Carbon Foam for Fuel Cell Humidification

Ronald D. Ott (Primary Contact), P. Kadolkar, J. W. Klett
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, TN 37831-6083
Phone: (865) 574-5172; Fax: (865) 574-4357; E-mail: ottr@ornl.gov

DOE Technology Development Manager: Nancy Garland
Phone: (202) 586-5673; Fax: (202) 586-9811; E-mail: Nancy.Garland@ee.doe.gov

Objectives

- To fabricate a compact, efficient humidification system to recover water and heat from the exhaust of a polymer electrolyte membrane (PEM) fuel cell to humidify the inlet air.
- Utilize carbon foam as heat and mass transport medium.
- Optimize carbon foam density, window and pore size to maximize efficiency in heat and water transport.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan:

- R. Thermal and Water Management

Approach

- Design test rig to evaluate the carbon foam's ability to absorb water, provide humidification, and provide heat rejection.
- Determine the ability to pass water through the carbon foam.
- Evaluate the structure of the carbon foam and how it pertains to its ability to function as a water and heat transfer medium.
- Analyze data to determine how the carbon foam could be used to develop an improved humidification system in order to reduce energy requirements, size and cost of a recovery unit.

Accomplishments

- Demonstrated the carbon foam's ability to absorb water and reject heat while humidifying air.
- Demonstrated the ability to pass water through the foam, proving that once water condenses on the foam, it will pass through.
- Demonstrated that the structure and window/pore size of the carbon foam are directly related to its ability to transfer heat and water.

Future Directions

- Tailor the window/pore opening size so that the wicking capability of the carbon foam is optimized to deliver saturated air at 80°C, at required flow rates, to the inlet air stream of a PEM fuel cell.
- Determine the effects of tailoring the window/pore opening size to the heat transfer capability of the carbon foam.

- Interface with a manufacturer of recovery units for fuel cell technology so that all aspects of a recovery unit are considered.
- Design a full-scale recovery unit to evaluate the carbon foam's ability to recover water from the exhaust side of the fuel cell.
- Demonstrate reduced need for ancillary equipment (no need for water pumps, heaters, etc…).
- Work alongside a fuel cell manufacturer to field test a carbon foam recovery unit on PEM fuel cells.

Introduction

The efficiency of the automotive polymer electrolyte membrane (PEM) fuel cell depends on many factors, one of which is the humidification of the inlet air. If the inlet air is not sufficiently humid (saturated), then the stack can develop dry spots in the membrane, and efficiency and voltage will drop. Therefore, it is necessary to ensure that humid inlet air at the proper elevated temperature is supplied to the stack. Current methods involve using a spray nozzle to atomize water droplets onto a cloth or wire mesh substrate. As the inlet air passes over the cloth, it gains moisture and becomes more humid; however, since the air is not preheated, the actual level of humidification (percent humidity) drops as the air is heated in the fuel cell. If heat could be supplied to the water efficiently, the system would become independent of the ambient conditions, the inlet air could become more humid at the proper temperatures, and the overall stack could maintain a high level of efficiency. Carbon foam has been demonstrated to be very efficient in heat transfer in previous work with power electronic heat sinks and automotive radiators. Using the carbon foam in the PEM fuel cell may solve the inlet air humidification problems.

This unique carbon foam (Figure 1) has a density between 0.2 and 0.6 g/cm^3 and a bulk thermal conductivity between 40 and 187 W/m·K. The ligaments of the foam exhibit a thermal conductivity higher than that of artificial diamond. Additionally, in combination with a very accessible surface area (>4 m^2/g), the overall heat transfer coefficients of foam-based heat exchangers can be up to two orders of magnitude greater than those of conventional heat exchangers (in some designs).

The high thermal conductivity, combined with a very high specific surface area, permits the carbon foam to use waste heat from power electronics, cooling fluids, and exhaust gases to vaporize water on the pore surfaces more efficiently than other media, thus enhancing humidification. The high conductivity of the foam will also permit heating of the inlet air, thereby supplying hot, humid inlet air to the fuel cell stack, regardless of the ambient conditions.

