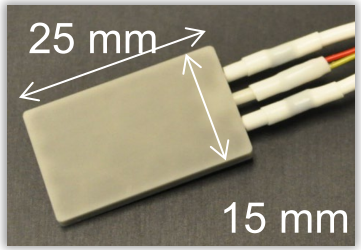
Evaporator thermal resistance:

$$R''_{th} = \frac{(\bar{T}_{heaters} - T_{liquid})}{Heat\ dissipated} \times \text{Total heater area}$$

Condenser thermal resistance:

$$R''_{th} = \frac{(T_{vapor} - \bar{T}_{inlet\ air})}{Heat\ dissipated} \times \text{Condenser frontal area}$$



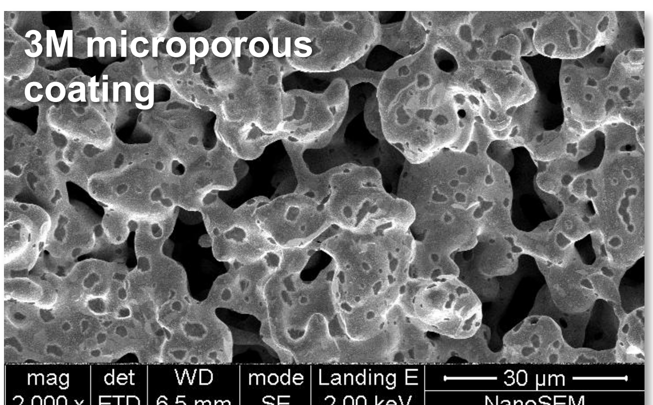


(Credit: Gilbert Moreno, NREL)

