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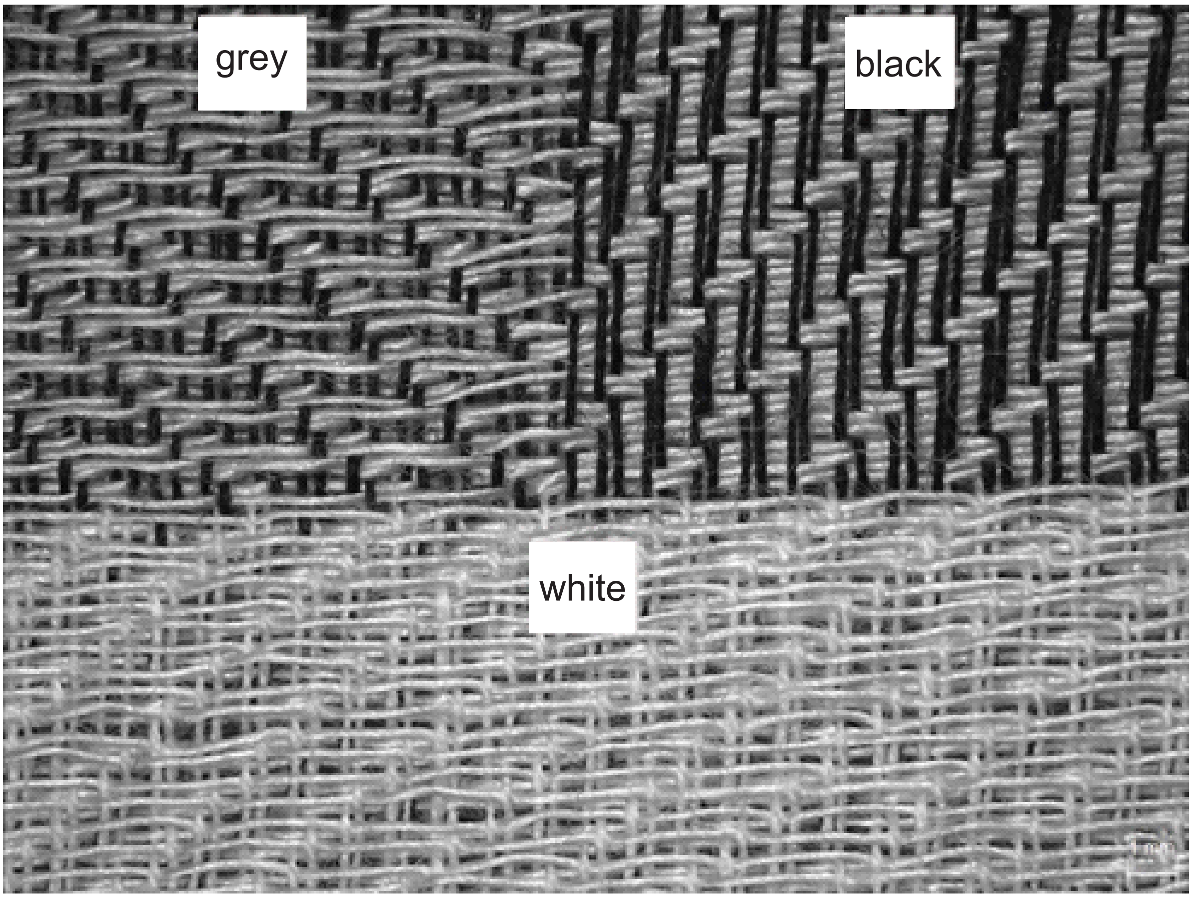
Special Issue: Transport properties and permeability of textile materials



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Specijalna sveska:
Transportna svojstva i propustljivost tekstilnih materijala

Special Issue:
Transport properties and permeability of textile materials

Gostujuća urednica / Guest Editor
Snežana Stanković
University of Belgrade, Faculty of Technology and Metallurgy, Textile Engineering Department, Belgrade, Serbia

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Transport properties and permeability of textile materials

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Abstract

Heat and mass transfer through textile fabrics play a crucial role in achieving optimal thermal comfort perception by a person. The governing properties of textile fabrics by which they influence heat and mass transfer from the human skin to the environment are thermal transport capacity, water vapor permeability, and air permeability. The transfer of liquid moisture through textiles is important for thermal comfort during frequent changes in physical activity or climate. Despite numerous studies on the transport properties of textile materials over the past years, investigation in this subject area is still needed. This special issue includes five articles that offer valuable information on the subject. Both commercial and specially designed textile structures were investigated within the presented studies with the ambitious goal of providing a new understanding of their transport properties. Within the first four papers presented, certain aspects of heat and mass transfer through textile materials were analyzed at the three scale levels: microscopic (fiber type), mesoscopic (yarn geometry and fineness), and macroscopic (fabric porosity) levels. The fifth article dealt with the influence of the seam type and the sewing thread fineness on the transport properties of the seamed structure.

Keywords: thermal comfort; air permeability; thermal insulation; moisture permeability; porosity.

EDITORIAL

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Comfort is a fundamental and universal need for a human being. Human perception of clothing comfort is a function of environment, garment, body, and psychological factors. Therefore, comfort is a multi-dimensional and complex phenomenon that is very difficult to define. According to a kind of universal definition, comfort is "a state of satisfaction indicating physiological, psychological, and physical balance among the person, his/her clothing, and his/her environment" [1]. The human body is a complicated thermodynamic system in which energy is produced by its metabolic activity and continuously dissipates into the environment to keep thermophysiological comfort, *i.e.* to achieve thermal equilibrium at normal body temperature with the minimum amount of bodily regulation (vasoconstriction, vasodilatation, sweating and shivering). The human perception of thermal comfort is the condition of the mind that expresses satisfaction with the absence of any unpleasant sensations of being too cool or warm or having too much perspiration on the skin. Being continuously in dynamic contact with the human body, clothing actively participates in the thermophysiological response of the human body, both to changes in physical activity and to changes in the environment. Therefore, clothing textiles' heat and mass transfer ability or transport properties are extremely important for a person's thermal comfort perception, allowing for the transfer of heat and perspiration generated by the body. The transport properties of textile materials include air permeability, water vapor permeability, and thermal transfer properties.

Efforts to achieve adequate transport properties of textile materials are mostly based on the engineering design of materials by adjusting their composition and geometrical structure achieved by the manufacturing methods and by the interaction of multi-scale (fiber, yarn, and fabric) hierarchical structure. Over the years, much research has been carried out to understand the transport properties of textile materials. However, considerable research efforts are still needed in this area to ascertain the explicit guidelines for the adequate design of clothing materials in terms of thermal comfort. Therefore, this special issue aims to contribute to these efforts by presenting new studies on the effects of material constituents (fiber, yarn, and fabric) on transport properties. The special issue consists of five articles. Two of them provide valuable insights into the understanding of heat transfer through specific textile fabrics. To fill the gap in the knowledge about the thermal behavior of rib knitted fabrics, Tasić *et al.* [2] investigated the thermal parameters of a range of rib knits differing in composition and knitting pattern. They attempted to establish explicit guidelines for

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engineering rib knits for socks based on end-use requirements. The study found that as the number of face loops on the technical face side of the knit increases, the coolness to the touch and thermal conductivity decreases. In addition, bamboo fiber has once again been proven suitable for hot climates.

Jacquard woven fabric refers to a specific woven structure that incorporates complex patterns directly into its weave rather than using printing or dyeing methods. The small number of studies on the transfer properties of jacquard woven fabrics inspired Kostajnšek and Bizjak [3] to investigate the influence of the size and distribution of the pattern and the type of weave (self-stitched double cloth, interchanging double cloth) on the thermal conductivity and air permeability of jacquard fabrics. The results reveal that the thermal conductivity of jacquard fabrics is affected by pattern size, with larger geometrical area leading to increased thermal conductivity. It has been shown in the study that the air permeability of jacquard fabrics is significantly influenced by the looseness of the weave, with the interchanging double weave being more permeable.

The water vapor permeability of clothing textiles refers to their ability to allow perspiration to pass through from the human body. Previous studies indicated water vapor diffusion as the dominant mechanism for moisture transport under steady-state conditions. The transfer of water vapor in fabric depends on the inter-yarn pores, as vapor can diffuse through air spaces in the fabric much faster than through the fibers themselves [4]. The research conducted by Tomovska *et al.* [5] specifically looked at the impact of biaxial extension on the water vapor permeability of polyamide pantyhose. Simulating the real wearing condition of the pantyhose, they found that for all extensions applied, the evaporative resistance significantly decreased as compared to the relaxed state due to enlarged inter-yarn pore size while stretching the knit. However, they also suggested that the linear density of the pantyhose's filament was responsible for the level of change in evaporative resistance with biaxial extension.

During high physical activity of a person when liquid perspiration is produced and needs to be transferred away from the skin to keep the thermal balance, the ability of next-to-skin garments to let the sweat pass through becomes essential for thermal comfort [6]. In this respect, Petrov *et al.* [7] evaluated the liquid management properties of an assortment of commercial knitted materials used for sport and leisure clothing. The knitted fabrics varied in fiber composition, mass per unit area, and porosity. It has been shown that the drying time of the samples correlates moderately with their mass and highly with their porosity. Considering the fact that modern sportswear garment is often made of several different textile materials, they suggest using pure polyester in garment areas that require quick drying. Being the most porous, it has a short drying time and the smallest wetting area.

Thermal comfort properties of textile materials are determined by fiber type (chemical and morphological specifications), physical and constructional properties of yarns and fabrics, and finishing treatment. Apart from these properties, garment design (in terms of style and design details) and fit can play a crucial role in achieving ideal thermal comfort [8]. Considering that the seam has a minimum of two layers of fabrics joined by sewing thread, assembling garment parts by using seems to produce the required design may affect the comfort properties of the garment. Maanvizhi *et al.* [9] investigated the effect of overlock and flatlock seam stitches, the most commonly used stitch types in active sportswear, on the transport properties of single jersey polyester seamed fabric. They also indicated the effect of sewing thread filament fineness on the heat and mass transfer through the seam structure.

We believe that the investigations presented in this special issue will enhance the current understanding of textile material transport properties, inspiring future research to improve clothing comfort.

I would like to thank all the authors for their efforts to prepare the articles or modify them based on the reviewers' comments. I also wish to express my gratitude to the reviewers for their valuable contributions. Special thanks to Editor-in-Chief Prof. Dr. Bojana Obradović for her guidance and support, and to the editorial staff for their assistance in producing this issue.

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Transportna svojstva i propustljivost tekstilnih materijala

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(Reč urednika)

Izvod

Sposobnost tekstilnih materijala da prenose toplotu i masu ima ključnu ulogu u obezbeđivanju optimalnog toplotnog komfora korisnika. Toplotna svojstva, propustljivost vazduha i vodene pare predstavljaju osnovne parametre tekstilnih materijala koji definišu njihovu sposobnost da prenose toplotu i masu. Često se kao četvrti parametar tekstilnih materijala ističe sposobnost prenosa tečnosti, koji uslovljava doživljaj toplotnog komfora pri čestim promenama nivoa fizičke aktivnosti i klimatskih uslova okruženja, kada dolazi do vremenskog zaostajanja u termoregulaciji ljudskog organizma. Uprkos brojnim istraživanjima transportnih svojstava tekstilnih materijala sprovedenih poslednjih godina, neophodna su dalja istraživanja u cilju uspostavljanja pouzdanih smernica inženjerskog dizajna odevnih tekstilnih materijala sa zadovoljavajućim svojstvima u pogledu toplotnog komfora. Stoga, ovo specijalno izdanje časopisa Hemijska industrija, koje obuhvata pet radova, ima za cilj da obezbedi dragocene informacije u ovoj oblasti. U okviru predstavljenih istraživanja, ispitivane su komercijalno dostupne ili posebno projektovane tekstilne strukture sa ambicioznim ciljem da se pruže nova saznanja o njihovim transportnim svojstvima. U okviru prva četiri rada razmatran je kompleksan uticaj hijerarhijske strukture tekstilnih materijala na njihova transportna svojstva, pri čemu su obuhvaćeni svi strukturni elementi: vlakna, pređe i tkanine (ili pletenine). Poslednji rad se odnosi na ispitivanje uticaja vrste šava i finoće šivaćeg konca na prenos toplote i mase kroz šavnu konstrukciju.

Ključne reči: toplotni komfor; propustljivost vazduha; termička izolacija; propustljivost vlage; poroznost

Natemu

Influence of structural and constructional parameters of knitted fabrics on the thermal properties of men's socks

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Abstract

The research is focused on determining the influence of structural and constructional parameters of rib knitted fabrics on the thermal properties of men's socks. Men's socks are made in three different pattern constructions of three types of basic yarns: bamboo, cotton and a cotton/polyester blend with the additional filament polyamide yarn and wrapped rubber wire for the so-called render socks. For all analyzed sock rib patterns, the most important structural parameters of the yarn and construction parameters of the knitted fabrics were determined. Thermal properties of socks such as the cool touch feeling property, thermal conductivity, heat retention coefficient and thermal resistance were determined by using Thermal Labo and Thermal Mannequin measuring devices. The structural and constructional parameters of knitted fabrics were shown to affect the investigated thermal properties of the socks, making them more or less insulating or heat conducting. Values of the warm-cold feeling parameter as well as thermal conductivity vary depending on the construction pattern, showing a decrease as the number of face loops is increased i.e. in the sequence R1:1> R3:1> R7:1. The ability to retain heat decreases in the opposite sequence R7:1 > R3:1 > R1:1. The highest values of heat retention were determined for R7:1 rib knitted socks by both methods. A regression equation has been established with thickness, loop length, mass per unit area and porosity as independent variables, and thermal resistance (determined by the Thermo Labo method) as the dependent variable. The loop length and mass per unit area were shown to contribute significantly to the model.

Keywords: yarn; rib knitted fabric; thermal insulation.

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ORIGINAL SCIENTIFIC PAPER

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1. INTRODUCTION

Socks are among the basic clothing items used in everyday life and are one of the most common products created by knitting. Socks not only serve to protect body parts from the cold, but nowadays they are an important fashion detail, which can visually improve the complete look of clothes. As a garment for the feet, they serve to absorb and remove moisture and sweat, preventing wet feet inconveniences, thus providing the necessary thermal and physiological comfort with the ability to adapt to the feet and leg shape [1].

In the sock production, along with polyamide, polyester and elastomeric (lycra, spandex) fibers, cotton, acrylic, viscose, linen, wool and their blends are used, as well as luxury fibers such as silk, cashmere and mohair. The most desirable are natural fibers such as cotton and wool, which have a very high ability to absorb moisture. Since the strength of natural fibers is low, the strength of socks is usually achieved by using synthetic fibers such as polyamide, polyester, acrylic and elastomeric fibers. Polyamide fibers have high dimensional stability and wear resistance, while acrylic fibers exhibit a long service life and provide softness and volume to socks. Daily wear socks are usually made of cotton for softness and comfort, while wool or acrylic fibers are more desirable for winter socks in order to warm the feet [2,3].

Knitted structures used in socks must be of adequate elasticity to fit the feet and legs. Rib knitted fabric, as well as smooth plain knitted goods are mainly used to produce socks. These structures are desirable because they provide

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elasticity and the ability to return to their original shape. The rubber part, so-called sock render, knitted on the upper part of the sock, prevents the sock from slipping down and is made of elastic threads. This rubber elastic part of the sock is usually 3 to 5 cm wide and is supported by a wrapped rubber wire or elastane (lycra). To ensure a long lifespan in the heel and toe area, a double heel is usually made, using fibers such as polyamide and cotton. Sometimes knitted structures made of fine and tough cotton yarns are used, which improve durability [2,3]. Also, in addition to the type of fibers, two special types of yarns with thermoregulatory effects, (*e.g*. Outlast and Coolmax) significantly affect characteristics and structure of the knit, especially in terms of thermal properties and air permeability. With 100 % pure fiber structures, similar values of thermal resistance were recorded for elastane or polyester, while slightly higher values were recorded for polyamide textiles [4,5].

Furthermore, it was observed that changing the stitch type affects the air permeability and thermal resistance properties of single knits. Increasing the porosity of a fabric by increasing the percentage of stressed seams results in an increase in air permeability of the fabric. Greater permeability can be achieved by alternating knitting and looping. The fabric thermal resistance depends primarily on air that is enclosed within the knitting structure. The most important factor affecting thermal resistance is the thickness of single knitted fabric [6].

Thermal-physiological comfort of socks depends on the type of yarn or fibers and their characteristics, density, thickness, bulk density, and porosity of the knit. Of the thermal-physiological properties, thermal conductivity, water retention capacity, air permeability and water vapor permeability stand out [7,8].

According to the available literature data, as well as in scientific discussions, certain shortcomings were observed leading to the idea for this research in the field of ribbed knitted socks. This research is based on carefully designed non-commercial knitwear patterns from specially selected yarns, suitable for sock production. Bearing in mind that the comfort and convenience of socks have very complex properties, this research aims to confirm the use of rib knitted socks with new findings in order to define characteristics needed to increase the thermal and physiological comfort. For this purpose, the effects of structural and constructional parameters of rib knits on the thermal and physiological comfort of men's socks intended for everyday use were investigated with the goal of engineering design of rib knits for socks for certain purposes.

2. EXPERIMENTAL

2. 1. Materials

Men's socks are made of three types of basic yarns (bamboo, cotton and a blended cotton/polyester yarn purchased from BIM tex, Leskovac), which are knit into each row along the entire length of the socks. Together with the basic yarn (dominant yarn with the highest percentage share in the raw material composition), filament PA 6.6 yarn (purchased from BIM tex, Leskovac) is also knitted at the beginning of sock knitting, the so-called render of socks, a wrapped rubber thread was introduced.

The raw material compositions and basic structural characteristics of yarns for making socks are shown in Table 1. These are single yarns, except polyamide, which is a two-folded multifilament yarn. The Z- and S-twist alternate, except for the rubber wire which had to be stabilized. The rubber yarn is present in the smallest amount of only 1 ± 3 mass.% in the composition of the sock, it is wrapped in two layers with the polyamide yarn of linear density of 78 dtex and is used to make socks at the beginning, the so-called render socks, with the width of 3-5 cm. This wrapped rubber yarn serves to hold the sock along the lower part of the lower leg, to fit well, not to shear, but at the same time, not to tighten too much and be uncomfortable.

The socks are made in the same pattern construction, rib construction, (the face of the sock is made on the lower cylinder and the back on the upper cylinder), with different number of loops on the face (7, 3 and 1 loop) and the same number of loops on the back (1 loop) (designated as R1:1, R3:1, and R7:1, respectively).

2. 2. Methods

Determination of the basic characteristics of yarn for socks was realized according to the appropriate standards: linear density of yarn was determined according to the standard SRPS EN ISO 2060: 2012; number of turns according to SRPS EN ISO 2061: 2016 and breaking force and elongation at break according to SRPS EN ISO 2062: 2012.

Testing of the basic parameters of the structure of knitted socks was also carried out according to the appropriate standards: horizontal and vertical density was determined according to the standard SRPS EN 14971: 2012; length of yarn in a loop according to the standard SRPS EN 14970: 2014; knit thickness according to SRPS EN ISO 5084: 2013; mass per unit area of knitted fabric according to the standard SRPS EN 12127: 2014.

The bulk density of the knitted fabrics [9] was determined according to the equation (1):

$$\gamma = \frac{m}{h} \tag{1}$$

where m is the average mass per unit area of the knit and h is the thickness of the knit.

