C. Carbon Foam for Electronics Cooling

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Objectives

- Collaborate with automotive partner to develop carbon foam heat exchanger and heat sink designs that dissipate more than 30 W/cm^2 using standard cooling fluids.
- Develop a strategy to reduce the high cost of carbon foam.
- Determine the foam structure or morphology that results in optimum heat transfer for various thermal management applications.

Approach

- Study fundamental mechanisms of heat transfer in carbon foam and develop an engineering model that allows comparison of conventional and carbon foam heat exchangers.
- Develop a cost model that can be used to guide process development efforts to reduce the high cost of carbon foam.
- Build and operate a passive evaporative cooling system (PECS) to evaluate and compare the performance of carbon foam and diamond heat spreaders.

Accomplishments

- Developed a process cost model that indicates that the price of the pitch precursors and the time and temperature of the carbonization and graphitization cycles have the greatest influence on the cost of carbon foam.
- Developed an engineering model of heat flow through carbon foam that indicates that carbon foam heat exchangers failed to perform as expected because cooling air flowing over the foam failed to access the extensive surface area. This would suggest that designs that force air through the foam and not over the foam would perform much better.
- Proved high-conductivity carbon foam to be an excellent heat spreader when evaluated in the PECS system; it dissipated more than three times the amount of heat dissipated using state-of-the-art diamond heat spreaders.

Future Direction

- Conduct processing studies focused on finding alternative low-cost pitch precursor materials to replace the current raw materials and therefore reduce the cost of carbon foam.
- Modify the structure or morphology of the carbon foam for optimum heat transfer. Modeling results indicate that more open, less dense structures with easily accessible porosity would increase the heat transfer.
- Operate the PECS using carbon foam heat spreaders with more open, less dense structures.

Introduction

Many improved electronic components introduced in recent decades, such as higher-power computer chips and power converters, generate significantly more heat and require more efficient devices for dissipating that heat. Many techniques have been explored to improve the efficiency of heat transfer devices, such as micro-channels, heat pipes, and other exotic designs; however, none has been able to adequately cool the electronics. These devices must incorporate very effective heat spreaders into the design of the heat sink to prevent localized hot spots and ensure that the temperature of the electronics does not exceed 125ºC.

The high-conductivity carbon foam developed at Oak Ridge National Laboratory (ORNL) is an open-cell structure with highly aligned graphitic ligaments (see Figure 1); studies have shown the typical interlayer spacing (d002) to be 0.3356 nm, very near that of perfect graphite (0.3354 nm). As a result of its near-perfect structure, thermal conductivities along the ligament are calculated to be approximately 1700 W/m•K, with bulk conductivities = 180 W/m•K. Furthermore, the material exhibits low densities (0.25 to 0.6 g/cm^3) so that the specific thermal conductivity is approximately four to five times greater than that of copper. The high conductivity combined with the very high surface area (20,000 m^2/m^3) results in overall heat transfer

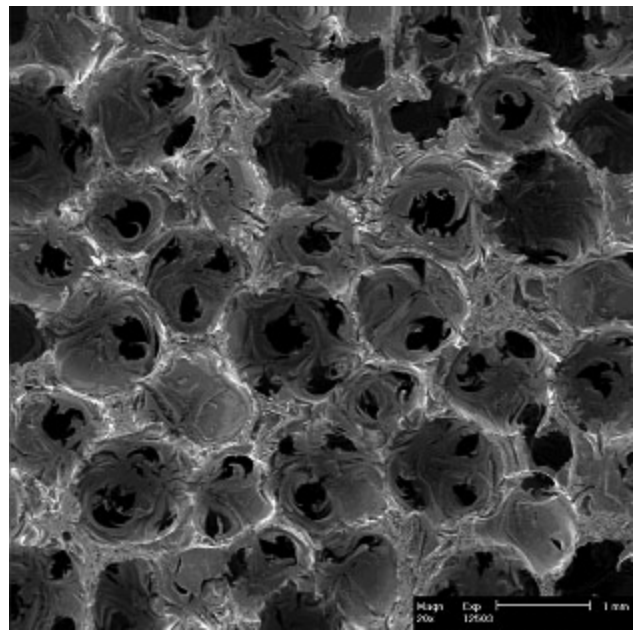

Figure 1. Graphite foam material developed at ORNL.

coefficients for foam-based heat exchangers that are up to two orders of magnitude greater than those of conventional heat exchangers. As a result, foam-based heat exchangers or heat sinks could be dramatically smaller and lighter than conventional ones.

Automotive and industry partners are very concerned about the high cost of high-conductivity carbon foam. They are convinced that the cost of carbon foam must be reduced significantly before it can be used in most automotive applications. Work was initiated during FY 2003 to determine what factors have the greatest impact on the cost of the foam. Once those factors have been identified, research efforts will be redirected to those areas.

