

Thermal Aging Properties and Electric Heating Behaviors of Carbon Fiber Paper-based Electric Heating Wood Floors

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Carbon fiber (CF) paper is an excellent material for use in electric heating wood floors systems. In this paper, a CF paper-based electric heating wood floor was prepared using a hot pressure process. The thermal aging properties and electric heating behaviors of the CF paper-based wood floors were studied using scanning electron microscopy (SEM), X-ray diffraction (XRD), differential scanning calorimetry (DSC), and a temperature recorder. The CF paper exhibited excellent thermal stability, and its structure and morphology did not show any changes after exposure to 110 °C for 15 h. The surface temperature of the CF paper increased as input voltage increased. The positioning of CF paper in the middle of wood floors was believed to be the optimum design for electric heating wood floors. Theoretical calculations showed that the CF paper based electric heating wood floors (1.1 m²) could increase room (3 m × 4 m × 2.6 m) temperature by 12.9 °C.

Keywords: Electric heating wood floor; Carbon fiber paper; SEM; XRD

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INTRODUCTION

In most regions, people are accustomed to warming their houses or buildings in winter by burning traditional energy sources (*e.g.*, coal, natural gases, and petroleum). However, rapid population growth and economic development has led to a sharp increase in energy consumption, which aggravates the substantial threats of environmental pollution to human health. Consequently, there is much interest in developing new energy technologies and reforming traditional energy technologies to protect the environment and achieve sustainable development.

Low temperature radiant heating technology is an efficient way to heat a room because it warms the house by convection. Also, it has the merit of saving space and energy (Lv and Li 2009). Reports have shown that the floors market had a value of up to 49.4 billion RMB in China alone (<http://www.chyxx.com/industry/201509/344523.html>). According to the heating layer position, low temperature radiant heating systems can be divided into two types, as shown in Fig. 1. In the first type (Fig. 1a), the heating layer is placed beneath the floors, and the room is heated by cycling hot water or with electric heating cables (Qi *et al.* 2012; Bojic *et al.* 2015; Zhou and He 2015; Luo and Yang 2016). The bottom layer is the heating storage layer, which is composed of phase change materials with high specific heats and low costs (Lin *et al.* 2004; Jeong *et al.* 2014). In the second type (Fig. 1b), the heating layer is set in the floors. Electric heating wood floor

is representative of this type and is one of the most promising methods for reducing environmental pollution.

Endowing wood floors with electric heating functionality raises the value of wood floor products, saves energy, and reduces environmental pollution (Kollmann *et al.* 1967; Armstrong 1978; Lin *et al.* 2005; Song *et al.* 2015a). Another merit of electric heating wood floor is the cost effectiveness due to the reduction of electric energy consumption (Zhang *et al.* 2016). This electric heating technology developed rapidly in China and relevant products have appeared on the market. Recently, carbon fiber paper-based electric heating membrane has been used in electric heating wood floors due to its good thermal stability, low cost, and adjustable electrical conductivity (Shi and Wang 2014; Yuan and Fu 2014; Yang *et al.* 2016; Zhang *et al.* 2016). Furthermore, carbon fiber paper can emit an infrared ray of 8 μm to 15 μm during use that is beneficial to the human body (Yuan and Fu 2014). The high electro-thermal conversion rate ($> 97\%$) of carbon fiber paper allows for its widespread application in electric heating wood floors (Song *et al.* 2015a). Zhang *et al.* (2016) studied CF paper-based bamboo floors and found that the floors have good thermal stability during the electrifying process and that CF paper had satisfactory interfacial properties with bamboo floor. However, they did not consider the influence of the position of CF paper in floors on electric heating performance. Yang *et al.* (2016) researched the electric heating behaviors of CF paper-based wood floor and showed that the surface temperature of the floor increased as input voltage increased. The vertical temperature difference in the room was less than 2 $^{\circ}\text{C}$. Yuan and Fu (2014) showed that carbon fiber paper had a good electric heating performance and that the resulting equilibrium temperature of CF-based wood floor was related to input power density. In addition, they found that the resistance of carbon fiber changed a small amount before and after electrifying. Although many Chinese companies have produced electric heating wood floor products and applied for patents, theoretical studies on electric heating wood floor were relatively inadequate, neglecting topics such as the thermal aging of CF paper, the position of heating layers in wood floor, and floor safety.

