Power Electronics Thermal Management

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National Renewable Energy Laboratory
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DOE Vehicle Technologies Program
2021 Annual Merit Review and Peer Evaluation Meeting

Project ID # ELT211

Overview

Timeline

- Project start date: FY 2019
- Project end date: FY 2023
- Percent complete: 50%

Budget

- Total project funding:
  - DOE share: $1,050,000
- Funding for FY 2020: $350,000
- Funding for FY 2021: $350,000

Barriers

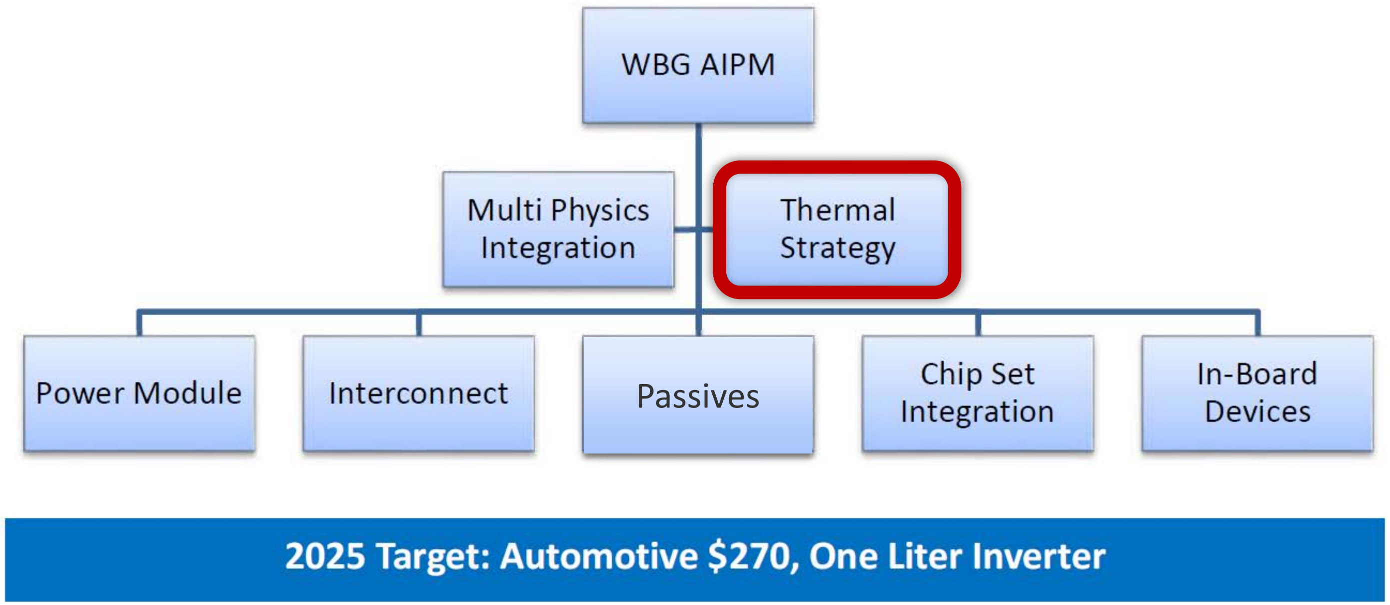
- Size and weight
- Cost
- Performance and lifetime

Partners

- Georgia Tech
- ROHM Semiconductor
- Oak Ridge National Laboratory (ORNL)
- Dielectric fluid manufacturers
- Project lead: National Renewable Energy Laboratory (NREL)

Relevance

- 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.
  - Challenge is to create a thermal solution that allows for packaging high-temperature (250°C) and high-heat-flux wide-bandgap (WBG) devices next to capacitors that typically cannot exceed 100°C.



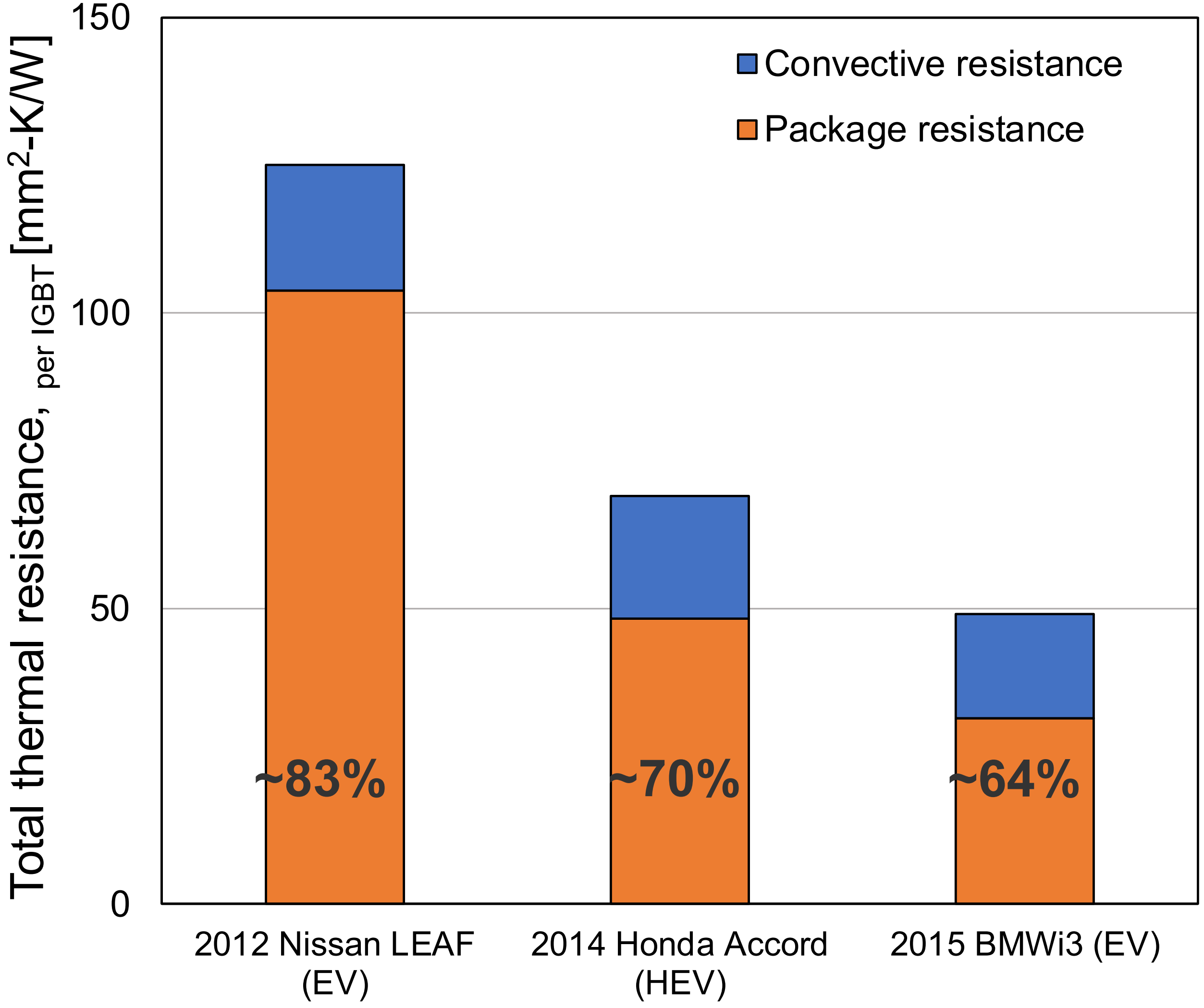
From 2017 Electrical and Electronics Technical Team Roadmap
https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf

AIPM: advanced integrated power module

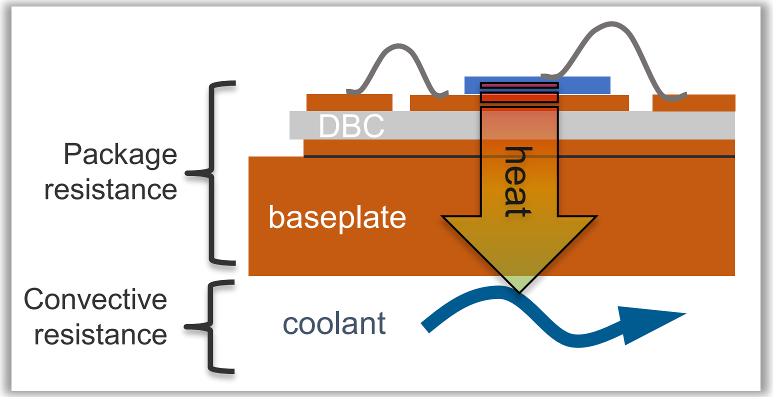
Milestones/Approach

Date	Description of Milestone or Go/No-Go Decision
March 2021 (*complete*)	**Milestone:** Conduct experiments to measure the thermal performance of the dielectric fluid heat exchanger using several candidate dielectric fluids (e.g., AC-100 and ATF). Compare these results with model predictions and FY 2020 Alpha 6 experimental results.
June 2021 (*in progress*)	Complete the thermal and thermomechanical co-optimization of the double-side-cooled, dielectric fluid module concept.
September 2021	Begin long-term dielectric fluid reliability evaluation.

