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Electrically heated wearable textiles produced by conventional pigmented inks containing carbon black

Abstract

Purpose - In the study reported here, carbon black containing coating formulations that are commonly used for conventional printing of textiles were considered for their utility as a functional coating on cotton woven fabric.

Design/methodology/approach - Specifically, electrical and thermal characterisation of the coating system was carried out to establish the feasibility of the system for use in manufacturing of flexible heating elements on textile substrates. The coating formulations were applied via simple padding technique followed by stitching the electrodes using a conductive yarn.

Findings - The heating elements of different sizes thus produced showed Ohmic behaviour as resistor and attained a targeted temperature difference of up to 40 °C within the applied voltage range. A prototype heater was also produced, and thermography results showed uniform heating and cooling of the heater that was incorporated into a jacket.

Originality/value - The proposed method is envisaged to be very practical for the realisation of completely textile-based heating elements of different shapes and sizes. Furthermore, the proposed manufacturing method can be used to convert conventional ready-made articles of clothing into heated textiles for various applications.

Keywords: Heated wearable textiles, Carbon black pigment, Padding technique, Electrical characteristics, Thermal characteristics

Introduction

Electronic textiles are fabrics that feature electronics and interconnections incorporated into them by either inserting wires into their structure or by printing conductive tracks onto the textile substrate. They present physical flexibility and typical size that cannot be achieved with other existing electronic manufacturing techniques (Agarwal and Agarwal, 2011, Stoppa and Chiolerio, 2014, Ghosh and Dhawan, 2006).

Heating textiles is a step ahead to flexible heating elements which are designed to save energy, provide heating for comfort and thermal therapy. Textile based heating elements consists of a substrate onto which a means of conduction/IR rays emission is incorporated. The heating elements are generally enclosed in garments or knitted into fabric layer hence are less visible and less susceptible to snagging or abrasion of these conductive segments. The properties of heating elements can easily be altered to offer a wide variety of applications.

Heating elements in textile fabrics can be constructed by incorporating conductive yarns or filaments during the fabric manufacturing stage (Dawit *et al.*, 2021). Conductive fabric for heating application can either be fabricated by coating single-wall carbon nanotubes (CNTs), or graphene/waterborne polyurethane (WPU) or polypyrrole on textile materials (Yang *et al.*, 2018, Hao *et al.*, 2018, Kim *et al.*, 2019). Another approach is to coat conductive polymer on yarns or fabrics using improved vapour deposition method and this can easily transform commercially available textiles into wearable electric heaters (Zhang *et al.*, 2017). Metal nano-fibres were employed to function as both a wearable heater and a wearable temperature sensor (Huang *et al.*, 2019). Textile based thermal actuators were also integrated to garments by stitching for thermal comfort of the wearers (Gagliardi *et al.*, 2018). However, an additive process such as printing is an attractive alternative primarily owing to the considerably fewer steps that have to be carried out to develop the end product for heating purpose (Pahalagedara *et al.*, 2017). All technologies are used according to desired application. The entire heating system is powered by rechargeable batteries. All electronic components can be removed before washing.

Inherent thermal properties of textile garments are utmost important since they are related to the comfort of human subjects especially for those living in very cold environment. Thermal properties of the fabrics can be evaluated by measuring their thermal resistance. Woven fabrics of various construction offer different values of thermal resistances

(Bhattacharjee and Kothari, 2009) which in combination with heating element can be utilised effectively for treatment of diseases through thermal therapy.

People living in high latitude regions and engaged in different occupations are frequently exposed to cold stresses which lead to Cold Weather Injuries (CWIs). CWIs are categorised as Freezing Cold Injury and Non-freezing Cold Injury. These injuries may cause trench foot, frostbite and frost nip which occur where temperature is very low thus causing the tissue fluid to freeze. Exposing human body to very low temperature reduces blood flow and damages human skin and tissues at different levels. It has been recommended that a whirlpool bath can be used with a temperature between 37 and 39 °C, to decrease the pain felt by the patient of freezing cold weather injury while for the treatment of non-freezing CWIs, slow rewarming at 37–39°C is required (Heil *et al.*, 2016). Several textile products which may serve as heaters have been proposed to serve the purpose (Hao et al., 2018, Kim et al., 2019, Yang et al., 2018). Use of heating garments may save people from such injuries or help those injured, recover more rapidly.

Raynaud's phenomenon (RP) is an episodic constriction of blood vessels in human subjects owing to extremely cold weather conditions. Mostly, such a phenomenon occurs in fingers and toes. Patients with primary Raynaud' phenomenon feel cold, pain and numbness of their fingers and toes. While secondary Raynaud's phenomenon may cause ischemia that can lead to ulcerations and/or death of body tissues which is a very serious health condition. Treatment of Raynaud's diseases involves conservative measures, pharmacological treatment and surgery (García-Carrasco *et al.*, 2008, Agbor *et al.*, 2016). However studies have shown that the management of RP remains quite a challenge (Lis-Zwi Ty, 2019).

