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Development of energy efficient Carbon Fiber based Convective Heater

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ABSTRACT

A heating element has been developed that uses processed fibrous carbon materials to serve as a conducting base, and a suitable binder material to increase its overall strength and performance characteristics. This has been further fabricated in the form of a wall heater. The device has been designed to work on natural convection currents without any forced air blast using fans and motors. The flexibility of the material enables its use in different shapes as room heaters, decorative wall heaters, as a heating element in electric iron, hot plates, heating pads etc. Various advantageous characteristics of the carbon fiber based heating element (over the conventional nichrome wire and other carbon based heating element) that contributes in the efficient working of the heater have been discussed, the most important being its low power consumption. The heater consumes less than 200 watt of power as compared to 1-2 kW ingested by the commercial heaters.

Keywords: Carbon composite; heater; porosity; resistivity

INTRODUCTION

The favorable strength to weight ratio of carbon fibers and their excellent mechanical properties have led to their use in diverse applications such as aerospace, sports and transport sectors. Another familiar, but often less used chattels of carbon fiber is its electrical conductivity. Poly acrilonitrile (PAN) based carbon fibers are not only mechanically strong (tensile strength of 3530 MPa for T-300 grade), but also possess electrical resistivity in a range to make it suitable for heating devices.

Processed metal wire products such as tungsten wire and nichrome wire, machined products of carbon materials such as anisotropic carbon materials and glassy carbon materials, and metal compounds such as silicon carbides are primarily used as resistive heating elements.[1-4] Among these, processed metal wire products are mainly used as heating elements for the heaters of consumer appliances, while carbon, metal compounds, and ceramics e.g. silicon carbide, lanthanum chromite, disilicides etc are mainly used for industrial ovens and other similar application. However, as conventional carbon heating elements are fabricated by machining them from large plates or blocks, the production process is not only complex and expensive, but it is also difficult to fabricate narrow or thin products with sufficient strength. In addition, as the products are machined from blocks, having a specific resistance value within a certain standard range; there is the problem that changing the shape is the only way to control heat generation.

Researchers has used carbon as a heating material.[5] Attempts have been made to fabricate electrically heated systems from appropriately shaped carbon fabric[6, 7] and those containing carbon/graphite fibers, as such woven or stranded into the strips, ropes, sleeves or strands of threads alone or with other materials with a protective layer of elastomer or other materials to overcome carbon's extremely poor abrasion and kink resistance.[8-12] It was found that the coating used in this method reduced the carbon material flexibility and increased the difficulty of making electrical attachments to it, and making electrically continuous seams. Recently carbon nanotube and graphene based transparent heaters have also been demonstrated.[13, 14]

The present study unveils a heating device incorporating strength and flexibility as compared to conventional carbon heaters and having sufficient heat generation efficiency in far infrared region. Moreover it is in the form of thin porous sheet, making it flexible and lightweight. High porosity further leads to the large exposed surface area of the material through which the heat is emitted thus increasing its overall thermal efficiency.

The flexibility of the material enables its use in different shapes. These could have a wide range of applications such

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as room heaters, decorative wall heaters, as a heating element in electric iron, hot plates, heating pads etc. It can be used in developing other devices for medical purpose and warm sleeping beds and/or blankets for defense personals in extremely cold areas. The invention has been protected via patent (applied for) no. 617DEL2009.

EXPERIMENTAL

Preparation of the Heating Element

The methodology for the preparation of the heating element involves chopping of carbon fiber in definite lengths (0.2 - 2.0 cm), followed by dispersing it in an aqueous medium to form a dispersed carbon fiber mat (of dimension 20 cm x 20 cm x 0.05 cm) using the proprietary paper making technique,[15] known as carbon fiber preform. It is a highly porous structure as shown by the SEM image in figure 1.

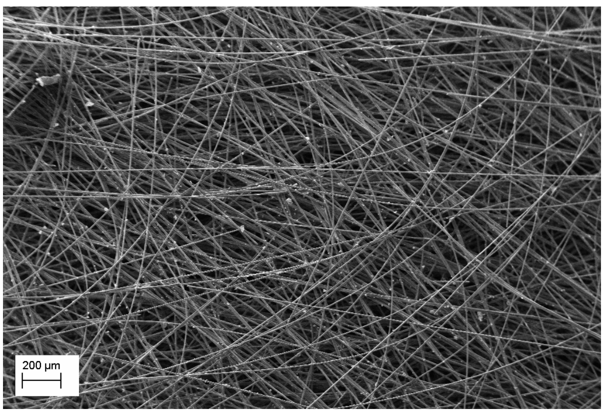

Figure 1. SEM of the carbon fiber preform.