Thermal Design Approach



- Reduce the total thermal resistance by reducing the package thermal resistance. Package resistance ~60%–80% of total resistance in conventional modules.
- Dielectric fluids enable a package **redesign to decrease the package resistance** (the dominant thermal resistance).
- **Potential to use ATF or other new driveline fluids** as the coolants.

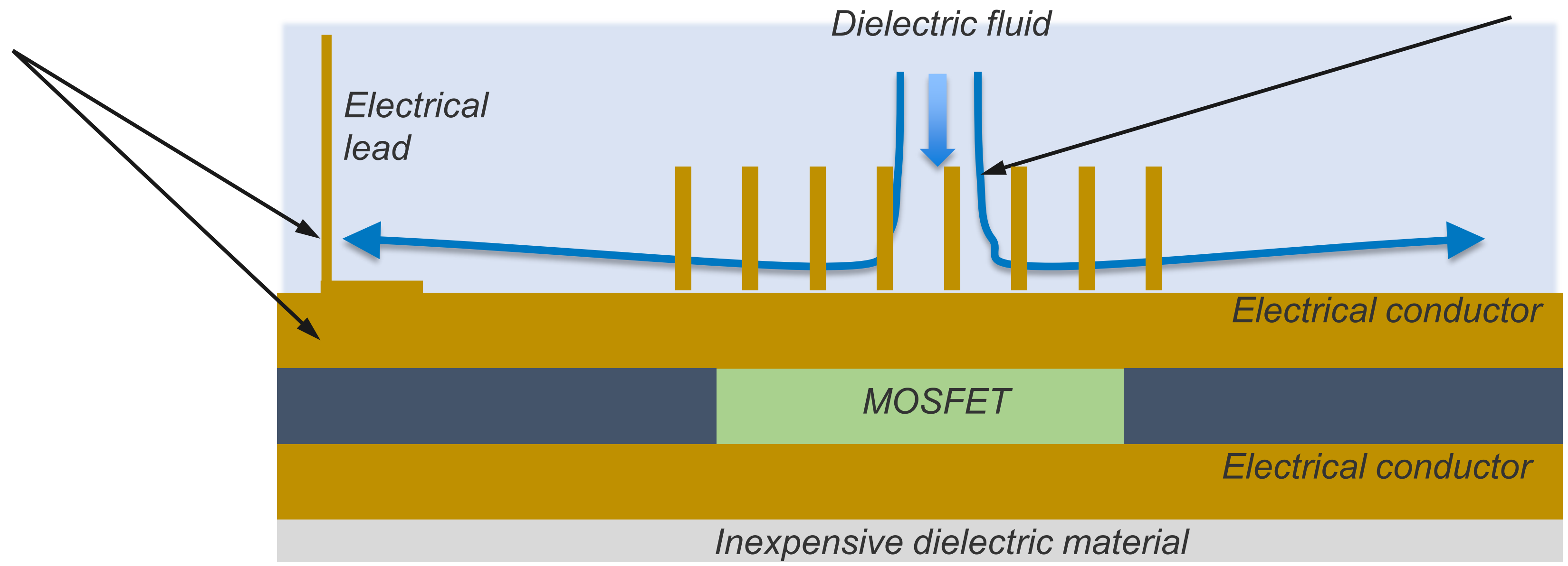


ATF: automatic transmission fluid; DBC: direct-bond copper; EV: electric vehicle; HEV: hybrid electric vehicle

Thermal Design Approach: Dielectric-Fluid Cooling Concept

Allows for cooling of the bus bars/electrical interconnects to lower capacitor and gate driver temperatures

Improved cooling (single-phase heat transfer) via jet impingement and finned surfaces



Eliminates expensive ceramic materials

Improves thermal performance over conventional DBC-based designs

- Reduced package/conduction resistance to 33% of total thermal resistance using a relatively high convection coefficient (17,300 W/[$m^2 \cdot K$])
- Designed single-side and double-side dielectric-fluid cooling concepts.

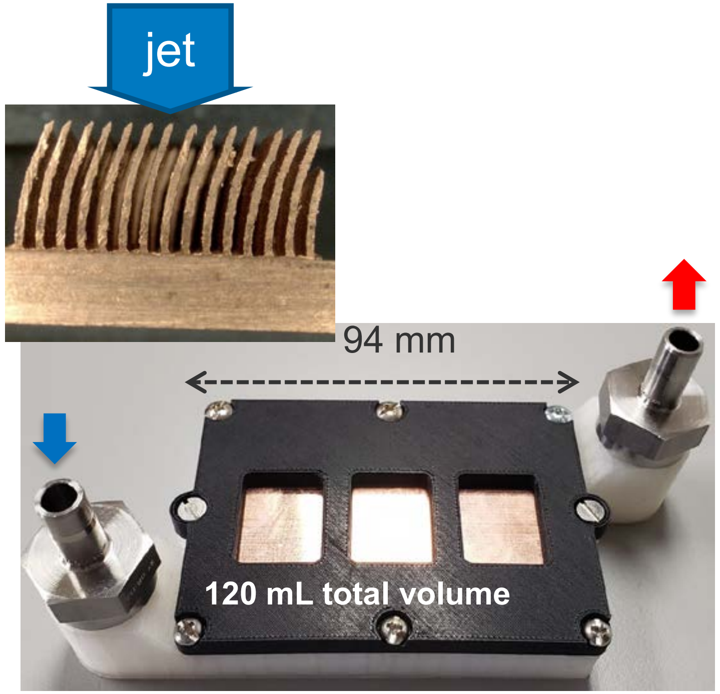
MOSFET*:* metal–oxide–semiconductor field-effect transistor

Conceptual Dielectric Fluid Cooling System (Single-Side Cooled Version)

Technical Accomplishments (presented in 2020 AMR)

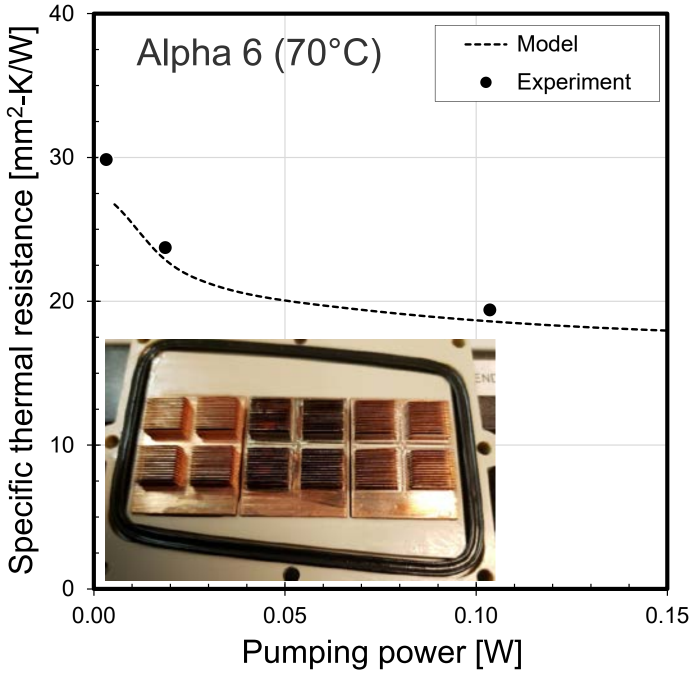
Designed a compact dielectric fluid cooling system to dissipate 2.2 kW of heat and provide a R''_{th} = 20 mm^2·K/W