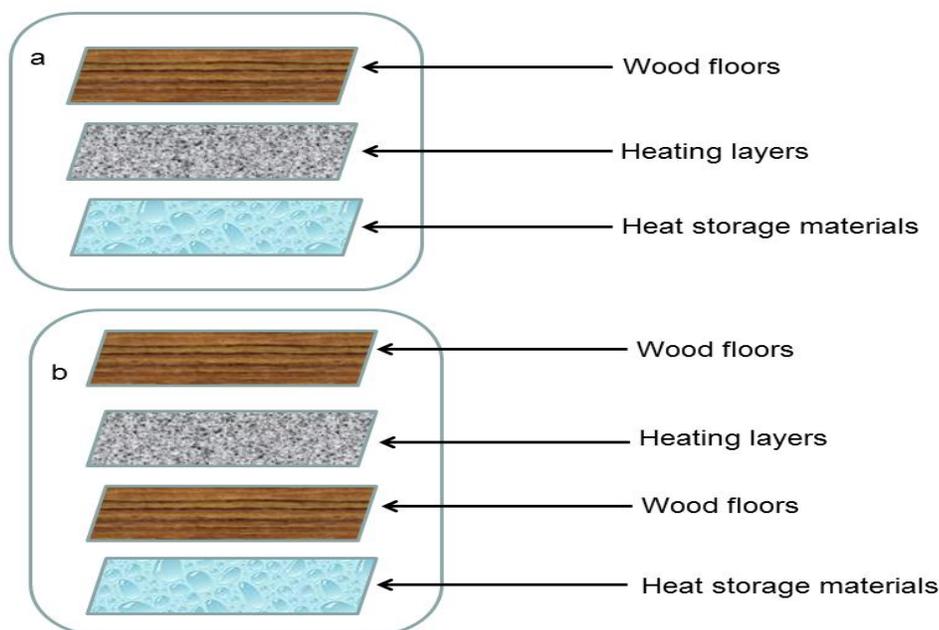


Fig. 1. Heating floors with the heating layers (a) below and (b) in the floors

In this work, electric heating wood floors with CF paper as the heating layer were produced. The structure and morphology changes of CF paper after extensive electric heating were studied using X-ray diffraction (XRD), scanning electron microscopy (SEM), and differential scanning calorimetry (DSC). Also, the position of CF paper in wood floors and the electric heating behaviors of CF paper-based wood floors were investigated in detail. This study obtained useful information for the production of electric heating wood floors.

EXPERIMENTAL

Materials and Preparation

Carbon fiber paper containing 8% carbon fiber was kindly supplied by the Beijing Yante Technology Corporation (Beijing, China). Eucalyptus veneer (2.2 mm thick) was purchased from Yulin Guangxi Exhibition Sen Wood Industry Co., Ltd. (Yulin, China). Urea formaldehyde resin adhesive was purchased from Dynea Chemical Co., Ltd (Shanghai, China).

Electrical heating wood floor materials were fabricated by compressing the eucalyptus veneer at 120 °C for 10 min. The veneer and carbon fiber paper were cut to dimensions of 300 mm × 120 mm and 280 mm × 80 mm, respectively. Every wood floor was composed of seven layers of veneer, and the adhesion content was controlled to 120 g/m². To evaluate the heat resistance performance of carbon fiber paper, carbon fiber paper was aged at 110 °C for 15 h (input voltage of 220 V).

Characterization

The surface morphology of carbon fiber paper before and after electrifying treatment was examined using a scanning electron microscope (SEM, Quanta 200, FEI Corporation, Hillsboro, OR, USA) with an accelerating voltage of 20 kV. The structural changes of the CF paper were studied using a Rigaku D/max 2500 VPC X-ray diffraction instrument (Tokyo, Japan) operating at 40 kV and 200 mA. The data was collected from $2\theta = 3^\circ$ to 50° with a scanning velocity of 8°/min. A DSC (Perkin-Elmer Diamond model, City, USA) was used to study the thermal behavior of the CF paper. The CF paper sample of 3 mg to 5 mg was heated from 20 °C to 200 °C at a heating rate of 10 °C/min. All DSC trials were performed in a nitrogen atmosphere to minimize the oxidative degradation. The electric heating behaviors were observed with a temperature recorder (SIN-R200D) made by Hangzhou Test Automation Technology Co. Ltd. (Hangzhou, China).