The porosity, P / %, of the knit [10] is calculated according to the equation (2):

$$P = \left(1 - \frac{m}{\rho h}\right)100 \tag{2}$$

where ρ is the density of yarn fibers.

Thermal properties of socks samples were measured by using the KES-F7 Thermo Labo Tester (Kato Tech Co., Ltd., Japan). For this purpose, the thermal conductivity λ, the heat retention coefficient α, the so-called warm-cold feeling q_{max}, and thermal resistance R_{ct} were measured, which allow functional and sensory evaluation of thermal properties of the knitted fabrics from the point of view of thermal comfort [11-13].

The thermal conductivity λ is determined according to equation (3):

$$\lambda = \frac{\phi h}{A \Delta T} \tag{3}$$

where ϕ is the heat flow, A is the area of the heat plate and ΔT is the temperature difference of sample.

The heat retention coefficient α is calculated on the basis of the measurement of the heat flux values without (W_0) and with the sample (W), expressed as a difference in these values in relation to the density of heat flux determined without the sample, equation (4):

$$\alpha = \frac{W_0 - W}{W_0}100 \tag{4}$$

The warm-cold feeling q_{max} / W·cm^{-2} is the measure of the maximum heat loss at the moment of simulation of skin contact with the fabric, which is the largest value of the instantaneous heat flow through the fabrics.

The thermal resistance R_{ct} is determined according to the standard ISO 11092:2014, equation (5) [11-13]:

$$R_{ct} = \frac{T_s - T_a}{H_c} A \tag{5}$$

where: T_s is the temperature of the measuring unit (skin temperature), T_a is the air temperature, A is the surface area of the measuring unit, and H_c is the dry heat flux, that flows through the material.

The thermal resistance was also determined by using the Thermal Mannequin (Faculty of Textile Technology, Croatia) according to the standard ISO 15831-2004. Measurements lasted for 20 min with collection of 10 measurements per minute with the average value printed at the end of each 1 min time interval. At the end of measurements, average values of temperature, power consumption, and total thermal resistance of the measured surfaces were automatically recorded. The so-called constant of the Thermal Mannequin, R_{ct0}, is determined by the following equation (6) [14,15]:

$$R_{ct0} = \frac{T_s - T_a}{H_0} A \tag{6}$$

where: R_{ct0} is the total thermal resistance of the empty surface of the measuring device together with the boundary layer of air along the surface (m^2 K·W^{-1}), A is the surface area on which measurements are performed, T_s is the surface temperature of the measured surfaces of the Thermal Mannequin, T_a is the ambient air temperature, and H_0 is the electric power required to heat the empty measured surface of the Thermal Mannequin (undressed mannequin).

After determining the constant R_{ct0}, the Thermal Mannequin was dressed in the selected garment and the operation of the device is monitored until a new thermal balance is achieved. After reaching the equilibrium, which can be detected by stabilization of the parameter values (numerically and by graphic representations), the thermal resistance R_{ctn} is determined according to the equation (7) [14,15]:

$$R_{\rm ctn} = \frac{\left(T_{\rm a} - T_{\rm s}\right)A}{H_{\rm m}} - R_{ct0} \tag{7}$$

where H_m is the supplied electric power required to maintain the temperature of the measured surfaces at the Thermal Mannequin. All measurements of thermal properties were performed at the Faculty of Textile Technology, Croatia.

2. 3. Yarn and socks characteristics

The data shown in tables 1 and 2 were obtained by measuring according to the specified standards at the institute Vunil d.o.o., Leskovac. Numerous values of the statistical parameter standard deviation are also shown in tables 1 and 2 (mean±standard deviation).

Table 1. Composition of raw materials and basic structural characteristics of yarns for making socks

Composition of raw materials of the socks		Content, %	Linear density, tex	Twist, m^{-1}	Breaking tenacity, $cN\cdot tex^{-1}$	Elongation, at break, %
Bamboo socks	Bamboo* (BB)	75.46	30.75 ± 1.3	610±9.6	13.53±1.1	15.12±1.3
	Polyamide (PA)	23.52	4.57×2 ± 0.5	93±7.1	41.75±0.9	30.44±1.6
	Wrapped rubber wire	1.02	100.40 ± 1.7	-	4.21±0.6	368±9.9
Cotton socks	Cotton* (CO)	77.49	30.10 ± 0.9	618±9.3	14.47±0.9	4.76±0.7
	Polyamide (PA)	21.48	4.52×2 ± 0.4	96±7.0	39.60±0.9	28.96±1.5
	Wrapped rubber wire	1.03	100.80 ± 1.6	-	4.39±0.5	345±9.7
Cotton/ Polyester socks	CO/PES* 60/40 %	75.22	29.70 ± 0.8	623±9.2	14.10±1.2	6.04±0.8
	Polyamide (PA)	23.77	4.49×2 ± 0.5	98±7.2	41.77±0.8	32.43±1.7
	Wrapped rubber wire	1.01	100.30 ± 1.7	-	4.34±0.5	352.78±9.8

*Basic yarns

A two-cylinder sock machine was used to make the socks, made by “Lonati Bravo 856” (Lonati, Italy), 95 mm ($3^{3/4}$ inch) in diameter, with 168 needles, while a special sewing device - "Rosso 025 full tronic" (Rosso, Italy) - was used to close the toes.

All sock samples (30 per the sock type) were made in the size number 11 with basic parameters: foot length 28 cm, sock leaf length without render 16 cm and render width 4 cm, which corresponds to the size of footwear 42-43. Table 2 presents the results of the most important construction parameters of rib construction socks and different raw material compositions.

Table 2. Design parameters of rib knitted socks size 11 (42-43)

Sock mark (basic yarn-pattern construction mark)	Thickness, mm	Horizontal density, cm^{-1}	Vertical density, cm^{-1}	Loop length, mm	Mass per unit area, $g\cdot m^{-2}$	Bulk density, $g\cdot cm^{-3}$	Porosity, %
BB-R1:1	1.70 ± 0.04	14.2 ± 0.4	9.7 ± 0.2	6.4 ± 0.1	339.8 ± 5.3	0.20 ± 0.02	86.8 ± 1.1
CO-R1:1	1.75 ± 0.08	14.3 ± 0.4	9.6 ± 0.3	6.3 ± 0.2	377.4 ± 9.0	0.21 ± 0.01	86.1 ± 1.4
CO/PES-R1:1	1.69 ± 0.1	14.4 ± 0.8	9.5 ± 0.4	6.1 ± 0.3	307.7 ± 8.5	0.18 ± 0.02	87.7 ± 1.6
BB-R3:1	1.68 ± 0.1	11.2 ± 1.4	11.9 ± 1.3	5.4 ± 0.5	318.9 ± 8.1	0.19 ± 0.01	87.5 ± 1.8
CO-R3:1	1.72 ± 0.1	11.3 ± 1.2	11.8 ± 1.3	5.3 ± 0.4	335.9 ± 8.4	0.19 ± 0.01	87.4 ± 1.6
CO/PES-R3:1	1.67 ± 0.09	11.1 ± 1.2	12.0 ± 1.3	5.4 ± 0.4	307.1 ± 7.7	0.18 ± 0.01	87.6 ± 1.4
BB-R7:1	1.65 ± 0.08	10.9 ± 1.0	12.2 ± 1.3	4.7 ± 0.6	318.1 ± 9.8	0.19 ± 0.01	87.3 ± 1.8
CO-R7:1	1.69 ± 0.07	10.8 ± 1.1	12.3 ± 1.4	4.7 ± 0.6	339.9 ± 8.3	0.20 ± 0.02	87.0 ± 1.8
CO/PES-R7:1	1.61 ± 0.08	11.0 ± 0.8	12.1 ± 1.0	4.6 ± 0.8	297.7 ± 9.5	0.18 ± 0.01	87.5 ± 1.5

3. RESULTS AND DISCUSSION

Knitted fabric is a flat textile product made of a large number of interconnected loops that make up basic structural elements of the knit. These are very complicated structures with many elements that define the final functional properties and therefore should be investigated and defined.

Table 3 provides results of testing the thermal characteristics of socks by a Thermo Labo tester and a Thermal Mannequin. Higher values of the parameter warm-cold feeling, q_{max}, represent a colder feeling and lower values a warmer feeling, *i.e.* a higher value means faster heat loss from the skin through the knit, while the knit leaves the impression of cooling [11]. According to the obtained results, it can be seen that q_{max} is highly dependent on the loop length and porosity. As the value for the mass per unit area or bulk density of the sock increases, q_{max} generally increases. Also, the values for q_{max}, vary depending on the pattern construction, showing a decrease in sequence, R1:1> R3:1> R7:1. The reason lies in the number of loops on the face (*i.e.* 1, 3 and 7 loops, respectively) and back (*i.e.* 1) and consequently the appearance of a more compact and even structure of rib construction, when the sock gives a warmer or cooler feeling.

Socks of the BB yarn give a greater sense of coolness, followed by articles of the CO yarn and finally of the CO/PES yarn. In this regard, it can be concluded that the sock marked BB-R1:1 is recommended for use in warmer days, *i.e.* in spring and summer. Socks with markings, CO/PES-R7:1 and CO-R7:1, proved to be a bit warmer, *i.e.* inducing lower feeling of cold on the skin, so they are recommended for wearing on colder days, *i.e.* in autumn and winter.

Thermal conductivity is one of the most important parameters for the insulating ability of a material and its measurement is based on the heat transfer from the warmer to the colder part, *i.e.* heat conduction. The increase in thermal conductivity signifies higher ability for heat transfer and lower thermal resistance [11-13]. It is noticeable that λ depends on the raw material composition of socks, pattern construction or loop length of the tested samples. For all socks of the same basic yarns, thermal conductivity decreases with the pattern construction order R1:1>R3:1>R7:1. Also, the values of λ are related to the loop length, thickness or the mass per unit area of the sock in proportional manner.

Considering the results for λ, it can be concluded that socks with base yarns of BB and CO achieve better heat conduction and are therefore recommended for use on warmer days, which is in line with the claim of the influence of the warm-cold feeling parameter.

The heat retention coefficient, α, decreases starting from R7:1 to R1:1 regardless of the raw material composition, which means that the construction and structure of the knitted fabrics are decisive factors that define the ability to retain heat. R7:1 sock retains more warm air in its volume as compared to socks with the other knitting patterns. While the CO/PES sock has the highest heat retention coefficient, the lowest α value was determined for the bamboo knits of any knitting pattern, which is explained by the structure and properties of the fibers used. Structure (surface morphology, fiber porosity, etc.) and fiber properties affect heat retention properties. For example, an interesting property is the thermal conductivity of individual fibers (*e.g.* for bamboo-like fibers the thermal conductivity is about 0.230 $W \cdot m^{-1} \cdot K^{-1}$; for cotton 0.464 $W \cdot m^{-1} \cdot K^{-1}$ and for polyester 0.141 $W \cdot m^{-1} \cdot K^{-1}$ [11]). Namely, considering the order of magnitude lower value for air of 0.026 $W \cdot m^{-1} \cdot K^{-1}$ [11] it is obvious that the thermal conductivity of textiles will be higher with the increase in the proportion of fibers in the volume of the material or the use of fibers with higher thermal conductivity.

The parameter thermal resistance of socks (determined by the Thermo Labo method), R_{ct}, varies according to the pattern construction, raw material composition or individual design parameters. In essence, the thermal resistance reflects the thermal insulation of the material and is greatest at rest because in that case the air under the sock is also at rest [12,13,16]. The highest values of R_{ct} were registered for R7:1 socks of rib construction marked R7:1, as well as for socks that have CO/PES as the basic yarn in the composition. Thus, the R7:1 rib knitted sock is the largest thermal insulator, while a sock marked R1:1 is the largest thermal conductor as also determined above and explained by a more compact and more even structure of R7:1 compared to the other patterns. The presence of 7 loops on the face and one loop on the back of the sock, implies a larger continuous contact surface and a more even number of contact points compared to the other rib knits (lower change of loops on the face and back), providing a larger area for skin contact, greater coverage and thus weaker heat dissipation. On the other hand, socks marked R3:1 and R1:1 have more frequent change of loops on the face and back, as well as a longer length of loops, which causes a special shape of rib knitted fabric that is more conductive. Socks that have the least values for thickness, loop length, mass per unit area or bulk density show the highest values for thermal resistance, which is not expected but is associated with a more dominant influence of other parameters that are decisive, *e.g.* by pattern construction or by the type of basic yarn.

It is interesting to consider the thermal resistance results of the socks determined by the Thermal Mannequin, R_{ctn}, where the socks are in a tense, slightly stretched state, similar to the wearing conditions. The R7:1 socks stand out providing significant resistance, while the lowest value of thermal resistance is registered for R1:1 socks. While the loop length values decrease in the sequence R1:1>R3:1>R7:1, there is a noticeable increase in the thermal resistance, R_{ctn}, in the sequence R1:1<R3:1<R7:1, regardless of the raw material composition. The values of porosity and sock thickness decrease in the series of marks R3:1>R7:1, which is opposite to the changes in R_{ctn}.

The values of R_{ctn} in socks of different pattern construction and raw material composition in the stretched state reflect the deformation of the loop in the rib knitted fabrics due to stress, when the whole structure is deformed, thus changing the thermal behavior. On the other hand, when measuring the thermal resistance in the relaxed state, R_{ct}, effects of the original structure and construction of the knit, density, loop size, thickness, porosity, *etc.* are more pronounced.

Table 3. Thermal properties of rib knitted socks determined by the Thermo Labo and Thermal Mannequin tests

Sock tags	Photographs showing the sock surface	Thermo Labo method				Thermal Mannequin method
		q_{max} / W·cm^{-2}	λ / W·m^{-1} K^{-1}	α / %	R_{ct} / 10^3 m^2 K·W^{-1}	R_{ctn} / 10^3 m^2 K·W^{-1}
BB-R1:1		0.100	0.050	18.64	32.31 ± 0.001	16.93 ± 0.0005
CO-R1:1		0.094	0.053	22.03	32.85 ± 0.001	16.97 ± 0.0005
CO/PES-R1:1		0.086	0.052	22.46	34.97 ± 0.0007	17.20 ± 0.0007
BB-R3:1		0.072	0.048	18.22	35.29 ± 0.0009	17.97 ± 0.001
CO-R3:1		0.066	0.052	22.88	37.04 ± 0.001	18.35 ± 0.001
CO/PES-R3:1		0.060	0.048	24.58	37.44 ± 0.001	18.39 ± 0.001
BB-R7:1		0.057	0.041	22.03	40.54 ± 0.001	19.57 ± 0.001
CO-R7:1		0.045	0.037	27.97	46.18 ± 0.002	19.98 ± 0.0009
CO/PES-R7:1		0.044	0.033	31.78	48.19±0.0009	19.99±0.0008

3. 1. Correlation and regression analysis of measurements

Figure 1 shows the correlation of the thermal resistance results determined by the Thermo Labo (R_{ct}) and Thermal Mannequin (R_{ctn}) methods for all socks investigated in the present study. The value of the obtained Pearson's correlation parameter (r = 0.949) indicated statistically proven linear correlation between the results measured by two different measuring devices. In other words, the correlation analysis of the thermal resistance results of the socks in the relaxed state measured by the thermal plate and the corresponding values for the socks in the stressed state determined by the Thermal Mannequin showed that there is a statistically significant correlation between the measurements (Fig. 1).

Next, multiple linear regression analysis is performed, which studies the relationship between several regression (independent) variables and criterion (dependent) variables and/or serves for prediction of the value of the dependent variable based on one or more regression variables. It is an extension of a simple linear regression in which there are now several independent variables (x_1, x_2, x_3…) used to study the effects on the dependent variable *(y)* [14,15].

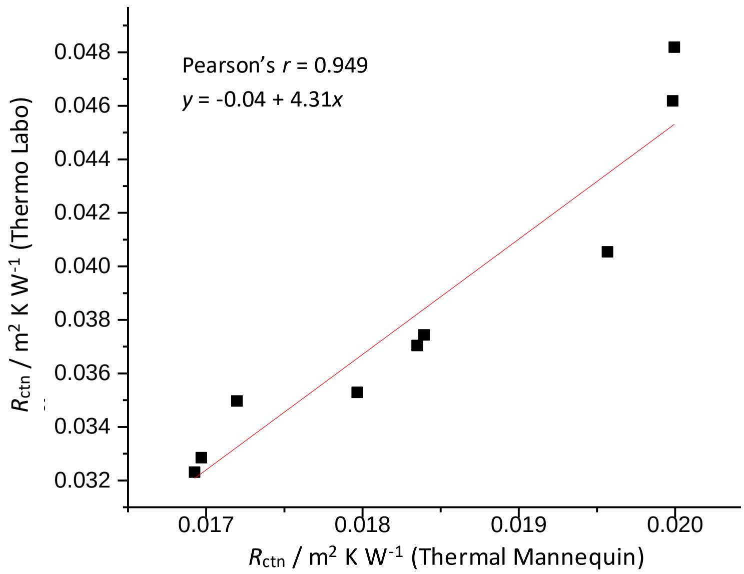

Figure 1. Correlation between thermal resistances determined for all sock types investigated in the present study by using Thermo Labo and Thermal Mannequin measuring systems

In the selected case, the dependent variable is the thermal resistance R_{ct} (determined by the Thermo Labo method) of bamboo socks in all knitting patterns. These sock samples were selected based on the lowest results for R_{ct}, regardless of the pattern construction. Thickness (T), loop length (L), mass per unit area (M), and porosity (P) were taken as independent variables, in order to explain the variability of the dependent variable, R_{ct}.

Tables 4 and 5 show the data of this type of analysis, starting from the applied parameters and their coefficients, through the basic statistical data on the success of the dependence description to the Anova analysis, *i.e.* analysis of variance.

According to Table 4, the regression equation-model, can be represented as in equation (8):

$$R_{ct} = 0.044 + 0.0064T - 0.0064L + 1.14\times10^{-4}M - 2.34\times10^{-4}P \quad (8)$$

Table 4. Values of the coefficients of the regression model for prediction of R_{ct} of bamboo socks

	Value	Standard error	*t*-value	Prob >|*t*|
Intercept, m^2 K·W^{-1}	0.044	0.056	0.78	0.48
T / mm	0.0064	0.022	0.28	0.79
L / mm	-0.0064	0.001	-5.97	0.0039
M / g·m^{-2}	1.14×10^{-4}	2.78×10^{-5}	4.10	0.0148
P / %	-2.34×10^{-4}	9.75×10^{-4}	-0.24	0.82

Given the very high value of the coefficient of determination (R^2 = 0.988), it is concluded that 98.8 % of the variability of the dependent variable can be explained by using the analyzed independent variables.

According to Table 4, the independent variables loop length and mass per unit area significantly contribute to the model (Prob > |t| = 0.0039 and 0.0148 < 0.05, respectively). The other variables, thickness and porosity have values for Prob > |t| > 0.05, so their contribution to the model is lower (Prob > |t| = 0.79 and 0.82, respectively), since these values exceed the standard level of significance (p = 0.05).

