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UTILIZATION OF A GRAPHITE FOAM RADIATOR ON A NATURAL GAS ENGINE-DRIVEN HEAT PUMP

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ABSTRACT

A natural gas engine-driven heat pump was outfitted with a graphite foam radiator to demonstrate its thermal efficiency and compare it with that of a conventional radiator. A sequence of tests was performed with the graphite foam radiator operating in series with the standard aluminum radiator. Most aluminum air-to-water radiators exhibit an overall heat transfer coefficient up to 100 W/(m^2·K). Laboratory experiments have demonstrated that a graphite foam radiator can achieve an overall heat transfer coefficient up to an order of magnitude larger.

The mesophase pitch derived graphite foam is a material that offers excellent thermal management capability. The foam has an accessible surface area of 4 m^2/g and an open cell structure with graphitic ligaments aligned parallel to the cell walls, giving it an overall bulk thermal conductivity of up to 175 W/(m·K). The bulk thermal conductivity of aluminum is 180 W/(m·K). The density of the graphite foam is a fifth of that of aluminum and its thermal diffusivity is three times greater than aluminum.

These properties allow the graphite foam to be utilized in radiator, or any other heat exchanger, designs that are more efficient than conventional radiators. A graphite foam radiator designed to reject a given amount of heat will be smaller in size, weigh less, require less cooling air, and be quicker at removing heat than a conventional aluminum radiator.

INTRODUCTION

A well-instrumented 15-ton natural gas engine-driven heat pump was used to study the efficiency of a graphite foam designed radiator. The heat pump has a 1.8-liter, four cylinder, engine with a standard aluminum radiator. The instrumentation is able to monitor and collect data associated with the water flow rate, water inlet and outlet temperatures, radiator air inlet and outlet temperatures, and relative humidity.

The mesophase pitch derived graphite foam is a material that offers excellent thermal management capability. The foam has an open cell structure (98% open porosity) with graphitic ligaments aligned parallel to the cell walls. Refer to Fig. 1 for the structure of the graphitic ligaments. The alignment of the graphitic ligaments in a three dimensional array, gives the foam homogeneous thermal properties, unlike carbon fibers that have unidirectional thermal properties parallel to the fiber axis. The thermal conductivity of the foam has been measured to be as high as 175 W/m·K, placing it on the level of 6061 aluminum, which has a bulk thermal conductivity of 180 W/m·K. Copper has a bulk thermal conductivity over two times higher, at 400 W/m·K. Table I lists the properties of the graphite foam as well as those for 6061 aluminum and copper. Some of the properties of the graphite foam cover a range of values due to the tailoring of the properties by the manufacturing process.

Most carbon foams produced today are reticulated glassy foams, Fig. 2, that have no graphitic structure to them (Glicksman et al., 1992). This leads to low thermal conductivities, less than 1 W/m·K (Doermann and Sacadura, 1996; Adams et al., 1998; Gibson and Ashby, 1988). Other pitch-derived carbon foams also exhibit low thermal conductivities and are used mainly for thermal insulators. Depending on the processing parameters, the mesophase pitch derived graphite foam can be an excellent conductor of heat or an insulator similar to the glassy and other pitch-derived carbon foams.

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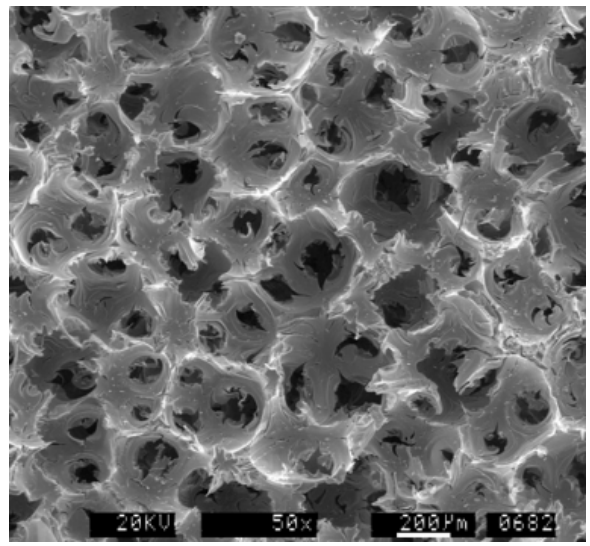
Table I. Properties of the graphite foam, 6061 aluminum and copper.

