A Review of Graphite Foam as Thermal Material

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ABSTRACT
With the increasing of power in equipment, the demand of effective cooling methods becomes pressing. The primary concerns in thermal management applications are high thermal conductivity, large specific surface area and low weight. Graphite foams which possess predominantly spherical pores with smaller openings between the cells constitute a novel highly-conductive porous material for high power equipment cooling application. These foams can be produced with bulk thermal conductivities almost equivalent to dense aluminum alloys with only 20% the weight of solid aluminum material. But in the commercial market, aluminum and copper are still the preferred material for thermal management. In order to give an overall view of the graphite foam material, this paper will introduce the structure and the properties of the graphite foam. Meanwhile, the different application for the graphite foam as a thermal material will be outlined and discussed. Some problems might block the graphite foam heat exchanger development also will be pointed out. In order to promote the development of graphite foam as a thermal material, some useful conclusion and suggestion will be highlighted in the end.

INTRODUCTION
Nowadays a lot of equipment power is increased. For instance, the power of computer chips is increasing, and the power of vehicle engines is also increasing. This increasing power leads to the increasing demand for effective methods of cooling. Currently thermal management has concerned about aluminum and copper heat exchangers and substrates. This is because of the high thermal conductivity (180 W/m.K for aluminum 6061 and 400 W/m.K for copper). But when weight is considered, the specific thermal conductivity (thermal conductivity divided by specific gravity) is only 54 and 45 W/m.K respectively. Thus, where the weight is significant concerned, it is important to find a light weight, high thermal conductivity and large specific surface area thermal management material.

An efficient thermal management method is to use a porous medium to increase heat transfer by the method of increasing the fluid-solid contact surface area and promoting fluid mixing. In this case, microcellular foam materials like metal or graphite foams can be considered as a class novel porous media, in which there is open cell structure. One example of graphite foam is developed at Oak Ridge National Laboratory in 1997. Klett et al. [1] found out the thermal conductivity of solid component of solid component of graphite foam was as high as 1700 W/m.K, which was about four times that of copper. The specific thermal conductivity was more than 150 W/m.K. On the other hand, the weight of graphite foam is only 1/5 that of aluminum. The special surface area is between 5000 and 50000 m²/m³.

Because the graphite foam has very high thermal conductivity, low weight and large special surface area, it is a very suitable material that is used in the thermal management. Graphite foam work begins in 1998. It is primarily for power electronic heat sink. In April 2001, the graphite foam started to be used for vehicle radiators. A lot of studies are carried out to analyze the graphite foam heat exchangers. But in the current heat exchanger or heat sink commercial market, aluminum and copper are still the preferred thermal material. In this case, there are still some problems blocking the development of graphite foam heat exchangers. Otherwise the graphite foam heat exchangers can be easily seen and purchased in the market.

In order to promote the development of graphite foam as a thermal material, this paper will give a clear overall view or conception about the graphite foam heat exchanger. First the structure of graphite foam is introduced in Section 2. Based on the structure of graphite foam, the thermal properties of graphite foam will be explained in Section 2 too. After that, the application of graphite foam heat exchanger will be highlighted in Section 3. In Section 4, some problems blocking the development of graphite foam heat exchangers will be pointed out. In order to contribute some effort to the development of the graphite foam, some useful conclusion and suggestion will be highlighted in Section 5.

2 STRUCTURE AND THERMAL PROPERTIES OF GRAPHITE FOAM
2.1 Structures
Carbon foams were first developed in the late 1960s as a reticulated vitreous (glassy) carbon foam [2]. The initial carbon foams were made by the pyrolysis of a thermosetting polymer foam to obtain a carbonaceous skeleton or reticulated vitreous carbon (RVC) foam. Fig. 1 is a photomicrograph of a typical RVC foam.

