CARBON FOAMS FOR THERMAL MANAGEMENT

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Abstract

A unique process for the fabrication of high thermal conductivity carbon foam was developed at Oak Ridge National Laboratory (ORNL). This process does not require the traditional blowing and stabilization steps, and therefore less costly. The resulting foam can have density values between 0.2 and 0.6 g/cc and can develop bulk thermal conductivity between 40 and 180 W/m·K. Because of its low density, its high thermal conductivity, its relatively high surface area, and its open celled structure, the ORNL carbon foam is an ideal material for thermal management applications. Initial studies have shown that the overall heat transfer coefficients of carbon foam-based heat sinks to be up to two orders of magnitude greater than those of conventional heat sinks.

Introduction

Carbon foams were first developed in the late 60's by Ford [1]. These initial carbon foams were made by the pyrolysis of a thermosetting polymer foam to obtain a carbonaceous skeleton or reticulated vitreous carbon (RVC) foam. RVC foams are attractive for many aerospace and industrial applications, including thermal insulation, impact absorption, catalyst support, and metal and gas filtration. They are thermally stable, low in weight and density, and are chemically pure; they have low thermal expansion, resist thermal stress and shock, and are relatively inexpensive. RVC foams are used as substrates and overcoated via a chemical vapor deposition process to fabricate foams of alternate compositions. Among the materials that can be deposited are refractory metals (e.g. niobium, tantalum, tungsten, rhenium) and their ceramic compounds (e.g. the oxides, nitrides, carbides, borides and silicides) [2]. Other applications for RVCs include: porous electrodes, high temperature insulation, filters and demisters, storage batteries, scaffolds, and acoustic control [3]. Figure 1 is a photomicrograph of a typical RVC foam.

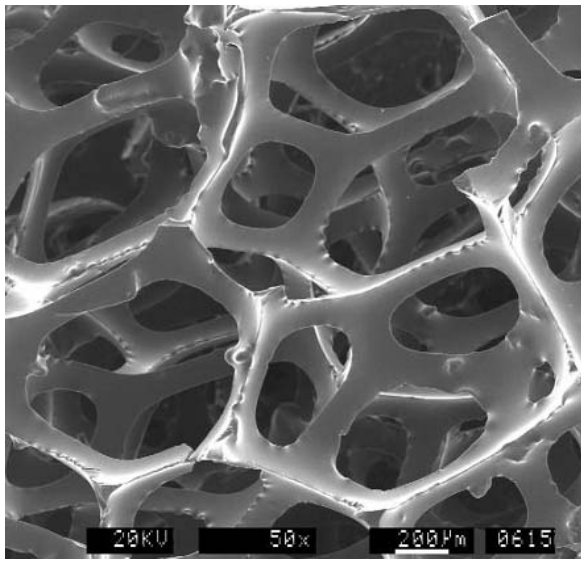
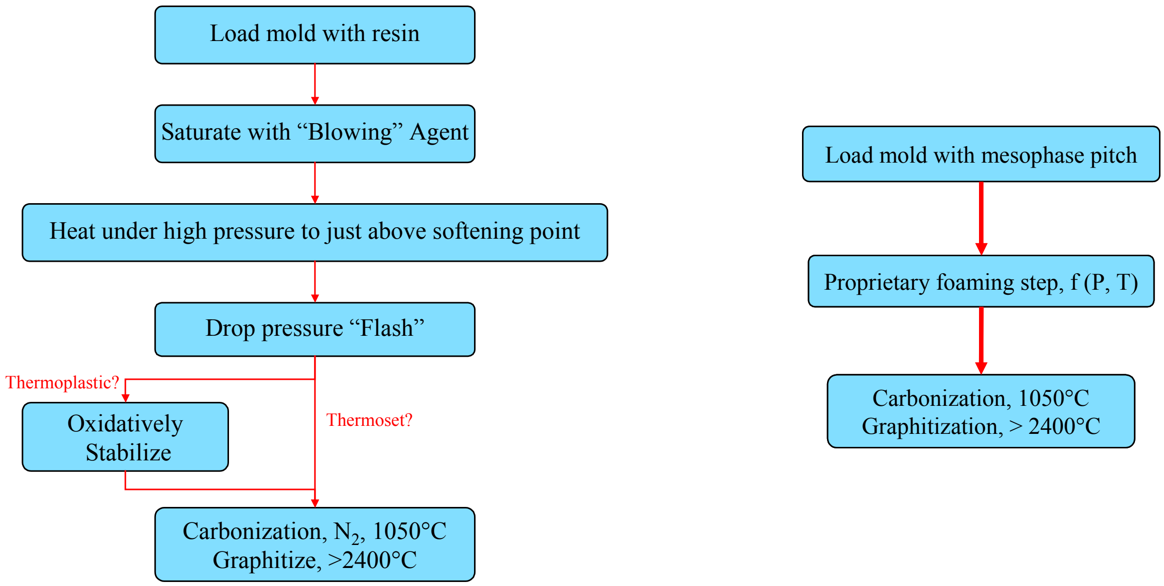


