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Assessment of Thermal Control Technologies for Cooling Electric Vehicle Power Electronics

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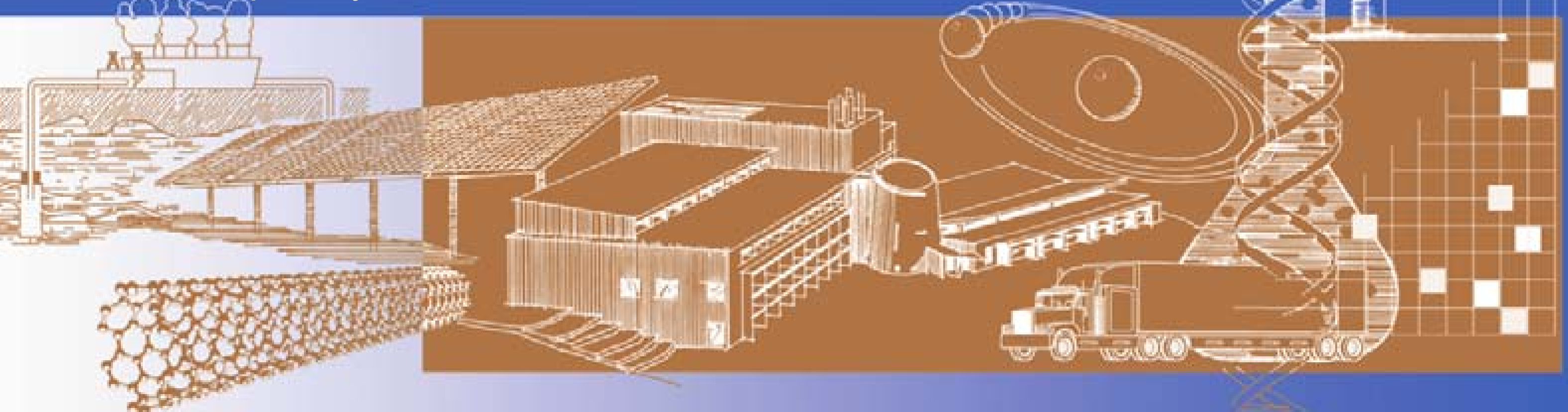

Assessment of Thermal Control Technologies for Cooling Electric Vehicle Power Electronics

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Abstract

The U.S. Department of Energy (DOE) FreedomCAR Program's technical targets for the electric traction system (power electronics and electric machines) of advanced vehicles require significant reductions in volume, weight, and cost while also meeting performance and 15 year life requirements [1]. The performance of the semiconductor switches and diodes, the ripple-current capability of the capacitors, and the life of the electronics all decrease as the operating temperature is increased. The current approach for cooling hybrid electric power inverters uses a separate cooling loop with water ethylene glycol coolant at approximately 70°C. This cooling system is used in hybrid electric vehicles (HEVs) in the market such as the Toyota Prius and Ford Escape. However, this approach is thought to be too large and costly to meet future vehicle requirements and achieve the kind of market penetration that would substantially reduce the United States' dependence on oil imports. A second approach that is being considered is to reduce the coolant system's cost by eliminating the separate cooling loop and cool the power electronics using engine coolant at approximately 105°C. This will require devices, such as trench or silicon-carbide (SiC) switches, that can operate at higher temperatures, as the ability to remove heat decreases as the temperature difference between the coolant and the electronic components decreases. While this solution is plausible, an optimized thermal control system design is required to overcome a number of technical barriers and meet the combined program requirements of performance, weight, volume, cost, life and reliability.

The National Renewable Energy Laboratory (NREL) is conducting research and development on a number of thermal control technologies aimed at improving thermal performance while reducing the cost, weight, and volume of the system. These research areas include:

- Advanced thermal interface materials
- Direct backside cooling
- Single and two-phase jet and spray cooling
- Air cooling
- Thermal system modeling.

This paper presents an overview of the research being conducted, with results from laboratory experiments and numerical modeling in each area.

Keywords: power electronics, thermal management, heat exchanger, air cooling, thermal interface material, spray cooling, hybrid vehicle

1. Background

To achieve FreedomCAR goals for cost, weight, and volume (see Table 1), significant advancements in the thermal management of both the power electronics and motors for the electric propulsion system must be achieved [1]. Through the optimization of existing technologies and the expansion of new pioneering cooling methods, higher power densities, smaller volumes, and increased reliabilities can be realized in the electric drive train components. Investigations and advancements into thermal issues can provide a viable path to the successful achievement of the FreedomCAR technical targets, while simultaneously enhancing the ability to apply new technologies in automotive applications as they mature.

The thermal management of electronics and electronic systems represents a major technical barrier to achieving specific FreedomCAR goals in 2020. The current approach to cooling hybrid electric power inverters uses a separate cooling loop with water ethylene glycol coolant at approximately 70°C. This cooling system is used in hybrid electric vehicles (HEVs) in the market, such as the Toyota Prius and Ford Escape. The FreedomCAR program's cost target for the electric traction drive system of an advanced propulsion vehicle is $8/kW of peak power, which is based on achieving a 3-year payback on the incremental vehicle cost. This means that the total traction system (power electronics and electric machines) cost target for a 55kW system is $440. A recent study by Oak Ridge National Laboratory estimated the cost of the power electronics and electric machine cooling loop to be approximately $175 [2]. The development of low cost, effective thermal management for power electronics and electrical machines is critical, not only to the performance and reliability of the electronics system, but also to meeting the program cost targets. To help reduce the costs of the system, it is desirable to use on-board coolants with as few additional components as possible. Two likely scenarios included in the FreedomCAR program roadmap include the use of an engine coolant loop (water ethylene glycol at 105°C) or the use of air cooling [1].

Table 1. Electric Propulsion System Goals and Technical Targets for the year 2020

FreedomCAR Goals	
Peak power	55 kW for 18 seconds
Continuous power	30 kW
Lifetime	>15 years (150,000 miles)
Technical Targets	
Cost	<$8/kW peak [a]
Specific power at peak load	>1.4 kW/kg [a]
Volumetric power density	>4.0 kW/liter [a]
Efficiency (10 to 100% speed, 20% rated torque)	94%

a. Based on a maximum coolant temperature of 105°C

Within this context, a number a thermal control technologies and approaches are possible. The following basic heat transfer relationships are useful in defining the scope of the problem and indicate possible solutions.

