Power Electronics Thermal Management

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National Renewable Energy Laboratory
June 2, 2020

DOE Vehicle Technologies Program
2020 Annual Merit Review and Peer Evaluation Meeting

Project ID # ELT211

Overview

Timeline

- Project start date: FY 2019
- Project end date: FY 2023
- Percent complete: 30%

Budget

- Total project funding
  - DOE share: $700K
- Funding for FY 2019: $350K
- Funding for FY 2020: $350K

Barriers

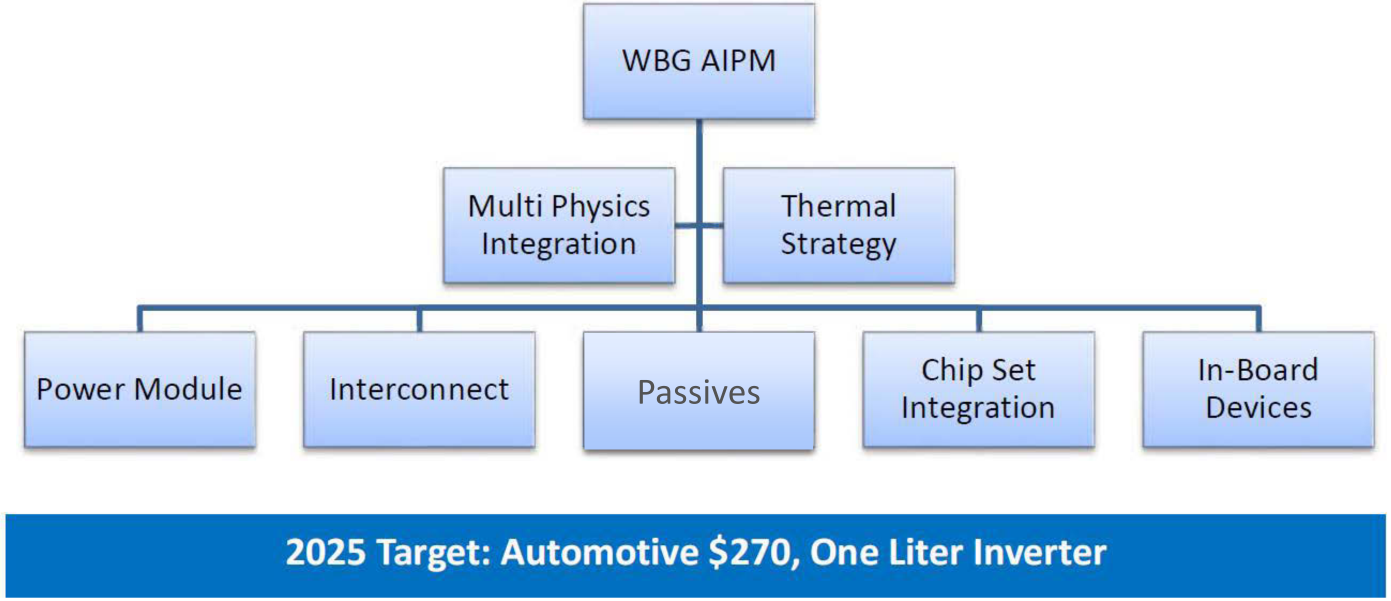
- Size and weight
- Cost
- Performance and lifetime

Partners

- John Deere
- Dielectric fluid manufacturers
- Oak Ridge National Laboratory (ORNL)
- Georgia Tech University (GT)
- 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

AIPM: advanced integrated power module

Milestones/Approach

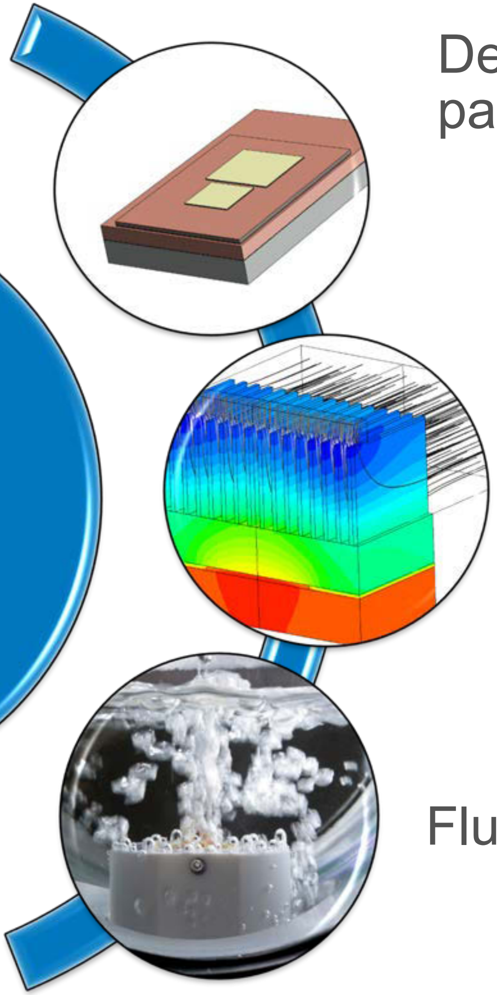
Date	Description of Milestone or Go/No-Go Decision
March 2020 (*complete*)	**Milestone:** Completed experiments to characterize the thermal performance of the dielectric-fluid-based heat exchangers (single-side cooled). Evaluated the effects of the dielectric fluid temperature and flow rate on thermal performance and pumping power.
June 2020 (*in progress*)	Design a double-side cooled, dielectric fluid heat exchanger to improve performance (beyond the single-side cooled design).
September 2020 (*in progress*)	Conduct experiments to measure the thermal performance and pumping power of the dielectric fluid heat exchanger using other dielectric fluids (AC-100) and automatic transmission fluids (ATFs) at various fluid temperatures and flow rates.

Overall Approach

Thermal strategy to reach a power density of 100 kW/L

Define the thermal target to achieve 100 kW/L

Design the cooling strategies to achieve the thermal target



Device packaging

Convective cooling

Fluid selection

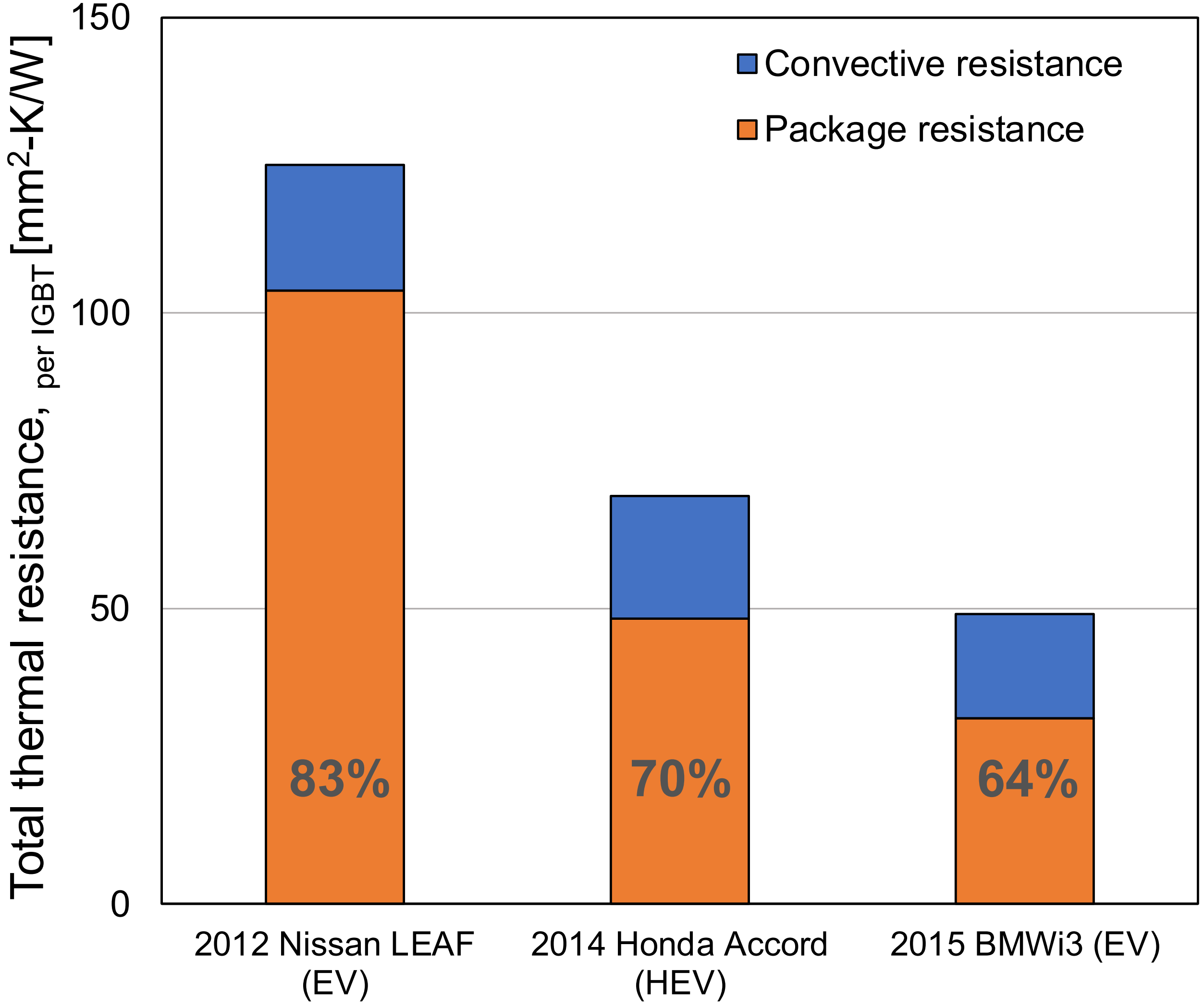
Photo Credit: Gilbert Moreno (NREL)