Analysis of variances for multiple regression, Table 5, tests the significance of the regression relationship, *i.e.*, checks whether the independent variables are relevant for describing the behavior of the dependent variable. This table highlights a statistically significant F-value (Prob> F = 4.47×10^{-4} < 0.05), so the use of this model is justified, *i.e.* the thickness, loop length, mass per unit area and porosity regressors cause at least 95 % variance of the R_{ct} variable. Thus, there is a statistically significant association between the key variable and its regression variables. In other words, the used regression model is practically usable because with the help of selected properties of socks, the thermal resistance of socks can be predicted with great reliability. In addition, the model could be tested for prediction of the values of thermal resistance for other socks produced from a similar raw material composition and different rib knitting patterns when the construction parameters, thickness, loop length, mass per unit area and porosity are known.

Table 5. Parameters of the Anova analysis for multiple regression of R_{ct} of bamboo socks

	Degrees of freedom	Sum of squares	Mean square	*F* value	Prob > *F*
Model	4	1.02×10^{-4}	2.55×10^{-5}	80.58	4.47×10^{-4}
Error	4	1.26×10^{-6}	3.16×10^{-7}		
Total	8	1.03×10^{-4}			

Normality and linearity of the distribution, as well as the existence of atypical points are analyzed in graphs presented in Figure 2. The upper diagram shows that the values of the dependent variable, experimentally determined and predicted by the model, are highly overlapping, implying that that the criterion of acceptability and significance of the regression model is met.

The lower diagram (Fig. 2) confirms that atypical points and large variations of residuals are absent *i.e.* deviations are fairly evenly distributed and most results are accumulated around a straight line, *i.e.* around point 0. The horizontal band pattern suggests that the residual variance is constant.

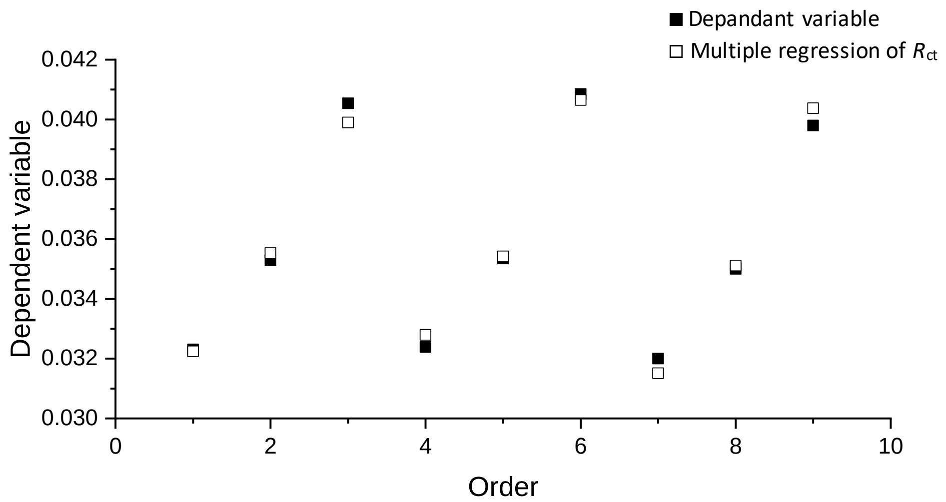

Figure 2. Diagrams of model validity and regularity of residuals

4. CONCLUSION

Thermophysiological comfort of knitted socks depends on many parameters. A comprehensive approach to measuring and calculating a number of parameters in the technological process including yarn characteristics, production variables and the final sock characteristics can provide reliable indicators for quality characterization of the properties of finished socks.

The results obtained in this research emphasize the fact that thermal properties of socks largely depend on the rib knitting pattern, type of the basic yarn in the blend and finally on the type of fiber out of which this basic yarn is made.

The results obtained in the present study for the parameter warm-cold feeling, thermal conductivity and heat retention coefficient varied depending on the construction pattern, mass per unit area, loop length, thickness and raw material composition. Socks of basic bamboo yarn are recommended for use on warmer days, *i.e.* in spring and summer. Socks marked CO/PES-R7:1 and CO-R7:1 proved to be warmer, so they are recommended for use on colder days, *i.e.* in autumn and winter.

Thermal resistance of the socks determined by using two methods (Thermo Labo and Thermal Mannequin) varied according to the construction pattern, raw material composition and individual tested properties. The R7:1 rib knitted sock is the greatest thermal insulator, while the R1:1 sock is the greatest thermal conductor in the present study, which is due to the fact that the R7:1 rib knitted sock has the most compact and even structure compared to the other knits, owing to the very construction and arrangement of loops. Also, thermal resistance values determined by the two methods for socks in the relaxed state and in the stressed state were shown to be linearly correlated with the statistical significance.

Multiple linear regression showed that the independent variables loop length and mass per unit area significantly affect the dependent variable - thermal resistance of socks (determined by the Thermo Labo method).

Based on the above, it can be concluded that bamboo (regenerated cellulose) socks, regardless of the knitting pattern, are more suitable for wearing during higher temperatures or in summer, while for lower temperatures, socks made of the CO/PES blend or pure cotton are better solution.

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Uticaj strukturnih i konstrukcijskih parametara pletenina na termička svojstva muške čarape

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(Naučni rad)

Izvod

Istraživanje je fokusirano na utvrđivanje uticaja strukturnih i konstrukcijskih parametara rebrastih pletenina na termička svojstva muških čarapa. Muške čarape izrađene su u tri različita prepletaja (1:1, 3:1, 7:1) od tri vrste osnovnih pređa: bambus, pamuk i mešavine pamuk/poliester sa dodatnom filamentnom poliamidnom pređom obmotanom gumenom niti za tzv. render čarape. Za sve analizirane uzorke čarapa u desno-desnom prepletaju, određeni su strukturni parametri pređa i konstrukcijski parametri pletenina. Uticaj pojedinih parametara na toplotna svojstva čarapa proveren je na temelju istrazivanja toplo-hladnog osećaja (toplota opipa), koeficijenta toplotne provodljivosti, koeficijenta sposobnosti zadržavanja toplote i toplotne otpornosti, određene pomoću mernih uređaja "Thermo Labo" i "Thermal Mannequin". Utvrđeno je da strukturni i konstrukcijski parametri pletenina utiču na toplotna svojstva čarapa, čineći ih manje ili više izolatorima, odnosno provodnicima toplote. Vrednosti parametra toplota opipa, kao i toplotna provodljivost variraju zavisno od prepletaja, pokazujući pad u nizu, R1:1 > R3:1 > R7:1. Sposobnost zadržavanja toplote opada u nizu, R7:1 > R3:1 > R1:1. Najveće vrednosti toplotne otpornosti određene pomoću oba primenjena metoda registrovane su kod čarapa rebrastog prepletaja oznake R7:1. Primenjena je regresiona analiza pri čemu su kao nezavisne promenljive izabrane debljina, dužina petlje, površinska masa i poroznost, dok je zavisna promenljiva toplotna otpornost određena primenom "Thermo Labo" uređaja. Pokazano je da nezavisne promenljive, dužina petlje i površinska masa značajno doprinose modelu.

Ključne reči: pređa; rebrasta pletenina; toplotna izolacija

Estimation of permeability properties of technologically developed jacquard fabrics

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Abstract

The study investigated how certain design parameters affect the permeability properties of jacquard fabrics. Six woven samples were made on the same cotton warp and with the same loom setting. The fabrics were made from two different types of weft yarns (cotton and Lyocell Clima), in two different pattern sizes (with larger and smaller monochrome areas), and two groups of double twill weaves (self-stitched double cloth, interchanging double cloth). We proved the importance of the size and distribution of the pattern/motif, the type of weave and the type of yarns used in the jacquard fabrics and the influence they have on the permeability properties in close relation to the aesthetic function. All patterns with interchanging double weave have significantly higher air permeability than patterns with self-stitched weave. For thermal conductivity, the influence of the raw material and the size of the pattern/motif is obvious. For fabrics with patterns with larger geometric areas, where the presence of weft threads on the surface is greater, the thermal conductivity is higher. The pattern size, on the other hand, does not affect the ultraviolet protection factor (UPF), unlike the raw material from which it is made.

Keywords: jacquard pattern; self-stitched / interchanging double weave; porosity; air permeability; thermal conductivity.

Available on-line at the Journal web address: http://www.ache.org.rs/HI/

1. INTRODUCTION

The use of jacquard fabrics has been popular in the textile and apparel industry for decades. They are used for both clothing and decorative purposes, precisely because of their appearance - diverse weaving patterns and use in various forms, which contribute to the final appearance and functionality of the fabrics. Modern jacquard fabrics can be made of a variety of fibres, from natural cotton or silk to blends with synthetic fibres such as polyester. What they all have in common is the jacquard structure, which means that the pattern is woven and shaped by a combination of different weaves and multicoloured yarns, usually creating complicated shapes in a complex structure, and they are in most cases stronger and thicker than many other fabrics. Some jacquard fabrics are double-sided, meaning that both the front and back side of the fabric are usable (*e.g.*, for decorative curtains), while others are clearly single sided, meaning that only one side of the fabric is usable (*e.g.*, for upholstered furniture).

Jacquard fabrics are not so widely used for clothing purposes, mainly because of the way they are made and their high price. Despite modern weaving technologies, digitization of processes and the use of CAD/CAM systems, the production of jacquard fabrics is still a challenge in itself. The doctrine of fast fashion does not allow the use of expensive jacquard fabrics, so they have been completely displaced by printed fabrics, and with the advantages of digital printing luxury jacquards have completely lost the battle. Only in haute couture, upholstery and interior design, this type of fabric continues to be used. This is also reflected in the small number of studies that have been conducted on the properties and characteristics of jacquard fabrics.

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Recently, the concept of sustainable fashion has come to the fore as sustainable principles have become a necessity in all production technologies, especially in the textile and apparel industry, which are among the biggest polluters. Sustainable production, product quality, product life cycle, recyclability and reusability are more important than price for many consumers. These are new circumstances in which jacquard fabrics have also become important for use in apparel. In addition, jacquard weaving of 3D woven structures for composites is also increasing in the field of technical textiles. Among the other 3D weaving techniques, multilayer weaving is interesting because of the variety and complexity of the possible 3D structures [1].

The literature review shows that most studies have been conducted to evaluate the physical-mechanical properties of jacquard fabrics used for upholstery. A study [2] was conducted on the self-cleaning properties of jacquard upholstery fabrics with different construction parameters. In this research, a nano-TiO_2 coating was applied to 18 double faced woven fabrics produced by the jacquard weaving technique with three different weft densities, two different raw materials for the warp threads, and three different face weave patterns under the same conditions using the sol-gel method. In addition to self-cleaning effectiveness, the effects of fibre type, weft setting and weave pattern on the air permeability of upholstery fabrics were also investigated.

The effects of design parameters of the woven fabrics are also reflected in the surface texture of the woven pattern, so their influence on the properties important to users was studied [3]. The effect of different weft yarn properties (yarn linear density and yarn types such as filament yarn, staple fiber yarn, and textured yarn) on surface abrasion performance of jacquard fabrics was investigated. The experimental results showed that the yarn properties and the degree of yarn crimp affect the abrasion resistance of the jacquard fabrics.

Bending properties of jacquard woven fabrics and the effects of weft density, weft yarn count, weave, and Lycra content in the weft on these properties have also been studied by Sule [4]. Different weft yarns were used on a viscose filament warp yarn for weaving jacquard satin fabrics. The experimental results showed that the bending rigidity of the fabrics in the warp and weft directions increases with increasing weft density and when thicker weft yarn is used. The bending rigidity is also influenced by the weave and, thus, by the number of interlacing points (4/1 satin and 7/1 satin), with fewer interlacing points inducing lower bending rigidity.

Properties of fabric depend on the raw material, the type of yarns and the construction properties of the fabric. The choice of material is important from the point of view that each material has its own properties, which are transferred to the fabric. Functionalization of fabrics allows influencing the physical-mechanical properties by using special yarns to improve for example elasticity [5,6], thermal regulation [7,8], protection against ultraviolet rays (UV) [9-11], *etc*. In addition, from the design point of view, the shape and size of the pattern, its frequency and distribution on the surface are also important, not only as a visual effect, but also in terms of the above-mentioned characteristics [12-14].

Permeability properties are of great importance for certain types of textiles, such as technical textiles (philtres), as well as for clothing and some decorative textiles, as they contribute to the comfort of the user. By comfort, we mean the ability to dissipate excess heat and/or water, regulate airflow, and protect against the effects of UV rays. The permeability of textiles depends on the type of penetrating medium, weather conditions, the geometric structure of the textile and the raw material [15,16].

The internal geometric structure of textiles, empty spaces of different shapes and sizes, *i.e.*, porosity and pore structure, are closely related to the permeability properties of textiles. Porosity is an important physical property of textiles and is defined as the volume of air in the total volume of the body, *i.e.* the ratio between the volume of empty spaces and the total volume of the textile. Porosity itself as a physical parameter of textiles is not sufficient for determination of the textile permeability. For a more accurate prediction, we need parameters that additionally describe the porosity, such as: the size, number, and distribution of pores. These provide detailed information about the internal geometric structure of fabrics and how it relates to the permeability properties of the fabrics. For this purpose, the Jakšić's porosity measurement method and optical methods for determining porosity parameters in woven fabrics were used in several experimental studies [17-21]. The authors' intention is to compare the two methods and obtain more descriptive data about the internal geometric structure of fabrics.

The aim of this work was to investigate how certain design parameters affect the permeability properties of jacquard fabrics and how to influence permeability by different jacquard patterns. The main objective was to determine the importance of the size and distribution of the pattern/motif, the type of weave (self-stitched/interchanging double cloth), and the type of yarns used in the design of jacquard fabrics, and the influence of these parameters on permeability properties in close relation to aesthetic function. For the porosity, size, and distribution of the pores, both the Jakšić and the optical method were used in the work. The influence of basic design parameters of jacquard fabrics on their properties is well known and well studied. However, the influence of design parameters as we ll as the weave structure, which determines the frequency of interlacing and compactness, has been studied to a much lesser extent. The aim of our research is therefore to focus not only on aesthetic function, but also on comfort and UV protection properties as functions of the structure of the jacquard weave.

2. EXPERIMENTAL

2. 1. Material

Six jacquard woven samples were produced on the same cotton warp (Tekstina d.o.o., Slovenia) (8×2 tex; warp sequence 1 black : 1 white) and with the same loom (Minifaber Spa, Italy) setting (40 warps/cm; 40 wefts/cm). The fabrics were made from two different types of weft yarns (Litia Spinnery, Slovenia) (cotton, 24 tex and Lyocell Clima, 25 tex), in two different pattern sizes (Figure 1; left - larger squares and right - smaller squares) and two groups of double twill weaves (Figure 3; self-stitched double cloth, interchanging double cloth). The sample labeling, characteristics of samples and on-loom settings are shown in Table 1.

Table 1. Characteristics of samples and on-loom settings

Sample	Pattern	Material and fineness, tex		Yarn density, cm		Yarn diameter, mm		Weave
		warp	weft	warp	weft	warp	weft	
1	larger	White CO 8×2 tex	CO 24 tex	40	40	0.1947	0.221	Double twill weaves
2	smaller							
3	smaller/ interchanging							
4	larger	Black CO 8×2 tex	Lyocell Clima 25 tex			0.2053	0.199	
5	smaller							
6	smaller/ interchanging							

For the design of fabric production, we used the program Arahne (Arahne d.o.o., Slovenia), which specializes in the development of CAD/CAM software for dobby and jacquard weaving [22]. In the design process, we combined the aesthetic side with the knowledge of how construction parameters and machine settings can affect the pr operties of the jacquard fabric. The size and shape of the pattern and its frequency can greatly affect certain properties of the fabric, both functionality and appearance. The surface texture and colour effect of the pattern on the fabric is determined by the weave, the yarn and its structure, the arrangement of the yarns, the density, and the colour of the yarns. In most cases, the surfaces in different areas of the pattern are not the same, so the size, shape, and frequency of the pattern play an important role.

Ratio of the size and shape of large and small patterns can be clearly seen in Figure 1. The length of the square in the fabric with the large pattern is 12.7 cm, while in that with the small pattern it is 7 cm, which is about 50 % smaller so that the frequency of alternating stripes where the weave changes is about 50 % greater. Patterns with larger areas (compared to smaller ones), exposes more of the yarn from which it is made and affects the surface by influencing the reflection of light, appearance of texture on the fabric surface, *etc.* The weave has also a major influence since it determines the interlacing points and the frequency of weft and warp threads on the surface and in the structure and this is also reflected in certain permeability properties (interchanging double cloth struc ture, self-stitched double cloth structure, weft/warp effect, *etc.*). Each part of the surface in the sample has a specific characteristic, so the differences in size and frequency of the sample area can be considerable.

For this purpose, to study the influence of the size and shapes in the jacquard patterns and the influence of different weave on the permeability properties, we created the first pattern with larger white, black, and grey squares that create a 3D visual effect (Figure 1, left), while the second pattern consists of frequently changing smaller squares (Figure 1, right). Different sizes and shapes in the jacquard patterns mean different frequencies of the different weaves, which affect the frequency of thread interlacing.

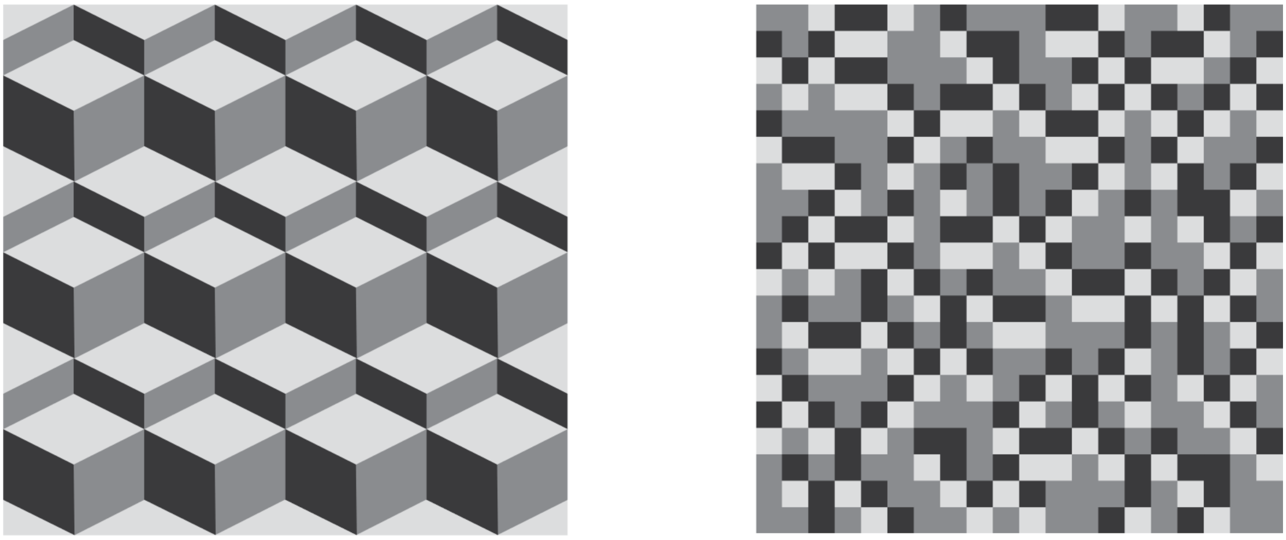

Figure 1. Patterns for fabrics in two different sizes (left - larger, right - smaller)

For all samples, a 1/5 twill double weave (Fig. 2) was used, a somewhat unclassical weave for all surfaces of the pattern but chosen to simplify the research study.