(1) $$Q_1 = h\ A\ (T_B - T_C\ )$$

(2) $$Q_2 = \frac{(T_H - T_B)}{(R_{solder} + R_{DBC} + R_{TIM} + R_{baseplate})}$$

(3) $$Q_3 = \dot{m}\ C_p\ (T_{C\,in} - T_{C\,out}\ )$$

Where:

- Q_1 is the amount of heat dissipated to the coolant (W),
- Q_2 is the heat transfer from the device to the baseplate/heatsink (W),
- Q_3 is the heat extracted by the coolant ($=Q_1$) (W),
- h is the heat transfer coefficient (W/m^{2}K),
- A is the area for heat transfer (m^2),
- T_B is the average temperature (°C) at the heat exchanger surface (Figure 1),
- T_C is the bulk temperature (°C) of the coolant,
- T_H is the device junction temperature (°C) (Figure 1),
- R_{solder}, R_{DBC}, R_{TIM}, and $R_{baseplate}$ are the thermal resistances (K/W) of layers within the inverter package,
- $\dot{m}$ is the mass flow rate of the coolant (kg/s),
- C_p is the specific heat of the coolant (J/kg-K),
- T_{Cin}, T_{Cout} are the coolant inlet and outlet temperatures (°C).

This basic, yet powerful set of heat transfer equations defines the controlling parameters of the problem and points to a number of possibilities for addressing the thermal control of power electronic devices.

- The total amount of heat (Q) generated in the electronic device can be reduced by improving device efficiency.
- The heat transfer coefficient (h) can be increased by using more aggressive heat transfer technologies such as jet impingement, spray cooling, and heat exchanger geometry.
- Surface area (A) can be increased by fin shape optimization, micro-surface enhancements, thermal spreading, and package configurations such as double-sided cooling.
- T_B can be increased to improve the thermal driving potential by reducing the thermal resistance within the insulated-gate bipolar transistor (IGBT) structure.
- T_C is likely to be a specified parameter such as 105°C coolant or available air coolant temperature
- T_H is the targeted device junction temperature which can be increased by new materials development such as trench IGBTs (175°C) and silicon-carbide (200°C), but may also depend on temperature limits of other materials within the package such as the solder joints, wire bonds and capacitors.
- The mass flow rate ($\dot{m}$) can be controlled by increasing the coolant flow rate but is limited by the allowable parasitic power and practical considerations such as pump size and coolant system limitations.
- C_p is a function of the coolant at specified conditions.

Achieving the goals of the program will likely require addressing multiple aspects of the relations described above. Ultimately, the most challenging part of the problem may be the cost target. The following sections summarize a number of research projects being conducted at NREL to address these issues.

2. Thermal Control Technologies

2.1 Thermal Interface Materials

Thermal interface materials (TIM) such as thermal grease pose a major bottleneck to heat removal from the IGBT package. Inverter packages still predominantly use thermal grease. This grease layer can contribute almost 40 to 50% of the total thermal resistance of the different layers in the package. Reducing the thermal resistance of the TIM can significantly aid in the FreedomCAR Program's goals of using glycol water at 105°C or even air cooling.

Figure 1 shows the different layers constituting a typical IGBT package in an inverter. In this case, the silicon die is soldered to the direct bond copper (DBC) layer, which is composed of an aluminum nitride layer sandwiched between two copper layers. In a typical IGBT package, the DBC layer is attached to the aluminum heat sink via an interface of thermal grease. Because of manufacturing variability, the DBC and cold plates have surface irregularities that lead to voids in the surface-to-surface contact. The TIM is used to help fill up these gaps and provide improved thermal contact. The interface material typically ranges from 25 microns to 100 microns in thickness and is a major contributor to the thermal resistance in the package.

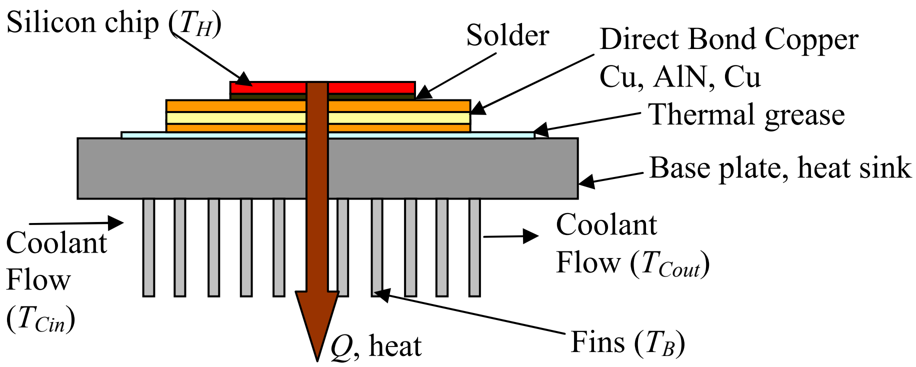


Figure 1. Different layers constituting the IGBT package in an inverter

To assess the current state of technology, NREL acquired a test stand based on the ASTM D 5470 test method [3] for measuring thermal resistance. The intent of acquiring the test stand was to characterize the thermal performance of novel as well as state-of-the-art thermal interface materials that are suitable for automotive applications and develop an unbiased, consistent database. Figure 2 shows the test apparatus in the Electrical Systems Laboratory at NREL, as well as details about the components of the test stand. The basic principle of ASTM D5470 has been outlined in a report to the DOE) [4]. Figure 2(b) shows the various components of the apparatus, which includes the hot plate with the cartridge heaters embedded in it, the cold plate with silicone oil circulating through it, the spreader blocks, the metering blocks, the resistance temperature detectors for accurate temperature measurement, and the pneumatic press for applying load on the sample under test.

We are testing a matrix of samples provided by industry partners and TIM suppliers. Thermal resistance measurements from the initial round of five thermal greases tested at NREL are in the range of 26.5 to 208 mm^2K/W for a TIM thickness of 75 microns. Each grease was tested at multiple thicknesses ranging from 25 to 150 microns. The measurement includes the bulk resistance of the material and surface contact resistance. It is worth noting here that the units for thermal resistance are in mm^2K/W, i.e. on a per unit area basis. While our tests showed good agreement with several manufacturers' specifications, two samples showed a large discrepancy. This is evidence of indications from industry partners that the in-situ performance of these materials does not always agree with the specifications. Additional testing is needed to bear this out. Another important aspect is that there are no universally accepted standards for thermal resistance measurements. We are currently collecting many more materials for testing, including several more greases along with pads, phase change materials, metallic TIMs, graphite-based TIMs, and carbon nanotubes. Results from these tests will be published later in the coming year.

To understand the impact of thermal resistance on chip temperatures, a 3D thermal finite element model of a typical inverter package was developed in ANSYS software. The domain used for the simulation is shown in Figure 3. Figure 3(a) shows an IGBT half-bridge, while Figure 3(b) shows a close-up revealing the different layers constituting the IGBT package.