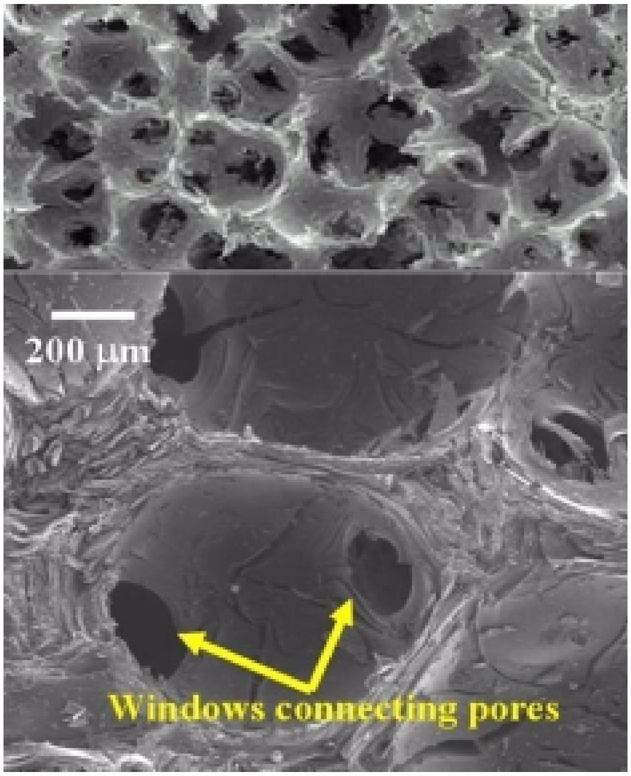

Figure 1. Oak Ridge National Laboratory's Carbon Foam Showing the Pore and Window Sizes

Approach/Results

To characterize the behavior of the foam as a humidifier, a test chamber (Figure 2) was modified to quantify its ability to saturate air with water. The system is designed with no gap around the foam

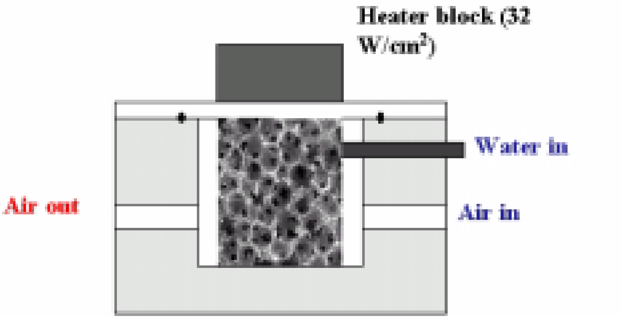

Figure 2. Schematic of the Humidification System

thereby forcing the fluid to pass through the windows and pores of the foam. A tube was inserted into the chamber to supply water directly to the foam, so it saturates the foam completely. As the air is forced through the foam, it forces the water over the surfaces of the foam, leading to efficient evaporation. As the water evaporates, it removes significant amounts of heat while simultaneously saturating the air. A simulated power inverter (cartridge heaters in a 5x5x2 cm aluminum block) is mounted to the aluminum plate and is capable of generating up to 800 W (32 W/cm^2). Refer to Table 1 and Figure 3 for the complete data set.

Table 1. Results of Humidification Tests at a Power Density of 19 W/cm^2

Water flow rate (cm^3/min)	0	10	20
Air flow rate (kg/min)	0.17	0.17	0.17
Electronics temperature (°C)	162	151	136
Outlet air temperature (°C)	103	73	58
RH% outlet air	<0.5	24	87
RH% @ 60°C	1.17	43.5	79
RH% @ 80°C	0.5	18.3	33

As seen in Table 1, the carbon foam reduced the electronics temperature with dry air alone. However, when the water was added to the foam for evaporation, the electronic temperature dropped. Because the latent heat of vaporization of water is several orders of magnitude greater than the sensible heat capacity of water and air, only small amounts of water are needed to effect a large absorption of energy. The relative humidity of the outlet air (inlet to the fuel cell) can be modified easily by changing the amount of water added to the foam. The problem will be to balance the heat rejection from the power electronics of the coolant with the volume of inlet air and water needed to humidify the inlet air.

