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Investigation of the Thermal Properties of Socks Knitted from Yarns with Peculiar Properties. Part II: Thermal Resistance of Socks Knitted from Natural and Stretch Yarns

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Abstract
This study is a continuation of experimental analyses to determine the thermal properties of socks. The influence of yarns from the different natural fibres of socks on the thermal conductivity coefficient of plain knits and plated plane knits with textured polyamide (PA) or elastane thread was assessed in Part I. The influence of the fibre yarns mentioned on thermal resistance was analysed. It was determined that a higher thermal resistance is characteristic for knits with Lycra thread, lower – for knits from pure yarns, and the lowest- for knits with textured PA thread. It was found that an increase in linear density occurs when there is a decrease in thermal resistance, especially in a combination with two pure yarns and one plated textured polyamide or elastane Lycra thread. The thermal resistance of samples manufactured from pure yarns and from a composition with PA thread was lower compared with samples which have Lycra thread.

Key words: *natural yarns, plated knitted socks, thermal resistance, thickness.*

Introduction

Consumers of textile and clothing products are becoming increasingly aware of the importance of comfort. In addition to aesthetic appearance, comfort is one of the main properties of clothing which affect the choice of a product. It is widely known that the transfer of heat, moisture and air through a garment are the most important factors for clothing comfort [1].

In our earlier work [16], we analysed the thermal conductivity coefficient of socks knitted from natural and textured yarns. It was determined that a higher thermal conductivity coefficient is characteristic for knits with textured polyamide (PA) thread, and lower – for knits with Lycra thread and for those from pure yarns. The most important influence on the thermal conductivity coefficient is the structure of knits. PA thread increases the thickness of samples, but the area density does not increase, which was shown by the thermal conductivity coefficient and thickness values of the samples in our previous study. In the present study, thermal resistance values were calculated on the basis of these two values and compared.

Many researchers have conducted studies to evaluate and analyse the thermal comfort of woven fabrics. They examined the effects of the fibre type and fabric composition on thermal comfort. The fiber composition and fabric structure or the presence of layers were revealed to affect the heat and moisture transfer properties of textiles. Studies on thermal wear showed that fabric properties influenced subjective wearing sensations and the microclimate inside clothing; however, these effects varied with the environmental conditions or physical activity levels. The authors examined the effects of fiber type and fabric composition on thermal comfort and found that the thermal sensation and thermal comfort of caps were influenced by the thickness, water absorption properties and thermal conductivity of fabrics [2].

Some of the researches [3 - 10] analysed the thermal comfort of various fabrics. They all noted that the wickability, air permeability and heat transfer influence the thermal comfort of a garment. In articles [4, 10] the effect of finishing on the comfort of cotton and polyester blend fabrics was analysed, and it was observed that fabric treatment with different levels significantly decreases the air permeability and wickability of cotton fabrics but does not affect polyester fabric properties. However, the thermal insulation value of both cotton and polyester fabrics increases to a similar degree. B. K. Behera and R. Mishra analysed the thermal comfort of fabrics produced from some non-conventional blends and light weight constructions such as wool/silk, wool/tassar, wool/linen, wool/cotton, silk/linen and pure wool, pure silk and a few synthetic fibre blended samples [3]. They found that the thermal insulation property of worsted fabrics is largely dependent on the areal density. Silk and silk blends also give good insulation, whereas wool in combination with linen gives a low insulation value due to less porosity. Moreover, it was observed that single yarn woven fabrics have exceptionally higher thermal insulaton compared to 2-ply warp woven fabrics.

Shinjung Yoo et al analysed the impact of fabric constructional variables on the thermophysical and sensorial properties of heat – resistant protective workwear fabrics made from aramid yarns [11, 12]. This class of clothing material was examined because heat – resistance protective workwear is often worn in hot and humid conditions, where comfort is a particularly important performance requirement. Ozdil et al reported on the thermal properties of 1 × 1 rib fabric knitted using various yarns with different properties [13]. The results showed that an increase in yarn twist and yarn count causes a decrease in thermal resistance values and an increase in water vapour permeability. Shoshani and Shaltiel noted that thermal insulation increases with a decrease in the density of fabric [14]. A. Marmarali et al observed that the parameters of thermal

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conductivity, thermal resistance, thermal absorptivity and air permeability are significantly affected by the tightness factor. Looser fabrics posses high insulation and high air permeability values [9]. The thermal properties of different cotton and Angora rabbit fibre blended fabrics were analysed by N. Oglakcioglu et al [15], in which they showed that an increase in the Angora fibre ratio in fabric affected thermal comfort properties. The statistical analyses showed that only fabrics with 25% of rabbit fibre generated a significant difference in these parameters.