- Predict 50% lower thermal resistance and 80% lower pumping power compared with 2015 BMWi3



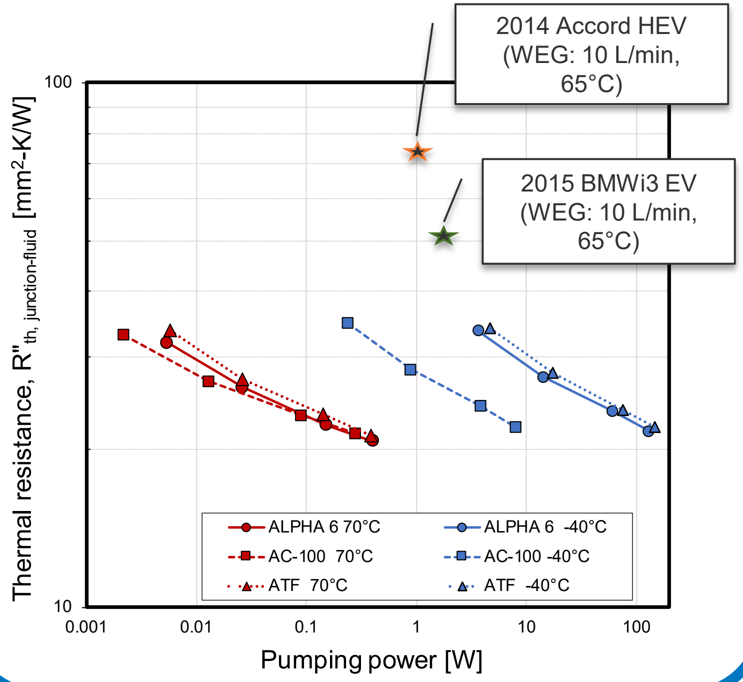
Conducted experiments using Alpha 6 dielectric fluid

- Confirmed the model predictions



Predicted the performance of different dielectric fluids

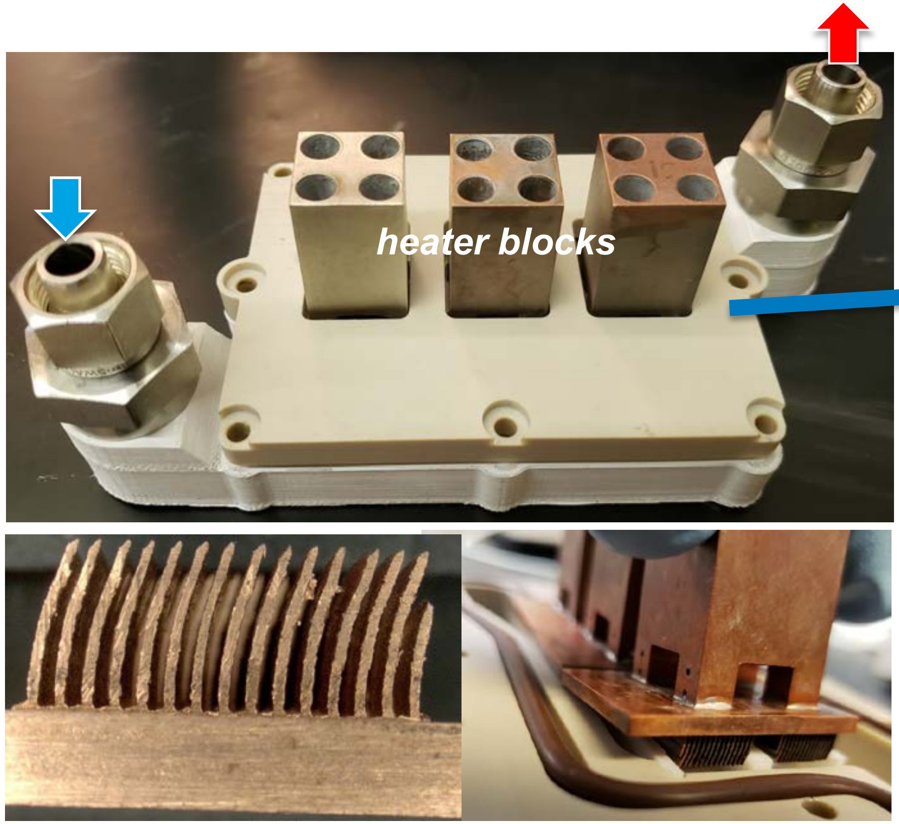
- Identified AC-100 as a good option due to its lower pumping power



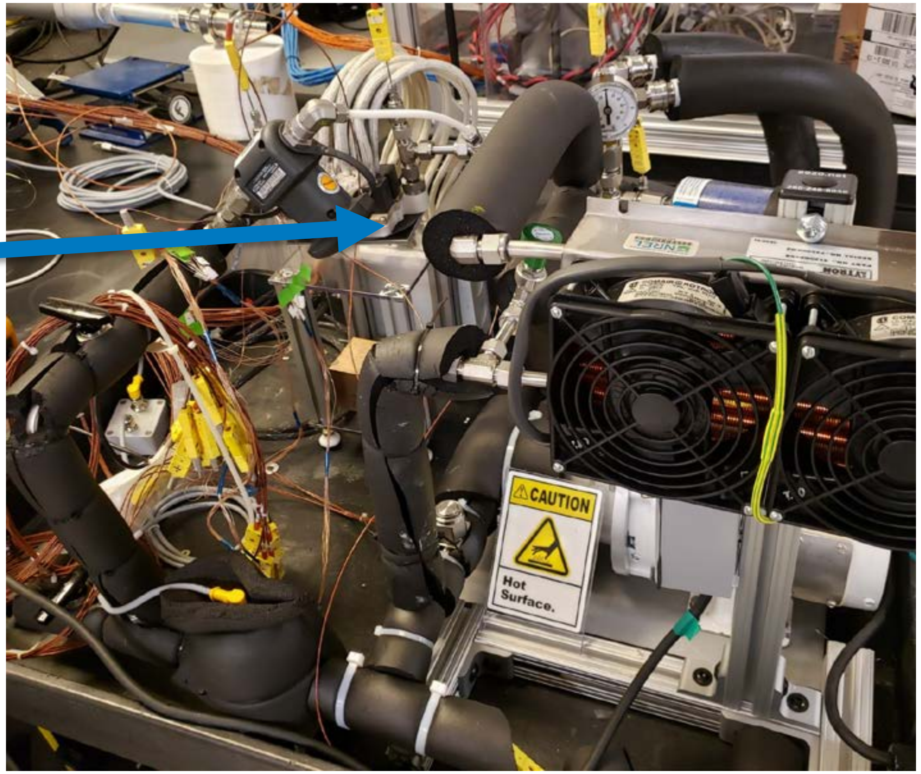
Moreno, G. et al., “Dielectric Fluid Manifold for Double-Sided Cooling,” Non-Provisional Patent Application 17/084,236 filed October 29, 2020.

Image credit: Gilbert Moreno (NREL), all images

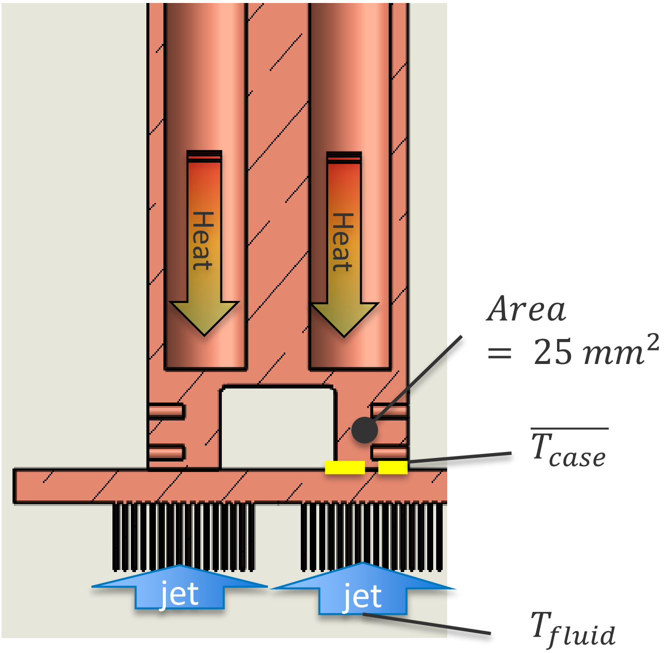
Measured Performance Using Different Fluids/Coolants