![Fig. 1. Typical RVC foam](image)

Typical foam forming processes utilize a blowing technique, or pressure release, to produce foam of the pitch precursor. When the carbon fiber is produced, the pitch foam is stabilized by heating in air or oxygen for many hours to cross-link the structure, and ‘set’ the pitch, so it does not melt during further heat treatment. Stabilization can be a very time consuming and expensive process depending on the part size. Oak Ridge National Laboratory [3] developed a new, less time consuming process for fabricating pitch-based graphitic foams without the traditional blowing and stabilization steps. This new foam is believed to be less expensive and easier to fabricate than traditional foams.

For detail structure of graphite foams, Klett et al. [1] gave an overall view of this new graphite foam structure. The average pore diameter is from 275 to 350 um in the ARA24-derived foams. For the Conoco-derived foam, the average pore diameter is from 60 to 90 um. The scanning electron micrographs of fracture surfaces revealing the pore structure of the Mitsubishi ARA24 and Conoco-derived foams heat-treated at 1000 °C are shown in Fig. 2 and Fig. 3 respectively. Both foams have a spherical structure with open, interconnected pores between most of the cells. After the analysis of graphite foam structure, it showed that pitch precursor characteristics affected foam structure and properties such as bubble size and ligament structure. It also showed that a pitch with a lower melting point would produce foams with larger pore sizes.

![Fig. 2. Photomicrographs of the foams produced from Mitsubishi ARA 24 pitch at different densities A<B. [1]](image)

Fig. 2. Photomicrographs of the foams produced from Mitsubishi ARA 24 pitch at different densities A<B. [1]

![Fig. 3. Photomicrographs of the foams produced from Conoco pitch at different densities A<B. [1]](image)

Fig. 3. Photomicrographs of the foams produced from Conoco pitch at different densities A<B. [1]

2.2 Thermal properties
Because of the special structure of the graphite foam, some special thermal properties can be found in the graphite foam. Mesophase pitch-derived graphite foam made with the ORNL process exhibit high bulk thermal conductivities, up to 182 W/m.K (it is about six time of copper), at densities up to 0.6 g/cm³, as shown in Table 1. On the other hand, the data in Table 1 shows that the thermal conductivity in z - plane is much larger than the one in x-y plane. This means the high thermal conductivity of the graphite foam only exists in a certain direction. This is one of the disadvantages of the graphite foam. The explanation of this property can be found in Klett et al. [4]. They explained the heat inside the grapheme lattice was transferred by vibrational modes represented as phonons. This heat transfer down the graphite lattice was extremely fast because of the very stiff nature of the covalent bonds, as shown in Fig.4. However, when a phonon reached a defect in the structure, the vibration of the atoms was interrupted and the phonon was considered “scattered”. On the other hand, the
position and vibration of atoms in neighboring planes may impede the vibration of atoms in the plane of interest. The crystal perfection controls thermal. In order to achieve high thermal conductivity in the graphite crystal, the structure must be comprised of aligned, straight graphene planes, and so on.

### Table 1 Properties of various graphite foams made with the ORNL method compared to commercially available PocoFoam.[4]

<table>
<thead>
<tr>
<th>Foaming process</th>
<th>Graphization rate (°C/min)</th>
<th>Average bulk density (g/cm³)</th>
<th>Maximum deviation in density (%)</th>
<th>→ Plane thermal conductivity $k_2$ (W/m·K)</th>
<th>→ Plane thermal conductivity $k_{nP}$ (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORNL graphite foam A</td>
<td>10</td>
<td>0.45</td>
<td>3.7</td>
<td>125</td>
<td>65</td>
</tr>
<tr>
<td>ORNL graphite foam B</td>
<td>10</td>
<td>0.59</td>
<td>-</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>ORNL graphite foam C</td>
<td>1</td>
<td>0.59</td>
<td>181</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>PocoFoam™ Solid 100118</td>
<td>-</td>
<td>-</td>
<td>0.61</td>
<td>3.2</td>
<td>102</td>
</tr>
</tbody>
</table>

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**Fig. 4 Planar structure of hexagonal graphite.[4]**

On the other hand, Gallego et al. [5] compared the aluminum-based heat sink with the graphite foam heat sink. 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, because of the graphite foam high thermal conductivity. Table 2 shows the cooling performance comparison between graphite foam and aluminum. In point of cooling performance, the graphite foam is much better than the aluminum. Another useful finding was that the graphite foam heat sinks can respond to transient loads faster than the traditional aluminum heat sinks. This response time may be crucial for power electronics.

