Dielectric Fluid Cooling of Power Electronics Modules

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INTRODUCTION

The need to increase volumetric power density in automotive power electronics requires innovations in their thermal management systems. Automotive power electronics modules are typically cooled using a water-ethylene glycol (WEG) solution. Modern automotive systems use baseplate-cooled or double-side-cooled configurations to cool the power modules. The baseplate-cooled configuration is used for single-side-cooled modules and directly cools the module's baseplate, eliminating the need for thermal grease. The ceramic component in the metalized ceramic substrates is typically the largest thermal resistance within the packaging structure. Double-side-cooled modules are typically compressed between two cold plates and use thermal grease at the module-to-cold-plate interface. The thermal grease layer is usually the largest thermal resistance for these double-side-cooled modules. The package conduction resistance is typically the largest thermal resistance. References [1–3] provide additional information on typical WEG-based power electronics cooling systems.

Ceramic is the most widely used dielectric material in power modules, but it can be the thermal bottleneck within the package. Using dielectric fluids as coolants enables eliminating the ceramic and thus reducing the package thermal resistance. However, dielectric fluids typically have poor properties compared with WEG, and thus using them is likely to result in lower heat transfer coefficients (e.g., higher convective resistance). Two-phase cooling can be used with dielectric fluids to increase heat transfer coefficients, but the dielectric fluids required for two-phase cooling are typically more expensive and are a concern due to perfluoroalkyl and polyfluoroalkyl substances (PFAS) [4].

This study involved designing and demonstrating a module cooled using dielectric fluid, single-phase heat transfer with AmpCool™ 110 dielectric fluid. A ceramic-free module packaging concept was used to package the silicon carbide (SiC) devices. Modeling was used to design the packaging and heat exchanger. The final concept was then fabricated, and experiments were conducted to measure its performance. The results were compared to existing WEG-cooled modules.

DIELECTRIC-FLUID-COOLED MODULE CONCEPT

The dielectric fluid module concept attaches the SiC devices directly onto copper substrates. The copper substrate functions as both an electrical conductor and heat spreader. This concept eliminates the thermally resistive ceramic component found in typical direct-bond copper modules (Figure 1). The dielectric fluid contacts the finned surface of the copper heat spreader to cool the devices on the opposite side. The devices are not directly contacted by the dielectric fluid to minimize material compatibility issues. Copper alloys (e.g., copper molybdenum) or metal matrix composites can also be used as heat spreader substrates to better match the coefficient of thermal expansion of the semiconductor devices.

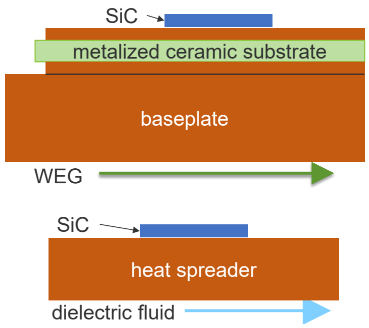

Figure 1. Schematics of a typical power electronics module (top) and ceramic-free, dielectric fluid module (bottom)

Jet impingement onto densely finned copper structures was used as the convective cooling strategy. The jet impingement configuration creates thin boundary layers at the impingement zone, allowing for locally high heat transfer coefficients. Slot jets impinge onto fins that are located directly behind the SiC devices.

Finite element and computational fluid dynamics (CFD) modeling were used to design the package to minimize thermal resistance. Modeling identified the optimal substrate thickness, fin dimensions, and slot jet width to maximize thermal performance. Figure 2 shows a computer-aided design (CAD) drawing of the half-bridge SiC power module concept that uses two SiC metal oxide semiconductor field effect transistor (MOSFET) devices per switch position.

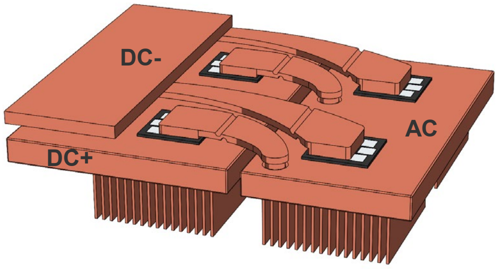

Figure 2. Conceptual ceramic-free, half-bridge module

A heat exchanger was designed to cool three half-bridge modules, or 12 devices (Figure 3). CFD modeling was used to design the heat exchanger channels to minimize thermal resistance, minimize pressure drop, and provide uniform temperature for the 12 SiC devices. The final design used 0.2-mm-thick fins that were 4-mm tall with 0.43-mm channel spacing. An effective heat transfer coefficient of about 17,300 W/m^2·K was predicted for a relatively low total flow rate of 4 L/min, equating to 0.33 m/s average jet velocity. More details of the dielectric-fluid-cooled module design and performance can be found in [5, 6].