Patients must learn to treat mild Raynaud's phenomenon with non-invasive measures. One of the ways to manage Raynaud's phenomenon is that the patients avoid exposure to cold and keep themselves warm (Hughes and Herrick, 2016). Several textile-based products including heated gloves, ceramic textiles and wearable electric heaters have been developed to maintain human skin at desired temperature which may alleviate the pain, numbness in the patients' fingers and toes. It would also help avoid further associated health complications of Raynaud's disease (Nottingham Trent University, 2015, Ko and Berbrayer, 2002, Gonos, 2016, Dawit et al., 2021, Kim et al., 2019).

Thermal therapy using heated textiles (which is a fabric containing specified metals emitting IR rays) have been found beneficial for the rehabilitation of diabetic patients by enhancing their blood circulation (Bau *et al.*, 2020). In another treatment, the reduction of free radical levels in healthy people and in patients with free radical-related disorders were reported by the use of ceramic textiles developed using mineral oxides microfibers coating (Nanobionic®) emitting IR Rays (Gonos, 2016).

A conventional pigmented ink system essentially contains pigment (as colorant or as a functional filler), binder, solvent(s) and additives (Solangi *et al.*, 2014). Metals, metallic oxides, conductive polymers and carbon-based materials can be utilised as conductive filler materials for the purpose of formulating conductive/resistive inks for the stated applications.

In the studies reported here, we have investigated the feasibility of a conventional pigment printing ink system containing carbon black as the conductive filler on cotton fabric to develop electrically heated wearable textiles. Carbon black has several advantages over other functional materials in applications for the development of conductive fabrics and electric heaters (Morris and Iniewski, 2013, Karousis *et al.*, 2016, Zeng *et al.*, 2014, Pahalagedara et al., 2017, Phillips *et al.*, 2017).

In one of the studies related to the development of wearable heaters, carbon black (CB) dispersion was prepared and then applied on knitted fabrics using a screen (Pahalagedara *et al.*, 2017). In another investigation, graphite and carbon black were combined in different ratios to formulate conductive ink. This ink was applied to the substrate using a screen (Phillips *et al.*, 2017). However, both formulated inks were transferred to the substrate by spreading without transforming it into a conventional print paste containing binder and thickener, which is usually prepared for printing of pigments.

In the studies reported here, commercially available carbon black pigment dispersions Printofix HRT and Printex U were transformed into print paste by varying pigment and binder ratio. Woven cotton fabrics were padded with the prepared carbon black pigment paste to evaluate electrical and thermal properties of the resulting fabrics, after array of electrodes were stitched on coated swatches to make heating elements of different sizes. It would aid in attaining a certain temperature change by connecting the heating elements to a variable power supply.

Thus, various conductive pastes were prepared to produce a wide range of surface resistivity, amount of current drawn and temperature difference. This opens up a vast field of application of heating elements, a few of which are stated above. Since heating elements can be coated on textile materials, it is possible to attain elements of any required shape and size making this a versatile technology. Different combinations of conductive inks can be applied to form various patterns to attain the required range of temperature on the desired surface to produce electro-thermal heaters.

Materials and Methods

Figure 1 presents flow chart showing the sequences of the processes followed for sample preparation and their testing.

(Insert **Figure 1** here)

Coating system

Carbon black pigment dispersion Printofix HRT, Binder Helizarin ET ECO (liq) and Thickener Lutexal HIT Plus Liq-C were kindly provided by Archroma Pakistan Limited. For electrical characterization and application onto the substrate, two coatings formulations with a Pigment:Binder ratio of 70:30 and 80:20 were prepared by adding the ingredients in the required amounts in a beaker and stirred for two minutes at 500 RPM using an overhead stirrer.

Substrate

Cotton is globally the most widely used natural fibre for apparels. The degree of polymerisation of cotton tends to decrease at temperatures above 150 °C but its basic structure stays intact (Alomayri *et al.*, 2014, Alomayri *et al.*, 2013, Xu, 2003). It's thermal decomposition and depolymerisation take place if cotton is exposed to temperatures above 200 °C for a few hours. In the present study, a bleached and mercerised 100% cotton fabric woven into a 1×1 weave structure of construction (40×40)/(123×73) and mass of 124.09 g/m^2 was used.

Sample preparation

The prepared coating formulations were applied onto the substrate by padding technique. For this purpose, a Roaches laboratory padder was used and padding was carried out at a speed of 1 m/min while the padder pressure was maintained at 1 bar. Consequently, a wet pickup of 100% was maintained for all of the samples. All the samples were dried in standard laboratory conditions for 24 hours prior to characterisation.