(a) (b)

Figure 2. Test apparatus for thermal resistance measurements: (a) facility setup at NREL, (b) apparatus

(a) (b)

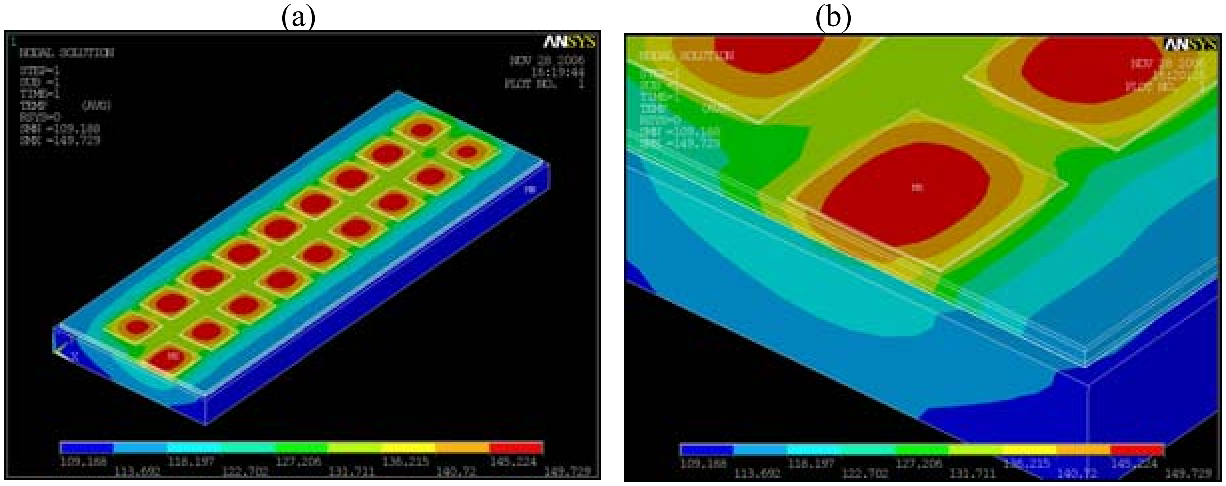


Figure 3. Domain for ANSYS 3D conduction model for illustrating the impact of TIM on the temperature fields: (a) IGBT half-bridge, (b) close up showing part of the structure and the different layers

For the simulations, the coolant temperature was fixed at 105°C, representing a glycol-water mixture at 105°C. Except for the resistance of the interface material, all other material properties in the model are based on a typical IGBT package. The heat flux was fixed at 100 W/cm^2 and the convective heat transfer coefficient used on the back of the aluminum baseplate was set at 50,000 W/m^{2}K. This represents an aggressive liquid cooling scheme. Figure 4 shows the impact of the TIM thermal conductivity on the maximum die temperature. The baseline case shown corresponds to the best of the grease samples measured at NREL with a thermal conductivity of 3.7 W/m-K. For the analysis the grease thickness was set at 75 microns for a thermal resistance of 26.5 mm^{2}K/W. The 5x TIM case corresponds to a TIM thermal resistance of 5.3 mm^{2}K/W (5-times lower than the baseline), while the 10x TIM case corresponds to 2.65 mm^{2}K/W. It should be noted that the thermal resistance values include the material bulk thermal resistance as well as the contact resistance.

Figure 4 shows that for the baseline case, there is a significant temperature jump across the TIM (approximately 17°C). For the 5x TIM case, the temperature rise across the TIM is small (about 4°C), while for the 10x TIM case, the temperature rise is even smaller (about 2°C). Interestingly, increasing the thermal conductivity beyond 5x does not significantly change the maximum die temperature. This implies that once the thermal resistance of the interface material is not the dominating resistance, it does not matter if its resistance is reduced further. Other layers in the package start dictating the thermal map of the package. It is also worth noting that the baseline case corresponds to a TIM thermal resistance of 26.5 mm^2K/W. If a higher thermal resistance were chosen as the baseline (which could be the case in an actual inverter), the impact of TIM resistance on the temperature results would be even more dramatic.

While the focus here is on the automotive power electronics cooling, it is worth noting that thermal interface materials also play a key role in connecting various components of the thermal solution in the microelectronics industry [5]. The continual increase in cooling demand for microprocessors has led to increased focus on improving the thermal interface materials. Significant advances have been made in the development of thermal greases/gels, phase change materials, solders, phase change metallic alloys, advanced polymers, and carbon nanotubes as interface materials.

