THERMAL MANAGEMENT SOLUTIONS UTILIZING HIGH THERMAL CONDUCTIVITY GRAPHITE FOAMS

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ABSTRACT

The recent development of light weight foams has led to novel light weight high strength carbon based materials and structures. These materials exhibit very high specific strengths and low thermal conductivities. Likewise, the novel development of a very high thermal conductivity graphite foam will lead to novel "out-of-the-box" solutions for thermal management problems. With a thermal conductivity equivalent to aluminum 6061 and $1/5^{th}$ the weight, this material is an enabling technology for thermal management problems ranging from heat sinks to radiators and satellite panels to aircraft heat exchangers. In addition, the open porosity will lead to novel designs that incorporate porous media heat exchangers and phase change materials. For example, by utilizing the foam as a heat exchanger, heat transfer coefficients over two orders of magnitude greater than current metallic designs have been measured. To further demonstrate this phenomenon, a heat exchanger (radiator) for a passenger automobile has been developed that is significantly smaller in size, and testing has demonstrated feasibility to improve the automobiles aerodynamic efficiency and reduce weight.

1. Introduction

In recent years there has been an increasing number of applications requiring more efficient and lightweight thermal management such as high-density electronics, hybrid diesel-electric vehicles, communication satellites, and advanced aircraft. The primary concerns in these thermal management applications are high thermal conductivity, low weight, low coefficient of thermal expansion, high specific strength and low cost (1). Such applications have focused on sandwich structures (a high thermal conductivity material encapsulating a structural core material) to provide the required mechanical properties (1). However, since structural cores (e.g. honeycombs) are typically low-density materials, the thermal conductivity of the overall composite through the thickness is relatively low (~3-10 W/m·K for aluminum honeycomb) (2, 3). One potential core material being explored is metallic foam: however, the thermal conductivities are still low, 5 - 50 W/m·K (3) and are not significantly greater than the out-of-plane thermal conductivities of typical carbon-carbon composites (see Table 1).

Existing carbon foams are typically reticulated glassy carbon foams with a pentagonal dodecahedron structure (7-9), illustrated in Figure 1, and typically exhibit thermal conductivities less than 1 W/m·K (3, 10 - 13). Other pitch-derived carbon foams have been reported and explored. Unfortunately, these are also thermally insulating and are designed for structural reinforcement rather than thermal management. The pitch-derived graphitic foams reported here exhibit a spherical morphology, and present a unique solution to this problem by offering high thermal conductivity with a low weight.

Table 1. Thermal properties of carbon fiber composites and other thermal management materials.

Material	Specific Gravity	Thermal Conductivity		Specific Thermal Conductivity*	
		In-plane	Out-of-plane	In-plane	Out-of-plane
		[W/m·K]	[W/m·K]	[W/m·K]	[W/m·K]
Typical 2-D Carbon-Carbon [4]	1.88	250	20	132	10.6
EWC-300/Cyanate Ester [5]	1.72	109	1	63	0.6
Copper [5]	8.9	400	400	45	45
Aluminum 6061[5]	2.8	180	180	64	64
Aluminum Honeycomb [2]	0.19	--	~10	--	52
Aluminum Foam [6]	0.5	12	12	24	24

* Defined as thermal conductivity divided by specific gravity.

