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Research on the Heating of Woven Carbon Fiber Fabrics Using Thin-Film Solar Cells

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Abstract
This study attempted to fabricate heating fabrics using thin-film solar cells. A lightweight and flexible thin-film solar cell was used as the power supply, and fabric samples made of carbon fiber heating lines were used as heating elements. Single-factor experiments of three factors (solar cell voltage, heating time, and carbon fiber heating line arrangement) were conducted, and their influence on the heating effect was analysed. Orthogonal experiments and variance tests were used to determine the influence of the three factors and the optimal heating process. All influential factors were shown to be statistically significant. This kind of heating fabric can be used in warm clothing or for heated clothing.

Keywords
thin-film solar cells, woven sample, heating carbon fiber lines, fabric density.

1. Introduction

Solar energy is abundant, inexhaustible, and provides a clean renewable energy source. The annual solar energy intercepted by the ground is about 2.16×10^{24} J, which is thousands of times higher than all human energy consumption [1-2]. Photovoltaic technologies provide some of the best ways to use this solar energy, but typical solar cells are made of hard substrates (such as glass) and are inflexible and easily broken , which limits their applications in some situations. Thin-film solar cells made of flexible materials (such as stainless steel, polyester films, etc.) are lightweight and have high conversion efficiencies, flexibility, non-fragmentation, and they are more suitable for use in garments [3-4]. Inspired by polar bears' thermal management, a laminated fabric composed of a CNT/cellulose aerogel with enhanced photothermal conversion and copper nanowire (CuNW)-based conductive network (CNN) layers was developed. This fabric displayed good photothermal conversion and also exhibited better conductivity to realise the Joule heating effect [5]. A flexible solar module was integrated into clothes that provided enough power to control a sound module for MP3 files or a portable-charging T-shirt [6-7].

Carbon fiber is a non-metallic conductive material with the general characteristics of carbon materials, such as high-temperature resistance, friction resistance, electrical conductivity, and thermal conductivity, and has shown great potential for applications in electric heating. Carbon fiber has been used as a heating matrix in infrared heaters, industrial furnaces, and medical physiotherapy. Because of the softness of different carbon materials, their excellent properties make them suitable for producing a variety of heating fabrics and garments [8-9]. In addition to their heating function, carbon-based fibers can also be used in transistors, nanogenerators, solar cells, supercapacitors, batteries, sensors, and therapeutic equipment using fiber-based electronics and storage devices. They have broad application prospects in the field of flexible and wearable electronic products [10]. Fabrics were coated with a hyperbranched polyurethane (HBPU) solution that contained multi-walled carbon nanotubes (MWCNTs), which may be a good method for achieving electrical heating [11]. Carbon nanotube films possess a high electrical conductivity, which demonstrates their promising e-thermal performance [12]. Recycled carbon fibers were manufactured into a heating fabric whose electrical conductivity was around 2.8×10^3 S m^{-1}, which could withstand up to 3000 double folds during durability tests [13].

A heating garment is a garment that generates heat through an external heating source to actively warm the human body. When a flexible solar cell is used as a low-voltage power supply and carbon fiber lines as the heating element, the two can be combined to form a self-heating fabric or garment [14]. Compared with traditional electric-heated garments, carbon fiber heating lines have a good heating effect at low voltages. Carbon fiber heating garments that use lightweight, flexible thin-film solar cells as a power source have higher safety and comfort. They can be applied to ordinary heating garments and are especially suitable for special protective garments for cold environments, such as outdoor warrior service and high-altitude mountaineering garments. In hot compress therapy, a hot compress dilates blood vessels, relaxes muscles, and promotes blood circulation. If a small area of a flexible carbon fiber heating body is applied to a specific part of a garment to generate heat, the garment can also be used as a hot compress [15-16]. With the development of solar cell technology, bendable, fold-resistant, and flexible solar panels as external power supplies will be increasingly used in smart, functional healthcare textiles. FeCo alloy magnetic nanofluids were prepared for magnetic hyperthermia treatment [17]. Forced-air and carbon-fiber warming systems were developed to transfer heat during major abdominal surgery[18]. Some new materials show potential smart insulation and heating applications, including two-dimensional crystals, which can potentially be processed into macroscopic fibers, making them suitable for use in flexible electronic devices and smart wearable devices [19]. Highly conductive and hydrophobic textiles with exceptional electromagnetic interference (EMI) shielding efficiency and Joule heating performance are composed of polypyrrole, MXene sheets, poly(ethylene terephthalate) textiles, and a silicone coating. The resultant multifunctional textile holds great promise for wearable intelligent garments, EMI shielding, and personal heating applications [20].

