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Knitted Heating Mats

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Abstract
The paper deals with conceptual designs and research on flexible knitted heating mats differing in construction from textile heaters on low-elastic woven or nonwoven-foil substrates. Two variants of heating mats with elasticity from 100 to 300 % of relative elongation were designed and manufactured using knitting technology. The heating elements of the mats were parallel-connected sets of electrically conducted carbon threads and synthetic threads coated with silver. With considerable elongation in the range of 210÷270 % no damage was observed to the heating elements and resistance changes during the stretching process equaled from 0.015 to 0.22 Ω/% of elongation. The optimum power of the knitted heater in the range from 16 to 41 W, with high thermal efficiency for a 12 V supply voltage, was obtained thanks to proper density of the electrically conductive threads (resistors) and the appropriate structure of the knitted fabric. The surface temperature of the heater can be adjusted from 34 to 43 °C, which corresponds to human thermal comfort. One of the variants of the knitted heaters was applied in the construction of the seat and backrest of an office chair.

Keywords
knitted heating mats, electroconductive threads, weft knitted fabrics, warp knitted fabrics, specific resistance, heating power.

1. Introduction

The issue of new textronic solutions in the field of smart materials includes, among others, electrically conductive textiles with specific functional characteristics [1,2,3,4]. The basic task of electrically conductive textiles is to carry electrical charges. Such textiles are often used to connect electronic and electric circuits, in the construction of shields protecting against electromagnetic radiation, as well as in heating elements, sensors etc. The characteristic property of such textiles is their conductivity and ability to carry electrical current [5,6]. The authors of various studies on electrical and electronic textiles present a number of possible applications based on woven fabrics, nonwovens or polymeric films [1,9].

In the scientific works presented in the area of textronics, J. Leśnikowski [7] positively verifies the thesis concerning the possibility of constructing a textile signal line with an impedance of 50 Ω on a woven fabric substrate. Analysis of the electro-conductive properties of textile anisotropic structures was carried out by M. Tokarska in her post-doctoral dissertation entitled "New approach to the assessment of electro-conductive properties of textile anisotropic structures" [8], which demonstrates the effectiveness of the Van der Pauw method for determining the surface resistance of electrically conductive fabrics. Fibrous materials with low longitudinal extensibility of a few percent are often used in the construction of textronic products, although most authors emphasize that modern textronic objects should be characterized by considerable flexibility, which facilitates their modifications and adaptation of the material to variable service conditions [1]. Publications entitled: "Textile Heating Elements with Electro-conducting Yarns, Evaluation of Their Properties. Woven heating elements" by J. Andrysiak, K. Sikorski, I. Frydrych [10] and "Intelligent textiles - overview of applications - part II" by W. Bendkowska [11] describe various solutions used in textile heating systems applied in sportswear (company Columbia), clothing for emergency workers (Gorix, USA), dive suits and car seats (Klan, Italy). An interesting solution is a fabric with heating properties manufactured by the Textile Research Institute in Lodz (Poland) in which the wefts are continuous metal yarns with a linear density of 110 tex, elongation of 1 %, and average linear resistance of 71 Ω/m [10]. Given the current state of the art in the area of smart textiles, the scientific goal was to develop design assumptions, verify the technology, and to present the results of preliminary studies on the functional characteristics of ***highly flexible knitted radiators***.

The main objective determined two basic areas of research. The first one was experimental recognition of the possibilities of manufacturing knitted fabrics with an intended and programmable output of generated heat. The second task comprised developing the concept and design of a highly flexible heating knitted fabric, together with the implementation of the project and describing the dependence of the fabric electrical parameters as a function of its stretch (elongation).

2. Knitted heating mat

In order to realize the first target, a functional knitted fabric was designed, to be used as a heating mat [12]. The mat is built of a double faced weft-knitted

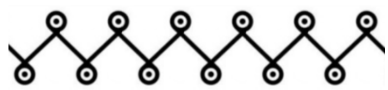

Fig. 1. Diagram of 1×1 rib stitch used in the construction of the heating mat

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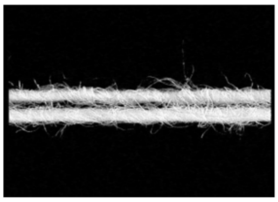
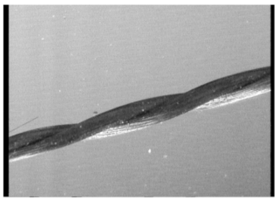
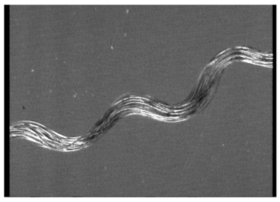
a) Threads parameters.

			
Cotton double thread of the type "wigonia", with linear density of 18 tex, dielectric	*Elastomeric core-spun thread braided with 6.6 polyamide with linear density of 78 tex, dielectric*	*Double carbon thread with linear density of 134 tex, linear resistance: R = 216 Ω/m*	*Polyamid thread 6.6 coated with silver, 99% purity, trade name Shieldex (company Statex Production & Vertriebs GmbH), with linear density of 11 tex 34 Z, 100 HT + B, linear resistance: R = 2 kΩ/m, [13,14]*

b) Mechanical characteristics of the threads.

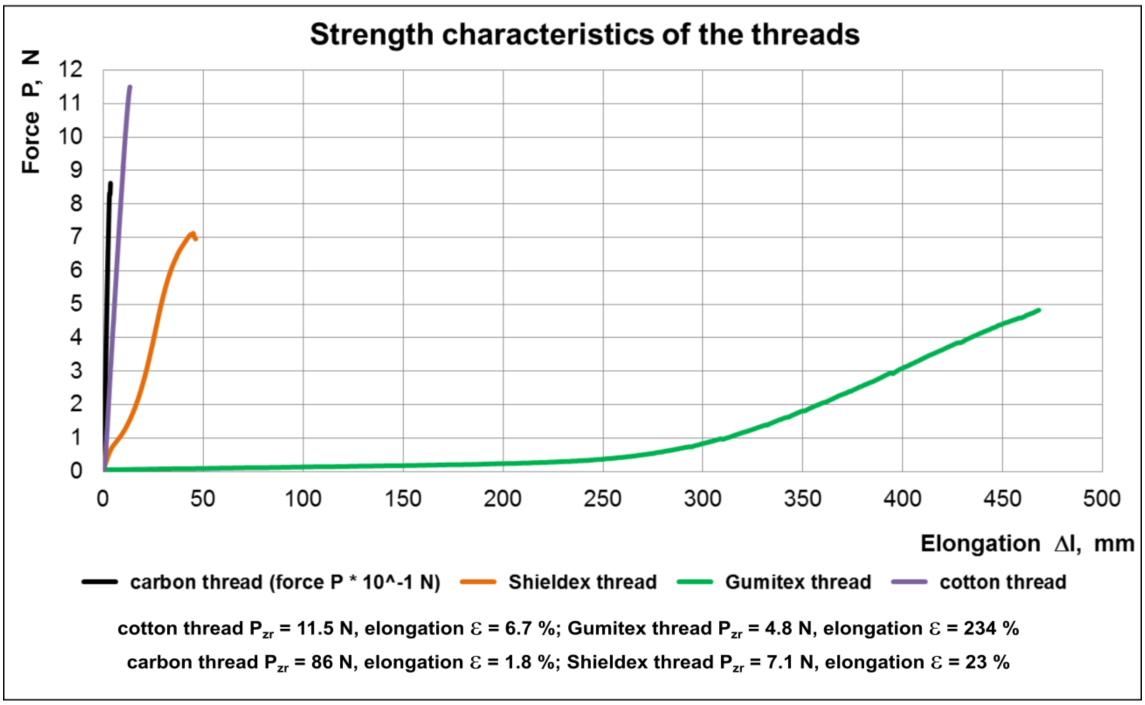


Fig. 2. Characteristics of the threads used for manufacturing knitted fabric

fabric with a 1×1 repeat (Fig. 1), made on a flat rib knitting machine with E5 gauge. The fabric contains alternating strips made of cotton and carbon fibers, the characteristics of which are shown in Fig. 2. The flexibility of the stitch facilitates the fitting of the fabric to the usable area, as the main applications of the mat are primarily in car seats and office chairs, as well as in specialized and rehabilitation chairs.