A number of authors have shown that a linear relationship exists between the thermal resistance and thickness of fabric, which is because the thickness of fabric influences fabric porosity in that a decrease in thickness causes a corresponding decrease in fabric volume, which is generally followed by decreases in the amount of insulation air in fabric interstices [1].

Thus far, there have been no investigations of the thermal resistance of knitted socks made from new fibres such as bamboo, soy, and blends with seacell. The influence of the fibres mentioned on thermal resistance was analysed in this paper. There have also been no analyses of thermal property control. We found that thermal resistance could be controlled by changing the Lycra or PA thread in the knitted samples.

Object of investigation

Experimental samples were made from the same material as in article [16]: 100% Cotton (C - 14 tex), 100% Bamboo fibre produced from cellulose (B - 14 tex), 100% Soybean protein (S - 14 tex), and blended yarns: 75% Cotton - 25% seacell (CS - 19 tex), 80% Bamboo - 20% flax (BF - 24 tex)[1]. All knits were plated with textured polyamide PA (20 tex) or elastane Lycra (2.2 tex) thread wrapped with textured PA (7.8 tex) as in previous analyses.

Methods of testing and calculations

Thermal conductivity coefficient measurements were repeated 6 times for radomly chosen parts of samples and thickness thereof, as in in our previous work [16]. Thermal resistance (R, m^{2}K/W) is calculated as a quotient of thickness and thermal conductivity parameters from the following:

$$R = \frac{b}{\lambda} \tag{1}$$

where b - thickness of the sample in m;

λ - thermal conductivity coefficient of the sample in W/mK.

Experimental results

The thermal resistance of socks manufactured from various yarns, such as pure, blended and a combination with textured polyamide PA or elastane Lycra thread wrapped with textured PA was analysed in this work. The same six groups of knits were used as in our previous work [16]. The first group of knits was (XX – SS, CC, BB) from 28 tex yarns, the second (XXX – SSS, CCC, BBB) – 42 tex, the third (XL – SL, CL, BL) – 24 tex, the fourth (XXL – SSL, CCL, BBL) – 38 tex, the fifth (XPA – SPA, CPA, BPA) – 34 tex, and the sixth (XXPA – SSPA, CCPA, BBPA) – 48 tex. The results of thermal resistance are presented in ***Figures 1, 2* & *3*** and ***Table 1***. Thickness measurements were repeated 3 times for radomly chosen parts of the samples, and relative error values were calculated; it was found that the error did not exceed 5%.

Regarding thermal resistance, the range of values obtained is significant, ranging from 0.0119 – 0.0401 m^{2}K/W. As is seen from Figure 1, knits with Lycra thread have the highest values (ranging from 0.0205 – 0.0401 m^{2}K/W), whereas lower values are shown by knits manufactured from pure yarns. The thermal resistance of samples made from two pure yarns is within the range of 0.0119 – 0.0166 m^{2}K/W, and from three – 0.0137 – 0.0195 m^{2}K/W. The thermal resistance of samples made from one pure yarn and one PA thread is within the range of 0.0132 – 0.0191 m^{2}K/W, and from two pure yarns and one PA thread the range is 0.0146 – 0.0203 m^{2}K/W. The thermal resistance of samples made from one pure yarn and one Lycra thread is within the range of 0.0206 – 0.0401 m^{2}K/W, and from two pure yarns and one Lycra te range is 0.0205 – 0.0304 m^{2}K/W.

Influence of different fibres and different linear densities on thermal resistance

A comparison was made of the thremal resistance of knits manufactured from cotton, bamboo, and soy yarns of the same linear density. In our earlier work, the thermal conductivity coefficient and thickness of samples were shown [16], based on which thermal resistance values were calculated.