Few studies have explored the application of the orthogonal experimental design (OED) method to optimise woven fabric design for heated functional garments. OED is an efficient, rapid and economical experimental method for multi-factor and multi-level research [21-23]. Because woven fabrics have good dimensional stability and mechanical properties, in this study, heating carbon fiber lines were formed into a plain-weave fabric, and the voltage was changed by the parallel connection of the thin-film solar cells. Finally, a woven heating fabric was formed through a circuit connection. The effects of the voltage of the thin-film solar cells, the heating time, and the carbon fiber heating line arrangement on the heating performance were studied. The results provide a theoretical reference for the design and research of heated functional garments.

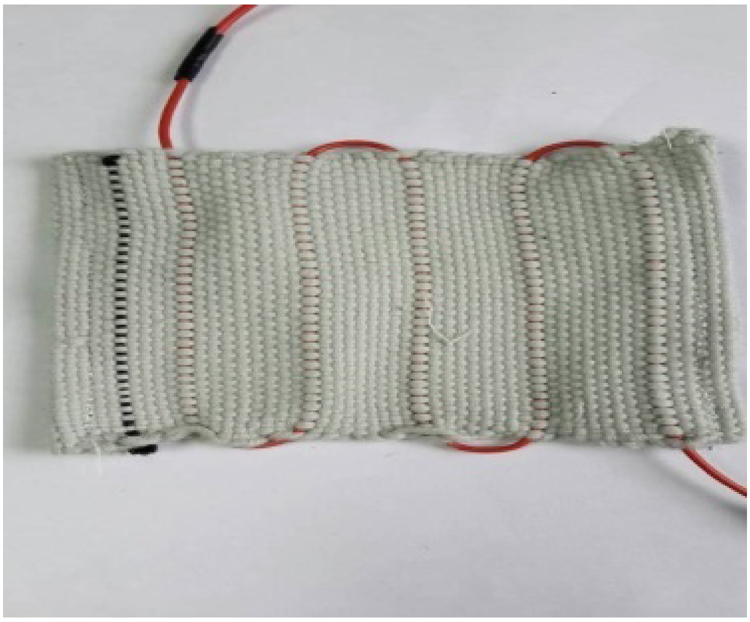

Fig. 1. Heating fabric

2. Experimental

2.1. Materials and equipment

An amorphous silicon thin-film solar cell was purchased from Dongguan Xinliangguang New Energy Technology Co., Ltd., with a voltage of 2 V, electrical current of 330 mA, and dimensions of 194×60 ×0.8 mm. 12k Teflon flame-retardant carbon fiber was purchased from Jiangsu Maisiyang Cable Co., Ltd., with a resistance of 0.33 Ω/cm. 2.5 mm copper wire was purchased from Guangdong Guide Wire and Cable Co., Ltd., with a resistivity of 0.001 Ω/cm. 100% cotton yarn was purchased from Fujian Minhou Huada Textile Co., Ltd., with a size of 15.2 tex×32. A GU101A sample loom was purchased from Jiangyin Longda Textile Machinery Co., Ltd, a VC890c multimeter from Shenzhen Shengli High Electronic Technology Co., Ltd., and an NTC (10K/3435) temperature sensor from Zhaoqing Sendor Electronic Technology Co., Ltd.

2.2. Weaving of heating fabric

The heating fabric was formed on the GU101A sample loom. The fabric structure was plain, and the four-page heald was worn by the pass-through method. The warp yarn was a cotton thread. The warp density of the fabric was 64 ends/10 cm and the weft density 40 ends/10 cm. The weft yarn was a cotton thread and a heating carbon fiber line, and the number of the two kinds of lines woven was matched according to design requirements. The heating line weaving density was designed to be 3, 4, ... 10 and 11 ends/10 cm. For a blank control group, the fabric was not woven into the heating line fabric, and the weft yarn was not cut when it was woven to ensure a continuous heating line. Five samples of each fabric were prepared. Figure 1 shows the heating fabric, where the red yarns are heating carbon fiber lines, and the grey are cotton threads.

