Power Electronics Thermal Management

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National Renewable Energy Laboratory
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DOE Vehicle Technologies Program
2023 Annual Merit Review and Peer Evaluation Meeting

Project ID # ELT211

Overview

Timeline

- Project start date: 10/1/2018
- Project end date: 9/30/2024
- Percent complete: 80%

Budget

- Total project funding: $1,660,000
  - DOE share: $1,660,000
- Funding for FY 2022: $350,000
- Funding for FY 2023: $260,000

Barriers

- Barriers addressed
  - Size and weight
  - Cost
  - Performance and lifetime

Partners

- Georgia Tech
- Infineum
- Oak Ridge National Laboratory (ORNL)
- SUNY Polytechnic Institute
- Project lead: National Renewable Energy Laboratory (NREL)

Relevance

- Improving thermal management is essential to increase power density and reliability.
- **Objective:** Develop thermal management techniques to enable achieving the (year 2025) DOE 100-kW/L power density target.

2025 DOE Target	Value
Power density	100 kW/L
Lifetime	300,000 miles
Cost	$2.7/kW

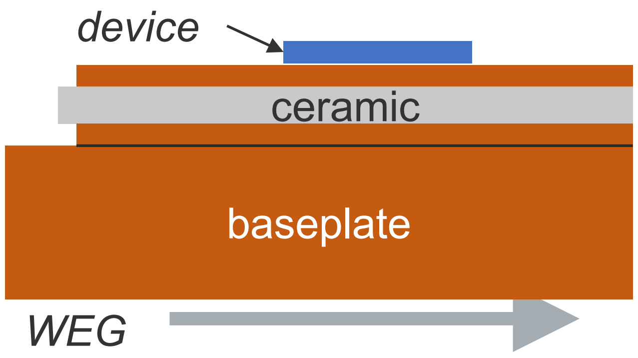
U.S. DRIVE. 2017. *Electrical and Electronics Technical Team Roadmap.*

Milestones

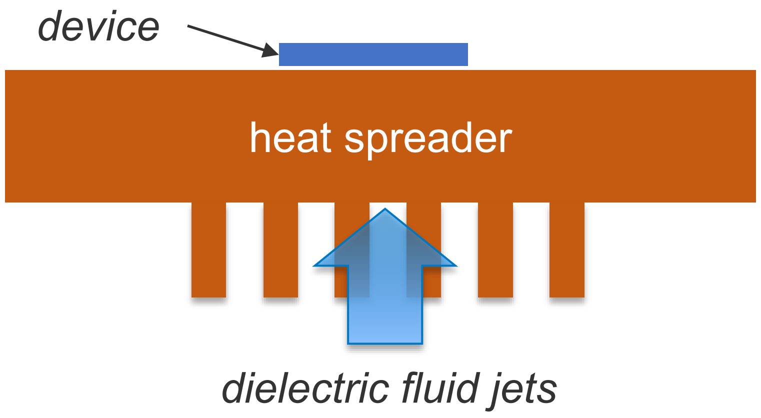
Date	Description
June 2023 (*complete*)	**Milestone:** Fabricate silicon-carbide power modules designed to be cooled using dielectric fluids. Conduct experiments to measure the junction-to-fluid thermal resistance and pumping power.

Approach: Dielectric Fluid Cooling Concept

Conventional DBC-based module



Dielectric fluid module



- Eliminate thermally resistive and failure-prone ceramic component
- Reduce package resistance by 18%–43%
- Use single-phase heat transfer
- Developed single- and double-side-cooled configurations.

Dielectric fluid cooling may enable:

- Cooling other components (e.g., capacitors)
- Using fluids found in vehicle
- Integrating inverter with the motor

DBC: direct-bond copper WEG: water-ethylene glycol

Approach: Addressing Concerns Associated With Dielectric Fluids

We have shown that a dielectric fluid cooling concept can provide a thermal resistance that is 56% lower compared to the WEG-cooled 2015 BMW i3 [1].

1. Thermal performance

(associated with poor fluid properties)

2. High pressure drop

(due to higher viscosities)

Predict that a dielectric concept can provide both lower thermal resistance and lower pumping power at −40°C fluid temperatures compared to WEG-based systems at 70°C [1].

4. Electrical performance

We will perform electrical simulations to evaluate the effect of the dielectric fluid on the module's electrical performance.

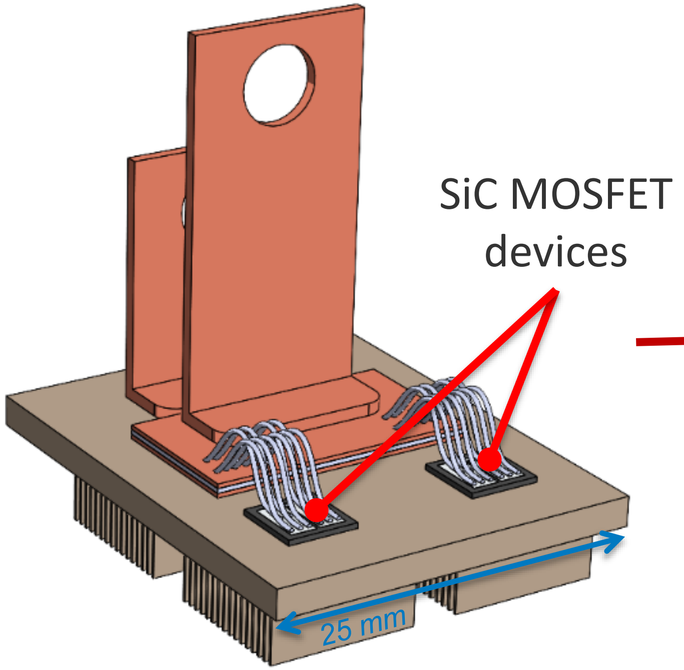
3. Reliability

We are fabricating a fluid loop to evaluate the long-term reliability of the dielectric fluid and heat exchanger. We will power cycle the ceramic-free module.

[1] G. Moreno, S. Narumanchi, J. Tomerlin, and J. Major. 2022. "Single-Phase Dielectric Fluid Thermal Management for Power-Dense Automotive Power Electronics." *IEEE Transactions on Power Electronics* 37 (10): 12474–12485.