RESULTS AND DISCUSSION

Morphology and Structure of Carbon Fiber Paper

As a key component of electrical heating wood floors, electric heating layer materials should have long-term heat resistant properties without any changes in morphology and structure. Carbon fiber paper consists of carbon fiber and cellulose. Carbon fiber has high strength, good conductivity, and excellent thermal stability, which have allowed its successful use in multiple fields (Song *et al.* 2015b, 2016). To evaluate

the thermal ageing properties of carbon fiber paper, carbon fiber paper was electrified and kept at 110 °C for 15 h, and the structure and morphology of the CF paper were studied.

Figure 2 shows the SEM images of the CF paper before and after thermal treatment. There were no obvious changes in morphology, but more fibrous matter formed, which resulted from the melting and solidification of some ingredients of the carbon fiber paper. However, the cellulose morphology of the CF paper did not change notably, indicating that the CF paper maintained good thermal stability at 110 °C.

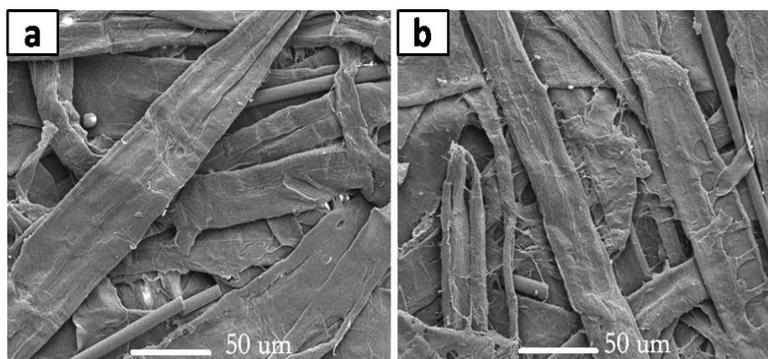


Fig. 2. SEM images of carbon fiber paper (a) before and (b) after thermal treatment

Figure 3 displays the X-ray diffraction patterns of the carbon fiber paper before and after long-term thermal treatment. Carbon fiber paper showed two strong X-ray diffraction peaks at $2\theta = 15.4^\circ$ and 22.7° , which were indexed to cellulose I (Qing *et al.* 2016). After thermal treatment, the diffraction peak positions and the intensity of cellulose crystals did not vary. These findings suggest that long-term thermal treatment did not influence cellulose structure and that the carbon fiber paper had excellent heat resistance.

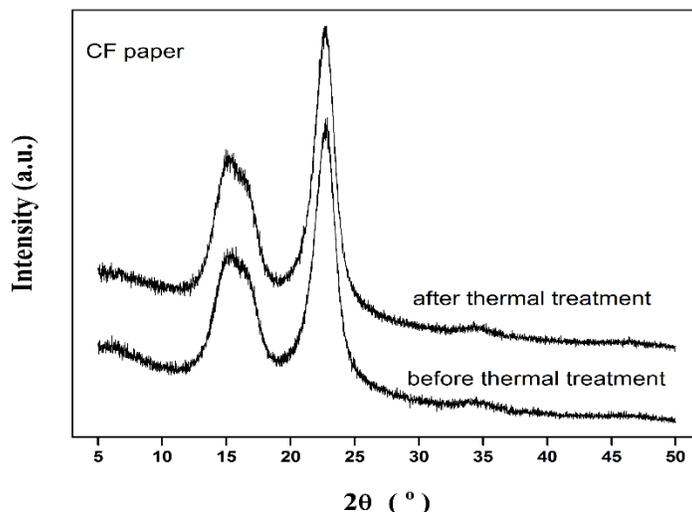


Fig. 3. XRD patterns of the carbon fiber paper before and after thermal treatment