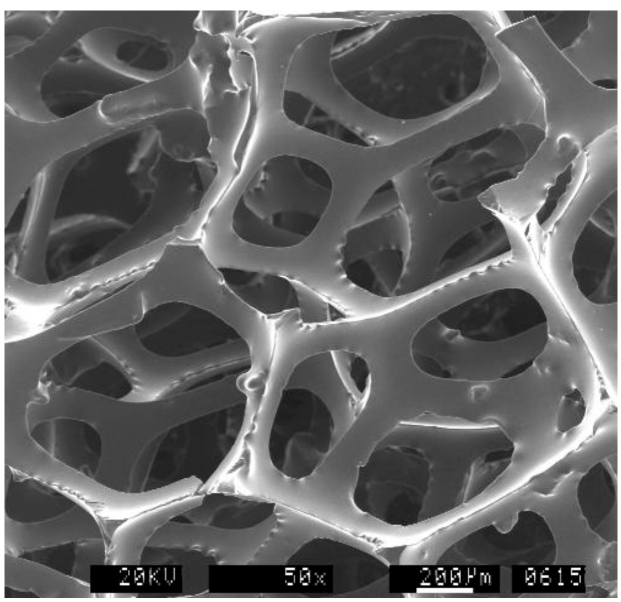


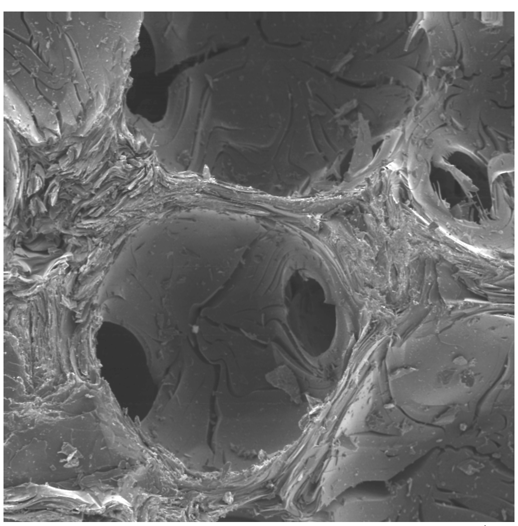
Figure 1. Typical reticulated glassy carbon foam produced by ERG Corporation.

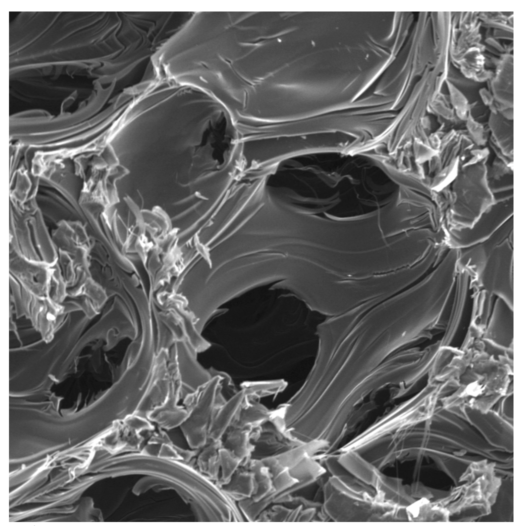
A new, and less time consuming process for fabricating pitch-based graphitic foams without the traditional blowing and stabilization steps has been developed at Oak Ridge National Laboratory (ORNL), licensed to Poco Graphite, Inc., and is the focus of this research. More importantly, these new foams are extremely thermally conductive, compared to existing carbon foams. It is believed that these new foams will be less expensive and easier to fabricate than traditional foams since the time consuming oxidative stabilization step has been removed. Potentially, the process will lead to a significant reduction in the cost of carbon-based thermal management and structural materials (i.e. foam-reinforced composites and foam core sandwich structures).

The following discussions focus on foams produced from a synthetic mesophase pitch from Mitsubishi Gas Chemical Co. labeled ARA24. While others have been explored with success, the vast majority of the data has been focused on this pitch due to its availability.

2. GRAPHITIC FOAMS

2.1 Microstructural Characterization Figures 2 and 3 are scanning electron micrographs of the pore structure of the foams heat-treated at 1000°C and 2800°C. The foams exhibit a spherical structure with open, interconnected pores between most of the cells. It is evident from the images that the graphitic structure is oriented parallel to the cell walls and highly aligned along the axis the ligaments. In fact, this feature is striking since it is clearly visible in foams with a final heat treatment of only 1000°C (Figure 2). Normally, in other graphitizable carbons, this texture is not clearly evident at these low temperatures. This highly aligned structure is significantly different from typical vitreous carbon foams: vitreous carbon foams are void of graphitic structure, have large openings and linear ligaments, and are mostly pentagonal dodecahedral in shape (Figure 1).





200 μm

Figure 2. Structure of Mitsubishi ARA pitch-derived carbon foam carbonized at 1000°C.

Figure 3. Structure of Mitsubishi ARA pitch-derived carbon foam graphitized at 2800°C

Moreover, it can be seen that in the junctions between ligaments, the graphitic structure is less aligned and possesses more folded texture. It is postulated that this arises from the lack of stresses at this location during forming. Therefore, the well ordered structure in these regions is primarily an artifact of the structure in precursor mesophase prior to heat treatment.

