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Investigation of a Novel Heating System: Experiments on the Electrical Heating Characteristics of a Carbon Fibre Energy System

Junhong Yang[1,2,*], Tong Zhao[1,2,3], Xuyang Cui[1,2], Jialing Zhu[1,2], Chen Jia[1,2], Xuanyu Sun[3], Jiancheng Liu[3], Zebin Chai[3], Yuyang Wang[3], Huimin Mao[2]

[1]Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, Tianjin 300350, China

[2]School of Mechanical Engineering, Tianjin University, Tianjin 300350, China

[3]Hebei Wang Yuan Pipe Industry Co., Hebei Province, China

*Corresponding author: Junhong Yang

Abstract

More and more attention has been paid to the application of electric heating technology with carbon fiber heating line. The research of electric heating property is of great significance for the efficient application of the electric heating technology of carbon fiber. A novel electrothermal characteristics test chamber about electric heating ground made of carbon fiber heating line (24K,length 12.5 m) was proposed and designed (length 1710 mm×width 1310 mm×high 955 mm). The dependence of the heating wire current and the surface temperature on the voltage, and the change of the temperature in the different parts of the heating element with the electrifying time were investigated. The results show that the current and surface temperature are well correlated with the voltage about carbon fiber heating line (R^2≥0.9899). The ambient temperature is 24°C and the power is 220V. Ambient temperature is 24°C, Energized 10min, the heating line surface temperature reaches 49°C. Energized 45min, the heating line surface temperature reaches 63°C.The average heating rate of the first 10 min is 2.5 °C/min. Therefore, by regulating the voltage, the heating temperature of the carbon fiber heating line can be adjusted, and the load demand can be quickly responded.

Keywords

Carbon fiber heating line； Electric ground heating； Electrothermal temperature rise.

1. Introduction

The research and application of carbon fibre hot wire electric heating technology, with its high electrical heat conversion efficiency, fast temperature rise and no heating medium, has received increasing attention [1-5]. Regarding the research on electrical heating performance, the literature is more focused on the preparation process of carbon fibre filaments and short cuts [6-8] and the processing process of heating elements (e.g. carbon felts, carbon crystals, heating lines, etc.) [9-10]. Currently, scholars at home and abroad have conducted research on the electrical heating performance of carbon fibre electric floor heating. M Hambach et al. [11] mixed carbon fibre 302 mm long and 702 μm thick with a cement base and found that the composite material could produce a rise in temperature suitable for heating rooms and walls when the volume content of carbon fibre was in the range of 1 to 2%; Zak, V.L et al. [12] proposed using carbon fibre material as a heater of the conductive base and embedding the heater into the floor to ensure thermal comfort. Yuan et al. [13] studied the microscopic heating

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mechanism of carbon fibre composite conductive paper in order to improve the heating uniformity of electric heating panels, pointing out that what affects the heating uniformity is the uniformity of carbon fibre monofilament distribution and the length of carbon fibres between the lap joints. Tan et al. [14] conducted an operational simulation for a carbon crystal electric heating panel heating system and selected a room of 4 m × 4 m × 3 m in the middle floor of a building in Beijing for an experimental study. Through analysis and discussion, it was determined that the average temperature of the area with a height of 1.5m plane as the control factor can guarantee the heating demand and the indoor temperature are guaranteed to be above 291K; Zhu et al.[2] designed a set of heating system using A new type of electric heating system using carbon fibre tape was tested and the average heating rate could reach 1.83°C/min.

Carbon fibre hot wire electric floor heating, according to the different laying modules, exists in two forms: carbon fibre hot wire flooring and carbon fibre hot wire and electric floor heating auxiliary materials to form the electric floor heating. In the study of the electrical performance of carbon fibre hot wire floor heating, Yang et al [15], tested the thermal performance of an electric floor with a built-in carbon fibre hot wire at 70V, 80V, 90V and 100V, all of which met the design average temperature of the floor surface specified in the Technical Regulations for Radiant Heating and Cooling [16]. The results indicated that the requirements of LY/T1700-2007 "Wooden Flooring for Floor Heating" [18] were satisfied. It can be seen that the current electric heating performance research is mainly aimed at electric floor heating using keel laying and relatively independent embedded heating line flooring wired in a series-parallel hybrid manner.

