Graphite Foam for Cooling of Automotive Power Electronics

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***Abstract* - Hybrid and fuel cell vehicles utilize the Si-based IGBT (Integrated Gate Bipolar Transistor) controller which must dissipate about 100 W/cm^2 heat and maintain a temperature below 125°C. The application of porous, high thermal conductivity carbon foam, a new class of advanced lightweight material, to the thermal management of this electronic system and the use of micro- and nano-scale thermal measurement methods for analyzing thermal transport in electronics are presented. Development of advanced carbon foam with different pore structure by variation of the foaming pressure is discussed. The use of carbon foam to remove the heat generated in power electronics has been studied in three approaches: 1) forced air convection, 2) water cooled heat exchanger, and 3) thermosyphoning.**

I. INTRODUCTION

In recent decades, many performance improvements in electronic components, such as higher-power computer chips and power converters, have led to significantly increased heat generation at small size scales and require more efficient strategies for microscale heat dissipation. A range of techniques such as micro-channels, heat pipes, and other novel designs have been explored with limited success to improve the efficiency of microscale heat transfer. Modern power electronics systems, such as those found in hybrid and fuel cell vehicles, must incorporate very effective heat spreaders into heat sink design in order to prevent localized hot spots and insure that the temperature of the Si-based electronic components does not exceed ~125°C.

The high-conductivity graphite foam developed at Oak Ridge National Laboratory (ORNL) exhibits an open-cell structure with highly aligned graphitic ligaments [1-3]. A scanning electron microscopic (SEM) image of the porous, high thermal conductivity carbon foam is shown in Fig. 1. Studies have shown the typical interlayer spacing (d_{002}) to be 0.3356 nm, very close to that of perfect graphite (0.3354 nm). As a result of its near-perfect structure, the thermal conductivity along the ligament is calculated to be approximately 1700 W/m-K, with bulk conductivities of up to 180 W/m-K. Furthermore, the material exhibits low densities (0.25-0.6 g/cm^3) such that the specific thermal conductivity is approximately four to five times greater than that of copper. This high conductivity combined with the very high specific surface area results in overall heat transfer coefficients for foam-based heat exchangers that are up to two orders of magnitude greater than those of conventional heat exchangers. As a result, graphite foam-based heat exchangers or heat sinks could be much smaller and lighter than conventional ones.

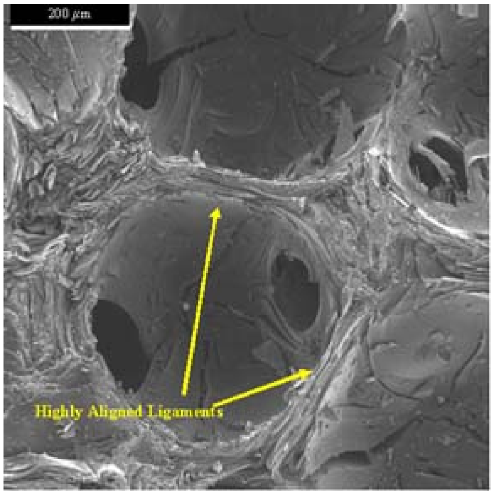


Fig. 1. SEM image of the high thermal conductivity carbon foam showing highly aligned graphitic ligaments.

Recently developed hybrid and fuel cell vehicles use electric motors which require high-powered electronics to manage the switching of high electrical voltage and current for motor control. These high-power electronics dissipate a considerable amount of heat that necessitates a heat exchanger and a separate radiator. The goal of this study is to investigate the application of carbon foam in three approaches: 1) forced air convection, 2) water cooled heat exchanger, and 3) thermosyphoning, to remove the heat generated in the power electronics. The first two approaches have been tested and results are presented, while the third approach is on-going.

In this paper, the development of advanced carbon foam is first presented. Design and testing of carbon foam cooling systems are discussed, and the use of microthermocouples to characterize interfacial thermal transport is analyzed.