Estimated heat load (100 kW WBG inverter): 2,150 W
Maximum device temperature: 250°C
Module and cold plate volume: <240 mL

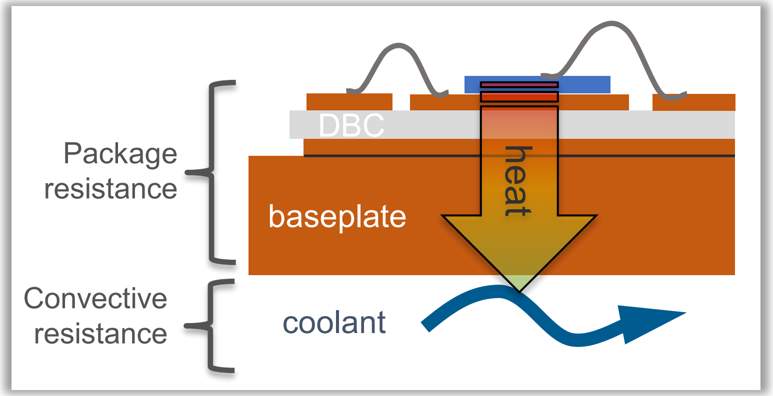
Volumetric thermal resistance target: <21 $cm^3 \cdot K/W$

Dielectric-fluid cooling (single-phase heat transfer) planar package concept

Thermal Design Approach



- Reduce the total thermal resistance by reducing the package thermal resistance. Package resistance (~60% to 80% of total) 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.

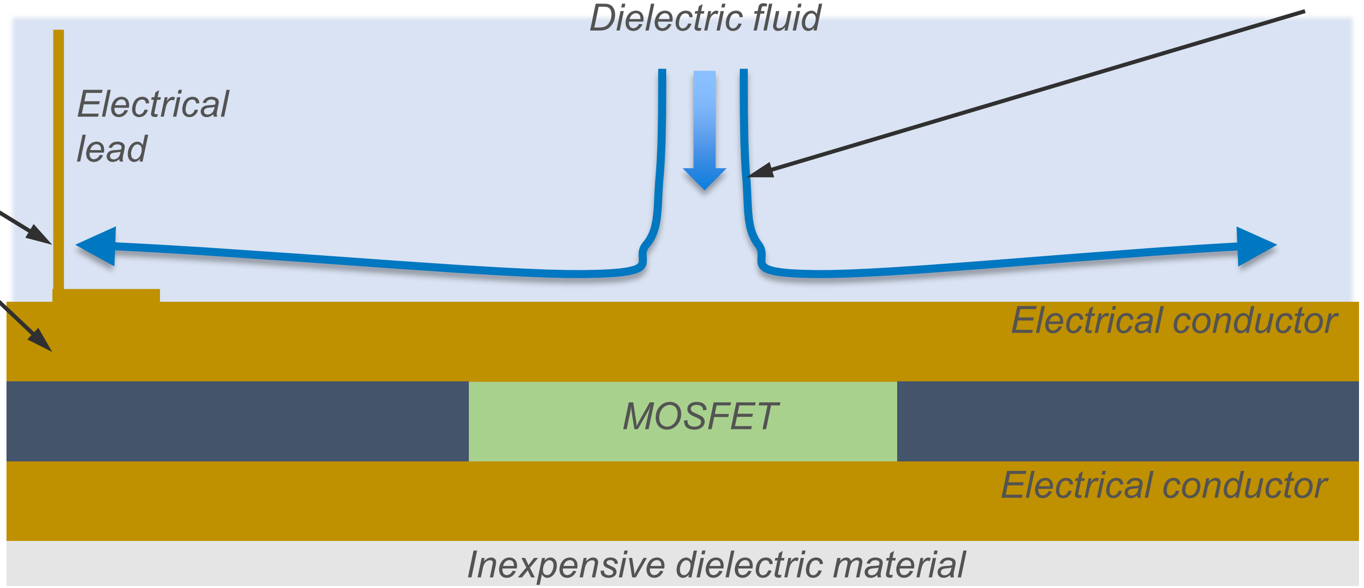


HEV: hybrid electric vehicle; EV: electric vehicle; DBC: direct-bond copper

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·K])
- Designed single-side and double-side dielectric-fluid cooling concepts.

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

Thermal Design Approach: Project Tasks

3. Conducted experiments and validated model (single-side cooled system)

2. Designed a jet impingement, dielectric fluid, single-side cooling system

4. Modeled different fluids to compare performance at different temperatures

1. Identified potential dielectric fluids (single-phase heat transfer)

High heat flux heat exchanger

5. Designing a double-side cooled, dielectric-fluid cooling system

Alpha 6, AC-100, and ATF fluid properties provided in Technical Back-Up Slide Section

Work presented 2019 AMR

Current work

Enable reaching 100 kW/L power density

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

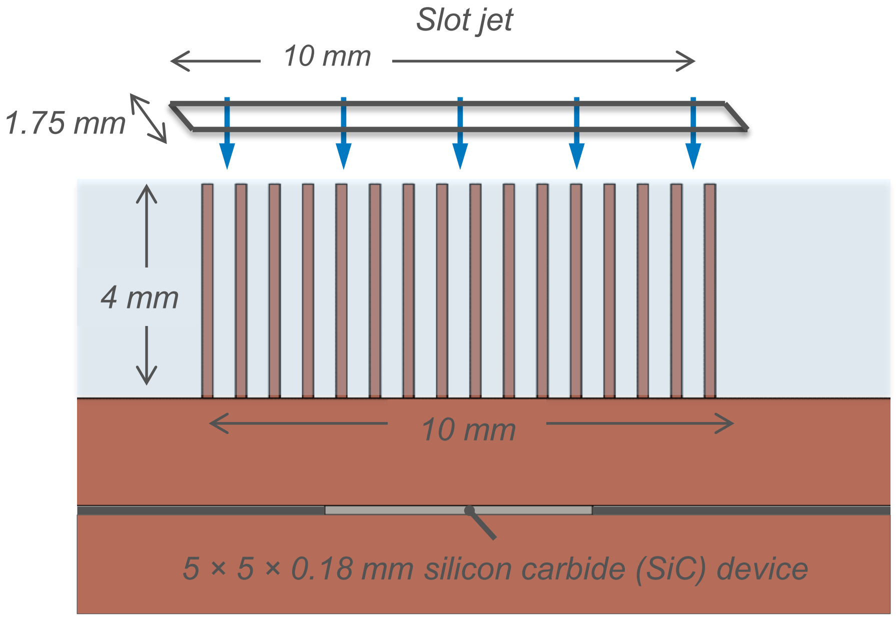
Technical Accomplishments (presented in 2019 AMR)

Achieved high thermal performance

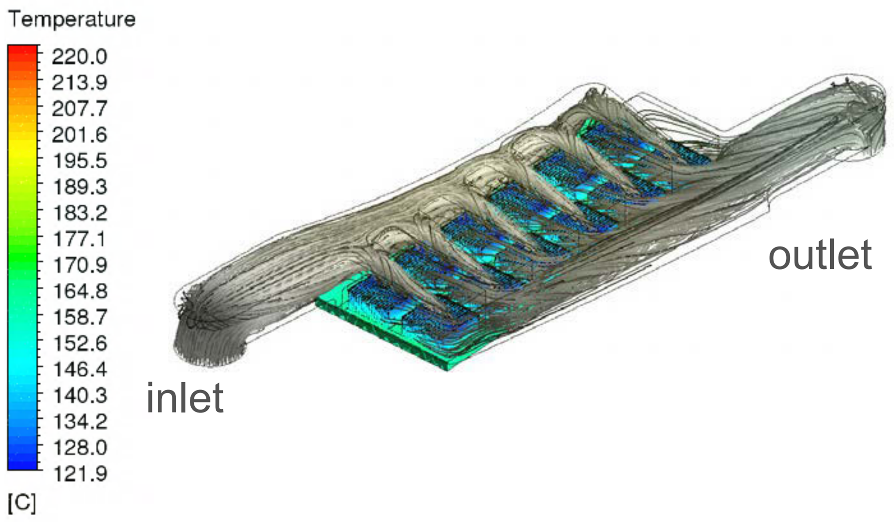
- Heat transfer coefficient 17,300 W/(m^2·K) at a relatively low jet velocity of 0.3 m/s
- **22 mm^2·K/W junction-to-fluid thermal resistance (per device)**

Compact size

- Achieved **120 mL total volume** for conceptual 12-device module and heat exchanger
- Requires 4.1 L/min total flow rate
- Predict we can dissipate 2.2 kW with 12 devices. Results in a $T_j \approx$ 220°C at a **heat flux ~716 W/cm^2**
- Compute **9 cm^3·K/W total resistance**, outperforms/lower than resistance target of 21 cm^3·K/W



Planar module, dielectric cooling concept



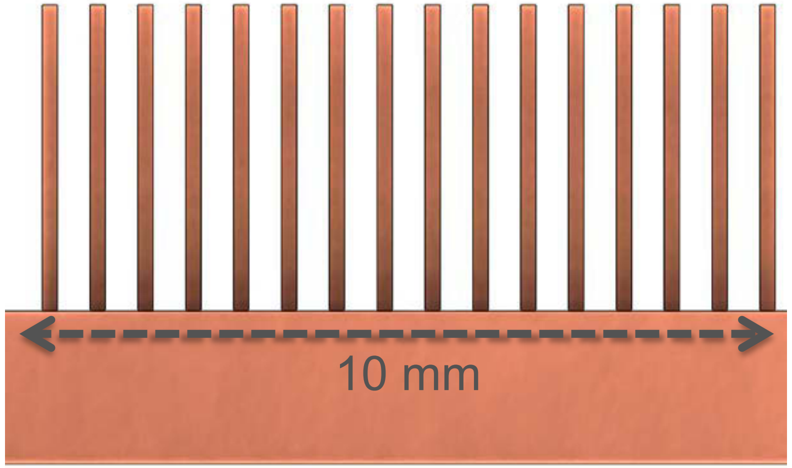
Conceptual power module with dielectric-fluid cooling system (PROV/19-69. Application No. 62/927,252). Results using Alpha 6 fluid at T_{inlet} = 65°C.