3D-printed the heat exchanger



Piped the heat exchanger into the dielectric fluid loop



$$R''_{th,\, case-fluid} = \frac{Area\,(\overline{T_{case}} - T_{fluid})}{Heat_{per\ heater,\, device}}$$

Measured the heat exchanger thermal resistance (R''_{th})

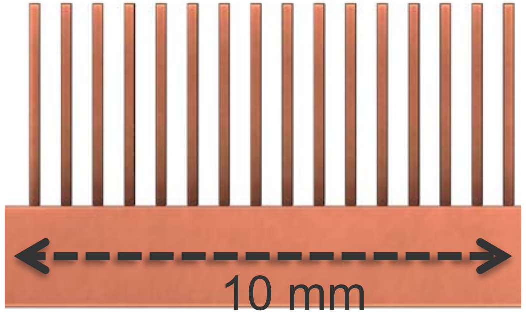
Every test condition repeated at least three times to ensure repeatable results

Image credit: Gilbert Moreno (NREL), all images

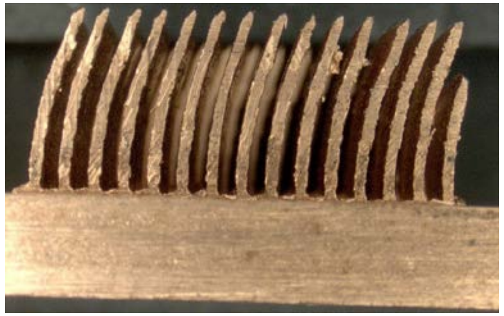
Heat Exchanger Thermal Resistance Using **AC-100**

- Conducted experiments at different fluid temperatures (30°C and 70°C) and flow rates (1–4 L/min)
- Obtained a good match between the experimental results and model predictions. **Confirmed the heat exchanger low thermal resistance.**

Modeled



Tested



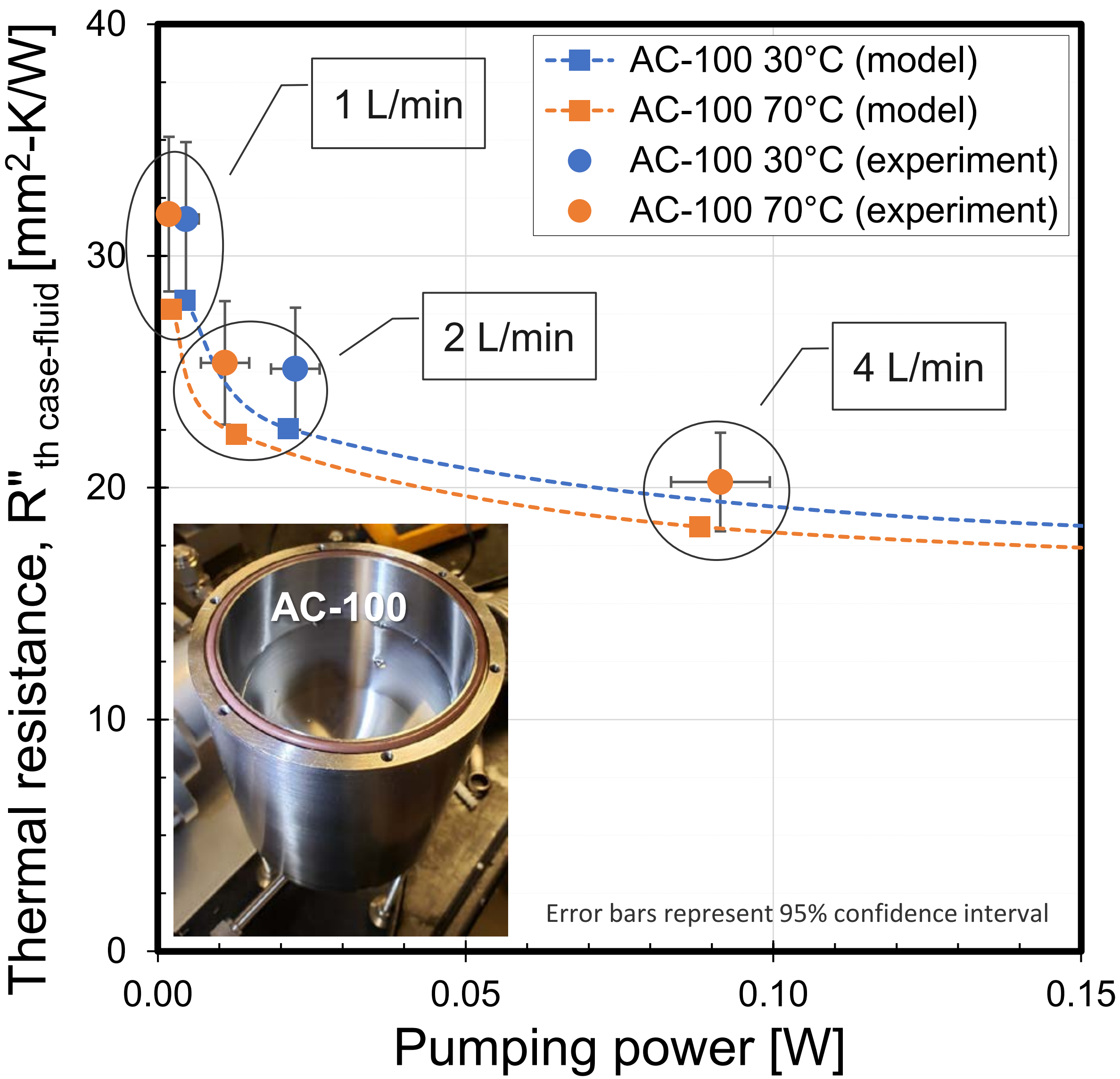


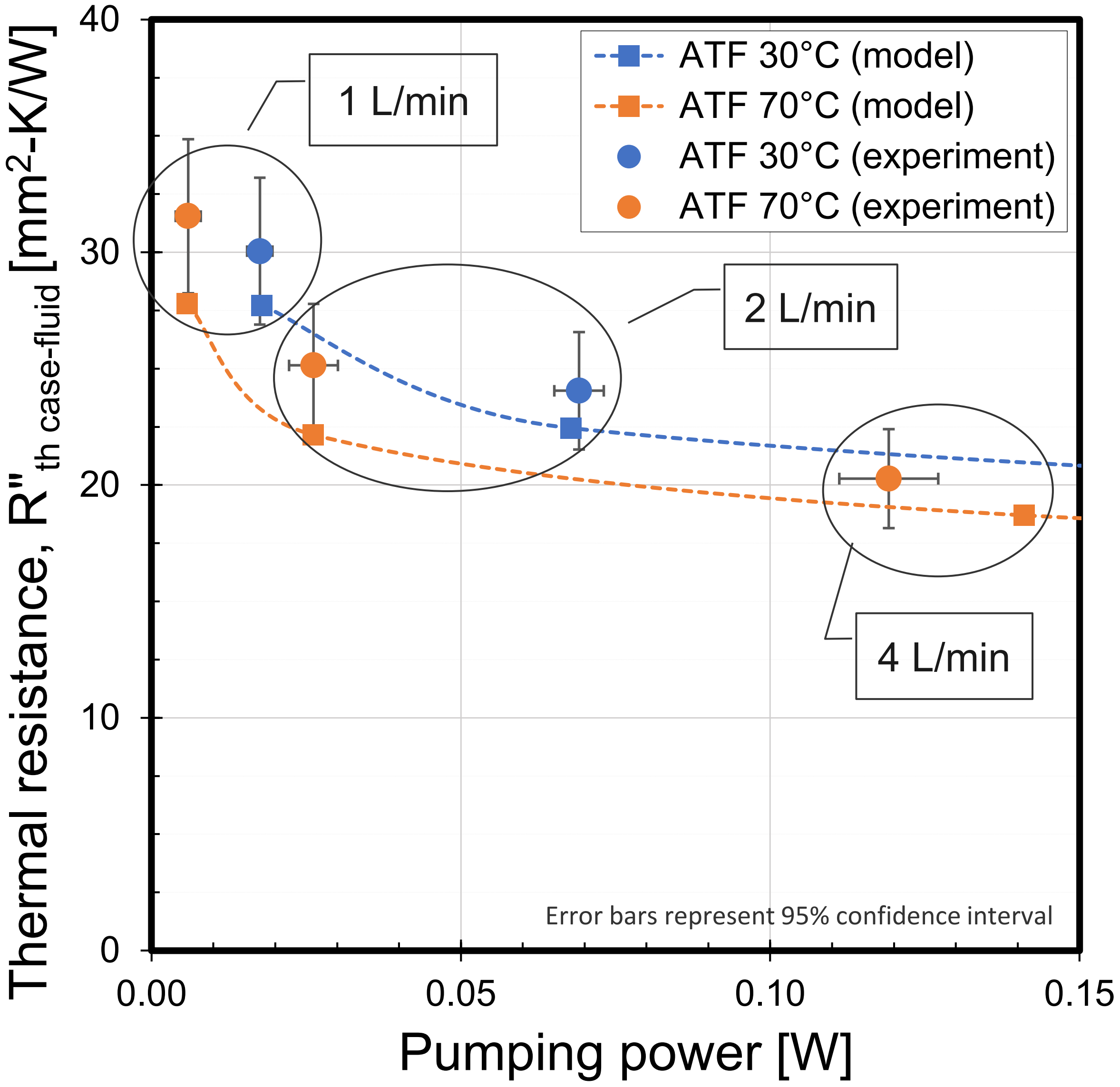
Image credit: Gilbert Moreno (NREL)