II. ADVANCED HIGH THERMAL CONDUCTIVITY CARBON FOAM MATERIAL

Based upon B.E. Thompson's modeling work [4] that shows the importance of controlling pore density and maintaining an open structure in order to maximize the benefits of the carbon foam's porous surface in thermal management applications, recent material development efforts have been aimed toward understanding the relationship between graphite foam structure and both roughness and area-recruitment phenomena. Carbon foam samples have been produced at three different values of foaming pressure, the processing variable that has been identified as most significantly affecting pore size and structure. Fig. 2 shows the variation of thermal conductivity and density for samples produced at low, middle, and high foaming pressures. The density, thermal diffusivity and compressive strength of the samples at the top, middle, and bottom portions of the foam are analyzed. Fig. 3 shows SEM images of the varied pore structures produced at three foaming pressures. This study demonstrates that different carbon foam pore sizes and structures can be produced.

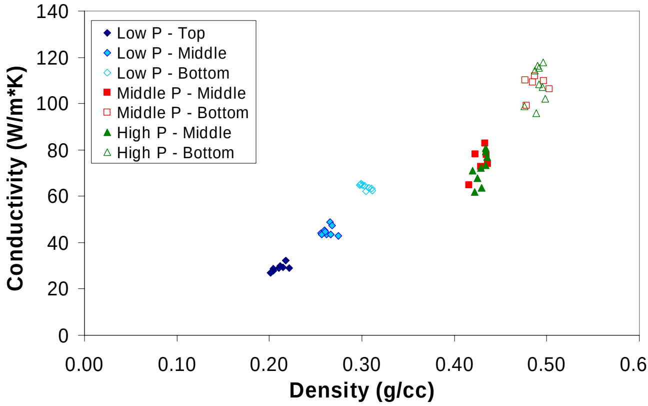
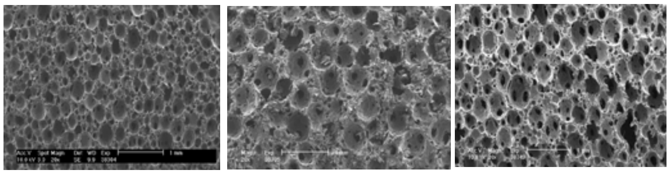


Fig. 2. Bulk thermal conductivity versus density for carbon foams produced at varying foaming pressures.



High foaming pressure Middle foaming pressure Low foaming pressure

Fig. 3. Pore structure of foams produced at varying foaming pressures.

III. DESIGN AND TESTING OF CARBON FOAM COOLING SYSTEMS

Hybrid and fuel cell vehicles using electric wheel motors require high power electronics for motor control. These electronics create a considerable amount of heat and require a heat exchanger and separate radiator. It is common practice to include three independent cooling systems in hybrid vehicles: one for the combustion engine, another for the power electronics, and a third for the transmission. This work explores the use of high thermal conductivity carbon foam as a heat exchanger in the cooling system of hybrid vehicle power electronics. The current aluminum pin-type heat exchanger used is re-designed utilizing carbon foam to increase the heat transferred from the electronics while maintaining or reducing the pressure drop of the coolant. Corrugated foam geometry is used in the design because the corrugations force the fluid to flow through instead of around the pores. Table 1 lists the engineering specifications for the cooling system design.

TABLE I

LIST OF ENGINEERING SPECIFICATIONS FOR POWER ELECTRONICS HEAT SINK OF HYBRID VEHICLE.

1. Dissipate 650 Watts of power
2. Maintain a chip operating temperature at or below 125°C
3. Operate in the temperature range -40 to 125°C
4. Maximum coolant pressure drop of 0.5 psi for coolant flow rate of 2 gpm
5. Fit in a similar size case as production design
6. Work for the life of the vehicle (~10 years or 150,000 miles)

Two approaches were evaluated: (a) liquid cooled heat exchanger and (b) forced-air heat exchanger:

A.. Liquid-cooled heat exchanger

The carbon foam with corrugated geometry was tested in a water-cooled heat exchanger, as shown in Fig. 4. In the operating temperature range, the heat transfer is approximately 15-20 W/cm^2. The shape of the carbon foam is shown in Fig. 5 with L = 50 mm, H = 25 mm, S = 10 mm, C = 1.5 mm, and t = 3.5 mm.