2.3. Circuit design of heating woven fabrics

The voltage across a series circuit is equal to the sum of the supply voltages. The total current of the parallel circuit is equal to the sum of the currents of the branches. Since the minimum current required for carbon fiber heating is 0.6 A, to increase the current, two solar panels must be connected in parallel. Then, the panels are connected in parallel to the required voltage, and the design voltages were 6, 8, 10, ..., 18 V, as shown in Figure 2.

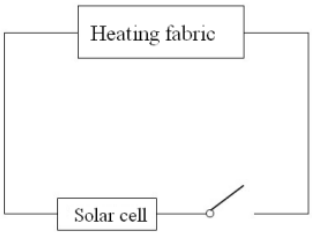

Fig. 2. Circuit design

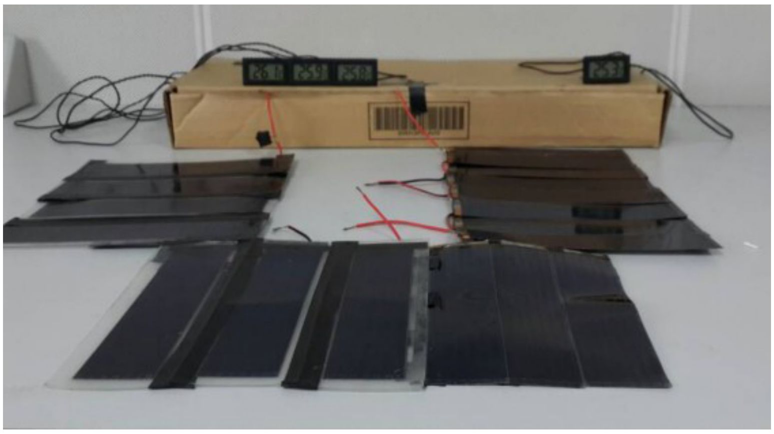

Fig. 3. Fabric heating test

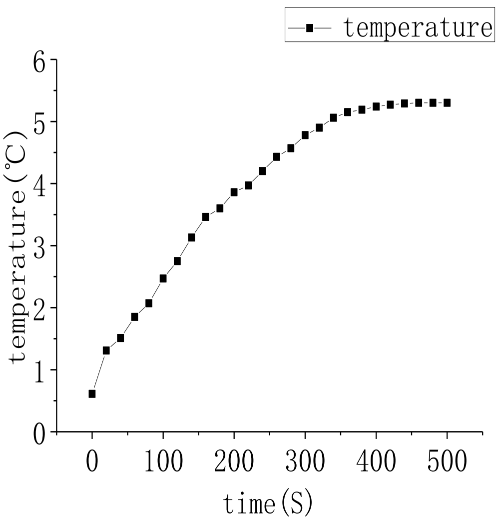

Fig. 4. Temperature change over time

2.4. Experimental test

Solar radiation intensity can greatly vary throughout the day, and at sunrise, sunset, and on rainy days, solar cells cannot produce voltage. To test the heating effect of the heating fabric and reduce experimental error, tests were conducted between 11:00 and 13:00 on a sunny day in May 2020 in Fuzhou University Town.

Due to the long span of the experiment, the study found that even at the same time on different days, the output current of the thin-film solar cells measured was different, and the current varied even at the same time on days before and after a rainy day.

The temperature change of the heating fabric was different under the same test conditions; however, to ensure accuracy, all experimental data from the same group were tested at noon on one day. Such an experimental treatment minimises the error and provides a reference value for future experimental research. The temperature sensor was placed in the middle of two heating wires and did not directly contact the heating wire. Figure 3 shows the experimental test. To ensure the accuracy of the temperature measurements of the heating fabric, a control group was used. The temperature increases at 5 different positions were selected for each test fabric, and the test results were reported as the average of 10 measurements.