Heat Exchanger Thermal Resistance Using **ATF**

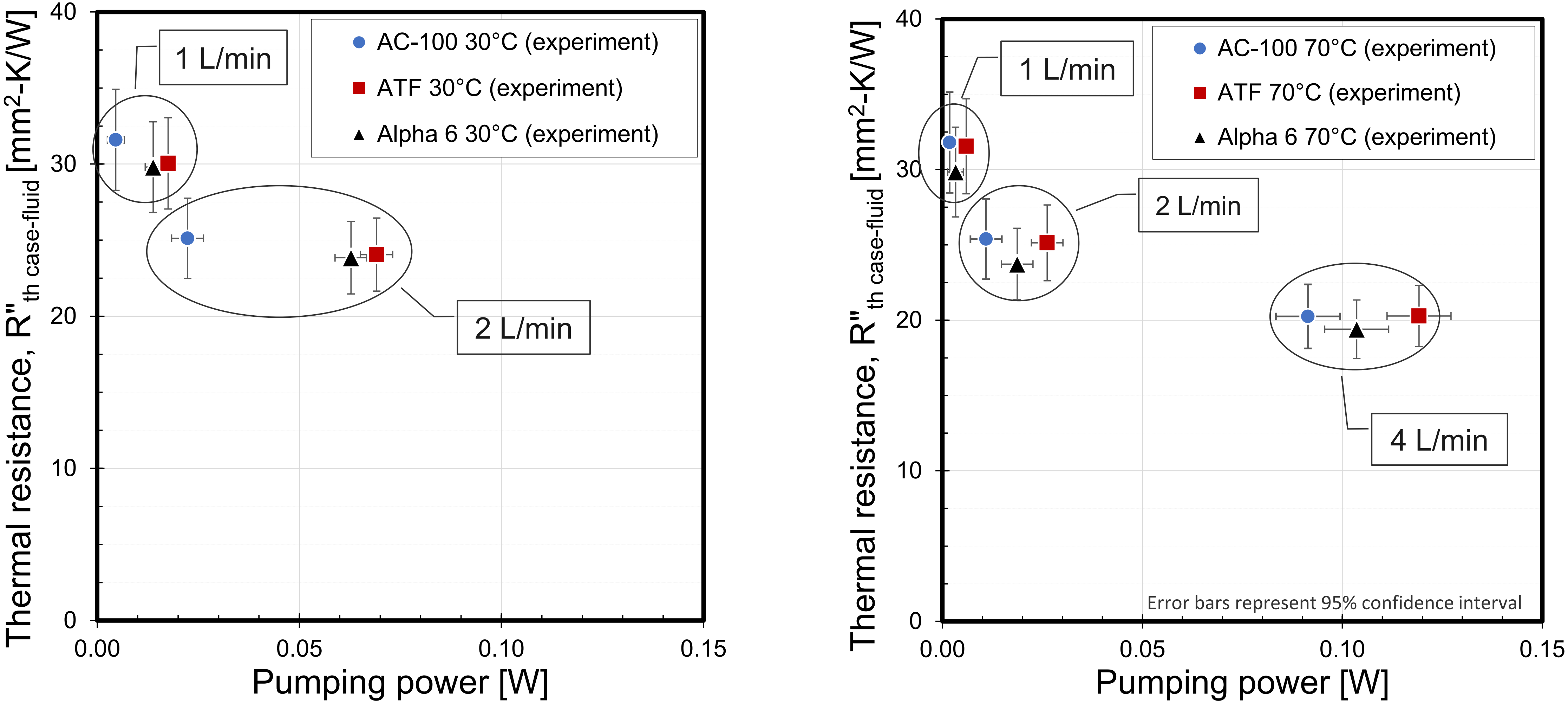
- Used Ford Mercon LV ATF
- Obtained a good match between the experimental results and model predictions. **Confirmed the heat exchanger low thermal resistance.**

Image credit: Gilbert Moreno (NREL)

Ford Mercon LV ATF in loop reservoir



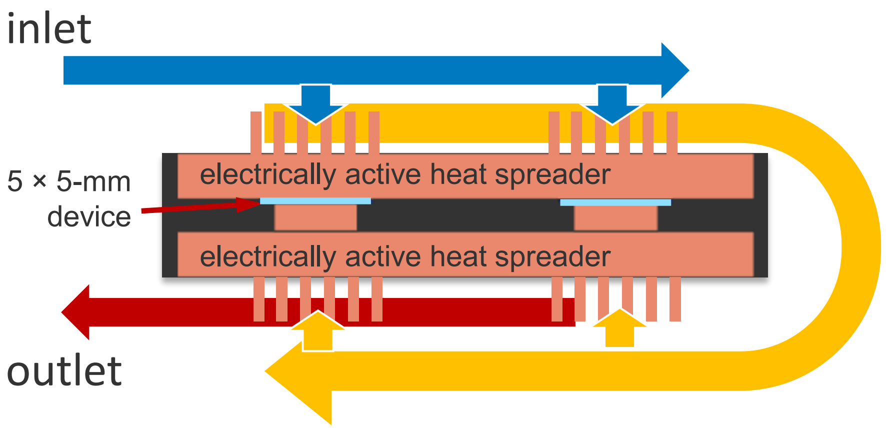
Comparing Performance of Different Fluids

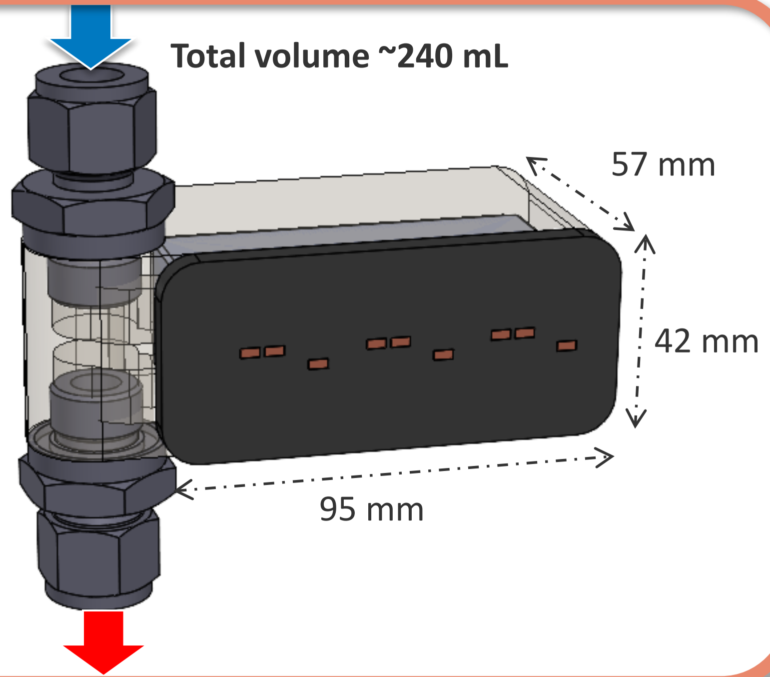


- All fluids provide similar thermal resistance values when compared at the same flow rate
- AC-100 is a good candidate due to its lower pumping power.