### Table 2 Comparison of air-cooled heat transfer coefficients obtained from graphite foam and aluminum. [5]

<table>
<thead>
<tr>
<th>Foam Type</th>
<th>Air-cool (15kPa-175 kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(h_0) (W/m²·K)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>(h_2) (W/m²·K)</td>
</tr>
<tr>
<td>PocoFoam™</td>
<td>70</td>
</tr>
<tr>
<td>Blood holes (pin-fin negative)</td>
<td>550</td>
</tr>
<tr>
<td>Blood holes (parallel to air flow)</td>
<td>-</td>
</tr>
<tr>
<td>Corrugated</td>
<td>-</td>
</tr>
<tr>
<td>Solid foam</td>
<td>250</td>
</tr>
</tbody>
</table>

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**2.4 Advantages and disadvantages**

Based on the special structure in graphite foam, the advantages of this material can be summarized:

1. High thermal conductivities (1700W/m·K);
2. Low weight, the density is from 0.2 to 0.6 g/cm³;
3. High special surface area (5000 to 50000 m²/m³).

On the other hand, there are some disadvantages for the graphite foam material:

1. High thermal conductivities only exists in a certain direction;
Due the complex internal structure of the foam, the pressure drop inside the graphite foam material is very high.

3 APPLICATION OF GRAPHITE FOAM
Due to the high thermal conductivities, low weight and large special surface area, the graphite foam is a good material for heat exchangers or heat sinks. One of the important applications of graphite foam heat sink is using in electronic packages cooling.

3.1 Electronic package cooling
Nowadays, rapid development in the design of electronic packages for modern high-speed computers has led to the demand for effective methods of chip cooling. The use of graphite foam has emerged as an effective cooling method because of its large internal contact surface areas which enhances convection at the pore level. Another important reason is that the coolant of electronic equipment can be air instead of water, due to the high thermal conductivity. The removing water can avoid the water leaking short the circuitry of electronic equipment.

Leong et al. [8] carried out experience to investigate heat transfer in graphite foams of four different configurations, which were used in electronic package cooling. These four configurations are shown in Fig. 5. After the test, the pressure drop for these four configurations graphite foam heat sinks is shown in Fig. 6. For the same inlet flow velocity, block and baffle foams presented the highest and lowest pressure drop respectively. Stagger and zigzag structures showed a similar flow resistance to air flow with pressure drop in the middle range. Leong et al. [9] used the Finite Volume Method to simulate these four graphite foam heat sinks. The results showed that one part of flow penetrates through the thin foam wall and remaining portion of air flows through the foam through the structured empty slots. The velocity distribution in stagger graphite foam is shown in Fig. 7. It was confirmed that enhanced convection heat transfer occurred at both the pore level inside the foam and at the surface of the structure foam wall.

Lu et al. [10] used the graphite foam as a wick in a vapor chamber. With ethanol as the coolant, the vapor chamber (25 mm x 25 mm x 6 mm) had been demonstrated at a heat flux of 80 W/cm². After testing, the results showed that the performance of a vapor chamber using graphite foam is about twice that of one using a copper wick structure. On the other hand, if the coolant was water, the performance can be improved more. Williams et al. [11-12] investigated several different channel insert configuration as mini-heat exchangers using both copper fins and graphite foam. After testing, the graphite foam was proved to have strong potential as a mini-heat exchanger. It was also observed that increasing the flow rate in the cooling channel resulted in lower power chip temperature. However, there seems to have a maximum flow rate at which no more significant improvement would be observed.