Figure 4 shows the DSC heating curves of the carbon fiber paper. Before thermal treatment, the carbon fiber paper exhibited a wide melting peak at 99.3 °C. This peak was not related to cellulose crystals, since cellulose is stable thermally up to 200 °C (Qing *et al.*

al. 2016). This might have been due to the melting of some ingredients in the CF paper. After thermal treatment, the melting curve of CF paper did not change, and melting temperature remained at 99.3 °C. However, the melting enthalpy of the CF paper notably decreased from 220.7 J/g to 185.1 J/g after thermal treatment. Due to the cellulose crystals were difficult to melt at experimental temperature range, the decrease in enthalpy of CF paper was ascribed to the reduction of low-boil crystallizing ingredients, which evaporated during the process of thermal treatment and therefore the amount of crystallizing ingredients lessened. Finally, on the second heating, the CF paper treated has a lower enthalpy compared with the untreated paper. Another reason is possibly related to the vaporization of the water contained in the cellulose.

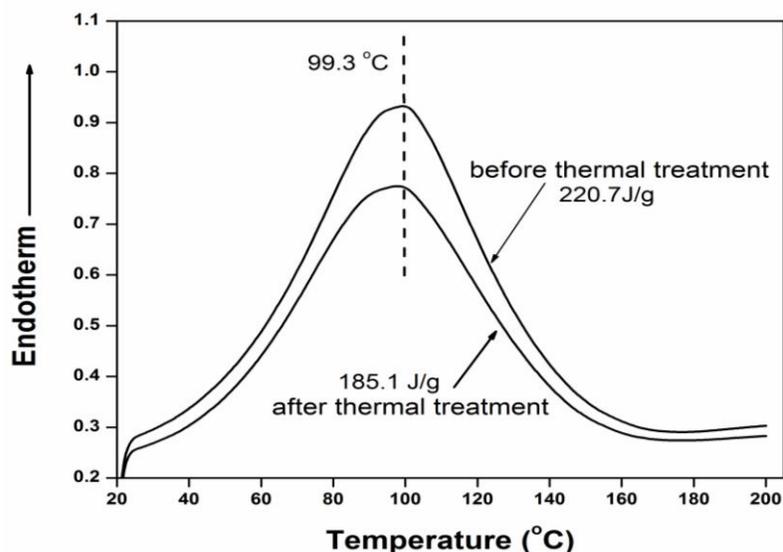


Fig. 4. The DSC curves of the carbon fiber paper before and after thermal treatment

Electric Heating Behaviors

The electric heating behaviors of wood floors were related to many factors, such as resistance, input voltage, and environmental temperature. Materials with lower resistances usually show notable electric heating effects (Song *et al.* 2015a). Elevating input voltage also caused indoor temperature to increase remarkably. Figure 4 shows the electric heating curves of the carbon fiber paper with different input voltages and the environmental temperature of 23.1 °C.

As shown in Fig. 5, the surface temperature of carbon fiber paper increased as input voltage increased. When input voltage was 10 V, the carbon fiber paper and environment quickly reached thermal balance and the ultimate temperature was only 24.5 °C. This result indicated that the input electrical energy was largely absorbed by the environment, resulting in difficulty achieving the required heating effect. As input voltage further increased to 220 v, the final temperature of the carbon fiber paper reached 107 °C. According to the new standard of electric heating materials (which has not been published officially), the surface temperature difference of electric heating materials should exceed 20 °C after 30 min of electrification. Consequently, in these experiments, the optimal input voltage was 110 V and the surface temperature of the carbon fiber paper reached 45 °C, exceeding 20 °C over the ambient temperature (23.1 °C). Though

excessively high temperature leads to increased power consumption and discomfort, excessively low temperature can be a consequence of ineffective heating.