The cotton part of the mat forms a passive area and consists of a total of 170 courses (Fig. 3). The mat is made of 34 courses (6.8 cm high) at the bottom, 96 courses (19.2 cm) in the middle section and 35 courses (7 cm) at the top. The carbon part is the proper heating area. 13 strips made of carbon fibers containing 5 courses each, of a total height of 13 cm were connected to each other in a parallel circuit.

In the electrical circuit designed, a laboratory power supply is the source of direct current, strips of a knitted fabric made of carbon fibers serve as the electrical receiver, while insulated laps of carbon yarns are the wires connecting the current source to the receiver.

Supplying power to the whole set of carbon strips (Fig. 4a) or only to some of them (Fig. 4b) allows to adjust the temperature of the mat. Because of the odd number of carbon strips, in mat variant M1b, the first two strips are joined together, while the rest are connected every second one. Application of a special two-stage switch cuts off the current flow to the heating elements in case of selective work of the resistors, which increases the resistance and decreases the current intensity. As a result, the mat has lower heating temperatures.

A huge advantage of the parallel connection used while joining the strips is the continuity of current flow through the conductor even when one of the stripes is damaged.

In the case of a serial connection, any damage to a single carbon strip would cut off the current flow through the remaining strips and, as a result, the mat would no longer function.

The yarns used to manufacture the knitted fabric were not chosen randomly. A cotton yarn with linear density of 118 tex is characterized by moderate resistance to high temperatures and does not conduct electricity. Within the working temperature of the mat (max. 60 °C), cellulose fibers will perform well as separators of carbon strips. A yarn made of carbon fibers with a linear density of 134 tex was used as a heat generator because of good electrical properties of the fibers.

Table 1 presents brief characteristics of the M1 heating mat. The supply voltage of the mat is fixed at a constant level of 12 V. The M1a variant has higher current intensity, therefore the power of the system is also higher, compared with the M1b variant of the mat.

Characteristics of M1 heating mat	
Supply voltage	12 V
Power	32 W for full powering of the strips, 16 W for selective powering
Maximum heating temperature	60 °C
Mat dimensions	470×300 mm
Additional information	The upper „patches" enable fastening the mat to the seat or back-rest

Table 1. Characteristics of M1 heating mat

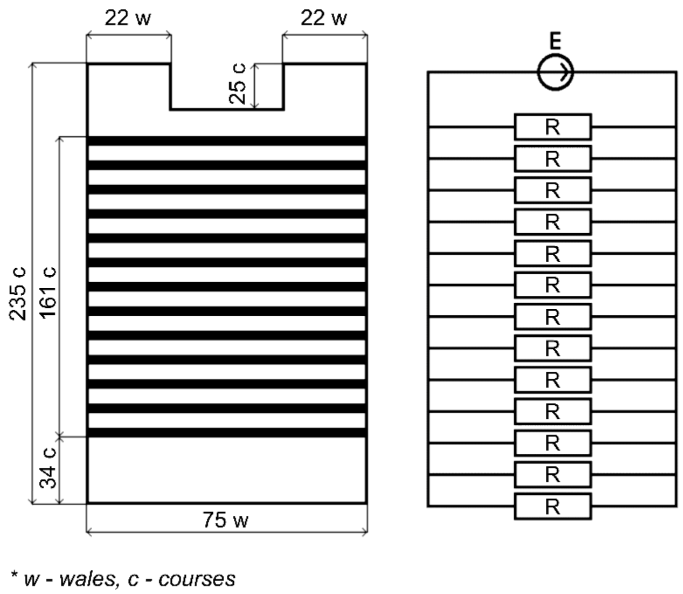


Fig. 3. Schematic diagram of heating mat M1 and parallel connection of resistors

2.1. Optimization of the construction of the heating mat

Optimization of the construction of the mat was based on selecting the electrical and structural values in such a way that the temperatures of the mat fell within the limits of human physiological comfort.

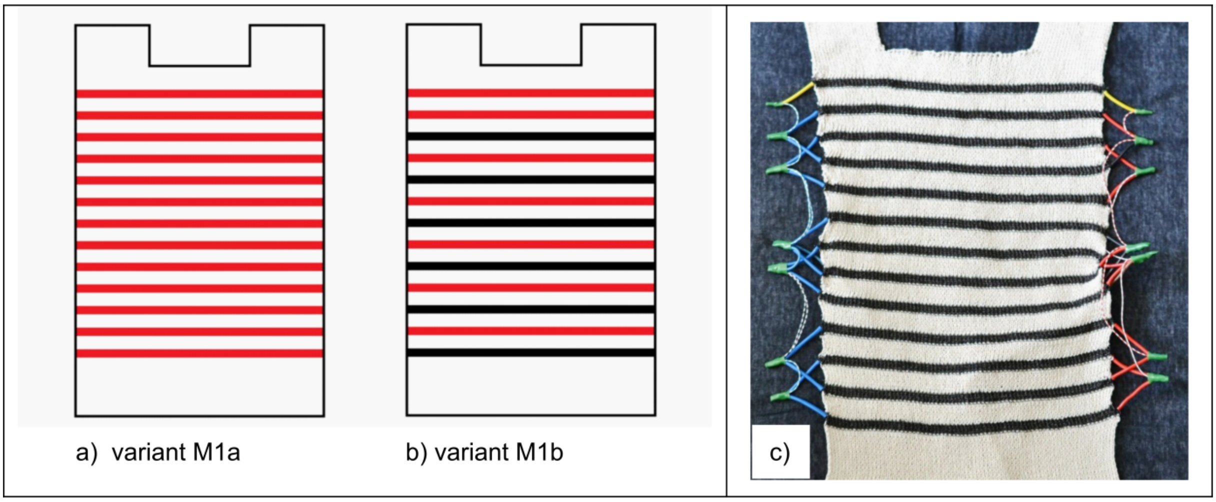


Fig. 4. Supplying power to carbon strips: a) full, b) selective c) real view of the system

Such considerations led to the selection of a strip made of 5 courses as the heating element. The measurement results for 5 courses are marked in red to distinguish the selected variant, although in some cases the strips with a different number of courses had slightly better results for the parameters tested.

Next, for basic research, a double faced fabric was produced consisting of six heating strips made of carbon yarn with a varying number of courses separated with ten courses made of cotton yarn (Fig. 5).