Results of the thermal resistance of knits for socks manufactured using two or three pure yarns for loop knits plated with PA or Lycra thread are presented in ***Figure 1***. The highest values are shown by knit variants plated with elastane Lycra thread. When elastane, knitted socks become thicker (the thickness increases by about 100%), the thermal resistance increases as well. There are differences in the average thickness values of all the knitted groups: the highest values are shown by the 3rd and 4th groups and the lowest by those from the 1st and 2nd groups. In ***Figure 2*** we can see the thermal resistance of different fibres. When samples were manufac-

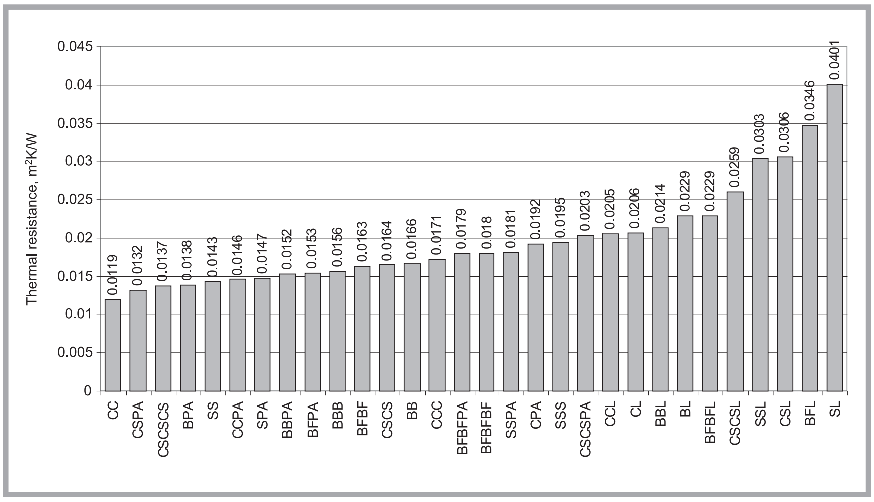

Figure 1. Thermal resistance of knitted sock samples.

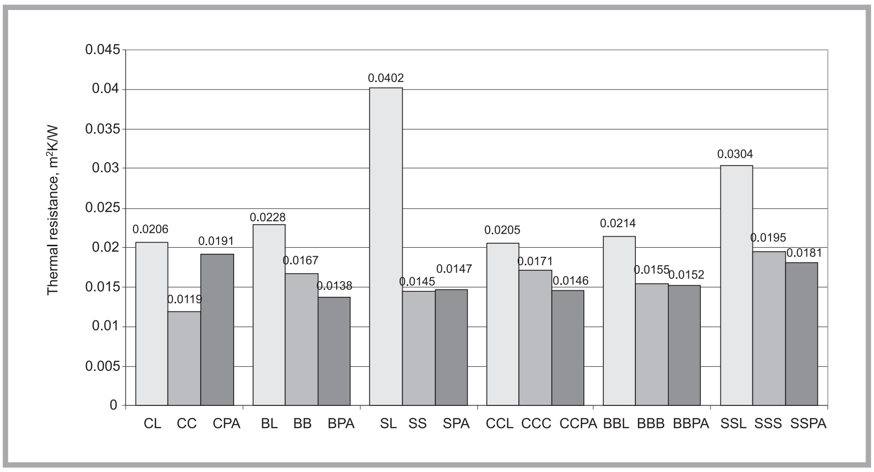

Figure 2. *Thermal resistance of knits manufactured from pure cotton (C), bamboo (B), soy (S) (linear density XX-28 tex, XXX-42 tex) and their combination with Lycra (XL-24 tex, XXL-38 tex) and textured PA (XPA-34 tex, XXPA-48 tex) thread.*

