Development and Characterization of Metal Woven Electric Heating Fabrics

N. Muthukumar, G. Thilagavathi, T. Kannaian and S. Periyasamy

Abstract The textile industry focuses on providing value-added functional textile materials to cater to the demands of the consumer world. Recently, a new field of research has emerged, which combines the benefits of the textiles with the world of electronics and technology yielding products and devices referred to as electro-active textiles or smart textiles. The various textile technologies such as weaving, knitting, sewing, and printing have been used to incorporate the electrically conducting elements with textile materials. In this work, a metal woven electric heating fabric was developed and characterized for heat generating property. The electric heating fabric was developed for weaving fine copper wire as weft and acrylic yarn as warp. The temperature–electrical resistance relationship of the developed fabric was determined. The main idea of the work is to design and develop electric heating fabric which can be used with a minimum power supply in order to obtain a wearable system.

Keywords Copper wire · Electro textiles · Electrical resistance · Heating fabric · Smart textiles

1 Introduction

Textiles, being the second most important needs of the human kind, it is the product which would not be replaced by any others though the technology is tremendously producing various consumer products. In the present scenario of increasing fashion, the textiles could be regarded as the materials that make man more than 50% than the usual perception of man and textiles being 50% each. Apart from the protection requirement of the body, there has been also the interest on various aspects such as the comfort, clothing care aspects, durability, and other stability conditions

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from the customers, nowadays value addition to textiles. In addition to the general requirements on textiles as just normal apparel, textiles are also expected to perform some of the human life supporting/enhancing/defending systems. Such textiles are recognized as either under functional textiles or even as smart textiles if they are responsive. Development of such textile structures uses various interdisciplinary products such as electronic gadgets, particularly the recent interests of flexible electronics, which may be used for various vital body symptoms continuous monitoring and the likes. The applications of functional and smart textiles are many and are increasing [1]. Following are the focused discussion on electro-active textiles, one of the functional/smart textiles, as the emphasis of the work and the article falls in this category.

One of the growing research areas of electro-active textiles is the electric heating garments. The electric heating garments can be used for military and other outdoor applications [2]. There is a lot of research work going on in the field of electrically heating garments in the past few years. The electric heating fabrics can be developed by introducing electrically conductive textile-based materials in the fabric. Materials like silver-coated and copper-plated yarns, carbon-based fibers, and tiny inox cables are textile-based conductive materials and used as a heating elements for electric heating fabric development. Weaving, knitting, sewing, and finishing are the different technologies available to incorporate the heating elements into the textile materials [3]. A power supply, electrical heating element, temperature sensor, and a user interface are the components required to design an electric heating fabric. In electric heating fabric, the function of the heating element is the energy converstion that is from electrical energy into thermal energy. The temperature sensor is used to measure the temperature of the human skin and atmosphere. The heating energy of the electric heating system was provided by the power supply. The electric heating system of heating fabric can be adjusted by the wearer by using the user interface. The electric heating fabric should be designed in such a way that the incorporation of these components into the clothing does not affect the comfort and user-friendliness of the wearer [4].

The working concept of electric heating fabric is shown in Fig. 1. The electric heating fabric is kept in the middle layer of the three-layer clothing. The total heat (Q_{tot}) given by the electric heating garment is calculated by

$$Q_{tot} = H_{sk} + H_{env} + H_{abs} \tag{1}$$

where H_{sk} is heat loss of the human body through the heating fabric and outer clothing to the atmosphere, H_{env} is heat loss of the electric heating fabric by radiation/convection to the atmosphere, and H_{abs} is heat absorbed by the heating fabric from heating element [5].