3. Results and discussion

3.1. Effect of test time on fabric heating performance

The density of the heating carbon fiber woven by the GU101A sample loom was 5 ends/10 cm, and the voltage of the thin-film solar cell was 12 V. The temperature of the heating fabric was tested as a function of time and recorded every 20 seconds. A graph of the temperature of the fabric versus time is shown in Figure 4. During the 420 s test, the temperature of the heating fabric increased. Figure 4 shows that the curve increased, but the slope decreased, i.e., the temperature of the fabric increased more slowly over time. After 420 s, the temperature did not increase any further and remained constant. Throughout the test, the fabric temperature increased by 5.3 °C, at an average rate of 0.8 °C per minute.

According to Joule's law ($Q=Pt$), the curve of the fabric temperature versus time in Figure 4 should increase linearly with time, but it changes regularly. Thin-film solar cells produce a current in sunlight, forming a loop. The heating line uses the Joule effect of current to convert electrical energy into heat, which increases the temperature of the heating fabric. Since the carbon fiber heating line has thermal resistance, it requires time to conduct heat in the fabric. Since the resistance R of the heating line gradually increased with the temperature, the heating efficiency $P=U_2/R$ will decrease at a constant voltage, causing the heating rate to become smaller. When the carbon fiber line is heated, the heating line and the fabric will also transfer the heat it has generated to the air, causing heat dissipation, and the temperature will remain unchanged when the heating and heat dissipation are balanced.

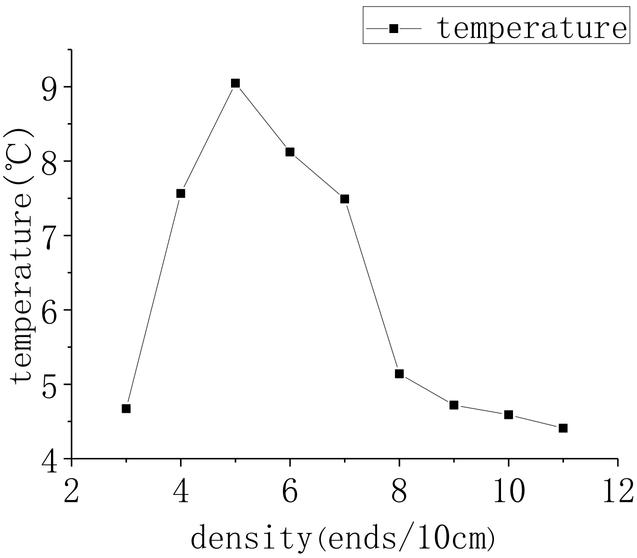

Fig. 5. Temperature change with density

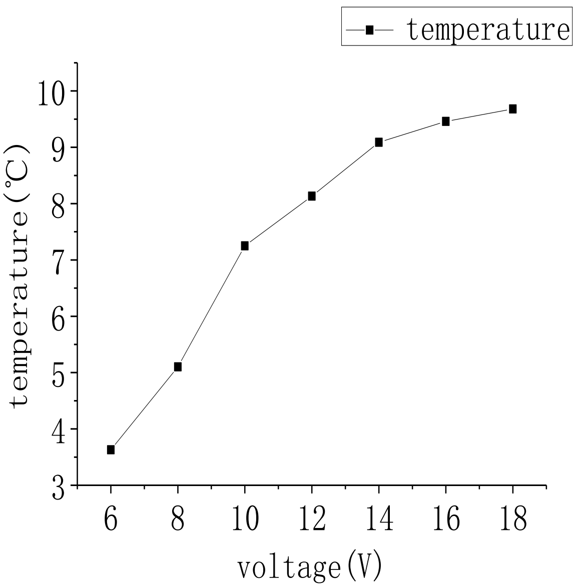

Fig. 6. Temperature change with voltage

3.2. Effect of arrangement density of heated carbon fiber line on the heating performance of the fabric

The voltage of the thin-film solar cell is 12 V, and the curve of the temperature of the heating fabric at 480 s as a function of the heating carbon fiber density change is shown in Figure 5. When the heating line density in the latitudinal direction of the fabric increased from 3 ends/10 cm to 5 ends/10 cm, the fabric temperature sharply increased to 9.1 °C. When the density of the heating carbon fiber line increased from 5 ends/10 cm to 8 ends/10 cm, the temperature sharply decreased. However, when the density was greater than 8 ends/10 cm, the temperature increase was more gradual. When the density was 11 ends/10 cm, the temperature rise was only 4.4 °C. It can be predicted from the trend shown in Figure 5 that as the density of the heating carbon fiber line increases, the temperature increase will gradually plateau.