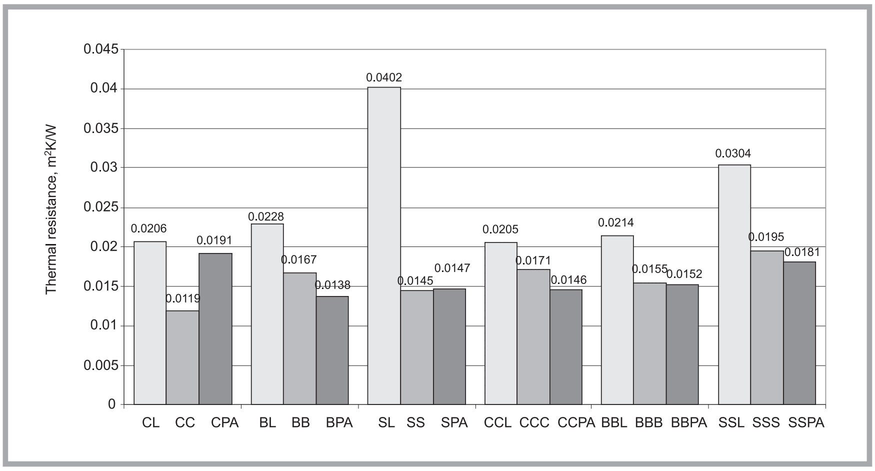

Figure 3. *Thermal resistance of knits manufactured from Cotton – seacell (CSCS-38 tex, CSCSCS-57 tex), comabination with Lycra (CSL-29 tex, CSCSL-48 tex) and textured PA (CSPA-39 tex, CSCSPA-58 tex); Bamboo – flax (BFBF-48 tex, BFBFBF-72 tex), a combination with Lycra (BFL-34 tex, BFBFL-58 tex) and textured PA (BFPA-44 tex, BFBFPA-68 tex) thread*

Table 1. *Summarised values of air permeability, the thermal conductivity coefficient and thermal resistance; "+" – maximum values, "x" – middle values, "-" – minimum values.*

Variants	Air permeability, mm/s	Thermal conductivity coefficient λ, W/mK	Thermal resistance R, m²K/W
1. Knits from pure yarns	+	-	-
2. Knits plated with textured PA thread	x	+	x
3. Knits plated with Lycra thread	-	x	+
4. Knits from two types of thread, XPA or XL	+	-	+
5. Knits from three types of thread, XXPA or XXL	-	+	-

tured from a combination of one pure yarn and one Lycra thread (XL – 24 tex), the highest thermal resistance was of knits manufactured from a combination of soy and Lycra, which was even 95% higher than that of samples knitted from a combination of cotton and Lycra thread, and 76% higher than that of knits from bamboo and Lycra thread. The thermal resistance of knits from a bamboo combination with Lycra and from a cotton combination with Lycra did not differ so widely. For samples manufactured from a combination of two pure yarns and one Lycra thread, the highest thermal resistance was of knits manufactured from a combination of soy and Lycra, which was 48% higher that of knits manufactured from a combination of two cotton yarns and one Lycra thread. Samples knitted from a combination of bamboo and Lycra have almost the same thermal resistance as knits from a cotton and Lycra combination. The thermal resistance of knits from two soy yarns and one Lycra thread was 76% higher than that of knits from a bamboo and Lycra combination. Soy yarns have a low coefficient of friction, hence they have a better filling property in knitted samples and decreased porosity; the porosity especially decreases in variants with Lycra thread.

When samples were manufactured from two yarns of pure fibres (XX-28 tex), cotton knit showed the lowest thermal resistance, which is because of its looser structure, high porosity, easier air flow, and the fact that the knit does not retain heat. The thermal resistance of knits manufactured from soy yarns was 22% higher than those of cotton, and knits made from bamboo showed even higher thermal resistance, which was 40% higher than that of cotton samples. The thermal resistance of knits from bamboo and soy fibres has similar values. When samples were manufactured from three pure yarns, the highest thermal resistance was of knits manufactured from three yarns of soy fibre, which was 14% higher than that of knits from three yarns of cotton fibre and even 26% higher than that of knits from three yarns of bamboo fibre. Samples knitted from three yarns of bamboo fibre have the same thermal resistance as knits from cotton.

When samples were manufactured from a combination of one pure yarn and one polyamide thread (XPA – 34 tex), the highest thermal resistance was of knits manufactured from one cotton yarn and one polyamide thread. Samples knitted from a combination of cotton and polyamide showed a 23% higher thermal resistance than knits from a combination of soy and polyamide thread. The thermal resistance of knits made from bamboo and polyamide was slightly lower than that of samples from soy and polyamide, and 28% lower than that of knits from cotton and polyamide. When samples were manufactured from a combination of two pure fibres and one polyamide thread, the thermal resistance of knits manufactured from two cotton yarns and polyamide thread was the lowest, which was also similar in the case of samples manufactured from a combination of two bamboo yarns and polyamide thread. Samples knitted from soy yarns and polyamide thread showed a 24% higher thermal resistance than samples knitted from cotton and polyamide. The thermal resistance of knits from two soy yarns and one PA thread was 19% higher than that of knits from bamboo and PA. When there is more than 40% Lycra or textured PA in a knitted structure, it determines the structure of the knitted sample, becoming thicker and tighter, the loops – more steady, and the structure is stable compared with knits from pure yarns.