Results

Cost Modeling of Carbon Foam

A detailed process economic model was constructed of the ORNL high-thermal-conductivity carbon foam manufacturing process.[1] The Excel-based model included the effects of 146 input variables on the expected sales price and manufacturing cost of this material. It also provides estimates of the capital investment, plant size, and employee level required. A set of values of the input variables was established as a baseline case, using data supplied by ORNL or obtained from industrial sources and potential suppliers. The results of the baseline case were analyzed to determine the most significant cost drivers (see Figure 2) and the sensitivity of results to these cost drivers. A set of advanced model analysis tools was used to visualize the relative magnitude of these drivers and their potential effect on product price. Risk analysis showed the probability of deviation from the expected product price. Another analysis provided insight into the sensitivity of results to production volume. From these results and analyses, we can provide the following results, which are based on high production volumes.

Assuming that major variables are close to the baseline values, the price of carbon foam at a production rate of 44,000 parts (2×3×1.5 in.) per week will be approximately \$4.95/piece (\$0.55/in.^{3}), with a manufacturing-only cost of \$2.97/piece (\$0.33/ in.^{3}).

This level of production will require a capital investment for equipment of approximately \$9.25 million and will require about 8400 ft^2 of manufacturing space, 29 technicians/operators, and 3 engineers.

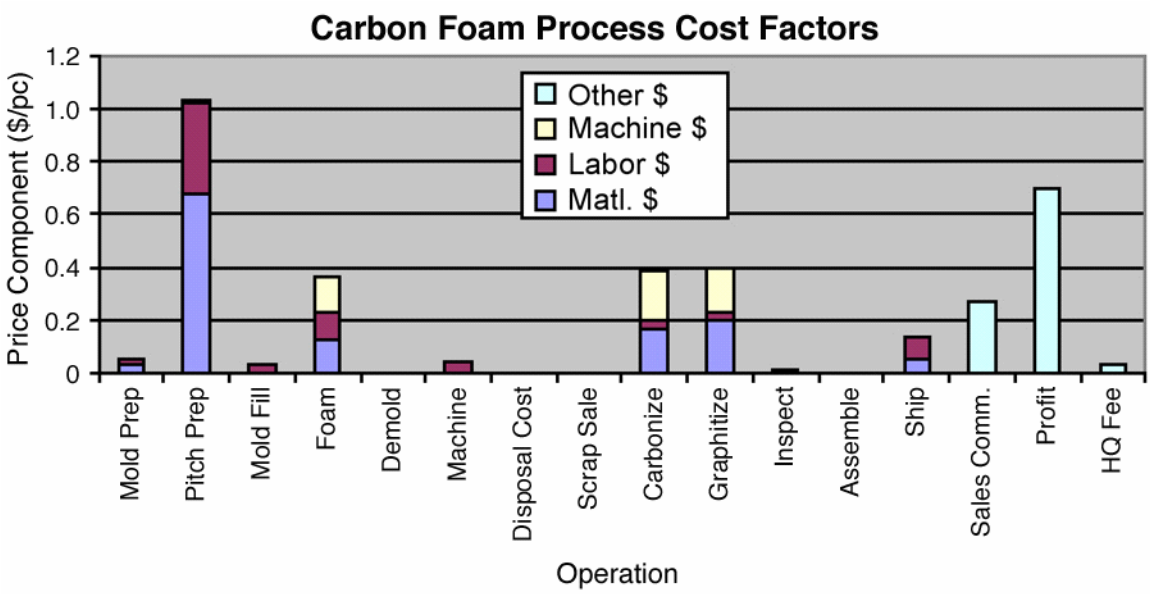

Figure 2. Carbon foam process cost factors.

The density of the foam product has the greatest influence on product price, on the basis of price per cubic inch. This result is apparently caused by the strong influence of amount of pitch required per volume of foam and the high sensitivity of foam price to pitch price.

Pitch price has the next greatest influence on foam price. Price could vary from \$0.45/in.^{3} to \$0.68/in.^{3} as the pitch price varies from \$3 to \$8/lb.

The pitch raw material accounts for 24% of the sale price of foam (see Figure 3).

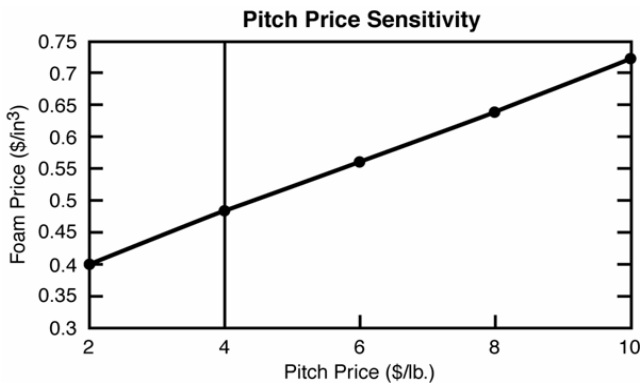

Figure 3. Correlation of the cost of the pitch precursor and the cost of carbon foam.

After business costs such as profit and sales cost, the three furnace operations are the next most important cost drivers. The carbonization and graphitization times and temperatures need to be reduced to minimize cost.

