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Influence of Screen Printed Layers on the Thermal Conductivity of Textile Fabrics

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Abstract
In the smart textile field the combination of textile and metallic materials is rising. In order to conduct electricity in textile, different methods are used. This paper deals with a new measuring method to determine the lateral thermal conductivity of a textile fabric. The technique starts by measuring the temperature distribution on the fabric using a thermographic camera. In addition to that, the method outlined in this paper will also allow to determine the change in thermal conductivity when an electric conducting layer has been screen printed on a textile fabric

Key words: *screen printing, thermal conductivity, textile, thermographic camera.*

Introduction

The four-point probe method is a flexible technique to measure the sheet conductivity of conducting layers [1].

Over recent years smart textiles have become popular as a concept. In order to manufacture these wearable textile systems, electroconductive textiles are needed. Electroconductive textiles can be achieved by using conductive fibres, yarn coatings, polymers or inks [1-9]. Applications are found in the medical field [10-12] for warning systems [13] and body heating [14]. The screen printing of conductive inks, a well-known technique in microelectronics to make hybrid circuits, has found use in many smart textile applications, such as radio-frequency identification (RFID tags), wiring boards, textile antennas, sensors, etc. [15-18].

Screen printing has the major advantage of being suitable for mass production. However, if one wishes to change the layout, new screens have to be made. Ink jet printing, on the other hand, is suitable for small quantities, and any change in the layout can be made through software. There is no need to adjust any equipment. Ink jet printing also offers the advantage that several new materials can be deposited on textile fabrics [19-21]. With screen printing it is mandatory that a printable paste be made first. As a consequence, the printed material is never 100 % pure and always contains a certain amount of solvents.

These conductive printed lines showed a rather high electric resistivity when silver inks were used during the screen printing process as compared to the bulk material [5].

Infrared thermography is rapidly gaining popularity amongst researchers in various fields like medicine, biology, material science, civil engineering, etc. Many researchers have explored the potential of infrared thermography to investigate several thermo-physical phenomena like heat transfer, measurement of thermal properties, non-destructive testing (NDT), greenhouse gas exchange and the diagnosis of diseases, as any process that leads to a variation in temperature of the object can be subjected to thermographic investigation [22]. In textile research infrared thermography is applied in different applications such as synthetic fibre spinning, clothing comfort, non-destructive testing of a composite, product development, mechanical property and failure analysis, thermal property analysis, heat transfer and drying [14, 23-24].

In this paper three different textiles were used, for which four conductors were screen printed with silver-based inks. In order to observe the thermal property and heat transfer, a thermographic camera was used, which showed that white textile has a higher value of heat transfer for all four conductors compared to dark textiles. To our knowledge, most papers dealing with the thermal conductivity of fabrics are limited to heat transfer in the direction perpendicular to the fabric. In this paper we are oriented towards lateral heat conduction in textiles [25].

Sample preparation

In this study two woven textiles were selected – Cotton/Polyester (33/67%) and Polyamide (100% PA). The physical and mechanical properties were determined by ISO standards and are listed in ***Table 1***.

The conductive ink for these textiles was provided by Henkel (***Table 2***), and the screen printed method was used [5].

The design has four lines of different width and a square as reference (***Figure 1***). In ***Table 3*** the parameters of the resistors are given

In order to analyse the thermal properties of the printed samples, a thermographic camera – FLIR T420 25° was used. The samples were hung and a current was supplied to each printed line separately from a DC power supply (EL301R Power Supply, Aim & Thurlby Thandar Instruments). The measurements were completed at room temperature. Each line was measured separately from the others. On each line two contacts were attached with electroconductive glue on both edges of the conductive sample, in order to have good electroconductive contact. The current supplied was increased from

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0.200, *0.500* to *1.050 A* and the voltage measured. To stabilise the temperature, the textile was left for 15 minutes, and then the temperature was recorded with the thermal camera. Data were collected for line *x* (recording line).

Figure 1 shows the schematic layout of the fabric used in our experiments. The fabric has a height $H = 23.7\ cm$ and width $W = 9.5\ cm$. Four resistors, R_1, R_2, R_3 and R_4, each with the same length but different width, were made by screen printing electric conducting ink on the fabric. In ***Figure 1*** the resistors are represented by the black areas. A small square shaped region was also printed as a reference for the thermographic measurements. At both ends, each resistor was equipped with a copper contact to supply the electric current. All thermographic recordings shown in this paper were made along the *x*-axis, passing through the middle of each resistor and the square-shaped region.