EXPERIMENTAL DEMONSTRATION

A SiC thermal demonstration module was fabricated and used to experimentally demonstrate the dielectric fluid (single-phase heat transfer) cooling concept. Two 650 V SiC devices (approximately 5 × 5 mm in footprint) were soldered to a finned copper heat spreader as shown in Figure 4. Electrical connections were provided to enable the conducting of current and heating the devices. Wire bonds were used for the top side source, gate, and Kelvin source terminals. The two devices were connected in parallel and represented one electrical switch.

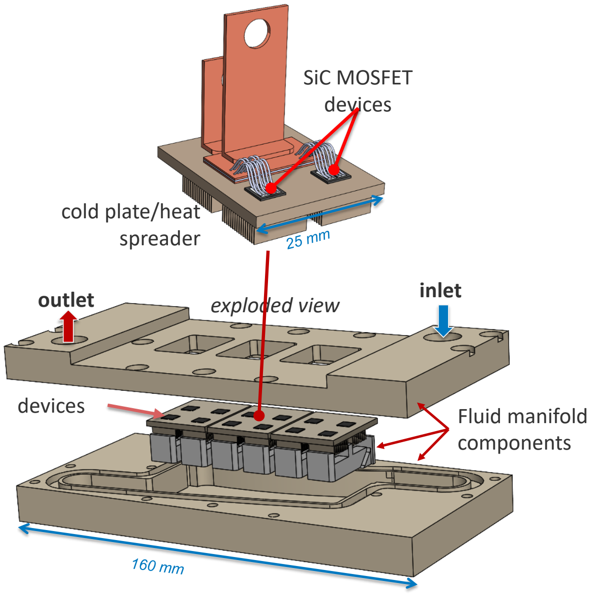

Figure 3. CAD images of the SiC-based module used for the thermal demonstration (top) and module within the heat exchanger assembly (bottom)

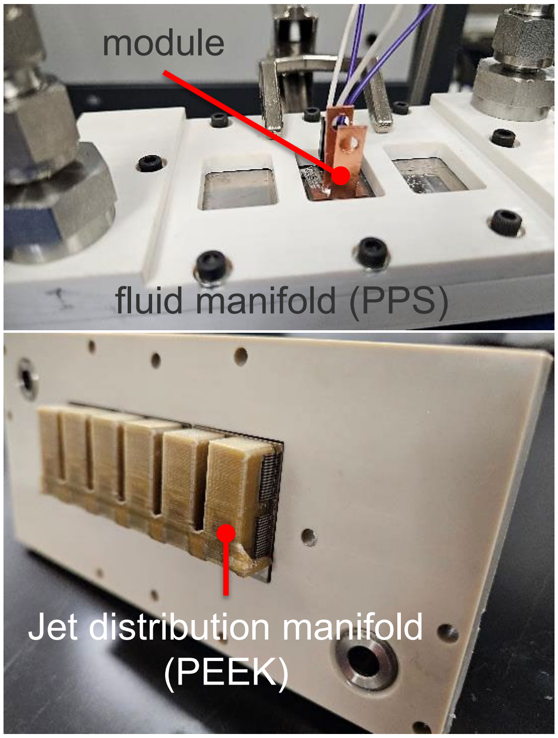

Figure 4. Photos of the assembled module and heat exchanger

The SiC module was then installed within a dielectric fluid heat exchanger. The heat exchanger consists of three parts (Figure 3). The top and bottom components were machined out of polyphenylene sulfide (PPS) and used to contain and distribute the fluid to multiple devices. The middle component is the jet distribution manifold, 3D-printed out of polyetheretherketone (PEEK) plastic and used to generate the slot jets that impinged onto finned structures directly below the devices. PPS and PEEK were used because they are high-temperature plastics, compatible with dielectric fluids, and used in automotive applications. Photos of the heat exchanger and module assembly are provided in Figure 4.

The heat exchanger and module assembly were piped into the dielectric fluid loop and electrically connected to the Power Tester (Figure 5). Experiments were performed to measure the junction-to-fluid thermal resistance and pumping power of the dielectric fluid heat exchanger using 70°C inlet fluid temperature at various flow rates (1 L/min to 4 L/min). AmpCool™ 110, a synthetic hydrocarbon, was the coolant used for these experiments. AmpCool™ 110 is a dielectric fluid intended for cooling battery packs and electric machines in electric vehicle applications [7]. The Power Tester was used to provide current to heat the devices and to measure the junction temperature. The junction temperature was measured via a temperature-sensitive parameter (i.e., body diode voltage drop). Calibration of the diode voltage drop to the temperature was performed initially.