Measurements of the resistance, voltage and intensity of current flowing through the carbon strips in order to determine the power were started after 24 hours of fabric relaxation. Moreover, before the measurement, the samples were acclimatized and the tests were performed at a constant relative humidity of 40 % and temperature of 21 °C. As shown in Fig. 5, the width of the knitted fabric is non-uniform. Measurements of resistance R, using a multimeter, were performed for two variants of fabric width: non-uniform - after 24 hours of relaxation and constant - as a result of applying the sample onto a plexiglass frame with a width of 22 cm (Fig. 6).

Table 2 presents the results of resistance measurements of individual heating strips made of carbon yarn for different widths of the fabric.

The results from Table 2 are shown in graphical form in Fig. 7. As can be seen, the increase in the width of the fabric for the number of courses from 1 to 6 results in a decrease in the resistance value.

The specific structure of the knitted loop, whose top arc is in contact with the bottom half-arcs of the loop placed in the above course, leads to possible short-circuit points (Fig. 8). A short-circuit point means that the resistance of the conductor decreases while the intensity of the flowing current goes up.

With an increasing number of courses made of carbon yarns in a given strip, the area S of the conductor cross section

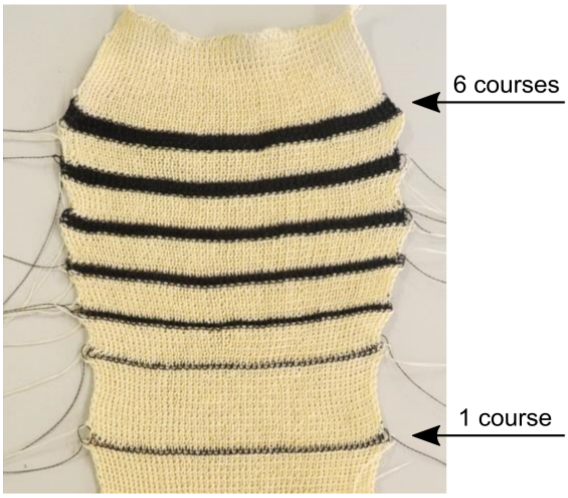


Fig. 5. Knitted fabric with six heating strips with a varying number of courses made of carbon yarn

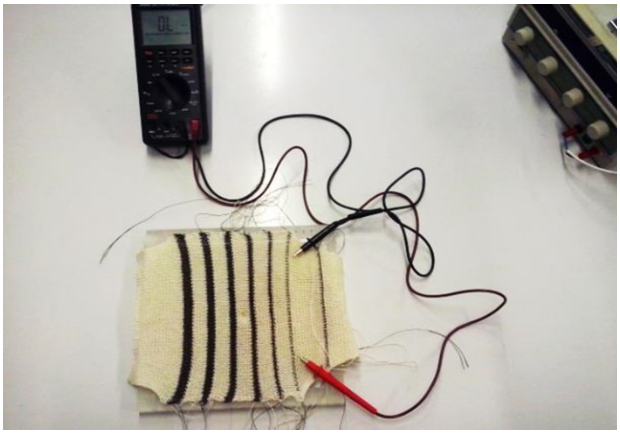


Fig. 6. Measuring resistance of a fabric with a constant width of 22 cm

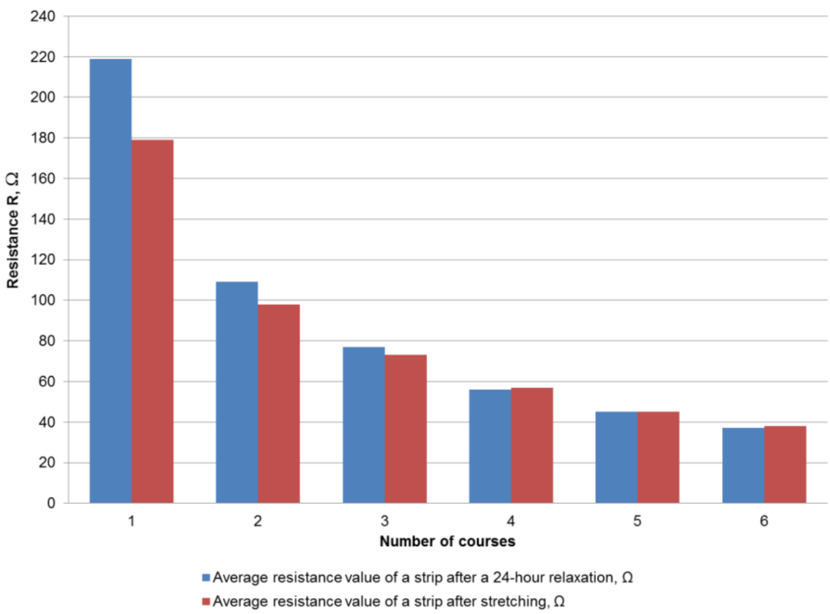


Fig. 7. Graph of resistance changes depending on the change of width of the carbon strip

Number of courses made of carbon yarn	Length of the strip after 24-hour relaxation, cm	Length of the course after stretching, cm	Length increase, %	Average resistance value of the strip after 24-hour relaxation, Ω	Average resistance value of the strip after stretching, Ω	Change in resistance value, %
1	15.0	22	47	219	179	-18.3
2	16.0	22	38	109	98	-9.7
3	16.5	22	33	77	73	-5.3
4	17.0	22	29	56	57	1.8
5	**17.5**	**22**	**26**	**45**	**45**	**0.0**
6	18.0	22	22	37	38	2.7

Table 2. Resistance measurements for individual heating strips of the fabric made of carbon yarn

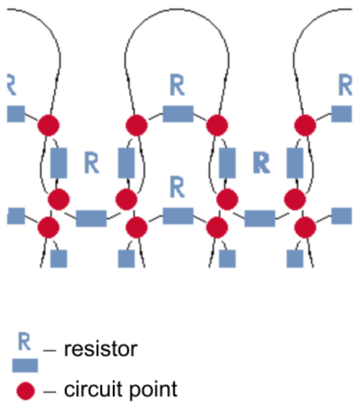


Fig. 8. Schematic drawing of short-circuit points in the structure of the knitted loop

increases, and at the same time the number of short-circuit points also grows, which results in a reduction in resistance of a single carbon strip. This phenomenon is confirmed by the formula for the conductor resistance: $R=\rho \cdot l/S$ [Ω] , where: ρ - specific resistance of the conductor material [($\Omega \cdot mm^2$)/m], for carbon fibers at 20 °C ρ equals 15÷40 ($\Omega \cdot mm^2$)/m, l - conductor length [m], S - conductor cross-sectional area [mm^2]. Subsequently, measurements were made of the current power flowing through the carbon yarns introduced into the fabric courses and of the temperature of the heating strips. If electrical current flows through a fabric strip of resistance R_i, it is accompanied by heat release according to Joule–Lenz's law. The heat is equal to the work done by the current intensity I and voltage U at time t: $W=U \times I\ t$ or $W= I^2 \cdot R_i\, t$ if, according to Ohm's law, we substitute $U = R_i I$. The value of effective voltage or direct (alternating) current determines the thermal power of the current (the ratio of work to time), which is expressed by the formula: $P_Q=W/t=I^2 \cdot R_i=U^2/R_i$ [$W=J/s=V \cdot A$]. During the research, the current intensity I was measured for the variable values of voltage U in the range from 0 to 30 V, for six variants of carbon strips. The system