Comparing knits manufactured from two pure yarns with those made from three pure yarns, it is obvious that the linear density increases, whereas the thermal resistance varies in different ways: The thermal resistance of pure knits and a combination with textured PA increase, and the thermal resistance of knits from a combination with Lycra thread decreases. Differences between the knitted variants of XPA, XL and variants of XXPA, XXL could be explained by the fact that textured PA or Lycra thread have a better influence on XPA and XL variants; the influence of stretch thread decreases in XXPA, XXL variants.

Results of the thermal resistance of knits for socks with blended yarns manufactured using two or three cotton-seacell and bamboo –flax yarns for loop knits plated with PA or Lycra thread are presented in ***Figure 3***. Comparing the thermal resistance of knits from blended yarns (CS, BF), we can see that the thermal resistance values are higher than those from pure yarns (C, B). There is the same range tendency of figures when blended and pure knits are compared i.e. the highest values are shown by knits with Lycra thread, and the lowest by knits from pure yarns and those with PA thread. From the figure we can see that for the combination with Lycra thread, the thermal resistance decreases when the linear density increases, and for the combination with textured PA, the opposite is the case: when the linear density increases, the thermal resistance rises as well. In samples from pure yarns, the variation in thermal resistance is different for knits of cotton-seacell or bamboo-flax. For cotton-seacell variants, the thermal resistance decreases when the linear density increases, while for bamboo-flax variants they behave to the contrary: when the thermal resistance increases, the linear density increases as well.

Verification of the correlation between the thermal resistance of samples from pure or blended yarns, their combination with Lycra and textured polyamide PA thread, and the area density and thickness was performed. There is no correlation between the thermal resistance and the factors mentioned for all knits from pure yarns plated with Lycra or PA thread. The highest correlation values were between the thermal resistance, the thickness or thermal resistance and the area density of knits from pure yarns and a combination with Lycra thread.

Conclusion

A "Warm – cool feeling" is a very important property, as a result of which a human can feel comfort or discomfort in various activities and environmental conditions. This feeling could be achieved by using different linear densities or different fibres for yarns.

For plated socks, combinations with textured PA or Lycra thread are commonly used, but these yarns should be less than 30% of all the stucture (XXL, XXPA). Because plated yarns have a great influence on thermal resistance, when knits manufactured from the same linear density of pure yarns in combination when one plated yarn is textured PA or Lycra threads. It was found that the increase in linear density determines the decrease in thermal resistance, which is especially obvious in all variants with a combination of two pure yarns and one plated (textured PA or elastane Lycra) thread. The highest thermal resistance values are shown by all knit variants plated with Lycra thread. Lower thermal resistance is shown by knits manufactured from pure yarns and those plated with textured PA thread. All variant combinations with Lycra thread could be used for warm feeling socks, which means that the highest thermal resistance values are shown by about one third of all knit variants plated with Lycra thread, and the remaining two thirds are represented by pure knits and those plated with textured PA thread. The thermal resistances of plated knits from soy with Lycra or PA thread are higher than those from bamboo with Lycra and PA thread. The thermal resistances of all knit variants from cotton yarns are lower than those from bamboo or soy variants, except for variant CPA, where the thermal resistance is higher. Thermal resistance could be increased or decreased by changing the Lycra or PA thread. Comparing socks knitted from different fibres (cotton, bamboo, soy, cotton-seacell, and bamboo-flax) for a warm season, the most comfortable would be those from pure yarns and their composition with PA thread, as these are characterised by a lower thermal resistance, making the wearer feel cool in such socks. Socks plated with (Lycra) should be used for a cold season, as they are characterised by a higher thermal resistance.

A summary of thermal comfort properties, such as air permeability, the thermal conductivity coefficient and thermal resistance, of pure and plated socks is in ***Table 1***, in which all values of air permeability, the thermal conductivity coefficient and thermal resistance are shown, from the minimum to the maximum [16, 17]. From this table we can see that for a cold season, the most comfortable would be socks plated with Lycra and textured PA thread. Comparing the 4th and 5th row (two and three yarns for the knit) of Table 1, we can see that knit variants XXPA and XXL have better thermal comfort properties for cold season socks. It is obvious that a thicker knit better retains heat and air, contrary to thin samples, where heat and air flows more easily. Therefore for the summer we suggest a knit combination with pure yarns (XX, XXX) and variants with one pure yarn and Lycra or PA thread (XPA, XL). The wearer will feel comfort because it will not be too hot wearing such socks in summer. Using two or three yarns in the knit allows to control air permeability, the thermal conductivity coeffiecient and thermal resistance.

Editorial note

1) *Man-made fibres manufactured from cellulose-bamboo pulp*

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