Moreno, G. et al., "High-Heat Flux, Dielectric-Fluid Cooling Method for Power Electronics." PROV/19-69. Application No. 62/927,252.

Experimental Validation: Fabricated the Finned Heat Spreaders

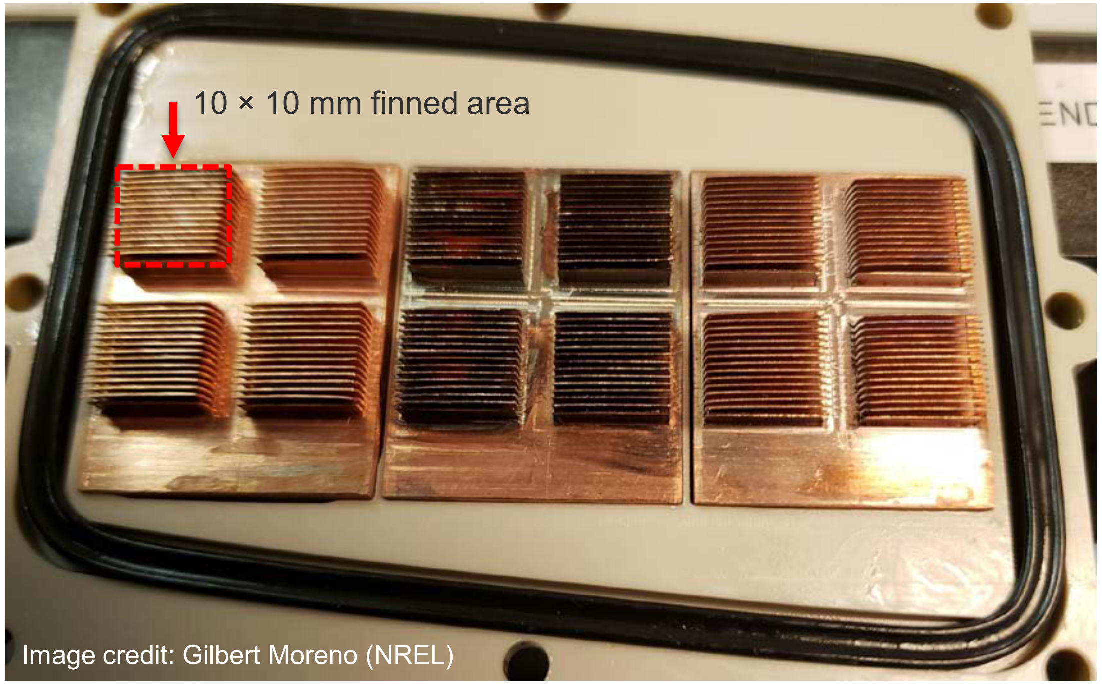
Modeled

As modeled:
16 fins total (per device)
thickness = 0.2 mm
height = 4 mm
channels = 0.43 mm



Actual

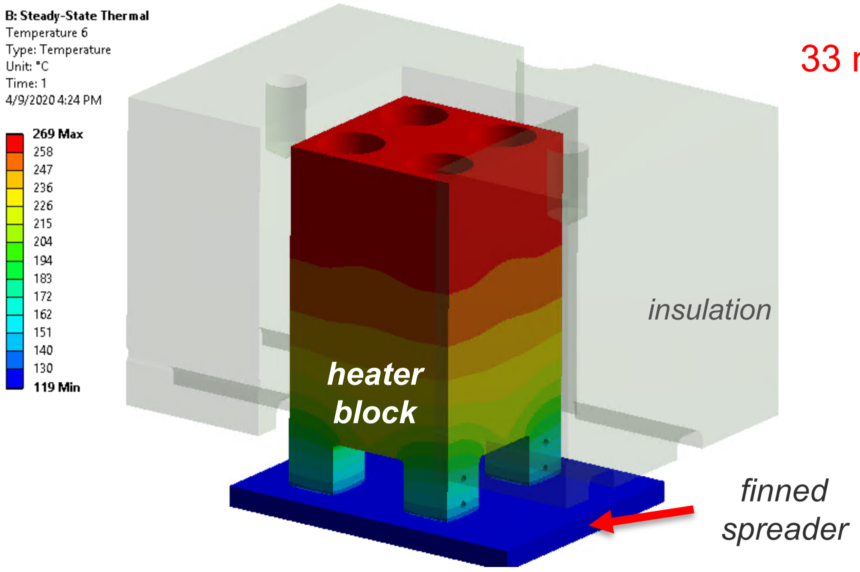
Measured:
15 fins total (per device)
thickness ≈ 0.25 mm
height ≈ 4 mm
channels ≈ 0.4 mm

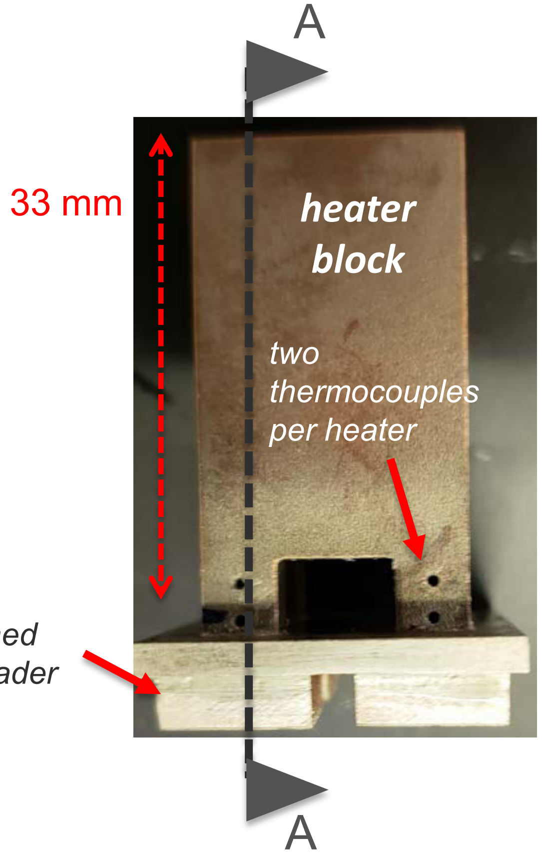


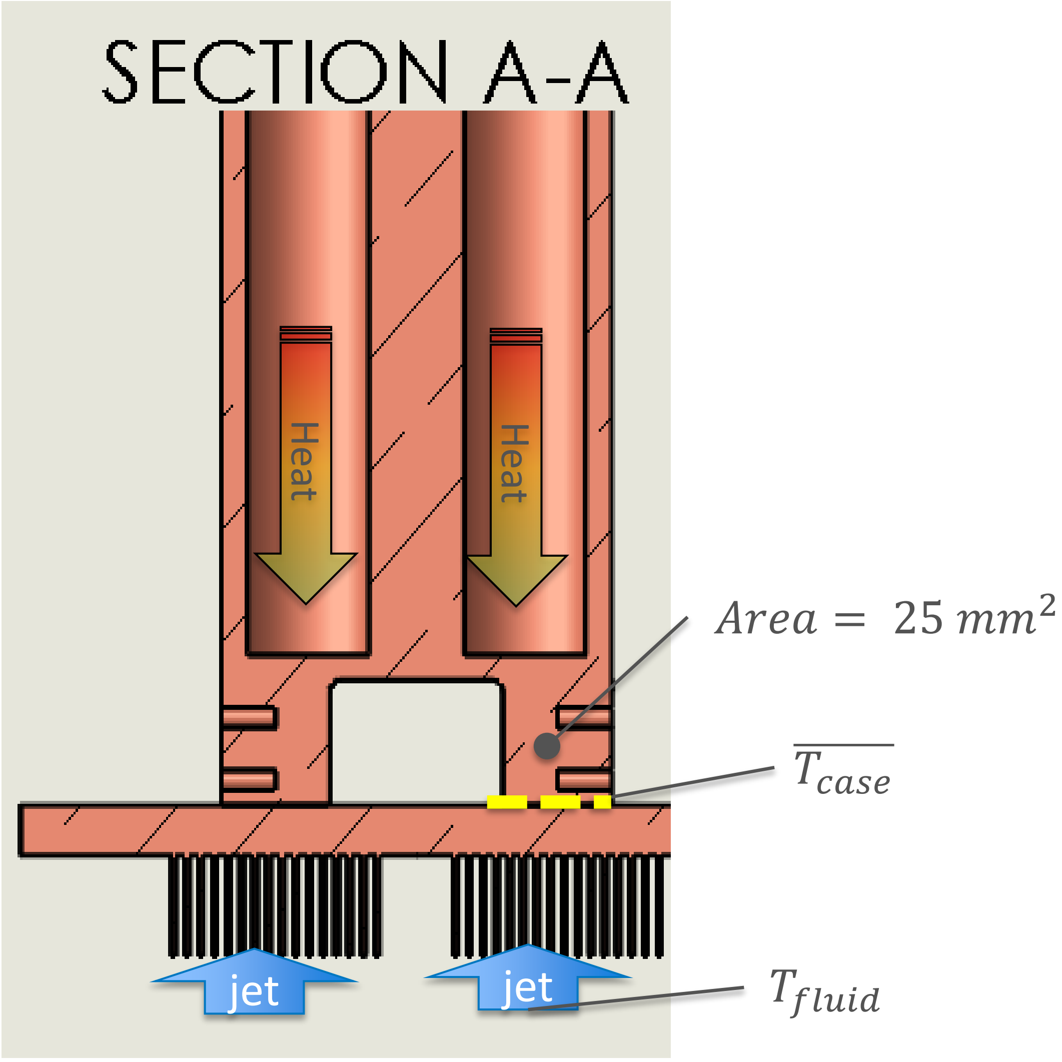
Finned heat spreaders mounted to plastic housing (PROV/19-69. Application No. 62/927,252). Twelve finned areas are directly above each device.