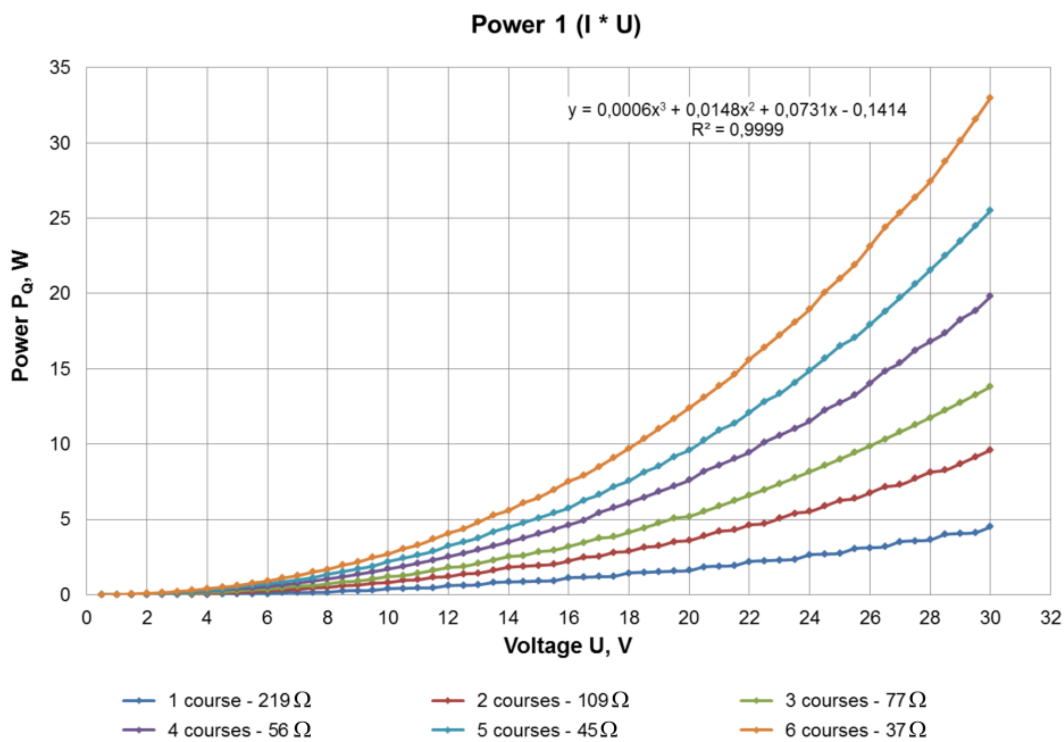


Fig. 9. Dependence of the power of courses made of carbon threads as a function of the voltage increase

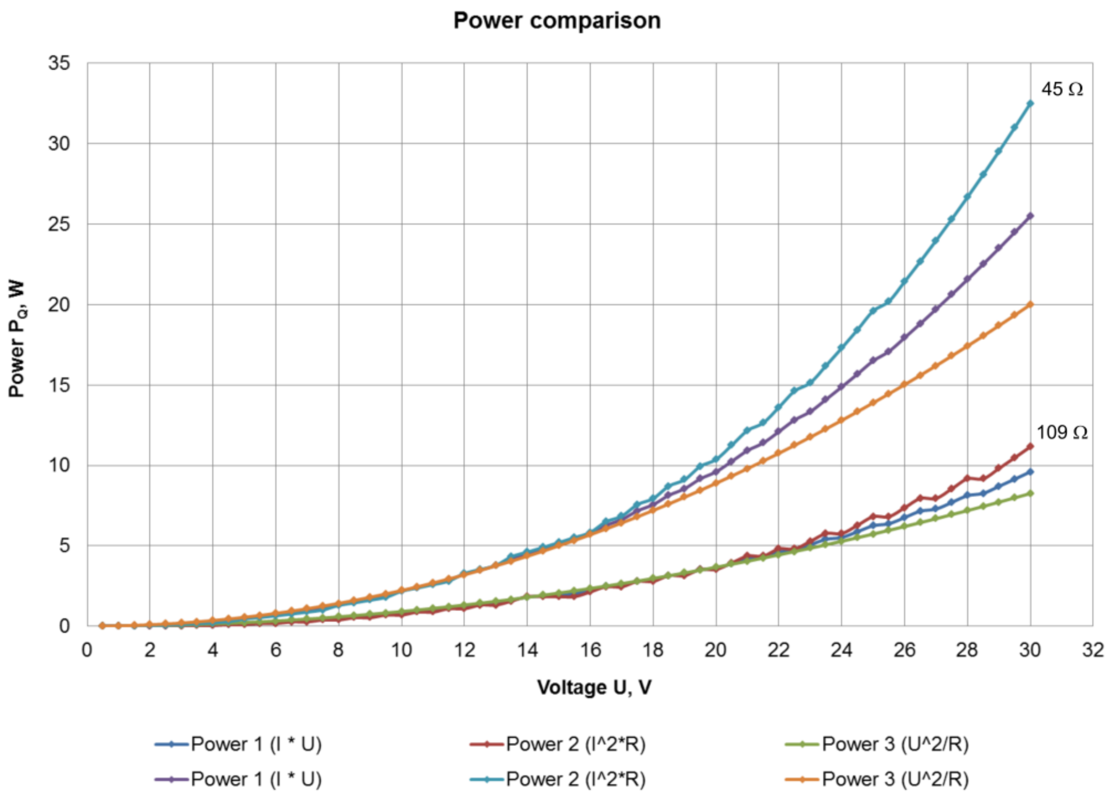


Fig. 10. Differences in thermal power depending on the calculation method

was powered by a laboratory power supply type DF 1730SL10A. During the measurements, the voltage was changed every 0.5 V in order to obtain the specific current increase. For each voltage setting and current intensity measured with the ScanTemp 485 pyrometer, the temperature was read on the radiator strips. The results of the measurements are shown in the graphs (Fig. 9, 10 and 11).

Width and resistance of the heating strip	Supply voltage	Power 1 (I×U), W	Power 2 (I^2·R), W	Power 3 (U^2/R), W
1 course 219 W	U = 12 V	0.60	0.55	0.66
	U = 24 V	2.64	2.65	2.63
2 courses 109 W	U = 12 V	1.20	1.09	1.32
	U = 24 V	5.52	5.77	5.28
3 courses 77 W	U = 12 V	1.80	1.73	1.87
	U = 24 V	8.16	8.90	7.48
4 courses 56 W	U = 12 V	2.52	2.47	2.57
	U = 24 V	11.52	12.90	10.29
5 courses 45 W	U = 12 V	3.24	3.28	3.20
	U = 24 V	14.88	17.30	12.80
6 courses 37 W	U = 12 V	4.08	4.28	3.89
	U = 24 V	18.96	23.09	15.57

Table 3. Values of thermal power for courses made of carbon threads

The results of the studies conducted confirm the above formulated relations arising from Joule's law, showing that thermal power increases with the increase of the applied voltage, which is higher for resistors with lower resistance. The dependence of the power increase as a function of the voltage is also described by a third order polynomial equation. The largest thermal power is observed in the case of the heating strip with a width of six courses. For the given range of voltage changes from 0 to 30 V, depending on the resistance of the courses made of carbon threads, the thermal power of the strips equals from 0 to 33.2 W. It should be noted that the power values presented are the product of the voltage and current intensity measured. The power calculated from the products ($I^2 \times R$ and U^2/R) differs significantly from that determined from the relation I×U, as shown in Table 3 and in the graph (Fig. 10).