A higher density of the heating carbon fiber line increased the length of the heating carbon fiber line in the circuit, which increased the resistance according to the resistance formula $R=\rho L/S$. At a constant voltage U, the resistance R increased, and the current I became smaller. When the current I was small, the internal voltage of the power source was reduced, and when the loop voltage was constant, the external voltage of the power source increased. $P=UI$ increases and decreases individually, but their product increases continuously, causing the heating power to increase. When the power reaches the maximum P_{max}, the resistance continues to increase, and the power will decrease. Due to the greater power, more heat is generated, and maximum power is generated. This corresponds to an optimal resistance, i.e., the heating line density is 5 ends/10 cm. As the carbon fiber heating line density continued to increase, the resistance increased, and the cell voltage remained at 12 V, causing the heating power to decrease. Theoretically, when the resistance tends to infinity, the heating power of the fabric will tend to 0; but considering the actual weaving process, the weft of the fabric is composed of the heating carbon fiber line, and the resistance is largest when they do not overlap. At this time, the heating line density is unlikely to be infinite but $\frac{10}{D}$ ends/10 cm (D is the diameter of the heating carbon fiber line in cm), and hence the heating power of the fabric infinitely tends to a positive value.

3.3. Effect of solar cell voltage on fabric heating performance

When the density of the heating carbon fiber line was 5 ends/10 cm, the energisation time was 480 s, and the temperature of the heating fabric changed with the voltage to form the curve shown in Figure 6. As the voltage of the thin-film solar cell increased, the temperature of the fabric also increased, but at an increasingly slower rate. When the voltage increased from 16 V to 18 V, the temperature increased by only 0.2 °C. According to the power formula $P=U^2/R$, when the voltage of the thin-film solar cell increased continuously, the heating law of the fabric per unit time

Level Factors	1	2	3
Voltage [V]	10	12	14
Time [s]	240	360	480
Density [ends/10cm]	4	5	6

Table 1. Three-factor level table

Factors / Test number	Voltage A [V]	Time B [s]	Empty column	Density C [ends/10cm]	Temperature [℃]
	1	2	3	4	
1	1	1	1	1	4.7
2	1	2	2	2	6.9
3	1	3	3	3	6.4
4	2	1	2	3	5.4
5	2	2	3	1	6.2
6	2	3	1	2	7.6
7	3	1	3	2	6.8
8	3	2	1	3	7.5
9	3	3	2	1	7.1

Table. 2 Experimental scheme and results
Note: Table 3 is a factor impact analysis of Table 2.

Category	Voltage A	Time B	Empty column	Density C
K_{1j}	6.000	5.633	6.600	6.000
K_{2j}	6.400	6.867	6.467	7.100
K_{3j}	7.133	7.033	6.467	6.433
$K_{1j(\text{一})}$	2.000	1.877	2.200	2.000
$K_{2j(\text{二})}$	2.133	2.289	2.156	2.367
$K_{3j(\text{三})}$	2.377	2.344	2.156	2.144
Range R_j	0.337	0.467	0.044	0.367
Main factors→minor factors	BAC			
Optimal scheme	A_3 B_3 C_2			

Table 3. Analysis of influential factors

did not follow the curve of the quadratic function. The reason is that the resistance of the heating carbon fiber line increased with the temperature, which slowed the heating power increase rate. Increasing the voltage can significantly increase the power to rapidly heat the fabric, but this also requires more thin-film solar panels. This will lead to a cumbersome and uneconomical heating system, which is not conducive to the practical application of heating fabrics.