2.2 Thermal Conductivity The thermal conductivity of the carbonized foams (Figure 4) was, as expected, very low (1-2 W/m·K) which is consistent with other porous carbon materials (14 -23). The thermal conductivity of the graphitized foams, however, varied linearly with density from 50 to 150 W/m·K (Figure 5). This is remarkable for a material with such a low density, 0.27 to 0.57 g/cm^3. The foam exhibits isotropic thermal conductivities comparable to the in-plane thermal conductivity of other thermal management materials and significantly higher than in the out-of-plane directions (Table 1). Although several of the other thermal management materials have higher in-plane thermal conductivities, their densities are much greater than that of the foam. Hence, the specific thermal conductivity (thermal conductivity divided by specific gravity) of the foam (>300 W/m·K) is significantly greater than most of the available thermal management panels (in-plane and out-of-plane). In fact, the specific thermal conductivity is more than six times greater than copper and five times greater than aluminum, the preferred materials for heat sinks.

It is clear that for weight sensitive thermal management applications or applications where transient conditions often occur, the graphitic foam can be superior in thermal properties to other available materials. The advantage of isotropic thermal and mechanical properties combined with open celled structure should allow for novel designs that are more flexible and more efficient.

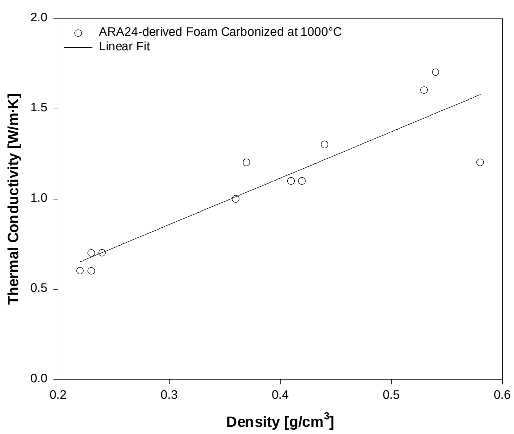


Figure 4. Thermal conductivity as a function of density for ARA Mesophase pitch-derived carbonized at 1000°C.

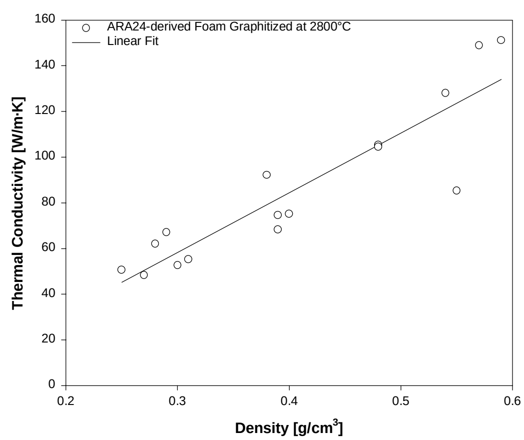
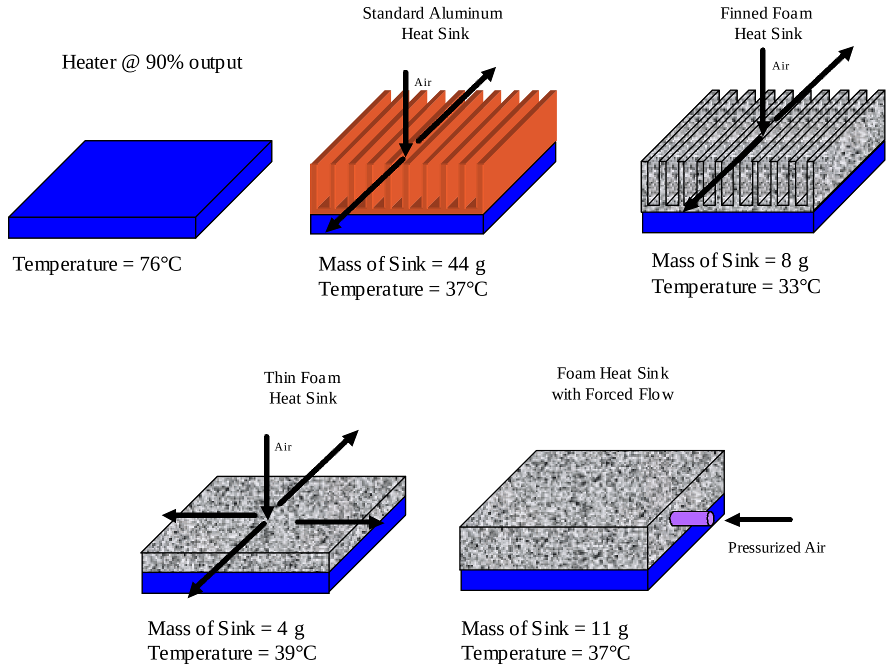