Figure 1. Typical RVC foam produced by ERG Corporation,

A new generation of carbon foams began in the 90's as research focused on the production of carbon foams from alternative precursors such as pitches and coal. Researchers from the US Air Force Materials Lab developed a process by applying a "blowing" technique to mesophase pitches to form a carbon foam. The foam is then oxidatively stabilized prior to carbonization and graphitization. These foams were developed primarily to replace expensive 3-D woven fiber preforms in polymer composites and honeycomb materials. This process was licensed to MER Corporation. A research group at West Virginia developed a method to use coal as a precursor for high strength foams with excellent thermal insulation properties and high strengths [4]. This process was licensed to Touchstone Research Group.

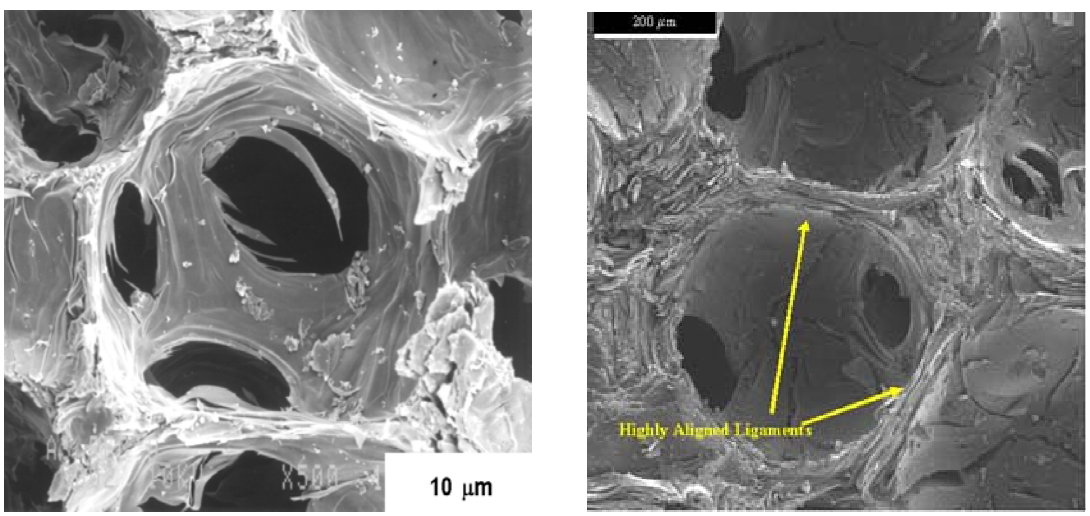
More recently, a process that does not required the "blowing" and stabilization steps was developed at Oak Ridge National Laboratory. The foam obtained with this process is of graphitic nature and of excellent thermal properties (bulk thermal conductivities of up to 180 W/m·K) [5]. This was the first repeatable foam with bulk thermal conductivities greater than 50W/m·K, and the process was licensed to Poco Graphite under the tradename PocoFoam™.

Figure 2 compares the steps of the carbon foam production processes developed at US Air Force and at Oak Ridge National Laboratory. A significant reduction in the number of processing steps is observed for the ORNL process. Figure 3 compares the structure of foam produced by the "blowing" process and that of the graphitic carbon foam developed at ORNL. The foam produced by the ORNL process develops highly aligned graphitic ligaments, responsible for the high thermal conductivity of the carbon foam. Table 1 lists typical properties of a variety of carbon foams available.



(a) (b)

Figure 2. Comparison of (a) traditional “blowing” technique for the production of carbon foams and (b) the ORNL’s developed process.



(b) (b)

Figure 3. (a) Carbon foam produced by the “blowing” process, and (b) mesophase pitch-based carbon foam produced at ORNL.

Table 1. Summary of typical properties of a variety of carbon foams.