Therefore, this paper adopts carbon fibre hot wire as the heat source body, simulates the laying and heating process of electric floor heating formed by carbon fibre hot wire and auxiliary materials, designs electric heating performance test chambers, conducts current-voltage and surface temperature-voltage tests of carbon fibre hot wire and temperature rise tests of the internal temperature of the heating element component over time, measures key data such as current-voltage and temperature rise, and carries out analysis with the aim of developing The aim is to provide a scientific basis for the development of carbon fibre heating cables for heating applications and the design of carbon fibre heating cables for electric floor heating.

2. Materials and methods

2.1. Materials

The 24K carbon fiber hair wire produced by Tianjin Jesman Building Materials Co., LTD was used in the test (1K means the nominal number of single fiber in a bundle of carbon fiber is 1000), as shown in Figure 1.

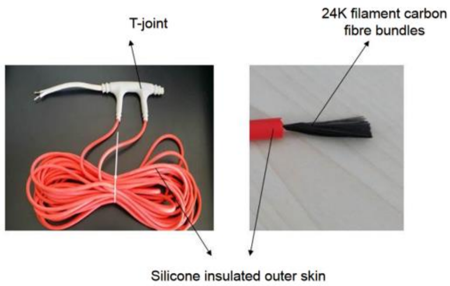

Figure 1 Structure composition of carbon fiber line

The carbon fiber hair wire is composed of an inner filament carbon fiber bundle and an outer insulating silica gel. Both ends of the hair wire are connected with tin copper wire to form a T-joint for connecting with the power supply. The basic physical and mechanical properties of filament carbon fiber bundles are shown in Table 1.

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Table1 Physical and mechanical properties of carbon fiber filament bundle

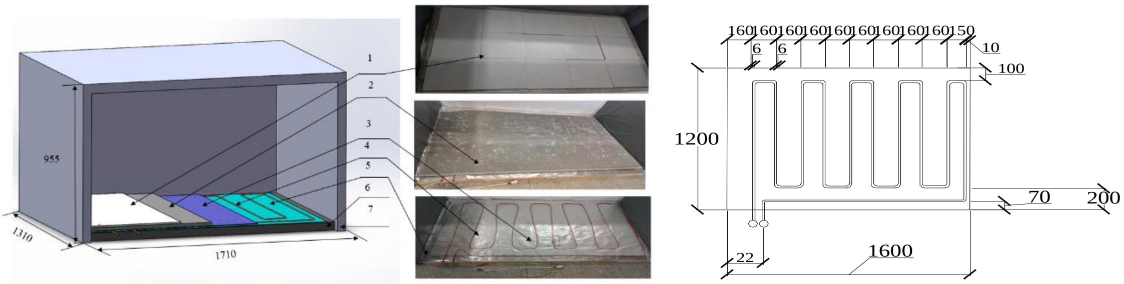
Density (g/cm^3)	Length (mm)	Diameter (mm)	Tensile Strength (Mpa)	Modulus of Elasticity (Gpa)
1.8	12500	6	4900	230

The carbon fibre heating element is made up of a 24K carbon fibre heating line and auxiliary materials for electric underfloor heating. The electric underfloor heating auxiliary materials include extruded polystyrene foam panels, reflective membranes, alkali-resistant glass fibre mesh, cement boards and ceramic tiles.

2.2. Experimental systems

To simulate the indoor environment, a multi-layer corrugated cardboard box with the same bottom area and a height of 50cm was added to the carbon fibre strip floor heating unit (800mm long x 600mm wide) as a peripheral material with good thermal insulation[2]. This test uses a thermal conductivity of 0.037W/(m-K), a height of 95.5cm of insulation with moulded polystyrene foam as the surrounding and top materials, forming a 1710 mm (long) x 1310 mm (wide) x 955 mm (high) carbon fibre heating line electric floor heating electrical performance test chamber, as shown in Figure 2.