Fig. 5. Tested graphite foam heat sinks of (a) block, (b) stagger, (c) baffle and (d) zigzag configurations. [8]

Fig. 6. Pressure drop versus inlet flow velocity of air flow through tested configurations. [8]

Fig. 7. Velocity distribution in stagger graphite foams. [9]
It is well known that the usage of thermosyphons in the thermal management of electronics is established and the methods for evaporator enhancement are of interest. Gandikota et al. [13] investigated the cooling performance of graphite foam for evaporator enhancement in thermosyphons and in pool boiling with FC-72 as the operating fluid. The total thermal resistance for the foam evaporator was shown in Fig. 8. The exhibited thermal resistance was very low, averaging about 0.024 K/W at low flux value. The thermal resistance was found to rise with increasing heat flux, but still remained advantageously low. On the other hand, Coursey et al. [14] presented the thermal performance of a graphite foam thermosyphon evaporator. The usage of the graphite foam as the evaporator in a thermosyphon enabled the transfer of large amounts of energy with considerable low temperature difference and without the need for external pumping. The geometry of the foam was found to significantly affect heat transfer in a nonlinear manner by changing the boiling area and the distance of this boiling area. Increasing the density of the foam was found to linearly affect heat transfer. After the non-dimensional analysis, it found out the heat transfer may be reduce due to the small size of the graphite pores. Heat loads as high as 149W were dissipated from a 1 cm² heated area for 52 degree wall superheat.

3.2 Vehicles cooling system
Another important utilization of the graphite foam heat exchanger is for vehicles cooling. Because the graphite foam is lightweight and transfer heat rapidly, it might improve the efficiency of transportation vehicles. Meanwhile, some people believe graphite foam is an enabling technology that will solve critical heat rejection problems that must be solved before fuel cell and advanced power electronics technologies are introduced into automobiles.

The graphite foam could be used to make a smaller, lighter car radiator. This might by placed away from the front of a car to give an energy saving and less polluting aerodynamic design. If the size of the front of the car can be reduced, the car does not push as much air in its forward motion, allowing it to use fuel more efficiently. Because a smaller radiator makes a car lighter and faster since it allows a more aerodynamic design, it is interesting for the automotive industry. Kett et al. [15] designed a radiator (as shown in Fig. 9) with the carbon foam. The heat transfer coefficients increased a lot. This led to significant reductions in the number of tubes needed for similar heat transfer. Thus, a typical automotive radiator that is 48 cm x 69 cm might be reduced to 20 cm x 20 cm in cross section with the same heat removal rate. Such a reduced size will reduce overall weight, cost, and volume of the system. Thereby the fuel efficiency can be improved.

3.3 Other application
Because of the high thermal conductivities in the graphite foam material, the time used for heat transfer inside the material will be very short. This is a big advantage for the energy storage applications. Lafdi et al. [16] investigated and predicted the thermal performance of graphite foams infiltrated with phase change materials for space and terrestrial energy storage systems. Because of the high thermal conductivity of graphite foams, the phase change material and foam system thermal performance had be improved significantly. Because in the phase change material energy storage process the higher thermal conductivity leads to the shorter time for charging and discharging time for any phase change material energy storage. The short time of charging and discharging leads to the better system performance.

4 PROBLEMS
Even though the graphite foam is an excellent thermal material, the graphite foam heat exchangers are still rare in the current commercial market. What problems are blocking the graphite foam heat exchangers development?