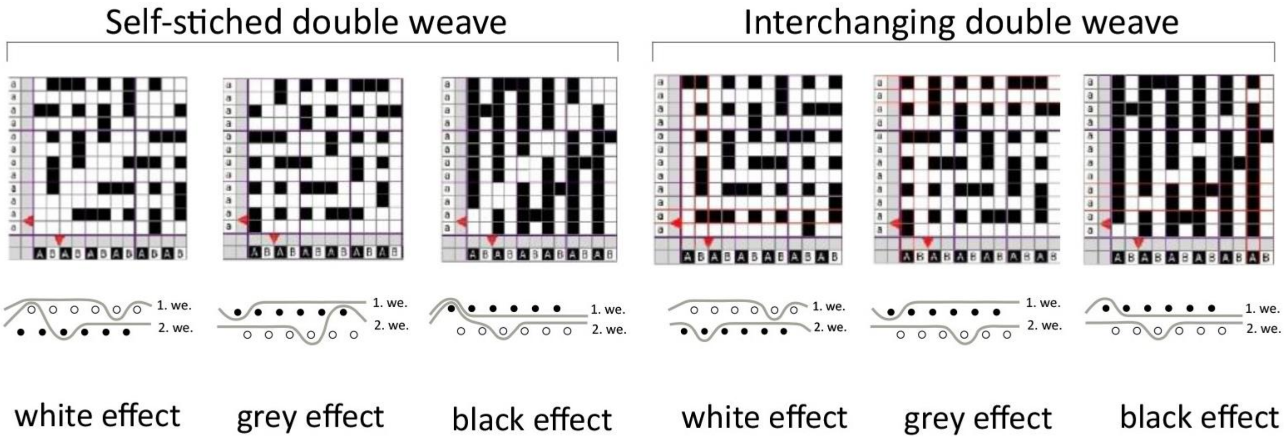

Figure 2. Weaves and weft cross sections for all three colours in jacquard patterns

To achieve the maximum black effect resulting from the colors of the yarn and the white weft threads (due to the warp sequence - 1A (black) 1B (white) and the weft sequence 1a (white), this was the only possibility to choose the stitching points as shown in the cross-section schema of black effect (Fig. 2, Self-stitched double weave). The black colour on the sample (Fig. 3, effect 2) was achieved with the warp weave effect, where the surface is dominated by a black warp. The white colour (Fig. 3, effect 3) was obtained with a weft effect combined with a white warp, with the studied white colour weft dominating the surface. The grey colour (Fig. 3, effect 1) was obtained with a weft effect in combination with a black warp, with the surface also dominated by the white colour weft.

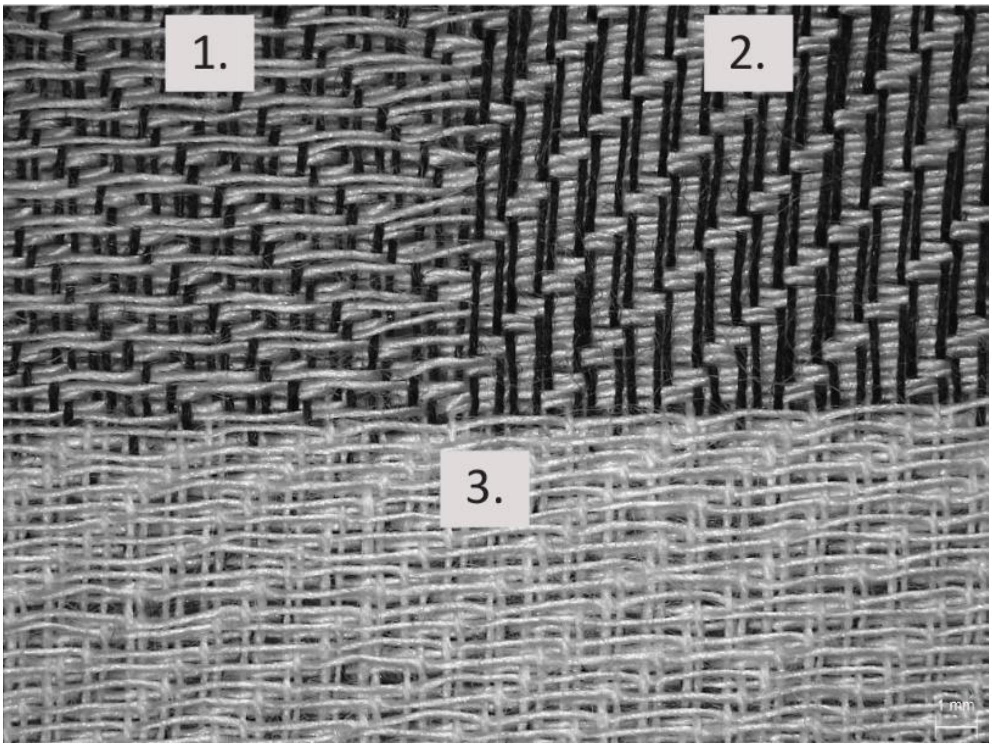

Figure 3. Different colour effects of woven fabric surface: 1. grey, 2. black and 3. white

2. 2. Methods

Physical, permeability and UV properties of the fabrics were investigated according to standard methods: warp and weft density (SIST EN 1049-2) [23], mass per unit area (SIST EN 12127) [24], thickness (SIST EN ISO 5084) [25], air permeability (SIST EN ISO 9237) [26], thermal conductivity (DIN 52 612) [27], UV transmission and reflection were measured and ultraviolet protection factor (UPF) was calculated, according to the standard EN 13758-1:2001 [28], size and distribution of pores were determined by using the Jakšić method [20].

The Jakšić method for determining the porosity of textiles is based on selectively squeezing the liquid in the pores out of the wet textiles by pressure. On the rotameter, at different pressure differences, the volume velocity of the air flow through a given surface of the dry sample is measured. The sample is then immersed in a liquid of known density and surface tension. When it is completely wetted, it is inserted into the measuring head of the rotameter and the pressure difference is determined until an air bubble appears. The differences are read, and the hydraulic diameter of the largest pore is calculated. Then the pressure is increased, and the pressure value is read at preselected volume flows. The measurement is completed when the volume has been squeezed out even from the smallest pores [20].

The optical method uses image analysis and is based on the transmission of visible light through a fabric. Image analysis is commonly used to successfully determine the open structure (or cover factor) of fabrics with sufficient accuracy. The purpose of the above method is to obtain faster and more accurate results by combining the results of image analysis with some results of porosity measurement. For this purpose, we used an open-source image processing program developed in ImageJ platform (open-source software) for analysis of scientific multidimensional images [29-32]. The visually displayed image processing is shown in Figure 4.

The fabrics in self-stitched 1/5 twill double weave are marked as sample 1, 2, 4 and 5, the fabrics in interchanging 1/5 twill double weave are marked as sample 3 and 6 (Fig. 2). The different distribution and frequency of interlacing in the fabric affects the compactness of the fabrics, making it possible to study comfort or protective properties, such as UV protection, as a function of the compactness of the pattern.

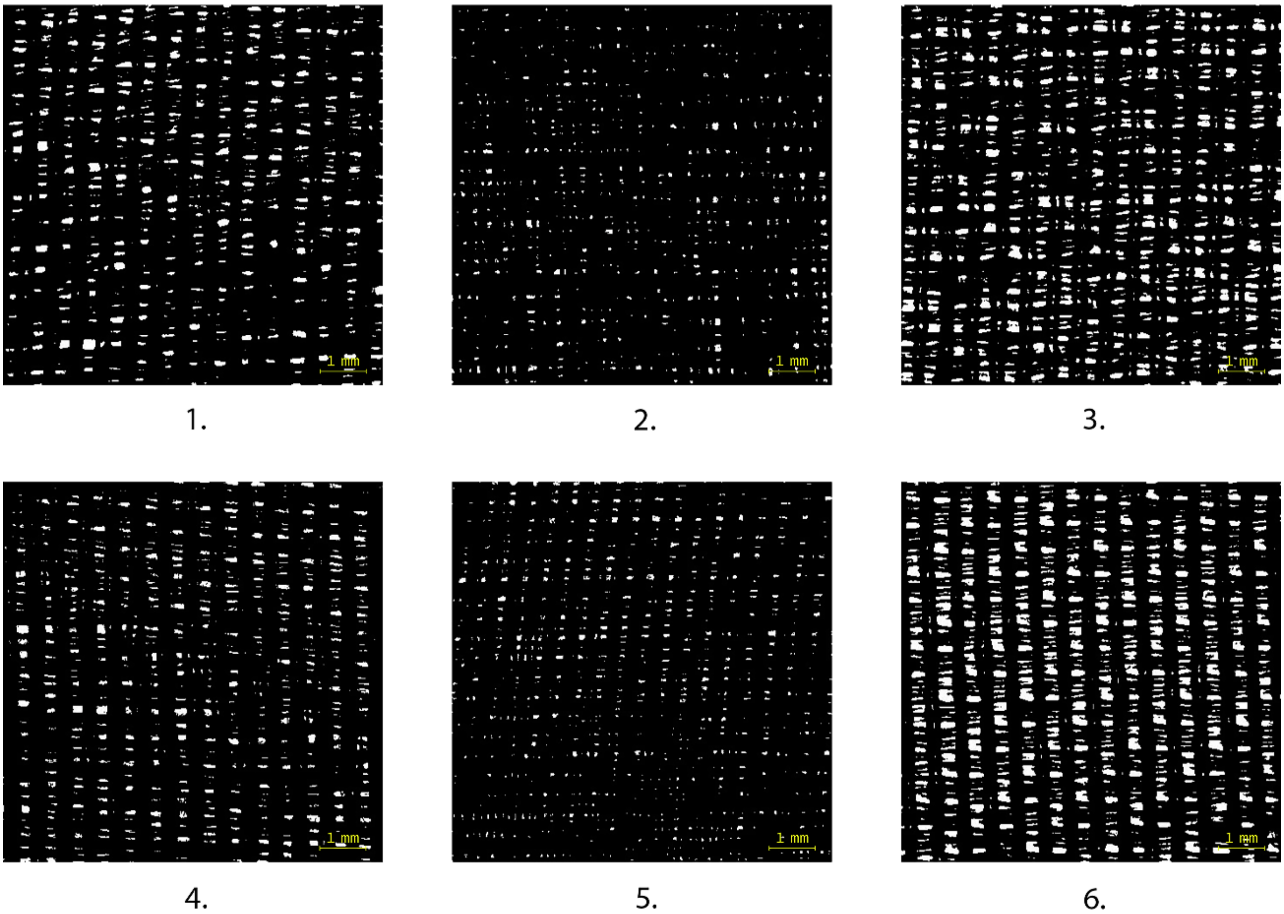

Figure 4. Visual images of all six samples in the light transmission function under stereo microscope (designation of samples from 1 to 6 according to Table 1).

2. 3. Statistical analysis

All statistical analyses were performed using the two-way ANOVA to determine the statistically significant parameters affecting the analysed properties. Two-way ANOVA is used to determine whether two different factors have an effect on a measured variable. Here, we determine whether the factors and the interaction between them affect the dependence variable. The interaction between factors A and B is statistically significant and has a consistent influence when ($F > F_{crit}$ and $p < 0.05$). For the analyses, we investigate the relationship between different materials - yarns (factor A) and different sizes of pattern and weave (factor B) with other physical, permeability and UV protective properties of the samples.

3. RESULTS AND DISCUSSION

The structural properties of the woven samples are shown in Table 2, with values for thread density, crimp, thickness, and mass per unit area of the fabric samples.

The size and distribution of pores between fibres were determined by using the Jakšić method also known as the flow method. The results of porosity analyses, bubble point (d_1), mean pore diameter (d_m), and mean open area fraction (P) determined by the above method, open area determined by using the image analyses (OA), and theoretically calculated number of pores are shown in Table 3. The pore size distribution is shown in Figure 5 for samples with cotton (a) and with Lyocell-Clima (b) in the weft direction.

Table 3 also includes the results of air permeability (Q) and thermal conductivity (k). The measured values of UV transmission (T) and UV reflection (R) as well as the calculated UV absorption (A) and ultraviolet protection factor (UPF) are listed in Table 4.

Table 2. Physical properties of woven samples

Sample	Density, yarns/cm		Crimp, %		Thickness, mm	Mass per unit area, g m^{-2}
	warp	weft	warp	weft		
1	39.2	43.0	4.6	4.4	0.904	188.6
2	39.4	43.0	4.2	4.2	0.899	190.2
3	39.2	42.2	4.6	4.0	0.979	190.6
4	39.2	42.6	4.6	3.0	0.826	180.4
5	39.0	41.8	3.4	3.6	0.800	176.8
6	40.4	43.4	4.2	3.6	0.844	175.0

Table 3. Porosity parameters of the samples, air permeability and thermal conductivity with corresponding correlation coefficients (corr)

Sample	d_1 / µm	d_m / µm	P / %	OA / %	N_{por} / cm^{-2}	Q / m^3 min^{-1} m^{-2}	K / Wm^{-1} K^{-1}
1	132	40.91	21.48	19.17	1685.6	96.31	0.1124
2	237	48.61	18.65	16.43	1694.2	86.71	0.1054
3	291	64.38	35.23	27.41	1654.2	136.94	0.0841
4	185	46.82	20.01	20.76	1669.9	104.11	0.0918
5	253	43.84	19.73	16.32	1630.2	99.75	0.0876
6	261	64.84	33.33	29.87	1753.4	146.7	0.0843
corr d_1		0.74					-0.78
corr d_{sr}			0.93	0.91		0.91	
corr P				0.95		0.96	
corr OA						0.97	
corr Q							-0.74

Table 4. Measured and calculated values of the UV parameters of the samples

Sample	UPF	T / %	R / %	A / %
1	15.82	7.07	32.76	60.17
2	16.05	6.88	28.95	64.17
3	9.25	11.17	28.48	60.35
4	6.75	16.19	38.41	45.4
5	7.58	14.81	41.22	43.97
6	5.16	19.98	42.97	37.06

The statistical analysis presented in Tables 5 to 7, explains the relationship between different materials (yarns) as well as different sizes of pattern and weave with other physical, permeability and UV protective properties of the samples.

Table 5. Two-way ANOVA results of some physical properties of samples

Source of Variation	Thickness, mm			Mass per unit area, g m^{-2}			Crimp, %		
	F	P-value	F_{crit}	F	P-value	F_{crit}	F	P-value	F_{crit}
Material	176.32	1.21×10^{-18}	4.019	1609.12	1.65×10^{-23}	4.260	13.71	0.00111	4.2597
Pattern	22.638	7.24×10^{-8}	3.168	10.186	0.00063	3.403	0.286	0.75400	3.4028
Interaction	4.474	0.0159	3.168	50.372	2.57×10^{-9}	3.403	2.00	0.15727	3.4028

Table 6. Two-way ANOVA results of porosity parameters, air permeability and thermal conductivity of samples

Source of variation	d_1 / µm			d_{sr} / µm			P / %		
	F	P-value	F_{crit}	F	P-value	F_{crit}	F	P-value	F_{crit}
Material	323.814	4.77×10^{-10}	4.747	0.5463	0.47405	4.747	1.161	0.3025	4.7472
Pattern	9321.51	7.08×10^{-20}	3.885	331.676	3.15×10^{-11}	3.885	181.288	1.08×10^{-09}	3.8853
Interaction	1086.30	2.75×10^{-14}	3.885	18.3108	0.00023	3.885	1.706	0.2228	3.8853
	OA / %			Air permeability, m min^{-1}			Thermal conductivity, W m^{-1} K^{-1}		
	F	P-value	F_{crit}	F	P-value	F_{crit}	F	P-value	F_{crit}
Material	6.112	0.0294	4.747	14.711	0.00033	4.020	128225.5	1.51×10^{-25}	4.747
Pattern	187.28	8.95×10^{-10}	3.885	130.119	2.23×10^{-21}	3.168	7118.62	3.57×10^{-19}	3.885
Interaction	1.984	0.1802	3,.885	0.33038	0.7201	3.168	407.35	9.35×10^{-12}	3.885

Table 7. Two-way ANOVA results of UV parameters

Source of Variation	UPF			*T* / %			*R* / %		
	F	*P*-value	F_{crit}	*F*	*P*-value	F_{crit}	*F*	*P*-value	F_{crit}
Material	455.505	6.52×10^{-11}	4.7472	702.030	5.12×10^{-12}	4.7472	803.807	2.3×10^{-12}	4.7472
Pattern	74.376	1.73×10^{-07}	3.8853	81.045	1.07×10^{-07}	3.8853	1.05757	0.3776	3.8853
Interaction	21.624	0.00010	3.8853	1.2028	0.3341	3.8853	48.6029	1.76×10^{-06}	3.8853

	A / %		
	F	*P*-value	F_{crit}
Material	2599.46	2.13×10^{-15}	4.7472
Pattern	72.1478	2.05×10^{-07}	3.8853
Interaction	42.678	3.51×10^{-06}	3.8853

The warp density of the woven samples (Table 2) is quite similar to the on-loom warp density (40 ends/cm). An increase in densities is observed in the weft. Crimp is higher in warp direction in samples with cotton in weft direction. Woven samples with thinner wefts reach the highest density in the weft and vice versa. This is also reflected in the density and thickness. The samples with cotton in the weft direction are the thickest and have greater mass, while the samples with Lyocell-Clima are 10 % thinner and have 6 % less mass per unit area. The samples with interchanging double weave (samples 3 and 6) have the largest thickness indicating the voluminosity of the samples.

All samples with interchanging double weave have significantly higher air permeability than samples with self-stitched double weave, although they have the greatest thickness and density. In addition, smaller diameter of the Lyocell-Clima thread results in the highest air permeability. In fabrics with interchanging double weave, the threads are loose in the fabric, and the many interstices allow greater air permeability; the looseness of the weave is crucial for the air permeability between the threads. In fabrics with self-stitched double weave, the threads lie compactly next to each other, so there are fewer spaces between the threads, resulting in poorer air permeability. The influence of the weave structure is very clear. We further strengthen the results by determining the porosity parameters. The samples with the interchanging double weave, samples 3 and 6 with the highest value of air permeability have the largest d_1, d_m, *P* and *OA*, and sample 6 has larger number of pores per surface area, which further confirms/explains the results. *T* is also highest for samples 3 and 6. Such a difference does not exist between samples 1, 2, 4 and 5. High correlation between d_m, *P* and *OA* with air permeability (corr. from 0.91 to 0.97) confirms the influence of porosity parameters on air permeability. Here we can confirm the comparability of the open area results measured by the Jakšić method (*P*) and the results obtained by image analysis (*AO*).

Considering the raw material, all samples with Lyocell-Clima in the weft direction have higher air permeability, values of d_1, d_m, number of pores, *OA* and *T*, which we attribute to the consequence of the smaller diameter of the yarn compared to the cotton weft.

Figures 5 show pore size distributions for samples with cotton and with Lyocell- Clima in weft direction.

The trend of the curves in the diagram is similar for both materials. Samples with interchanging double weave (samples 3 and 6) differ from the others.

Samples 3 and 6 are similar, about 36 % of all pores are 25 -22 µm in diameter, 32 % are about 14 µm, 7-10 % of all pores are 46 µm in diameter and larger. In samples 1, 4 and 5, about 57-64 % of all pores have a diameter of 15-21 µm, 8 % of all pores have a diameter of 46 µm and larger. In sample 2, 70 % of pores have a diameter of 17 µm, 1 3 % are about 43 µm in size, and 6 % of all pores have a diameter of 58 µm and larger.