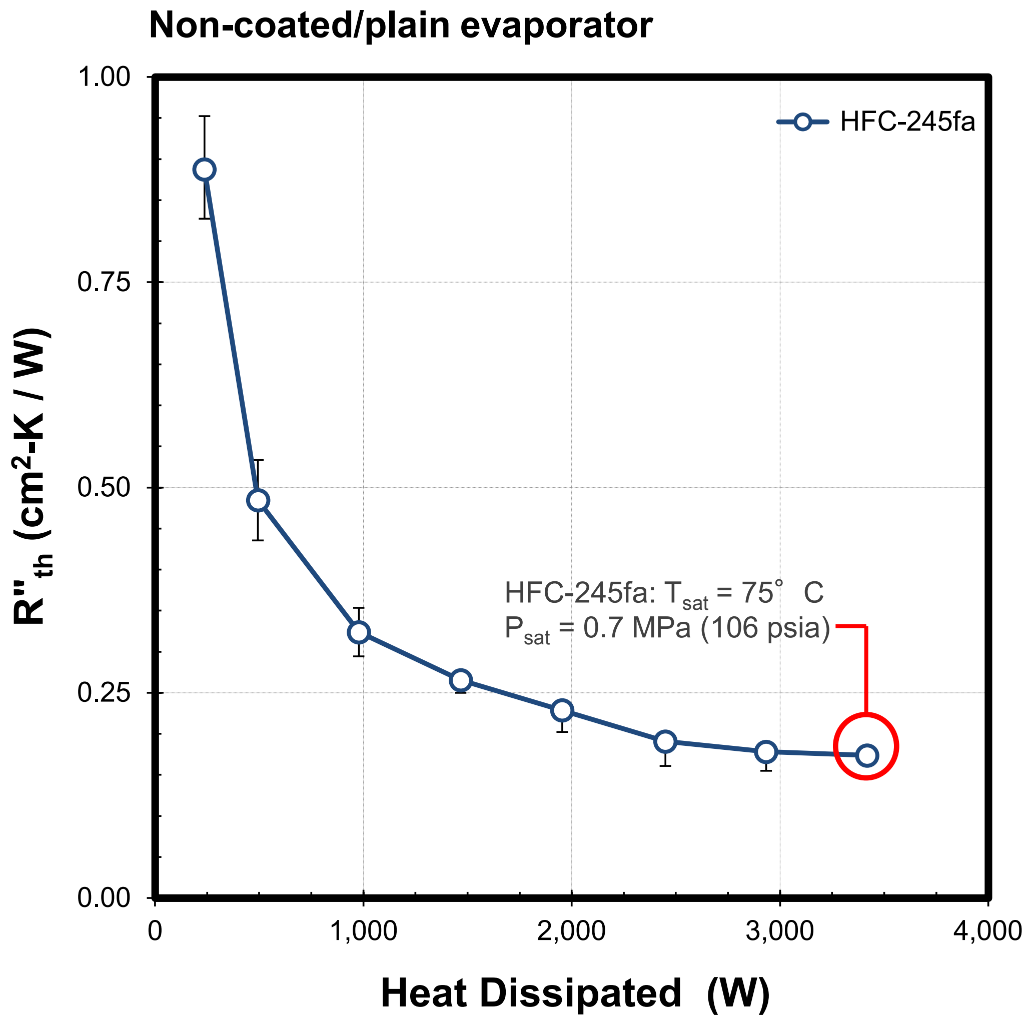
Evaporator Thermal Performance

HFC-245fa (250 mL, 330 g)

- Dissipated 3.5 kW of heat in steady-state conditions with a 250-mL charge
- Limited by the heater power capacity
- Increase heat dissipation and decrease thermal resistance using enhanced surfaces



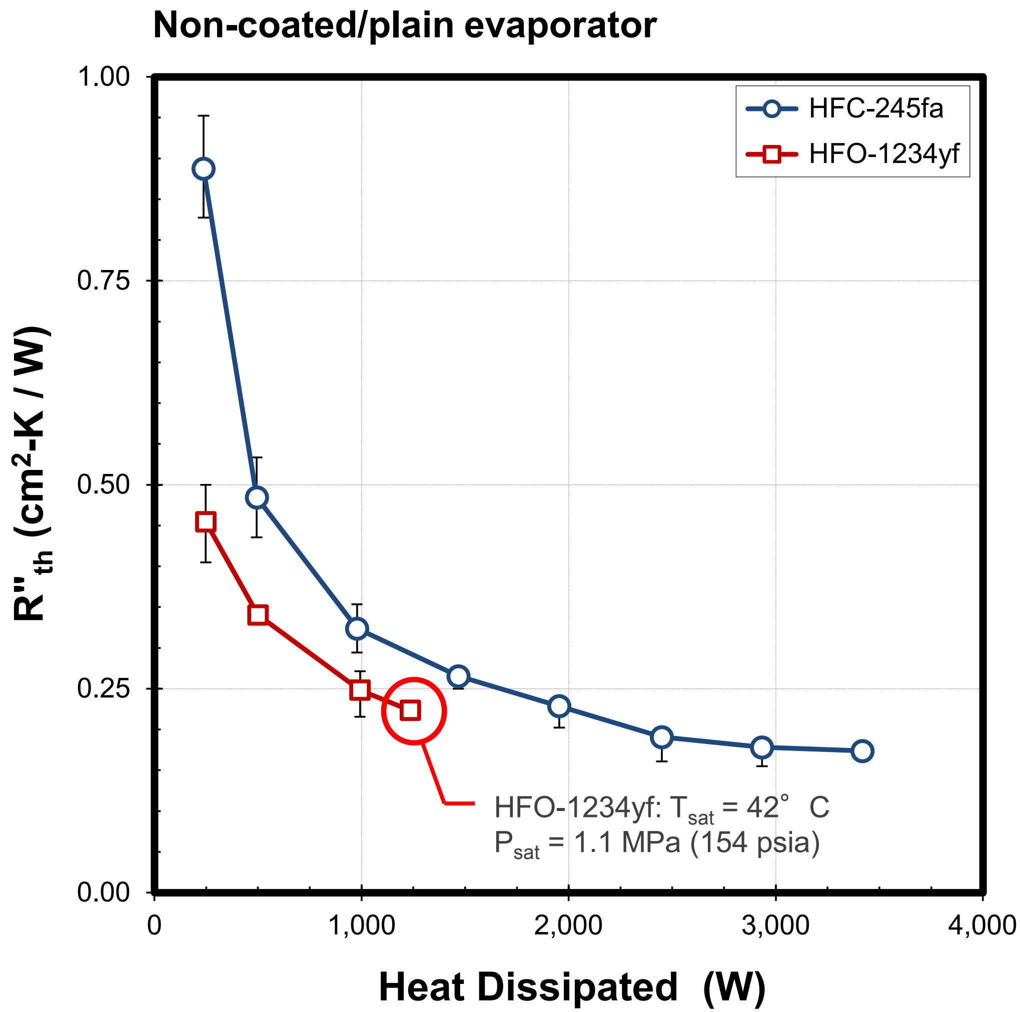
(Credit: Bobby To, NREL)