		Graphite foam	6061 Al	Co
Density	g/cm^3	0.25 – 0.65	2.7	8.9
Porosity		0.71 – 0.89	0	0
Fraction open porosity		0.98	0	0
Coef. of thermal expansion	ppm/°C	4	24	16.5
Tensile strength	MPa	0.7 – 1.6	270	310
Tensile modulus	GPa	0.40	69	115
Comp. strength	MPa	1 – 3.5	-	-
Comp. modulus	GPa	0.1 – 0.8	70	-
Thermal diffusivity	cm^2/s	3.0 – 4.5	0.81	1.17
Thermal cond.	W/(m·K)	0.3 - 175	180	400
Specific thermal cond.	(W/(m·K))/ (g/cm^3)	200 - 300	63	45

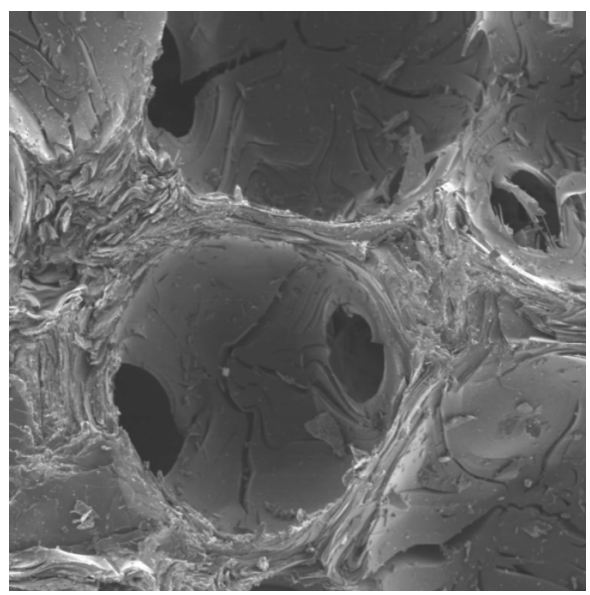
The graphite foam also has a high thermal diffusivity, 3.0 – 4.5 cm^2/s. As a comparison, the thermal diffusivity of 6061 aluminum is 0.81 cm^2/s and that for copper is 1.17 cm^2/s. The foam is capable of removing heat more rapidly than aluminum or copper, in other words the foam is able to dissipate a given amount of heat faster. With a low density and high thermal conductivity the foam exhibits extraordinarily high bulk specific thermal conductivity. The bulk specific thermal conductivity of the foam is in the range of 200 to 300 $(W/m{\cdot}K)/(g/cm^3)$, while that for 6061 aluminum is 63 $(W/m{\cdot}K)/(g/cm^3)$ and that for copper is 45 $(W/m{\cdot}K)/(g/cm^3)$. So, the graphite foam is able to conduct as much heat away as aluminum, but weighs almost 5 times less and is able to remove that heat at a faster rate. Another aspect that makes the graphite foam an excellent thermal management material is that it is dimensionally stable with a low coefficient of thermal expansion, 4 ppm/°C. The coefficient of thermal expansion for 6061 aluminum is 24 ppm/°C and that for copper is 16.5 ppm/°C.

The manufacturing process can be altered to control the density and pore size of the graphite foam, with little to no change in the thermal conductivity. Pore sizes can range anywhere from 60 to 300 μm and densities from 0.25 to 0.6 g/cm^3. The foam can be produced for optimal performance, with regards to pore size and density, depending on the application. The graphite foam has a significant amount of accessible surface area, measuring in the range of 4 m^2/g.