For the realisation of electrodes in the substrate, a 4-ply silver coated Nylon yarn having resistivity of 0.2 Ω/m as used. The electrodes were stitched into the coated substrate using the saddle stitch technique with a stitch length of 3 mm. In this step, different sizes of the anticipated heating patches were produced by stitching electrodes of length 5 cm, 10 cm, 15 cm and 20 cm with a gap of 1 cm between adjacent electrodes as shown in Figure 2. This arrangement of electrodes allowed electrical and thermal characterisation of heating elements of the said lengths and widths of 1 cm, 2 cm and 3 cm.

(Insert **Figure 2** here)

Analysis and characterisation

Electrical characterisation

Measurement of the surface resistivity was carried out for the coated samples to identify the ones that qualified for further testing. For this purpose, a 3 cm × 3 cm parallel plate electrode was used in conjunction with a portable multimeter and the average of five readings was considered. To record current drawn at specific voltages, the samples were energised using a desktop type DC power supply which could provide constant voltage from 5.0 volts to 25.0 volts.

Thermal characterisation

For thermal characterisation, the heating elements were energised using the DC power supply and the voltage was increased at intervals of 2.5 volts starting from 5 volts. The setup is shown in Figure 3. Values of current drawn by each heating element and the temperature achieved were noted after 10 minutes of the power being supplied to the samples. Using an Infrared radiation thermometer having a spot ratio of 1:8, the temperature values were recorded after 10 minutes of energizing the circuit and at five different points along the length of the heating element as shown in **Error! Reference source not found.**3. Using an infrared radiation thermometer having a spot ratio of 1:8, the temperature values were recorded at five different points along the length of the heating element after 10 minutes of energising the circuit. The ambient temperature was considered as the initial temperature to calculate the temperature difference achieved. Thermographs of the heater patch were recorded using a Fluke Ti125 thermal imaging camera.

(Insert **Figure 3** here)

Results and discussion

The surface resistivity values were found to be 1.27 kΩ/□ and 4.05 kΩ/□ for the substrates coated with 80 : 20 and 70 : 30 (Pigment : Binder) formulations, respectively. Thus, samples from both of the formulation sets were considered for further analysis. This is because that a higher binder proportion has inferior electrical characteristics but superior properties in terms of retention on the substrate.

The electrical characteristics of all of the samples were thoroughly analysed as per the procedure outlined in the Electrical Characterisation section. As shown in Figure 4(a, b), for all of the samples, a more or less linear relationship between the current drawn and the voltage applied was observed. This indicates that the heating elements possessed ohmic behaviour as conductors.

(Insert **Figure 4** here)

In the context of the present study, the temperatures that the prepared samples could achieve was of direct relevance. Thus, the temperature difference achieved at various applied voltages were also recorded for all of the samples using a non-contact IR thermometer. The relevant results, provided in Figure 5(a, b), show that the temperature difference from ambient increased with the increase in the current drawn. It is noteworthy that the current drawn and temperature attained were not strongly correlated for heating elements of different sizes. In the present study, we had aimed to achieve a temperature difference of up to 50 °C. This is because that temperatures greater than 40 °C are not considered to be comfortable for human skin in case of heat transfer by direct contact with the skin. In the context of this consideration, most of the samples that were produced qualified for further analysis. . One of the objectives of this study was to produce a prototype in the form of a jacket, thus, samples of size 15 cm x 2 cm were considered for further testing as this was considered to be a nominal size for the selected garment. This is because that a plurality of heating elements of this size could cover a substantial area of the back panel of the prototype garment.

(Insert **Figure 5** here)

In order to record the heating profile, the selected 15 cm × 2 cm heating elements were energised with a constant voltage of 20 volts for 10 minutes and the temperature achieved was recorded at intervals of two minutes. The results shown in Figure 6 clearly indicate that as the current drawn became constant, the temperature (and the temperature difference from ambient) also became constant.

(Insert **Figure 6** here)

Thermography of the prototype

The proposed textile-based heating system was incorporated into a jacket to demonstrate its practicality. For this purpose, four heating patches of size 15 cm × 2 cm were connected in parallel as shown in the circuit diagram in Figure 7. The assembly was attached to the back panel of the jacket using snap buttons. To obtain the thermographic images and the values for current drawn by this circuit, constant DC voltages supply of 20.0 and 22.5 volts were provided for ten minutes. The relevant data provided in Table I show a direct relationship between the applied voltage and the current drawn by the heater comprising of four heating elements of 15 cm × 2 cm connected together in parallel. This is in line with the results obtained for a single heating element.

