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ANALYSIS OF THE EFFECT OF FABRIC STRUCTURE AND APPLIED VOLTAGE ON THE HEAT FLUX OF THE THREE-LAYER HEATING FABRICS

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Abstract: *In recent years, the use of electrical heating garments was dramatically intensified because of their wide range of application in different industries. One of the common ways to produce these textiles is integration of heating elements in fabric. Taking into account this conditions, in this research 8 groups of three-layer heating fabrics were produce using different weave pattern on the front and back layers, two levels of weft to heating element ratio and two warp ratio of back and front layer. The mentioned three layer fabrics were warp stitched woven fabrics in which the heating element (tungsten) was embedded in the middle layer as wadded weft. In order to report the heat performance of fabrics, thermal parameters such as the heat flux under two different voltages and at different sides of the fabrics were evaluated by using flux meter sensor. Moreover, this sensor was situated at different positions in relation to the fabric, in order to simulate various functional conditions of the heating fabric. According to the results, the voltage, ratio of weft to element and ratio of warp yarns in front and back layer, had significant influence on the measured heat flux. On the other hand, the weave pattern and technical side of the fabric did not have significant effect on the heat flux.*

Key words: *Heat Performance, Voltage, Thermal Behaviour, Fabric Structure, Tungsten Heating Element*

1. INTRODUCTION

Recent growth in the field of wearable electronics, have abounded new areas of application such as health care, defense and ergonomic monitoring. Meanwhile, much focus has been shifted toward electrical heating garments. The aim of using electrical heating textiles is to produce heat for the wearer. These textiles usually contain sensors, activators, data processors, energy source and user interface [1, 2]. There are many research works going on in the field of electrical heating garments, in past few years. Muthukumar et al. (2019) designed and developed electric heating fabrics by copper wires in weft and acrylic yarns in warp, which can be used with a minimum power supply in order to obtain a wearable system [3]. Nazem Boushehri et al. (2019) fabricated a three-layer heating fabric and measured the rate of increasing temperature and found the best element type in order to be used in these fabrics [4]. Park et al. (2016) investigated the influence of the distance of heating unit from body in multilayered winter clothing system on heating efficiency. It was found that the closeness of the heating unit to the skin would result in higher heating efficiency of electric heating clothing [5]. Neves et al. (2015) used a numerical approach to study the heat transport through a blanket with an embedded smart heating system. In this research it was revealed that to ensure an optimal comprise between the thermal performance of product and temperature of the surface, the distance between the wires should be small [6]. Hao et al. (2012) presented an improved fabrication method for the flexible heating fabrics which were developed by silver filaments or coated silver yarns. In this regard, the resistance thermostability and extreme load current of various conductive materials were analyzed to present the best conductive material to be utilized in the mentioned fabrics [7]. Kayacan et al. (2009) developed electric heating pads using steel fabrics and investigated the heat generation. It was found that power supply, size of pads, number of plies and amount of conductive yarns are the most important parameters that affect the heating performance of electrical heating textiles [8].

In this research it is intended to study the influence of fabric structural parameters and also the amount of exerted voltage on the heat flux of the woven three-layer heating fabrics.

2. EXPERIMENTAL

2.1 Sample preparation

Eight kinds of three-layer warp stitched woven fabrics were designed and produced on a handloom machine with 8 shafts, in the way that the front layer and back layer fabrics consisted of two kinds of weave patterns (Twill 2/2 and Plain) and the tungsten heating element were embedded in the middle layer as wadded weft. Moreover, the presence of heating element in the fabric structure had two conditions of 6 and 12 (for example after 6 weft yarn insertion, 1 heating element was embedded). In addition, there was two different ratios of warp yarn in back and front layer. In four groups of the fabrics, the number of warp yarns in both layers were the same (1:1) and in the other groups this ratio was 1:2. The specifications of the three layer woven fabrics are shown in Table 1.

