Design and Fabrication of a Joule Heated Fiber-Reinforced Carbon Aerogel for Insulation

A. JAMES CLARK SCHOOL OF ENGINEERING

THE DEPARTMENT of MATERIALS SCIENCE AND ENGINEERING

Stephen Barbagallo, Ellen Cesewski, Naveed Chowdhury, Joseph Langreo, Colin Qualters, Nathaniel Schreiber
Department of Materials Science and Engineering, University of Maryland, College Park, MD 20742

Background

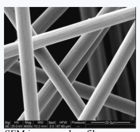
Cold Weather Clothing

Current high-performance clothing systems that are designed to assist the wearer in combatting extremely cold weather situations rely heavily on the concept of layering in order to protect and insulate. A Joule-heated, ultra-lightweight material could be a solution to actively warm the wearer in addition to providing thermal insulation. A battery-powered product like this could greatly benefit the cold weather clothing industry.

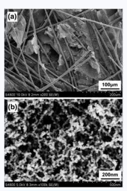
Joule Heating

Charge carrier collisions transfer kinetic and vibration energy to ions, which often manifests as heat within the conducting material. So-called Joule heating can be used to our advantage to actively heat a material using current.

Carbon Aerogels and Carbon Fibers



SEM image: carbon fibers. Piñero-Hernanz et al. 2008 [1]



SEM images: (a) CFCA composite, (b) Carbon aerogel. Feng et al. 2012 [2]

Carbon aerogel is an ultra-low density, highly porous material made up of a fibrous carbon network.

Carbon fibers are highly conductive fibers and are also quite flexible, lending increased electrical conductivity and flexibility to a carbon aerogel.

Carbon fiber-reinforced carbon aerogels (CFCA) have been investigated for their thermal and electrical properties, but have not previously been designed for a joule heating application.

Research Questions

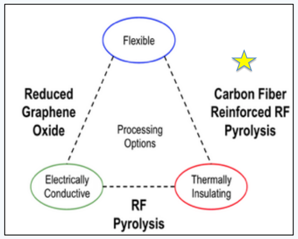
(i) Will carbon fiber-reinforced carbon aerogel thermally perform as well as synthetic down with marginal heat generation from Joule heating?

(ii) Which variation in processing parameters will yield an aerogel with minimum thermal conductivity for a practical electrical conductivity for joule heating potential?

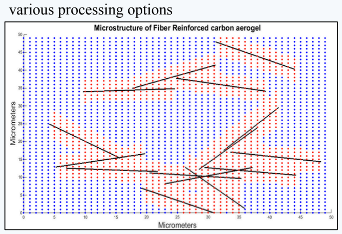
Design and Modeling

CFCA: Carbon fiber-reinforced carbon aerogel

Design Components	Desired Performance
Volume fraction of carbon fibers	1. Acts as a thermal insulator
Porosity: pore size, pore density	2. Joule heating capability
Monolith shape and thickness	3. Flexible, mechanical durability



Material property tradeoffs of different various processing options



MATLAB generated composite microstructures (blue aerogel, red fibers)

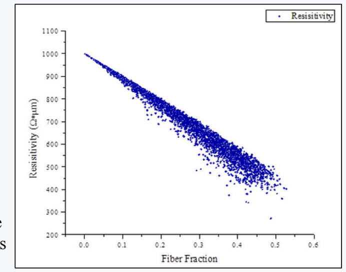
Modeled Resistance

Line scan:

$$R_{line} = (\#blue)*(R_a) + (\#red)*(R_f) + (\#red-blue)*(R_{t_{rb}}) + (\#blue-red)*(R_{t_{br}})$$

Sheet Resistance:

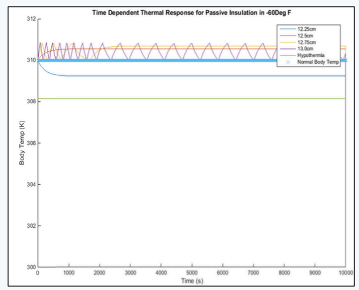
$$R_{sheet} = \left(\sum_{i=1}^{\frac{width}{diameter}} \frac{1}{R_{column}(i)} \right)^{-1}$$



As we increase fiber fraction content, the distribution of sheet resistivities increases due to increased fiber connectivity in the composite.

Modeled Heat Generation

Insulating and heat generating performance success and failure at -60°F for a specified porosity and carbon fiber fraction.



Promising power generation for current applied across thin strips of composite instead of bulk fabric form.

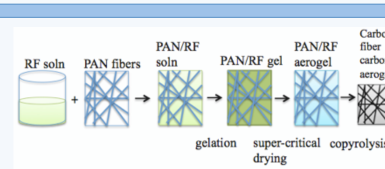
Resistivity (Ω-m)	Cross Sectional Area(m^2)	Resistance (Ω)	Current Applied (A)	Power Generated Per Strip (W)
6.4E-04	0.0001	1.17E+01	0.1	1.17E+00
6.4E-04	0.0001	1.17E+01	0.5	5.86E+00
6.4E-04	0.0001	1.17E+01	1	1.17E+01
6.4E-04	0.0001	1.17E+01	10	1.17E+02
6.4E-04	0.0001	1.17E+01	100	1.17E+03

Prototypes

Lack of access to a supercritical dryer severely inhibited our prototype development. We were able to experiment with two less favorable types of aerogel drying which provided useful information about the scalability of processing this material.

Aerogel Drying Techniques In This Project

Supercritical Drying	Ideal: minimizes shrinkage and cracking	No viable supercritical dryer available for use
Ambient Drying	Pro: no high tech equipment Con: shrinkage, cracking, time consuming	Yielded dense, brittle samples
Freeze Drying	Non-ideal: shrinkage and cracking, need freeze dyer	Yielded promising RF aerogels, unable to carbonize



RF aerogel RF/PAN aerogel

Left: Freeze dried RF and PAN-fiber RF aerogels showed promise, but we were not able to carbonize the samples to CFCAs for testing.

Conclusions

1. The microstructure of a fiber/aerogel composite can be modeled and used to predict resulting electrical conductivity.
2. CFCA composite may perform as well as industry standard for thermal insulation.
3. Our current design geometry is ineffective for Joule heating applications as a bulk fabric, but may be useful as a heating component within a composite fabric or device.

Future Directions

- A controllably Joule-heated aerogel should continue to be studied for both wearable and non-wearable applications.
- Our next steps would be to fabricate samples using a supercritical dryer and to thoroughly characterize electrical and thermal performance as part of a device or component.

Acknowledgements

Dr. Ray Phaneuf
Dr. Robert Bonenberger
Dr. Yifei Mo
Dr. Liangbing Hu
Doug Henderson

References

1. Piñero-Hernanz R, García-Serna J, Dodds C, Hyde J, Poliakoff M, Cocero MJ, Kingman S, Pickering S, Lester E. Chemical recycling of carbon fibre composites using alcohols under subcritical and supercritical conditions. The Journal of Supercritical Fluids. 2008;46(1):83–92.
2. Feng J, Zhang C, Feng J. Carbon fiber reinforced carbon aerogel composites for thermal insulation prepared by soft reinforcement. Materials Letters. 2012;67(1):266–268.