Evaporator Thermal Performance

HFO-1234yf (250 mL, 280 g)

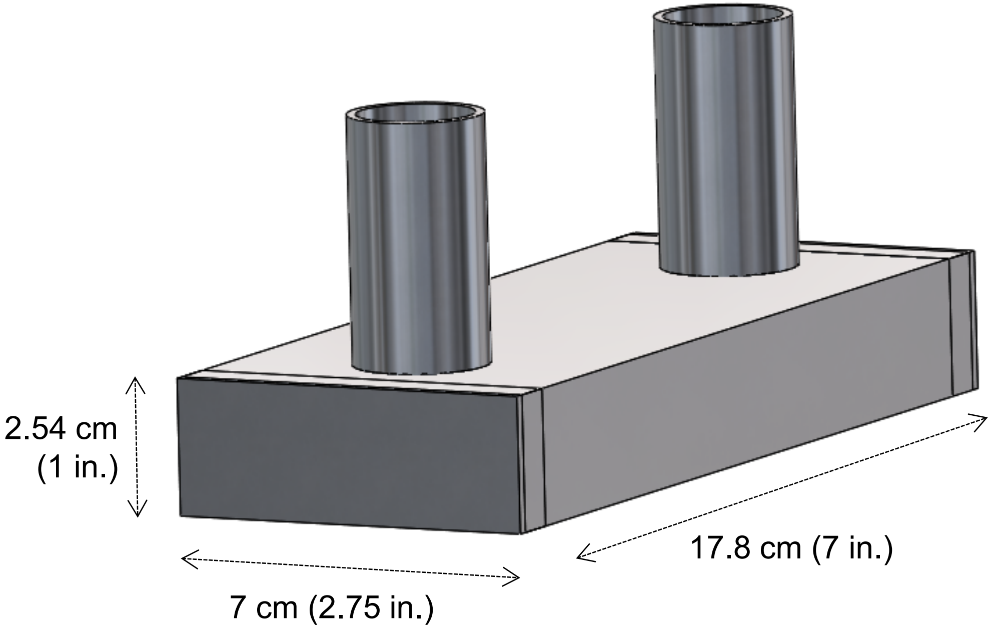
- Prototype limited heat dissipation to 1.3 kW with HFO-1234yf because of higher pressures. Expect we could dissipate more heat by increasing system pressure capacity
- HFO-1234yf's higher heat transfer coefficients resulted in lower evaporator thermal resistance



Advanced Evaporator Design

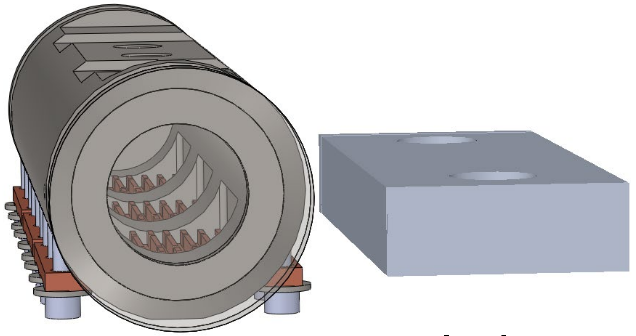
Identified techniques to increase performance and reduce the size of the evaporator

- Designed to cool six Delphi power modules
- Increased evaporation surface area to improve thermal performance
- Fabricated from low-cost materials (aluminum) using low-cost manufacturing techniques
- Reduced refrigerant requirements to 180 mL, (HFO-1234yf = 200 g, HFC-245fa = 240 g)

