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Heat Exchangers for Heavy Vehicles Utilizing High Thermal Conductivity Graphite Foams

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ABSTRACT

Approximately two thirds of the world's energy consumption is wasted as heat. In an attempt to reduce heat losses, heat exchangers are utilized to recover some of the energy. A unique graphite foam developed at the Oak Ridge National Laboratory (ORNL) and licensed to Poco Graphite, Inc., promises to allow for novel, more efficient heat exchanger designs. This graphite foam, Figure 1, has a density between 0.2 and 0.6 g/cm³ and a bulk thermal conductivity between 40 and 187 W/m·K. Because the foam has a very accessible surface area (> 4 m²/g) and is open celled, the overall heat transfer coefficients of foam-based heat exchangers can be up to two orders of magnitude greater than conventional heat exchangers. As a result, foam-based heat exchangers could be dramatically smaller and lighter.

INTRODUCTION

Contemporary thermal management has centered around aluminum and copper heat sinks and substrates. This is due to the very high thermal conductivity (180 W/m·K for aluminum 6061 and 400 W/m·K for copper). However, when weight is taken into account, the specific thermal conductivity (thermal conductivity divided by specific gravity) is only ~54 and 45 W/m·K respectively. Therefore, in automotive applications, where weight is a significant concern, it is imperative that a lighter weight thermal management material be found.

Mesophase pitch-derived graphitic foam, on the other hand, can be considered as an interconnected network of graphitic ligaments and, thus, should exhibit isotropic material properties. More importantly, such a foam will exhibit extremely high thermal conductivities along the ligaments of the foam (up to 5 times better than copper) and, therefore, will exhibit high bulk thermal conductivities. Metallic foams, on the other hand, are also being explored as a potential thermal management material. However, the thermal conductivities are still low, 5 - 50 W/m·K (1). Existing carbon foams are typically reticulated glassy carbon foams with a pentagonal dodecahedron structure (2, 3, 4) and exhibit thermal conductivities less than 1 W/m·K

(1, 5, 6, 7). The pitch-derived graphitic foams reported here, Figure 1, exhibit a spherical morphology, and present a unique solution to this problem by offering high thermal conductivity with a low weight.

Figure 1. High Thermal Conductivity Graphite Foam.

Two devices are currently used for thermal management: heat exchangers, which transfer heat energy from one area of a device to another, and heat sinks, which absorb heat. Currently, most cooling heat exchangers for high-power electronics use layers of water-cooled aluminum or copper plate mounted below the electrical circuitry to transfer heat from hotter areas to cooler areas. This presents a unique problem in that if a crack or leak forms, then the water would short the circuitry and destroy the units. By using high thermal conductivity graphitic foam as the core material for these heat exchangers, the effective transfer of heat can be significantly increased while reducing the size and weight of the heat exchanger. But more importantly, it is potentially possible to utilize air to cool the device, thereby removing the water from the system.

A new, less time consuming process for fabricating mesophase pitch-based graphitic foams without the traditional blowing and stabilization steps has been developed at Oak Ridge National Laboratory (ORNL) and is the

focus of this research. Initially these foams possess a thermal conductivity of 106 W/m-K at a relatively low density of 0.54 g/cm³. Potentially, the process will lead to a significant reduction in the cost of graphitic-based thermal management materials (i.e. foam-reinforced composites and foam core sandwich structures).

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 2. The foam exhibited a density of approximately 0.5 g/cm³ 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/m²-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/m²-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 2. Schematic representation of heat exchanger with cooling air forced through pores of foam. Overall heat transfer coefficient measured at 11,000 W/m²-K.

Because the pressure drop was significant a design similar to a current radiator was constructed as shown schematically in Figure 3 to reduce pressure drop. This new design, targeted for an 800 hp racing engine, 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 cm². 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 approximately 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 approximately 43°C for dry air. The overall heat transfer coefficient was calculated to be 977 W/m²-K and since the desired inlet coolant temperature was achieved, this was deemed a successful test.

Figure 3. Schematic representation of heat exchanger with enhanced surface area machined into foam for enhanced heat transfer and reduced pressure drop. Note that several rows of this design were employed in the final version.

HEAT SINKS

In order to characterize the behavior of the foam as a sink material for power electronics, a test chamber (Figure 4) was built to quantify its power dissipation capacity. As shown in Figure 2, the foam is mounted to an aluminum plate (usually by brazing) and placed in a cavity where

the cooling fluid flows. The system is designed with no gap around the foam, thereby forcing the fluid to pass through the pores of the foam. The system is sealed with o-rings, and pressure taps are inserted into the chamber to measure the pressure drop of the system. A simulated power inverter (cartridge heaters in a 5 cm x 5 cm x 2 cm aluminum block) is mounted to the aluminum plate and is capable of generating up to 800 Watts (32 W/cm²). As the cooling fluid passes through the system, the temperatures of the heater and inlet and outlet fluid are measured. The overall heat transfer coefficient (U_o) is calculated from Equation (1) where ΔT_{LM} is the log mean temperature difference, A is the area of foam attached to the aluminum plate, and q is the heat dissipated to the cooling fluid.

$$U_o = q / (A \cdot \Delta T_{LM}) \quad (1)$$

Figure 4. Schematic of test rig.

RESULTS

In the first experiment a solid block of foam (5 cm x 5 cm x 3.175 cm) at a density of 0.47 g/cm³ was brazed to the aluminum using SuperBraz® low temperature braze. Ambient air was passed through the foam at 140, 280, and 420 liters per minute. The temperature of the heater versus heater power density at various flow rates is plotted in Figure 5. The overall heat transfer coefficient versus airflow is plotted in Figure 6 and the pressure drop is plotted in Figure 7. The overall heat transfer coefficient is very high compared to that of a standard automobile radiator (2500 vs. 30 W/m²·K).

Figure 5. Temperature vs. Power.

Figure 6. Overall heat transfer coefficients.

Figure 7. Pressure drop through the foam.

CONCLUSIONS

The high conductivity graphite foam presents a unique solution to the increasing cooling demands of power electronics and other automotive components. With novel designs, it is possible to eliminate cooling water and utilize air as the primary cooling fluid. This is a logical step since the heat is rejected to air eventually. In a parallel effort, radiators designed with the carbon foam exhibit a 10-fold increase in heat transfer coefficients. Higher heat-transfer coefficients should lead to significant reductions in the number of tubes (i.e. reduction in surface area) needed for similar heat transfer. Therefore, a typical automotive radiator that is 48cm x 69cm might be reduced to 20cm x 20cm in cross section with the same heat removal rate. Such a reduced size will reduce overall weight, cost, and volume of the system, thereby improving fuel efficiency.

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