Numerous different techniques for creating electric heating fabrics have been studied by many research groups. Wang et al. investigated the heating performance of three-layer electric heating garment using a thermal manikin. The better heating performance of the garment was observed when the heating fabric was in the middle

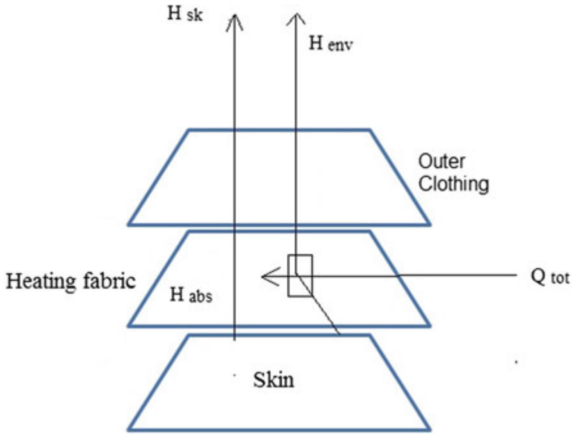

Fig. 1 Heating transfer mechanism of a heating fabric

layer of the garment compared to the other two [6]. Kanyan et al. developed electric heating pads using steel fabric and investigated the heat-generating properties. It was found that the heat-generating property of pads vary for a particular period of time with respect to the number of plies used to construct the heating pad. They concluded that the size of the heating pad, number of plies used or amount of conductive yarn used to construct the heating pad, and power supply used are the important parameters influencing the heat-generating properties of the heating pad [7]. Hao et al. investigated the heating behavior of plain woven electric heating fabrics made from silver filaments and silver-coated yarns. The results showed that the fabrics made from silver filaments had better heating performance compared to fabrics made from silver-coated yarns [8]. Poboroniuc et al. manufactured electric heating fabrics using different types of conductive yarns by knitting technology and investigated heat-generating properties of the developed fabrics. They found that the developed heating fabrics generate heat up to 20 °C with electric power of 1.7 W [9]. Mey et al. designed an electric heating pad with the size of 8 cm × 45 cm using silver-coated nylon yarn in a shirt by knitting. It was found that the temperature of the shirt incorporated with the heating pad increased up to 12–14 °C from the room temperature for 5 W power supply. They also demonstrated that a portable battery can supply this amount of power for 8–10 h [10]. In our previous work, we have fabricated an electric heating fabric by stitching silver-coated nylon yarn over the polyester fabric. In this, silver-coated nylon yarn acts as a heating element. It was found that the temperature of the developed electric heating fabric was increased up to 16 °C from the room temperature for 9 V power supply. It was also found that 0.92 W required for 1 °C rise in temperature [11].

It was concluded from previous studies that, the electrically conductive fabrics made from woven structure have better performance for heating applications compared to the knitted structure due to its structural properties. Hence, in this study, weaving technology was chosen for electric heating fabric development. We have developed a metal woven electric heating fabric using copper wire. The heating fabric was designed in such a way that it can be operated with a minimum power supply and also user-friendly.

2 Materials and Methods

In this work, fine copper wire has been used as a heating element. Copper has a low specific electrical resistivity. It has good thermal conductivity and low heat capacity compared to other heating wire materials. Due to its high ductility, the risk of fracture is very small [12]. The copper wire having a diameter of 150 μm with linear resistance of 1.8 Ω/m was used as weft. The acrylic yarn having 40^s Ne (143 μm) was used as warp. Acrylic yarn was chosen as warp because of its good thermal resistance value [13]. Acrylic yarn and copper wire were sourced from in and around Coimbatore, Tamilnadu, India.

2.1 Fabrication of Electric Heating Fabrics

The copper woven electric heating fabric was developed on a desk loom by introducing copper wire in the weft direction and acrylic yarn as warp in a plain weave pattern. Because of stable conformation, dense structure, smooth surface, and less shrinkage, the plain weave was selected in this study. The developed fabric had a size of 8 cm $\times$ 8 cm and is shown in Fig. 2. The developed fabric had EPI of 60, PPI of 56, and thickness of 0.6 mm. The developed copper woven fabric had GSM of 170.