Modeling of Porous Carbon Foam Heat Exchangers

An engineering model[2] was developed that provides values for the thermal resistance and pressure drop in air-water heat exchangers with plate-fin and annular-fin configurations, based on a combination of the following:

- measurements of bulk conductivity of porous carbon foam
- well-established correlations for convective heat transfer from tubes, plates, and fins
- measured thermal resistance at the interface between aluminum and porous carbon foam with a number of different joints
- an engineering approximation for the effects of porosity on convective heat transfer

The model was compared both with available measurements obtained with conventional aluminum heat exchangers and with copycat heat exchangers made from carbon foam. Agreements between calculated and measured values of the heat transfer coefficient and pressure drop were sensible and within about 15% and 10%, respectively, which is adequate for typical design needs in thermal engineering.

The model suggests that finned carbon foam heat exchangers failed to perform as expected because the air flowing over the carbon foam failed to access the extensive surface area. If radiator designs could be developed that effectively use the surface area, 20 to 60% improvements over optimum aluminum-finned heat exchangers could be achieved. Note that the performance of a carbon foam heat exchanger is controlled more by the surface area accessed than by the high conductivity of the foam. This suggests that the porosity, pore density, dendrite structure, and strength of the carbon foam should be optimized simultaneously to enhance heat transfer with minimal increase in pressure losses.

It may not be possible to access sufficient surface area of carbon foam in conventional finned heat exchanger designs. This would suggest that designs that force air through the foam, and not over the foam, may be required. The structure of the foam would act like the fins of conventional heat exchangers. These designs would use all of the available surface area because the structure of the foam would act as the "fins."

In a cost model developed recently, the development of less-expensive pitch precursors was found to have the most dramatic effect on the cost of the carbon foam. Low-cost precursors have not been pursued in the past because we were concerned that the thermal conductivity would be negatively impacted. The engineering model was exercised to determine the significance of the thermal conductivity of the carbon foam for the performance of radiators. It was quite surprising to learn that a 25 to 50% reduction in thermal conductivity had only a minor effect (~5%) on the performance of the heat exchangers.

Passive Evaporative Cooling

A PECS was built in FY 2003 and operated extensively at ORNL. A simple schematic illustrating the concept is shown in Figure 4. A more thorough description of the operation of the system is included in article 2D, "Evaporative Cooling of Power Electronics" in this annual report. Similar systems developed by the National Security Agency that contained a limited-surface-area diamond heat spreader were able to achieve a power density of 28 W/cm^2 and were considered to be state-of-the-art

technology. The system that was operated at ORNL with

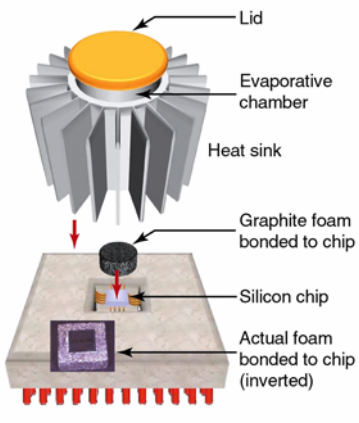

Figure 4. Schematic diagram of the evaporative cooling system.

a graphite foam heat spreader was able to achieve a power density of over 120 W/cm^2, more than four times the power density attained using the diamond heat spreader. The graphite foam has proved to be an excellent heat spreader because of the extensive surface area, the very high thermal conductivity, and the fact that the foam is easily wetted by the evaporative coolants.

Conclusions

A process cost model was developed that evaluated the effect of more than 100 variables on the cost of carbon foam. The model indicates that the price of the pitch precursors and the time and temperature of the carbonization and graphitization cycles have the greatest influence on the cost of carbon foam. An engineering model of heat flow through carbon foam was also developed that indicates that carbon foam heat exchangers failed to perform as expected because cooling air flowing over the foam failed to access the extensive surface area. Additional research is needed to understand the relationship between material structure and heat transfer. Findings suggested that more-porous, less-dense foams would recruit additional surface area—provided, of course, that the carbon structure has adequate strength. The capability to control pore density (pores per inch) and to maintain an open pore structure (percentage of open pores) is important if the benefits of the porous surface structure are to be realized in practical applications. Finally, carbon foam proved to be a very effective heat spreader when used in an evaporative cooling system. The carbon foam heat spreader was able to dissipate more than four times as much heat as the previously used diamond heat spreader.

References

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2. B. E. Thompson, A. G. Straatman, R. Culham, M. Yovanovich, A. G. Hunt, Q. Yu, and P. Oosthuisen, *Modeling of Porous-Carbon-Foam Heat Exchangers*, February 28, 2003.

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N. C. Gallego, A. D. McMillan, and S. K. Stinton, "Effect of Heat Treatment on the Rheological Properties of Mesophase Pitch and Final Properties of Carbon Foam," presented at Carbon '03: An International Conference on Carbon, Oviedo, Spain, July 6–10, 2003 (to be published in the proceedings).

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