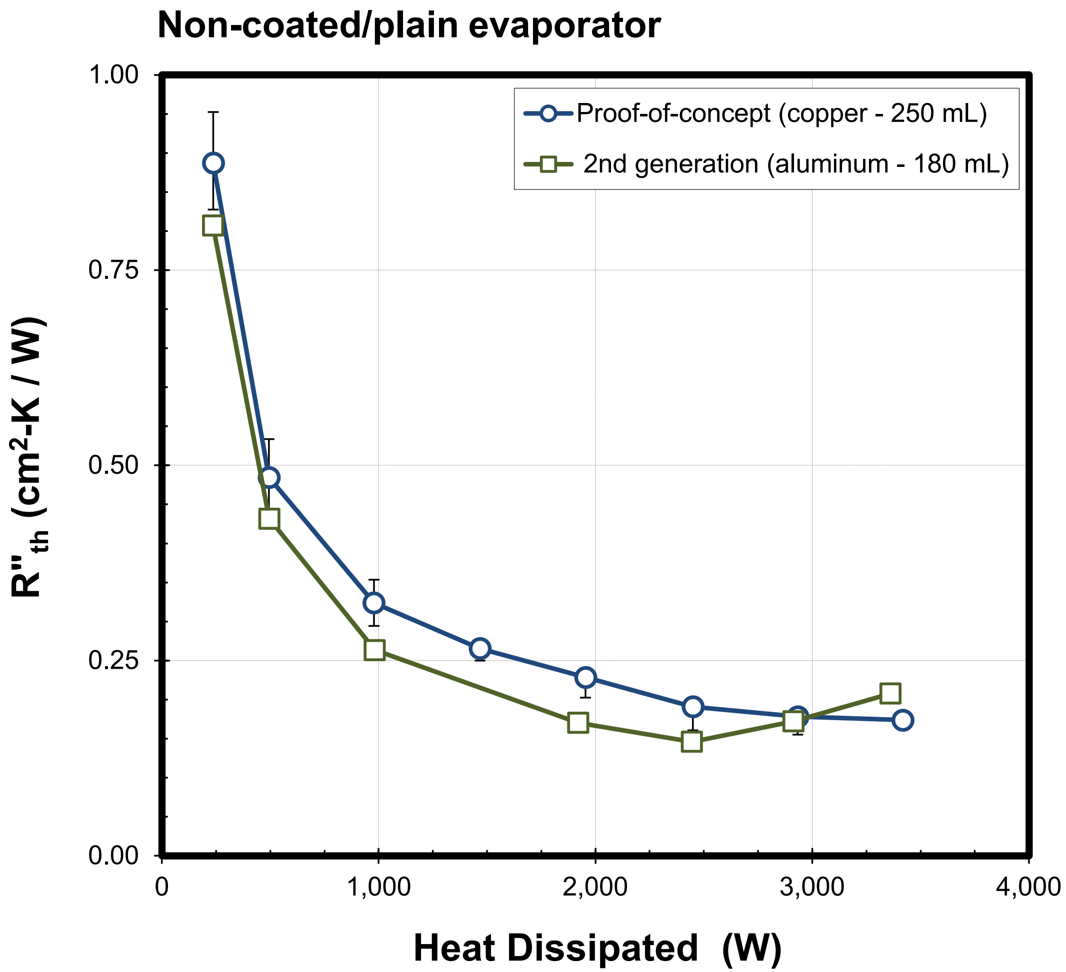


Advanced Evaporator Performance

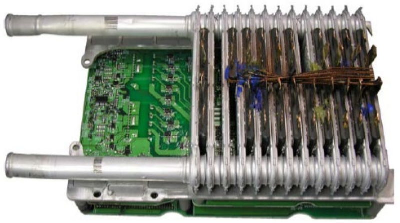
- Dissipated 3.5 kW of heat with only 180 mL of HFC-245fa
- Reduced thermal resistance with improved design
  - Smaller aluminum evaporator outperforms copper evaporator



- Pressure–temperature fluctuations at higher power levels (≥ 3 kW)
  - Microporous coating may eliminate/reduce fluctuations