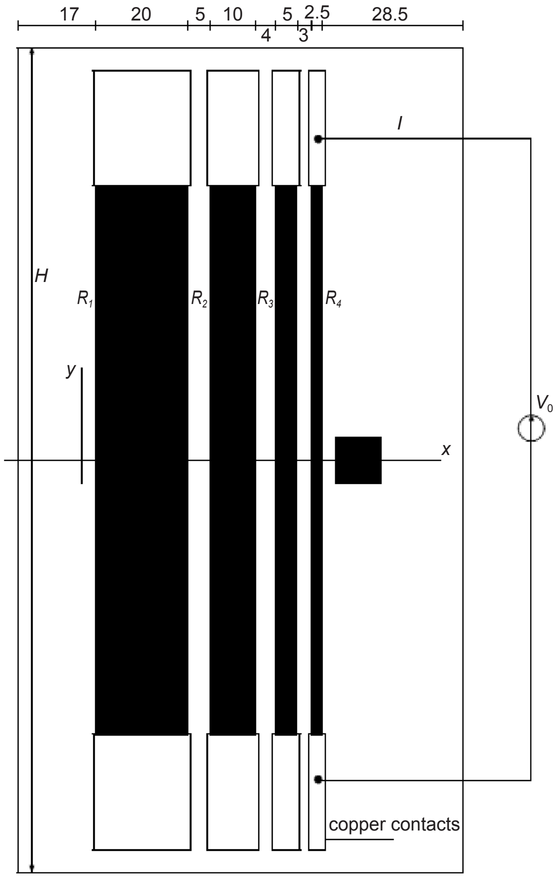

Figure 1. *Layout of the fabric with screen printed resistors (R_1, R_2, R_3 and R_4) and copper contacts. All dimensions in mm.*

Table 1. *Properties of textiles applied.*

Woven textile materials	Colour	Yarn density of fabric		Type of textile weave	Basic weight, g/m²	Specific heat, J/kg/K
		Warp, threads/cm	Weft, threads/cm			
Cotton/Polyester (CO/PES)	Dark blue	32	20	Twill 2/1	240	1166
Polyamide (PA)	White	45	32	Twill 2/2	99	1600

Mathematical model

First of all, a model will be presented which will enable us to calculate the temperature distribution in the fabric. By comparing these theoretical results with the experimental data, the thermal parameters of the fabric will be found, as will be outlined further on in this paper. More specifically, the thermal conductivity of the non-printed and printed parts of the fabric will be analysed.

Taking into account that the thicknesses of the fabric and screen printed conductors are much smaller than the other dimensions, the temperature distribution can be considered as being two dimensional: *T(x,y)*. Due to the fact that the heating resistors (R_1, R_2, R_3 and R_4) are much longer in the y-direction than in the x-direction, the problem can be further simplified to a one dimensional analysis (***Figure 1***). In other words, the temperature distribution depends only on *x: T(x).* Heat transfer is due to thermal conduction in the fabric and screen printed conductors. The fabric was hung vertically during the experiments so that both sides were cooled equally. From the front and rear side of the fabric, heat will be released by convection to the ambient air and by radiation to the surrounding solid objects. The heat transfer equation is then given by ***Equation (1)***.

$$kt_s\frac{d^2\Delta T}{dx^2} - 2h\Delta T = -p \qquad (1)$$

where: *k, W/m K* – is the thermal conductivity; t_s, *m* – the thickness of the fabric; *h*, $W/m^2\ K$ – the total heat transfer coefficient to the ambient; ΔT is the temperature rise above the ambient; *p*, W/m^2 is the heat generation in the screen printed resistor per unit area.