The differences result from the variability of the resistance R of the knitted fabric, caused by an increase in the temperature of the heating elements according to the relation: $R = R_o (1 + \alpha \times T)$, where:

R_o - resistance at 0 °C, T - conductor temperature, α - temperature coefficient of conductor resistance. For the analyzed electrically conductive strips with a number of courses from 1 to 6, for the

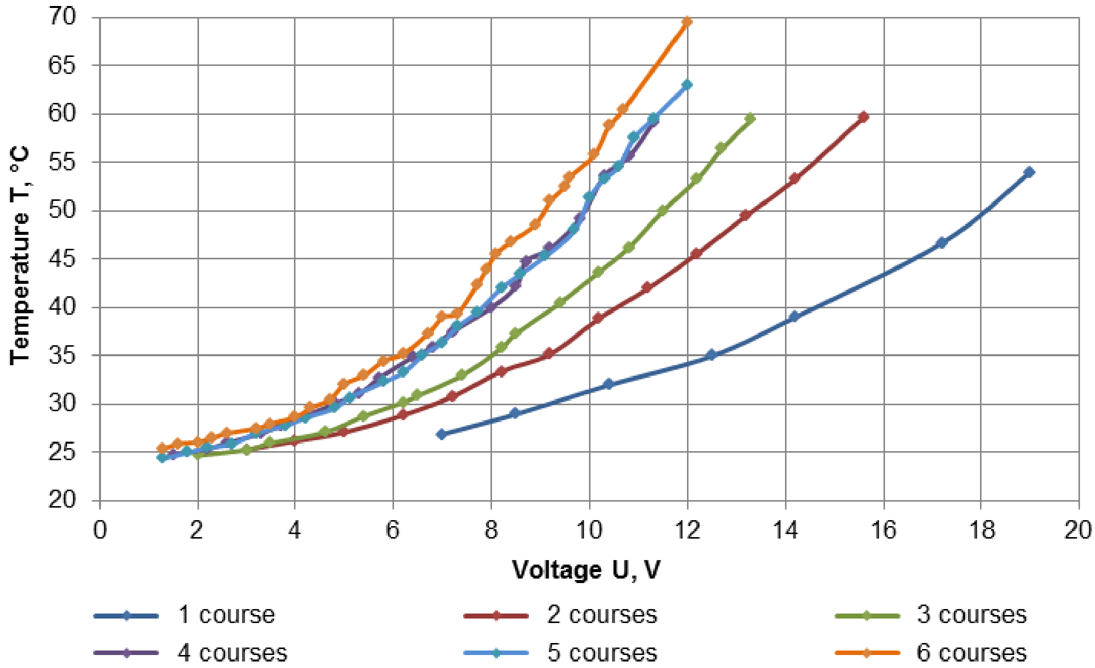


Fig. 11. Diagram of temperature dependence on the voltage change for strips made of carbon yarn with different numbers of courses

Variant	Number of carbon yarn courses in 1 strip	Number of cotton yarn courses in 1 strip	Number of carbon yarn strips	Equivalent resistance of the radiator, R_{iz} , Ω	Number of cotton yarn strips	Number of remaining courses	Heaating surface, %	Current I, A	Thermal power of the heater, P_{Qi}, W
1	5	8	13	3.46	12	74	69	2.70	25.2
2	5	9	13	3.46	12	62	74	2.70	25.2
3	5	10	13	3.46	12	50	79	2.70	25.2
4	**5**	**8**	**8**	**5.62**	**7**	**139**	**41**	**1.68**	**15.9**
5	**5**	**8**	**9**	**5.00**	**8**	**126**	**46**	**1.91**	**18.2**
6	**5**	**8**	**10**	**4.50**	**9**	**113**	**52**	**2.11**	**20.0**

Table 4. Selection of the number of carbon yarn strips and strips and courses made of cotton yarn in a knitted radiator

supply voltages most often applied: 12 V and 24 V, the power ranges from 0.6 to 4.1 W and from 2.6 to 19.0 W (Table 3). In the case of temperature changes on the surface of the heater, the highest temperature values can be observed for a fabric width of six courses (Fig. 11).

When analyzing the diagram, it can be seen that course 1 reaches the lowest temperature of about 54 °C for the highest supply voltage of 19 V. The highest temperature (70 °C) and, at the same time, the lowest voltage of 12 V are obtained for the strip with 6 courses.

Analysis of the results led to the selection of a strip with 5 courses made of carbon yarn. This variant was characterized by low resistance when supplied with a voltage of 12 V, optimum heating temperature, good efficiency and moderate power losses. As a result, the number of 5-course strips required for the design of the heating mat was calculated (Table 4).

In Table 4 (fifth column), the equivalent resistance R_{iz} for parallel connections was calculated based on Kirchhoff's first law, i.e. $R_{iz} = \sum_{n}^{i=1} \frac{1}{R_i}$, where n is the number of resistors (carbon strips connected in parallel) .

The data presented show that the heating mat designed with eight up to ten heating strips made of carbon threads arranged in five courses generates a heating power of 16 to 20 W when supplied with a voltage of 12 V.

It should also be emphasized that thanks to the considerable elasticity of the knitted fabric, equal to e = 108 % when stretched along the courses (heating strips) there was no damage (breaking) to the knitted structure of the heater, and continuity of current flow through the carbon strips was maintained. Similarly, while stretching the fabric along the wales up to ε=56 %, no damage was done to the fabric structure or heating strips.

3. Highly flexible knitted heating mat

3.1. Conceptual design

An innovative concept was developed for the construction of a highly flexible knitted heating mat (Fig. 12 a and b). The mat is constructed in the form of a composite (hybrid) ternary structure. The first element of the mat is the basic knitted fabric (1) characterized by high elasticity, whose relative elongation reaches several hundred percent.

Electrically conductive threads of varying resistance (2) are built in the base of the structure. One of the variants proposed are threads acting as heating elements. In the second variant it was assumed that electrically conductive threads with low resistance can serve as paths for transmitting electrical signals.

The third important element of the construction are the high- strength threads (3), whose task is to limit the maximum elongation of the knitted fabric, so that the functional electrically conductive threads are not broken during use or in the stretching process.

Fig. 12b shows the assumptions for the construction of a highly flexible heating mat. The basic knitted fabric is made of multi-guide warp-knitted stitches. Depending on the requirement, the structure may consist of two or three basic stitches, such as tricot or cord stitches with an underlap in opposition or a-jour structures with a small cover factor (for example pillar and weft stitches). The choice of warp-knitted stitches is not a random one. It results from the fact that they are characterized by greater flexibility than weft-knitted ones. The second important factor is that in the case of warp-knitted structures it is much easier to shape the cover factor of the fabric. However, most important is the possibility of introducing into the basic knitted fabric the electrically conductive threads, arranged in the configuration of wefts or other stitches in the longitudinal arrangement of the wales or transverse of the courses, as well as at any angle to the oriented axes of the courses and wales.