Table 1: *fabrics specifications*

Sample No.	Weight (g/m^2)	Thickness (mm)	Weave pattern “Front Layer”	Weave pattern “Back layer”	Element ratio to weft	Ratio of warp yarn in front to back layer	Weft density (cm^{-1})
1	578.13	3.03	Twill 2/2	Twill 2/2	6	1	48.9
2	517.47	2.48	Twill 2/2	Plain	6	1	38.8
3	542.28	3.16	Twill 2/2	Twill 2/2	12	1	45
4	513.23	3.03	Twill 2/2	Plain	12	1	39.8
5	473.96	2	Twill 2/2	Twill 2/2	6	2	25.5
6	475.97	1.88	Twill 2/2	Plain	6	2	24.7
7	462.53	1.97	Twill 2/2	Twill 2/2	12	2	23.9
8	462.87	1.96	Twill 2/2	Plain	12	2	23.5

As an example, the weave pattern, drafting plan and the peg plan for weaving of the sample No. 4 is shown in Figure 1. It is necessary to mention that the heating element insert after 6 or 12 weft. All the samples were woven using 24/2 Nm Acrylic yarns for both weft and warp yarns of the front and back layers.

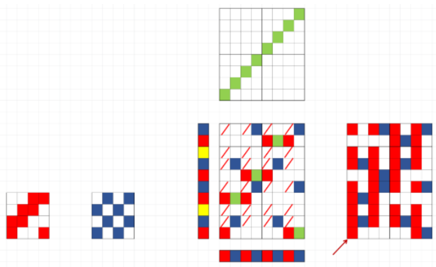
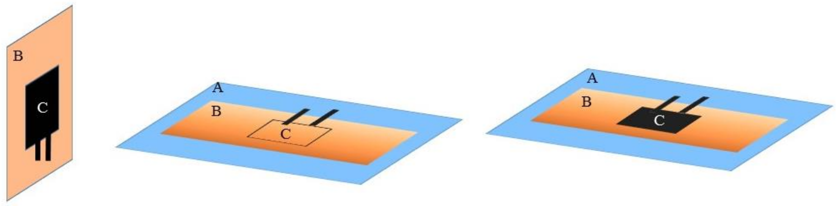


Fig. 1*: The weave pattern, drafting plan and the peg plan of sample No. 4*

In order to evaluate the heating performance of three-layer heating fabrics such as the maximum heat flux and maximum temperature, the heating sensor (FHF02SC) which had the ability to measure both temperature and heat flux at the same time, was utilized. The mentioned sensor was laid out in 3 different positions relative to the fabrics, as shown in Figure 2. In this figure (a, b and c) are insulation area, heating fabric and heart flux sensor respectively.



Beside hanging fabric *Under the fabric* *Above the sample*

Fig. 2*: Schematic of position of sensor related to the fabrics*

Three positions flux-meter with regards to the heating fabrics are:

- Positioning of the sensor on the three-layer heating fabric which is situated on an insulated surface
- Positioning of the sensor below the three-layer heating fabric (between the fabric and an insulated surface)
- Positioning of the sensor on a hanging fabric

The main reason to conduct this experiment was to find out the performance and heat loss of heating fabric in different situations.
The output value of the sensor is voltage and the maximum heat flux is calculated according to the following equation:

$$S = 5.95 \times 10^{-6}\, V \qquad \textbf{(1)}$$

Where V is the voltage (mV) and S is the amount of heat flux passing through the sample (W/m^2) and 5.95 is the specific coefficient related to the heat flux sensor.

3. RESULT AND DISCUSSION

3.1. Heat flux of heating fabrics

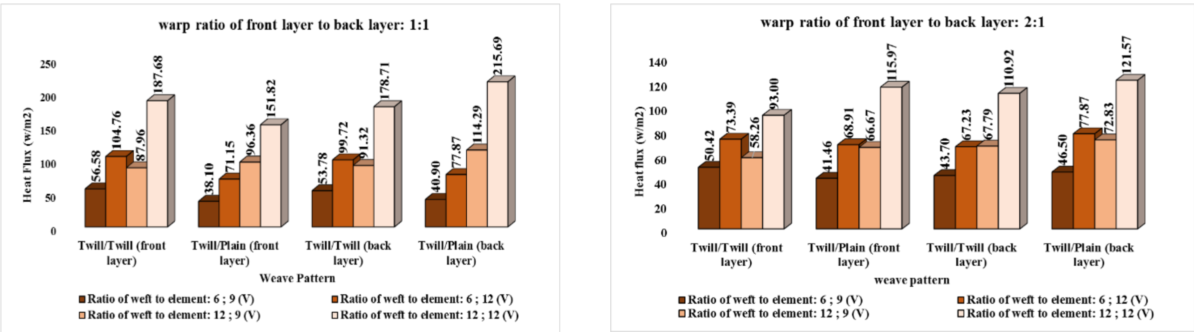
Heat flux of electrical heating fabric is one of the most important features of these textiles. In this regard, the heat flux of woven fabrics was measured under two voltages of 9 (V) and 12 (V), in different positions of sensor against the fabrics. The amount of maximum heat flux in the samples are gathered in Table2.