(Insert **Figure 7** here)

(Insert **Table 1** here)

The temperatures attained by individual heating elements in the circuit were also recorded at regular intervals in order to establish if the heating profile was uniform over the entire area of the heater. The results, tabulated in Table II, show that considerably uniform heating was achieved in different elements. The slight variations could be attributed to slight variations in the coating.

(Insert **Table II** here)

Thermograph of the heater was recorded ten minutes after heating and cooling cycles. Figure 8(a) show the thermograph recorded after 10 minutes of supplying 20 volts to the heater. The highest temperature recorded was 70 °C. Upon disconnecting the power supply, the heat dissipated uniformly across the plane of the heater as shown in Figure 8(b). The uniform distribution of heat in the plane of the heater is favourable for the target applications because it results in a larger effective area of the heater. A proposed manner in which the heater can be incorporated into a garment is exemplified in Figure 9.

(Insert **Figure 8** here)

(Insert **Figure 9** here)

Conclusions

In this study, a conventional pigmented coating system was studied for its application in making e-textiles in general, and a completely textile-based heating system in particular. For the realisation of heating elements on cotton fabric substrate, coating systems containing carbon black as the functional pigment were applied by a simple padding technique and electrodes were subsequently stitched into the coated fabric using a conductive yarn. Results of the electrical and thermal characterisation indicated that the heating elements possessed ohmic behaviour and attained a considerable temperature increase within the tested voltage range. A temperature difference of up to 40 °C was considered useful for the target applications, *i.e.* heated textile articles of clothing and thermal therapies for the treatment of the diseases. A prototype garment was also developed in which the heater incorporated achieved a temperature difference of approximately 35 °C from the ambient. Thermographs of the heater indicated that a uniform temperature was achieved over the entire area of the heater. The method proposed in the present study can be used to manufacture heating elements of different shapes and sizes in a few relatively simple steps. This can be done by cutting the coated fabric into the required shape/size and then stitching the electrodes into it. The technique can also be employed to convert conventional clothing articles into electrically heated clothing articles. This is because that the heating elements can be produced as complete systems on their own and subsequently incorporated into a clothing article by simple methods such as using snap buttons, etc. This approach will also help mitigate potential detrimental effects of washing cycles on heating elements.

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Figure Captions

Figure 1 Sequence of steps followed for sample preparation and testing

Figure 2 Array of electrodes stitched onto the padded fabric for the realisation of heating elements of different sizes

Figure 3 (a) Setup for energizing the circuit for thermal characterization, (b) points where temperature was recorded using IR thermometer

Figure 4 Current vs Voltage profiles for (a) samples coated with 80 : 20 and (b) 70 : 30 (Pigment : Binder) formulation

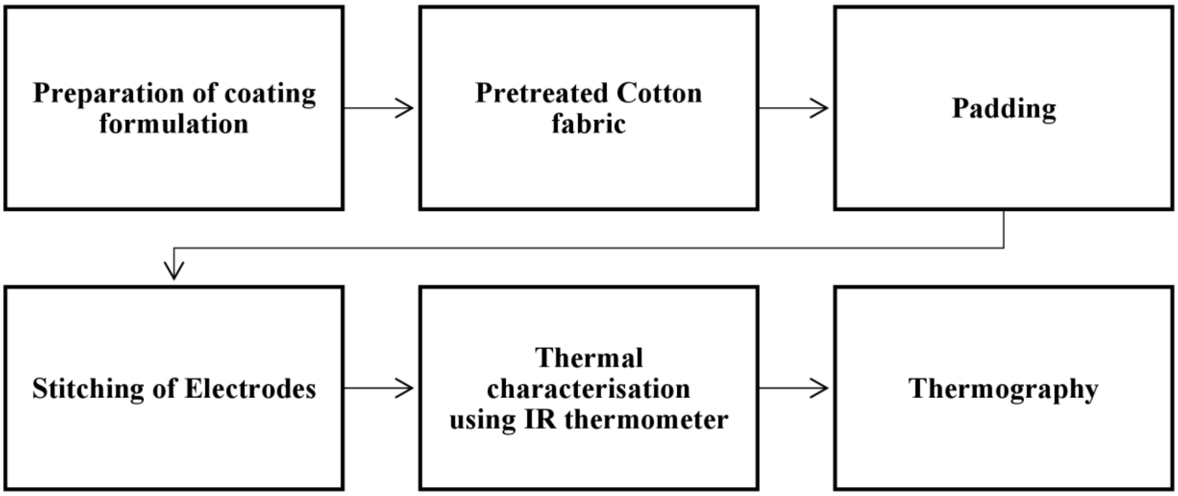
Figure 5 Temperature difference achieved at different voltages for (a) samples coated with 80 : 20 and (b) 70 : 30 (Pigment : Binder) formulation