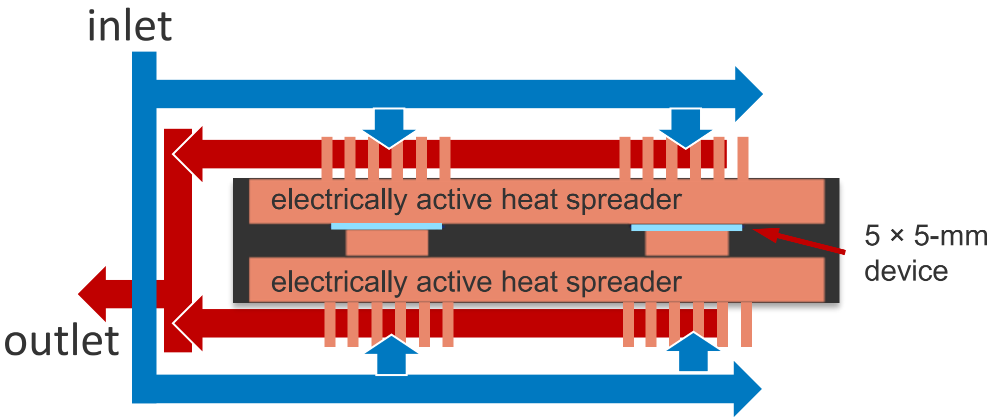
Double-Side Cooled Concepts

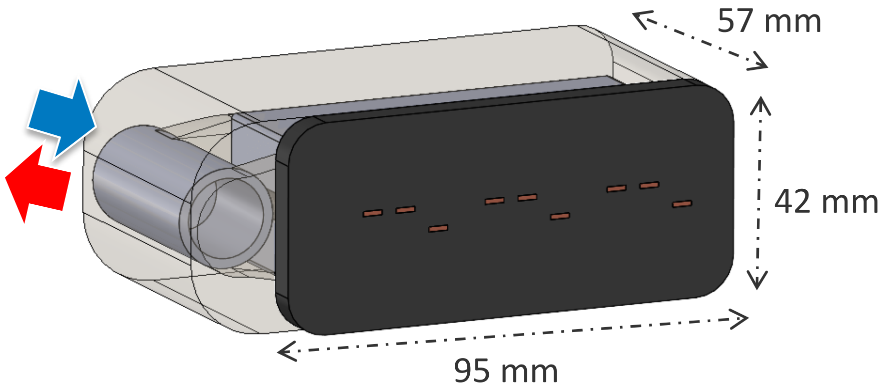
Series flow configuration





Parallel flow configuration

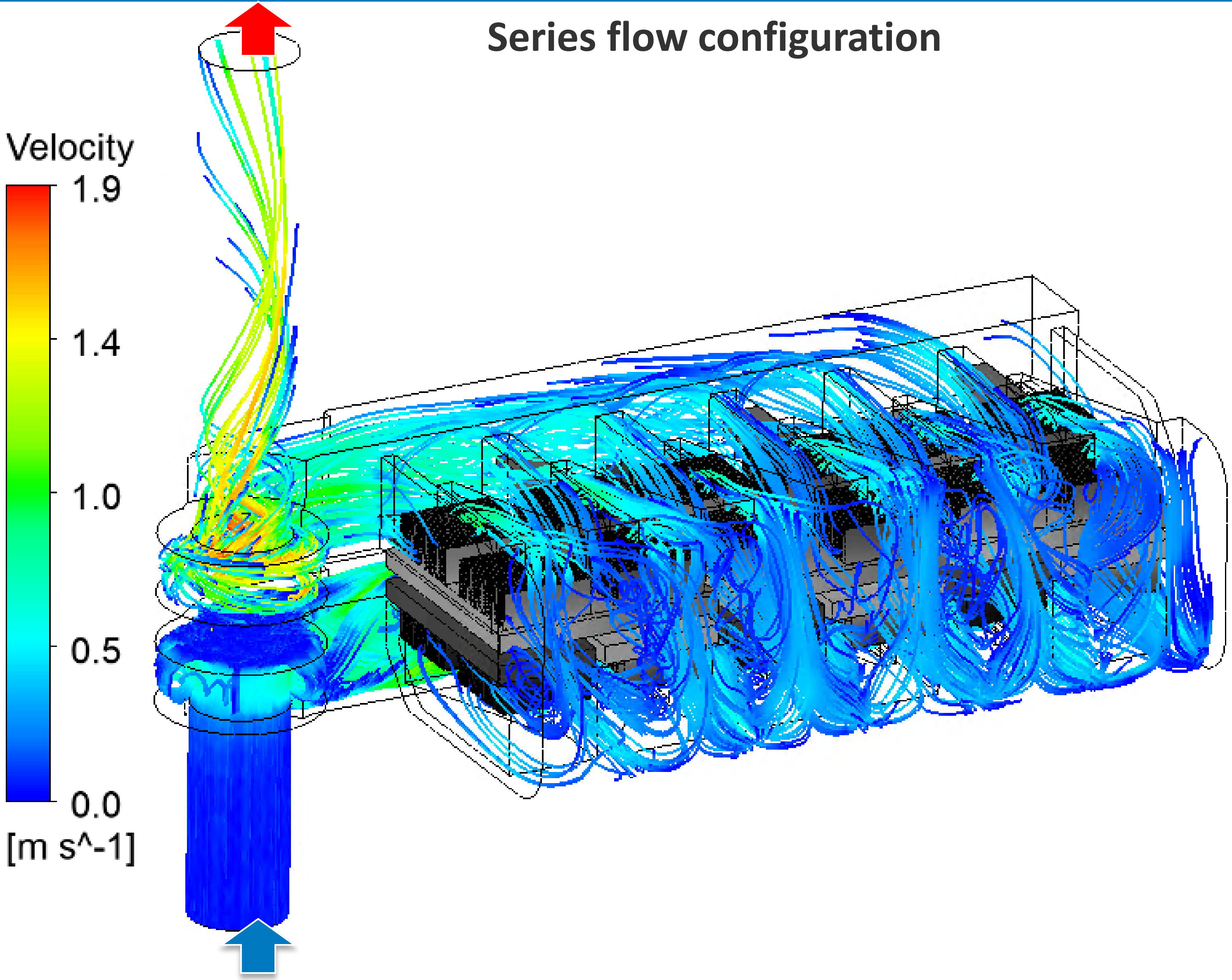




Moreno, G. et al., "Dielectric Fluid Manifold for Double-Sided Cooling," Non-Provisional Patent Application 17/084,236 filed October 29, 2020.

