Thermal Management of Electric Vehicle

Power Electronics

Introduction

The U.S. Department of Energy (DOE) Freedom CAR Program sets certain goals and technical targets for the electric traction system (consisting of power electronics and electric machines) of advanced vehicles [1]. These requirements are designed so that hybrid electric vehicles (HEV) and electric vehicles (EV) gain enough market penetration to ensure a significant reduction in United States' dependence on foreign oil. In order to achieve these targets, significant reductions in volume, weight and cost of the thermal management system have to be achieved. At the same time, the performance and lifetime requirements have to be met. This paper reviews possible approaches for replacing the current cooling system used in hybrid electric vehicles (HEVs).

Background

Power electronics (inverters, DC-to-DC converters, etc.) are vital to hybrid electric vehicles (HEVs), constituting the interface between the energy sources and the traction drive motor. DOE's FreedomCAR program establishes goals and technical targets for the electrical traction system of advanced vehicles. These requirements are summarized in Table 1.

Thermal management of vehicle electronic systems represents a major technical barrier to achieving those goals. The current approach for cooling hybrid electric power inverters uses a distinct cooling loop with water ethylene glycol coolant at

FreedomCAR Goals	
Peak power	55kW for 18 seconds
Continuous power	30kW
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%

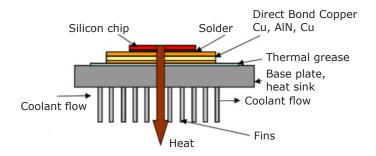[a] Based on a maximum coolant temperature of 105°C

Table 1. Electric Propulsion System Goals and Technical Targets for Year 2020 [1]

about 70 ^{o}C. Researchers at Oak Ridge National Laboratory estimated the cost of the cooling system for power electronics and electric machine to be approximately $175 [2]. Clearly, this solution does not meet the future targets for cost, performance and size. 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 decrease the costs of the system, it is desirable to use on-board coolants with minimal additional components as possible. Two possible approaches 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].

Several ways of reducing the junction to ambient thermal resistance have been investigated [1]. These include new thermal interface materials (TIM), new package designs and enhanced convection.

a) Thermal Interface Material

Critical semiconductor elements in an inverter are insulated gate bipolar transistors [IGBT] and diodes. Figure 1 shows the different layers constituting a typical IGBT package in an inverter. 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. The thermal resistance of the grease layer can contribute 40 to 50 % of the total thermal resistance of the package [3]; therefore reducing this resistance can significantly aid in achieving the goal of eliminating the separate cooling loop currently used in hybrid electric vehicles. Figure 2 shows test results for several grease samples [1]. The baseline case shown corresponds to the best of the grease samples measured at National Renewable Energy Laboratory (NREL) with a thermal conductivity of 3.7 W/m-K. 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.

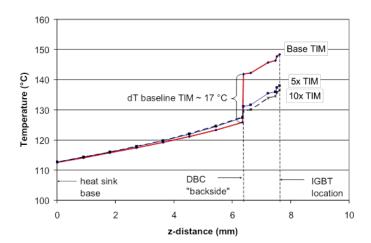Figure 1. Typical Inverter Package Composition [1]

Figure 2. Influence of TIM Thermal Resistance on Die Temperature [2]

Figure 2 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). It is interesting to note that increasing the TIM's thermal conductivity beyond 5x does not significantly change the maximum die temperature.

b) Direct Backside Cooling

Another approach to reducing the package thermal resistance is NREL's patented technology [4]. Holes are cut through the base plate all the way to the DBC backside. Nozzles are placed under the DBC with coolant jets impinging on the backside. The nozzles are positioned in such a fashion that the jets are directly under the IGBTs and diodes. This design combines the benefits of reducing the overall thermal resistance and applying high convective heat transfer coefficients. This solution eliminates the need for TIM by removing several layers in the stack up. Figure 3 (a) shows a cross section of the novel package design; Figure 3 (b) presents a snapshot of the model used for structural and thermal analyses.
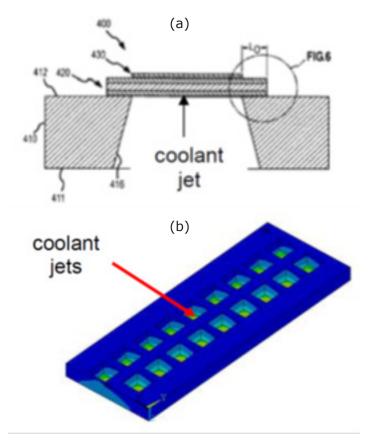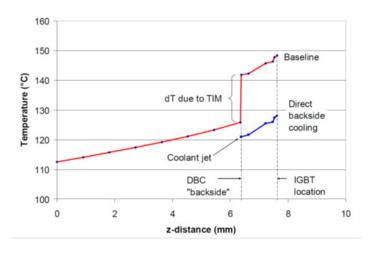
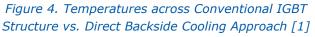Figure 3. Direct Backside Cooling of a Power Inverter [1]