3.4. Experimental results and analysis of orthogonal experiments

According to the conclusion of the single-factor experiments, the voltages of three kinds of thin-film solar cells were selected as 10 V, 12 V, and 14 V; three time periods : 240 s, 360 s, and 480 s; and three kinds of heating line densities : 4 ends/10 cm, 5 ends/10 cm, and 6 ends/10 cm. Regardless of the interaction between the factors, $L_9 3^4$ is the smallest orthogonal table that satisfies the condition. The design header is shown in Table 1, and the experimental scheme and results in Table 2.

The first number corresponding to the row of K_1 indicates the sum of the index values corresponding to factor 1 at the level of 1, and is recorded as K_{11}. The first number in the subscript is the horizontal number, and the second number represents the factor. The first number corresponds to the row of $K_{1(\text{一})}$ is $K_{11(\text{一})}$, $K_{11(\text{一})}=K_{11}/3$, and so on; the range Rj = max{$K_{ji(\text{一})}$}-min{$K_{ji(\text{一})}$}, where $K_{ji(\text{一})}$ is the average value of the index of factor *i* at level *j*.

For factor 1 (voltage), $K_{31(\text{三})} > K_{21(\text{二})} > K_{11(\text{一})}$, thus a voltage of 14 V was the best level; for factor 2 (time), $K_{32(\text{三})} > K_{22(\text{二})} > K_{12(\text{一})}$, the optimal time was 480 s; for factor 3 (heating line density), $K_{24(\text{二})} > K_{34(\text{三})} > K_{14(\text{一})}$, thus the density of 5 ends/ 10 cm was the best level. It can be seen from the extremely poor result $R_2>R_1>R_3$ that time is the most influential factor among all parameters, followed by voltage, and then heating line density. Therefore, the comprehensive analysis shows that the best combination of the fabric heating process is A_3 B_3 C_2, that is, a voltage of 14 V, a time of 480 s, and a heating line density of 5 ends/10 cm. It was experimentally verified that under the optimal heating conditions, the maximum temperature increase of the heating fabric was 7.9 °C, which demonstrates the accuracy of the optimal heating process.

The variance test for the orthogonal table is shown in Table 4. After calculation and analysis, it was found that the influence of each factor on the experiment is significant.

4. Conclusions

Carbon fiber heating lines were woven into a heating fabric by a process that involved non-cutting of the weft yarn. The fiber was connected to external flexible thin-film solar panels, and a carbon-fiber heating fabric based on a thin-film solar cell was produced which could be used to prepare a heated garment. The single-

Source of variance	Sum of squared deviation S_j	Degrees of freedom f_j	Mean square $\overline{S}_j$	F_j value	Significance
A Voltage	1.982222	2	0.991111	55.7493	Significant
B Time	3.508889	2	1.754444	9.868624	Significant
C Density	1.842222	2	0.921111	5.181185	Significant
e Error	0.035556	2	0.017778		

Table 4. Analysis of variance

Note: $\overline{y}=\frac{1}{n}\sum_{i=1}^{n}y_i$; $T=\sum_{i=1}^{n}y_i$; $Q=\sum_{i=1}^{n}y_i^2$; $P=\frac{T^2}{n}$;

n is the total number of experiments, and y_i is the experimental result (i=1, 2, ⋯, n); $S_j=\frac{r}{n}(\sum_{i=1}^{r}K_i^2)-P$; $f_j=r-1$; $\overline{S}_j=\frac{S_j}{f_j}$; $(F_j=\frac{\overline{S}_j}{S_{e^\Delta}})$;

r is the number of levels, and j is the factor; when $F_j< F_{0.1}(2,4)$ is not significant; $F_{0.1}(2,4)=4.32$.

factor experiments of the thin-film solar cell voltage, heating time, and carbon fiber heating line arrangement showed that the temperature of the heating fabric increased with time and voltage, but the rate of which became increasingly slower. Upon increasing the carbon fiber density, the optimum heating effect was obtained at a density of 5 ends/10 cm. The orthogonal experiment showed that the factors affecting the heating of the fabric were time, voltage, and density. The optimal heating time was 480 s, the carbon fiber density 5 ends/10 cm, and the voltage 14 V. The results showed that the three factors significantly influenced the heating effect of fabrics.

Acknowledgements

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