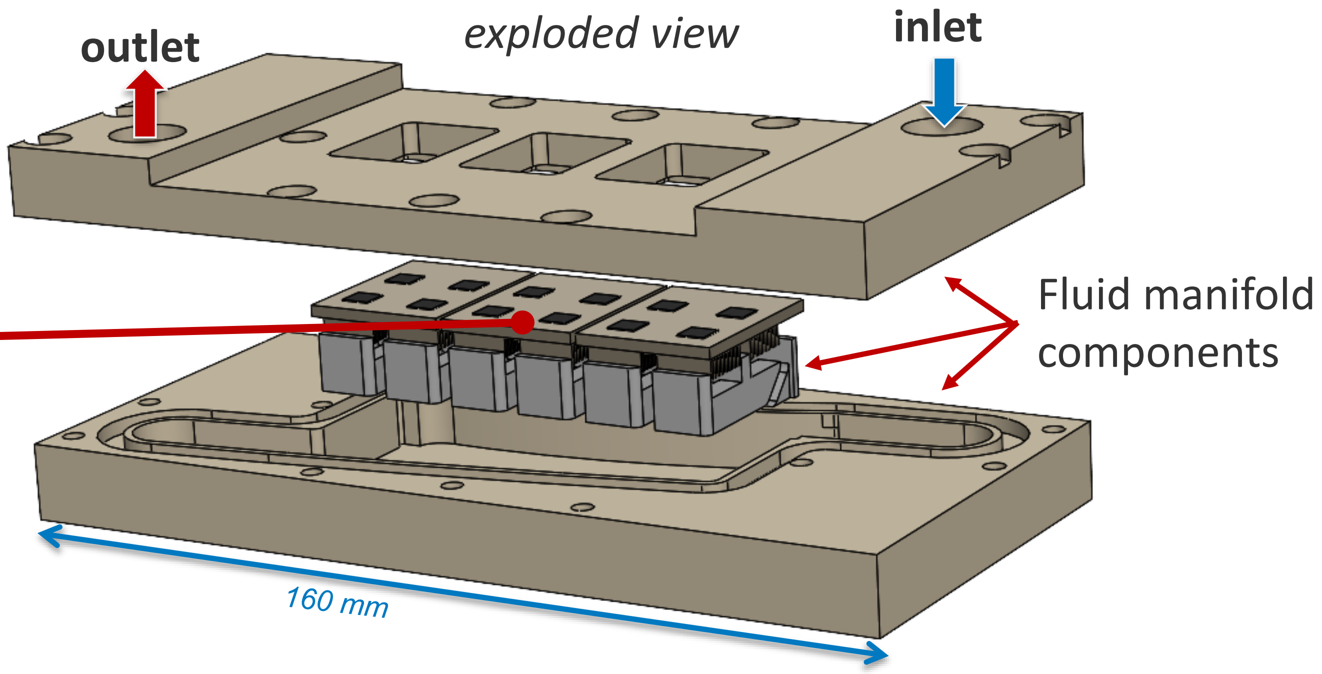
Technical Accomplishments: Dielectric Fluid Cooling Demonstration Using a SiC Module

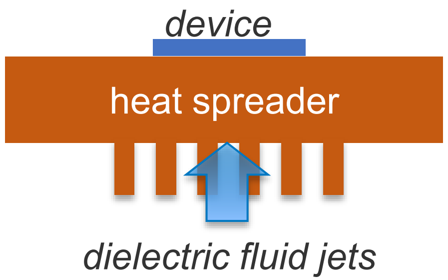
Fabricated a SiC-based module (thermal demonstration module)



cold plate/heat spreader (nickel-plated)

Installed module within dielectric fluid manifold/heat exchanger



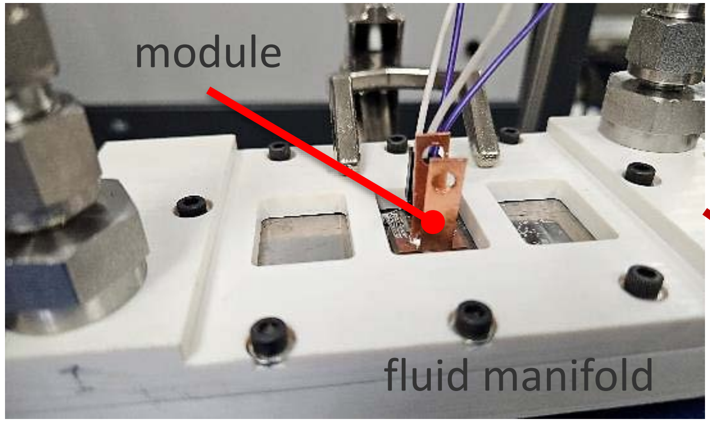


MOSFET: metal–oxide–semiconductor field-effect transistor

G. Moreno, S. V. J. Narumanchi, K. S. Bennion, R. M. Kotecha, P. P. Paret, and F. Xuhui. 2020. “Jet Impingement Manifolds for Cooling Power Electronics Modules.” Non-Provisional Patent Application 17/084,236, filed October 2020.

Technical Accomplishments: Dielectric Fluid Cooling Demonstration Using a SiC Module

Module and heat exchanger



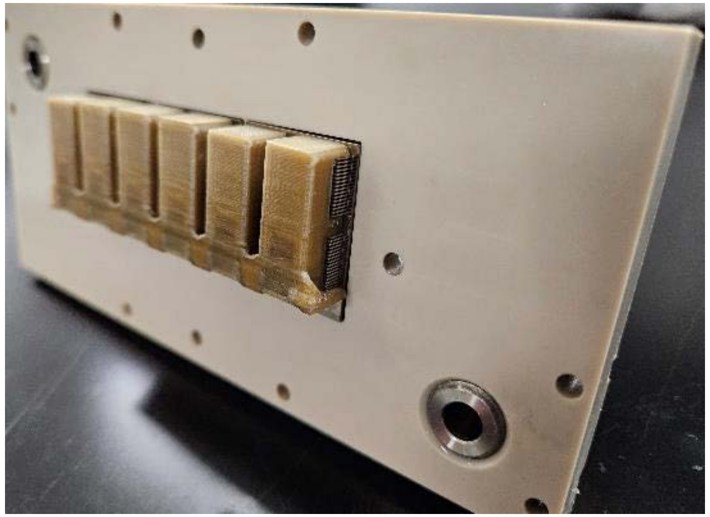
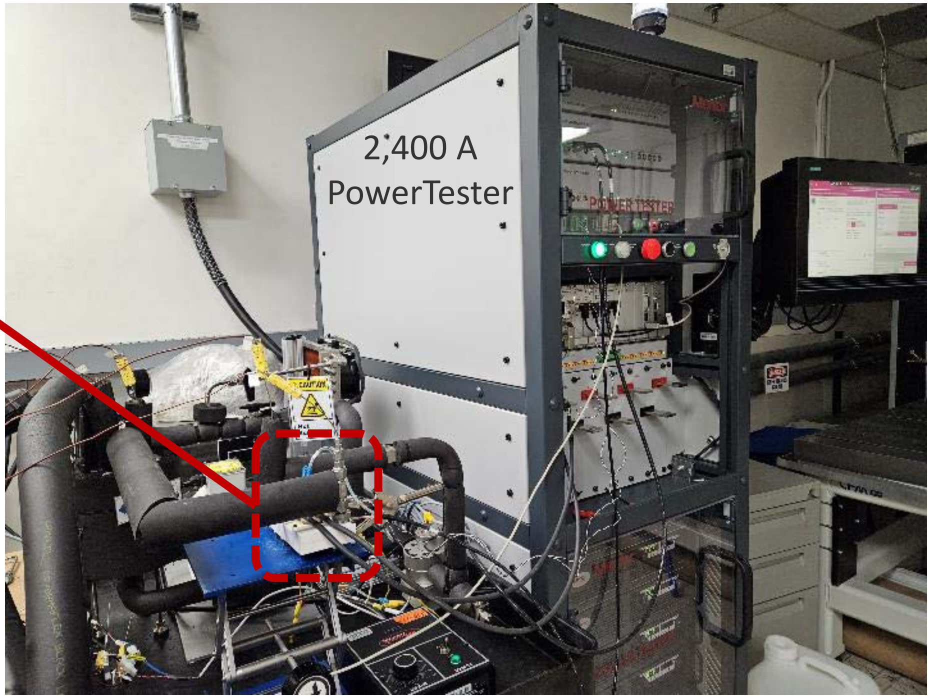