Figure 4 shows typical temperature differences across different layers for the conventional IGBT structure versus 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°C. The low thermal resistance IGBT structure shows a temperature difference of only about 8°C.

c) Two Phase Sprays and Jets

Further increase in the heat transfer coefficients achieved in direct backside cooling with liquid jets can be realized by using impinging jets with phase change. R134a (currently used in automotive air conditioning systems) and HFE7100/7200 have been identified as fluids suitable for use as coolants for automotive applications. HFE7100 and HFE7200 have good thermal and dielectric properties, can be used at atmospheric pressure and are environment friendly. A cross section of the test vessel used for two phase cooling experiments is shown in Figure 5.

Simulations showed that the overall package thermal resistance reduced by as much as 60%. The low resistance IGBT structure could remove 100 W/cm^2 with 105°C coolant, or two thirds more heat than current technology [1].

Figure 4. Temperatures across Conventional IGBT Structure vs. Direct Backside Cooling Approach [1]
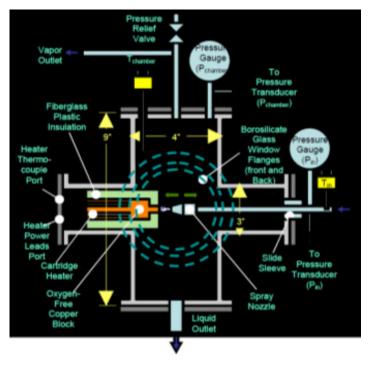

Figure 5. Cross Section of the Test Vessel [1]

Several experiments have been completed with HFE7100 as working fluid, spanning a range of flow rates for both jets and sprays [1]. Commercially available nozzles were used for spray experiments, while rectangular slot jets (0.25 mm width) were used for the jet impingement experiments. Fig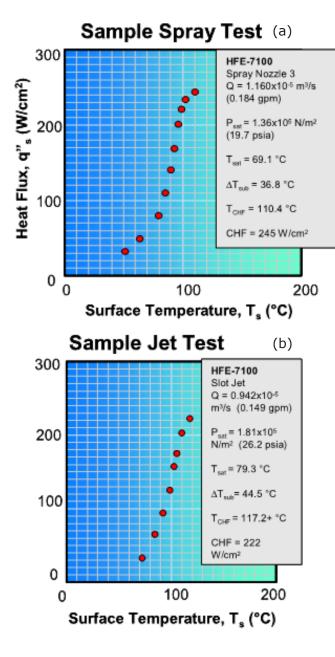ure 6 shows sample boiling curves obtained. Figure 6(a) shows data points collected for a spray experiment in which the fluid inlet temperature is 32.3°C. The effective heat transfer coefficient at critical heat flux (CHF=245 W/cm^2) is about 31,370 W/m^{2}K. For the sample jet experiment (Figure 6(b)), the fluid inlet temperature is 34.8°C and the effective heat transfer coefficient at CHF (222 W/cm^2) is approximately 27,000 W/m^{2}K. This set of experiments demonstrates that heat fluxes of 200 to 240 W/cm^2 can be dissipated from a heated surface using HFE7100 as the working fluid.

d) Air Cooling

The use of air as a coolant for vehicle power electronics is an attractive option. The direct use of air simplifies the cooling loop and eliminates the need of a secondary coolant. Figure 7 shows a typical arrangement for using air as the cooling fluid. Ambient air is filtered, then pressurized and distributed via manifolds over micro-channel heat exchangers situated near the heat-generating sources.

In order to be able to dissipate the heat fluxes generated by vehicle's power electronics, high convective heat transfer coefficients are needed. Micro-channel geometries can enhance the heat transfer coefficient and increase the surface area available for convection cooling. Two such commercially available devices are presented in Figure 8.