It is possible to design radiators out of the graphite foam that exhibits nearly two orders of magnitude increase in surface area when compared to currently produced aluminum radiators. Dramatically enhancing the heat transfer from the engine coolant to the air. Typical automobile radiators exhibit 100 to 200 m^2 (surface area)/m^2 (frontal radiator area). The surface area of a radiator is a function of its efficiency in dissipating the heat from the engine coolant to the air. The higher the surface area of the radiator the more efficient it is at transferring heat to the air. In laboratory experiments, heat transfer devices fabricated from graphite foam have shown surface areas near 10,000 m^2. Thus, with higher surface area available in the foam, it is possible to reduce the size of the radiator and still maintain the same amount of cooling capacity.



1(a)



1(b)

Figure 1. (a) Micrograph of the cell structure of the ORNL graphite foam. (b) Higher magnification illustrating the alignment of the ligaments. The diameter of the cells is approximately 400 μm.

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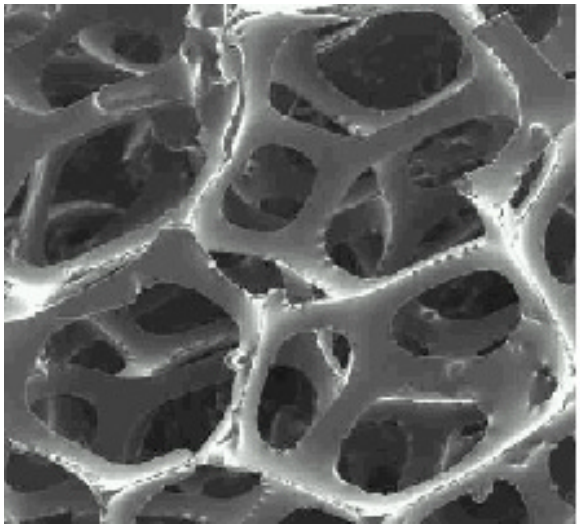


Figure 2. Micrograph of the cell structure of a reticulated glassy foam. The diameter of the cells is approximately 500 μm.

EXPERIMENTAL PROCEDURE

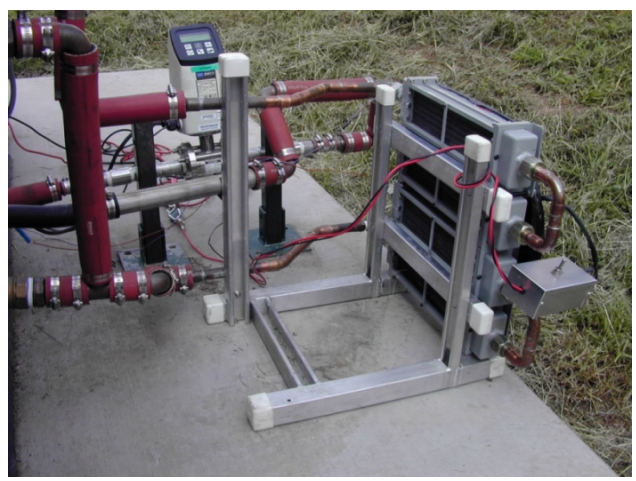
The graphite foam radiator was constructed utilizing aluminum oval tubing and manifolds. The fins and necessary curvature, in order to match the oval tubing, were machined in the graphite foam and then brazed onto the aluminum tubing. The tubing/graphite foam fin structures were stacked on one another to assemble one of the four cores of the radiator. Refer to Fig. 3 (a) for a picture of the graphite foam radiator. Each core consists of seven tubes with a graphite foam fin structure brazed to it. The tubes were soldered to the aluminum manifolds and the manifolds were piped together.

Each core of the graphite radiator measured 0.305 m wide x 0.076 m high x 0.038 m in depth giving it a frontal area of 0.023 m^2. The overall surface area of each core measured 0.42 m^2. So, with four cores the overall frontal area and surface area were 0.092 m^2 and 1.68 m^2, respectively, and a volume of 0.0035 m^3. The dimensions of the standard aluminum radiator were 0.53 m wide x 0.476 m high x 0.051 m depth giving it a frontal area of 0.254 m^2. Based on the frontal area and that most automotive radiators exhibit 100 to 200 m^2 (surface area)/m^2 (frontal radiator area), the conservative available surface area for the standard aluminum radiator would be 25.4 m^2. The volume of the standard aluminum radiator was 0.013 m^3.