The first problem is faced by the graphite foam heat exchanger is the high pressure drop. Because of the complex internal structure of the foam, the flow resistance inside the graphite
foam is very high. This causes a very high pressure drop inside the graphite foam heat exchanger. Thus the performance of a graphite foam heat exchanger is controlled more by the surface area accessed than by the high conductivity of the foam. Due to the high flow resistance, it is difficult for the cooling air to reach the surface for transferring the heat. In this case, the efficient area for heat transfer is reduced a lot. On the other hand, the high pressure drop requires a very powerful fan to push the air through the graphite foam heat exchanger. The powerful fan might be very expensive or very large. In this case, it requires a large space for the fan. That may be a problem when the space is limited. In order to resolve the high pressure drop problem, it is suggested by Callego et al. [17] that, the porosity, pore density, ligament structure, and strength of the graphite foam should be optimized simultaneously to enhance heat transfer with minimal increase in pressure loses.

The second problem is the mechanical properties. Klett [18] conceded that the graphite foam was not exceptionally strong. Its tensile and compressive strength and its other mechanical properties are not as good as those of aluminum and copper. Haskell et al. [19] tested the thermal properties and the mechanical properties. It showed that tensile strength of graphite foam was much lower than the one of aluminum or copper. The data is shown in Table 4. In the point of Klett [18], when the graphite foam was impregnated with epoxy resin, the compressive strength can increase then times. However, by tweaking the fabrication process to improve the foam's mechanical properties, the high thermal conductivity might sacrifice.

Table 4 Comparative thermal and physical properties of metals and foams. [19]

<table>
<thead>
<tr>
<th>Thermal Properties</th>
<th>Copper</th>
<th>Aluminum</th>
<th>Foam A</th>
<th>Foam B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Thermal Conductivity (W/mK)</td>
<td>391</td>
<td>180</td>
<td>127</td>
<td>175</td>
</tr>
<tr>
<td>Specific Thermal Conductivity (W/mK/g/cm³)</td>
<td>45</td>
<td>63</td>
<td>218</td>
<td>313</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Density (g/cm³)</th>
<th>Tensile strength (Mpa)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.9</td>
<td>270</td>
<td>~</td>
</tr>
</tbody>
</table>

The third problem is the dust blocking. Nowadays most researches about the graphite foam heat exchangers or heat sinks focus on the electronic equipment cooling. Little work is on vehicle radiator application. The main reason for this is the dust blocking problem. Due to the structure of graphite foam, it is easy to block the open cells inside the foams by dust, if there is a lot of dust in the air. Meanwhile it is difficult to clean the dust inside the open cells. This will reduce the efficient surface area for heat transfer. Thus the thermal performance will be reduced. In the electronic cooling application, the ambient air normally is clean. Not much dust is inside the air. So the dust blocking problem is not so serious in the graphite foam heat exchangers which are used for electronic package cooling. When the graphite foam heat exchanger is used as a radiator to cool a car engine, the air around the radiator is full of dust (when the car is driven on a road or mountain). In this situation, the open cells inside the graphite foam heat exchanger will be blocked by dust easily. So the blocking problem is more serious in the radiators than the electronic cooling heat sinks.

Due to these problems, the development of the graphite foam is very slow and difficult. A lot of work has to be done before a good commercial graphite foam heat exchanger appears in the market.

CONCLUSIONS AND SUGGESTIONS

The graphite foam has very high thermal conductivity, low weight and large specific surface area. These properties make the graphite foam good for thermal material. The graphite foam can be used as heat sinks to cool the electronic packages. Meanwhile the graphite foam can be used as a radiator to cool the vehicle engines. Sometimes, the graphite foam can be used in the energy storage application.

However, due to the complex internal structure of graphite foam, there is very high pressure drop when the air goes through the graphite foam. This might be required a very powerful fan. There are some other disadvantages for the graphite foam. One is the low tensile strength. Another one is the high thermal conductivity only exists in a certain direction. All these problems block the development of graphite as thermal material.

A lot of work has to be done on the graphite foam. But the most important work is to improve the manufacture process, so that the internal structure of the graphite can be changed. After improving the internal structure, the pressure drop might be reduced, and the tensile strength may be increased.

REFERENCES