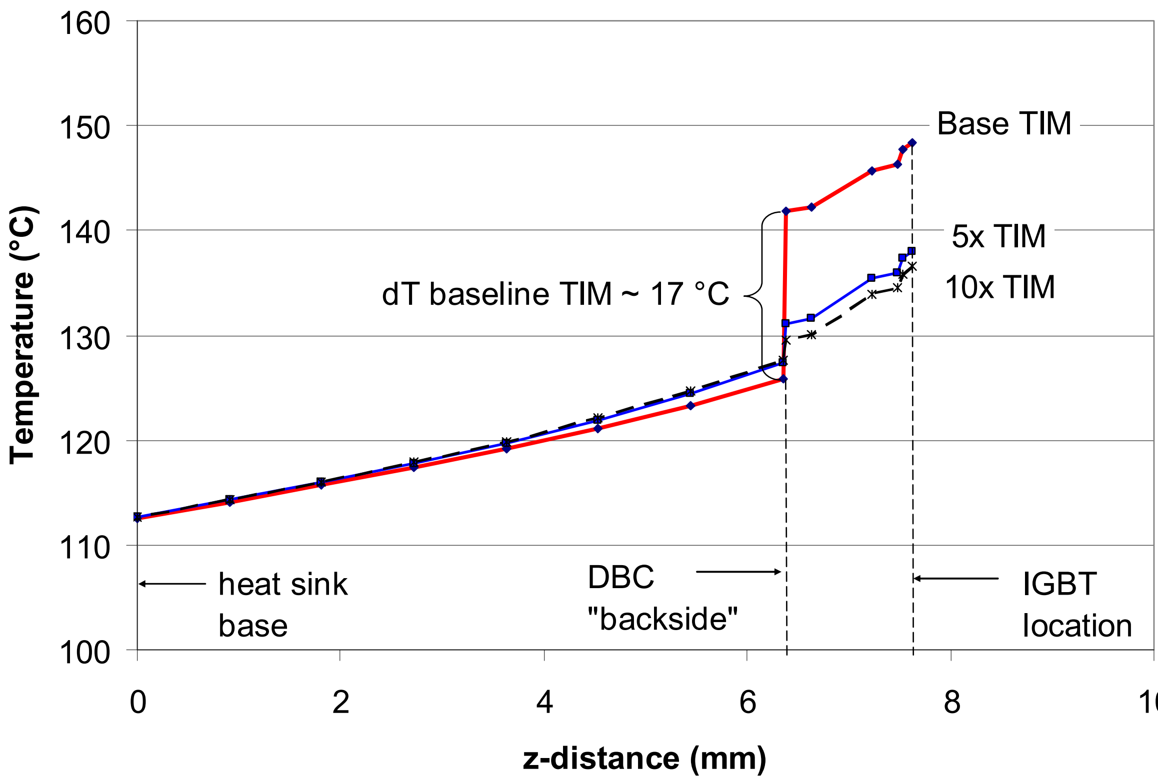


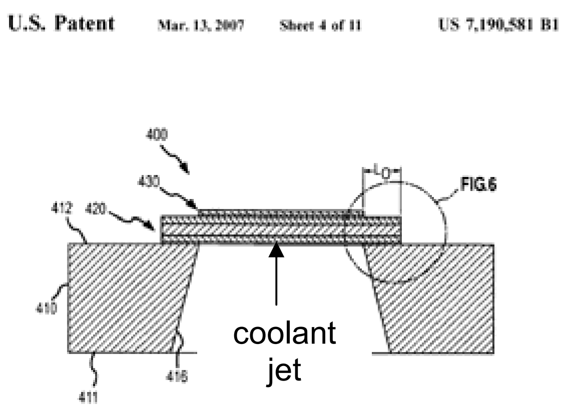
Figure 4. Temperature impacts of TIM thermal resistance for base TIM, 5-times lower resistance, and 10-times lower resistance

2.2 Direct Backside Cooling

While the improvement of TIMs has the potential to significantly reduce the package thermal resistance and maximum junction temperature, another approach is to develop new packaging alternatives that completely eliminate the need for TIMs. NREL has recently developed a patented IGBT structure (US Patent # 7190581) that eliminates several layers in the package structure to enable its effective cooling with a 105°C inlet coolant temperature [6]. In the patented design, holes are cut through the base plate all the way to the backside of the DBC (see Figure 5(a)). Nozzles are positioned under the DBC with coolant jets impinging on the backside. The nozzles are positioned such that the jets are directly under the IGBTs and diodes. Because the coolant comes in direct contact with DBC, thermal resistance between the power module and the heat exchanger is eliminated. This design combines the benefits of reducing the overall thermal resistance and applying high convective heat transfer coefficients. A recently published state-of-the-art review of high heat flux cooling technologies refers to direct back side cooling as a very promising technology in the near future [7]. NREL has developed thermal and structural models of the proposed low thermal resistance architecture to assess the design feasibility. Simulations showed very promising results, with overall package thermal resistance reduced by as much as 60%. The weight of the base plate could be reduced as portions of the base plate are eliminated to allow direct coolant access to the DBC. We modeled this structure with various hole sizes, and performed structural and thermal analyses for it (Figure 5(b)).

Figure 6 shows the results of an NREL thermal analysis, showing typical temperature differences across different layers for the conventional IGBT structure and also the low thermal resistance IGBT structure. For the conventional IGBT structure, the temperature increase from the heat exchanger's surface to the chip is about 35^{o}C. The low thermal resistance IGBT structure allows thermal grease to be completely eliminated and the temperature difference is only about 8^{o}C.

(a)



(b)

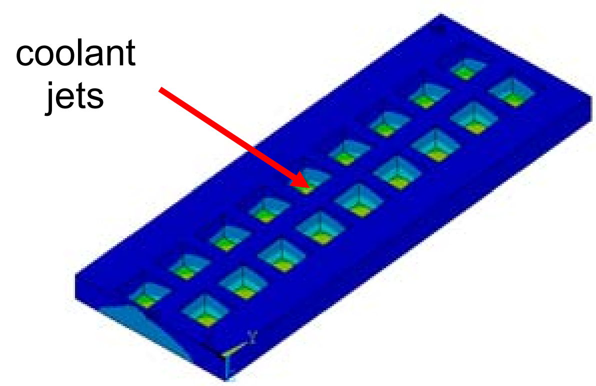


Figure 5. Direct backside cooling of power inverter, (a) cross-section of NREL patented backside cooling, (b) direct backside cooling thermal model

The low thermal resistance IGBT structure with direct backside cooling could have a significant impact on the thermal control of power electronics. If successful, this technology could enable the US automotive industry to eliminate a separate cooling loop and also allow the use of engine coolant at 105°C to cool the power electronics unit directly. This approach also has the potential of reducing the weight of the heat exchanger. In the existing technology, the heat exchanger may represent as much as 30% of the weight of an inverter. The direct backside cooling apparatus shown here could reduce that portion to 20% of the total weight of the inverter. While not fully optimized, our simulations have shown that the current technology using serpentine channel fin heat exchangers can remove approximately 60 W/cm^2; the low resistance IGBT structure could remove 100 W/cm^2 with 105°C coolant, or 2/3 more heat. The direct backside cooling approach appears very promising in terms of cost, weight, and volume reductions. A number of technical challenges, such as the long term reliability of the required seals and the potential for erosion at the DBC, still remain. Additionally, aspects of the design, such as the nozzle geometry, have yet to be fully optimized. NREL will be conducting experimental investigations of these attributes with a prototype heat exchanger assembled onto an industry supplied inverter. We will also be working with an industry partner to demonstrate the concept integrated with an inverter.