We wanted to confirm that the air permeability of samples with higher fractions of smaller pores is lower than that of samples with lower fractions of larger pores.

The highest UV protection factor (UPF) exhibited the sample 2 with cotton in weft direction, smaller pattern, and self-stitch double weave, and the sample 1 with cotton weft and larger square pattern, and only these two samples meet the classification of good protection (UPF = 16). None of the other fabrics provide good UV protection. The best protection is provided by fabrics made of cotton yarn with the largest diameter that affects the covering area. It is obvious that the size of the pattern does not affect the UPF, unlike the material from which it is made.

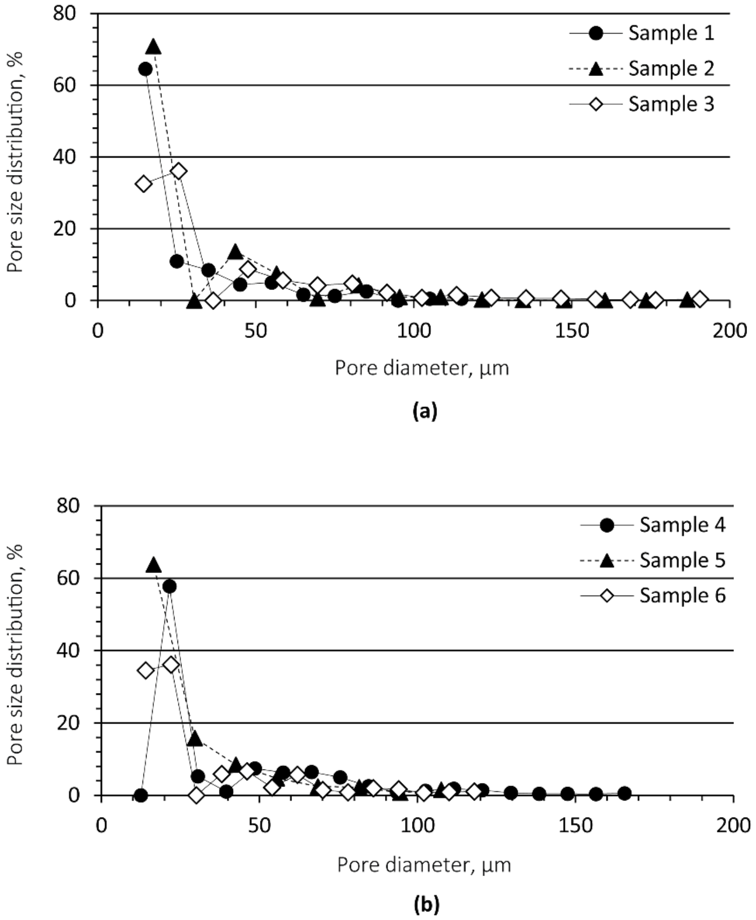

Figure 5. Pore size distribution curve of the samples with cotton (a) and Lyocell-Clima (b) in weft direction

A higher T was demonstrated for fabrics with an interchanging double weave, which is less compact and has a larger open area than fabrics with a self-stitched double weave. This is evident by inspecting Figure 4 and the results of the OA data in Table 3. Despite the difference in density, the T value is related to the yarn diameter, with the lowest values obtained for samples with cotton in the weft direction (yarn with the largest diameter). The highest R value is recorded for the sample with a larger pattern (43 %), and the lowest for samples with the smaller pattern and self-stitched double weave (35 %). The pattern size influences appearance of the white weft on the surface - therefore the reflection is greater as the pattern is enlarged. Absorption is highest for samples with cotton in weft direction (62 %) compared to Lyocell-Clima samples (42 %).

3. 1. Statistical processing

Different yarns affected thickness, mass, and crimp, which is expected and confirmed by the two-way analysis ANOVA. The interaction between factors A (different material) and B (different pattern) is statistically significant as $F > F_{crit}$ and $p < 0.05$. The magnitude of the F-statistic is obviously higher for factor A than for factor B so we can say with greater statistical confidence that the difference in materials has a greater effect on thickness, mass, and crimp in the weft direction (Table 5).

Samples with an unstitched structure have the highest air permeability and the best thermal insulation, as we found.

In the analyses using two-way analysis ANOVA, the interaction between factors A and B is statistically significant ($F > F_{crit}$ and $p < 0.05$) for the air permeability. The magnitude of the F-statistics is higher for factor B than for factor A. Thus, we can confirm with greater statistical confidence that the difference in patterns and weave has a greater effect on the air permeability (Table 6).

In the analysis of thermal conductivity, the influence of the raw material and the size of the pattern/motif is obvious. In fabrics with patterns with larger geometric areas, where the representation of individual weft threads on the surface is larger, the thermal conductivity is higher than in fabrics with patterns with smaller geometric areas. Fabrics with cotton yarn in the weft direction have the highest thermal conductivity. Better thermal insulators are fabrics with Lyocell-Clima in the weft. High/strong negative correlations (corr. -74) between the thermal conductivity and air permeability and between the thermal conductivity and d_1 (corr. -78) were demonstrated. The application of the two-way analysis ANOVA shows that different materials and consequently the pattern size influence the thermal conductivity. The difference in materials has a greater influence on the thermal conductivity, but interactions between the material and the pattern can be also observed (Table 6).

In the statistical analyses of UV parameters, the interaction between factors *A* and *B* is statistically significant ($F > F_{crit}$ and $p < 0.05$). The magnitude of the *F* statistic is higher for factor A than for factor *B*. We can confirm with greater statistical confidence that the difference in materials has a greater effect on all UV parameters than different patterns (Table 7).

4. CONCLUSION

We have found that the permeability properties of the fabric are influenced not only by the basic design parameters, but also by the size and shape of the jacquard pattern. The design of the pattern influences the frequency of thread interlacing, the frequency of thread transition from the back to the front side of the fabric and vice versa, and the frequency of floating of individual threads.

We can conclude that the thickness of the fabrics is not always an indicator of the permeability properties of the fabric, generalising that thicker fabrics are less breathable. The study shows that the compactness of the weave and the yarn diameter are also important. Thus, it was demonstrated that all samples with interchanging double weave have significantly higher air permeability than samples with self-stitched double weave, even though they have the greatest thickness and density. In addition, a smaller diameter of the Lyocell Clima thread results in the highest air permeability.

When considering the thermal conductivity of fabrics, along with the size of the pattern/motif, the influence of the raw material is obvious. For larger geometric patterns, where the percentage of weft yarns on the surface is larger, the thermal conductivity is higher than for fabrics with patterns with smaller geometric areas. Fabrics with cotton yarns in the weft have lower thermal insulation than fabrics with Lyocell-Clima in the weft, which is obviously due to the functional yarn used. However, the statistical analysis confirmed that the raw material has a greater influence on the thermal conductivity than the pattern size.

The jacquard fabrics used in this study are not designed to provide adequate UV protection and, if used for protective purposes, would require additional finishing for UV protection. Nevertheless, we were able to investigate the effects of the type of the threads used, the compactness of the weave reflected in the position and thread, on UV protection properties of the samples. The best protection is provided by the fabric made of cotton yarn with the largest diameter, which affects the covering area. It is obvious that the size of the pattern does not affect the UPF, unlike the raw material from which it is made, which was confirmed by the statistical analysis.

When designing jacquard fabrics for a specific purpose where permeability properties are important, great attention should be paid to pattern size, weave and the use of functional yarns.

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Ocena svojstava propustljivosti žakar tkanina dobijenih tehnološkim postupkom

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Izvod

U okviru ovog istraživanja ispitivan je uticaj određenih parametara dizajna na svojstva propustljivosti žakar tkanina. Proizvedeno je šest tkanina od iste pamučne pređe za osnovu i sa istim tehnološkim parametrima razboja. Tkanine su izrađene od dve različite vrste pređa za potku (pamuk i Lyuocell Clima), u dve različite veličine dezena (sa većim i manjim monohromatskim površinama) i dve grupe dvostrukih keper prepletaja (dvoslojne tkanine spojene sopstvenim žicama, dvoslojne tkanine sa mestimičnom zamenom pozicije gornje i donje tkanine). Dokazan je značaj veličine i raspodele motiva, vrste prepletaja i vrste pređa korišćenih za izradu ispitivanih žakar tkanina. Takođe je ustanovljeno da je uticaj ovih parametara na svojstva propustljivosti u bliskoj vezi sa estetskim karakteristikama tkanina. Sve dvoslojne tkanine u prepletaju gde dolazi do mestimične zamene pozicije gornje i donje tkanine imaju značajno veću propustljivost vazduha u poređenju sa dvoslojnim tkaninama koje su spojene sopstvenim žicama. Očigledan je uticaj sirovinskog sastava i veličine motiva na toplotnu provodljivost žakar tkanina. Tkanine sa većim površinama motiva, gde je izraženije prisustvo potke, odlikuju se većom toplotnom provodljivošću. Sa druge strane, pokazalo se da, za razliku od sirovinskog sastava, veličina motiva ne utiče na ultraljubičasti zaštitni faktor (engl. ultraviolet protection factor, UPF) žakar tkanina.

Ključne reči: žakar motiv; spajanje sopstvenim žicama / spajanje zamenom pozicije gornje i donje tkanine; poroznost; propustljivost vazduha; toplotna provodljivost

Water vapour permeability of nylon pantyhose

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Abstract

Comfort properties of clothing are one of the main indicators of clothing quality and have been widely investigated in the past decades. This research concentrates on the water vapour permeability of nylon pantyhose, by examining behaviours in the relaxed state, as well as under extension of knits of 100 %, comparative to wear conditions and above 100 %. Permetest apparatus was used to measure the water vapour permeability according to the standard ISO 11092. The results indicate that for very fine fabrics permeability stays constant under extension, while for fabrics above 44 dtex the water vapour permeability changes significantly with extension.

Keywords: comfort; biaxial extension; knitted fabric.

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ORIGINAL SCIENTIFIC PAPER

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1. INTRODUCTION

Comfort properties of clothing are among the main indicators of clothing quality and have been widely investigated in the past decades. Clothing comfort can be defined as a "state of satisfaction indicating physiological, psychological, and physical balance among the person, his/her clothing, and his/her environment" [1]. Thermo-physiological comfort, a subset of clothing comfort, pertains to two basic properties: thermal resistance (or insulation), and water vapour resistance (or permeability) [2].

Thermal comfort involves the maintenance of body temperature within relatively narrow limits, while clothing should support the temperature insulation by resisting or helping heat exchange between the body and the environment. Along with insulation, adequate transport of water vapour from the body to the external environment should be provided. Although the human body does not have specific cutaneous receptors for the sensation of humidity, humans are sensitive to skin moisture caused by perspiration, as heat transfer due to evaporation can be perceived [3].

Water vapour can pass through textile layers by four basic mechanisms: diffusion of the vapour through the layers; absorption, transmission and desorption of the vapour by the fibres; adsorption and migration of water vapour along the fibre surface, and transmission of water vapour by forced convection [4,5]. Under regular atmospheric conditions and during normal activity levels, conduction, convection and radiation are the principal means of releasing the heat produced by the metabolism to the atmosphere, while the body temperature is maintained by perspiration in the vapour form. With the increase in atmospheric temperature or activity level, production of heat becomes very high, so the sweat glands are activated to produce liquid perspiration in order to increase the heat transmission from the skin to the atmosphere. The vapour form of perspiration is known as insensible perspiration and the liquid form as sensible perspiration [6].

Temperature and dampness were identified in literature [3] as relevant parameters for socks comfort as warm or wet feet during sport activities are associated with being uncomfortable. The thermophysiological comfort of knitted fabrics in general and socks in particular has been explored by numerous studies. Sampath *et al.* [7] showed that knitted sportswear of spun polyester and polyester/cotton fabrics provided better thermal insulation and warmer feeling at

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initial touch compared to micro denier and filament polyester. Fabrics made of cellulose fibres, such as cotton, regenerated bamboo, flax and rayon [8], protein fibres such as wool [9,10] or acrylic fibres [11,12] were also investigated in respect to thermal comfort properties. The results indicate that the thermophysiological comfort is a complex property where both fabric structure and fibre content contribute to the overall comfort properties. By inspecting the literature, it can be observed that research mostly concentrates on the more common fibre types, such as polyester or cotton. In a more recent research study focusing on plain man's socks [13,14] thermophysiological comfort of socks in a wet state was investigated, as well as the effect of preheat setting on socks. Moreover, the authors drew attention to a disparity between the current testing methods of socks comfort and actual wearing conditions. Knitted fabrics with their elastic nature deform during wear causing the increase in porosity, and thus affecting comfort properties. Various factors regarding biaxial stretching of knits [15-18] such as yarn jamming, fabric geometric relations, fabric stress-strain relations, development of biaxial geometry, yarn friction, extensibility and fabric rupture will influence not only the knit mechanical behaviour, but also the comfort properties. Both theoretical [19] and practical implications [20] on knitted fabrics comfort are being investigated in recent years.

The objective of this study was to determine the effect of yarn fineness (T_t) and fibre content on the water vapour permeability of polyamide (nylon) and polyamide blend pantyhose. Furthermore, the effect of biaxial extension simulating real wearing conditions on water vapour permeability is investigated. Insight into the comfort properties of pantyhose can add to the understanding of the actual behaviour of these fabrics during wear.

2. EXPERIMENTAL

2. 1. Materials

Samples were knitted from commercially available yarns on industrial circular knitting machine with four systems, diameter of 4 in and 400 needles. Filament composition of the pantyhose was pure polyamide (nylon), with standard and microfiber filaments, as well as blends of polyamide and covered elastane. The filament density ranged from 17 dtex with 3 filaments (sample 17P) to 88 dtex (sample 88CE) composed of double 44 dtex yarn with 13 filaments. The pure polyamide was knitted as single jersey, while the addition of elastane was through knitted hopsack structure. Physical and structural properties of the samples are presented in Table 1. The samples are made of fine filaments, with low mass per unit area. The thickness of fabrics was determined by a custom made Alambeta instrument at a pressure of 200 Pa, while the fabric mass per unit area was determined according to the EN 12127 standard. In addition, fabric density, air permeability (A_p) and theoretical porosity of fabrics are shown in Table 1.

Table 1. Sample specifications

Sample*	T_t / dtex	Stitch density, cm^{-2}	M / g m^{-2}	t / mm	ρ / kg m^{-3}	A_p / l m^{-2} s^{-1}	P / %
17P	17/3	1050	57.7	0.28	206.1	4111.0	81.9
22P	22/5	810	60.9	0.30	203.0	2122.0	82.2
33P	33/10	525	81.7	0.39	209.5	1315.0	81.6
44E	44/13	1350	143.9	0.50	287.8	484.9	75.0
44P	44/13	720	89.5	0.44	203.4	1334	82.2
44M	22/20x2	735	133.4	0.47	283.8	473.8	75.1
66M	33/34x2	630	136.4	0.49	278.4	291.5	75.6
78P	78/24	630	144.6	0.49	295.1	598.2	74.1
88CE	44/13x2	360	164.2	0.66	248.8	367.5	78.4

*Sample code: Number - yarn fineness, P - pure polyamide, M - microfiber polyamide, CE - polyamide-covered elastane blend

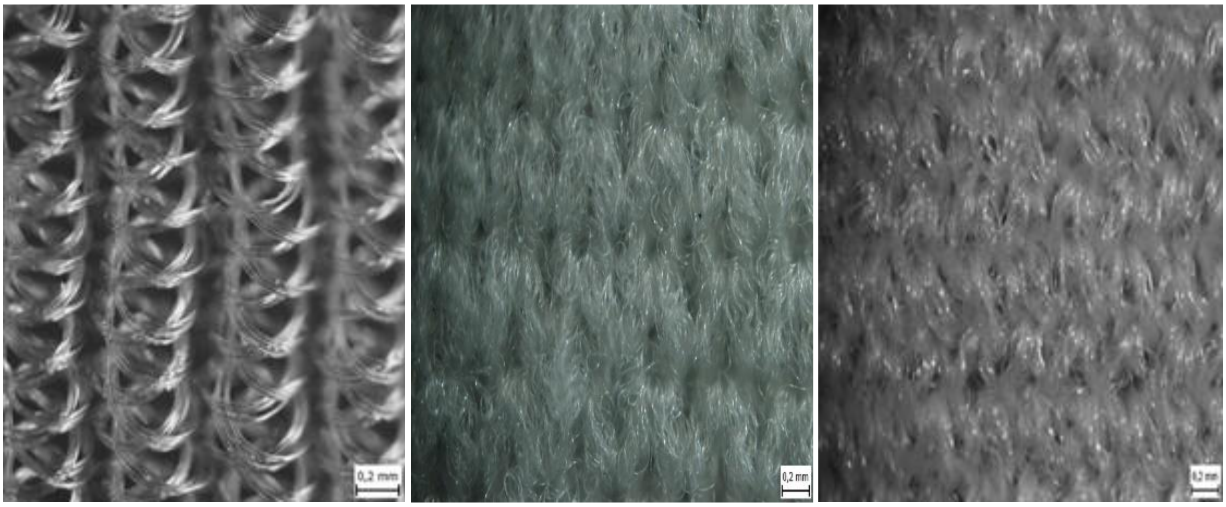
Air permeability was tested by using a SDL ATLAS MO21A tester (SDL Atlas, USA) according to the ISO 9237:1995 standard, under a pressure of 50 Pa as very thin fabrics were examined. Theoretical porosity (P / %) was calculated from fibre density (ρ_0 / kg m^{-3}) and fabric density (ρ / kg m^{-3}), using Equation (1):

$$P = \frac{\rho_0 - \rho}{\rho_0} 100 \tag{1}$$

Standard fibre densities for polyamide (ρ_0 = 1.14 g cm^{-3}) and elastane (ρ_0 = 1.15 g cm^{-3}) were used for the calculation. The fabric density (ρ) was calculated by using the fabric mass per unit area (*M*) and thickness (*t*), Equation (2):

$$\rho = \frac{M}{t} \tag{2}$$

Figure 1 shows the microscopic images of selected samples by using an Olympus BX51 microscope (Evident, Japan).



Sample 17P Sample 66M Sample 44E

Figure 1. Optical microscopy images of the surfaces of samples

2. 2. Water vapour permeability

The evaporative resistance R_{et} / Pa m^2 W^{-1} of the textile fabrics according to the standard ISO 11092 was measured by using a Permetest instrument (Sensora Instruments, Czech Republic). The instrument was placed in a closed chamber to maintain stable environmental conditions. The instrument works on the principle of heat flux sensing through a porous layer with a heat power measuring system. Temperature of the measuring head is maintained at room temperature for isothermal conditions. The heat supplied to maintain a constant temperature with and without the fabric mounted on the plate is measured. To calculate the evaporative resistance, Equation (3) was applied:

$$R_{\mathrm{et}} = (p_{\mathrm{wsat}} - p_{\mathrm{wo}})\left(\frac{1}{q_{\mathrm{s}}} - \frac{1}{q_0}\right) = C(100 - \phi)\left(\frac{1}{q_{\mathrm{s}}} - \frac{1}{q_0}\right) \tag{3}$$

Here, p_{wsat} / Pa is the water vapour saturate partial pressure valid for the temperature of air in the measuring laboratory, p_{wo} / Pa is the partial water vapour pressure in the laboratory air, ϕ / % is the relative humidity, and q_{s} / W m^{-2} and q_{o} / W m^{-2} represent the heat flux density lost by the moist measuring head for the case of measurement with the sample and without the sample, respectively.