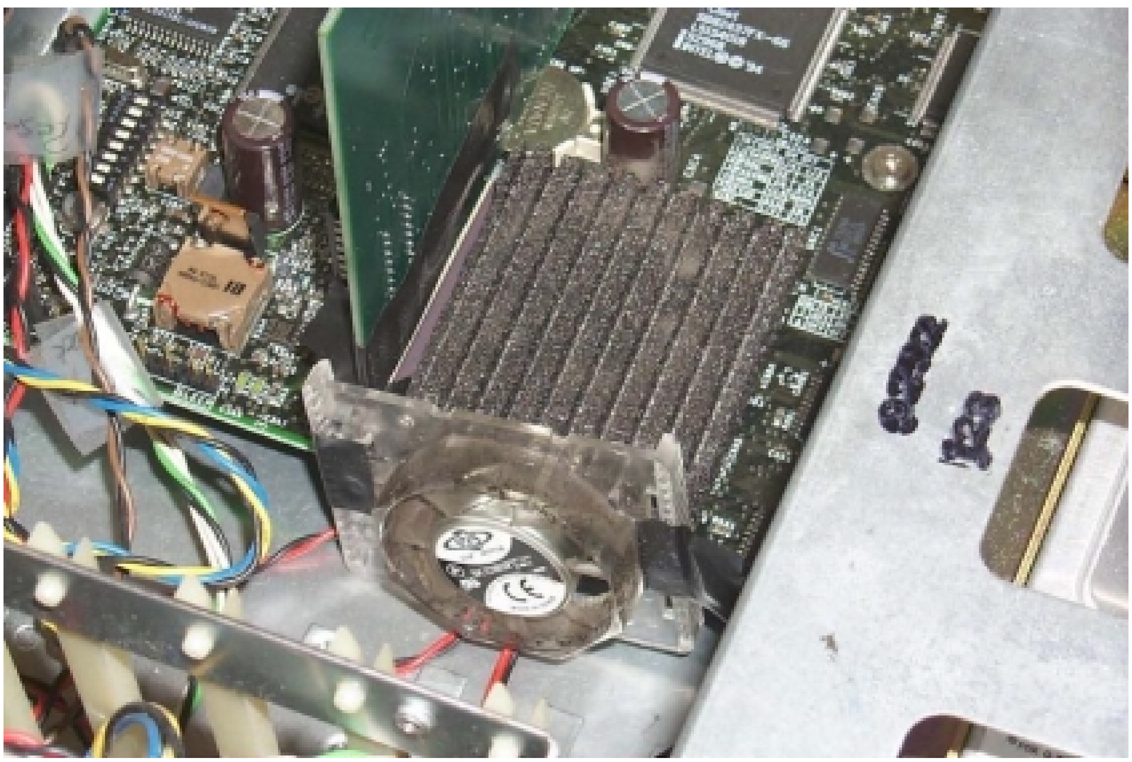
Figure 5. Thermal conductivity as a function of density for ARA Mesophase pitch-derived graphitized at 2800°C.

2.3 Foam-based Structures and Devices The foam is very versatile: it can be made in large samples, is easily machined, laminated with facesheets, or net shape formed. Also, successful densification with aluminum, carbon, epoxy, and thermoplastic resins has been accomplished, demonstrating the use of foam as the reinforcement in a composite structure where high thermal conductivity is required, but at a lower cost than traditional high conductivity carbon fibers.

2.3.1 Heat sink applications To test this ability to transfer heat, the foam was machined into a finned heat sink resembling a standard aluminum heat sink from a Pentium 133 microprocessor (see Figure 6). First, a 10W 2-in. x 2-in. heater (similar output to a Pentium processor) was mounted beneath a 2-in. x 2-in. x 1/8-in. aluminum plate and placed at 90% output. The equilibrium temperature of the center of the aluminum plate was 76°C. The standard aluminum heat sink from the Pentium 133 computer was mounted on the aluminum plate and air was passed over it. The equilibrium temperature of the aluminum plate reached 37°C after 5 minutes. When the finned foam heat sink was mounted on the heater (after 76°C equilibrium was attained with no heat sink), the equilibrium temperature of the aluminum plate was 33°C (with the same air flow). Since the mass of the foam heat sink was significantly lower than the aluminum (8 g vs. 44 g), this was an important achievement. The foam is more efficient because the exposed surface area (due to the structure of the porosity) is larger than the aluminum heat sink. With this in mind, the fins were machined off the finned foam heat sink and the test repeated. Remarkably, the temperature of the aluminum plate equilibrated at 39°C. A significant achievement since the thin foam sink weighed only 4 grams (compared to 44 for the aluminum heat sink).