In order to ensure high elasticity of the structure, the basic knitted fabric is made of elastomeric threads and electrically conductive threads are introduced in a so-called zig-zag form. The geometry of the arrangement of these threads is characterized by the length l_{ip} of the elementary section AB and the angle α_{np}, which defines the position of the thread in relation to the horizontal arrangement of the courses. Parameters l_{ip} and α_{np} can also be indirectly described by the width s_w and the height h_w of the arrangement repeat of elementary thread AB.

When the fabric is stretched in the longitudinal direction towards the acting forces P, straightening of the electrically conductive threads takes place, which causes an increase in the angle α_{np} to the limit value $\pi/2$, an increase in h_w to the limit value l_{ip}, and a decrease in the value s_w ($s_w \cong 0$).

When the limit value of threads straightening is exceeded, i.e. when $h_w > l_{ip}$, elongation of the electrically conductive material takes place and the thread is broken.

From the geometrical model of the thread arrangement presented, it can be concluded, that larger elongation of the knitted structure, while maintaining the continuity (no damage - breaking) of the thread, can be obtained for the increased lengths of elementary sections l_{ip} and for small angles of thread inclination α_{np}.

In order to prevent the breaking of the electrically conductive thread, which would lead to the damage of the heater, so called protective threads were introduced into the knitted fabric. Their function is to ensure that in the extreme stretching conditions, the limit $h_{w,max} = l_{ip}$ is not exceeded.

Just like the electrically conductive threads, the protective ones are arranged in the form of a zig-zag, with such geometric parameters that in the stretching process and during the final straightening, the limit value h_w satisfies the inequality: $h_{w,zab} = l_{iz} < h_{w,max}$. Describing the function of protective threads, it can be said that in the stretching process they are vertically straightened and prevent the complete straightening of the zig-zag of electrically conductive filaments. To prevent damage to the knitted structure, the protective threads are characterized by high strength. It should be noted that the geometry of the thread arrangement can be programmed by means of the design and structural parameters of the fabric stitches.

3.2. Design and knitting technology

A highly flexible warp-knitted fabric with electrically conductive threads was designed. The stitch is a weft three-guide structure. The basic knitted fabric is made up of a component pillar stitch with open loops (full threading) and a weft inlay with a lap along 2 t_u (Fig. 13). Elastomeric threads braided with polyamide with a linear density of 78 tex (Fig. 1) were selected for the basic fabric. The relative elongation of highly elastic threads of the gumitex type equals 234 %. The third component stitch of the knitted fabric is a weft stitch made of electrically conductive threads. This stitch is formed as a so called zig-zag (red threads in Fig. 13). Height of stitch repeat R_w = 6 courses, repeat width R_h = 8 wales. To keep the diagram readable, only one thread was depicted. In two variants of the project, two types of electrically conductive threads were taken into account: variant W2.1 – double carbon threads with a linear density of 134 tex, variant W2.2 – threads PA6.6 coated with silver of the Shieldex type with a linear density of 11 tex (threads characteristics Fig. 1). The protective threads were neglected in the project.

The stitches of the two variants of the fabrics designed were made on a Karl Mayer Raschel knitting machine of the type RL5NF with a needle gauge E12. Knitted strips with a width of 50 mm (Fig. 14 and 15) were produced. One knitted strip was made of 56 warp threads with full threading of the guide bars of the first and second component stitch. Figures 15 a and b show two variants of the knitted fabrics with electrically conductive threads. In variant W 2.1, four

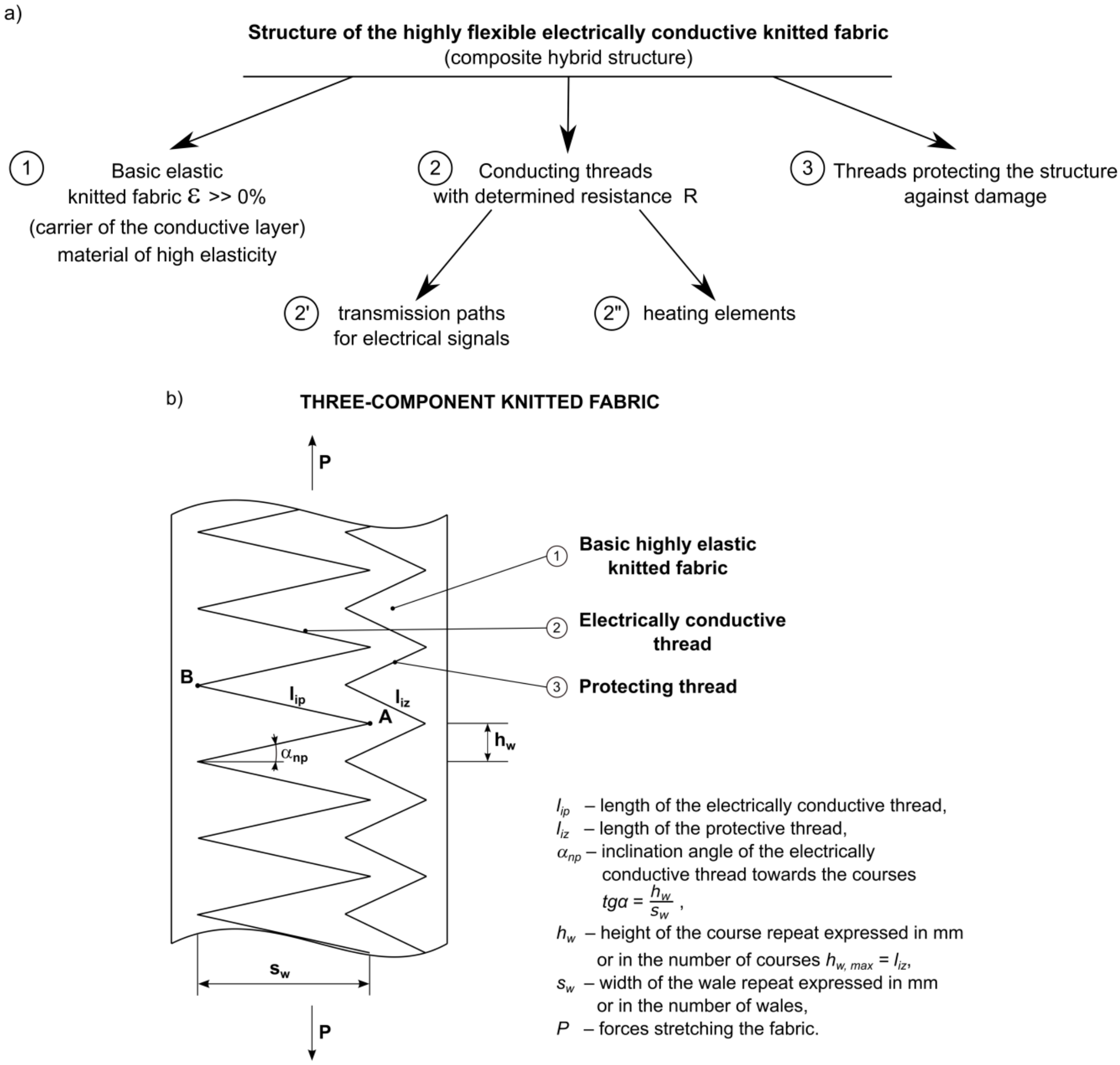


Fig. 12. Concept of highly flexible electrically conductive knitted fabric: a) conceptual idea, b) constructional assumptions of the fabric structure