In the profile direction, a 50 mm thick extruded plastic board and a 3 mm thick reflective film are laid on the bottom layer, with the carbon fibre heating line placed above the reflective film and the cement board acting as a thermal storage layer.



1 floor; 2 cement board; 3. Glass fiber net; 4 Carbon fiber hair wire; 5 Reflection film; 6 Extruded board; Foam plastics for insulation

Figure 2 Electrothermal characteristics test chamber

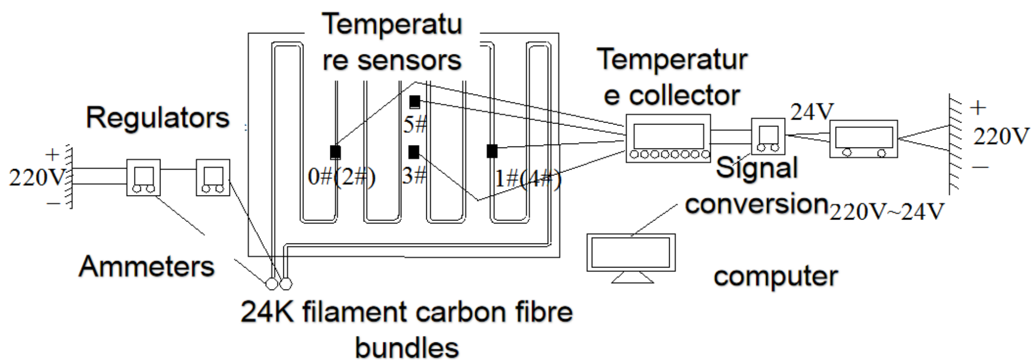


Figure 3 Schematic diagram of carbon fiber line electrical heating test system

Carbon fibre heating line electric floor heating electrical performance test system as shown in Figure 3. By accessing the contact regulator at both ends of the carbon fibre heating line, the current-voltage change relationship of the heating line is tested at voltages from 0V to 220V under the rated power of the regulator. And, using the regulator, test the voltage at 0V, 30V, 60V, 90V, 120V, 140V, 160V, 180V, 200V, 220V, the relationship between the surface temperature of the heating line with time.

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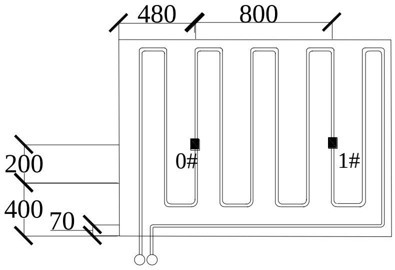
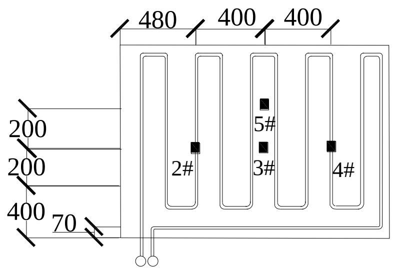
The location of the temperature sensors is shown in Figure 4. 0# and 1# temperature sensors are arranged on the carbon fibre hot wire to test the change of surface temperature over time; 2#, 3#, 4# and 5# temperature sensors are arranged on the cement board, where 2# and 4# are horizontally located in the same position as 0# and 1#, and 3# and 5# are horizontally located in the middle of two adjacent carbon fibre hot wires to be able to record the temperature change.



(a)



(b)

Figure 4 The arrangement of the temperature sensor: (a) Carbon fiber hair wire layer temperature sensor layout (mm), (b) Carbon fiber hair wire layer temperature sensor layout (mm)

The test system, consisting of a carbon fibre hot wire electric floor heating test chamber and electric heating performance test apparatus, is a simulation of the indoor carbon fibre hot wire electric floor heating laying and heating process, and can realise the current-voltage test of the hot wire, the temperature-voltage test of the surface of the hot wire and the monitoring of the temperature of the carbon fibre hot wire and the internal temperature distribution of the electric floor heating during the heating process.