Table 2: *Maximum heat flux (W/m^2) in three different positions of sensor*

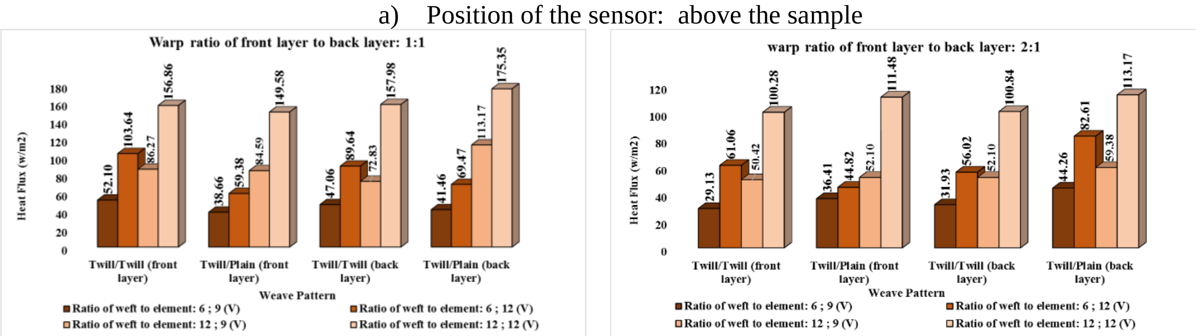
Sample No.	on the hanging fabric				under the sample				above the sample			
	Back layer		Front layer		Back layer		Front layer		Back layer		Front layer	
Voltage (V)	12	9	12	9	12	9	12	9	12	9	12	9
1	111.5	58.82	120.4	76.19	89.64	47.06	103.6	52.1	99.72	53.78	104.7	56.58
2	85.71	49.30	71.15	40.34	69.47	41.46	59.38	38.66	77.87	40.9	71.15	38.10
3	187.1	97.48	177	103.08	158	72.83	156.9	86.27	178.7	91.32	187.7	87.96

4	177.6	92.44	181	95.80	175.4	113.2	149.58	84.59	69.22	114.3	151.9	96.36
5	75.63	42.58	76.19	43.14	56.02	31.93	61.06	29.13	67.23	43.7	73.39	50.42
6	74.51	42.02	75.07	43.14	82.61	44.26	44.82	36.41	77.87	46.50	68.91	41.46
7	113.8	59.94	118.3	71.15	100.9	52.10	100.3	50.42	111	67.79	93	58.26
8	123.8	66.67	129.4	80.11	113.2	59.38	100.9	52.1	121.6	72.83	116	66.67