It was assumed that the ambient air and all surrounding objects are at the same temperature, the value of which is used here as the reference temperature $\Delta T = 0$. Factor 2 in ***Equation (1)*** is due to the fact

Table 2. *Properties of silver-based conductive ink applied.*

Ink type	Ink 1
Solid content, %	65
Cure condition, 120 °C	15 minutes
Sheet resistance, Ω/sq/25 μm	<0.030

Table 3. *Parameters for the silver conductive screen printed samples.*

	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8	l_9
Pattern	20	5	10	4	5	3	2.5	3	10
Textile 1 (CO/PES)	20.5	4.5	11	3.5	6	3	3	2.5	10
Textile 2 (PA-1)	20	4.5	10.5	3.5	5.5	3.5	2.5	3	10
Textile 3 (PA-2)	20	4.5	10.5	3.5	5.5	3.5	2.5	3	10

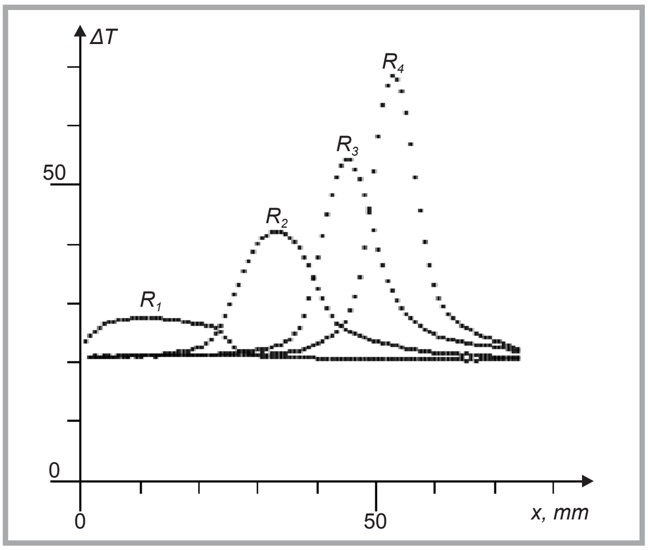

***Figure 2.** Temperature plots when R_1, R_2, R_3 & R_4 are heated, respectively.*

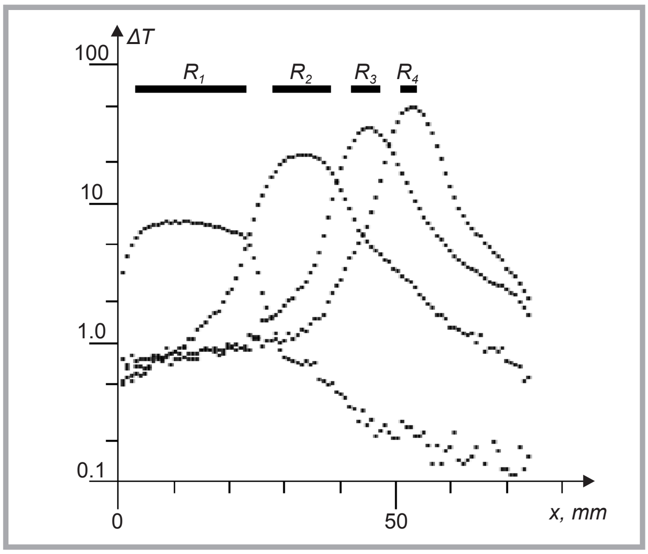

***Figure 3.** Semi logarithmic plots of the temperature rise above ambient.*

that both sides of the fabric are cooled equally.

The two dimensional model ***Equation (1)*** assumes implicitly that the fabric is a homogeneous material, which is never the case for a textile fabric made by weaving or knitting. Hence the thermal conductivity *k* should be interpreted as an average value, usually lower than the thermal conductivity of the bulk material the yarns are made of.

During all the experiments, only one resistor was powered, so that $p = 0$ everywhere outside the heated one. If $p = 0$, ***Equation (1)*** can be rewritten as:

$$\frac{d^2\Delta T}{dx^2} - \frac{\Delta T}{L^2} = 0 \qquad (2)$$

where *L* is the characteristic length, given by:

$$L = \sqrt{\frac{kt_s}{2h}} \qquad (3)$$

The most general solution of ***Equation (2)*** is given by:

$$\Delta T = Ae^{-x/L} + Be^{+x/L} \qquad (4)$$

where *A* and *B* are two integration constants to be determined by the boundary conditions. If we consider only the part on the right side of the heating resistor, it turns out that:

$$\Delta T = Ae^{-x/L} \qquad (5)$$

is the dominant term, and consequently *B exp(x/L)* can be neglected. On the left side of the heating resistor the opposite conclusion will hold: *B exp(x/L) >> A exp(-x/L)*. In order words the temperature drops exponentially if the observation point moves away from the heat source.