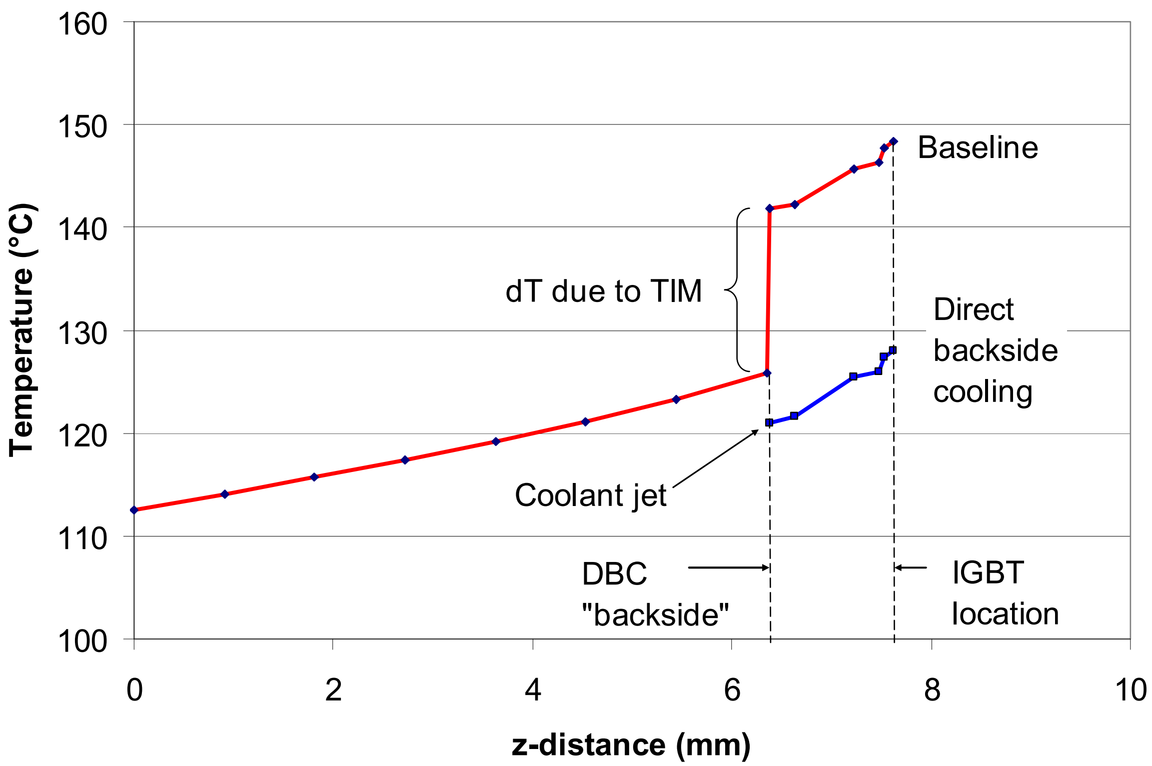


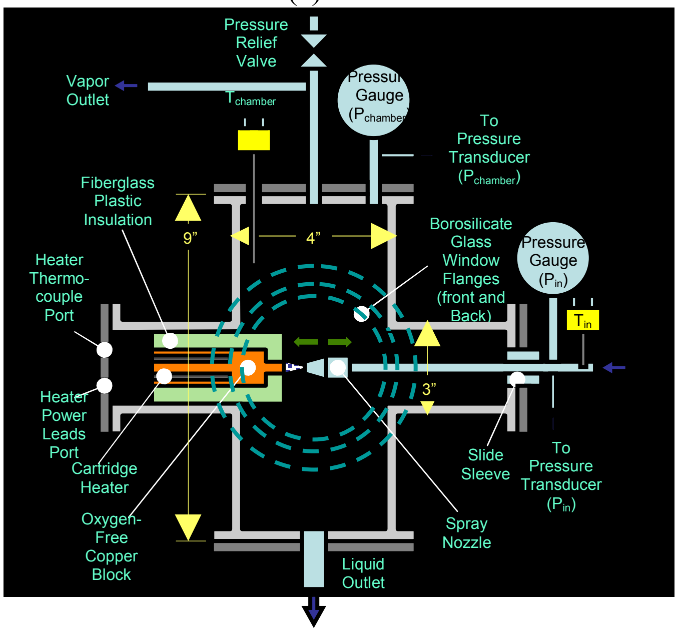
Figure 6. Temperature at different layers for the conventional IGBT structure for baseline configuration vs. a direct backside cooling approach

2.3 Two-Phase Sprays and Jets

In addition to our efforts with direct backside cooling with liquid jets, we are also exploring impinging jets with phase change to cool the IGBT package. Our initial efforts have focused on identifying appropriate coolants for the two-phase application [8] and in developing computational fluid dynamics models of the two-phase jet impingement process [9, 10]. R134a (currently used in automotive air conditioning systems) and HFE7100/7200 have been identified as fluids which are particularly suitable for use as coolants for automotive applications [8, 11]. HFE7100 and HFE7200 have good thermal and dielectric properties, can be used at atmospheric pressure, have low global warming potential, and zero ozone depletion potential.

During this past year, NREL worked with Mudawar Thermal Systems to fabricate a test vessel/experimental apparatus that would enable experiments with jets and sprays in the two-phase regime. The test apparatus and a cross section of the test vessel are shown in Figure 7. The test surface area 10x10 mm, which is a typical semiconductor switch size. The test surface is the top surface of an oxygen-free copper block, which is surrounded by fiberglass insulation. Cartridge heaters supply heat on the bottom side of the copper block. One thermocouple is embedded into the copper block and the temperature of the center of the copper block close to the target surface is measured. The surface temperature is backed out from a thermal conduction analysis. The liquid inlet temperature, the liquid flow rate, the temperature in the chamber, the pressure in the chamber, and the inlet pressure are all measured. Further details of the apparatus have been provided in an NREL report to DOE on spray cooling [9].

(a)



(b)

Figure 7. (a) Cross-section of the test vessel, (b) Snapshot of the entire two-phase loop

A number of experiments have been completed with HFE7100, spanning a range of flow rates for both jets and sprays. Spray nozzles were acquired from an industry vendor, while rectangular slot jets (0.25 mm width) were used for the jet impingement experiments. Figure 8 shows sample boiling curves for spray and jet experiments. Figure 8(a) shows a sample spray experiment in which the fluid inlet temperature is 32.3°C and the rest of the parameters are indicated on the graph. The effective heat transfer coefficient at critical heat flux (CHF=245 W/cm^2) is about 31,370 W/m^{2}K.

For the sample jet experiment (Figure 8(b)), the fluid inlet temperature is 34.8°C and the effective heat transfer coefficient at CHF (222 W/cm^2) is 26,942 W/m^{2}K. Broadly, this set of experiments demonstrates the conditions under which 200 to 240 W/cm^2 can be dissipated from a heated surface using HFE7100 as the fluid.

To understand these results in the context of IGBT package cooling, we performed numerical modeling in FLUENT. Figure 9 shows the domain that was used for this analysis. In this model, the silicon die temperature was maintained at 125°C and appropriate heat transfer coefficients mentioned have been imposed on the copper as well as the aluminum layers as shown in Figure 9. Figure 9(a) indicates the performance of a spray while Figure 9(b) shows the performance of a jet. The results show that jets and sprays of HFE7100 could be used to extract upwards of 200 W/cm^2 while keeping the die temperature at 125°C.

While the heat transfer performance of two-phase jets and sprays appear to meet the program requirements, the greatest challenge will be to develop a system that has an acceptable overall system cost. Outstanding thermal performance may allow the individual electronic switches to be operated at higher power levels, which could reduce the system cost and the number of devices.