Figure 6. Sample Boiling Curves for Spray and Jet Experiments [1]
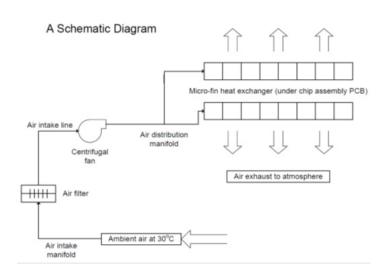
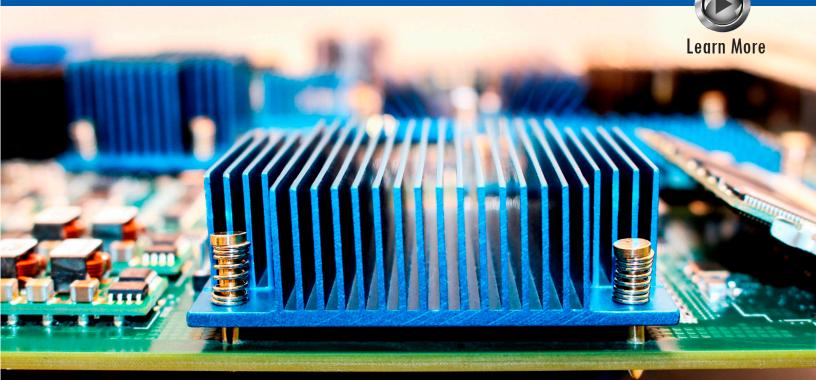Figure 7. Schematic Diagram for Air-Cooling Power Electronics [1]

Figure 8 shows a CPU cooler with micro-channels (a) and a micro-jet array (b). Thermal models developed at NREL [1] show that for a micro-channels configuration, with copper as fin material and base plate maintained at 125 ^{o}C, heat fluxes from 60 to 180 W/cm^2 can be dissipated.
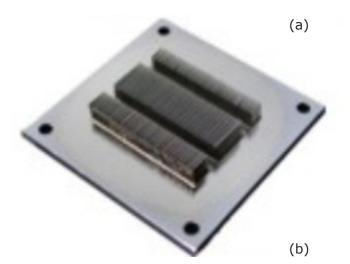
Conclusions

The thermal management of advanced vehicles power electronics constitutes a major technical barrier to achieving specific FreedomCAR goals for 2020. Currently, hybrid electric power inverters are cooled with a separate loop using water ethylene glycol at approximately 70°C as coolant. This approach is costly relative to the overall 2020 cost target of $8/kW for a 55kW traction system. Two suggested approaches included in the FreedomCAR

(a)

(b)

Figure 8. Schematic Diagram for Air-Cooling Power Electronics [1]

program roadmap are the use of an engine coolant loop (water ethylene glycol at 105°C) and the use of air cooling.

Several thermal management solutions aimed at improving thermal performance while reducing cost, weight, and volume of the system have been investigated. Thermal interface materials with resistances in the range of 3 to 5 mm^{2}K/W can greatly assist in the realization of the FreedomCAR program goal of using engine coolant at 105°C or air cooling. Direct backside cooling, both in single phase and two-phase configurations, has the potential to dissipate significant amounts of heat fluxes (up to 200 W/cm^2) from the chip. Although direct backside cooling appears very promising, several technical challenges, such as reliability of

the seals and potential erosion at DBC, have to be overcome. Air cooling shows a lot of promise, especially with future technologies expected to allow higher chip junction temperatures (for example, high temperature IGBTs operating at 175°C and SiC devices operating at even higher temperatures).

References:

1. **Kelly, K.J., Abraham, T.,Bennion, K., Bharathan, D., Narumachi, S. and O'Keefe, M. "Assessment of Thermal Control Technologies for Cooling Electric Vehicle Power Electronics", 23rd International Electric Vehicle Symposium (EVS-23), Anaheim, California, December 2-5, 2007.**

2. **O'Keefe, M., and Bennion, K.," Comparison of Hybrid Electric Vehicle Power Electronics Cooling Options", Vehicle Power and Propulsion Conference, Arlington, Texas, September 9-12, 2007.**

3. **Advanced Thermal Solutions, Inc., Qpedia eMagazine ,"Decreasing Thermal Contact Resistance by Using Interface Materials", Volume II, 2008.**

4. **Hassani, V., Vlahinos, A., and Bharathan, D., "Low Thermal Resistance Power Module Assembly", US Patent # 7190581, March 13, 2007.**