As we are mainly interested in the measurement of thermal conductivity of the fabric (or fabric with a screen printed layer), the exact values of *A* and *B* are not required to determine the thermal conductivity. On the other hand, knowledge of the characteristic length *L* is sufficient to provide the value of thermal conductivity due to ***Equation (3)***. Of course, one needs to know the value of the heat transfer coefficient *h,* which will be outlined in the next section.

The exponential function in ***Equation (5)*** suggest that a plot of *ΔT(x)* vs. *x* on a semi logarithmic scale will be represented as a straight line, the slope of which being *1/L*. Further on in this work, this statement will be verified experimentally.

Determining the global heat transfer coefficient h

During the experiment, fabric with dimensions *23.7 x 9.5 cm²* was hung vertically. Heat losses to the ambient occurred in two ways: natural convection cooling to ambient air and by radiation to all surrounding solid objects (walls, ceiling etc). Natural convection means that no fan cooling was applied here. Consequently the heat transfer coefficient is then the sum of two components:

$$h = h_c + h_r \qquad (6)$$

where h_c and h_r denote the heat transfer coefficient due to convection and radiation, respectively.

For a vertical plate of height *H*, the following correlation can be found in several textbooks about natural convection cooling [26]:

$$h_c = 1.485\left[\frac{\Delta T}{H}\right]^{1/4} \qquad (7)$$

where *ΔT* is the temperature difference between the plate (fabric in our case) and ambient air. *H* has to expressed in *m (H=0.237 m).* For a typical value of *ΔT*=20 we obtain the value $h_c = 4.51\ W/m^2 K$.

Regarding the heat transfer coefficient by radiation, the following formula is used [26]:

$$h_r = 4\sigma T_0^3 \qquad (8)$$

where $\sigma = 5.6703\ 10^{-8}\ W/m^2\ K^4$ is the Stefan Boltzmann constant. and T_0 is the absolute ambient temperature expressed in Kelvin ($T_0 = 273 + 20 = 293\ K$). We then obtain the value $h_r = 5.70\ W/m^2\ K$.

The global heat transfer coefficient h is then found to be [27]:

$$h = h_c + h_r = 4.51 + 5.70 = 10.20\ \frac{W}{m^2K} \qquad (9)$$

It must be remarked here that the fabric was intentionally hung vertically in all our experiments, because coefficient h_c can then be evaluated accurately. If the fabric had been put on a table, the value of h_c would not have been so easily known and the heat transfer by conduction through the table would have been difficult to estimate as well due to the unpredictable thermal contact resistance between the fabric and table.

Experimental results

A lot of experiments were carried out, all of which gave similar results. Hence we will only provide here the results for a polyamide substrate, the thermographic temperature plots of which recorded are shown in ***Figure 2***.

At first, it is noted that the maximum temperature is much higher for the thinnest resistor R_4. This is simply due to the fact that the power density per unit resistor area was higher for the smaller resistors.

Figure 3 displays the same results as ***Figure 2***, but this time the temperature rise above the ambient ΔT is shown, and a logarithmic scale is used. This was done in order to verify theoretical formula ***Equation (5)*** more easily. Indeed, on a semi-log scale, exponential function ***Equation (5)*** will be represented by a straight line. A closer look at ***Figure 3*** reveals that several parts of the experimental graphs can be very well fitted to a straight line. It should be noted that these fittings can only be applied outside the heated resistor, which is due to fact that ***Equation (5)*** is a solution of ***Equation (2)*** but not a solution of ***Equation (1)*** as long as $p \neq 0$.

In ***Figure 4*** only the curve corresponding to the heating of the thinnest resistor R_4 has been drawn. Several parts can be fitted quite well to straight lines so that a good fit with ***Equation (5)*** can be performed. If one proceeds from the heated resistor R_4 towards the left (***Figure 1***), the first region shows a slope corresponding to a constant length of $L = 2.71$ *mm*. Further on, in the screen printed region of the not heated resistor R_3, a good fit is obtained with $L = 5.42$ *mm*. The different slope values can only be explained by a change in thermal conductivity. If the non-printed textile has a thermal conductivity k and the screen printed part k_{ink}, we obtain from ***Equation (3)***:

$$\frac{k_{ink}}{k} = \left[\frac{5.42}{2.71}\right]^2 = 4 \qquad (10)$$

It means that the lateral thermal conductivity (i.e. parallel to the fabric) is increased 4 times due to the screen printed layer. This is not surprising because the screen printed electric conducting ink contains silver and carbon particles, which enhance both the electric and thermal conductivity.