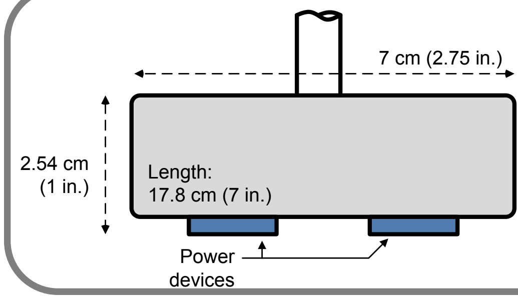


Advanced Evaporator Performance: Power Module Cooling

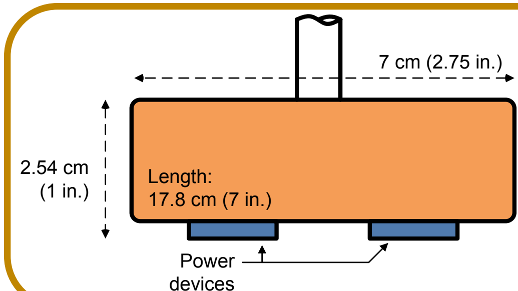


Double-side cooled inverter

Image courtesy of Oak Ridge National Lab



Indirect two-phase cooling (aluminum evaporator)



Indirect two-phase cooling (copper evaporator)

	R''_{th} (mm^2-K/W)	% R''_{th} Reduction
Lexus Hybrid (2008) double-side cooled modules	33.2*	-
Two-phase: aluminum evaporator (*finite element analysis results*)	**13.9**	**58%**
Two-phase: copper evaporator (*finite element analysis results*)	**11.5**	**65%**

based on die footprint

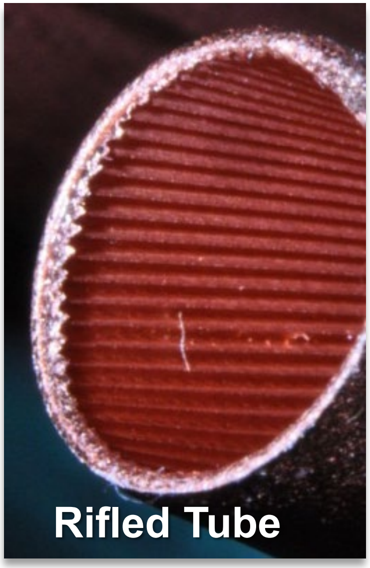
- **Reduced thermal resistance by 58% to 65%** with the advanced evaporator design compared with state-of-the-art cooling system
- **Increased device heat flux by as much as 189%**

* Calculated using one side of the die (12.78 mm × 12.78 mm)
* Performance from: Sakai, Yasuyuki, Hiroshi Ishiyama, and Takaji Kikuchi. Power control unit for high power hybrid system. No. 2007-01-0271. SAE Technical Paper, 2007.

Condenser Thermal Performance

Refrigerant	R"$_{th}$ (cm^2- K/W) *[~250 cfm, 38 W fan]*		
	Plain Tubes	Rifled Tubes	Reduced R"$_{th}$ with Rifled Tubes
HFC-245fa	**9.30**	**7.58**	**18%**
HFO-1234yf	**8.12**	**6.06**	**25%**