Property	Ultramet's RVC [a]	ERG's RVC[b]	Touchstone[c]	MER[d]	ORNL[e]
Density (g/cc)	0.042	n/a	0.16-0.50	0.016-0.62	0.25-0.65
CTE (ppm/^{o}C)	1.15-1.65	1.2-1.8	6.2	n/a	2.0
Compression Strength (MPa)	0.763	0.28-0.48	15.2-20.7	1.7-7.0	1.0-3.5
Tensile Strength (MPa)	0.810	0.17-0.35	1.14-6.90	n/a	0.7-1.6
Thermal Conductivity (W/m·K)	0.085	n/a	0.40-17.50	0.05-210	0.3-180

[a] From Ultramet's website, http://www.ultramet.com/
[b] From ERG Corporation website, http://ergaerospace.com/rvc.htm
[c] From Touchstone website, http://www.cfoam.com/
[d] From MER website
http://www.mercorp.com/mercorp/CGraphiteFoams/C_Graphite_Foams.html
[e] Data obtained at ORNL.

Applications in Power Electronics Cooling

In recent decades, many improvements in electronic components 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 efficiencies of heat transfer devices, such as micro-channels, heat pipes, and other exotic designs. One design utilizes metal foams with great efficiency to enhance heat transfer by increasing the surface area of heat transfer dramatically. These metal foams have been successfully used as heat exchangers for airborne equipment, compact heat sinks for power electronics, heat shields, and air-cooled condenser towers and regenerators.

Due to its light weight, high thermal conductivity and high surface area, ORNL's carbon foams are being evaluated as a heat sink material for cooling of power electronics. A test rig, shown schematically in Figure 4, was designed for the measurements. It consisted of a block of carbon foam (2 in x 2 in x 1.25 in) brazed to a metal plate and a heater mounted on the other side of the plate (the heater having the same footprint area of the carbon foam block). The carbon foam was then placed into an insulated nylon channel where an o-ring and four c-clamps were used to ensure a tight seal between the base-plate and the channel. Cooling air or water was then forced through the channel, removing heat from the foam block. The gaps between the foam and the channel walls were very small, which ensured that the fluid traveled through the pores of the carbon foam.

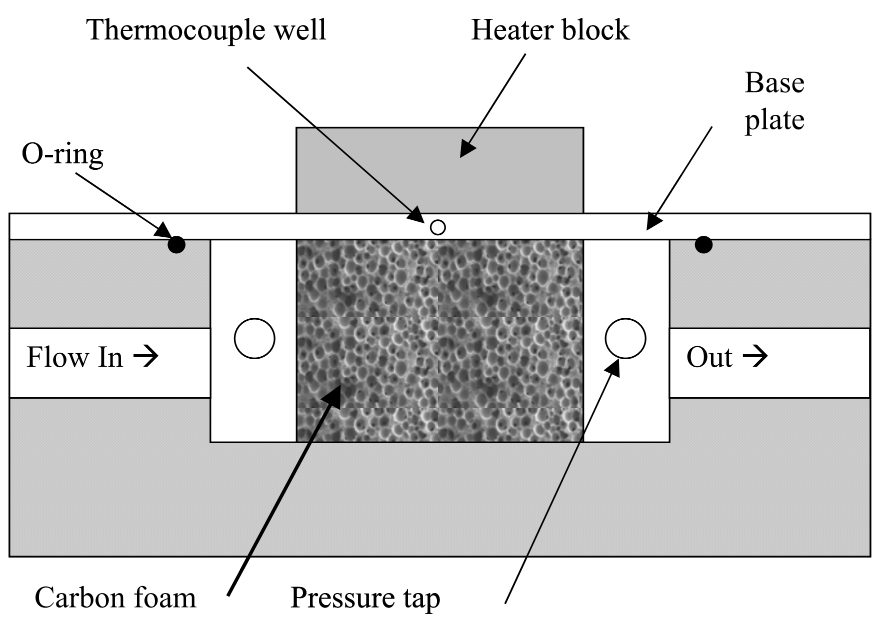


Figure 4. Schematic of heat sink test configuration.