Image credit: Gilbert Moreno (NREL)

Dielectric fluid loop and PowerTester

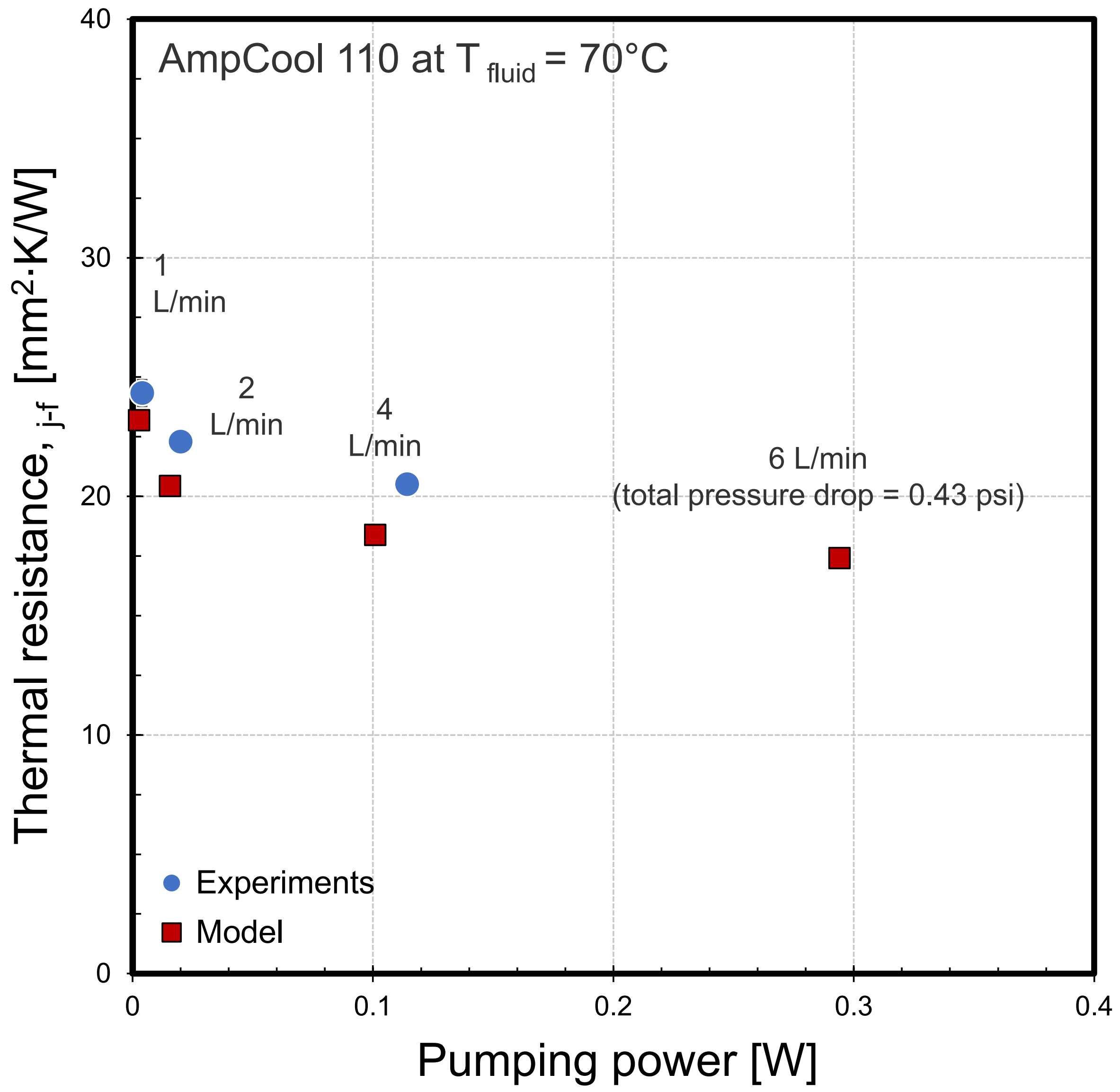


Dielectric fluid loop circulating AmpCool 110

Process:

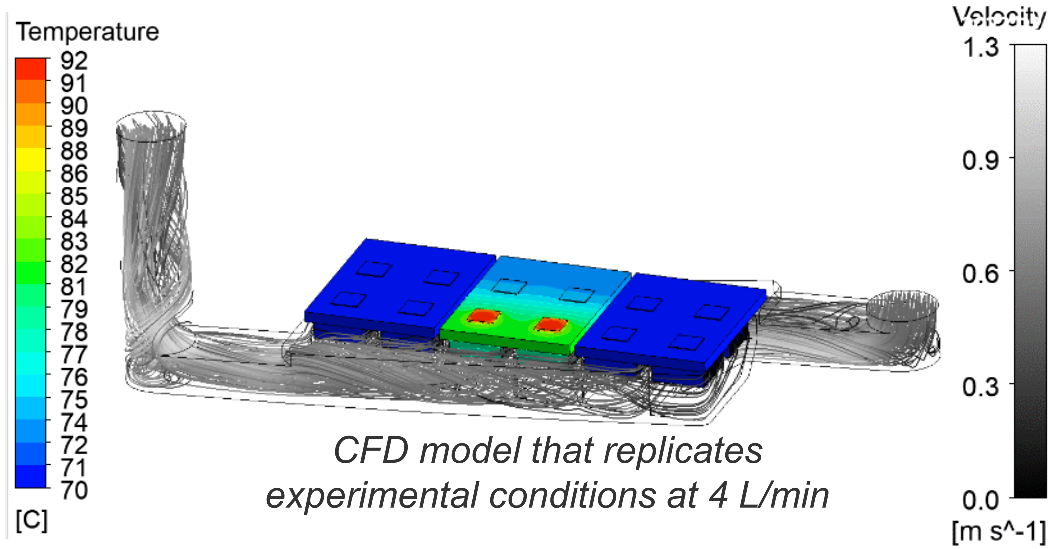
1. Calibrate to obtain temperature versus body-diode voltage drop correlation using small sense current
2. Apply power pulse to devices to steady-state conditions
3. Turn off the power pulse and measure device temperatures via voltage measurements
4. Repeat process for various test conditions (e.g., flow rates).

