Carbon Foam for Thermal Management of Fuel Cells

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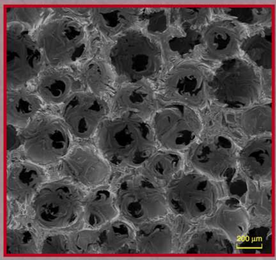
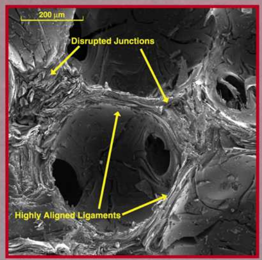
Physical Properties





DKD-x® Fiber
2800°C
k ~ 600 W/m·K

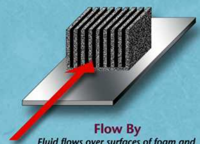
ORNL Graphite Foam
2800°C
k ~ 1700 W/m·K

Material	Density (g/cm^3)	Thermal Conductivity (W/m·K)
Aluminum 6061	2.7	180
Copper	8.9	400
Carbon Fiber	2.2	1000
Synthetic Diamond	2.5	1500
Graphite Foam Ligament	*2.23*	*1700*
Perfect Diamond	2.5	2500

High Thermal Conductivity with high surface area (A) will combine to yield high bulk apparent heat transfer, >180 W/m·K

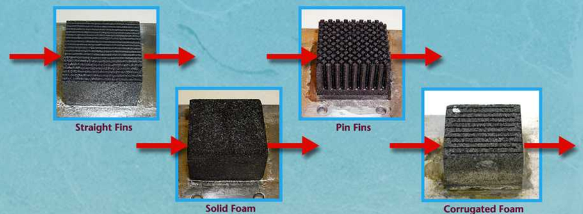
Power Electronics

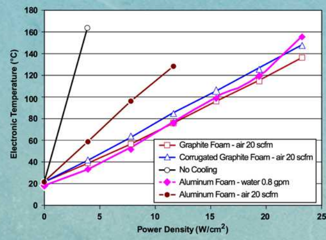
Miniaturization of power electronics often results in overheating and failure of these circuits. Compact heat sinks are being developed to dissipate the waste heat more efficiently



Flow By
Fluid flows over surfaces of foam and heat is transferred from fin surfaces to fluid

Flow Through
Fluid flows through pores of foam and heat is transferred from surfaces of pores to fluid





Heat Sink	Pressure Drop (psi/in)
Aluminum Foam	0.06
Graphite Foam	2.42
Corrugated Graphite Foam	0.17

- Solid graphite foam has very high pressure drops
- Corrugated graphite foams can reduce pressure drop dramatically (almost to that of aluminum foams)
- Graphite foams can remove as much heat with air as aluminum foam can with water

Modeling Convective Heat Transfer

By modeling the convective heat transfer from the foam to fluids, engineers can begin to perform optimization design parametrization of heat exchangers and other heat transfer devices

Darcy-Forcheimer Equation for flow through porous media

$$0 = -\nabla p - \frac{\mu}{\kappa}\mathrm{v} + \frac{\mu\rho}{\sqrt{\kappa}}|\mathrm{v}|\mathrm{v}$$

Equation of Continuity

$$0 = \nabla^2 P - \left(\frac{\mu}{\kappa} - \frac{\mu\rho}{\sqrt{\kappa}}|\mathrm{v}|\mathrm{v}\right)(\nabla \cdot \mathrm{v})$$

Heat Equation in Fluid

$$0 = \nabla \cdot (-k_w \nabla T_w) - \rho C_p DT + \dot{q}_{gained}$$

Heat Equation in Foam

$$0 = \nabla \cdot (-k_f \nabla T_f) - \dot{q}_{loss}$$

Model heat transfer from foam to fluid as a source/loss term - q

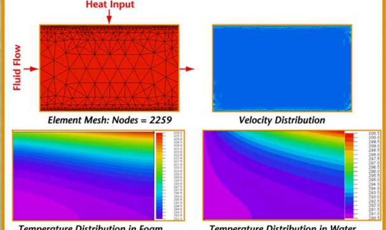
$$\dot{q}_{loss} = \dot{q}_{gained} = -h_{loc} \cdot A_{spec} \cdot (T_f - T_w)$$

Note: All values are localized values

Method:

- Use Finite Element Modeling to simulate a model "Flow-through" heat sink as described above
- FlexPDE, a FEM program for the PC
- Compare results to measured results from experiments

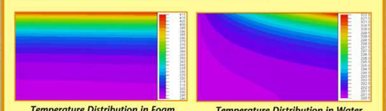
Results of Model with Graphite Foam



Element Mesh: Nodes = 2259 — *Velocity Distribution*

Temperature Distribution in Foam — *Temperature Distribution in Water*

Results of Model with Aluminum Foam



Temperature Distribution in Foam — *Temperature Distribution in Water*

Power Input	Water Flow Rate (gph)	Pressure Drop (psi)	Measured Base Plate Temperature (°C)	Predicted Base Plate Temperature (°C)	Measured Outlet Water Temperature (°C)	Predicted Outlet Water Temperature (°C)
300 W	25	3.5	300.3	299.6	293.8	293.7
300 W	45	7.0	296.8	297.2	292.6	292.4
600 W	25	3.5	308.7	308.4	296.3	295.8
600 W	45	7.0	303.4	303.6	293.9	293.9

Results:

- FEM modeling can predict convective heat transfer from foam to fluid flowing through pores
- Model needs to be expanded to predict convective heat transfer from finned foam structure to a fluid
- Model needs to be expanded to predict heat transfer from foam to a boiling liquid to simulate evaporative cooling systems (humidification)

Other Research of Foams for Fuel Cells

Use of the foam as an evaporative cooling medium

- Use of the foam to provide simultaneous humidification and electronics cooling has been demonstrated
- Demonstrated power dissipation rates of up to 100 W/cm^2
- Currently working with NSA to further develop this technology

Significant research into joining and characterization

- Special solders and brazes have recently been developed
- Corrosion, fouling, vibration, and durability characteristics are being examined

Use of foam for interconnects/bipolar plates

- Electrical conductivity is extremely high, >700 S/cm in plane
- Spongy nature of foam prevents brittleness found in other graphite interconnects
- Coatings with chromium and other metals to protect from oxidation
- Can be used as the substrate for the membrane
  - Both solid oxide and PEM fuel cells

Use of the foams for catalyst support for low temperature cracking of ammonia

- Supplying pure hydrogen for fuel
- Recover waste heat, catalyze reaction, and improve efficiency of fuel cell

Coatings for protection from oxidation and corrosion

- Silicon Carbide vapor deposition
- Chromium depositing technique (packed cementation)
  - This technique can be used to deposit other materials on to the surfaces of the foam

Conclusions

- Engineering solutions, such as corrugation, can be found to overcome some of the deficiencies of the foam to dramatically reduce pressure drop
- Modeling of convective heat transfer for fluid flowing through foam has been successful. Further work is needed to extend this to other engineering problems with foam
- There are many other areas of interest that have developed in utilizing the graphite foam, such as catalyst supports, interconnects, and membrane supports

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