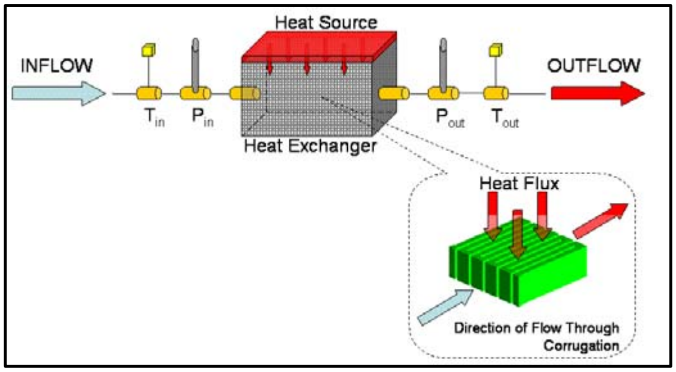


Fig. 4. Experimental test set up for liquid-cooled heat exchanger.

For hybrid power electronics cooling applications, the heat exchanger must dissipate ~30 W/cm^2. This means that engineering specifications #1 and #2 from Table 1 were not met. Knowing the foam and fluid could operate over this temperature range validated specification #3. Specification #5 was met using the foam as a replacement for the pin fin aluminum heat exchanger, and no life cycle estimate was done to validate spec #6. This potentially allows the existing pin finned heat exchanger to be replaced with corrugated foam geometry, reducing the number of cooling systems in the hybrid car from 3 to 2. Calculations showed the average heat transfer coefficient is 1064 W/m^{2}K. This suggests that the design could be considerably improved through the flow rate control and foam porosity, based on comparison with carbon foam characterization studies conducted at ORNL.

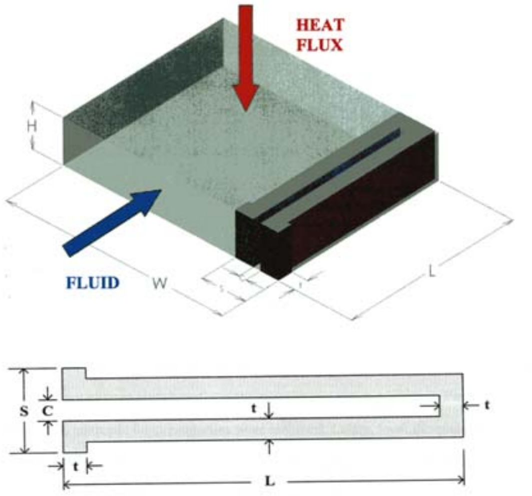


Fig. 5. Shape and dimension of the carbon foam.

In order to characterize the pressure drop imposed by the liquid cooled carbon foam heat exchanger, the pressure drop across the housing was recorded 1) when no foam was present, 2) when corrugated foam was present, and 3) when blind hole (holes drilled parallel to the flow in a solid block) foam was present. All three data sets were within 10% of each other, with no distinct separation, implying that the housing is the dominant source of pressure drop. This can be attributed to the change in cross-sectional area from inlet to housing and from housing to outlet. Therefore, a different pressure drop measurement setup is needed.

B. Forced-air heat exchanger

Another approach is to use forced-air convection for heat removal and eliminate the need for a radiator and cooling loop. This test setup is shown in Fig. 6. The width of the groove in the corrugated carbon foam is 1.6 mm, the wall thickness is 3.4 mm, and the depth of the groove in the foam is 59 mm.