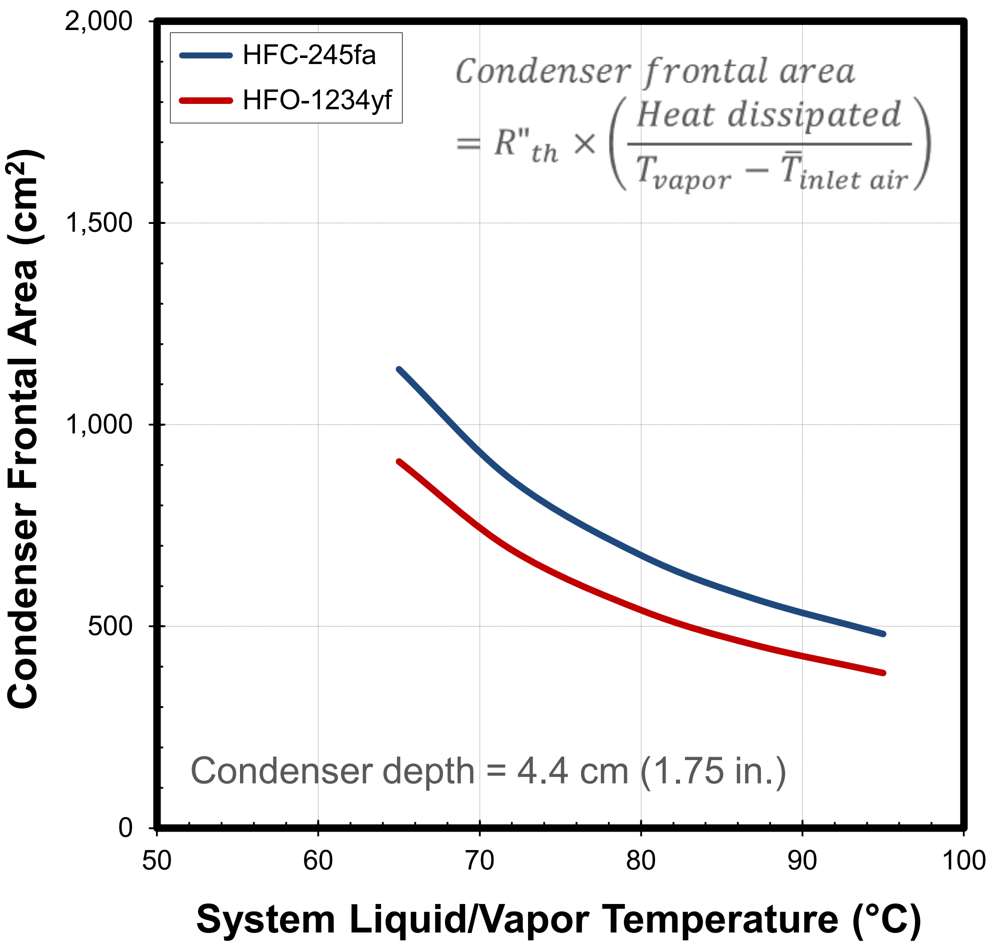
$$R''_{th} = \frac{(T_{vapor} - \bar{T}_{inlet\ air})}{Heat\ dissipated} \times \text{Condenser frontal area}$$



(Credit: Gilbert Moreno, NREL)