Constant *C* was determined by the calibration procedure where a special hydrophobic polypropylene reference fabric was used. The measurement was conducted 3 times on randomly chosen parts of the fabrics, and average values and standard deviations were calculated. All measurements were conducted in a laboratory at a temperature of 21±0.5 °C and 50±1 % relative humidity. The samples were acclimatized to the laboratory conditions for a period of 48 h.

2.3. Extension of samples

For the extension simulation, the pantyhose was loaded on a model leg (Salzmann MST Switzerland) of medium size (24 cm) as per specification of the standard method (RALGZ-387/1). The pantyhose samples were marked with a circular testing template of 5 cm in diameter. After unloading, the socks were extended to the marked circle with the help of an embroidery hoop. This provides a biaxial extension of the sample, simulating the wearing conditions. Measurements were taken on a relaxed sample, as well as on samples extended to the original surface of 5 cm in diameter (area

19.6 cm^2), 5.5 cm in diameter (area 23.7 cm^2), and 6 cm in diameter (area 28.3 cm^2). The extensions correspond to 100, 121 and 144 % of the original dimensions.

In order to quantify the degree of extension a cover factor was introduced. The cover factors of the samples were calculated by using image analysis technique by taking photographs under an Olympus BX51 microscope (Evident, Japan) at a magnification of 5× and analysing the macro porosity by using the "R" programme.

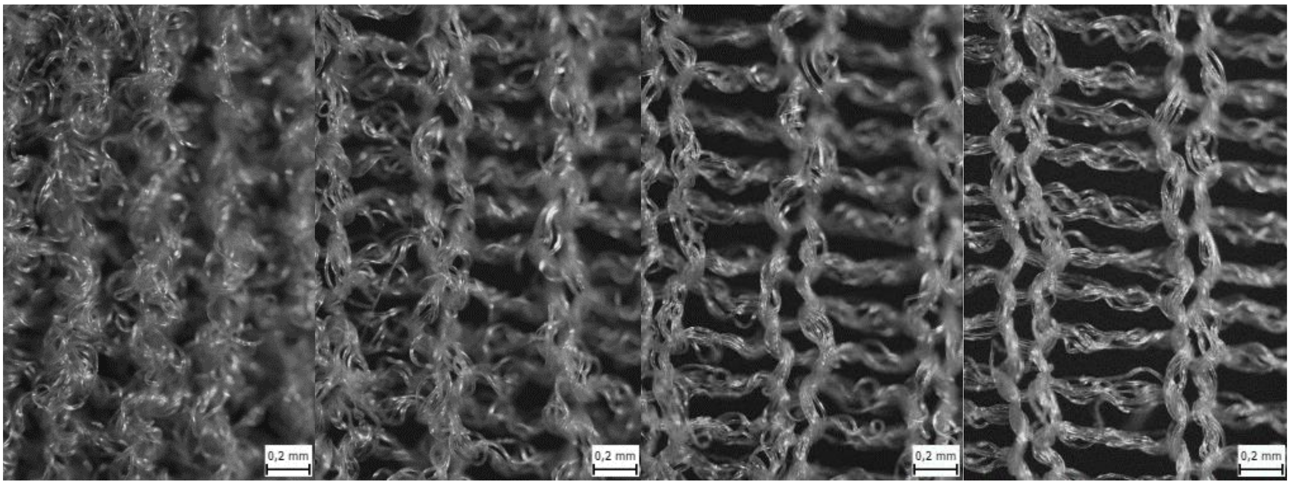


Figure 2. Micrographs of the sample 22P under biaxial extension

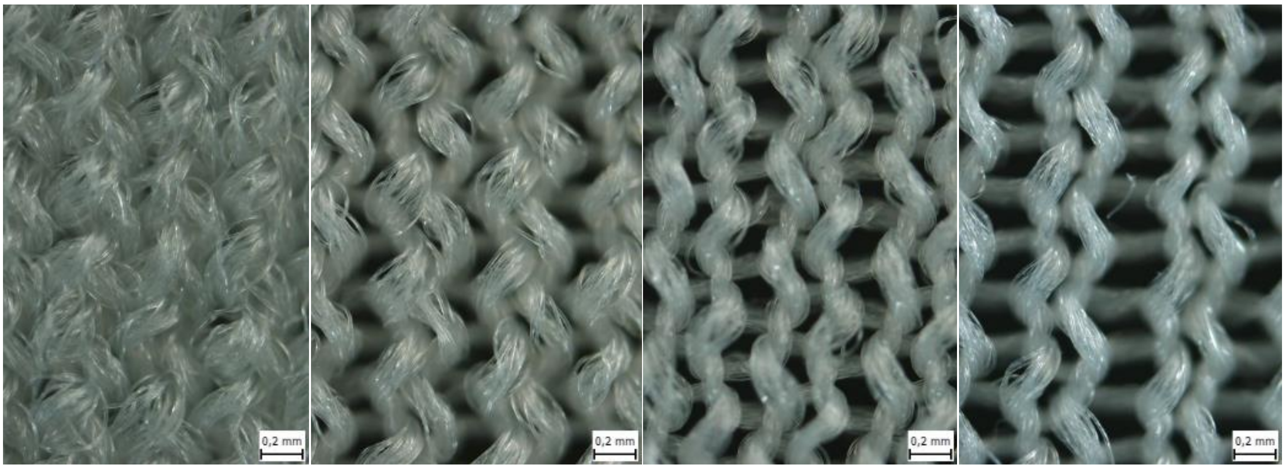


Figure 3. Micrographs of the sample 78P under biaxial extension

To illustrate deformation in the knitted fabric under extension, samples with comparable structures (single jersey), with low (22 dtex) and high (78 dtex) yarn fineness, are shown on Figures 2 and 3. It is visible that the higher the extension the larger the gaps between the loops. This is particularly noticeable for samples with finer filaments. To calculate the cover factor, firstly, the black pixels on the images, with a standard cut-off threshold for black, are counted. This presents the porosity of the fabric in the image. The reciprocal value of the porosity, in percent, represents the cover factor. This is a relatively accurate representation of the two dimensional porosity of the fabrics. The cover factor was better correlated to the theoretical porosity of samples in relaxed state (correlation coefficient of 0.74) compared to air permeability (correlation coefficient of 0.59). Cover factors calculated for the samples in relaxed state and under extension are given in Table 2.

Table 2. Cover factors of fabrics under extension

Sample	Extension , %			
	0	100	121	144
	Cover factor			
17P	88.9	81.9	77.0	73.5
22P	86.0	78.2	71.6	64.4
33P	88.5	82.2	79.1	79.2
44E	94.2	84.5	78.1	76.6
44P	94.4	82.8	78.9	74.8
44M	97.7	92.7	87.3	81.8
66M	98.1	92.5	88.7	84.5
78P	94.9	89.4	82.5	76.4
88CE	89.2	86.2	86.5	83.2

2. 4. Statistical analysis

An ANOVA analysis paired with a post-hock Tuckey test was conducted to see whether the differences were statistically significant, with a significance level of 0.05. SPSS Statistics (IBM, NY) was used to conduct the statistical analysis. An analysis of variance (ANOVA) was used to compare the effect of extension on the evaporative resistance. The F-values and p-values of the statistical analysis are presented in Table 3. The statistical significance of facors was based on a p-value lower than 0.05. For samples where a significant difference was revealed post hoc comparisons using the Tukey HSD test were conducted. When samples are different under different extension the groups are denoted with different letters in Table 3.

3. RESULTS AND DISCUSSION

All examined samples showed low evaporative resistance (R_{et}) values in their relaxed state, indicating good water vapour permeability. The R_{et} values range from 1.0 to 2.9 Pa m^2 W^{-1}, as shown in Table 3. The lower the R_{et} values indicate better transport properties. Knitted fabrics have an open structure, with large porosity, therefore they naturally offer quite high water vapour permeability. Furthermore, as the samples were knitted from filaments, there was minimal blocking of the pores. For comparison, standard men's socks knitted from staple yarns show R_{et} values between 5 and 9 Pa m^2 W^{-1} [13]. The ANOVA results are listed in Table 3.

Table 3. Evaporative resistance of fabrics under extension and statistical analysis results

Sample	Extension , %				ANOVA	
	0	100	121	144	*F-value*	*p-value*
	R_{et} / Pa m^2 W^{-1}					
17P	1.00	1.27	1.13	1.20	1.228	0.361
22P	1.37	1.23	1.50	1.50	3.451	0.072
33P	1.53^{ab}	1.63^{a}	1.73^{ab}	1.37^{b}	**6.769**	**0.014**
44E	2.53	2.33	2.47	2.33	0.973	0.452
44P	1.73	1.63	1.60	1.53	1.667	0.250
44M	2.70^{a}	1.77^{b}	2.13^{b}	2.10^{c}	**49.061**	**0.000**
66M	2.73^{a}	2.03^{b}	2.03^{b}	2.20^{b}	**18.857**	**0.001**
78P	2.50^{a}	2.07^{b}	2.37^{ac}	2.13^{bc}	**9.778**	**0.005**
88CE	2.93^{a}	2.23^{b}	2.30^{b}	1.83^{c}	**82.778**	**0.000**

Superscripts signify: a, b, and c denote means significantly different at α=0.05, means shareing subscripts indicate similarity with noted groups.

The evaporative resistance has a high positive correlation to the fabric mass per unit area and the filament fineness (Figs 4 and 5). Coarser yarns knit into heavier fabrics. In a relaxed state, as seen in Figures 2 and 3 (0 % extension), the bulkier yarns fill in the pores in the loop structure and present a barrier for moisture transport. Samples containing micro fibres show the lowest water vapour permeability, as microfibers have more micro pores which present large barriers for the moisture transfer. Fabrics that are more porous provide easier transport of air, so air permeability is commonly used as a measure for the porosity of fabrics. As can be seen in Figure 6, transport of fluids through the fabrics increases as porosity (and air permeability) increases. Therefore, there is a strong negative correlation between air permeability and water vapour resistance.

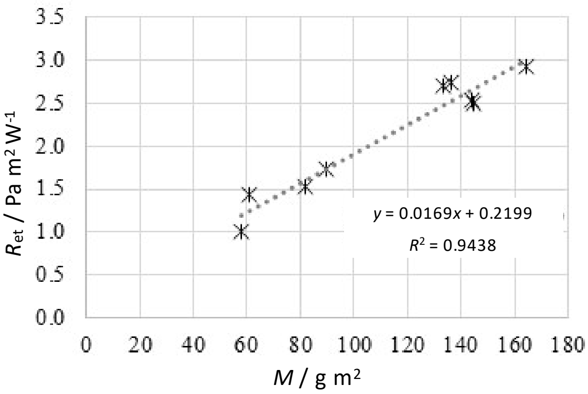


Figure 4. Correlation of R_{et} and speciffic mass

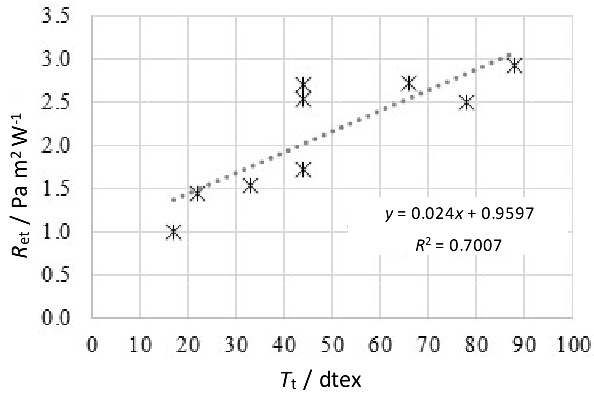


Figure 5. Correlation of R_{et} and yarn fineness

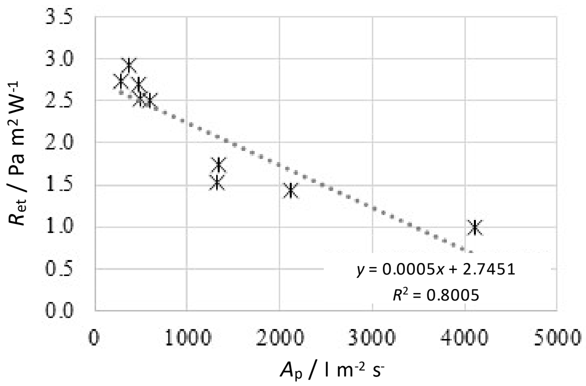


Figure 6. Correlation of R_{et} and air permeability

Subsequently, the evaporative resistance of the samples was measured under extension. The results are presented in Table 3 and Figure 7. As can be seen in Figure 7, for all three levels of extension the evaporative resistances decrease compared to the relaxed state.

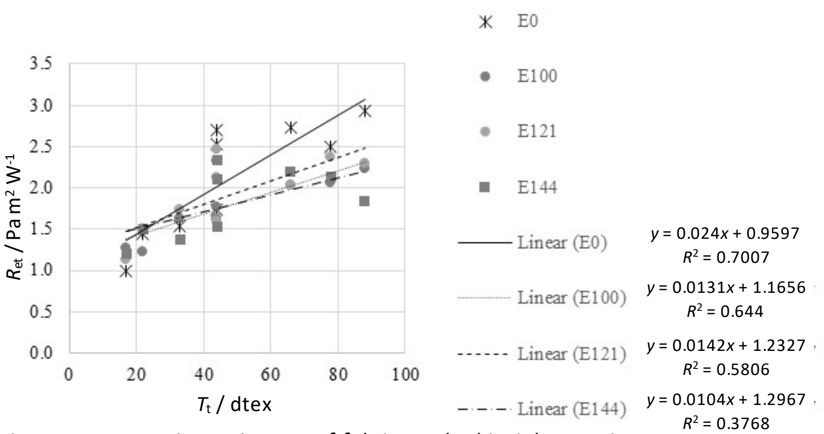


Figure 7. Evaporative resistance of fabrics under biaxial extension and the best linear fits

The post-hock tests show a clear difference between evaporative resistance of fabrics in the relaxed state (marked [a]) compared to those under extension for samples 33P, 44M, 66M, 78P and 88CE. Fabrics for opaque pantyhose (over 44 dtex) under extension of 100 and 121 % behave similarly in their evaporative resistance, while larger extensions (144 %) result in further improvement of water vapour permeability. All of these samples are thicker, have higher mass and lower porosity. In the range of 33 to 44 dtex mixed results were found. When the fabric yarn fineness is 44 dtex or lower, the porosity of the relaxed fabric is higher and water vapour permeability does not change considerably with extension. Employing microfiber in the sample 44M led to a lower vapour permeability, and therefore this sample behaves similarly to those made from higher-fineness yarns. Sample 33P, which has a lower stitch density, and is therefore less expandable, also showed lower R_{et} values on the highest extension; however, on low extensions the values are similar to the relaxed state.

To estimate porosity, a cover factor was calculated from the microscopic images representing two dimensional porosity of the fabrics, since standard methods of measuring air permeability did not yield consistent results under extension for the finer samples. Although cover factors are relevant when examining other comfort parameters, such as thermal conductivity [22], correlations with R_{et} are low. Namely, the correlation coefficient for relaxed fabrics was $p = 0.65$, under extension of 100 % it was $p = 0.58$, under extension of 121 % $p = 0.57$, and under extension of 144 % it was $p = 0.49$. The low correlations are due to the fact that cover factors measure the surface, rather than the volumetric porosity of samples.

4. CONCLUSION

The presented research was focused on investigation of evaporative resistance of nylon and nylon elastane blends pantyhose. All examined samples showed low evaporative resistance values in their relaxed state, ranging from 1 to 2.9 Pa m^2 W^{-1} indicating excellent water vapour permeability, due to low mass, low yarn fineness and good porosity. With biaxial extension, the evaporative resistance drops significantly for fabrics over 44 dtex, while for fabrics with lower yarn fineness (thinner yarn) there were insignificant differences, as their porosity is very high even in the relaxed fabric state. Further research is needed to better understand the behaviour of very thin pantyhose fabrics under extension, in order to understand better the actual behaviour of these fabrics during wear.

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Propustljivost vodene pare najlon ženskih hulahop čarapa

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(Naučni rad)

Izvod

Svojstva komfora odeće, kao što su sposobnost prenosa toplote, vazduha i vodene pare, predstavljaju neke od glavnih indikatora njenog kvaliteta, te su stoga bila predmet većeg broja istraživanja poslednjih decenija. U okviru ovog istraživanja ispitivana je propustljivost vodene pare ženskih najlon hulahop čarapa, u njihovom relaksiranom stanju, kao i prilikom istezanja pletenine od 100 % (što odgovara uslovima nošenja) i više (121 i 144 %). Za merenje propustljivosti vodene pare korišćena je aparatura "Permetest" prema standardu ISO 11092. Rezultati pokazuju da kod vrlo finih pletenina (izrađenih od tankih filamenata) nema promena u propustljivosti vodene pare prilikom njihovog istezanja, dok kod pletenina izradjenih od filamenta finoće iznad 44 dtex propustljivost vodene pare raste proporcionalno sa istezanjem.

Ključne reči: komfor, dvoaksijalno istezanje, pletenina

Transfer of liquid and water vapour through knitted materials

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Abstract

Active sportswear has certain functions that should meet the expected properties and improve the performance of athletes. In addition to functionality, an important aspect of sportswear is thermal and physiological comfort. By choosing the right clothing for athletes, the dynamic and thermal load can be significantly reduced because sports require unhindered mobility, and clothing must be adapted to the body and absorb sweat. Proper vapour and liquid flow in textile materials are important from a comfort point of view. Therefore, in this research, seven representative samples were selected that are used for clothing intended for sport and leisure. Using an infrared thermal camera, the transfer of liquid on the surface of the material was precisely monitored, until the final stage when the material is completely dry. The obtained results show that fabric made of 100 % polyester has the shortest drying time, while the highest vapour permeability was exhibited by fabric made of viscose and elastane yarn. Those fabrics should be considered as the most suitable for sportswear because they do not cause discomfort when worn. Infrared thermography is a very useful method in research because it provides reliable data, especially when it comes to the drying time of the material.

Keywords: knitted fabric; wetting; thermography; drying; sportswear.

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1. INTRODUCTION

Clothing is a basic human need, and since ancient times people have made clothes and adapted them to their needs. Man is exposed daily to various unfavourable, difficult working and living conditions. In such conditions, the function of clothing has always been to protect the body from external influences. According to the defined use and special characteristic, clothing can be divided into several categories such as work wear, protective clothing, uniforms, casual wear, special purpose clothing, sportswear, etc. Sportswear plays an important role in daily life. When buying or designing sportswear, one should be paying close attention to the comfort properties, either thermophysiological or sensorial [1–6], which are expected to be adequate during material use as long as possible [7]. There are three types of sportswear: clothes that are worn during leisure time, clothes that serve as fashion items, and clothes for active participation in sports activities. Clothes that are worn during leisure time are sports clothes that are most often worn at home when increased physical activity or sweating are not expected. Sports clothes that serve as fashion items were created through the cooperation of fashion houses, fashion designers, and sports brands, with professional athletes, and the most attention is paid to fashion design and the aesthetic appearance of the clothes. Active sportswear is often expected to be very light so that it does not hinder the athlete in his activities. This type of clothing must not interfere with or restrict movement and often is required to meet additional conditions that are in line with the specifics of the particular sport. By providing physical protection and comfort to the wearer, clothing can have a significant impact on the performance of professional and non-professional athletes during competition or training sessions. Extreme and dangerous sports require protective and durable clothing that have to protect the body from various weather conditions such as wind, rain, snow, and sun. The performance of sportswear is also influenced by the thermodynamic, aero-

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dynamic, and hydrodynamic properties of the material used, as well as by the material structure, design, and finishing [8–12]. For the performance evaluation, the textile industry uses a variety of quality tests. Among the most used instruments that determine the transfer of water vapour and liquid through materials are a sweating guarded hotplate, moisture management tester, and permetest. Still, in order to complement those results or to get insight into the specific behaviour, different additional instruments and methods may be used. One of these is based on the use of infrared thermal camera for evaluation of the material transfer properties, more precisely the material wetting time, the wetting speed of a liquid on the material, and the time required for drying of the material [13]. Infrared thermography is a non-contact method of measuring temperature, and it is based on measuring the intensity of infrared radiation [14-17]. The term thermography comes from the Greek words therme - heat and graphene - to write [16]. This means that after the thermographic measurement, a permanent record of the measured quantities remains, and this record is called a thermogram [17].