Double-Side Cooled CFD Results: Fluid Distribution

Series flow configuration



AC-100 inlet temperature of 70°C and total flow rate 4 L/min

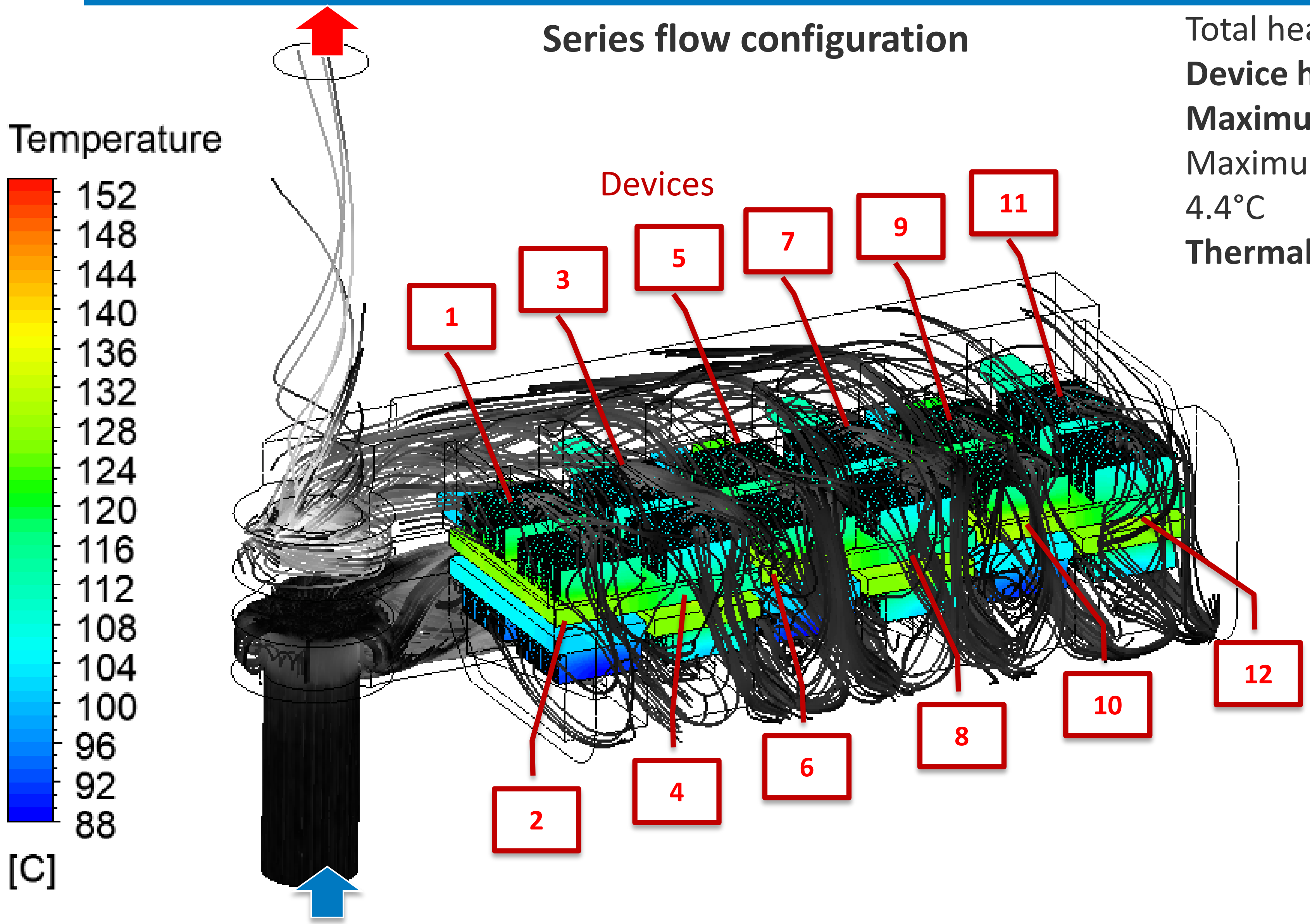
- **Pressure drop: 0.6 psi (4.2 kPa) from inlet to outlet**
- Thermal operating conditions and results on next slide.

CFD*:* computational fluid dynamics

Moreno, G. et al., "Dielectric Fluid Manifold for Double-Sided Cooling," Non-Provisional Patent Application 17/084,236 filed October 29, 2020.

Double-Side Cooled CFD Results: Temperatures

Series flow configuration



Total heat dissipated: **2,150 W** between 12 devices

Device heat flux: 716 W/cm²

Maximum temperature: 154°C

Maximum temperature variation between devices: 4.4°C

Thermal resistance: 12 mm²·K/W

Device	Maximum Temperature [°C]
1	149.2
2	149.1
3	153.5
4	152.6
5	150.7
6	150.0
7	153.4
8	153.0
9	152.3
10	151.7
11	152.1
12	152.5

Moreno, G. et al., "Dielectric Fluid Manifold for Double-Sided Cooling," Non-Provisional Patent Application 17/084,236 filed October 29, 2020.

Summary of Performance

System	Thermal resistance (junction-to-fluid)	Flow rate	Pressure drop	T_j maximum	Device heat flux	Total volume (power modules and cold plate)
	$mm^2 \cdot K/W$	*L/min*	*Psi [kPa]*	*°C*	*W/cm^2*	*mL*
2015 BMW i3, (WEG cooled)	49	10	1.4 [9.6]	175	214*	900
Single-side cooled dielectric fluid	**20**	**4.1**	**0.2 [1.4]**	**175**	**525***	**120**
Double-side cooled dielectric fluid	**12**	**4.1**	**0.6 [4.1]**	**175**	**875***	**240**

* Estimates assuming T_{fluid} = 70°C

Responses to Previous Year Reviewers' Comments

- **Reviewer comment:** "*The approach seems reasonable and well thought out. The reviewer liked that the focus is outside of what one would expect most OEMs and their suppliers to pursue.*"
  - **Response:** We agree, we are focusing on a new cooling technology that is not currently being used in automotive applications to provide information on a new and high-performance cooling concept that may allow the use of new driveline fluids as coolants.
- **Reviewer comment:** "*Given that the concept of jet impingement with dielectric fluid was proven so successful, could the project put more emphasis in the future on the optimization of the hydraulic circuit and conduct durability testing? These are critical aspects for a successful deployment of the technology.*"
  - **Response:** We agree, we are working to improve the fluid flow path to enable lower pressure drop and improved die temperature distribution, and we are also initiating work to evaluate the long-term durability of dielectric fluids.

Collaboration and Coordination

- Collaborating with **Georgia Tech.** Providing an advisory role to graduate students working on developing advanced cooling technologies for power electronics
- Collaborating with **ORNL** to understand the effects of dielectric fluids cooling strategy on device electrical performance
- Collaborating with **ROHM Semiconductor** to build and demonstrate dielectric fluid-cooled modules using SiC devices
- **Dielectric fluid manufacturers** provided guidance on dielectric fluid selection, fluid properties, and application.

Remaining Challenges and Barriers

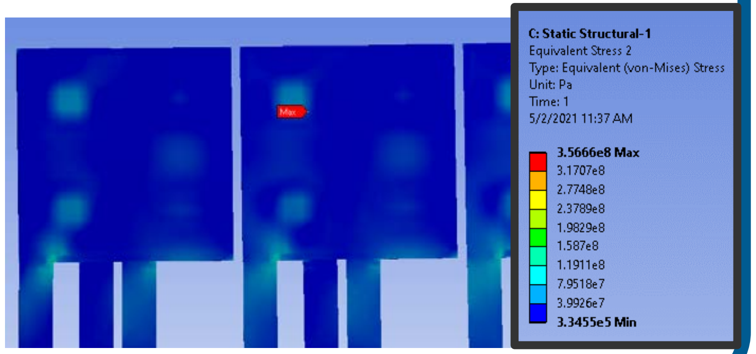
- Questions related to the long-term reliability of the dielectric fluids
  - We have initiated work to evaluate the long-term reliability of the fluids
- Effect of dielectric fluid cooling strategy on device electrical performance
  - We are working with ORNL to conduct electrical modeling and address this issue
- Determining the allowable maximum fluid operating temperature—how far below the flash point should we operate?
- Industry adoption of new (non-conventional) technology.

Proposed Future Research

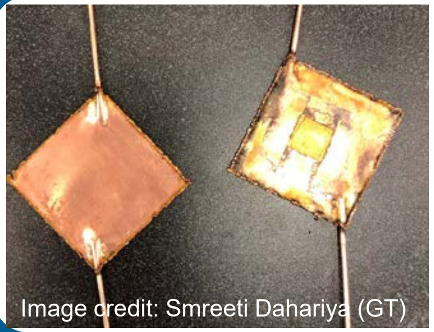
FY 2021

- Co-optimize the thermal and thermomechanical performance of the double-side cooled, dielectric fluid concept
- Initiate experiments to evaluate the long-term reliability of the dielectric fluids
- Collaborate with ORNL to understand the effect of the dielectric fluid cooling strategy on device electrical performance
- Collaborate with Georgia Tech (GT) to develop the advanced cooling technologies.

Thermomechanical results



Automotive pump to be used in the dielectric fluid reliability evaluation



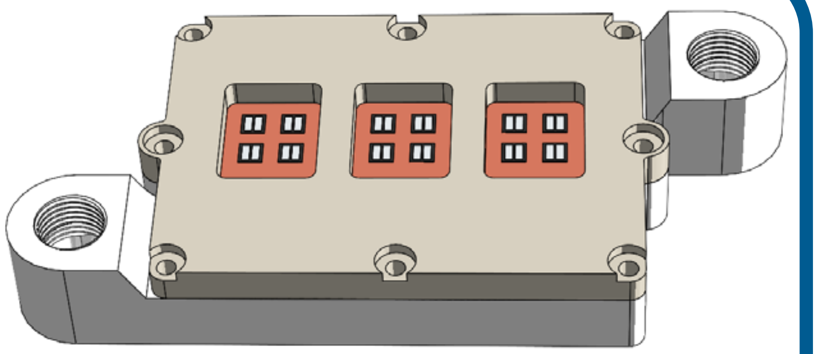
Vapor chamber cooling technology developed by GT (AMR EDT251)

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

Proposed Future Research

FY 2022 and beyond

- Fabricate and demonstrate dielectric fluid-cooled modules using SiC devices
  Develop double-side cooled modules for experimental demonstration
- Evaluate new dielectric fluids
- Collaborate with Georgia Tech to develop the advanced cooling technologies.