In a final test (see Figure 6), another finned foam heat sink was machined and installed on a Pentium 133 processor in an operational computer (the image analysis system used in this research). It has been operating with the fan for 12 continuous months without problems.





Foam heat sink in Pentium 133 microprocessor

Figure 6. Computer chip heat sinks made from graphitic foam.

2.3.2 Heat exchanger applications In a test to demonstrate the ability of the foam to transfer heat in a heat exchanger application, a block of foam 10.1 centimeter (cm) square by 2.54 cm thick was fitted with three aluminum tubes (0.635 cm diameter) as shown in Figure 7. The foam exhibited a density of approximately 0.5 g/cm^3 and a thermal conductivity of approximately 150 W/m·K. Water flowing at 11.34 liters per minute and 80°C was pumped through the tubes and ambient air at 560 liters per minute at 25 degrees Celsius was forced through the foam (in a duct type arrangement). The temperature drop of the water was measured to be approximately 3°C and the temperature change of the air was recorded. Strikingly, the temperature of the ambient air passing through the foam increased by up to 30°C (unlike most heat exchangers of this size).

The overall heat transfer coefficient was calculated to be between 6,000 and 11,000 W/m^2·K and was dependent upon humidity. This is different from most air/water heat exchangers where humidity does not affect heat transfer coefficient significantly. Most air/water heat exchangers, like a radiator on a car, exhibit a overall heat transfer coefficient of about 30-45 W/m^2·K. While this test demonstrates a remarkable increase in heat transfer coefficient and provides the tool to reduce the size of heat exchangers dramatically, the pressure drop through the foam was approximately 5.4 KPa/cm. This is not unreasonable for land-based systems where developing a pressure head is feasible. However, in an automobile or airplane where weight and power is a significant concern, this large pressure drop presents a potential problem for an efficient design.

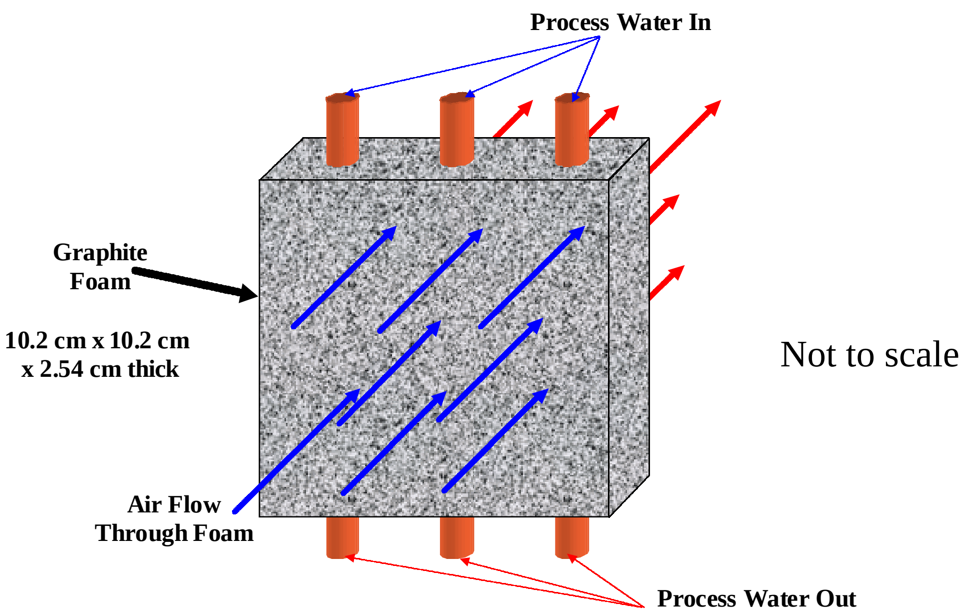


Figure 7. Schematic representation of heat exchanger with cooling air forced through pores of foam. Overall heat transfer coefficient measured at 11,000 W/m^2·K.