The 1.8-liter engine's cooling system was modified in order to accept the graphite foam radiator. Figure 3 (b) illustrates how the graphite radiator is piped into the cooling system of the 1.8-liter engine. This arrangement allows the standard radiator to operate unaccompanied by the graphite radiator, operate both radiators in series and for the graphite radiator to operate alone.

The conditions for the three experiments were; (Test 1) standard radiator running alone, (Test 2) standard radiator running in series with the graphite radiator, and (Test 3) graphite radiator running alone. Ten minutes of data was collected for each test, after a steady state was reached. Refer to Table II for the air and relative humidity conditions for each test. The coolant was a mixture of propylene glycol and water. Table II shows the volume percent of propylene glycol for each test.

3(a)



3(b)

Figure 3. (a) Picture of the graphite foam radiator. (b)Picture of the graphite foam radiator attached to the 1.8-liter engine of the heat pump.

RESULTS AND DISCUSSION

Table III lists the temperature and calculated heat removal for the three tests. Test 1, standard radiator alone, removed 16,555 W of heat and had a calculated overall heat transfer coefficient of 32 W/(m^2·K). The overall heat transfer coefficient is calculated by dividing the heat dissipated by the product of the surface area and the log mean temperature difference (ΔT_{LM}) (Incropera and De Witt, 1985). The surface area used for this calculation, for the standard radiator, was 25.4 m^2 as stated in the experimental procedure.

Test 3, graphite foam radiator alone, dissipated 14,820 W of heat and the overall heat transfer coefficient calculated using 1.68 m^2 surface area was 182 W/(m^2·K). This value is 5.7 times greater than the standard radiator's overall heat transfer

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coefficient, establishing the graphite foam as a more efficient radiator at removing heat from the coolant and transferring it to the surrounding air.

Table II. Outdoor and coolant conditions during experiments.

		Test 1	Test 2	Test 3
Outside temperature	°C	30.6	30.7	30.8
Relative humidity		35.3%	35.5%	33.2%
Volume % propylene glycol		26.9%	20.8%	20.8%

The overall heat transfer coefficient for the two radiators in Test 2 were lower than the respective values when tested alone. The value for the standard radiator was19 W/(m^2·K) while that for the graphite foam radiator was 107 W/(m^2·K). These values are lower due to the lower water flow during Test 2, 7.5 lpm versus 15.9 and 18.2 lpm for Test 1 and Test 2, respectively.

The efficiency of a radiator can also be stated by the amount of heat it is able to dissipate with respect to its volume (Q/radiator volume). This value for Test 1 and Test 3 was 1,275 kW/m^3 and 4,234 kW/m^3, respectively. The graphite foam radiator showing an efficiency 3.3 times higher than that of the standard aluminum radiator. The natural gas input to the engine for all the tests was 65.5 kW. Both the standard and graphite foam radiators rejected approximately 25% of the input power from the natural gas.

SUMMARY

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Table III. Testing conditions for the three tests performed with the standard aluminum radiator (std.) and the graphite foam radiator (foam).

Test	1 (std.)	2 (std.)	2 (foam)	3 (foam)
Water in (°C)	79.7	70.3	80.1	98.8
Water out (°C)	63.1	54.3	67.7	86.0
Water flow rate (lpm)	15.9	7.5	7.5	18.2
Water flow rate (kg/s)	0.26	0.12	0.12	0.29
Air in (°C)	39.5	39.9	32.2	31.6
Air out (°C)	61.7	53.4	47.2	53.1
Air flow (kg/s)	0.74	0.56	0.36	0.69
ΔT_{LM} (°C)	20.7	15.6	34.1	50.0
Q (W)	16555	7679	5931	14820
Overall heat transfer coefficient (W/(m^2·K))	32	19	107	182
Q/(radiator volume) (kW/m^3)	1,273	591	1,695	4,234
Natural gas input (kW)	65.5	65.5	65.5	65.5
% of input gas rejected by radiator	25%	12%	9%	23%

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