Figure 6 Temperature achieved by the 15cm × 2cm heating element produced using (a) 80 : 20 and (b) 70 : 30 (Pigment : Binder) formulation, at 20 volts

Figure 7 Circuit diagram for the heater incorporated into the prototype

Figure 8 Thermograph of the heater after (a) 10 minutes of power supply and (b) after 10 minutes of disconnecting the power supply

Figure 9 Proposed heating system incorporated into a ready-made garment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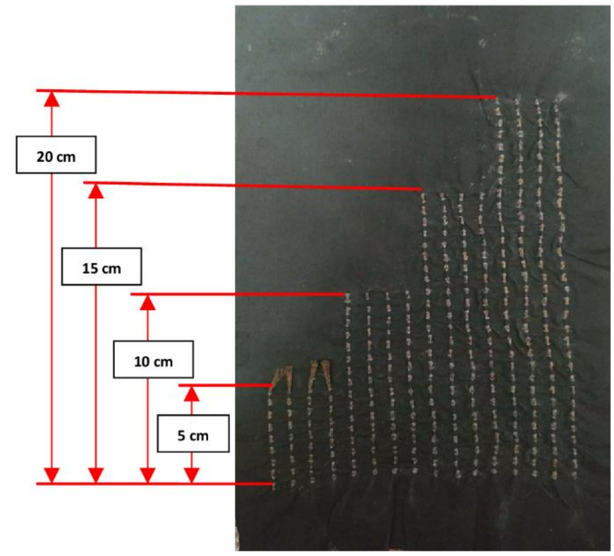
Pretreated Cotton fabric
Padding
Stitching of Electrodes
Thermal characterisation using IR thermometer
Thermography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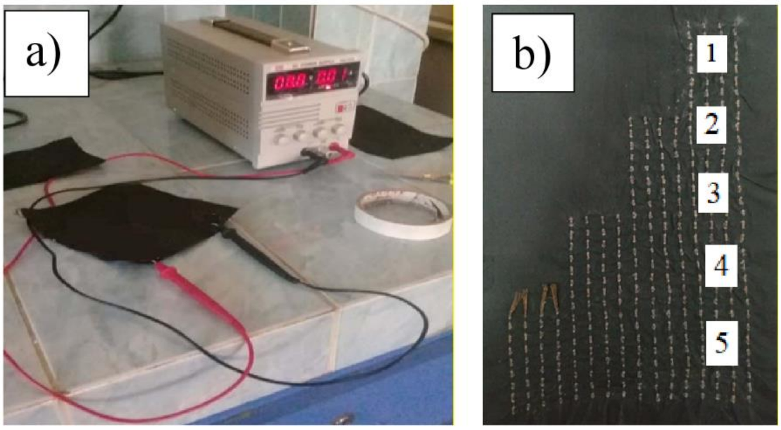
a)
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1
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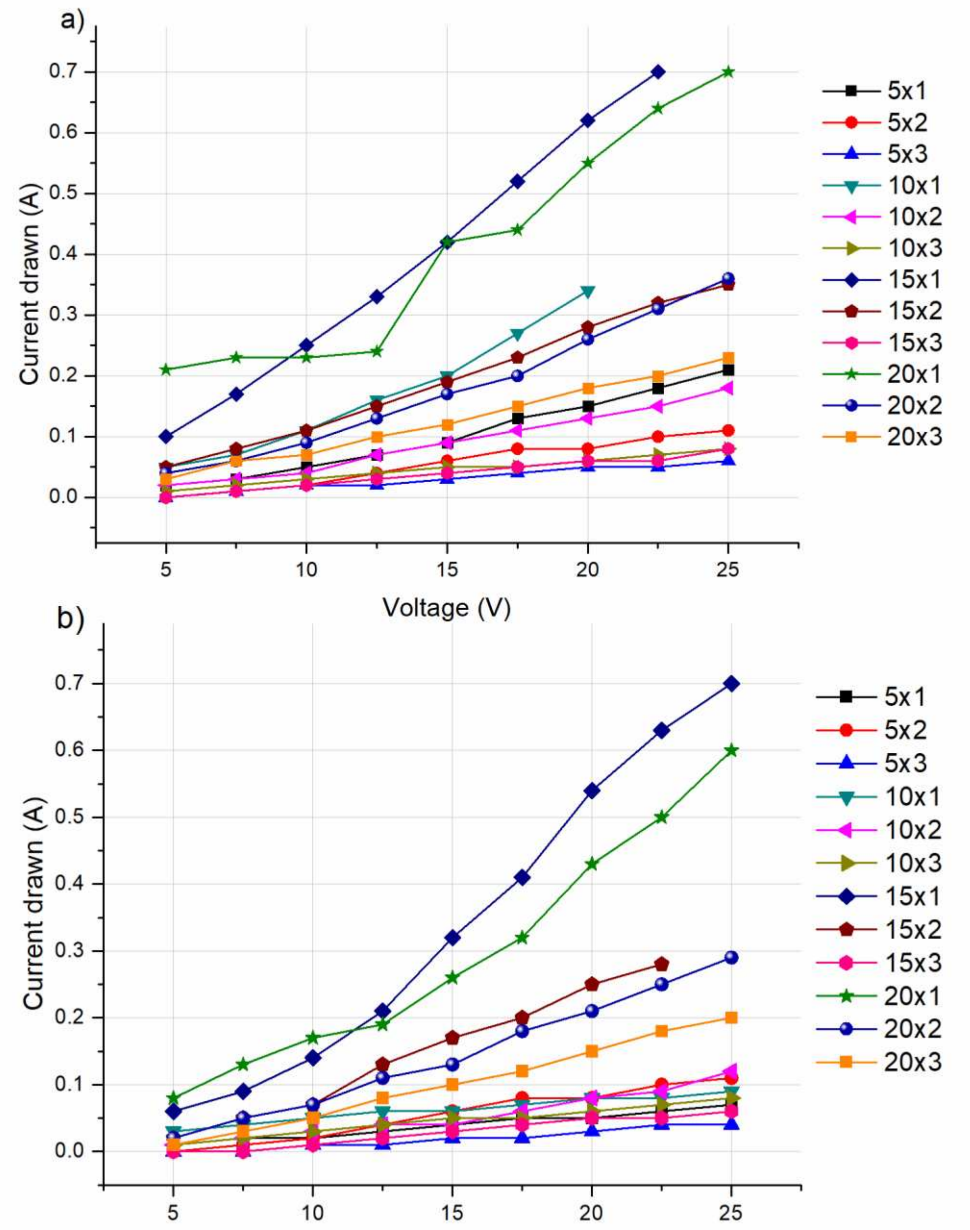