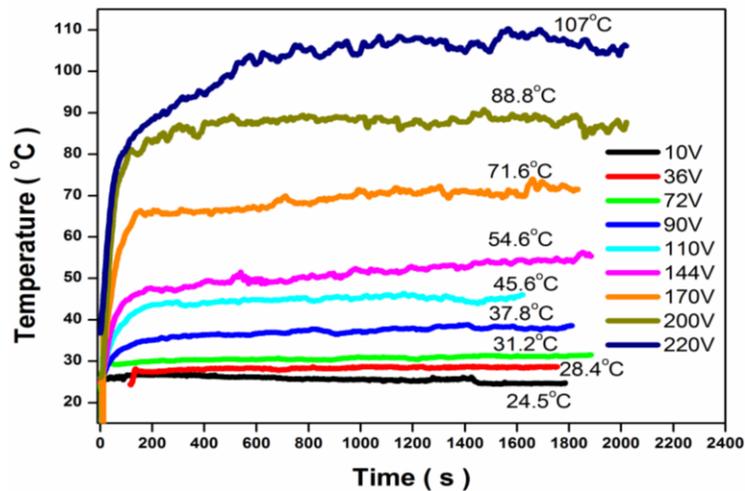


Fig. 5. The electric heating curves of the carbon fiber paper with different input voltages

In these experiments, the wood floors were composed of 7 layers of veneers, and the position of the carbon fiber paper in wood floors had a noticeable impact on the electric heating behaviors of wood floor, as shown in Fig. 6. Based on the position of the CF paper in the wood floors from the bottom to top, the prepared electric heating wood floors were labeled as CF 1, CF 2, CF 3, CF 4, CF 5, and CF 6. After 30 min of electrification, the wood floors exhibited different electric heating behavior depending on the position of the CF paper, which is displayed in Fig. 6b. The top surface temperature of the wood floors increased as the position of the CF paper increased from CF1 to CF6. The wood floors exhibited higher surface temperature when the position of the carbon fiber paper was closer to the top surface of the wood floors. For CF1, the top surface temperature of wood floors was 8 °C. The bottom surface temperature for CF1 was identical to top surface temperature for CF6 and was measured as 47.1 °C.

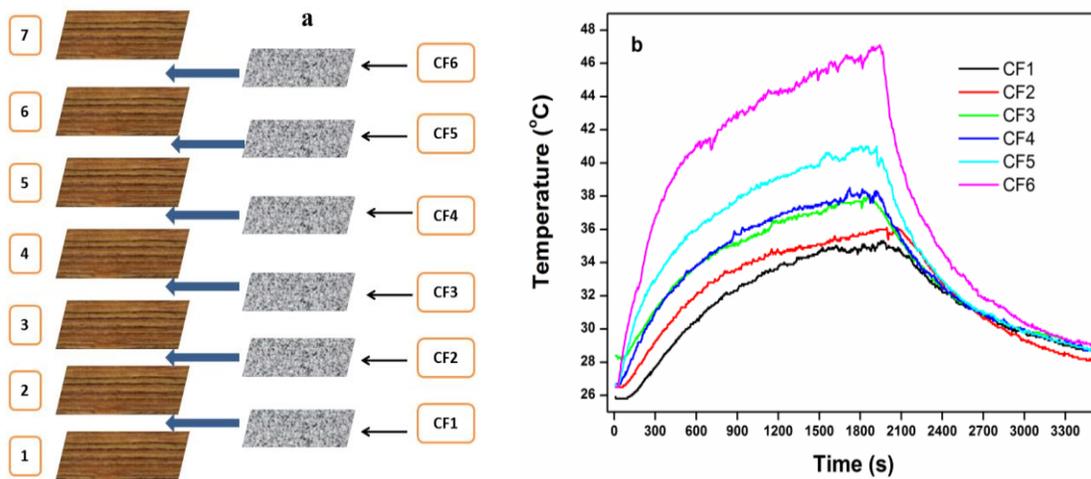


Fig. 6. (a) A sketch of CF paper position in electric heating wood floors; (b) the heating curves of the electric heating wood floors with different CF paper positions

For the wood floors, if the temperature difference between the top surface and the bottom surface of the wood floors was too great, the wood floors deformed during the heating process. Figure 5b shows that the temperature difference between CF3 and CF4 was very small (less than 1 °C). Thus, the CF3 and CF4 positions were the optimum designs for carbon fiber paper-based wood floors.

Calculation of Thermal Quality

Electric heating wood floors, a low temperature radiation heating technology, will be a prominent heating technology in the future. Carbon fiber paper acted as a key component of electric heating wood floors and became a main candidate material for the heating component of electric heating wood floors due to its low cost, thermal stability, and high electric thermal conversion efficiency (> 97%). Research has demonstrated that the heating effects are dependent on the resistance and size of CF paper, input voltage, heating space, and wood floors design (Song *et al.* 2015a).