(a) (b)

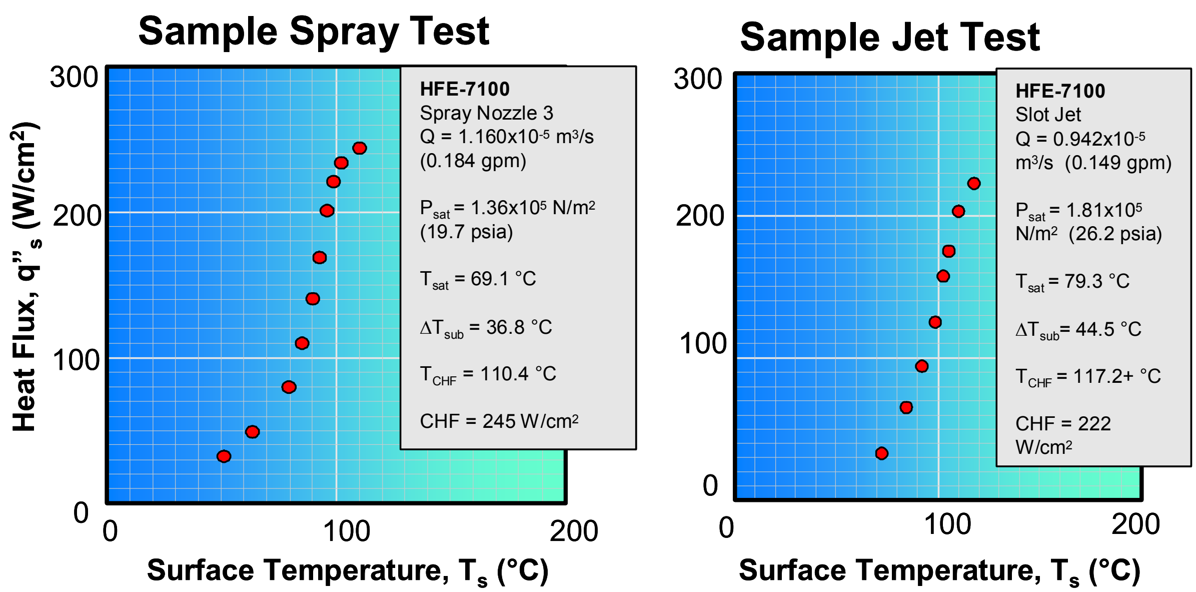


Figure 8. (a) Boiling curve for a sample spray experiment, (b) Boiling curve with a sample slot jet experiment

(a) (b)

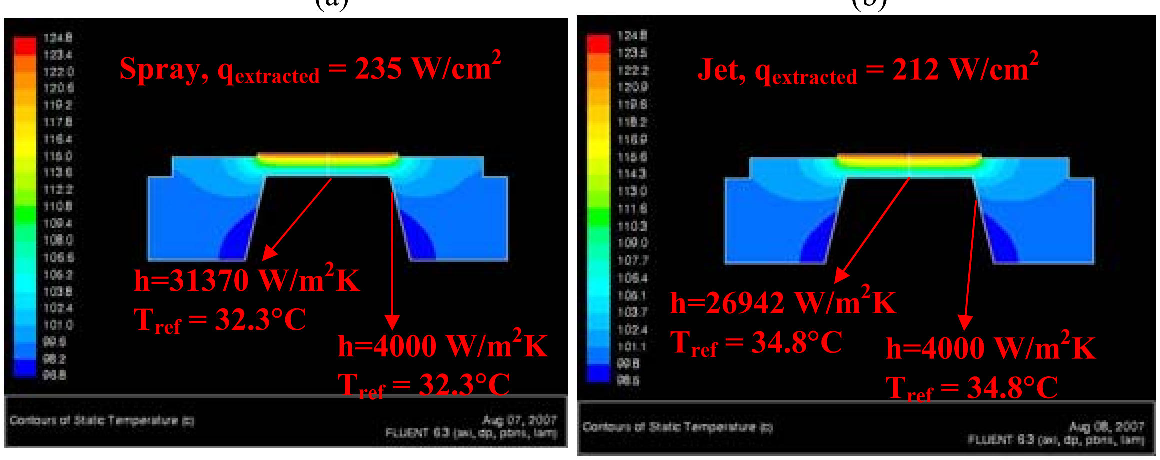


Figure 9. (a) Performance of an HFE 7100 spray, (b) Performance of an HFE 7100 jet

2.4 Air Cooling Systems

The use of air as a coolant for silicon switches remains an attractive option. The use of air for cooling has many advantages. Air remains the ultimate heat sink for all heat rejection from an automobile. All the heat rejected, either directly or through the use of an intermediate coolant loop, must end up in the air. The direct use of air can eliminate many components of the cooling loop and the necessity for carrying a secondary coolant.

Ambient air is assumed to be available at a nominal 30^{o}C for all the vehicle cooling strategies. The use of such air increases the overall temperature-driving potential available to reject heat from the chips. Air, when used as the cooling medium, is benign, nontoxic, and free when compared to many other fluids. Airflow is also amenable to being modulated in a transient manner to suit the needs of the system, as the system load varies during operation.

Air cooling has many drawbacks as well. Air is a poor heat transfer medium, with low thermal conductivity and low density. A fan or a compressor must move the airstream to the required hot spots, requiring additional parasitic power loads. The coefficient of performance for such a system tends to be low.

Figure 10 shows a typical arrangement for using air as the cooling fluid. Ambient air is drawn through an appropriate filter, then forced by a centrifugal fan and distributed via manifolds over micro-channel heat exchangers located in close proximity to the heat-generating sources. Heat is transmitted via highly conductive fins that also possess high surface areas for heat transfer. Laminar flow, established in the micro-channels adjacent to the fins, convects heat from the fins to the exiting airflow.

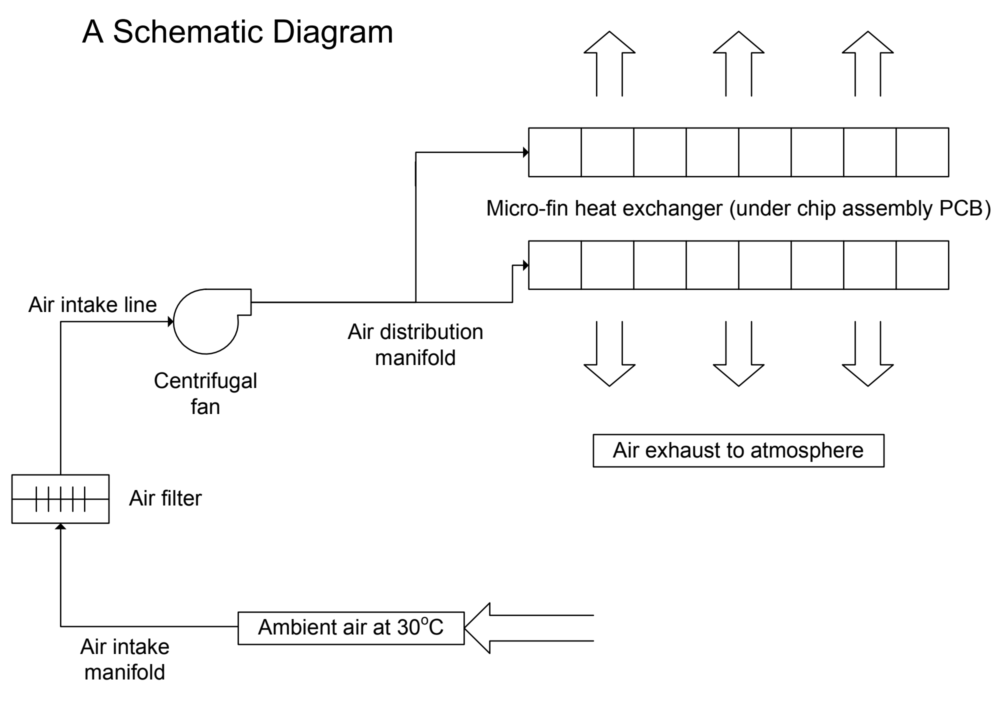


Figure 10. Schematic diagram for cooling power electronics with air

Typical industrial airflow applications nominally achieve a heat transfer coefficient of about 40 W/m^2K. If we use this value, the required surface area is about 800 cm^2. That is, the heat generated in the chip area of nominal 1 cm^2 must be spread out over an area larger by a factor of 800. This requirement indicates that typical industrial air heat transfer coefficients fall well below the needs to accomplish the task at hand.