SiC devices cooled with dielectric fluids

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

Summary

Relevance

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

Approach/Strategy

- Develop dielectric-fluid cooling strategies to decrease junction-to-fluid thermal resistance and enable high-heat-flux dissipation.

Technical Accomplishments

- Conducted experiments to measure and compare the performance of AC-100 and ATF and confirmed model predictions.
- Completed the design of two double-side cooled, dielectric fluid cooling concepts. CFD predicts cooling system can dissipate heat fluxes >700 W/cm^2 while maintaining maximum junction temperatures at ~154°C using only 4-L/min flow rate and providing a total pressure drop of 0.6 psi (4.2 kPa)
- Provided information on a new, high-thermal-performance power electronics cooling technology that may enable reaching the 100-kW/L power density target and allow for the use of new driveline fluids.

Collaborations

- Georgia Tech University, ORNL, ROHM Semiconductor, dielectric coolant manufacturers.

Acknowledgments

Susan Rogers, U.S. Department of Energy

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Thank You

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NREL Transforming ENERGY

Technical Back-Up Slides

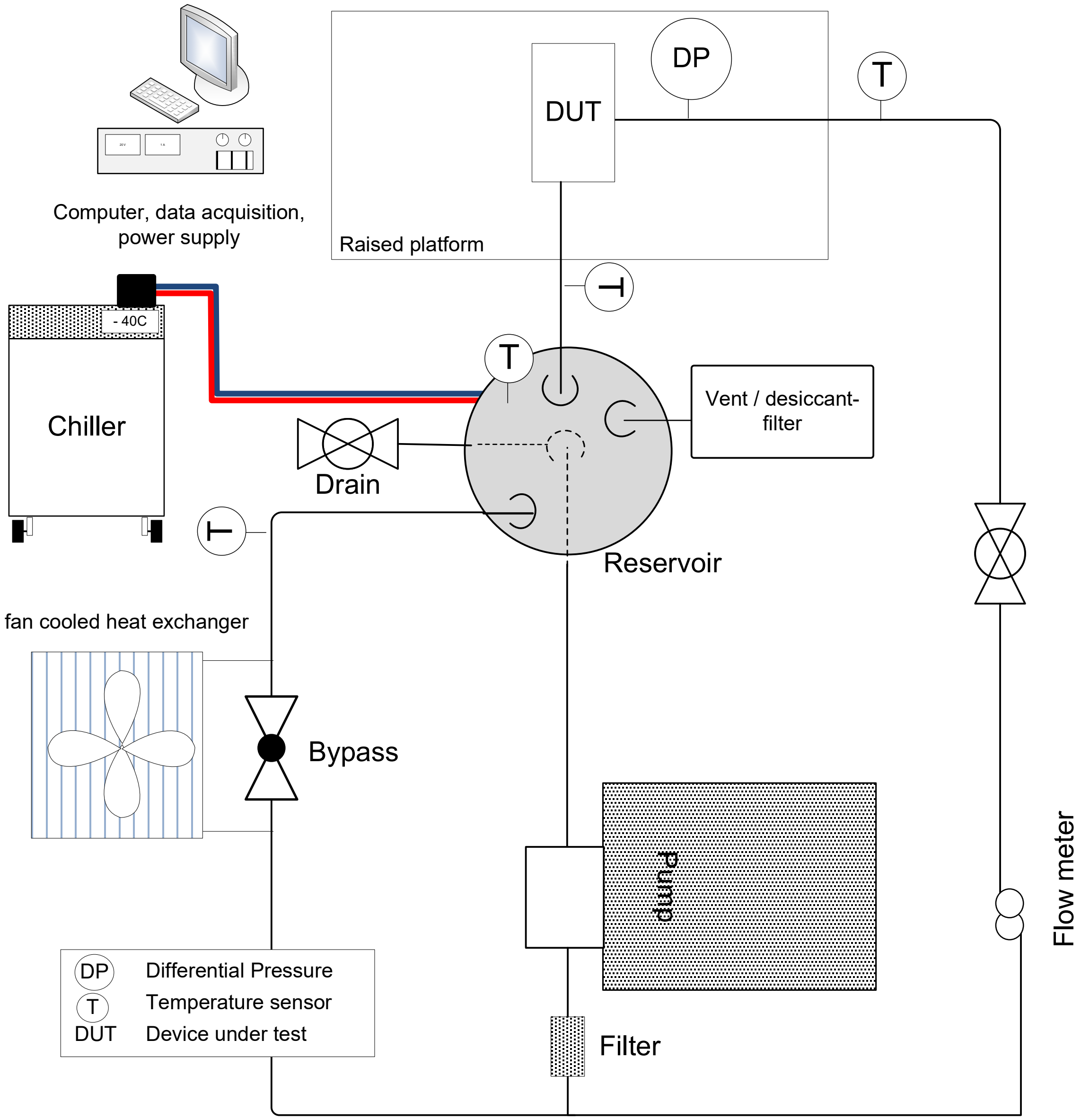
Dielectric Fluid Properties

- Selected synthetic hydrocarbons that are used in electronics cooling (single-phase) applications:
  - Alpha 6: DSI Ventures
  - AmpCool (AC)-100: Engineered Fluids
- Potential to use automatic transmission fluid (ATF) to decrease cost, use fluid already qualified for automotive use, enable motor–inverter integration.
- Challenge is to create a cooling system with high thermal performance using fluids with relatively inferior heat-transfer properties as compared to water-ethylene glycol (WEG).

Fluid *(properties at 70°C)*	**Thermal conductivity [W/(m·K)]**	**Specific heat [J/(kg·K)]**	**Density [kg/m³]**	**Viscosity [Pa·s]**	**Flash point [°C]**	**Pour point [°C]**
Alpha 6 [1]	0.14	2,308	792	0.0091	246	−57
AC-100 [1]	0.13	2,326	761	0.0025	180	−55
ATF [2]	0.16	2,131	836	0.012	199	−45
WEG (50/50) [3]	*0.42*	*3,513*	*1,034*	*0.0013*	*>121* [4]	*−36* [5] *(freeze point)*

[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] Alshamani, Kaisar. 2003. “Equations for Physical Properties of Automotive Coolants.” SAE Technical Paper.
[4] Valvoline. “Safety Data Sheet ZEREX HD Nitrile Free Extended Life 50/50 Antifreeze Coolant.” Accessed April 1, 2019. https://sds.valvoline.com/valvoline-sds/sds/materialDocumentResults.faces.
[5] Valvoline. 2020. “Product Information: Valvoline ZEREX G05 Antifreeze Coolant.” https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

Dielectric Fluid Flow Loop



Reviewer-Only Slides

Publications and Presentations

Publications and Presentations:

- Moreno, G. et al. 2021. "Electric-Drive Vehicle Power Electronics Thermal Management: Current Status, Challenges, and Future Directions." *Journal of Electronics Packaging*. https://doi.org/10.1115/1.4049815.
- Moreno, G. "Power Electronics Thermal Management." 2020 DOE VTO Annual Report.

Patent Applications and Records of Invention (ROI):

- Moreno, G. et al., "Dielectric Fluid Manifold for Double-Sided Cooling." Non-Provisional Patent Application 17/084,236 filed October 29, 2020.
- Moreno, G. et al., "Compact Dielectric Fluid Manifold for Multiple Double-side Cooling Configurations." ROI-20-72, submitted March 12, 2020.
- Roan, T. et al., "Evaporator Stacks and Electronic Assemblies", Non-Provisional Patent Application No. 17/018,255.
- Cousineau, K. et al., "Condensers and Electronic Assemblies", Non-Provisional Application No. 16/870,230, filed May 8, 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.