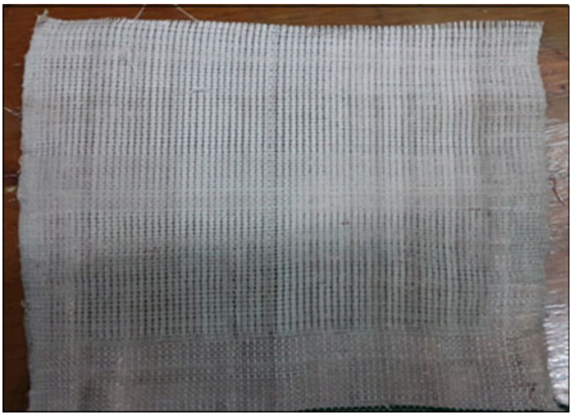

Fig. 2 Image of the copper woven electric heating fabric

2.2 Characterization of Heat-Generating Property

As per joules law, if the current I flows through a resistance R, then voltage V and power absorbed P are determined by using Eqs. 2 and 3.

$$U = R \times I \tag{2}$$

$$P = V \times I \tag{3}$$

In an electrical resistance heating, this power is converted into heat. In case of copper woven heating fabric, the resistance consists of thin metal wires. The resistance offered to the current flow by the internal friction of the electrons in the lattice generates heat in the developed fabric.

Figure 3 shows the experimental setup used to study the heating behavior of the developed electric heating fabric. It has a power supply (9 V battery), AC and DC multimeter (voltage, resistance, etc.), and a temperature sensor. The temperature of developed metal woven fabric can be raised by employing the power supply using 9 V battery and the heating behavior of the developed fabric was observed in point of temperature and electrical characteristics. A carton was used to keep the fabric during characterization in order to measure the actual surface temperature of the electric heating fabric.

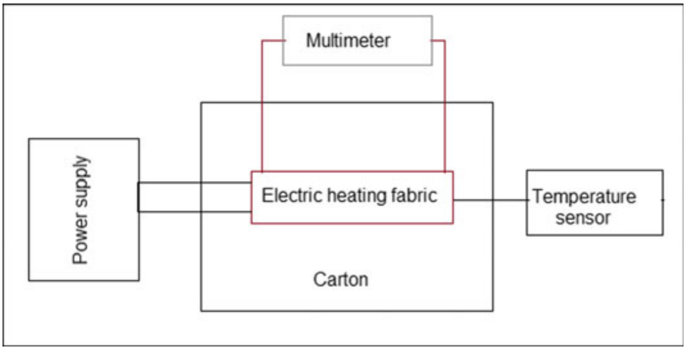

Fig. 3 Experimental setup for heating fabric characterization

3 Results and Discussion

3.1 Heat-Generating Property of Copper Woven Fabric

In this research work, to study the heating behavior of the copper woven fabric, a 9 V battery was used as a power supply. During experiment, the copper woven fabric provided approximately 20 °C heating within 5–6 min period and temperature of the fabric remained the same for the rest of the period. The maximum temperature rise of the developed copper woven fabric was 40 °C. The current flow in a wire is because of the free electrons movement and as they move they tend to also colloid with each other which would increase with the increase in their flow rate driven by the potential difference. Such collisions would result in heat generation and would depend on the square of the flow of current and hence the relationship is given as following

$$Q = I^2 RT \tag{4}$$

where,

Q Amount of heat,
I Electric current,
R Amount of electric resistance in conductor, and
T Time.

Figure 4 shows the relationship between recorded temperature and electrical resistance of the fabric for the applied voltage of 9 V. It was observed that there is an increase in temperature with an increase in electrical resistance. The surface resistance of copper woven fabric increased from the initial resistance of 8–35 Ω/square. It was also observed that the amount of heat generated is proportional to the electrical resistance of the wire. This may be due to there is no change in the current in the circuit and also current flow. The positive coefficient value of a variable in the equation indicated that the increase in electrical resistance value increases the temperature of fabric. The coefficient of determination (R^2) of the linear regression curve is 0.986 indicating its goodness of fit. The relationship between the temperature (T) of the metal wire to its electrical resistance can be expressed as

$$R_{\mathrm{T}} = R_{\mathrm{ref}}(1 + \alpha(T - T_{\mathrm{ref}})) \tag{5}$$

where α is the temperature coefficient of resistance and it is resistance change factor per °C of temperature change [14]. A positive coefficient for a material means that its temperature increases with an increase in resistance. The electrical resistance of copper wire is dependent upon collision processes within the wire. Hence, it is expected that there is an increase in electrical resistance with an increase in temperature because of more collisions. The temperature coefficient of resistance of the developed copper woven fabric was 2.5×10^{-3}.