Moreno, G. et al., "High-Heat Flux, Dielectric-Fluid Cooling Method for Power Electronics." PROV/19-69. Application No. 62/927,252.

Experimental Validation: Completed the Heater Design



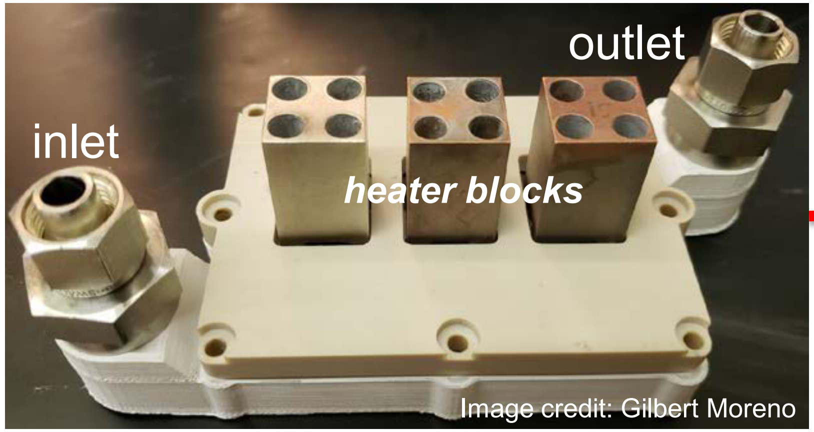




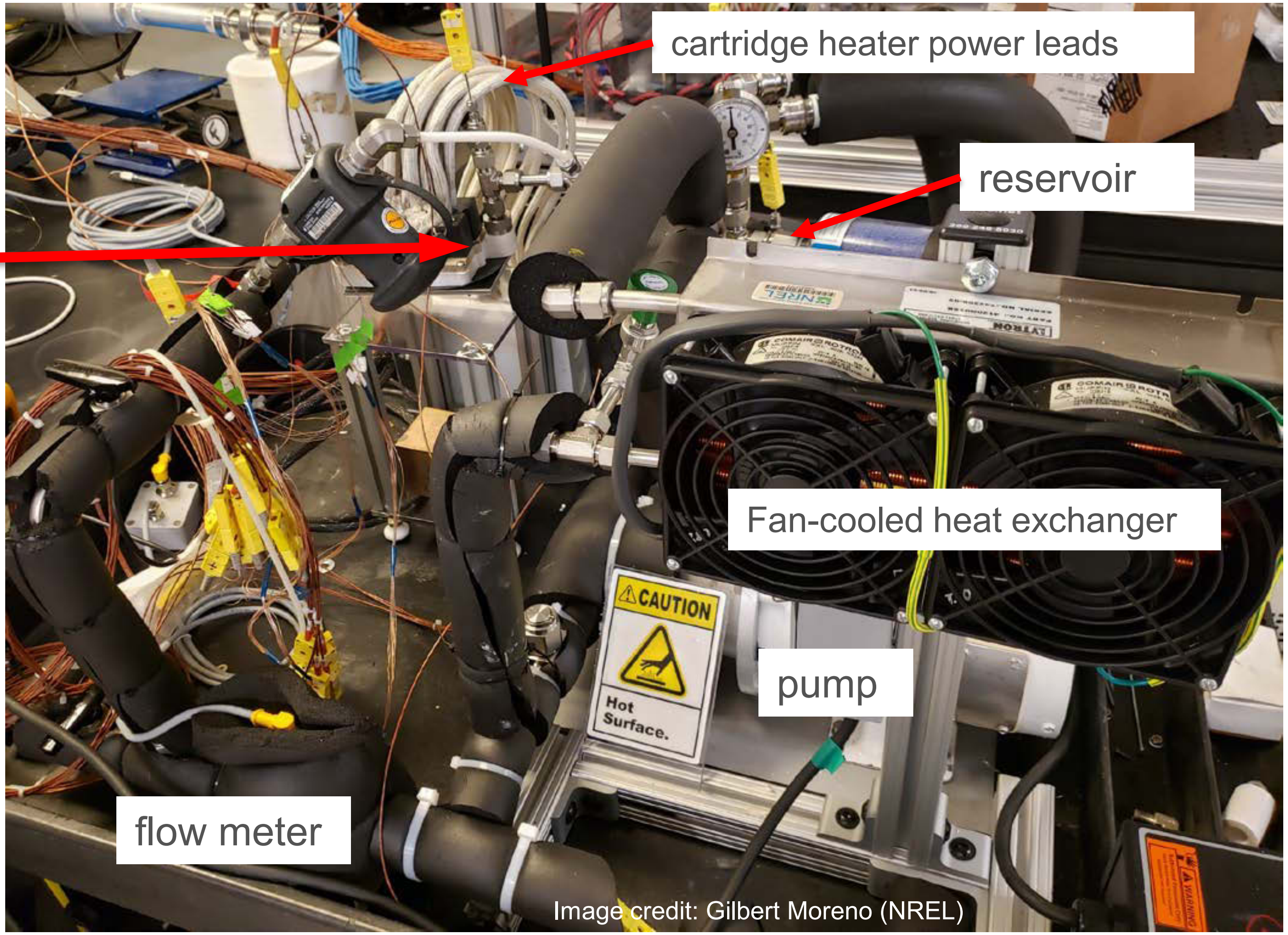
$$R''_{th,\,case-fluid} = \frac{Area\left(\overline{T_{case}} - T_{fluid}\right)}{Heat_{per\ heater,\,device}}$$

- Designed a cartridge heater system to simulate the 12 SiC devices.
- Heater blocks are soldered to finned heat spreaders.
- Measured the heat exchanger (case-to-fluid) thermal resistance.