An electric heating wood floor with dimensions of 300 mm × 120 mm × 15 mm and 1 m³ space were selected to study the heating behaviors of electric heating wood floors. Assuming there is no heat loss in the heating process and the input electric energy can turn into heat completely, the calories (Q) produced by carbon fiber paper could be calculated as follows (Eq. 1),

$$Q_1 = Q - Q_2 \quad (1)$$

where Q is the obtained calories supported by electric current, Q1 represents the absorbed calories of 1 m³ space, and Q2 is the calories absorbed by wood floors.

If the electric energy is completely converted into heat, no heat transfer hysteresis takes place among veneers, and carbon fiber and adhesive are present, then Q, Q1, and Q2 could be determined as follows (Eq. 2 and Eq. 3),

$$Q = U \times I \times t = \frac{U^2}{R} \times t \quad (2)$$

$$Q_1 + Q_2 = cm(T_2 - T_1) = \Delta T \times (c_{\text{veneers}} m_{\text{veneers}} + c_{\text{air}} m_{\text{air}} + c_{\text{adhesive}} m_{\text{adhesive}} + c_{\text{paper}} m_{\text{paper}}) \quad (3)$$

where U is the input voltage, I is the current, R is the resistance of the CF paper (700 Ω), t is the time (s), c is the specific heat capacity of matter, m is the mass, T₁ is the initial temperature at heat equilibrium, and T₂ is the end temperature at heat equilibrium.

According to Table 1, Eq. 1 could be written further as follows (Eq. 4),

$$\frac{U^2}{R} \times t = 2414.1 \times (T_2 - T_1) \quad (4)$$

Table 1. Physical Parameters of Veneers, Air, Adhesive, and CF Paper

	Veneers	Air	Adhesive	CF Paper
Density(kg/m ³)	960	1.29	1180	—
Specific heat capacity (J/kg · °C)	2000	1012	1460	1900

Excellent thermal stability makes the resistance of CF paper change only slightly before and after electrifying. The effects of CF paper can be neglected because very few calories are absorbed by the CF paper. As shown in Eq. 4, the input voltage has an important role in heating efficiency. If input voltage is 110 V, an indoor temperature increase of 12.9 °C can occur within 30 min. For instance, if the initial temperature is 5 °C in 1 m³ of space, the temperature will reach 17.9 °C at 30 min later. Thus, installing electric heating wood floors with 1.1 m² of space would make a room of 3 m × 4 m × 2.6 m increase in temperature by 12.9 °C.

CONCLUSIONS

1. In this paper, carbon fiber paper-based wood floors were examined for the changes in structure and morphology of carbon fiber paper aged at 110 °C for 15 h. The position of the carbon fiber (CF) paper in wood floors and the electric heating behaviors of wood floors were also studied.
2. After being aged at 110 °C for 15 h, carbon fiber paper exhibited good thermal stability. SEM micrographs showed that the surface morphology of CF paper had not changed but formed some fibrous linkages. The positions of the X-ray diffraction peaks and the strength of the CF paper did not vary, indicating excellent stability of the cellulose crystal structure.
3. Differential scanning calorimetry showed that the CF paper had a melting temperature at 99.3 °C, which was ascribed to the melting of other components of the paper rather than the ageing process. However, the melting enthalpy of the paper decreased remarkably.
4. The placement of the CF paper in the middle of wood floors was acceptable because the upper surface temperature of wood floors was similar to the bottom temperature. If the electric energy was turned into heat completely, theoretical results showed that CF paper-based wood floors (1.1 m²) would make the temperature of a room (3 m × 4 m × 2.6 m) increase by 12.9 °C in 30 min when the input voltage was 110 V.

ACKNOWLEDGEMENTS

This article was supported by the Postdoctoral Science Foundation of China (No. 2014M560138 and 2016T90150) and the Research and Demonstration of High Value Processing Technology and Equipment of Agricultural Products in Fujian Province (2014NZ0003).

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Submitted: July 31, 2017; Peer review completed: September 30, 2017; Revised version received and accepted: October 24, 2017; Published: October 31, 2017.

DOI: 10.15376/biores.12.4.9466-9475