The preform is impregnated with novolac type phenolic resin, such that the volume of the cured resin is equal to that of the carbon fiber. The impregnated carbon fiber mat is then molded into sheet by compression molding technique. Following molding, a post-cure is performed in air to ensure full curing and cross-linking of the resin. The SEM of the carbon fiber/ resin composite sheet so formed is shown in figure 2.

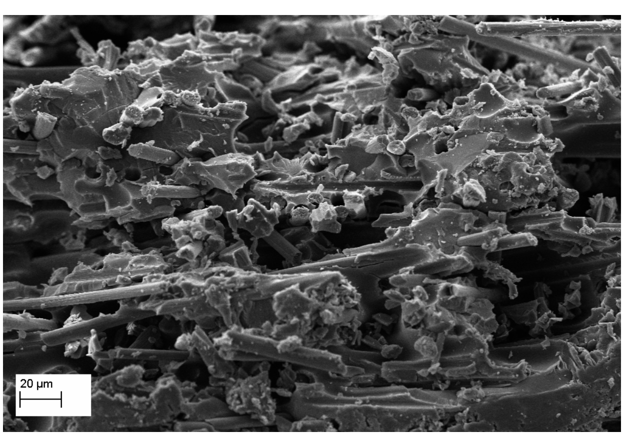

Figure 2. SEM of the carbon fiber/ resin composite.

The composite sheet (to be used as the heating element) was shaped in such a way that the total in-plane resistance from one end to another is ~300Ω . Thus, the dimensions i.e. length (l), width (w), and thickness (t) of the heating element can be proportionally varied for achieving higher surface area (and therefore high thermal efficiency) and for a required application, while maintaining a constant resistance of ~ 300Ω. The heater can therefore be manufactured in various sizes as per the requirements.

Characterization of the Heating Element

The X-ray diffraction examination of the samples was performed on Rikagu powder X ray diffractometer model: XRG 2KW using Cu Kα radiation. The connected pore volume was determined using mercury porosimetry analyzer (model: Poremaster (33/60), P/N 05060, obtained from Quantachrome instruments, USA). In this method, mercury (Hg) with its very high surface tension (4.80 x 10^{-5} J cm^{-2}) is forced into the pores of the sample. The amount of Hg uptake as a function of pressure allows one to calculate the various parameters related to the porous network. The electrical resistivity of the composite was measured using the four probe technique. Kiethley 224 programmable current source was used for providing current. The voltage drop was measured by Keithley 197A auto-ranging microvolt DMM. The Flexural strength and modulus were measured on the INSTRON machine model - 4411 according to ASTM: D 1184 – 69.

Fabrication of the Heater

Electrical connections were made at both ends of the heating element, which was then fixed in between a pair of sheets of electrical insulating material (mica in this case). The vertical assembly is then fixed in between a metallic frame in such a way that a gap of approximately 2 cm is available for circulation of the air convection currents as shown in figure 3 (a). A gap of 1 cm approx is also maintained between the wall and heater assembly to ensure natural and upward convection currents through the heater for efficient transfer of heat to the surroundings (figure 3 (b)) as the heater is designed to be mounted vertically on the wall (figure 3 (c)).

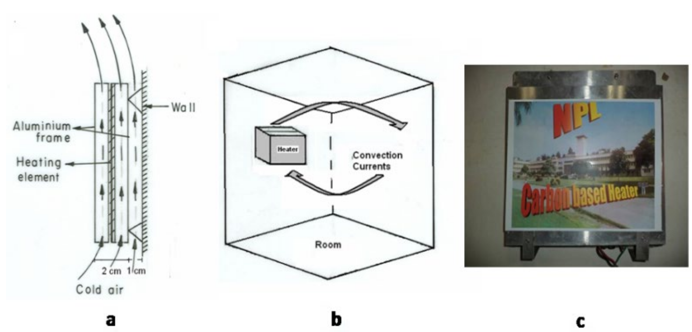

Figure 3. Schematic of (a) the cross section of the heater, (b) the convection currents set up in the room, and (c) photograph of the wall mounted heater.