a)
Current drawn (A)
Voltage (V)
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0.2
0.3
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0.5
0.6
0.7
5
10
15
20
25
5x1
5x2
5x3
10x1
10x2
10x3
15x1
15x2
15x3
20x1
20x2
20x3
b)
Current drawn (A)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
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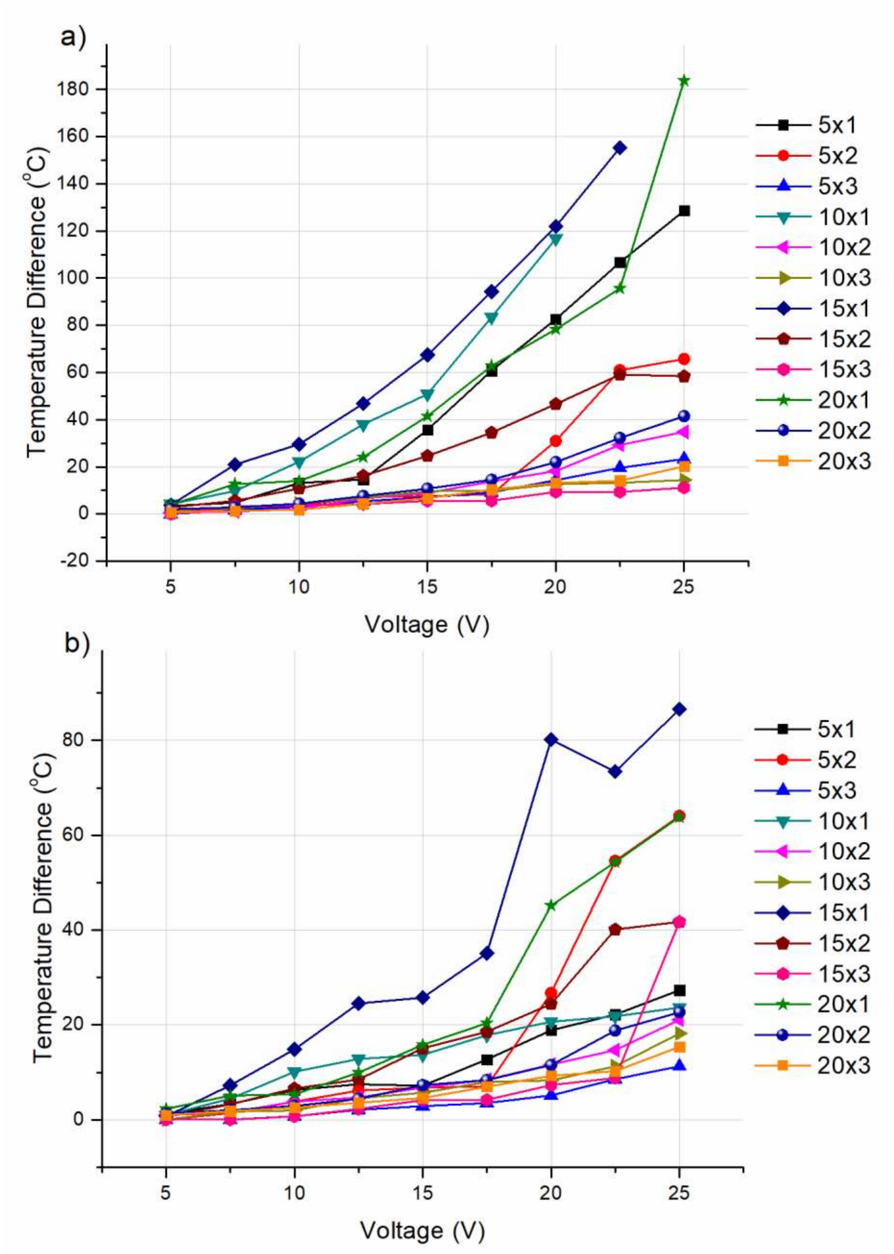