Technical Accomplishments: Dielectric Fluid Cooling Demonstration Using a SiC Module



Experimental results and comparisons to model predictions

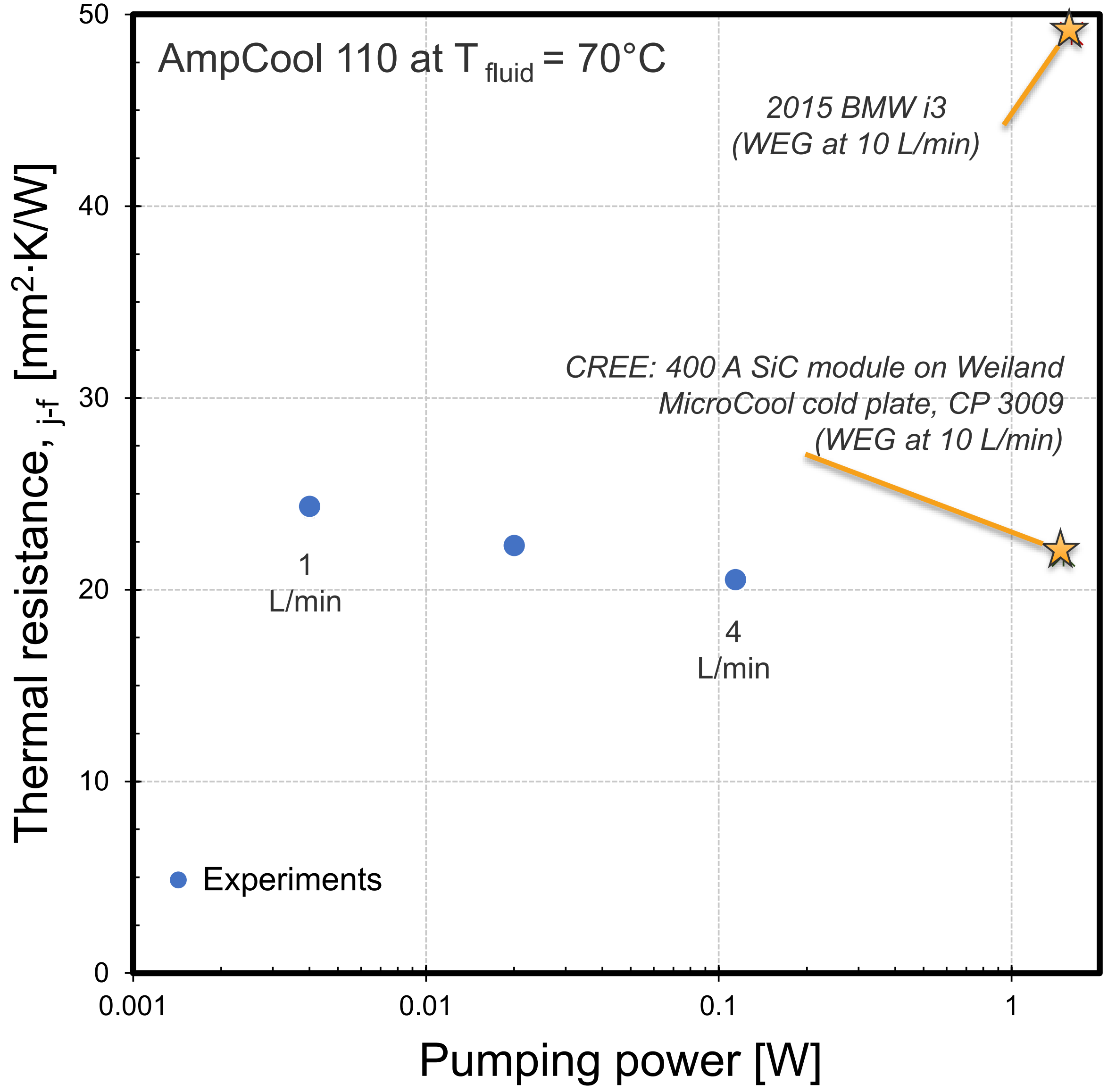
- Applied 116-W/cm^2 heat flux for both devices using 75 amps
- Model predictions in agreement with experimental results
  - Maximum deviation is ~10% for the thermal resistance.



CFD model that replicates experimental conditions at 4 L/min

CFD: computational fluid dynamics, j–f: junction-to-fluid

Technical Accomplishments: Dielectric Fluid Cooling Demonstration Using a SiC Module



Performance comparisons to WEG-based cooling systems

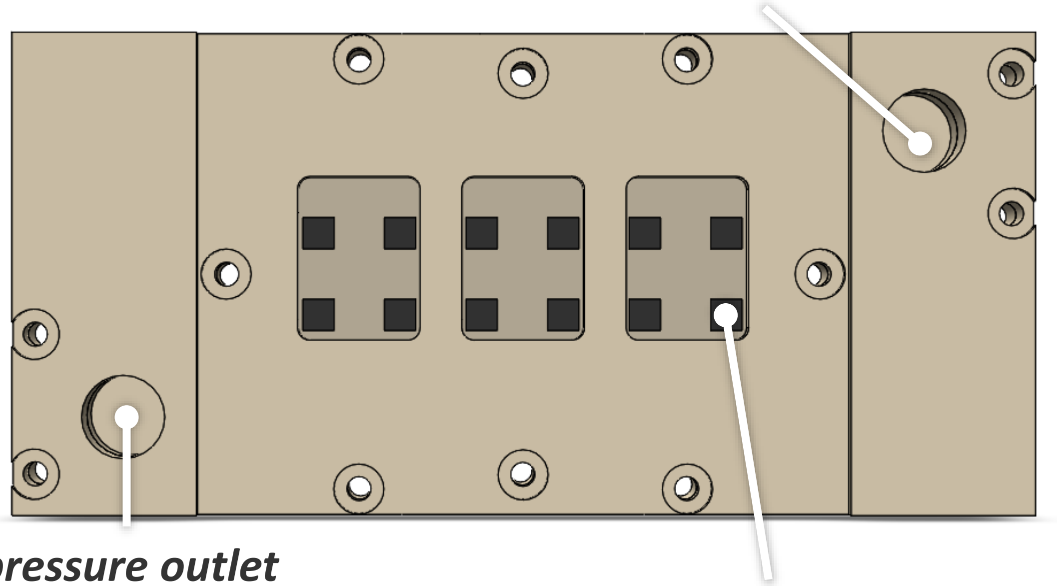
- 58% lower thermal resistance and 90% lower pumping power compared to 2015 BMW i3
- 6% lower thermal resistance and 90% lower pumping power compared to Cree module on advanced performance cold plate.