3. Results and Discussion

3.1. The relationship between the current and voltage

The current-voltage fitting function y=0.00551x-0.07088 (R^2=0.99493) was measured, as shown in Figure 5. Zhao et al. [1] studied the thermal performance of a carbon fibre electric heating panel with dimensions of 600mm x 890mm and found that the carbon fibre composite conductive paper had a good linear relationship between current and voltage. The relationship was fitted to a graph of input voltage versus current for the carbon fibre composite conductive paper tested in the literature [1], resulting in a function y = 0.00288x-0.00664 (R^2 = 0.9994). Compared to the fitted function relationship for the hairline, the carbon fibre hairline current-voltage also has a good linear relationship. And, Mei et al. [19] . tested the current-voltage relationship by using nano-carbon fibre/epoxy composites with different nano-carbon fibre mass fractions, which also showed a good linear relationship.

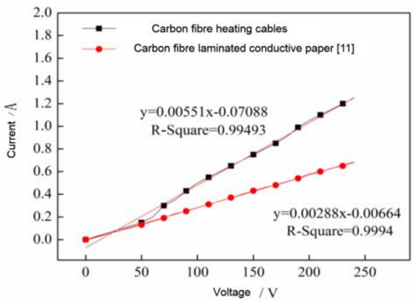


Figure 5 The curve of A-V of carbon fiber composite material

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3.2. The relationship between the surface temperature and voltage

Further analysis of the relationship between input voltage and surface temperature of the heating line, the ambient temperature is 24°C, the surface temperature of the heating line - voltage fitting function $y = -0.03073x^2 + 9.16758e^{-4}x + 24.09472$ ($R^2 = 0.9899$), as shown in Figure 6. The surface temperature of the carbon fibre heating line varies parabolically with the input voltage. Therefore, the carbon fibre hot wire current and surface temperature and voltage have a very good correlation ($R^2 \geq 0.9899$). This provides a scientific basis for the use of voltage to regulate the heating temperature of the carbon fibre hot wire electric floor heating system in order to respond quickly to the load demand.

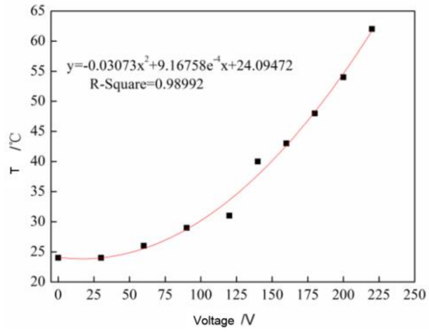

Figure 6 The curve of T-V of carbon fiber line

3.3. Electric underfloor heating energised heating test results

The ambient temperature was 24°C. The test was carried out by applying 220V voltage and using a temperature sensor to record the internal temperature rise of the electric floor heating, and in order to ensure the repeatability of the test, three tests were carried out, each time energised for 45 min.

3.3.1. Carbon fibre heating line heating test

Figure 7 (a) records the temperature rise of the carbon fibre heating line. From Figure 7(a), it can be seen that the temperature rise trend of 0# and 1# temperature sensors is the same. Taking the 0# temperature sensor as an example, the carbon fibre heating line heats up through a fast heating zone (0-10min), a slow heating zone (10-40min) and a gentle heating zone (40-45min), and finally the surface temperature rises to 63°C, as shown in Figure 7(b).

In the first 10 min of power, the surface temperature of the heating line changes quickly with time, the average heating rate of up to 2.5 °C/min, the surface temperature from 24 °C to 49 °C; power to 20 min to 40 min, the heating line heating rate is slower, the average heating rate of 0.5 °C/min, the surface temperature rose to 63 °C; after the slow heating zone, the surface temperature of the heating line to 0.1 °C/min rate into the flat zone.

Compared with the average heating rate of 1.83 °C/min measured by Zhu et al.[2] using carbon fibre tape as an electric floor heating element, the average heating rate of carbon fibre hot wire was lower than that of carbon fibre tape due to the outer layer of carbon fibre filament bundles having an outer layer of silica gel compared to carbon fibre tape, which increased the thermal resistance in the heat transfer process. However, in the fast heating zone, the average heating rate of the carbon fibre hairline is significantly higher than that of the carbon fibre tape, and the carbon fibre hairline has the characteristic of fast heating.