After the testing block was assembled, power was added to the heaters and the voltage and current were measured to find the exact power output of the heater. The heater dissipated heat into the metal plate and hence into the foam block, which acted as a heat sink. The inlet and outlet bulk fluid temperatures were measured, along with the temperature of the base plate of the heater. Pressure taps were also mounted on both sides of the carbon foam block to measure the pressure drop of the system. The overall heat transfer coefficient is then calculated utilizing the following relation:

$$h = \frac{Q}{A \cdot \Delta T_{LM}} \tag{1}$$

where:

h = Heat transfer coefficient [W/m^2·K]

Q = Heater power dissipation [W]

A = Heater and foam footprint area [m^2]

ΔT_{LM} = Log mean temperature difference [K]

Initial measurements using water as the cooling fluid, were performed on blocks of carbon and of aluminum foam. The temperature of the heater versus the heater power density for a variety of configurations is plotted in Figure 5. This Figure clearly demonstrates that carbon foam dissipates more heat than aluminum foam. Another significant difference in the materials is shown as the non-linearity in the profile for the aluminum foam. This is a result of the low thermal diffusivity of the aluminum foam. After a change in the power level of the heaters, the aluminum foam heat sink took more than 20 minutes to reach an apparent steady state condition, while the carbon foam heat sink reached steady state in approximately 2 minutes. Very high heat transfer coefficients (~2600 $W/m^2 \cdot K$) were calculated for the carbon foam heat sinks, compared to those of aluminum foam heat sinks (~250 $W/m^2 \cdot K$), however the pressure drop of this system was fairly high compared to that of the aluminum foam.

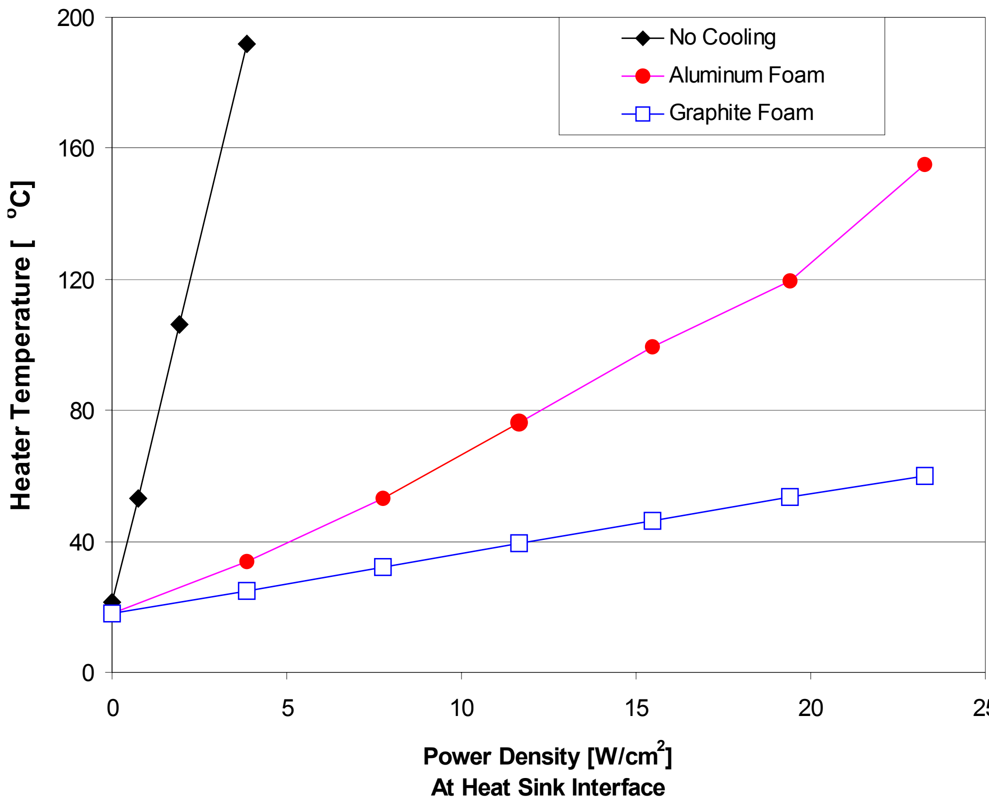
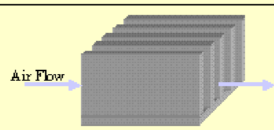
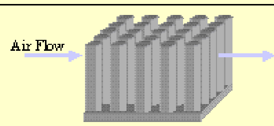
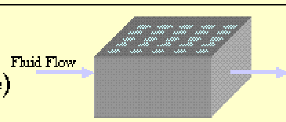
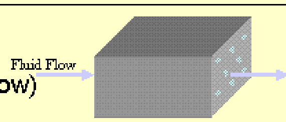
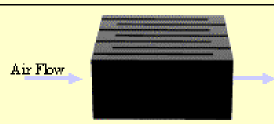
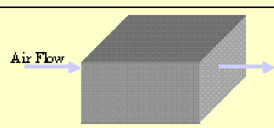