Technical Accomplishments: New Driveline Fluids Evaluated

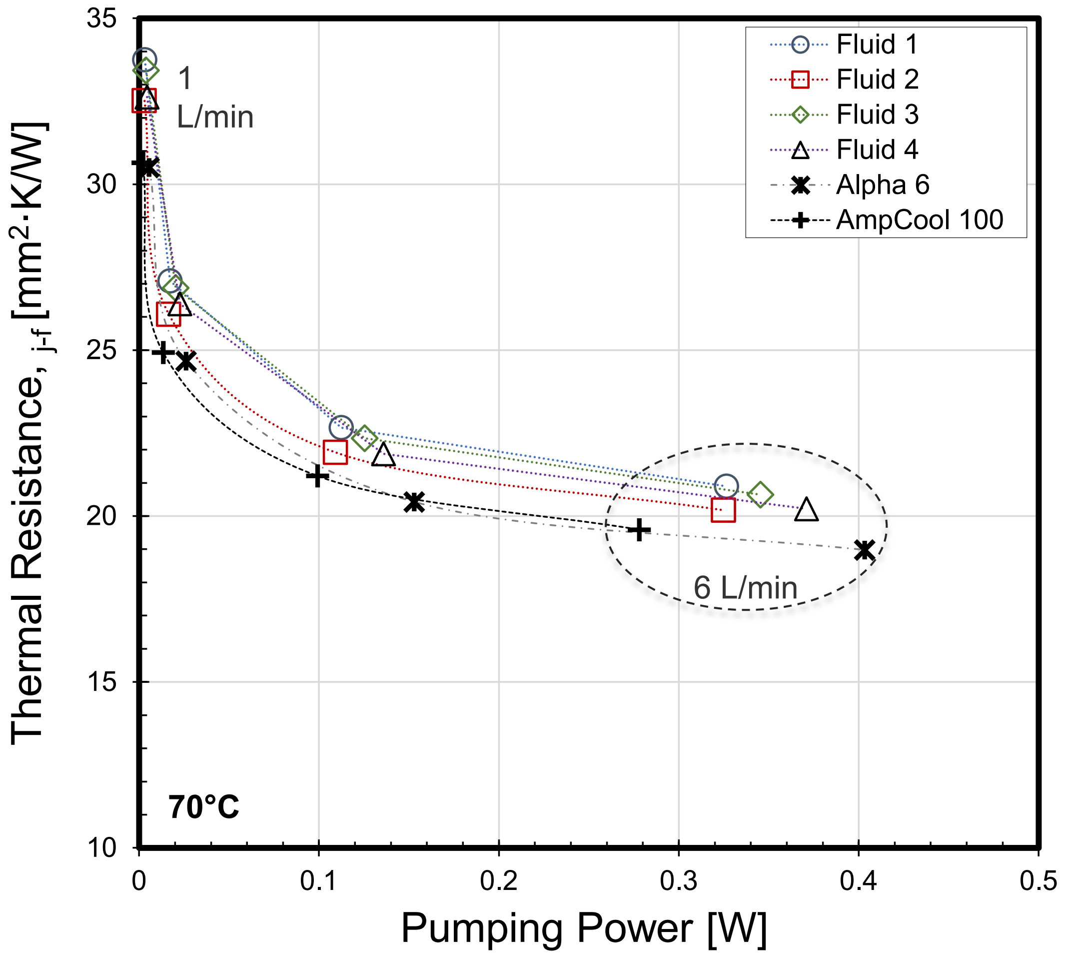
Collaborating with Infineum to evaluate new fluids that are being designed for direct cooling of power electronics in electric-drive vehicles.

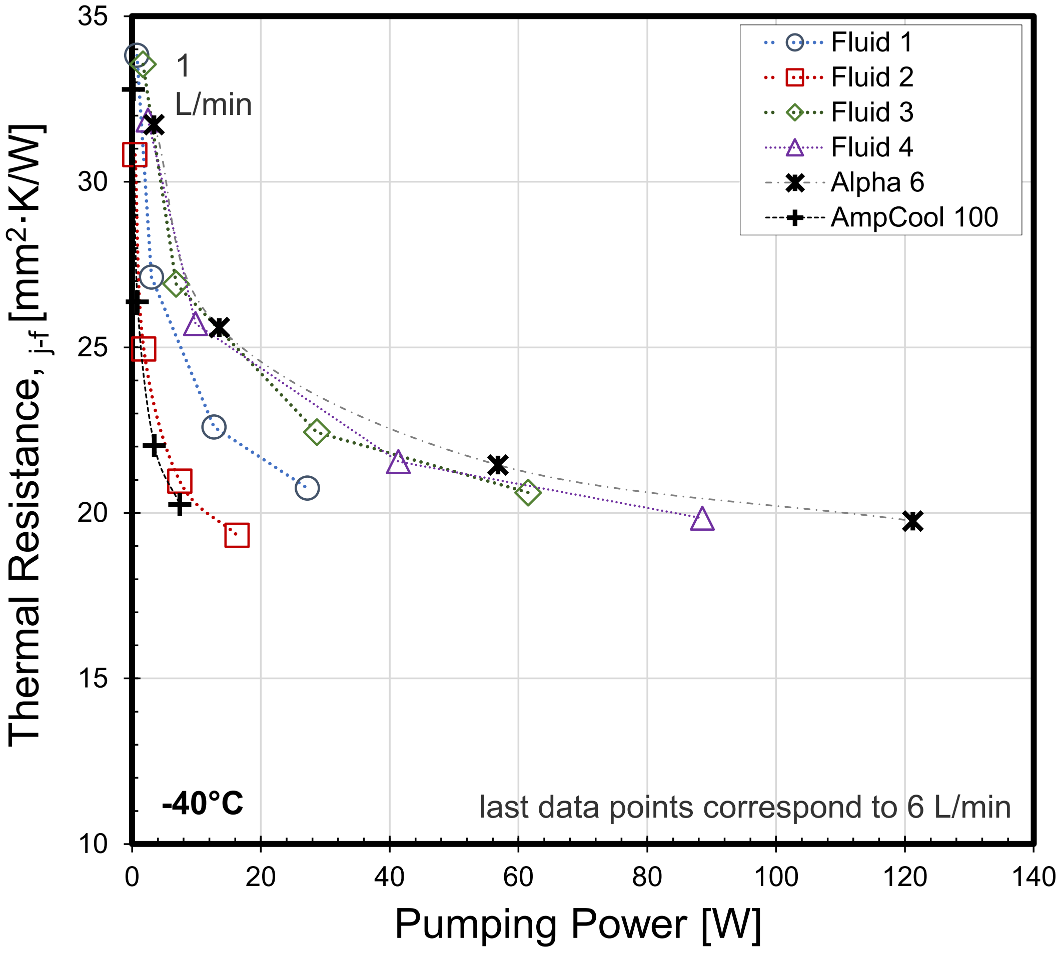
- Evaluated four new developmental fluids via modeling at various fluid temperatures and flow rates
- Compared performance of the four fluids with each other and with other dielectric fluids that we have evaluated
- Provide guidance on which fluid has the best performance to help guide their fluid design
- Estimate the performance of the dielectric fluid concept with these potentially new driveline fluids.