Critical applications for air cooling occur in applications related to gas turbine blade cooling. Extremely high-heat fluxes must be removed to maintain a lower temperature at the turbine blades. The gas turbine industry, federal labs, and universities are expending significant effort to research blade cooling. Cooling for power electronic components can benefit from many of these studies related to blade cooling.

As an example of such an application, Marques and Kelly [12] report on the fabrication and performance of micro-pin fin arrays. Their studies use 500-µm diameter fins in air passages that are 500 µm apart. They report air-side heat transfer coefficients of up to 8000 W/m^2K.

Micro-channel geometries can enhance the heat transfer coefficient and provide large area enhancements. We found two types of devices that are currently being offered as cooling devices for personal computer central processor units (CPUs). These are microchannel devices and microjet arrays. Figure 11(a) shows the internal elements of a CPU cooler with micro-channels and Figure 11(b) shows a micro-jet array. (Courtesy Preytek Co., Inc., and International Mezzo Technologies, Inc., respectively).

(a) (b)

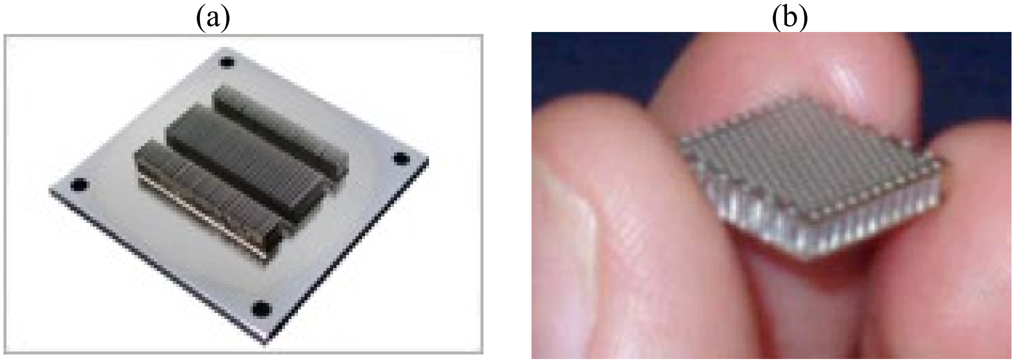


Figure 11. Photographs of micro-channel and micro-jet devices (Courtesy Preytek Co. Inc., and International Mezzo Technologies, Inc., respectively).

We have developed thermal analysis and computational fluid dynamics models for both micro-jets and micro-channel arrays. Our models have shown that for air flow through the micro-fin channels, with copper as the fin material and base plate held at 125°C, we were able to achieve heat fluxes in the range of 60 W/cm^2 to 180 W/cm^2. With aluminum as the fin material the range was 50 W/cm^2 to 150 W/cm^2.

Cooling with air may or may not meet the requirements for the current generation of silicon-based devices that require the maximum temperatures at the chip be limited to 125°C. Future technologies, however, are expected to allow higher temperatures at the chip, with the trench IGBTs operating at 175°C and SiC devices operating at even higher temperatures. With these higher temperatures, air cooling may become practical.

2.4 Thermal Systems Requirements

The objective of NREL's thermal systems research is to facilitate the integration of FreedomCAR thermal control technologies into commercially-viable advanced automotive systems, including hybrid electric, plug-in hybrid electric, and fuel cell vehicles. To do this we are evaluating the thermal control technologies developed and characterized in our laboratory in a thermal systems context. Three areas of information are needed to effectively carry out this task:

1. Better understanding of the dynamic system cooling needs (i.e., thermal duty cycles)
2. Understanding of the performance characteristics of the various thermal control technologies that have been proposed (obtained from modeling and our laboratory work) and
3. Understanding of the system implications and trade-offs of various thermal control technologies from (2) to address the cooling needs of (1) in terms of performance, weight, volume, cost, and reliability.

To investigate power electronics cooling requirements, we examined data collected on the standard version of the Toyota Prius Hybrid Electric Vehicle (HEV) as well as a plug-in hybrid electric vehicle (PHEV) conversion of the same vehicle at the NREL. We used efficiency data for the Prius's main traction motor and inverter from work conducted by Oak Ridge National Laboratory and supplemented this with simulation work using Argonne National Laboratory's PSAT model of the Toyota Prius HEV system. Figure 12(a) shows a flow diagram of the integrated analysis tools that were used where MG2 refers to the electric traction motor. Figure 12(b) shows a sample of the simulated heat generation predicted over the aggressive US06 driving cycle. Standard urban and highway dynamometer cycles and an on-road were also simulated.

(a) (b)

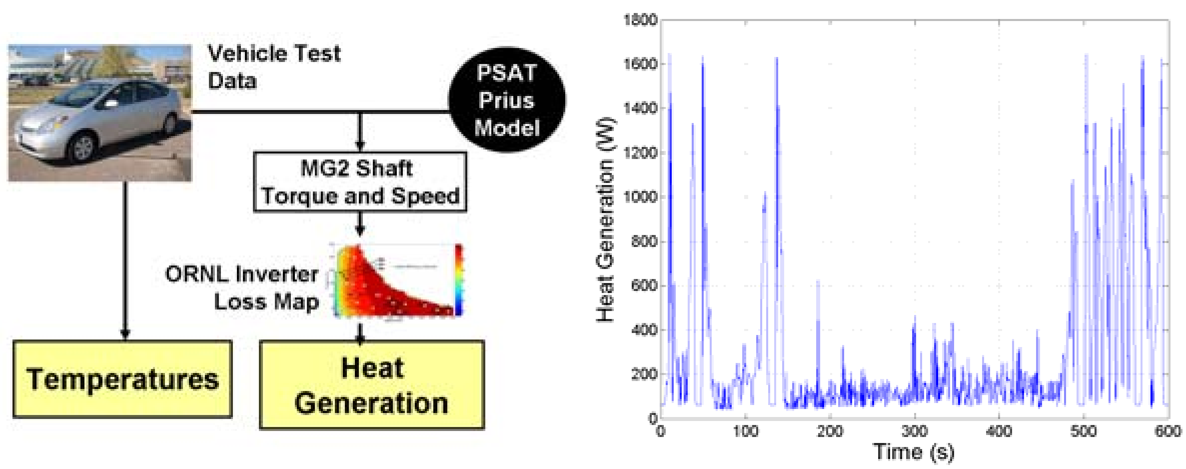


Figure 12. Modeling of power electronics dynamic heat generation: (a) integrated modeling process, (b) dynamic heat generation profile for Prius inverter on US06 driving cycle.