Engineering specifications listed in Table 1 are analyzed for the forced-air packaging system design. Two specifications, #1 and #2, were not met. To validate the operating temperature (#3) range, the thermal properties of each material were used to insure that they could withstand extreme temperatures. Since it was air cooled, the pressure drop (Spec #4) was not needed. Spec #5 was validated by choosing dimensions that were similar. There was no life cycle estimate to validate Spec #6. The prototype maintains the chip temperature below 125°C at a maximum power density of 2.4 ± 0.4 W/cm^2. The carbon foam has a maximum heat transfer coefficient of 320 ±100 W/m^2-K. These results were obtained with a flow rate of 12.1 ± 0.5 CFM and are shown in Fig. 7.

Both the liquid-cooled and forced-air heat exchanger designs found the convective coefficient of the foam to be lower than expected, possibly due to the lack of a bonding agent between the foam and the heat sink, uncertainty in the heating element specifications, and the inability to control water and airflow rates over a large range. More precise test setups and heater designs should be used in future testing.

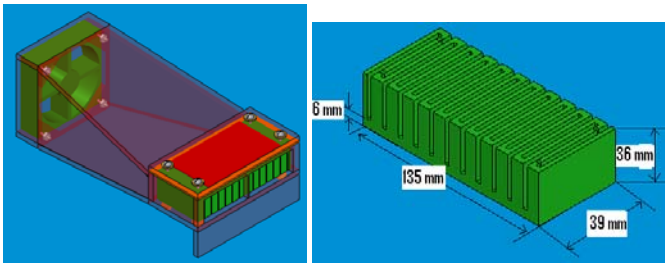


Fig. 6. Shape and dimension of the carbon foam.

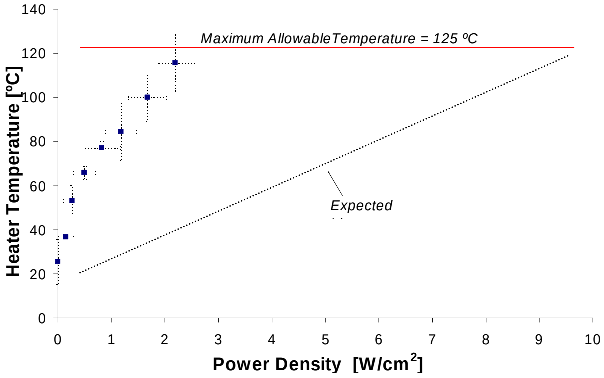


Fig. 7. Heater temperature vs. power density illustrating that the prototype cannot meet expected performance (points correspond to experimental data).

C. Thermosyphoning

The concept of thermosyphoning using phase-change evaporative liquid is shown in Fig. 8. This idea takes advantage of the high thermal conductivity carbon foam to dissipate heat to an evaporative liquid surrounding the foam. This prototype for automotive hybrid power electronic cooling is still under development at the University of Michigan and Oak Ridge National Lab.

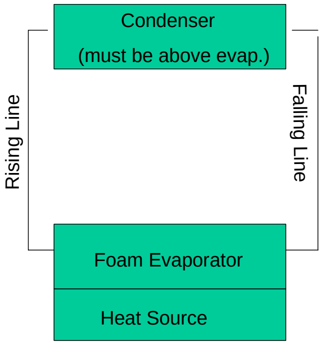


Fig. 8. The concept of thermosyphoning heat exchanger.

III. MICROTHERMOCOUPLE FOR CARBON FOAM INTERFACE TEMPERATURE MEASUREMENTS

In order to characterize the different bonding techniques used to form a low-impedance thermal interface between the foam and a metal heat sink block, a microthermocouple probing station has been assembled, as shown in Figures 9 and 10. This technique has been previously used to measure microscale heat transfer and quantify conduction, convection, and radiation terms in electronic and optoelectronic devices such as semiconductor lasers [5]. The station makes use of a NIST-traceable microthermocouple setup from Sable Systems that has 25μm spatial resolution, 0.2^{o}C accuracy, and 10mK temperature resolution. The metal block is heated and maintained at a set temperature by use of a thermistor and feedback-controlled Peltier element (controller: Newport 3150, Peltier element from Melcor), and the microthermocouple is scanned over the foam bonding interface. Because the microthermocouple is much smaller than the ligaments that make up the foam, this technique is useful for tracing the path of heat between the metal block and the foam and for characterizing the different thermal impedances of the various bonding techniques.