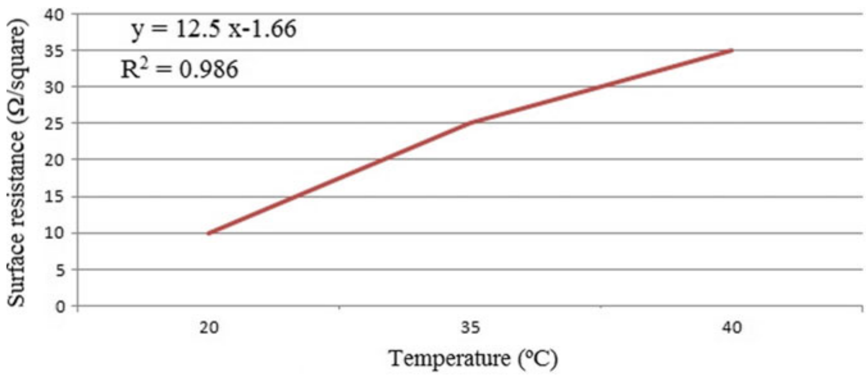

Fig. 4 Relation between fabric temperature and electrical resistance

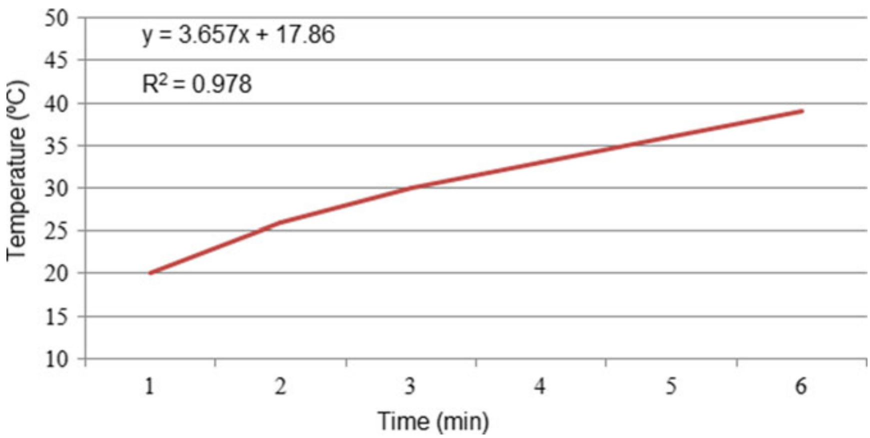

Fig. 5 Relation between fabric temperature and time

Figure 5 shows the relationship between the temperature rise of copper woven fabric and time. It was found that the temperature of the developed copper woven fabric increases with increase in time. It was also observed that the amount of heat generated is proportional to time. This may be due to there is no change in electrical resistance and current flow. The positive coefficient value of variable in the equation indicated that the increase in time increases the temperature of the copper woven fabric. The coefficient of determination (R^2) of the linear regression curve is 0.978 indicating its goodness of fit.

In this study, a battery having an output voltage of 9 V was used. The capacity of the battery was 2400 mAh which means that 2.4 A can be delivered for one hour. Such a battery can supply 21.64 W of power for one hour. From the experimental trails, it was found that the power consumed by the fabric to rise 1 °C temperature was 0.5 W; hence, 10 W is required to give a temperature rise from 20 to 40 °C. The developed fabric can be used for heat-generating application for approximately 2 h with 9 V battery.

4 Conclusion

In this work, a metal woven electric heating fabric was developed by weaving fine copper wire as weft and acrylic yarn as warp. It was found that the temperature of the developed copper woven electric heating fabric rises during the power application. The increase in temperature of the copper woven fabric is proportional to the increase in electrical resistance value and time. The temperature–resistance relationship demonstrated a linear trend with a goodness of fit (R^2 value) of over 98%. The developed metal woven fabric can be used with a 9 V battery. The developed metal woven fabric provides approximately 20 °C heating above the room temperature.

The developed electric heating fabric can be used domestic or in medical treatments. For example, localized heating of the human body can help a patient for quicker recovery. Some of the major features of the electro-active textile developed in this work are structure simplicity and flexibility which would make them find a wide application particularly in the field of warmth demanding applications. To provide the required power supply to the fabric, an adjustable regulator can be incorporated.

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