Experimental Validation: Fabricated the Dielectric Fluid Loop

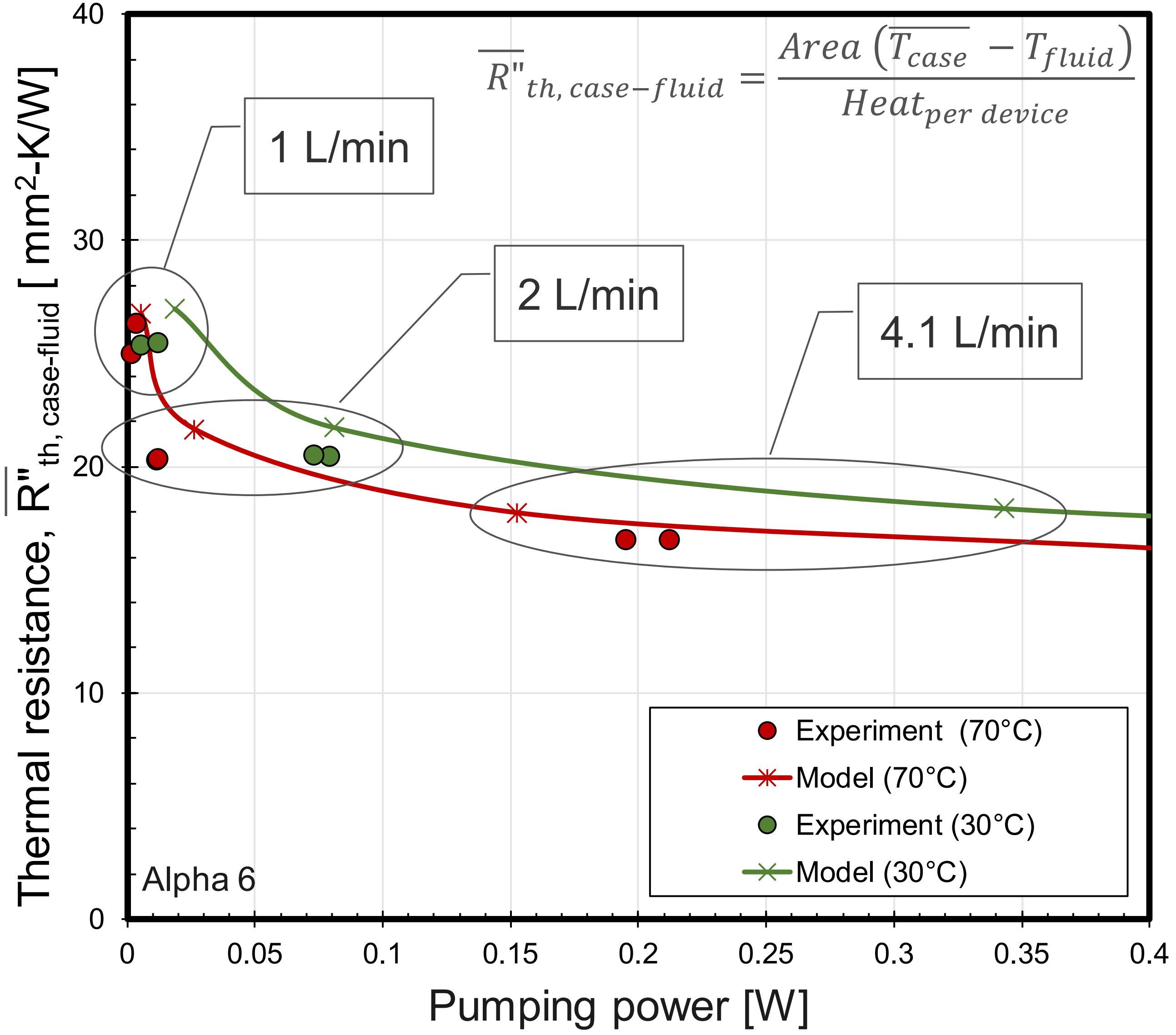


- Fabricated a polycarbonate prototype of the dielectric-fluid heat exchanger via 3D printing (cartridge heaters and insulation not shown).
- Completed fabrication of the dielectric fluid loop.
- Measured the heat exchanger (case-to-fluid) thermal resistance at various fluid flow rates and temperatures.



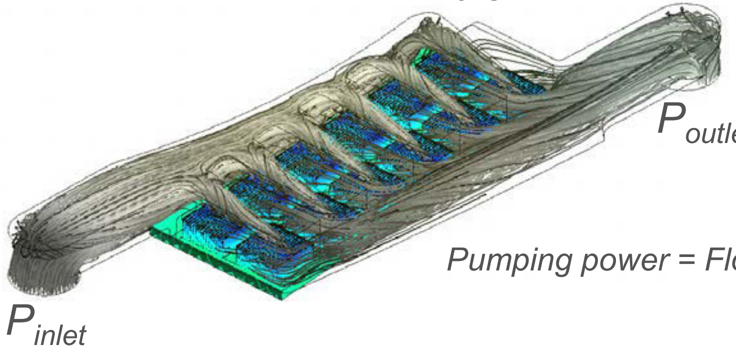
Dielectric fluid loop (schematic provided in Technical Back-Up Slides)

Experimental Results and Comparisons with Model



- Obtained a good match between experiments and model.
- Changing fluid temperature has minimal effect on thermal resistance but does affect pumping power.
- **Confirmed the heat exchanger low thermal resistance values. Provided confidence in model predictions.**

Model: inverter-scale, conjugate heat transfer CFD



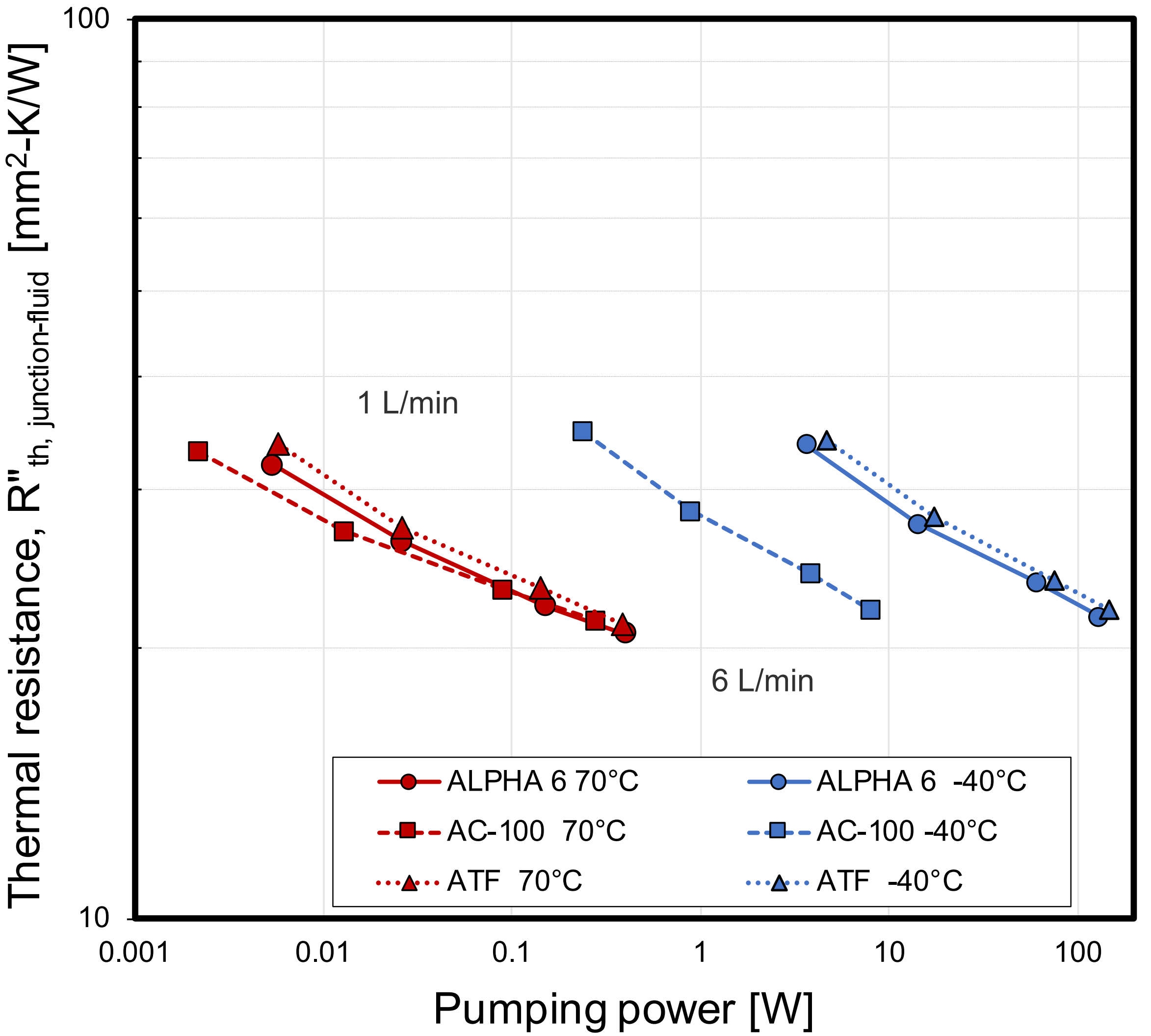
Pumping power = Flow rate × (P_{inlet} – P_{outlet})

CFD: computation fluid dynamics

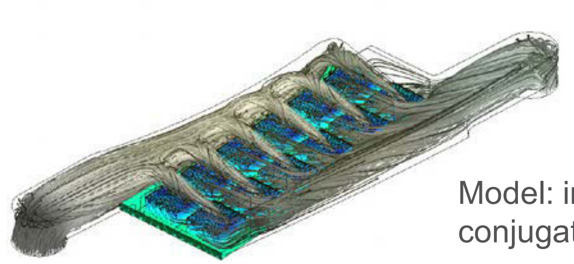
Technical Accomplishments

Compared Fluid Performance at Different Fluid Temperatures

- Modeled performance of Alpha 6, AC-100, and ATF at 70°C and −40°C fluid temperatures at different flow rates (1 L/min to 6 L/min).
- Changing fluids and varying temperatures has a minor effect on thermal resistance but has a big effect on pumping power when compared at the same flow rates.
- Predict ATF performance to be similar to Alpha 6 because they have similar properties.



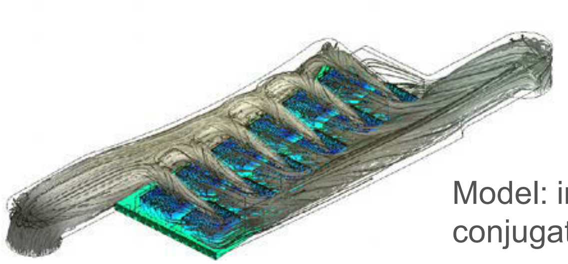
Data at all temperatures, including 30°C, are provided in Technical Back-Up Slides. The first data points correspond to 1 L/min, the last data points correspond to 6 L/min for all curves shown.