The thermographic system consists of a thermographic camera and a thermogram processing unit (software). The sensor in a thermographic camera measures the amount of energy that falls on its surface and corresponds to the radiation intensity of a defined part of the infrared spectrum. The amount of thermal energy emitted from the surface is directly proportional to the surface temperature. Changes in temperature result in changes in emissive power, which is shown by the Stefan-Boltzmann's equation:

$$E = \varepsilon\sigma T^4 \tag{1}$$

where E is the emitted energy, ε is the emissivity coefficient, σ is the Stefan-Boltzmann constant [5.67×10^{-8} W m^{-2} K^{-4}], and T is the body temperature. This relationship is very important as it is very sensitive in calculating temperature from the radiant power and can distinguish areas with different temperatures due to different emissivities. The Stefan-Boltzmann's law is considered the basic law governing infrared thermography [18,19].

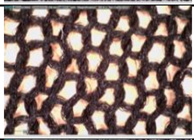
Thermography is divided into qualitative and quantitative in terms of the information it provides, and into passive and active in terms of motivation. Qualitative thermography aims to provide the basic information about the temperature distribution on the surface of the studied object, while quantitative thermography is used to provide accurate temperature values on the surface of the examined object [20,21]. Thermography is used in sports to find various traumas within the human body and to determine temperature changes in an active athlete depending on the type and intensity of training [22,23]. Back in 1975, the first research study was published in the field of sports using infrared thermography [24]. Thermography allowed trainers and athletes to observe changes in the body temperature in specific parts of the body to prevent muscle injuries and to get an insight into the health of athletes [19,24,25]. Infrared thermography may be successfully used in different areas of sport: sports medicine, physical therapy, sports performance, and research [26]. In research papers, experiments are mainly based on thermoregulation in a cold or warm environment and sweating during exercise [27-31]. For example, thermography, using an infrared thermographic camera, provided insight into the change in body temperature in active futsal athletes before and after indoor training, in order to perform detailed body mapping. The developed body maps would further be used to design ergonomic sportswear for futsal players. The results showed that infrared thermography is an extremely useful method for adjusting the construction of clothing and certain types of training. This is very important because of the athlete's performance and his comfort in wearing these clothes [32]. Mijović and co-workers chose a research objective to investigate whether thermography can be used to assess heat and moisture transfer within clothing systems used by police officers in the field [33]. An infrared imaging system was used to identify the body temperature pattern of healthy adult men engaged in controlled physical activity in a temperature-controlled environment. Research results have shown that thermography is an effective tool for assessing skin temperature and perspiration evaporation from clothing. The information gathered can be applied in the design of new clothing systems to maximize the body's cooling effect through evaporation of perspiration [33]. Similarly in another study [34], the aim was to show possibilities of using infrared thermography for determining the heat transfer in protective clothing with four different sets. The kits were carefully designed to ensure optimal wearing comfort in temperate and cold climates with the focus on functionality. The obtained thermographic measurements assembled in thermograms showing temperature distribution on the surface of the subject's body and of protective clothing by color coding. Temperature distribution indirectly provides information about different states of the surface itself or if it reflects the structure and internal state of the observed object. By measuring temperature distribution on subjects working outdoors at low temperatures, thermal insulation of protective clothing can be assessed [34]. From this short literature review, it is clear that infrared thermography has a great potential for research and experiments in the field of clothing evaluation [26,35,36]. Still, the use of this technique for evaluation of mass transfer properties (especially liquid and moisture transfer) is to be expanded. Therefore, the present research focuses on aspects of thermography application for evaluation of liquid transfer through textile materials. To assess the advantages of the additional measuring methods, this research also includes evaluation of water vapour transfer characteristics by using the Absolute Moisture Meter PCE-MA. The PCE-MA device provides weighting of the material to determine the moisture content.

2. EXPERIMENTAL

2. 1. Materials and material characterization

For the experimental part of this research, seven representative single jersey knitted fabrics were selected so to cover a wide range of available materials at the market (in terms of the raw material and knitted structure). All those materials are specifically produced to be used for the production of leisurewear or fashion sportswear that is in direct contact with the skin (*i.e.* for the production of T-shirts and short trousers). Characteristics of the materials are shown in Table 1.

Table 1. Characteristics of the materials

Sample ID	Micrograph	Raw material	Mass per unit area, g m^{-2}	Yarn count, tex	Knitting density (horizontal / vertical), stitches cm^{-1}	Thickness, mm	Porosity factor
M1		100 % PA 6	111.61 (St.dev. 2.524)	18	11/15 (St.dev. 0.5)	0.800 (St.dev. 0.017)	0.93
M2		100 % PES	73.42 (St.dev. 0.552)	18	9/11 (St.dev. 0)	0.465 (St. dev. 0.007)	0.67
M3		100 % PA 6.6, recycled	109.02 (St.dev. 1.192)	18	11/13 (St.dev. 0.5)	0.478 (St.dev. 0.0079)	0.89
M4		4.5 % Lycra 38.2 % wool 57.3 % viscose	162.88 (St.dev. 1.277)	28	10/14 (St.dev. 0.5)	0.798 (St.dev. 0.010)	0.97
M5		3.2 % EA Lycra 29.0 % linen 67.8 % viscose	225.32 (St.dev. 6.774)	28	10/14 (St.dev. 0.5)	0.940 (St.dev. 0.022)	0.97
M6		93 % viscose 7 % elastane	248.49 (St. dev. 0.060)	22	16/35 (St.dev. 0.5)	0.651 (St. dev. 0.032)	0.99
M7		91 % cotton 9 % elastane	209.56 (St. dev. 0.050)	12	16/30 (St.dev. 0.5)	0.682 (St. dev. 0.017)	0.97

*The standard deviation is given in parenthesis.
**The standard deviation of the porosity factor for all samples is < 0.015 %.

The mass or materials per unit area was measured by using an analytical scale with a 4-digit accuracy (0.1 mg). Round samples with the area of 1 dm^2 were used, and for each material 10 measurements were performed. The yarn count was determined by weighing a skein of yarn in the length of 10 m. A total of 20 measurements for each yarn was made. The fabric horizontal and vertical densities were determined by counting the number of stitches in the length of 1 cm and for each specimen, 10 repetitions were performed. Thickness of the material was measured by using a thickness gauge meter DM-2000 (DM 2000 – Wolf, Germany). The specimen was conditioned in the standard testing atmosphere before testing, and for each specimen, 10 replicate measurements were performed. Structure of the materials was visualized by using a Dino-Lite Edge AM7915MZT digital microscope (AnMo Electronics Corporation, Taiwan) and further used for calculation of the porosity factor using the MATLAB software (MathWorks, MA).

2. 2. Determination of material transfer properties

Two methods of testing the selected knitted fabrics were performed relevant for the textile industry. The first method aimed at evaluation of moisture transfer properties of the material, more precisely, wetting time of the material, speed of liquid spreading through the material, and the time required for the material to completely dry. The wetting time of the material is observed along the material, while the speed of liquid expansion is the time required for a certain amount of liquid to spread in the directions of the x- and y-axes (mm/s). In this manuscript, artificial sweat was used as liquid. Sweating of athletes was simulated by using diluted acidic sweat (AS) pH 5.5 prepared according to the ISO 105-E04:2013 standard [37].

During the test, liquid was transferred to the sample surface by using a pipette, that is 0.5 cm^3 of artificial sweat was applied to each sample (Fig. 1). Prior to testing, materials were left for 24 hours on a flat surface in the standard atmosphere (20±2 °C and 65±2 % of relative humidity).

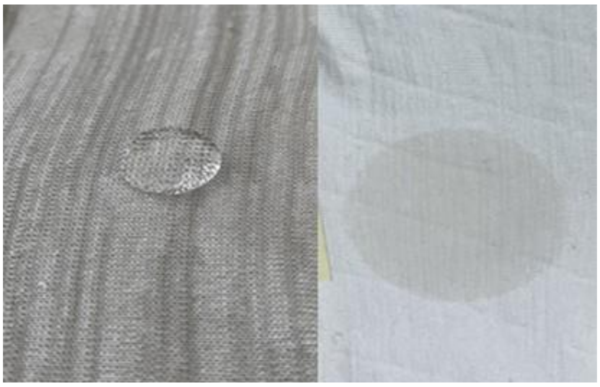


Figure 1. Application of a liquid drop and absorption in the material

After applying the liquid to the selected material, the TESTO 872 infrared thermal camera (TESTO, Germany) supplied with additional TESTO IRSoft v4.8 software (Fig. 2) was used to detect the breakpoints that mark the beginning and end of different process phases. The combination of a thermal camera and efficient image processing methods allows precise monitoring of the wet area of the material during the wetting and drying phases. The used thermal camera has the possibility of measuring in the temperature range from -30 to +650 °C with an accuracy of ± 2 %. Images were processed with the correction of emissivity for parts of the image up to individual pixels. This method allowed determination of critical points in the thermal image, as well as recording of hot and cold points.

Three important phases were observed in this experiment: the wetting, the static, and the drying phase throughout which the infrared camera was used. The wetting phase is represented by the time required for the applied liquid to spread completely over the surface of the material. The static phase begins immediately after the wetting phase ends and the main moment characterizing the material is when the wet area begins to shrink (Fig. 3).

During the measurement process, the wetting diameter (in the *x* and *y* directions), surface area and the wetting speed of the material were determined. The wetting speed was calculated, as the ratio of the wetting diameter to the wetting time.

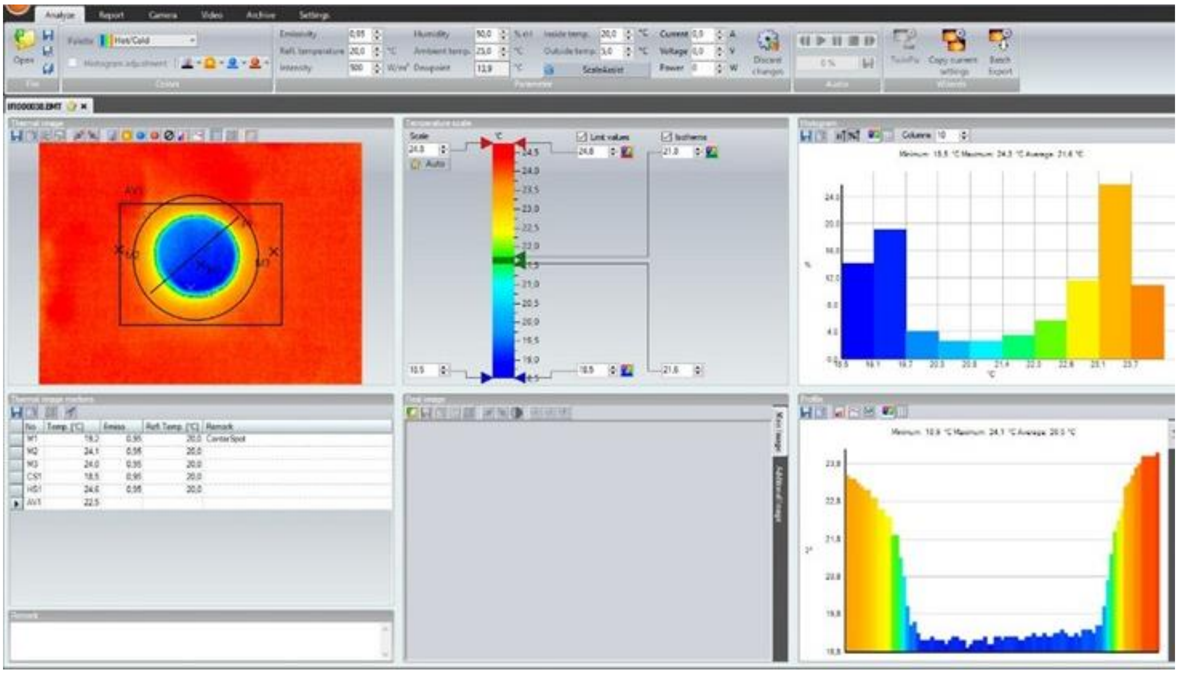


Figure 2. Example of processing of a thermogram

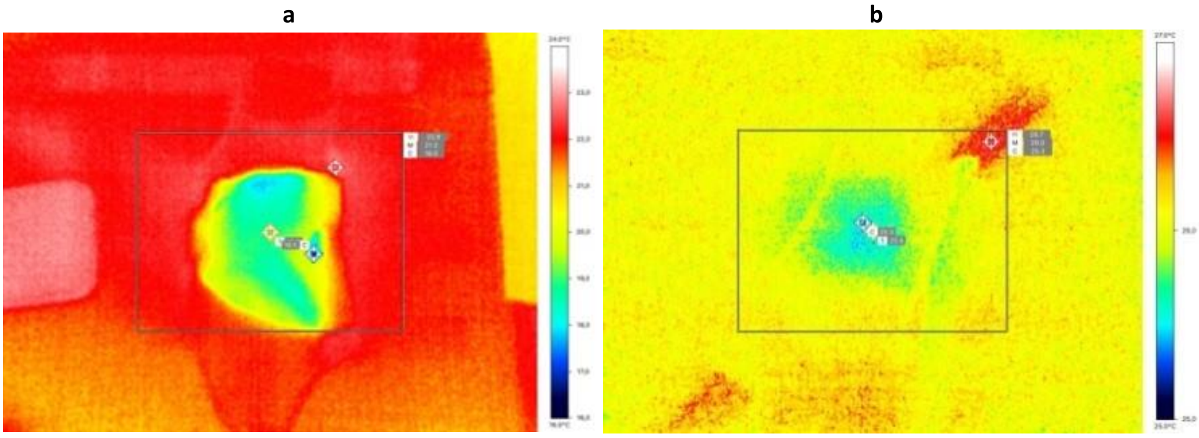


Figure 3. Example of thermograms during material drying: a - wet material; b - drying phase

Drying time is the time required for a certain amount of water to evaporate from the surface of the material. The drying phase begins after the end of the wetting process, including the static phase. This time is determined as duration from the first breakpoint to the end of drying. All measurements were carried out indoors, at a temperature of 20±2 °C and relative humidity 60±5 %. During the measurements, materials were placed on a dry flat surface. The measurements were performed in triplicates.

In the second method, an Absolute Moisture Meter PCE-MA (PCE Instruments, Germany) was used to determine the water vapour permeability. The PCE-MA device provides weighting of different materials and determination of their moisture contents. A heating chamber is heated by halogen lamps up to 199 °C. The material is dried and moisture meter calculates moisture content from the mass difference. As an additional modification of the method, a semi-permeable cellophane sheet was placed between the liquid and the dry material to simulate transfer of water vapour. The principle is adapted from the international standard ISO 11092 [38]. The device is set to a temperature of 41 °C and a time of 15 min. Three measurements were performed for each sample and the average value and coefficient of variation were calculated. Based on the data obtained in the experimental part of the work, a statistical analysis of the data, *i.e.* correlation, was made using the Statistica 14.0. program.

3. RESULTS AND DISCUSSION

Results of all conducted measurements are provided in Tables 2 to 4, and Figures 4 and 5. As could be seen from the data presented in the experimental part (Table 1), the selected fabrics differ regarding to the raw material as well as the mass per unit area ranging from an average of 73 g m^{-2} (sample M2, 100 % polyester) to 248 g m^{-2} (sample M6, 93 % viscose and 7 % elastane).

Table 2 shows the correlation between the mass, knitting density, thickness, and porosity factor of the material. The porosity factor is defined as the ratio between the volume of the fibres in a unit cell and the volume of the unit cell of the knit and ranges from 0 to 1. As can be seen from the results, the correlation between the fabric mass and porosity factor is positive and moderate (0.77). Furthermore, the correlation between the knitting horizontal density and knitting vertical density is positive and strong (0.97). Porosity has a significant influence on the physical properties and comfort properties of the fabric. It can be noticed that the porosity factor is the smallest in sample M2 (0.67), confirmed also visually at the micrograph showing significantly larger pores than in the other materials. This automatically affects the mass per unit area, which is the lowest for this material. Sample M6, which has the highest mass per unit area, as well as the highest knitting density, also has the highest value of the porosity factor (0.99). This material is very densely knitted, and its pores are very dense, barely visible in the micrograph (Table 1).

Table 2. Fabric properties correlation

Variable	Mass	Knitting density Dh	Knitting density Dv	Thickness	Porosity factor
Mass	1.000000				
Knitting density Dh	0.664513	1.000000			
Knitting density Dv	0.736102	**0.974121**	1.000000		
Thickness	0.473108	-0.103492	-0.099253	1.000000	
Porosity factor	**0.765153**	0.520324	0.503044	0.736641	1.000000

Marked correlations are significant at p <0.05000

Results of drying and wetting times are presented in Table 3 showing relatively short wetting time. Sample M6 (93 % viscose and 7 % elastane) had the longest wetting time (22 s), followed by sample M1 (15 s) and M3 (9 s). The material M2 (100 % PES) had the shortest wetting time (0.9 s only), which was expected considering the porosity factor. Due to the very large pores in M2, liquid applied at the surface passes through the material very quickly.

Table 3. Test results

Sample		Wetting time, s	Wetting diameter, mm		Wetting surface area, mm^2	Wetting speed, mm s^{-1}		Drying time, h
			x - axis	y - axis		x - axis	y - axis	
M1	Avg.	15.20	29.00	34.33	778.85	2.07	2.33	2.29
	CV, %	27.06	13.79	14.95	16.89	44.40	19.43	6.93
M2	Avg.	0.88	32.00	33.67	844.83	42.74	42.69	0.91
	CV, %	37.65	15.63	6.18	14.94	60.41	40.81	5.66
M3	Avg.	8.80	31.67	34.33	853.47	3.73	4.11	1.74
	CV, %	25.77	11.96	1.68	11.33	22.41	29.14	8.68
M4	Avg.	2.15	53.33	50.67	2138.90	27.13	25.42	1.97
	CV, %	31.47	14.32	9.33	22.88	42.64	35.69	6.77
M5	Avg.	1.81	51.33	51.33	2073.19	29.61	29.24	2.20
	CV, %	25.54	6.84	13.82	16.48	23.89	18.06	8.42
M6	Avg.	21.89	33.67	34.67	914.20	1.64	1.63	2.25
	CV, %	26.71	3.43	13.01	10.20	34.30	17.09	3.83
M7	Avg.	2.43	67.00	64.67	3413.34	30.53	29.12	1.69
	CV , %	36.68	5.38	8.93	13.88	40.19	35.82	4.27

Avg. – Average value, CV - Coefficient of variation

On the other hand, the time required for drying of the selected set of materials was in the range 0.91 to 2.29 h. The fastest drying material is M2 (100 % PES) as expected, exhibiting up to 2.5-fold shorter drying time than those of the rest of the investigated materials. Considering the composition and the structure of the knitting fabric (mass, thickness, and porosity factor), polyester proved to be the most suitable when it comes to drying clothes intended for athletes.