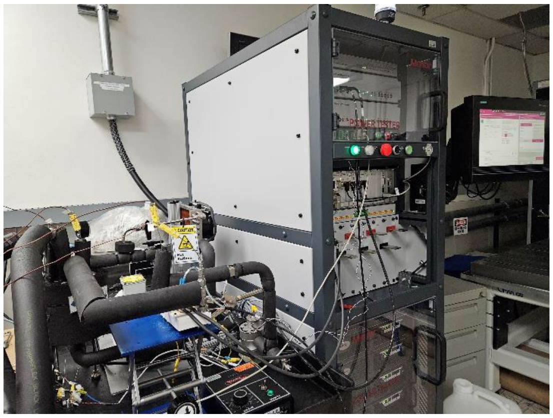

Figure 5. Photos of the module heat exchanger assembly piped into the dielectric fluid loop and electrically connected to the PowerTester

Figure 6 shows the junction-to-fluid specific thermal resistance versus the pumping power. The specific thermal resistance (R''_{th}) was defined per Eq. 1:

$$R''th = Area \cdot (T_j - T_f)/Heat \quad (1)$$

where *Area* is the area of one SiC device, T_j is the junction temperature, T_f is the inlet fluid temperature, and *Heat* is the heat per device. The pumping power is the total flow rate multiplied by the pressure drop (inlet to outlet).

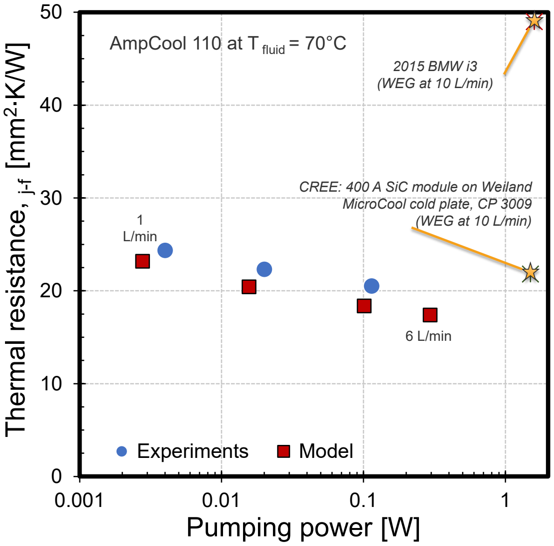

Figure 6. Junction-to-fluid specific thermal resistance versus pumping power results, with comparisons to existing WEG technology

The experimentally measured results are found to be in good agreement with CFD model predictions (within about 10%). The simulations were performed at a higher flow rate case of 6 L/min to evaluate the effect of a higher flow rate on performance. The dielectric fluid cooling system results were compared with the performance of the 2015 BMW i3 power electronics and a Cree™ SiC module single-phase liquid WEG-based thermal management systems. Both the BMW i3 and Cree™ modules were cooled with WEG at a 10-L/min flow rate and 65°C inlet fluid temperature and used metalized copper substrates. The 2015 BMW i3 uses silicon insulated-gate bipolar transistor technology and a copper, pin-fin cold plate for cooling [3]. The Cree™ SiC module (WAB400M12BM3) was cooled using a Wieland cold plate (CP3009) with thermal grease at the interface. The dielectric fluid cooling system (at 6 L/min) is found to reduce thermal resistance and pumping power by 65% and 80%, respectively, compared with the 2015 BMW i3 power electronics thermal management system. Compared to the Cree™ module thermal management system, the dielectric fluid concept reduces the thermal resistance and pumping power by 20% and 80%, respectively. A low thermal resistance of 17.4 $mm^2 \cdot K/W$ was predicted at 6 L/min.

AmpCool™ 110 was used for this demonstration because it is a fluid intended for electric vehicle use (e.g., cooling the batteries and electric machine). Other fluids have also been experimentally evaluated including Alpha 6 [8] and Ford Mercon LV. New driveline fluids being developed by Infineum specifically for electric-drive vehicles have also been evaluated via modeling and have shown performance comparable to AmpCool™ 110. Additional details from this work can be found in [9].

CONCLUSIONS

A dielectric fluid cooling system was designed to cool power electronics modules using single-phase heat transfer. Single-phase heat transfer was used because it allows for the use of new driveline fluids (driveline fluids are oils and cannot be used for two-phase cooling), it is a simpler implementation (two-phase cooling can be perceived as complicated), and it may enable integrating the power electronics with the electric machine (assuming both components can be cooled with the same driveline fluid).

A SiC module and heat exchanger were designed, fabricated, and used for an experimental demonstration of the dielectric-fluid-cooled concept. Experiments were conducted using AmpCool™ 110 dielectric fluid at various flow rates and a 70°C inlet temperature. The dielectric fluid concept provides both lower thermal resistance and pumping power values compared to WEG-based cooling systems. Junction-to-fluid thermal resistance values as low as 17.4 $mm^2 \cdot K/W$ were predicted through validated models.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by Susan Rogers, Technology Manager for the Electric Drive Technologies Program, Vehicle Technologies Office, U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy. This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for DOE under Contract No. DE-AC36-08GO28308. Funding provided by the 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 article, or allow others to do so, for U.S. Government purposes.

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