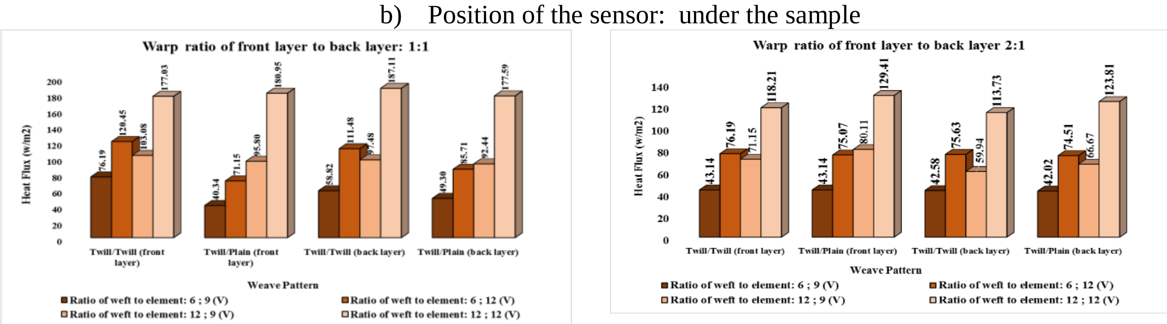
The results of the maximum heat flux are shown in Figure 3. As the plots demonstrates, the heat flux of samples subjected to 12V voltage had higher heat flux, compared to the heated samples exposed to the voltage of 9V. Moreover, the samples that were woven by ratio of weft to element 12, presented higher heat flux in comparison to the samples woven by ratio of weft to element 6, because the same voltage was applied to shorter length of tungsten heating element. According to the result, the measured heat flux in samples woven with the warp ratio of front layer to back layer 2:1 was lower than other samples. This phenomenon occurred because of the different weft density of the mentioned fabrics as shown in Table 1.



a) Position of the sensor: above the sample



b) Position of the sensor: under the sample



c) Position of the sensor: on the hanging sample

Fig. 3*: The maximum amount of heat flux in different positions*

After measuring the heat flux of woven fabrics and investigation the effect of fabric structure on maximum heat flux, an ANOVA statistical analysis was performed at 95% confidence range. The result of statistic test is shown in Table 3.

Table 3: *Statistical analysis of maximum heat flux*

	P-Value				
	Warp yarn ratio of each layer	Weave pattern	Ratio of weft to element	Technical side	voltage
Above sample	0.000	0.877	0.000	0.629	0.000
Under sample	0.000	0.208	0.000	0.184	0.000
Beside hang out sample	0.000	0.054	0.000	0.424	0.000

As the results show, warp yarn ratio of each layer, ratio of weft to element and voltage have significantly affected the maximum heat flux. Also it could be concluded that the weave pattern of each side of the fabric and also the technical side did not have significant impact on the maximum heat flux.

In the next step, in order to classify the position of heating sensor against the fabric, statistical analysis of results using the ANOVA test and the post hoc Duncan test was conducted (significance level $\alpha=0.01$). The outcome of the Duncan test is presented in Table 4. According to the results, the testing condition in which the sensor was positioned above the sample or on the hanging sample, were categorized in the same group. Because of the presence of the insulating surface under the fabric, whenever the sensor was situated under the fabric, the measured heat flux was at the minimum level.

Table 4: *Statistical analysis on maximum heat flux*

Duncan Test			
Position of the sensor	N	Subset	
		1	2
Under	96	79.7395	
Hang out	96		91.2011
Above sample	96		92.5030
Sig.		1.000	0.666

On the other hand, when the sensor was positioned above or on the hanging fabric, the heat loss occurred from both sides of the sample. Therefore, the heat transfer from the sample to the environment was greater. It should be noted that, in addition to conductive heat transfer, due to the presence of air flow around the sample, a portion of heat was also transferred to the environment by means of convective heat loss process. Thus, the overall heat flux in these two states was greater than the state that the sense was placed under the sample.

4. CONCLUSION

In this study, eight groups of three-layer warp stitched woven fabrics with tungsten heating elements, two kind of weave patterns in each layer, two kind of heating element density and two different warp ratio of front to back layer were designed and produced. After the production of fabrics, the effects of fabric structural parameters and the applied voltage to the heating system were investigated on the heating performance of the fabric. According to the results the highest amount of heat flux was obtained in case of application of the voltage 12 (V) to the fabric with the weft to element ratio of 12, which means that the combination of shorter length of the wire and higher voltage produces the maximum heat flux. Moreover, from statistical point of view, these parameters have significant effect on the heat flux. Different ratios of warp yarns in front and back layer affects the construction and the consequent porosity of the fabric. Therefore, this parameter statistically has affected the maximum heat flux passing through the fabric. Another result was that the weave pattern and technical side of the fabric did not affect the heat flux, considerably. Finally, the position of the sensor against the three-layer heating fabric influenced the measured heat flux significantly in each situation. The mentioned result is an indication to the fact that thermal performance of fabrics is different in various environmental conditions.

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