Therefore, another design was tested in which a block of foam approximately 20.3 cm square by 2.54 cm thick was fashioned with eight 3/8” tubes press-fit through the foam similar to Figure 8. However, unlike the previous test, through holes were machined as shown in Figure 8 so as to allow the passage of the cooling air through the holes and reduce the pressure drop. While the specific size of the holes and number are proprietary, the total surface area of the holes was 948 cm^2. This radiator was placed on a NASCAR Winston Cup racing car, with an 800 hp V8 gasoline high performance engine. An electric fan forcing approximately 5663 liters per minute through the heat exchanger (radiator) was ducted to the system. The engine was pumping approximately 56.8 liters per minute of coolant (pure water) through the radiator at a temperature of 210°C. The radiator reduced the temperature of the water by only 1°C and, therefore, rejected approximately 7.2KW of heat to the ambient air. Unfortunately, the engine requires a heat rejection of approximately 33 KW of heat and, hence, the device was insufficient. However, the overall heat transfer coefficient was calculated to be 943 $W/m^2 \cdot K$ based on the external surface area of the foam through holes where the heat is being exchanged. Comparing this to the a heat transfer coefficient of 30 $W/m^2 \cdot K$ in the 68.6 cm x 48.3 cm x 7.6 cm radiator on the car previously, there was hope that if the a similar size design was constructed with the proper amount of surface area, the heat could be rejected with a radiator that was significantly smaller than the current systems.

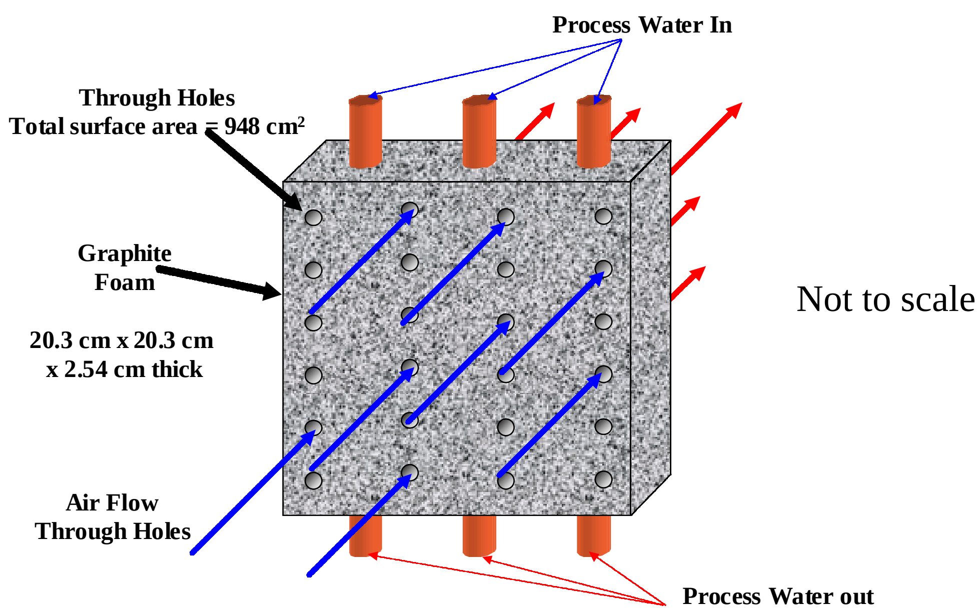


Figure 8. Schematic representation of heat exchanger with cooling air forced through channels in foam. Overall heat transfer coefficient measured at 943 $W/m^2 \cdot K$.