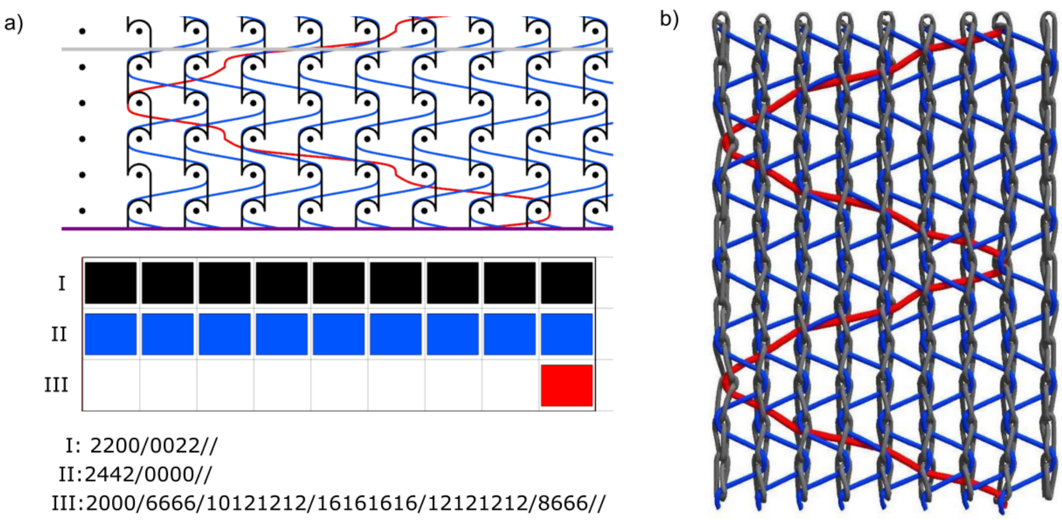
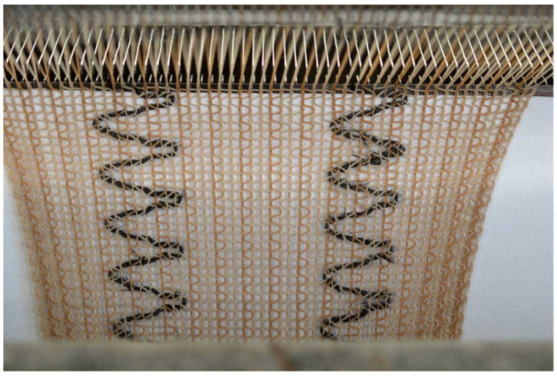
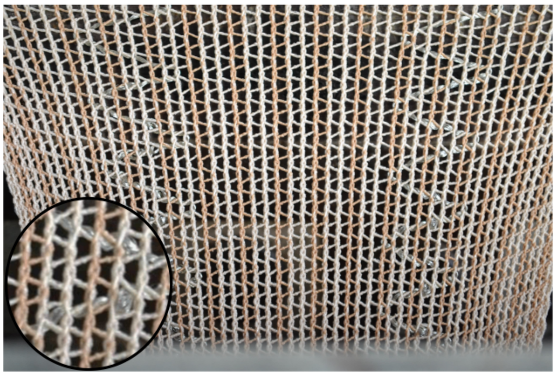


Fig. 13. Three-guide warp-knitted fabric built of weft stitches with electroconductive threads: a) schematic diagram of stitches, b) real 3D view of the stitch

Fig. 14. Technology of manufacturing a knitted strip with carbon threads on a warp-knitting machine Karl Mayer type RL5NF



variant W 2.1 – carbon threads



variant W 2.2 – Shieldex type threads

Fig. 15. Highly elastic strip with electrically conductive threads

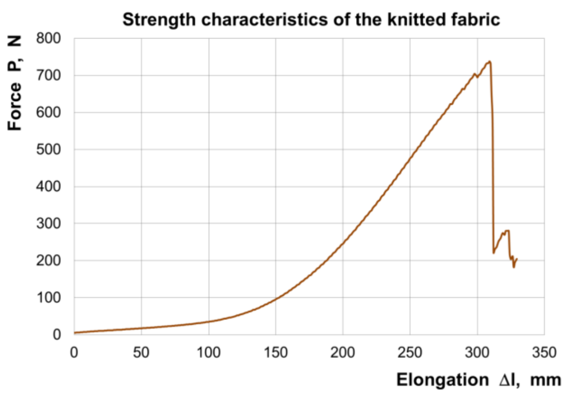


Fig. 16. Mechanical characteristics of the fabric in the stretching process

carbon threads were introduced into the width of the strip, and in variant 2.2 - six threads of the Shieldex type were used.

After dry relaxation the fabric course density P_r equaled 120 courses/10 cm, and the wale density P_k = 112 wales/10 cm. Fig. 16 shows mechanical characteristics of the fabric in the stretching process. The longitudinal breaking force of the knitted strip equaled 738 N/50 mm (13.13 N/wale) and the relative elongation ε = 310 %.

The variants of the knitted fabrics obtained confirmed the correctness of the design assumptions and the effectiveness of the technology of knitting on warp knitting machines in the production process of highly flexible heating materials or structures transmitting electrical signals. The next stage of the research was to determine how much the loads affecting the heating strips in the stretching process influence the changes in the resistance parameters of the electrically conductive threads introduced.

In variant W 2.1, a system of 4 carbon threads with a linear resistance of 216 Ω/1 m of the thread was parallelly connected along the length of 100 mm. In variant W 2.2. six silver-coated threads with a resistance of 2 kΩ/1 m of the thread were joined.

The upper and lower parts of the strips were connected with a silver thread by sewing on a lockstitch sewing machine. Similarly prepared samples were acclimatized before measurements, and tests were performed at a constant relative air humidity of 40 % and temperature of 21 °C. The samples of knitted strips of a length of 100 mm were fixed in the grips of the Haunsfield testing machine of the type H50K-S, and stretched at a speed of V = 50 mm/min (Fig. 17). The stretching process was carried out in six stages for the specific elongation values of each stage. After stretching the sample and 5 minutes of relaxation, the resistances of the electrically conductive threads were read on the ohmmeter.