RESULTS

Characteristics of the Heating Element

The high performance of the heater is attributed to the special properties of the carbon based heating element. The element is light weight having a bulk density of ~ 0.6-0.7 g/cc, while the density of the carbon fiber used as the raw material is 1.7 – 1.8 g/cc. The low density of the element is due to the special processing technique which involves uniform dispersion of carbon fibers to generate porosity as is clear from figure 1.

The XRD curves of the carbon fiber preform and the composite are shown in figure 4. The (002) peak of the carbon fiber preform is quite broad which signifies the disordered/ polycrystalline nature of the material.

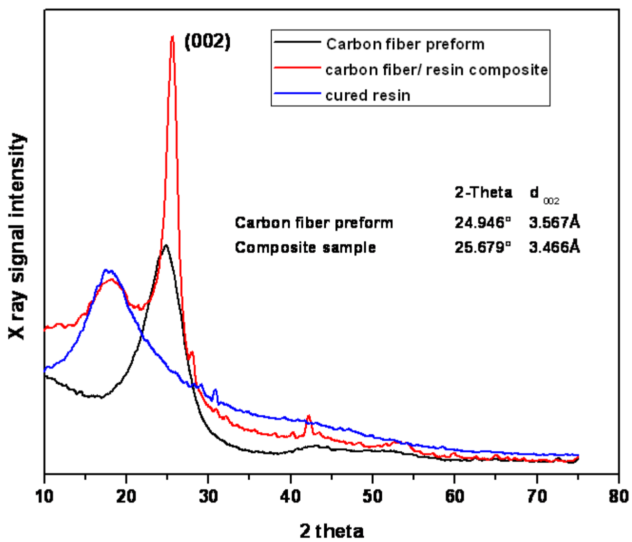

Figure 4. X ray diffraction curves of the carbon fiber preform and composite sample.

Along with the (002) peak of carbon at 25.68°, the green sample shows an additional peak at 18.24° which is due to the cured resin. A slight decrease in the d_{002} peak is observed for the green sample as compared to the carbon fiber preform. This is quite surprising since any change in the carbon fiber structure should take place only beyond heat treatment temperature of 1500°C, which is normally the processing temperature of T-300 carbon fibers. The decrease in the d_{002} spacing of green sample may therefore be interpreted due to realignment of graphitic planes near the carbon fiber surface as a result of high stresses generated during the curing process of the phenolic resin. Such stresses at the fiber /resin interface have been reported during the graphitization of the carbon fiber/ phenolic composites,[16]

The preform is a highly porous structure with a porosity of 92 – 95 % with 90 % of the pores connected. The pore size distribution of the preform is however quite broad with pores having diameter in the range of 60 – 380 µm as shown in figure 5. This is also very clear from the SEM image (figure 1).

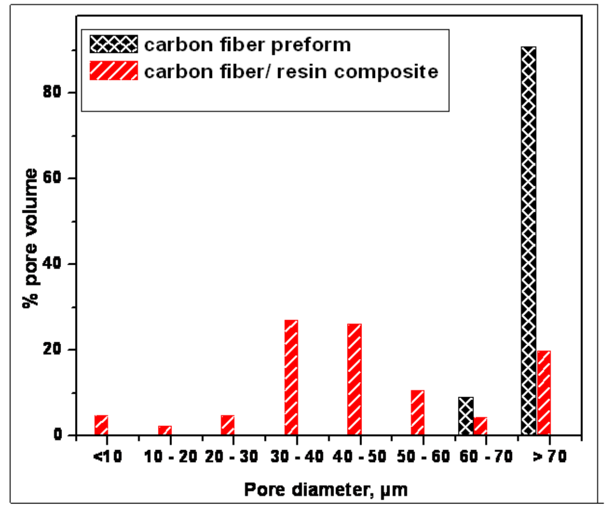

Figure 5. Pore size distribution curves of the carbon fiber preform and composite sample.

The green sample is comparatively a dense structure with porosity of ~ 60 – 62 %. Since phenolic resin has the tendency to form closed pores, the measured connected pore volume reduces to nearly 29%, i.e. less than half (~ 47%) of the total pore volume. As the pores of the preform are filled with the resin, the pore size distribution shifts towards smaller pores (figure 5) with nearly 75% of the pores lying in the range of <60 µm. The highly porous structure of the composite increases its overall surface to volume ratio resulting into high flux of heat radiation.