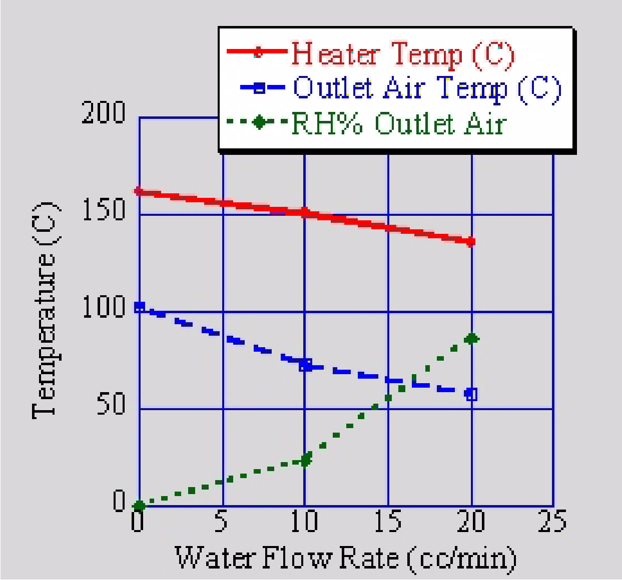

Figure 3. Heater Temperature as a Function of Power Density for Various Water Flow Rates for Humidification

Water flow experiments through the foam were conducted by passing a specified amount of water through a funnel with a piece of carbon foam placed at the base of the funnel. The carbon foam piece measured 10 mm in diameter and 10 mm in length. There were three different densities utilized, thus with varying pore and window sizes. Refer to Table 2 to review the data for the experiments. As can be seen, the low-density foam had lower thermal conductivity, larger window size (more open structure), thus higher water flow rates than the higher density foams.

A heat flow resistance model designed for carbon foam radiators has been helpful in further development of heat exchangers utilizing the carbon foam. It has shown that the highest resistance to heat flow is convective heat transfer at the foam/air surface. Therefore, there is a need to allow more air to pass through the foam in order to take advantage of the tremendous amount of surface area available. This leads to examining more open structured carbon

Table 2. Results of Water Flow Experiments Utilizing a 10 mm Diameter by 10 mm Long Piece of Carbon Foam with Three Different Densities

Density (g/cm^3)	0.403	0.492	0.556
Thermal conductivity (W/m·K)	26.56	71.62	90.72
Window size (mm)	0.195	0.148	0.147
Pore size (mm)	0.381	0.382	0.501
Water flow rate (cm^3/sec)	0.259	0.072	0.049

foams which lead to higher water flow rates and high heat transfer.

Conclusions

Carbon foam is an ideal medium for a recovery unit to humidify and heat the inlet air of a fuel cell. While it has been demonstrated to be able to humidify inlet air to near-saturation levels, several problems exist. First, the volume of water needed is enormous, and it is anticipated that the water will have to be captured in the exit stream of the fuel cell. By cooling the exit stream while humidifying the inlet air, the dew point of the exit gas can easily be reached, and water will condense, allowing the water to be recycled.

Second, while the fuel cell inlet air will be required to operate at several atmospheres above ambient for proper fuel cell application, this pressure will be sufficient to force the air through the foam. With less dense carbon foams, the pressure drop across the foam will be significantly less. Other future work of this project will be to collaborate with a fuel cell manufacturer to develop a prototype humidifier and test it in a real system. Because the water balance on the system will be the most difficult task to overcome, several different designs will be desired to optimally achieve the humidification while recovering excess water from the fuel cell.