The selected stages of the stretching cycle of the knitted fabric are shown in Fig. 18, while the diagram in Fig. 19

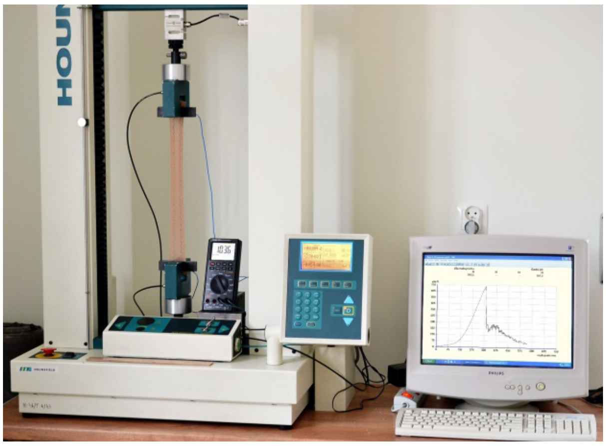
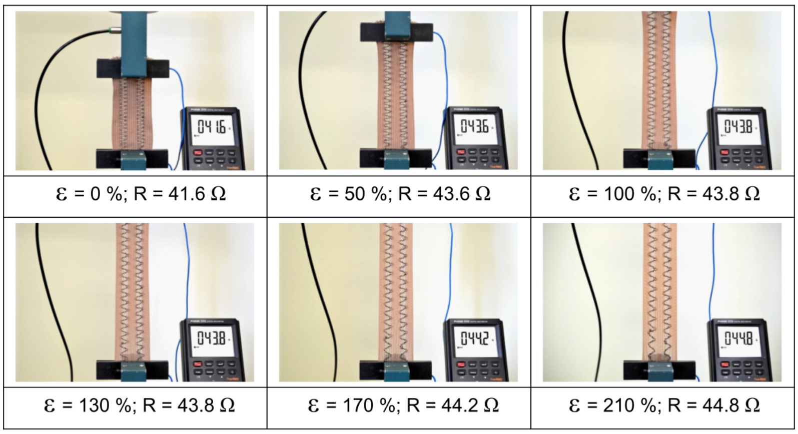


Fig. 17. Methodology of measuring resistance changes of electrically conductive threads in the process of stretching a knitted strip

a) knitted fabric with carbon threads



b) knitted fabric with Shieldex threads

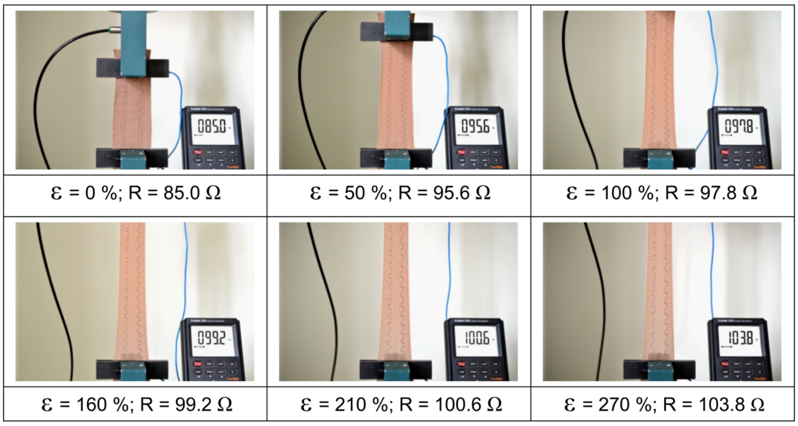


Fig. 18. Selected stages of the stretching cycle for a knitted fabric with electrically conductive threads

presents the dependencies of changes in the thread resistance. The research presented shows that the resistance of electrically conductive elements increases together with the elongation of the highly elastic structure of the basic fabric. The nature of resistance increase R = f (Δl) takes the form of the fourth degree polynomial function (regression coefficient R^2 = 0.98).

For carbon threads in the elongation range ε= 210%, resistance R increased by 3.2 Ω, whose per unit growth of elongation $\Delta R/\varepsilon$ equals 0.0152 Ω/%. For silver-coated threads in the elongation range e = 270 %, the increase DR is 18.8 Ω and the resistance increase in relation to elongation equals 0.2218 Ω/%. Taking into account relative resistance changes in relation to elongation, i.e. $(\Delta R/R)/\varepsilon$ the increases are as follows: for carbon threads $3.7 \cdot 10^{-4}$, and for silver-coated threads $2.6 \cdot 10^{-3}$. In the interpretation of the results of resistance changes obtained, one should refer to similar behaviors of electrically conductive textiles. In our case, the electrically conductive threads introduced were to serve as heating elements, therefore it would be reasonable to analyze the changes in heating power (heat exchange balance) and temperature changes on the surface of the heater. Such analyzes will be made in the next study.

4. Summary

The nature of the research was twofold. The summary of the first part demonstrates that on the basis of a classical double-faced cotton knitted fabric of elasticity up to 100 % of relative elongation, it is possible to construct heating elements made of carbon yarns with a significant heat output. The heating surface of the knitted fabric ranged from 41 to 79 %. The structure of the radiator consisted of parallely connected resistors made of carbon strips. In the optimum variant of the heater, the heating elements consisted of five consecutive courses connected with each other and were made of carbon yarns separated by eight courses of cotton yarn. With the structure of the heating mat containing 8÷10 carbon strips and 7÷9 cotton strips the surface of the heating element equaled from 41 to 52 % of the total area. With 12 V supply voltage, the thermal power of the heating mat obtained equaled from 15.9 to 20.3 W, which provided a surface temperature of 34-43 °C, corresponding to human thermal comfort. In the case of connecting every second resistor (carbon strip) the heating power was doubled.

Summarizing the second stage of the research, it is important to emphasize that the elasticity of the heater reached 300 %

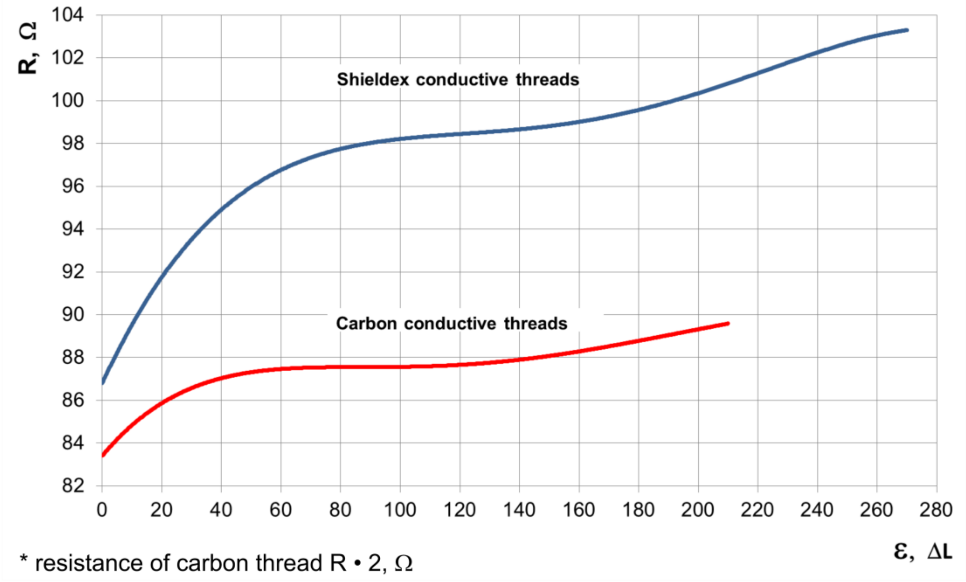


Fig. 19. Characteristics of resistance changes as a function of fabric elongation

when the proper stitch was selected and elastomeric threads were used. Despite a considerable elongation, no damage was observed to the heating elements. Just like in the first variant of the mat, in this case parallel connections were also used of carbon heating threads with a linear resistance R = 216 Ω/m and polyamide shieldex-coated threads with a resistance of 2 kΩ/m. Tests of the radiator stretching up to 210-270 % of relative elongation showed resistance changes between 0.0152 and 0.2218 Ω/% of the elongation.

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