***Model description**: Used dielectric fluid heat exchanger*



Technical Accomplishments: New Driveline Fluids Evaluated-Model Results





T_{fluid} = 70°C

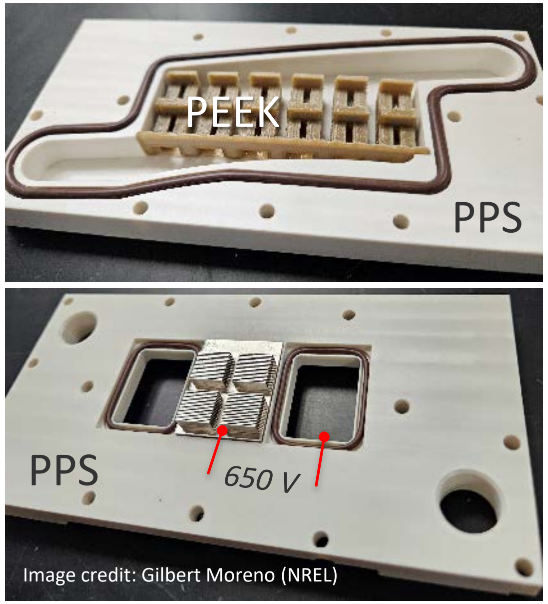
- No significant difference in performance between the four fluids

T_{fluid} = −40°C

- Fluid 2 provides the lowest thermal resistance and pumping power. Its pumping power is ~82% lower compared to Fluid 4.

Technical Accomplishments: Fabricated an Experimental Apparatus To Evaluate Long-Term Reliability of the Dielectric Fluid and Heat Exchanger

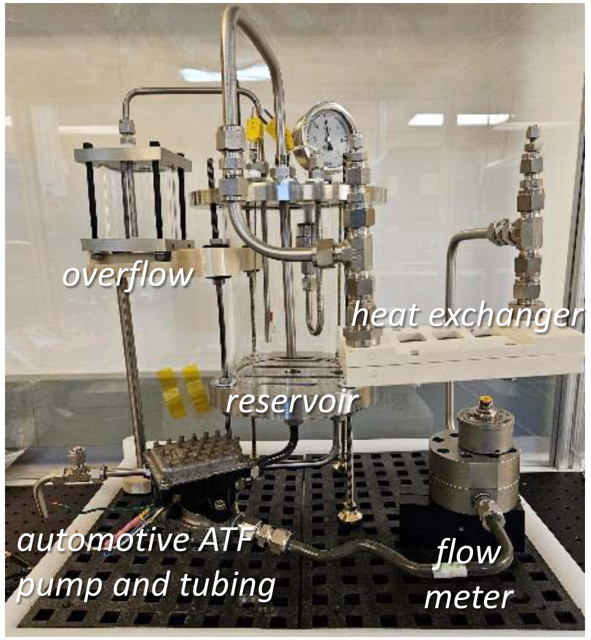
Evaluate material compatibility



Using automotive, high-temperature plastics to evaluate compatibility with dielectric fluids

Evaluate changes to fluid properties

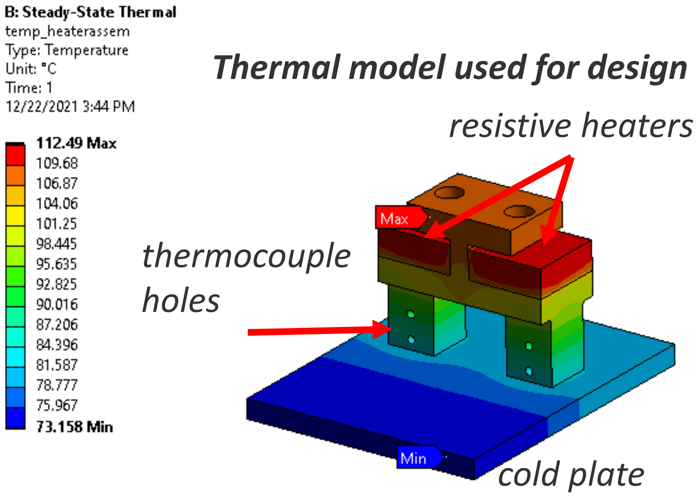
- Thermal properties: thermal conductivity, specific heat, viscosity
- Electrical properties: dielectric breakdown, dielectric constant.



Expose the fluid to:

- Elevated temperatures: 70°C bulk fluid temperature, 90°C contact
- Electric potential: 650 VDC
- One-year duration

Evaluate heat exchanger thermal performance



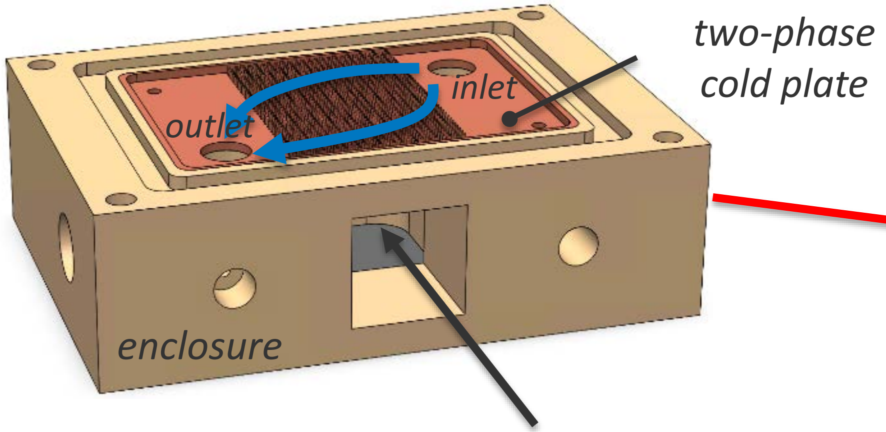
Measuring heat exchanger thermal resistance and pressure drop

ATF: automatic transmission fluid, PEEK: polyetheretherkytone, PPS: polyphenylene sulfide

Technical Accomplishments: Collaborating With Georgia Tech To Evaluate Two-Phase Cooling Strategies

Georgia Tech (Dr. Yogendra Joshi) is developing two-phase-based power electronics cooling systems