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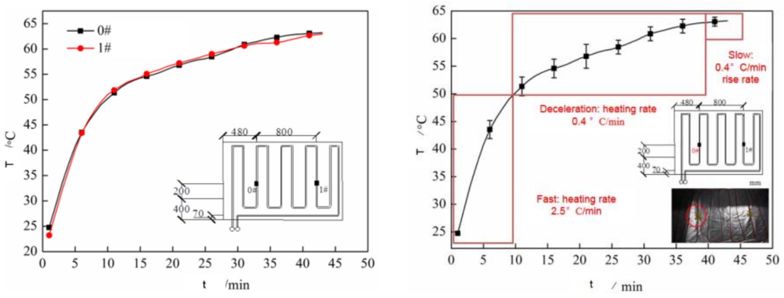


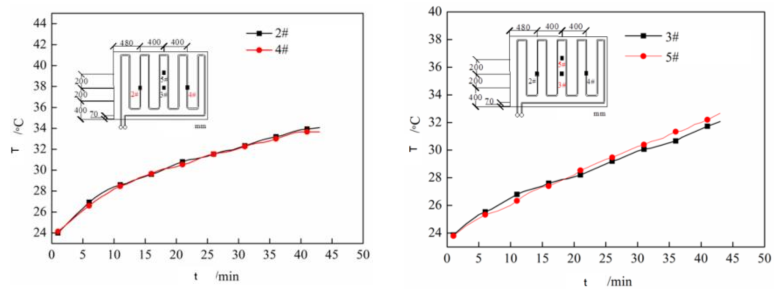
(a)0# and 1# (b) 0#

Figure 7 Temperature rise at carbon fiber line

3.3.2. Cement slab layer warming test

Figure 8 (a) records the temperature rise in the cement slab, horizontal position with 0# and 1# temperature sensors. In Figure 8 (a), the temperature rise trend of 2# and 4# temperature sensors is the same. Taking 2# temperature sensor as an example, the temperature rise process goes through a rapid temperature rise zone (0-10 min) and a smooth zone (10-45 min), and finally the temperature rises to 34°C. In the first 10 min, the temperature of the 2# temperature sensor changed significantly with time because the heating line was in the fast warming zone, and the temperature rose at a rate of 0.44°C/min; in the later period, the temperature rose more slowly than in the earlier period, with an average warming rate of 0.17°C/min and a warming rate of 0.23°C/min for the whole power-on cycle.

Figure 8(b) records the temperature rise of the 3# and 5# temperature sensors on the cement board, horizontally positioned between the carbon fibre heating lines. In Figure 8(b), the temperature rise trend of the 3# and 5# temperature sensors is consistent, from 24°C to 32°C, with an average rise rate of 0.18°C/min.



(a)2# and 4# (b) 3# and 5#

Figure 8 Temperature rise at cement layer

4. Conclusion

In this work, a novel type of carbon fibre hot wire electric floor heating electric heating performance test chamber was designed and the following main conclusions were drawn from the carbon fibre hot wire current-voltage test, the carbon fibre hot wire surface temperature-voltage test and the internal heating element component warming test.

(1) 0V ~ 220V, carbon fibre heating line current and surface temperature and voltage has a very good correlation ($R^2 \geq 0.9899$). Carbon fibre hot wire energised current - voltage has a good linear relationship between ($R^2 = 0.99493$), carbon fibre hot wire surface temperature - voltage is a parabolic relationship ($R^2 = 0.9899$). In the design of the actual carbon fibre hot wire electric floor heating temperature regulation control parameters, the voltage can be adjusted to achieve the heating temperature regulation and rapid response to the load demand.

(2) At an ambient temperature of 24°C and 220V power, the surface temperature of the heating line reaches 49°C at 10 min and 63°C at 45 min. The average heating rate in the first 10 min was 2.5°C/min, with the characteristics of rapid heating.

(3) Carbon fibre hot wire electric floor heating uses a wire-shaped heating element as the heat source. When energised for 45 min, the surface temperature of the cement board reached 33°C with a linear change (R^2=0.97279) and an average warming rate of 0.2°C/min.

Acknowledgements

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