Results from the simulated drive cycles showed that heat generation in the Prius traction motor inverter is less than 1700 W with cycle-averages of heat generation from 100 to 300 W typical over the 12 IGBTs and 12 diodes. Heat generation events that approach 1700 W are brief in duration lasting several seconds. The Prius motor was observed to generate peak power only up to 44 kW during our testing with cycle-averages of motoring power ranging from 4-13 kW over the simulated cycles. This is significantly less than the 55 kW peak and 30 kW continuous targets required by the FreedomCAR program. Thus, the thermal duty cycles required by the FreedomCAR targets would be more intense than those predicted for the Prius. Additional details from this analysis are included in a separate NREL report to DOE [13].

With growing awareness and interest in PHEVs, the need to understand the potential impacts on the power electronics and electric machines is apparent. NREL recently conducted a study to quantify the impact that PHEV duty cycles may have on power electronics and electric machines. The study confirmed that the electric traction drive's continuous power requirement increases for PHEVs relative to HEVs. The increase in continuous power leads to an increase in the thermal demands on the electric traction drive components. Increased thermal load may require significant thermal control improvements to the electric motor. While incremental improvements power electronics thermal control may be required relative to current production HEV components that use dedicated liquid cooling. Details from this investigation will be published in the coming year.

Parametric investigations on system implications for the previously discussed thermal control technologies being developed at NREL were carried out analytically (i.e., via computational design tools) using a design of experiments approach. Details of this study were recently published [14]. This investigation examined how various design factors affect the steady-state maximum heat dissipation of an inverter package under various semiconductor device junction temperature constraints. The design factors we examined are coolant temperature, number of sides available for cooling, effective heat transfer coefficient, maximum semiconductor junction temperature, and interface material thermal resistance. Three different inverter package configurations were evaluated in the analysis

The study concluded that heat dissipation of 200 W/cm^2 over both IGBT and diode surface areas may be possible with coolant temperatures of 105^{o}C and above, coupled with a maximum junction temperature of only 125^{o}C, using advanced package designs (integrated heat sink (IHS) or direct backside cooling (DBSC)) with double-sided cooling and an aggressive heat transfer coefficient (see Figure 13). With the existing set of cooling technologies investigated, no single-sided cooling solutions were found to be able to dissipate the 200 W/cm^2 FreedomCAR target heat flux using 105^{o}C coolant and a maximum junction temperature of 125^{o}C. Even with more advanced materials that enable a junction temperature tolerance of 200^{o}C, a dedicated heat transfer design is needed to dissipate heat fluxes of 200 W/cm^2 over the IGBT and diode surface areas for a single die. Free convection does not appear to be an option for the surface areas and dissipation rates needed, even at 200^{o}C junction temperature.

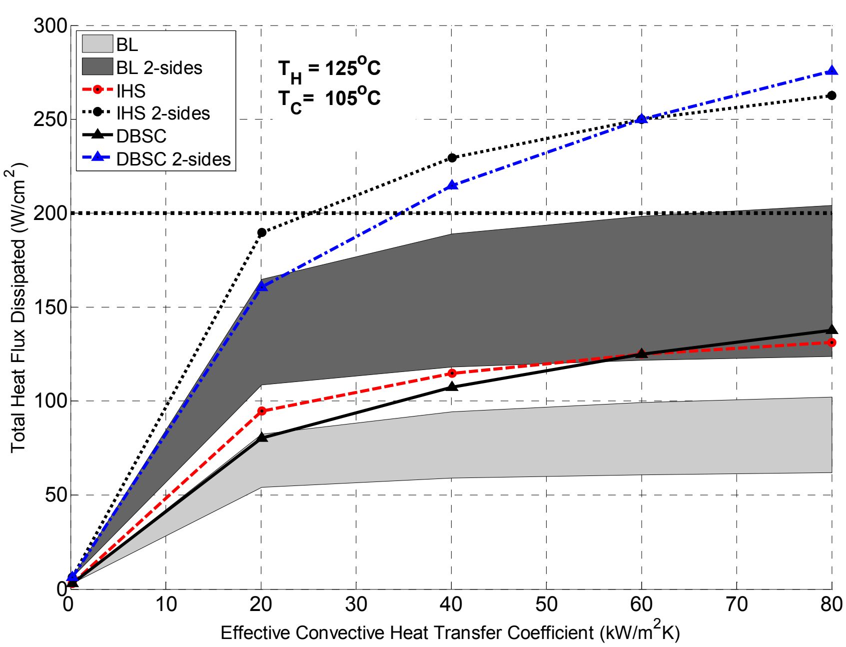


Figure 13. Results of parametric study showing total heat flux dissipation for various effective convective heat transfer coefficients and coolant temperatures

3. Conclusions

The thermal management of electronics and electronic systems represents a major technical barrier to achieving specific FreedomCAR goals in 2020. The current approach for cooling hybrid electric power inverters uses a separate cooling loop with water ethylene glycol coolant at approximately 70°C. This approach is costly relative to the overall 2020 cost target of $8/kW for a 55kW traction system. Two likely scenarios included in the FreedomCAR program roadmap are the use of an engine coolant loop (water ethylene glycol at 105°C) and the use of air cooling.

NREL is conducting research and development on a number of thermal control technologies aimed at improving thermal performance while reducing cost, weight, and volume of the system. Both single phase and two-phase jets and sprays have the potential to dissipate significant amounts of heat fluxes (up to 200 W/cm^2) from the silicon die. This will help in reducing the area and number of devices required, hence reducing the cost, weight and volume of components. Thermal interface materials with resistances in the range of 3 to 5 mm^2K/W can greatly assist in the realization of the FreedomCAR program goal of using engine coolant at 105°C or air cooling. Cooling with air may or may not meet the requirements for the current generation of silicon-based devices that require the maximum temperatures at the chip be limited to 125°C. Future technologies, however, are expected to allow higher temperatures at the chip, with the trench IGBTs operating at 175°C, and SiC devices operating at even higher temperatures. With these higher temperatures, air cooling may become more practical.

Each of the cooling options discussed has an impact on the overall power electronics system complexity, cost, weight and volume, and achieving the goals of the program will require addressing these issues. Ultimately, the most challenging part of the problem may be meeting the aggressive cost target.

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