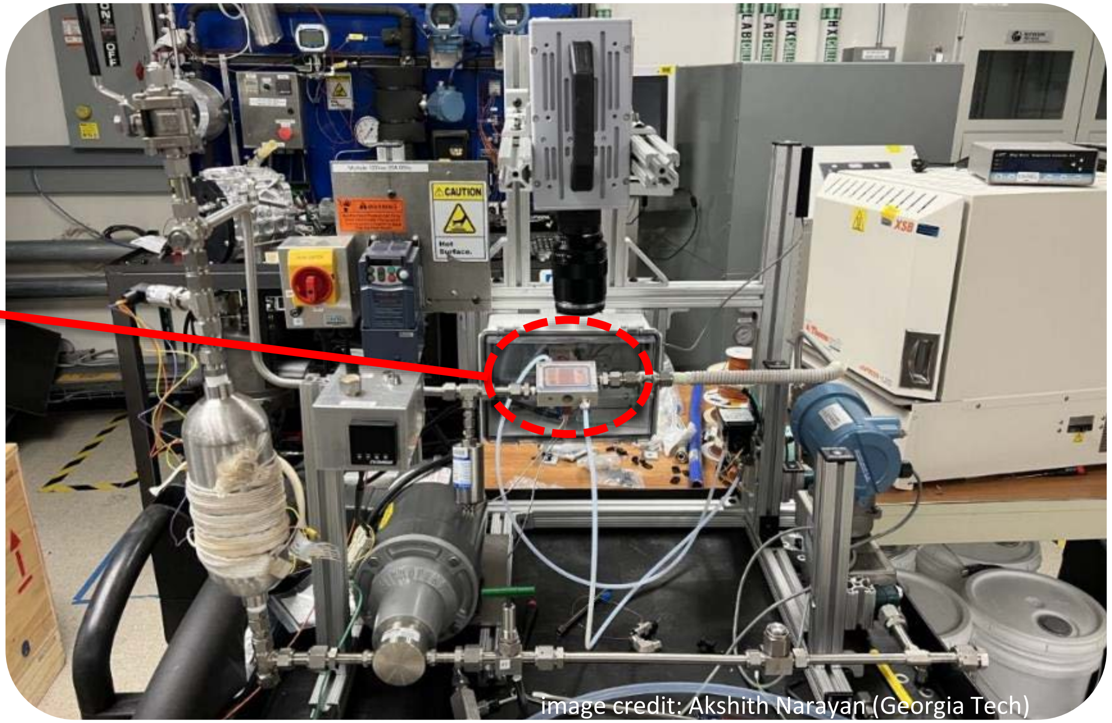
- Two-phase heat transfer coefficient can be >100,000 $W/m^2 \cdot K$



1. Cartridge heaters
2. Suny Polytechnic Institute SiC MOSFET devices

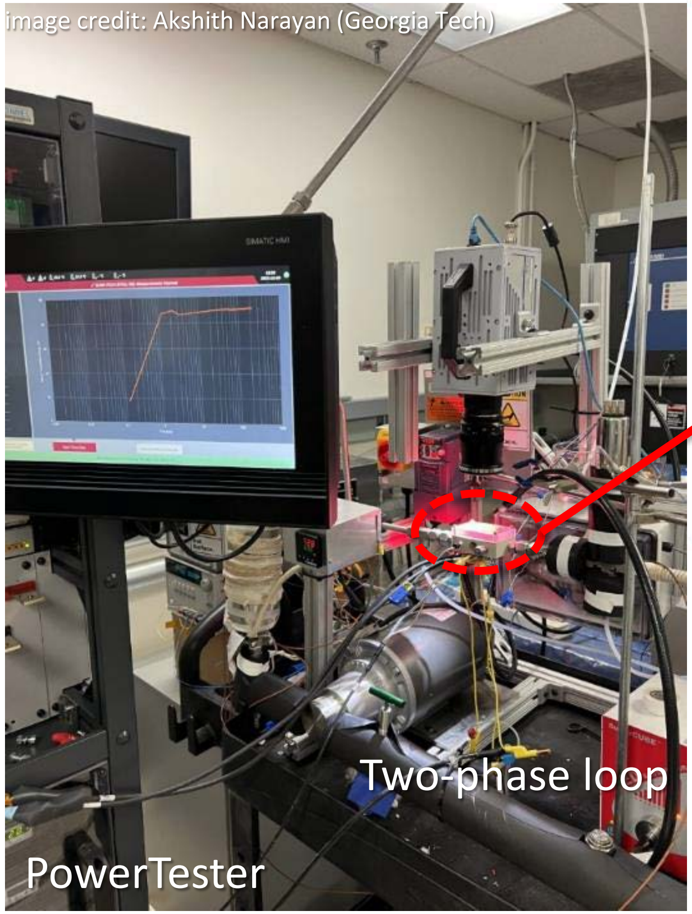
NREL helped design and fabricate the experimental apparatus used for the experimental demonstration

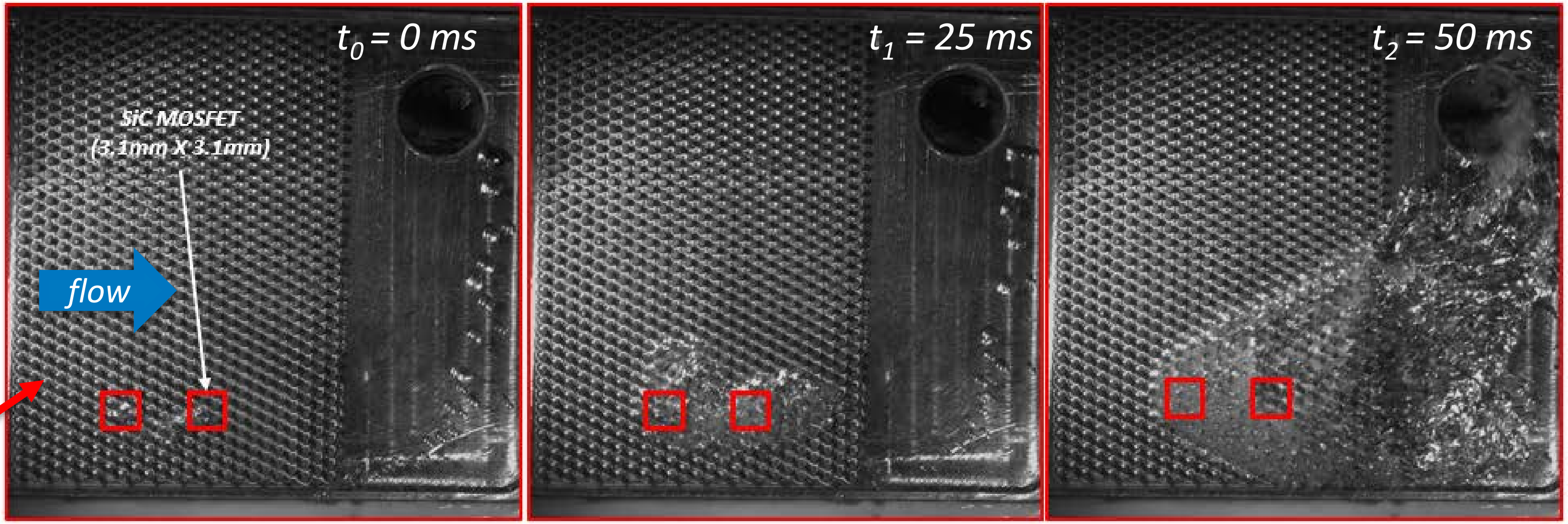
- Georgia Tech graduate intern at NREL conducted experiments.