Therefore, in a final test, a heat exchanger (radiator) for a NASCAR racing car was designed and constructed as shown schematically in Figure 9. This new design accounted for the need for very high surface area of the external fins of foam. The specific design cannot be shown due to its proprietary nature; however, the total external fin surface area was 7561 cm^2. Aluminum 6061 tubes with an internal dimension of 0.782 cm were press-fit through the foam and then the fins and through holes were machined out of the foam. The through holes in this system yielded a very small resistance to air flow and, remarkably, a 0.03 KPa/cm pressure drop through the system was achieved. There were several rows of finned tubes (not shown in Figure 10) ducted to a fan providing 39,300 liters per minute of ambient air (dramatically smaller than the 1.7 million liters per minute of air at 180 mph that the cars currently operate). The overall dimensions of the radiator was 22.9 cm x 17.78 cm x 15.27 cm deep, and significantly smaller than the current radiators. The hot engine coolant (pure water) was maintained at 57.5 liters per minute at 99.4°C in a steady state test. At steady state, the water coolant temperature dropped from 99.4°C to 91°C, which is the desired engine inlet coolant temperature (inlet temperatures below this will reduce efficiencies of the engine). At the given coolant flow rate, this is equivalent to 33.5 KW of heat rejected to the air and an increase from ambient of 43°C for dry air (41°C for air at 60% relative humidity). The overall heat transfer coefficient was calculated to be 977 $W/m^2 \cdot K$ and since the desired inlet coolant temperature was achieved, this was deemed a successful test.

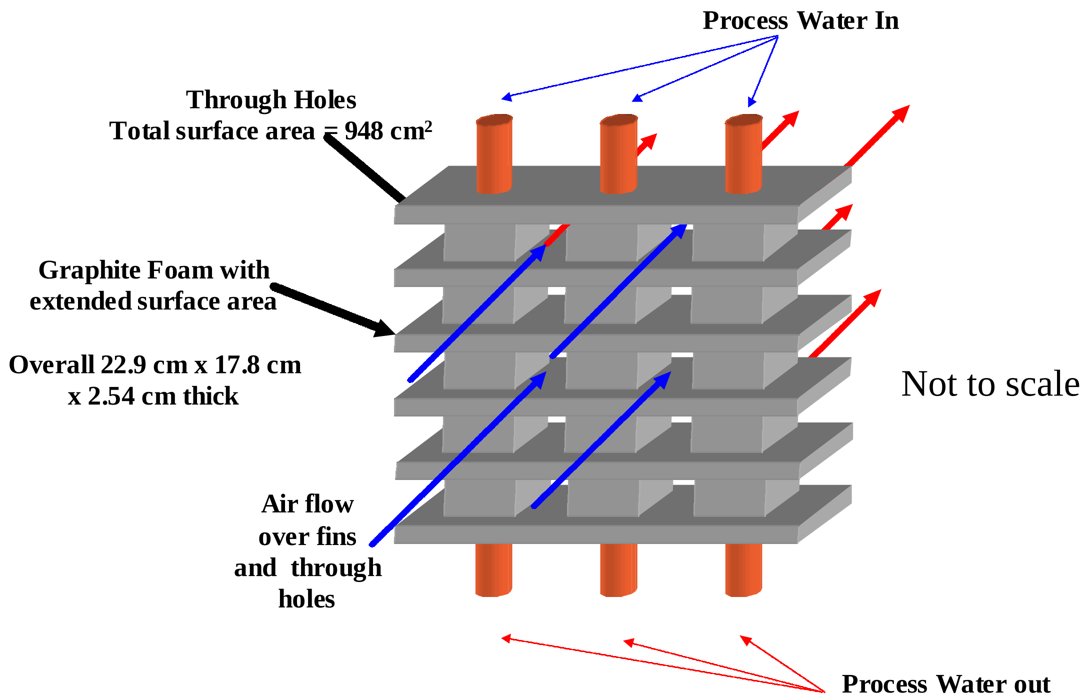


Figure 9. Schematic representation of heat exchanger with enhanced surface area machined into foam for enhanced heat transfer and reduced pressure drop. Overall heat transfer coefficient measured at 977 $W/m^2 \cdot K$.

3. CONCLUSIONS

The remarkable thermal properties of the foam described here (an isotropic bulk thermal conductivity as high as 150 $W/m \cdot K$ and a specific conductivity up to 6 times greater than that of copper) is potentially an enabling material for many technologies. These unique thermal properties, combined with the continuous graphitic open celled network throughout the foam (unlike carbon fiber reinforced composites), should lead to novel and interesting methods of thermal management.

Although the data and discussion presented in this paper illustrate the potential of this material to be an enabling technology for many applications, further work is needed. Even though a design for an automobile radiator which is dramatically smaller than current systems has been developed, when the full potential of this material is utilized, a design for a radiator will most likely not resemble the normal concept of a radiator. The data presented here illustrate that the foam will be most useful and efficient when not used simply as a replacement for existing thermal management materials, but rather when the full potential of its unique structure is utilized in out-of-the-box designs.

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