Figure 5. Heater temperature vs. power density for aluminum and carbon foam (fluid flow 0.75 gpm water)

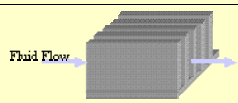
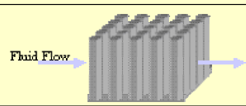
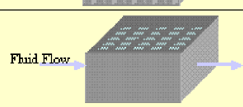
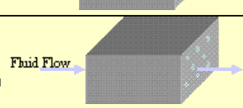
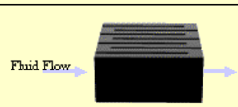
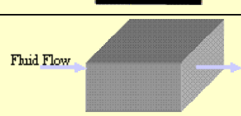
Further work was directed to engineering a system in which a high heat transfer coefficient was maintained while reducing the pressure drop. For this purpose a number of carbon foam geometries were evaluated to reduce the pressure drop. The first concept was to mimic current finned heat sinks; other designs included pin-finned and blind holes (both perpendicular and parallel to the fluid flow). Table 2 lists the heat transfer coefficients and their corresponding pressure drop for these systems and compares them to those of aluminum foam (where applicable), the fluid utilized was air, at a flow rate of 15 cfm. As it is observed in this table, the pressure drop is reduced significantly by modifying the geometry of the heat sink, while the heat transfer coefficients are still considerably better than those obtained with the aluminum.

Table 2. Comparison of air-cooled heat transfer coefficients obtained for graphite foam and aluminum foam.

Air Cool (15cfm-172 in/s)	Aluminum		Carbon Foam	
Geometry	Heat Transfer Coeff. h, (W/m²·K)	ΔP/L (psi/in)	Heat Transfer Coeff. h, (W/m²·K)	ΔP/L (psi/in)
Finned 	70	<0.05	1000	<0.05
Pin-Finned 	550	<0.05	1500	0.05
Blind-holes (pin fin negative) 	-	-	2000	1
Blind-holes (parallel to air flow) 	-	-	3100	0.35
Corrugated 	-	-	4100	0.1
Solid Foam 	250	<0.05	2600	2

Additional work was performed in order to compare the results obtained utilizing both water and air as the cooling fluid (see Table 3). As it is observed, greater heat transfer coefficients are obtained with water as the cooling fluid. However the values obtained with carbon foam and air are still considerably higher that those with aluminum heat sinks, indicating that perhaps air could be used with the proper geometries of the foam in some applications. The use of air-cooling would dramatically reduce the complexity of the cooling systems used to cool power electronics by eliminating the recycling of the fluid.

Table 3. Comparison of air-cooled and water-cooled heat transfer coefficients obtained for carbon foam.

Foam Geometry		Air Cool (15cfm-172 in/s)		Water Cool (0.75gpm-1.2 in/s)	
		Heat Transfer Coeff. h, ($W/m^2 \cdot K$)	ΔP/L (psi/in)	Heat Transfer Coeff. h, ($W/m^2 \cdot K$)	ΔP/L (psi/in)
Finned		1000	<0.05	2100	0.5
Pin-Fin		1500	0.05	2500	0.5
Blind-holes (pin fin negative)		2000	1	4600	0.5
Blind-holes (parallel to air flow)		3100	0.35	4500	0.5
Corrugated		4100	0.1	9500	0.033
Solid Foam		2600	2	23000	2

CONCLUSIONS

- ORNL has developed a process for the fabrication of high conductivity carbon foams. This process does not require the "blowing" and stabilization steps, thus reducing the manufacturing time, and most importantly, the cost of the foam.
- ORNL's carbon foam is an efficient thermal management material. When compared with aluminum-based heat sinks, it was demonstrated that the foam-based heat sink can be used to reduce the volume of the cooling fluid required or potentially eliminate the water cooling system altogether.
- Carbon foam heat sinks respond to transient loads significantly faster than traditional heat sinks. This response time may be crucial for power electronics, as it could dramatically lower temperatures during peak loads. These peak loads drive the cooling system requirements even though they are experienced for a minimal amount of time during the operational life.

ACKNOWLEDGEMENTS

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3. ERG Corporation website, http://ergaerospace.com/rvc.htm

4. Stiller; Alfred H., Peter G. Stansberry, and John W. Zondlo, "Method of making a carbon foam material and resultant product," US Patent 5,888,469, (1999).

5. Klett, J., US Patent 6,033,506 "Process for making carbon foam," (2000).