two-phase fluid loop with HFE-7200

Technical Accomplishments: Collaborating With Georgia Tech To Evaluate Two-Phase Cooling Strategies





Visualization of incipience boiling of HFE7200 over pin-fins at 635-W/cm² device heat flux

- Completed experiments with both resistive heaters and SiC devices
- Achieved:
  - Heat fluxes as high as 934 W/cm²
  - Thermal resistance values as low as 12.8 mm²·K/W
  - Pumping power of 0.08 W (1 L/min at 0.7 psi)

- **See Georgia Tech EDT251** for more information regarding this work.

Responses to Previous Year Reviewers' Comments

- This project was not reviewed last year.

Collaboration and Coordination

- Collaborating with **Georgia Tech (*Yogendra Joshi*)** to evaluate two-phase-based, dielectric fluid cooling of power electronics.
- Collaborating with **Infineum (*Ryan Rieth, Sonia Oberoi, and Scott Campbell*)** to evaluate new driveline fluids being developed for electric vehicle direct cooling applications.
- Collaborating with **SUNY Poly (*Woongje Sung*)** to use their SiC devices in our demonstration modules.
- Collaborating with **ORNL** to understand the effects of dielectric fluids cooling strategy on device electrical performance.
- **Dielectric fluid manufacturers** provided guidance on dielectric fluid selection, fluid properties, and application.

Remaining Challenges and Barriers

- Effect of dielectric fluid cooling strategy on device electrical performance.
- Mechanical aspects of the design.
- Determining the allowable maximum fluid operating temperature—how far below the flash point should we operate?
- Industry adoption of new (nonconventional) technology.

Proposed Future Research

- We will perform electrical simulations to evaluate the effect of the dielectric fluid on electrical performance.
- Perform power cycling on the ceramic-free module to evaluate for reliability.
- Complete the dielectric fluid reliability evaluation.
- Collaborate with Georgia Tech to develop the advanced cooling technologies.

Any proposed future work is subject to change based on funding levels

Summary

Relevance

- Effective thermal management is essential to achieve the 2025 DOE power density (100 kW/L), reliability (300,000 miles), and cost ($2.7/kW) targets.

Approach/Strategy

- Evaluate, develop, and demonstrate high-performance thermal strategies that use dielectric fluids as coolants.

Technical Accomplishments

- Demonstrated that dielectric fluid concepts (single-phase heat transfer) can outperform WEG-based cooling systems using a custom fabricated SiC module and new fluids designed specifically for electric vehicle cooling applications.
- Evaluated new driveline fluids that are being developed for direct cooling of power electronics applications. Identified a promising fluid concept that provides superior performance.
- Collaborated with Georgia Tech and demonstrated high heat flux (934 W/cm^2) and low thermal resistance (12.8 mm^2·K/W) using a two-phase dielectric fluid cooling approach using SUNY Poly-provided SiC devices.

Collaborations

- Georgia Tech, Infineum, SUNY Poly, ORNL, dielectric coolant manufacturers.

Acknowledgments

Susan Rogers, DOE

NREL EDT Task Leader

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Thank You

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NREL/PR-5400-85894

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Technical Backup Slides

Dielectric Fluid Properties

Fluid *(properties at 70°C)*	Thermal conductivity [W/(m·K)]	Specific heat [J/(kg·K)]	Density [kg/m^3]	Viscosity [Pa·s]	Flash point [°C]	Pour point [°C]	Dielectric strength [kV]	Dielectric constant
Alpha 6 [1]	0.14	2,308	792	0.0091	246	−57	58	-
AmpCool 100 [1]	0.13	2,326	761	0.0025	180	−55	60	-
ATF [2]	0.16	2,131	836	0.012	199	−45	-	-
AmpCool 110 [3]	0.13	2,325	783	0.0034	193	−57	60	2.08

[1] Communications with vendor (DSI Ventures or Engineered Fluids)
[2] Kemp, Steven P. and James L. Linden. 1990. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid." SAE Technical paper.
[3] webpage: https://www.engineeredfluids.com/products/ampcool/. Some values were interpolated

Reviewer-Only Slides

Publications and Presentations

Publications and Presentations:

- Feng, X., Moreno, G., Narumanchi, S., and Paret, P., 2022, “Multiphysics Co-Optimization Design and Analysis of a Double-Side-Cooled Silicon Carbide-Based Power Module,” InterPACK2022, ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems.
- Moreno, G., Narumanchi, S., Tomerlin, J., and Major, J., 2022, “Single-Phase Dielectric Fluid Thermal Management for Power-Dense Automotive Power Electronics,” *IEEE Transactions on Power Electronics* 37 (10): 12474–12485.
- Moreno, G., Narumanchi, S., Feng, X., Anschel, P., Myers, S., and Keller, P., 2022, “Electric-Drive Vehicle Power Electronics Thermal Management: Current Status, Challenges, and Future Directions,” ASME *Journal of Electronic Packaging* 144 (1).
- Moreno, G., 2022, “Power Electronics Thermal Management,” In 2022 DOE VTO Annual Report.

Patents and Patent Applications:

- Roan, T. J., Singh, B. N., Moreno, G., and Bennion, K. S., 2023, “Evaporator Stacks and Electronic Assemblies.” Patent number U.S. 11,594468 B2, issued Feb. 28, 2023.
- Cousineau, E., Moreno, G., Bennion, K. S., Roan, T. J., and Singh, B. N., 2022, “Condensers and Electronic Assemblies.” Patent number U.S. 11,388,840 B2, issued July 12, 2022.
- Moreno, G., Narumanchi, S. V. J., Bennion, K. S., Kotecha, R. M., Paret, P. P., and Xuhui, F., 2020, “Jet Impingement Manifolds for Cooling Power Electronics Modules.” Non-Provisional Patent Application 17/084,236, filed Oct. 29, 2020.

Critical Assumptions and Issues

System-level implications (e.g., remove the heat from the dielectric fluid) of the dielectric cooling concept have not been considered at this point.

Industry adoption/acceptance of new coolants and cooling technologies are also challenges.