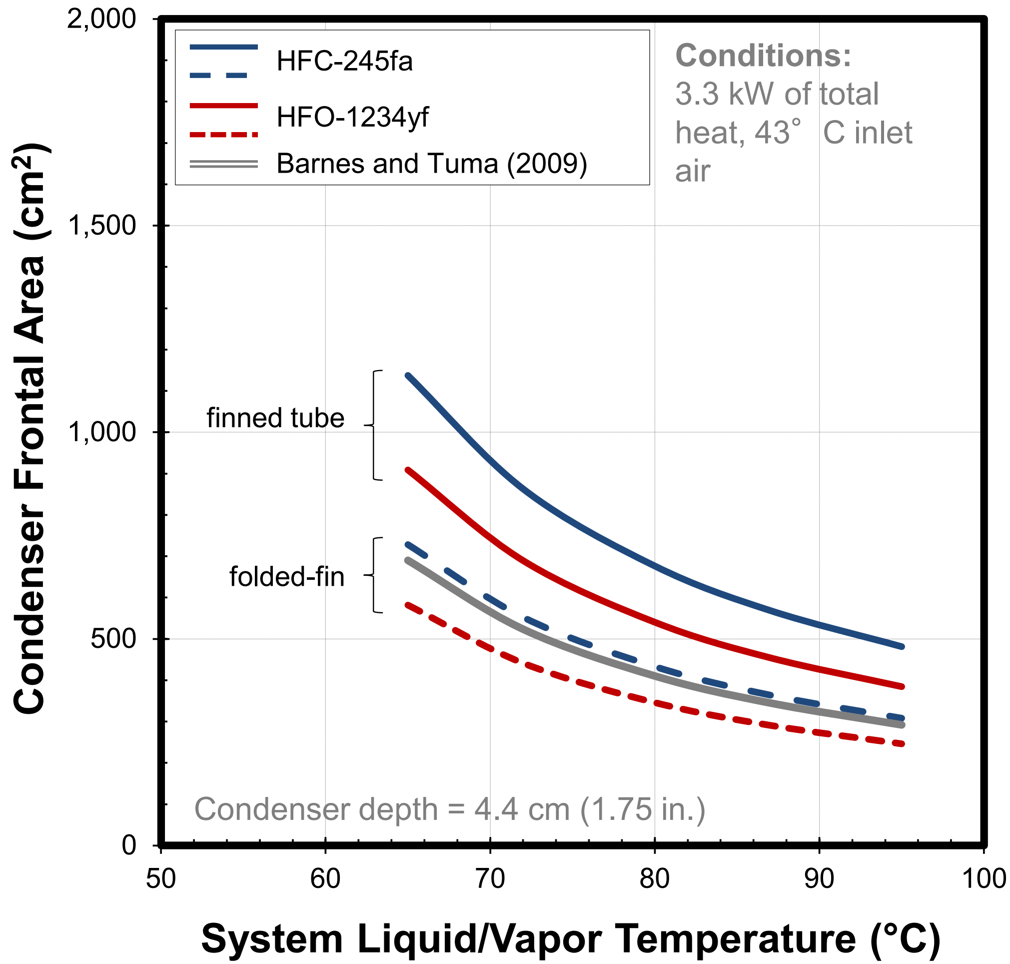
- Rifled tubes enhance condensation heat transfer and thus reduce condenser thermal resistance by 18% and 25% for HFC-245fa and HFO-1234yf, respectively
- HFO-1234yf provides lower condenser thermal resistance values compared with HFC-245fa
  - 13% plain tubes
  - 20% rifled tubes

Condenser Size versus System Temperature (Finned-Tube Condenser)

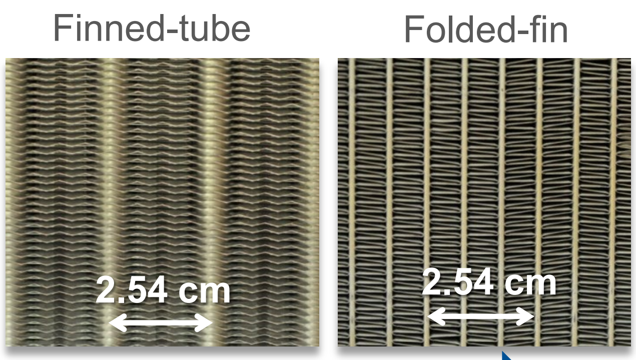


- Estimated condenser frontal area/size requirements at various refrigerant temperatures for the operating condition:
  - 3.3 kW of total heat, 43°C inlet air
- Higher refrigerant temperatures enable a more compact condenser
- HFO-1234yf's higher performance allows for a smaller condenser

Condenser Size versus System Temperature (Folded-Fin Condenser)



- Estimated the size requirements for a brazed folded-fin condenser → matched air-side surface area (assumed air-side was the dominant thermal resistance)



(Credit: Gilbert Moreno, NREL)

~36% more air-side surface area for folded-fin condenser

Conclusions

- Demonstrated that a passive, two-phase cooling system can dissipate inverter-scale head loads (3.5 kW) with only 180 mL of refrigerant
- Improved the evaporator design to increase its performance and reduce its size
  - Evaporator features enabled the aluminum evaporator to outperform the copper evaporator
  - Increase power module heat flux by as much as 189% as compared with state-of-the-art automotive systems
- Measured the condenser thermal resistance and conducted analysis to size the condenser at various operating temperatures

Future Work

- Evaluate the effect of cooling system inclination/orientation on thermal performance
- Experimentally quantify key system metrics (thermal resistance, coefficient of performance, volume, weight) and compare against conventional cooling systems
- Develop industry partnerships to demonstrate a two-phase cooled inverter system

Acknowledgments:

Susan Rogers and Steven Boyd, U.S. Department of Energy

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