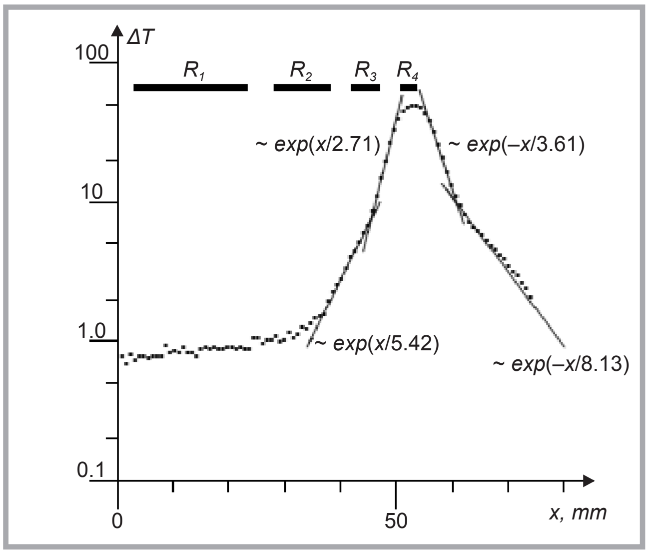

Figure 4. *Semi logarithmic plot of the temperature rise due to the heating of* R_4*. Fittings and corresponding exponential functions are shown.*

If one proceeds to the right, starting from resistor R_4, a good fit is obtained with $L = 3.61$ *mm*. This value is different from what is found on the left side, although both sides were not screen printed. This difference in characteristic lengths (*2.71 mm vs. 3.61 mm*) is due to the fact that a textile fabric is not a homogeneous and uniform material from the thermal conduction point of view. A woven structure has a lot of very small air cavities between neighbouring yarns in both the warp and weft directions. Even a small difference in yarn density may give rise to larger or smaller air cavities, which influences the average thermal conductivity. If one proceeds further on towards the right, once again a screen printed region is obtained give a good fitting with $L = 8.13$ *mm*. This time we get:

$$\frac{k_{ink}}{k} = \left[\frac{8.13}{3.1}\right]^2 = 5.07 \qquad (11)$$

which is also different from the previous value of *4*. Again the non-uniformity of textile fabrics is responsible for this result. If there is a bit more free space among neighbouring yarns, more ink can be pressed in these air cavities by a squeegee during the screen printing process.

Further away from the heated resistor *R4, i.e.* $0 < x < 35$ *mm* (***Figure 4***), fitting with a straight line is no longer possible. The reason is the small temperature rise ΔT (< 1 K), which is dependent upon the accuracy of the thermographic camera. It must be emphasised here that we are dealing with temperature differences ΔT. The thermographic camera records the temperature along the x-axis, then the temperature at a point far away from the heat source is measured as well and treated as the reference room temperature. The latter value is then subtracted from the recorded values. This explains why the accuracy drops dramatically as soon as one is dealing with a temperature rise below one degree.

In ***Equation (9)*** we calculated the value $h = 10.2$ *W/m²* for the heat transfer coefficient. From ***Equation (3)*** we can then evaluate the thermal conductivity by:

$$k = \frac{2hL^2}{t_s} \qquad (12)$$

For $L = 2.71$ *mm* e.g. we get $k = 0.074$ *W/m K*. This value is less than the thermal conductivity of polyamide fibres – *0.24 W/m K*. This result is obvious because we are measuring the thermal conductivity of a fabric not of a single yarn. A fabric is made of yarns, but in between them there is a lot of empty space filled with still air, giving rise to a lower thermal conductivity. If we use the value $L = 5.42$ *mm* for the screen printed region, we get $k_{ink} = 0.296$ *W/m K*. This higher value is due to the electric conducting ink which was screen printed on the fabric. The ink fills the air gaps between yarns and, moreover, the silver particles in the ink also enhance the thermal conductivity.

Conclusions

In this paper a method has been presented to measure the thermal conductivity of a fabric. The method is based on the use of a screen printed resistor which is heated by an electric current. The temperature distribution next to this resistor is recorded with a thermographic camera, which is then compared with the theoretical one, providing us with the thermal conductivity of the fabric in the lateral direction.

The thermal conductivity of a fabric turns out to be less than the conductivity of the bulk material the yarns are made of. It was observed that the screen printed layer enhances the thermal conductivity of the fabric. ❏

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