a)
Temperature Difference (°C)
Voltage (V)
b)
Temperature Difference (°C)
Voltage (V)
5x1
5x2
5x3
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10x3
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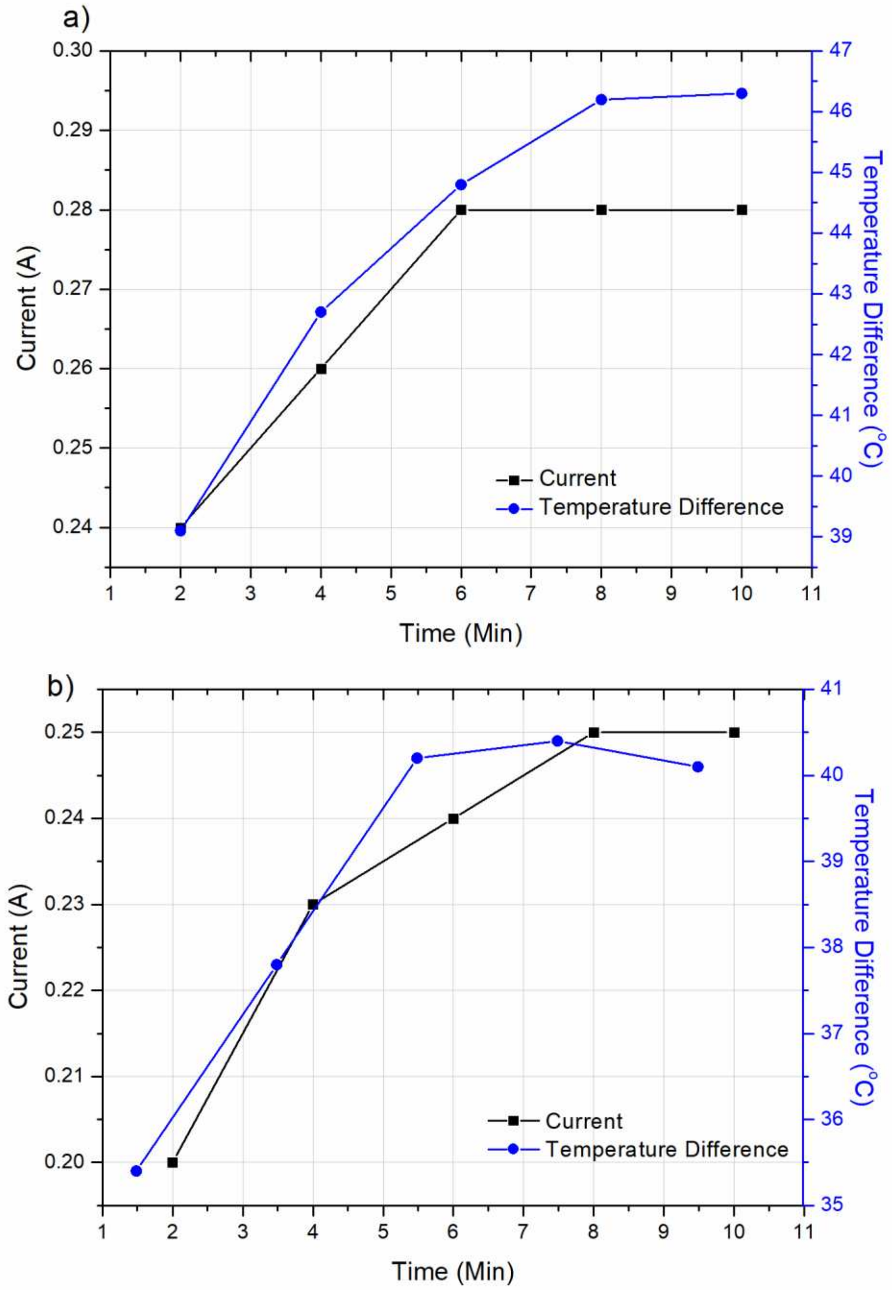
20x1
20x2
20x3