The experimental apparatus consists of a heater, sample mount, and probe. The heater consists of two nearly identical copper plates with a Peltier cooler sandwiched between them. To maintain good thermal conductivity, the Peltier is coated on both sides by thermal grease (Artic Silver ®) and held tightly via the two bolts which hold the copper plates together. The thermistor used to regulate the temperature of this heat source is located in the copper plate closest to the sample. The sample mount consists of a support post and an aluminum platform on which to rest the sample blocks. The probe consists of an adjustable metal tip to which the microthermocouple itself is taped. The end of the small wire of the thermocouple is left free but bent to be near the end of the metal probe. An optical microscope is used to measure the position of the microthermocouple.

The microthermocouple readings were somewhat noisy due possibly to convection effects. The highest and lowest observed readings were recorded and averaged to give the temperature at each specific point along the surface. Error bars are shown on the plots. As the probe is moved from point to point, it must only be carefully touched to the surface, so as to ensure proper contact and minimize bending. In this manner, temperature profile data can be measured with some degree of accuracy, which we hope to further improve.

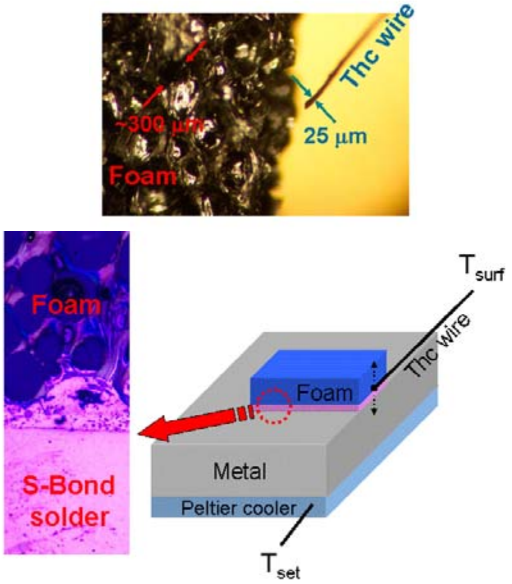


Fig. 9. (top) Comparison of microthermocouple size with foam pore size; (bottom) Scanning of microthermocouple over bonding interface between foam and metal block.

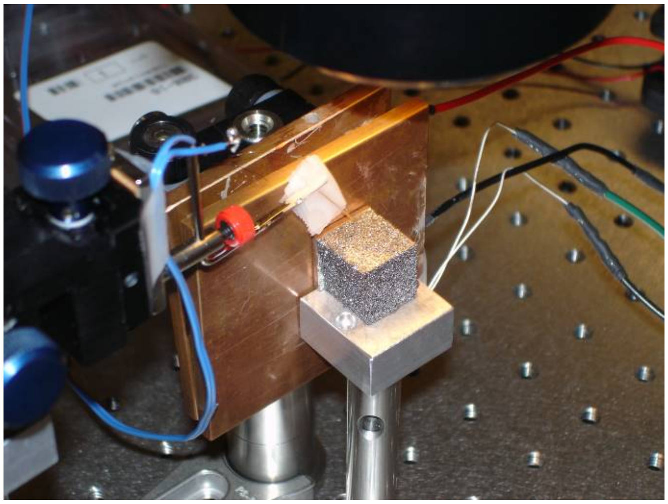


Fig. 10. Microthermocouple probe setup

ACKNOWLEDGMENTS

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