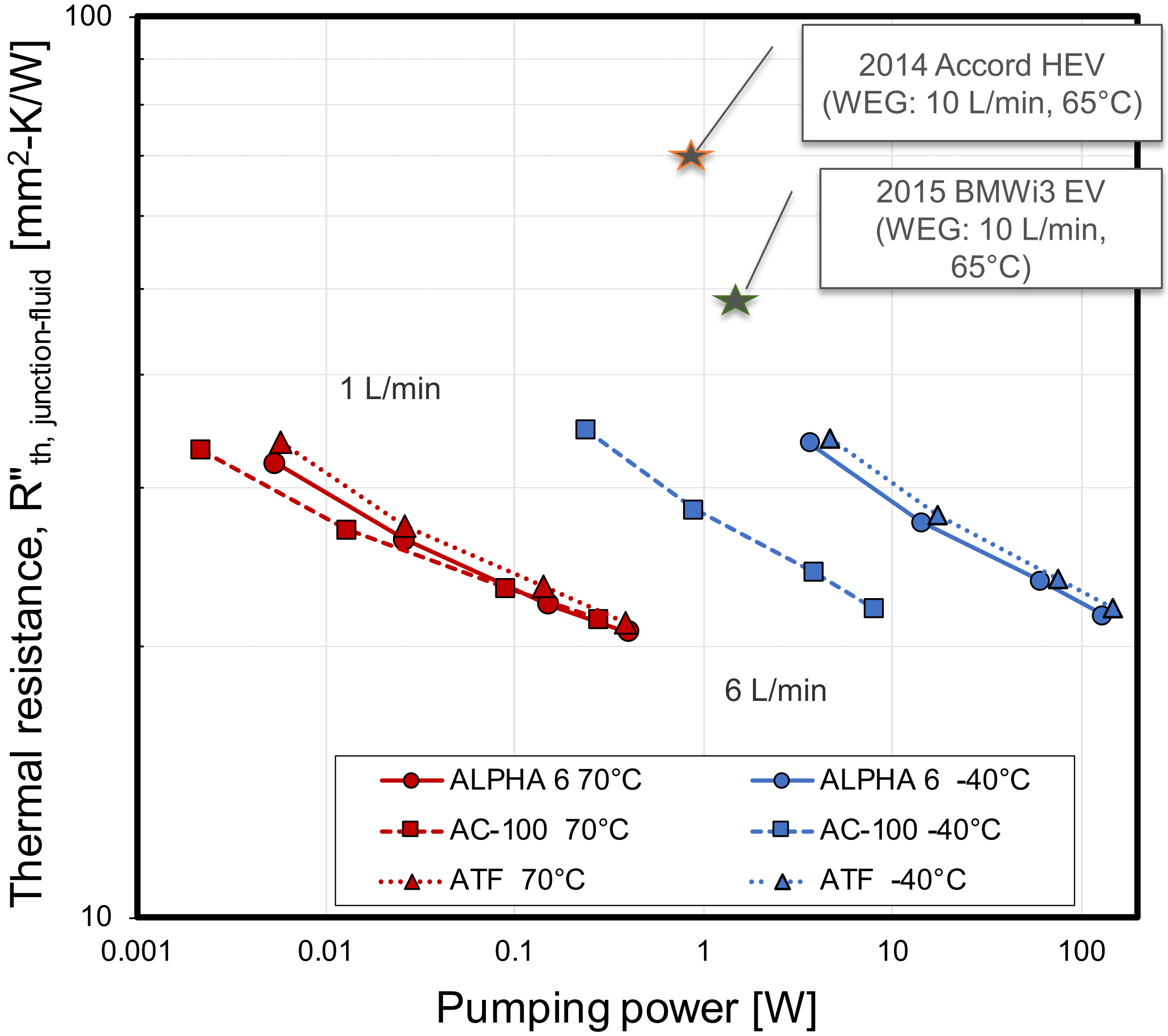
Model: inverter-scale, conjugate heat transfer CFD

Compared Performance with Existing Automotive Systems

- Predict that all dielectric fluid cases provide lower thermal resistance compared with 2014 Accord HEV and 2015 BMWi3 EV.
- AC-100 may be the best option due to its lower pumping power. **At −40°C, it's predicted to have a lower pumping power and thermal resistance compared with 2014 Accord HEV and 2015 BMWi3 EV**.
- **Results indicate that higher viscosities at low temperatures may not be a problem if the correct fluid is chosen and coupled with a low pressure-drop system.**



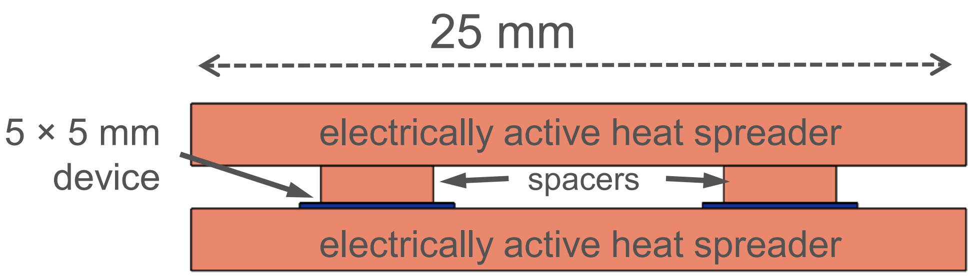
Model: inverter-scale, conjugate heat transfer CFD



Data at all temperatures, including 30°C, are provided in Technical Back-Up Slides. The first data points correspond to 1 L/min, the last data points correspond to 6 L/min for all curves shown.

Dielectric Fluid, Double-Side Cooled Module

Conceptual dielectric fluid, double-side cooled module



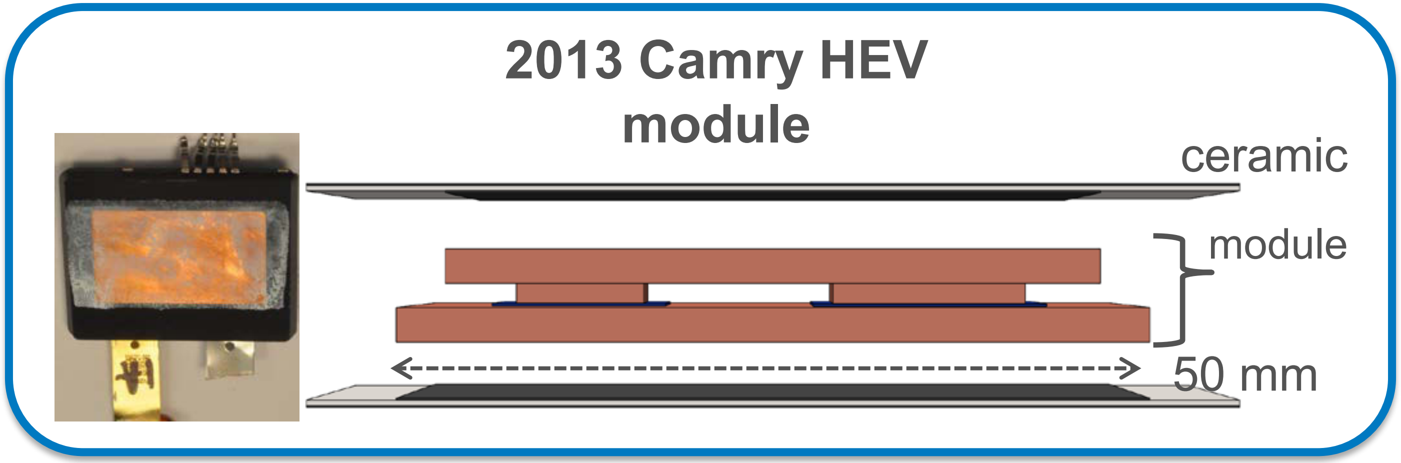
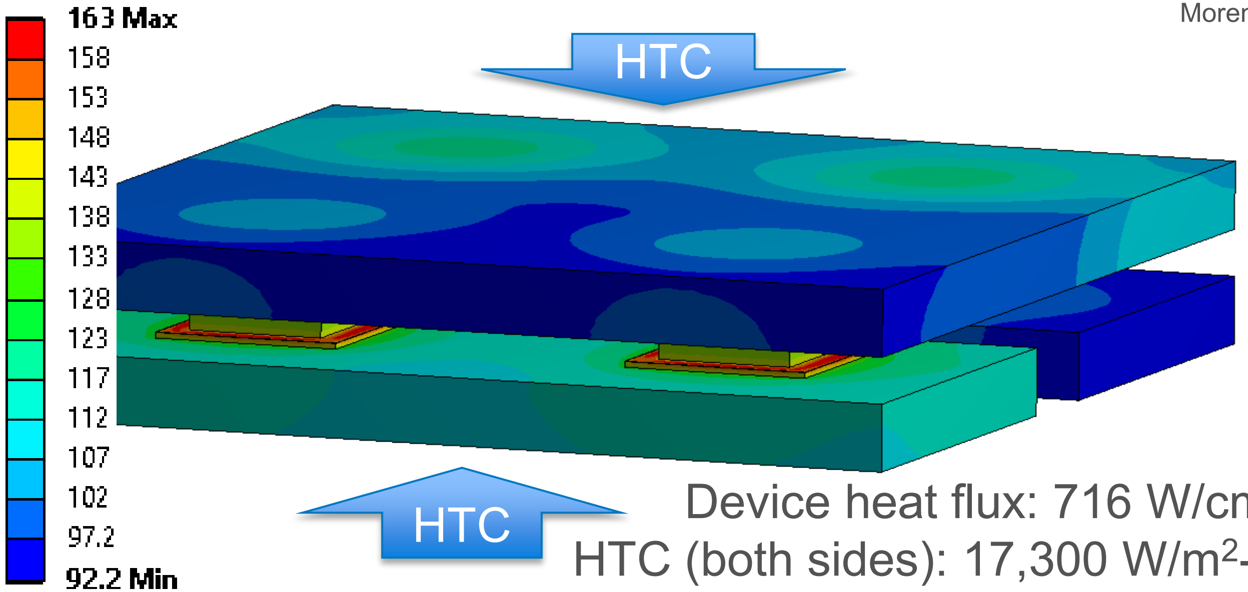


Image credit: Gilbert Moreno (NREL)



Device heat flux: 716 W/cm^2
HTC (both sides): 17,300 W/m^2-K

- Double-side cooled module design similar to 2013 Camry HEV module.
- **Predict 163°C maximum junction temperatures at 716 W/cm^2 heat flux** using HTCs from single-side concept; ~57°C temperature decrease compared to single-side concept.
- **Allows for $T_{max.\ junction}$ <175°C due to double-side cooled configuration.**

HTC: heat transfer coefficient

Summary of Results

	Single-side cooled, dielectric fluid concept	Double-side cooled, dielectric fluid concept	Target
Maximum junction temperature [°C]	220 [1]	163 [1]	<250 [2]
Total heat dissipated [W]	2,150	2,150	2,150
Heat flux per device [W/cm^2], maximum	716	716	N/A
Volumetric thermal resistance [cm^3·K/W]	9	11	21
Pumping power [W]	0.15 [1]	0.21 [1]	N/A

Developed dielectric fluid-based cooling strategies that we predict can enable reaching 100 kW/L power density.