The total exposed surface area of the carbon element is >3 m^2, whereas the total surface area of the nichrome wire is only 0.03 m^2.

The flexibility of the heating element can be estimated from the fact that the flexural strength of the element is > 250 MPa, while its flexural modulus is in the range of 12 – 14 GPa. This gives the strain to failure of the sample > 2 %, which despite being less than the nichrome wire, is more as compared to other forms of carbon, like graphite (0.1 – 0.2%) and carbon fiber (1.1– 1.2%).

The resistance of the element at room temperature is 300 ohms and reduces to 285 ohm on heating (at nearly 200°C). Decrease in the resistivity at higher temperatures is a characteristic of carbon materials. Other metals (nichrome wire) show an increase in resistance at elevated temperatures.[17]

Performance of the Heater

The carbon heater when plugged directly to the mains was found to consume much less power ~185 watt (RMS) as compared to 1-2 kW ingested by the conventional room heaters. The electrical measurements were made directly with the help of Fluke 41 power analyzer which shows (fig. 6) the values of voltage and current as 229 volts and 0.8 amps respectively.

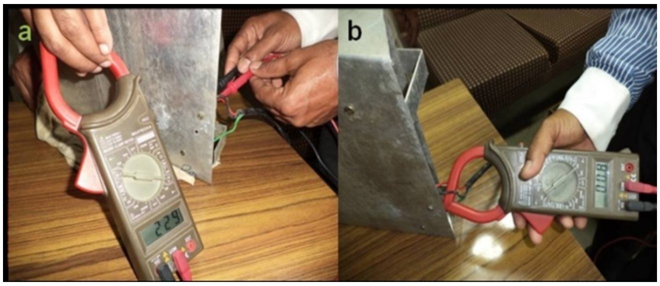

Figure 6. Measurements of (a) voltage and (b) current of the heating device

Along with the low power consumed the performance of the heater can be judged by the temperature reached during its operation. The surface temperature of the heating element (when packed) was found to be 205 - 253°C. As shown in figure 7, while the temperature of the hot air coming out is more than 200°C, that of the front panel is 36°C.

Figure 7. Figure showing the temperature of (a) the hot air coming out of the heater and (b) the front panel

The ambient temperature (in the periphery of 1.5 meters) after switching on the heater was 35 - 48 °C, as compared to the initial room temperature of 19 – 20 °C. The curve shown in figure 8 gives the variation in the temperature with increasing distance from the body of the heater. The readings verify the heating efficiency of the device as compared to other carbon fiber based heaters as demonstrated by Borisova et.al.[12].

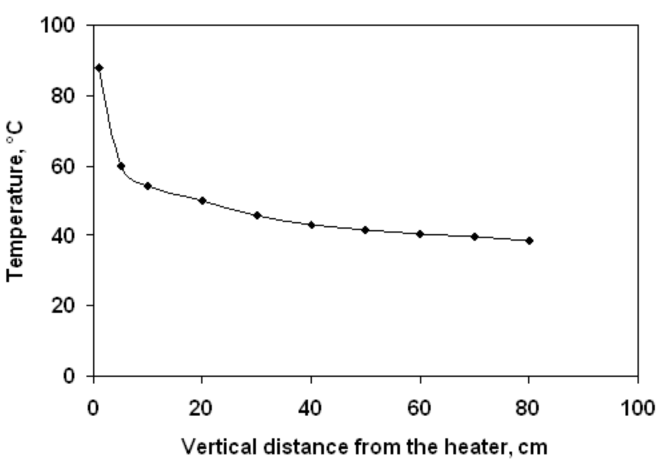

Figure 8. Variation in the temperature with increasing distance from the heater.

The temperature range of the carbon heater allows it to be designed to work with enhanced durability in natural convection mode. This is not possible in the case of the conventional heaters, where forced convection is required as the high temperatures reached (~ 600°C) may lead to the oxidation of the heating element. The carbon heater prepared in the present study was tested continuously for more than 500 hours, without any significant change in current.

Conclusions

The carbon based heaters have been successfully prepared that offers high contact area to the air flow and thus consumes much less power (~185 watt) as compared to conventional room heaters thus offering a new way to combat rising heating bills and energy consumption. The heaters can be wall mounted thus saving space and operate silently without fans. Using free convection technology they deliver a comfortable heat and not a blast of hot air and offers safe operation as compared to conventional blowers and oil based heaters. The flexibility of the element enables its use in different shapes.

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