a)
0.30
0.29
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Current (A)
47
46
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44
43
42
41
40
39
Temperature Difference (°C)
Current
Temperature Difference
1 2 3 4 5 6 7 8 9 10 11
Time (Min)
b)
0.25
0.24
0.23
0.22
0.21
0.20
Current (A)
41
40
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38
37
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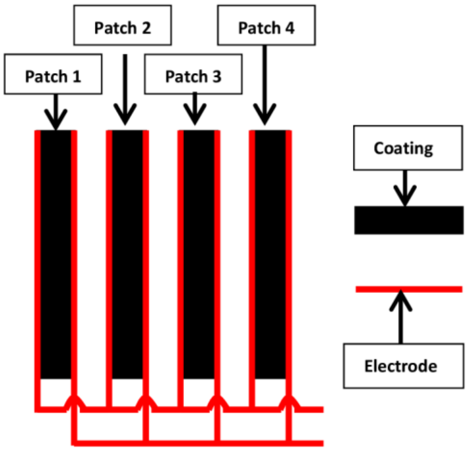
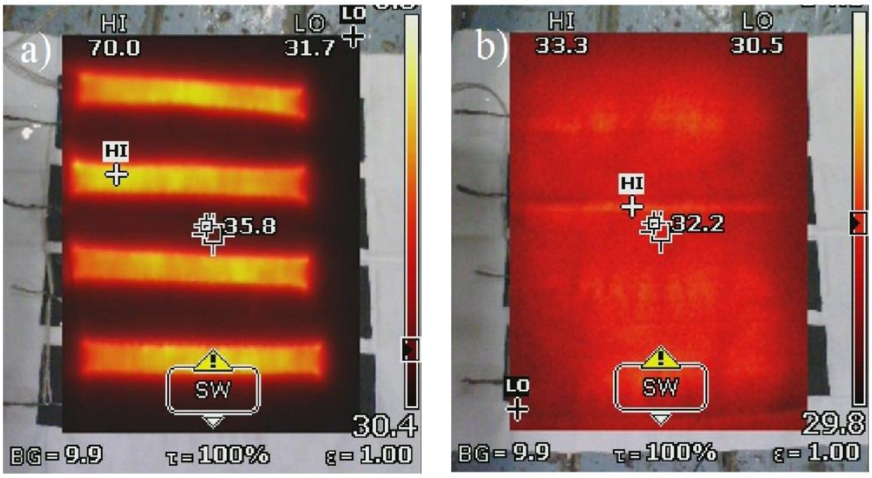
35
Temperature Difference (°C)
Current
Temperature Difference
1 2 3 4 5 6 7 8 9 10 11
Time (Min)


Patch 1
Patch 2
Patch 3
Patch 4
Coating
Electrode


a)
HI
70.0
LO
31.7
LO
HI
35.8
SW
30.4
BG=9.9
τ=100%
ε=1.00
b)
HI
33.3
LO
30.5
HI
32.2
LO
SW
29.8
BG=9.9
τ=100%
ε=1.00


Ready-made garment
Heater panel

Table I Current drawn by the prototype heater

Time (min)	Current Drawn (A)	
	At 20 volts	At 22.5 volts
0	0.42	0.48
1	0.46	0.52
2	0.48	0.55
3	0.48	0.56
4	0.49	0.57
5	0.50	0.58
6	0.51	0.58
7	0.51	0.58
8	0.51	0.59
9	0.51	0.59
10	0.51	0.59

Table II Temperature change achieved at each patch over time at 20 volts

Time (min)	Temperature change (°C) for individual patches							
	Patch 1		Patch 2		Patch 3		Patch 4	
	20 volts	22.5 volts	20 volts	22.5 volts	20 volts	22.5 volts	20 volts	22.5 volts
4	24.2	24.4	28.6	32.1	28.6	32.4	21.7	26.7
6	24.2	25.5	28.6	32.4	28.6	32.6	22.0	27.9
8	24.3	27.7	29.3	33.4	29.4	34.6	25.5	31.0
10	26.0	28.7	30.0	34.8	29.6	34.9	26.6	31.1

Electrically heated wearable textiles produced by conventional pigmented inks containing carbon black

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