[1] Computed/measured at 4 L/min and 70°C Alpha 6 inlet temperature.
[2] USDRIVE, 2017, *Electrical and Electronics Technical Team Roadmap*.

Responses to Previous Year Reviewers' Comments

- **Reviewer comment:** The reviewer said that the approach is fine, but the assumptions are not. 250 degrees Celsius (°C) for the die temperature is not feasible. The die may be able to handle this temp, but the bonding or other design parameters limit the temperature to only a few degrees above IGBT (insulated-gate bipolar transistor).
  - **Response:** We agree that the packaging of the high-temperature devices is the main issue. We have designed a double-side cooled approach that we predict limits the device temperatures <175°C while meeting the thermal target.
- **Reviewer comment:** The reviewer said the technical accomplishments to date are satisfactory. In the evaluation of the cooling concepts, considerations on the weight should be included. Also, comparison with state-of-the art solutions should be updated to more recent results.
  - **Response:** We agree with the reviewer comments. We have developed concepts that are significantly smaller than current systems (~¼ size of 2015 BMWi3 EV) and can be made using a lightweight (plastic) manifold, and thus the weight should also be reduced. We have also added thermal resistance and pumping power comparisons to a more recent automotive system (2015 BMWi3 EV).

Collaboration and Coordination

- John Deere (industry): Two-phase cooling for high-packaging-density planar inverter (CRADA)
- Georgia Tech University: Collaborate to evaluate and develop advanced cooling technologies (two-phase and inter-device cooling)
- Elementum3D (industry): Provide 3D-printed metal parts to evaluate new heat exchanger concepts
- ORNL
- Dielectric fluid manufacturers

CRADA: cooperative research and development agreement

Remaining Challenges and Barriers

- **Creating a reliable, leak-free cooling system:** main challenge is sealing the electrical leads that penetrate through the power module.
  - Developed a concept (ROI-20-72 Compact Dielectric Fluid Manifold for Multiple Double-Side Cooling Configurations) that may allow for sealing the modules and cooling of electrical interconnections.
- **Pumping power requirements** at low temperatures due to higher fluid viscosity.
  - Results indicate that higher viscosities at low temperatures may not be a problem if the correct fluid is chosen and coupled with a low pressure-drop system.
- **Fluid compatibility with power electronics materials:** selected fluids should be compatible with electronics materials, but experiments should be conducted to verify compatibility.
- **Long-term reliability** questions of the dielectric fluid under power electronics operating conditions.
- **Industry adoption** of new (nonconventional) technology.

Proposed Future Research

FY 2020

- Complete design of the double-side cooled, dielectric fluid concept.
- Conduct experiments with AC-100 and ATF at various fluid temperatures and flow rates.
- Collaborate with Georgia Tech to develop the advanced cooling technologies.

FY 2021 and beyond

- Fabricate a prototype of the double-side cooled concept.
- Experimental demonstration/validation of the double-side dielectric fluid concept.
- Evaluate the long-term reliability of the dielectric fluids.
- 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 year 2025 DOE power density (100 kW/L) and cost ($2.7/kW) targets.

Approach/Strategy

- Define a thermal target required to achieve the 100 kW/L power density.
- Design dielectric-fluid cooling strategies to meet the thermal target and enable high power density.

Technical Accomplishments

- Conducted experiments to measured the dielectric-fluid heat exchanger (case-to-fluid) thermal resistance at various fluid flow rates and temperatures. Obtained a good match between experiments and model. Results confirm that the single-side heat exchanger concept can meet the thermal target.
- Identified AC-100 as a good option due to its lower pumping power. At −40°C, it's predicted to have a lower pumping power and lower thermal resistance compared with 2014 Accord HEV and 2015 BMWi3 EV.
- Designing a double-side, dielectric fluid-cooled heat exchanger. Predict that this concept can dissipate heat fluxes >700 W/cm^2 (per device) while maintaining junction <175°C. This concept is also predicted to meet the thermal target.
- **Developed dielectric fluid-based cooling strategies that we predict can enable reaching 100 kW/L power density.**

Collaborations

- John Deere, Georgia Tech University, Elementum3D, dielectric coolant manufacturers, ORNL

Acknowledgments

Susan Rogers, U.S. Department of Energy

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Thank You

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL Transforming ENERGY

Technical Back-Up Slides

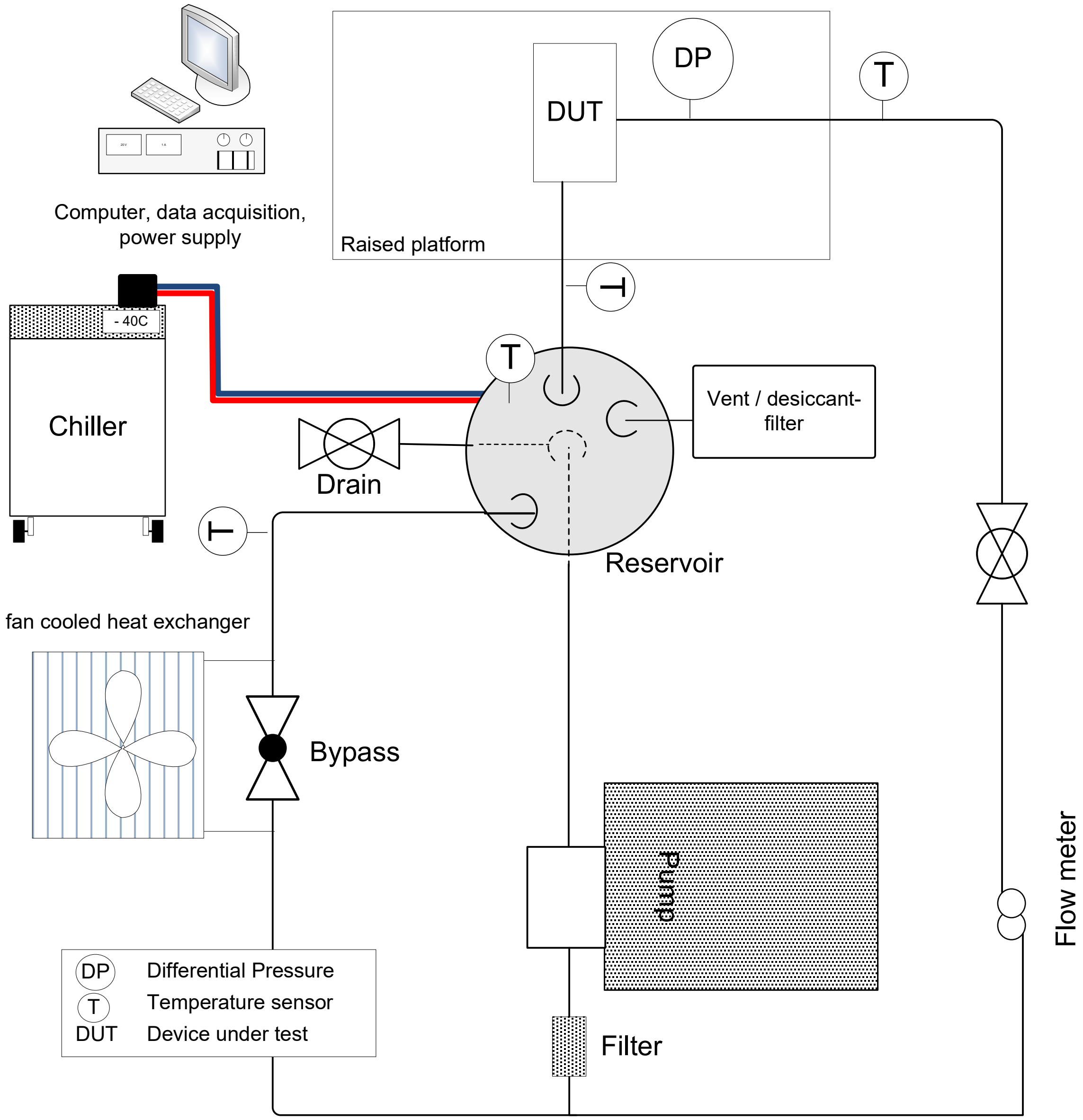
Dielectric Fluid Properties

- 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)*

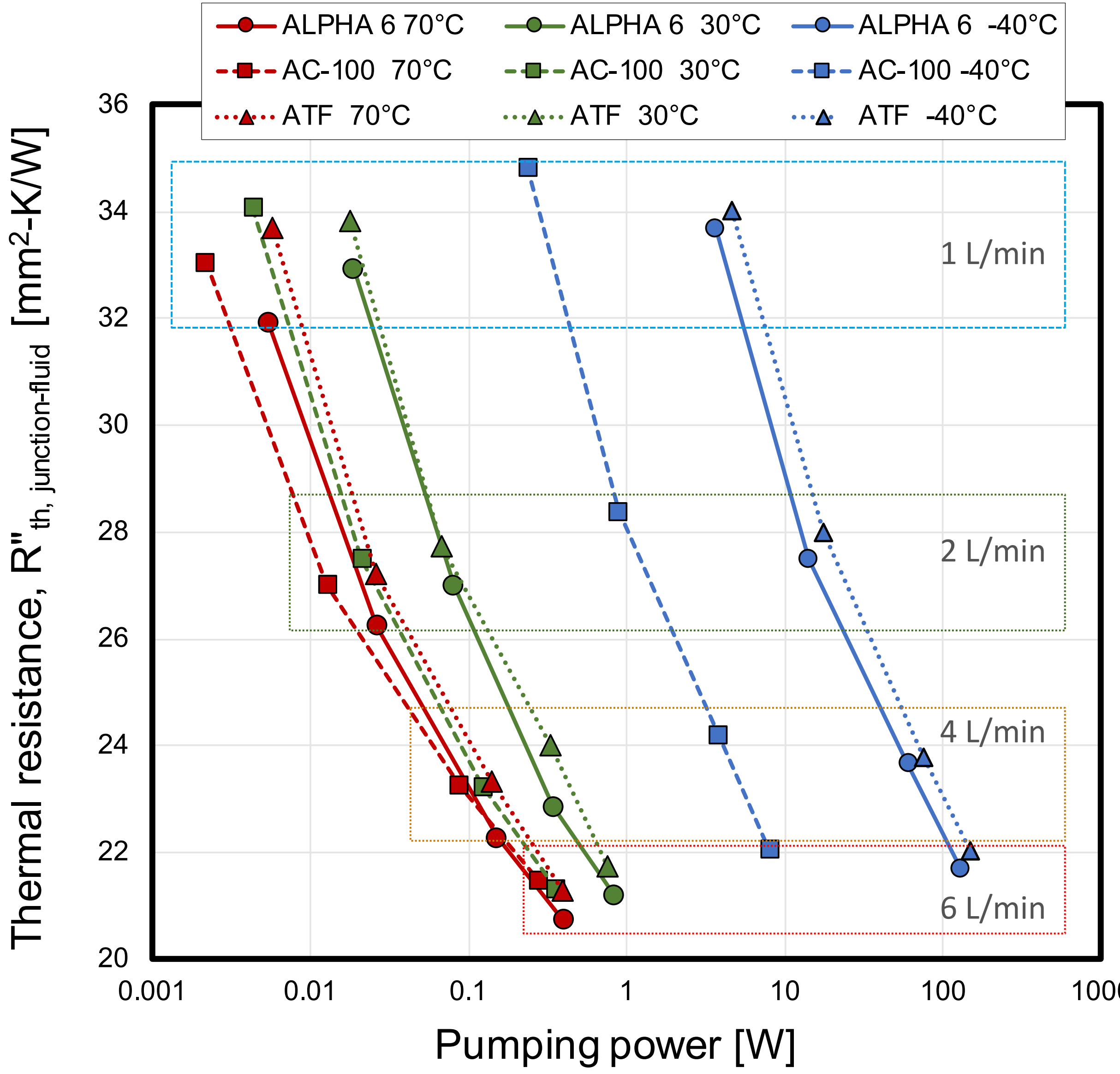
[1] Communications with vendor (DSI Ventures or Engineered Fluids)
[2] Kemp, Steven P. and James L. Linden. 1990. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid." SAE Technical paper.
[3] Alshamani, Kaisar. 2003. "Equations for Physical Properties of Automotive Coolants." SAE Technical Paper.
[4] "Safety Data Sheet ZEREX HD Nitrile Free Extended Life 50/50 Antifreeze Coolant." Valvoline. Accessed April 1, 2019. https://sds.valvoline.com/valvoline-sds/sds/materialDocumentResults.faces.
[5] "Product Information: Valvoline ZEREX G05 Antifreeze Coolant." 2018. US_Val_ZXG05_AFC_HD_EN.Pdf. https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

Dielectric Fluid Flow Loop



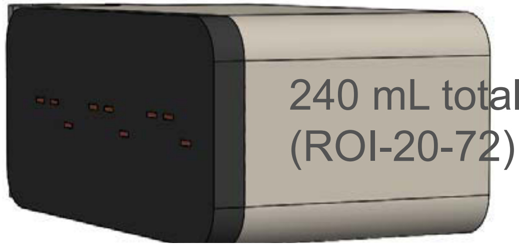
Effect of Fluid Temperature: CFD Model Results for Single-Side Cooled Concept

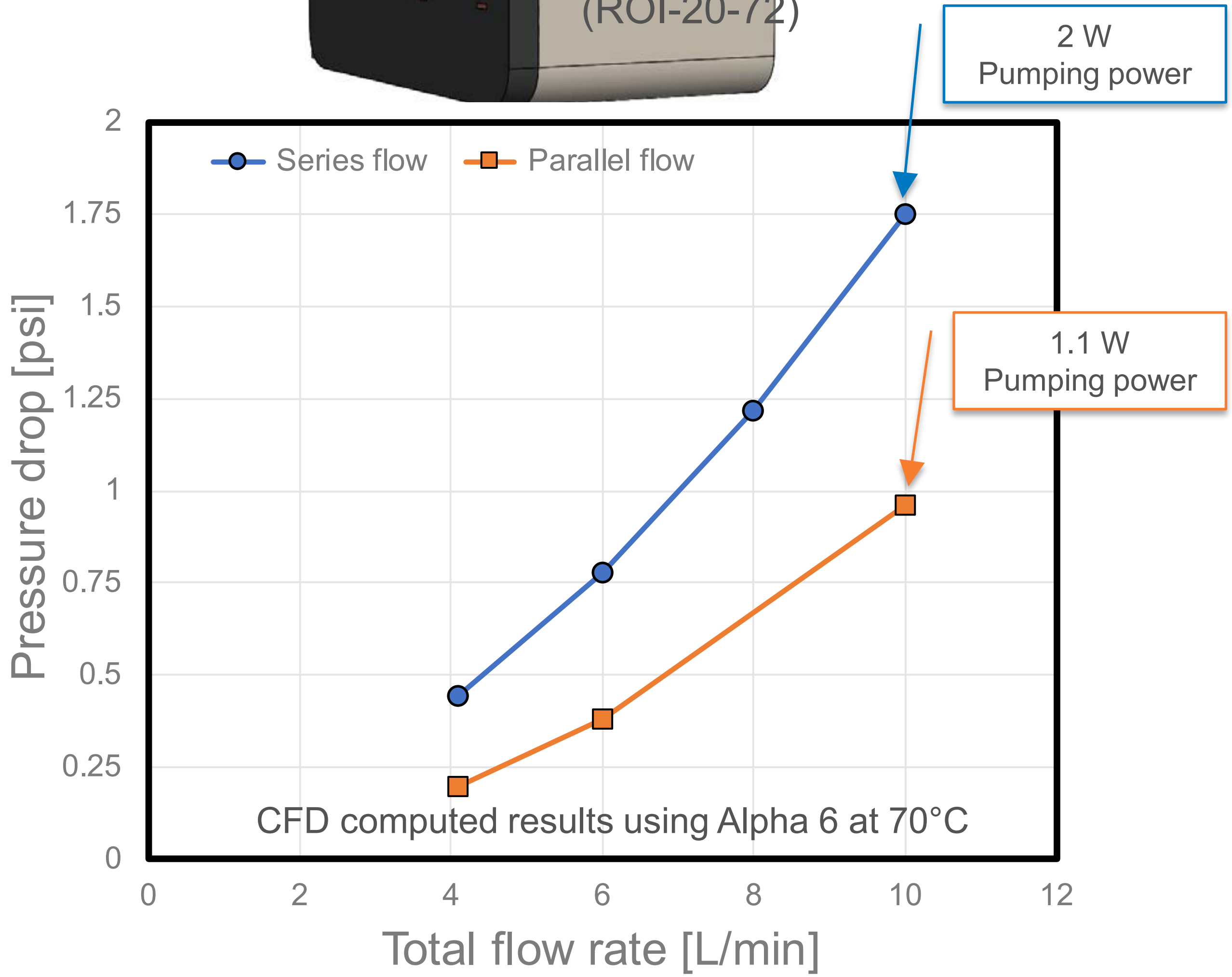
- Different fluids provide similar thermal resistance performance when compared at same flow rate.
- Changing fluid temperature has minimal effect on thermal resistance but has a big effect on pumping power.



Dielectric Fluid, Double-Side Cooled Heat Exchanger Pressure Drop versus Flow Rate Performance

- Total volume for the heat exchanger and conceptual modules is 240 mL.
- Computed pressure drop versus flow rate characteristics for series and parallel flow configurations. **Pressure drop is <2 psi** for all flow rates.





NREL Record-of-invention (ROI)-20-72 Compact Dielectric Fluid Manifold for Multiple Double-Side Cooling Configurations