For athletes who run and produce large amounts of sweat, it is very important to keep the heat balanced. If the material causes discomfort when worn, especially during physical activities, the human body automatically resists it. Athletes feel uncomfortable, concentration decreases, and most importantly, the athlete performance is affected.

Wetting diameters (Table 3) were measured at the moment when acidic sweat as completely distributed over the material. As can be seen from the results presented, the smaller the diameter, the longer the wetting time is. An example of this can be seen in sample M6, which has a wetting time of 22 s, and wetting diameters along the *x*- and *y*-axes of 34 and 35 mm, respectively. By measuring the wetting diameter in the direction of the *x*-axis and the *y*-axis, it was possible to calculate the surface area (Table 3). The material M1, which had a relatively long wetting time, has a minimum wetted surface of 779 mm^2, while the sample with the largest wetting surface, M7 (3413 mm^2) had a fairly short wetting time of 2.4 s.

The wetting speed of the liquid in the x and y directions was then calculated showing the highest values in both directions for the sample M2, which showed the shortest wetting time and the lowest values for the sample M6.

To investigate the strength of the relationship between material characteristics defined in Table 1 and measured properties related to sweat management (*i.e.* the wetting time, wetting surface, wetting speed and drying time) correlation coefficients are given in Table 4. As can be seen from the results presented, the correlation between the drying time and the fabric mass per unit area is positive and moderate (correlation coefficient is 0.60). Correlation between the fabric mass per unit area and the other observed properties (wetting time, wetting surface, and wetting speed) is weak. As already mentioned in the paper, the porosity factor significantly affects the drying time of the material. It is evident that the correlation coefficient between the drying time and porosity factor has a high value (0.88), and this indicates a high degree of linear dependence. The relationship between the other observed properties is relatively weak.

Table 4. Correlations of wetting parameters with the material properties

Variable	Mass	Yarn count	Knitting density direction of wales	Knitting density direction of courses	Porosity factor
Wetting time	0.234206	-0.084231	0.493905	0.524861	0.336889
Wetting surface	0.507821	-0.085781	0.358170	0.308215	0.437805
Wetting speed, x-axis	-0.106434	0.063257	-0.337963	-0.286365	-0.466929
Wetting speed, y-axis	-0.127209	0.056356	-0.355022	-0.302841	-0.496658
Drying time	**0.595548**	0.411127	0.298055	0.315297	**0.877540**

Marked correlations are significant at p <0.05000

Figure 4 shows wetting and drying (W-D) profiles of all seven tested materials. Wetting duration presents the time required for the liquid to reach its maximum distribution on the material (area), while the drying duration presents the time required for the liquid to completely evaporate from the surface of the material. It can be said that the drying duration begins at the moment when the wetting duration ends, which also includes the static period.

For each sample in this study, the changes in behavior can be seen. It can be seen that the curve of sample M7 shows the largest area of the wet part. When the wetting surface reaches its maximum (approx. 43.5 cm^2), the drying duration begins, which in this sample is relatively short compared to the remaining samples. Sample M1 shows the curve that has the longest drying duration, but also the smallest wet area, while the sample M2 has the shortest drying duration. Based on the presented results (Figure 4), It can be concluded that specimen M2 is the most suitable material for sportswear. Due to its short drying time and the relatively small wetted surface of the material, it does not cause wearing discomfort. For top athletes, it is very important that the material dries quickly when sweating, so that it does not spread to the skin and cools the body, reducing the performance of active athletes.

Water vapour permeabilities (Figure 5) were in the range from 314 to 499 g cm^{-2} h^{-1} with the mean value for all seven samples of 388 g cm^{-2} h^{-1}. The highest water vapour permeability was exhibited by the sample M6 (499 g cm^{-2} h^{-1}), which in the previous method showed the longest wetting time, the lowest speed of liquid expansion on the surface and a relatively small diameter of the wetted surface.

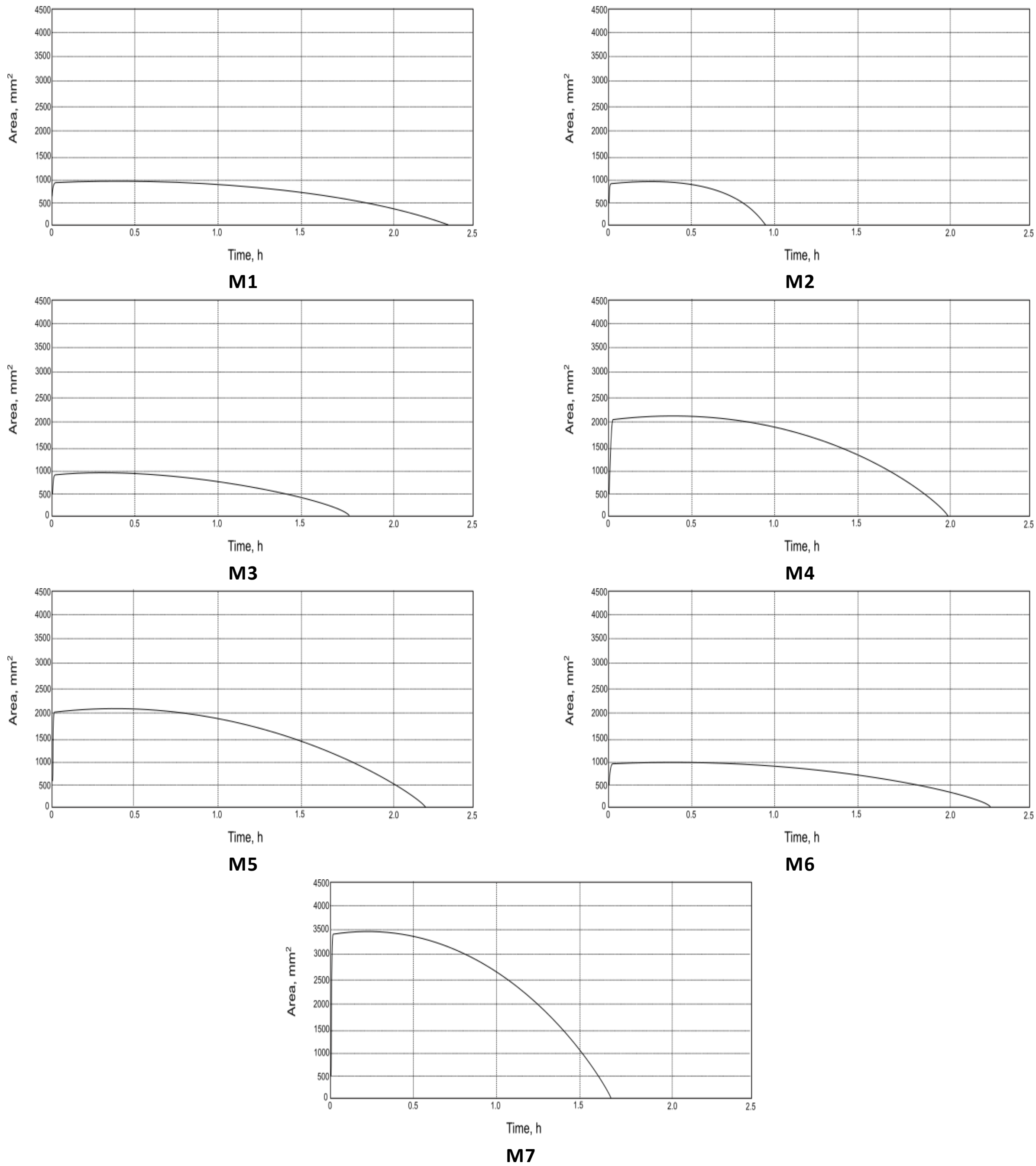


Figure 4. W-D profiles of the investigated materials as the wet area over time

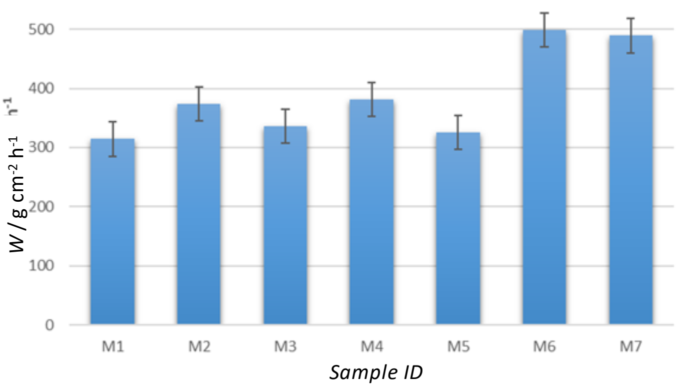


Figure 5. Water vapour permeability

4. CONCLUSION

This paper focuses on the investigation of liquid moisture properties by using thermography to observe changes in temperature that are associated with the amount of moisture on the surface of fabrics. The obtained results indicate that polyester is the most suitable material when it comes to drying clothes intended for athletes. For athletes who run and produce large amounts of sweat, it is very important to maintain an even temperature. Of all seven tested samples, we can highlight 3 materials. The 100 % PES (M2) material has the highest porosity and dries very quickly. The other two are materials with elastane (M6 and M7) that have high water vapour permeability. All three materials can be considered suitable for sportswear. Nowadays, a single sportswear garment is made of several different materials, *i.e.* different materials are combined in the construction of the garment itself. In some parts of the garment, a material that dries faster is needed, while in other parts, the used material that has to be more elastic withstanding the stresses (stretching) that occur every day when playing, while at the same time having higher water vapour permeability. The obtained results confirmed previous research in this field. Due to its short drying time and its smallest spreading wetting area on the surface of the material, it does not cause wearing discomfort, and athletes can perform physical activity without any hindrance. Likewise, infrared thermography has proven to be a useful method for research because it provides reliable data, especially when observing drying time.

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Prijenos tekućine i vodene pare kroz pletene materijale

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(Naučni rad)

Izvod

Sportska odjeća danas je bitan element za sve vrste sportskih aktivnosti diljem svijeta. Aktivna sportska odjeća je odjeća određenih funkcija koja zadovoljava očekivana svojstva i pruža odgovarajuću pomoć sportašima u postizanju sportskih rezultata. Osim funkcionalnosti, važan aspekt sportske odjeće je toplinska i fiziološka udobnost pri nošenju. Pravilnim odabirom odjeće, sportašima se značajno može smanjiti dinamičko i toplinsko opterećenje jer sport zahtijeva nesmetanu pokretljivost, a odjeća mora biti prilagođena tijelu i upijati znoj. Odgovarajući protok vodene pare i tekućine u tekstilnim materijalima važan je s gledišta udobnosti. Stoga je u ovom istraživanju odabrano sedam reprezentativnih uzoraka koji se koriste za odjeću namijenjenu sportu i slobodnom vremenu. Za ispitivanje su korišćeni infracrvena termalna kamera i uređaj za mjerenje apsolutne vlage. Pomoću infracrvene termalne kamere bilo je moguće precizno pratiti prijenos tekućine na površini materijala, sve do završne faze kada je materijal potpuno suh. Rezultati pokazuju da je poliester najprikladniji materijal za izradu sportske odjeće jer ne izaziva nelagodu pri nošenju, a infracrvena termografija je vrlo korisna metoda u istraživanju jer daje pouzdane podatke, posebice kada je u pitanju vrijeme sušenja materijala.

Ključne reči: Pletivo; močenje; termografija; sušenje; sportska odjeća

Study on thermal comfort behaviour of seams made of micro-denier polyester sewing thread for high active sportswear

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Abstract

This work aims to investigate the thermal comfort behaviour of polyester seamed fabric regarding the change in sewing thread filaments fineness for two different seam classes: seam 514 and seam 607. Five seamed fabric samples were constructed with using micro-denier polyester filament of 16.66 tex made of five different filament numbers (38, 48, 108, 144 and 288). It was noticed that the seam thermal properties, air and water vapour permeability, and wicking can be improved if the seam is constructed with using the micro-denier polyester sewing thread. It was also found that the investigated properties increase with the increase in the sewing thread filament fineness on the seam line. The statistical results have also shown that the sewing thread filament fineness is significantly affecting thermal behaviour of the seamed fabric.

Keywords: clothing comfort; seams and stitches; thermal behaviour of seams; sewing thread; micro-denier filaments.

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1. INTRODUCTION

Clothing comfort is an essential garment requirement, especially for garments like sportswear. There are two components of clothing comfort, one is thermo-physiological and the other one is sensorial comfort. Heat and moisture transfer of clothing and the manner of maintaining the heat balance of the human body during activities is termed as thermo physiological wear comfort, while mechanical interaction of the fabric with the skin is termed skin sensorial comfort. The latter indicates possible prickle, irritation, bending, and softness and adherence of the wet fabric [1]. In case that clothing is not transmitting sweat and heat effectively to the surrounding this leads to accumulation of excess heat and could even cause death [2]. Active sportswear design should address both aesthetic requirements and thermal comfort optimization [3]. To attain the comfortable state, the cloth should be able to transmit the body heat and both sensible and insensible perspiration to the surrounding environment quickly.

The moisture management properties are also influencing thermo-physiological properties of cloth [4]. Many studies focus on improving the ability for quick-absorbing and transferring the moisture to the surrounding. In addition to that, seam comfort should be also studied to avoid the body sweat stored on the seam line which can lead to skin rashes due to continuous rubbing of damp seamed fabric during various levels of activities. As mentioned by many researchers, fabric comfort is always different from the seam comfort [4]. Improving the seam comfort will contribute to the overall garment comfort. The seam has a minimum of two layers of fabrics that are joined by the sewing thread. It is proved that the flat lock seam has higher thermal insulation than the overlock and adhesive seams.

Seam's thickness, bulkiness and tightness affect garment thermal comfort properties [5]. Seam consists of multi-layers, which limit the heat and moisture transfer in and around the seams and thereby affect thermal properties of clothing [6]. It was reported in literature that the fabric made of micro-denier polyester shows better comfort properties

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than the fabric made of staple polyester fibre. In the former case, heat enters more quickly because of the smaller diameter of the micro-denier fibres providing also softer feel to the skin [7]. Increase in the fibre liner density leads to increased thermal resistance and lower thermal conductivity and absorptivity, giving a warm feel to the wearer [8].

One approach to improving the seam comfort is by modifying the sewing thread characteristics by which the overall garment comfort can be improved especially for garments like high active sportswear. Traditionally, sportswear seam is constructed by using the sewing thread, which is made of spun polyester yarns. This study is mainly focused on the influence of micro-denier polyester sewing thread on the thermal comfort properties of the flatlock seam. Subjectively, it was observed that the seam made of such a thread provides a softer texture than the seam made of the standard sewing thread. Twist in the yarn is one the factors influencing the wicking of yarn [9]. In this research, a modified sewing thread is made of textured micro-denier polyester yarns with different fineness: from medium fine to micro fibres. A staple micro fibre or filament has the linear density of approximately 1 denier or less [5].

2. MATERIALS AND METHODS

2. 1. Sewing thread preparation

In order to study the impact of micro-denier filaments on the seam comfort properties, five sewing threads with different fibre fineness (from medium fine to micro fibres) are taken. The fabric used for constructing seams was 100 % polyester which is manufactured in Tirupur, India. Sewing threads of 16.6 tex are made of textured micro-denier polyester filaments with five different filament numbers 38, 48, 108, 144, and 288 with the low twist per metre 157, represented as 3.94, 3.1, 1.38, 1.04, and 0.52 dpf (denier per filament), respectively. These polyester filaments are manufactured by Reliance Industries limited, India.

2. 2. Seam preparation

As per the ASTM D6193-11 standard practice for stitches and seams, the most common ones that are used for the construction of sportswear are the Class 500 overlock or overedge and the Class 600 covering stitch or flatlock [4].

2. 3. Flatlock and overlock stitch seam

For the most commonly used Stitch class 607, five thread flatlock stitched seams were constructed using the Class 2: lapped seams are prepared using five different sewing threads (*i.e.* 3.94, 3.1, 1.38, 1.04, and 0.52 dpf) and are represented as FLseam1 to FLseam5, respectively. Similarly, for the second important stitch class 514, four thread overlock stitched seams are constructed using the Class 5: superimposed seams are prepared using the same five different sewing threads (with the same different finenesses) represented as OLseam1 to OLseam5, respectively.

Increasing the number of seams within the sample increases the impact of seams on the overall thermal comfort components of the tested sample. The flatlock seams are prepared by overlapping the fabric raw edges for a small magnitude of seam allowances. This flatlock seam employs 3 needle threads, 1 looper thread and 1 spreader. The overlock seams are prepared by overlapping the two fabric raw edges and sewing together and it is pressed to one side when it is opened. It employs 2 needle threads and 2 looper threads. The gap between seams was maintained as 2.54 cm in both flatlock and overlock seamed fabric (Table 1). 10 samples in total were constructed, with five overlock seams of various finenesses and five flatlock seams of various finenesses.

2. 4. Air permeability

Textest FX 3300 air permeability tester (TEXTEST made in Switzerland) was used to evaluate the air permeability of all samples at a pressure of 100 Pa (according to the standard ASTM D737-18). Average of ten readings was noted for each sample. All the test samples are tested at standard atmospheric conditions (22°C and 65% RH).

2. 5. Moisture vapour transmission rate

Moisture vapour transmission rate was evaluated by Permetest instrument (Labthink Instruments Co.Ltd, China) based on the ISO 11092 standard.

2. 6. Thermal conductivity and resistivity

Thermal comfort properties of seamed fabrics are measured by using an Alambeta instrument (Sensora, Liberec, Czech Republic). The seamed fabric with a series of stitches is tested as per the test procedure of the standard ISO 11092. Thermal resistivity is calculated by the equation:

$$R = h / \lambda \tag{1}$$

where R is the thermal resistance, h is the fabric thickness and λ is the thermal conductivity.

2. 7. Vertical wicking

The fabric samples were cut into 25.4×2.54 cm strips; seam lines were introduced along the lengthwise centreline of the strip and immersed vertically in a distilled water container up to 2 cm of the fabric sample for determining the vertical wicking behaviour of seamed and unseamed fabric. Every 5 min, the water travelled upward on the strip was measured as the height of wicking of water by the sample and each sample was inspected. This test was carried out as per the BS 3424 standard.

2. 8. Statistical analysis

The One-way ANOVA test results prove that there are significant differences in thermal characteristics when the sewing thread filament fineness varies on the seam line and there are significant differences in thermal characteristics among the various seam and stitch classes. The results of the ANOVA analysis are tabulated in Table 2. In order to confirm the reliability of the results, Tukey HSD method is also done using SPSS software and the results are shown in the Table 3.

Table 1: Technical parameters of seams constructed with single jersey 100% polyester fabric (175 g m^{-2} weight); stitch density in all cases was 4 stitches per cm

Sample	Seam class and stitch class	Seam thickness, mm	Sewing thread filament fineness, dpf
Seam 1	Class1: Superimposed seam; Stitch class: 514 (Overlock stitch)	1.90	3.94
	Class2: Lapped seam; Stitch class: 607 (Flatlock stitch)	1.80	3.94
Seam 2	Class1: Superimposed seam; Stitch class: 514 (Overlock stitch)	1.81	3.10
	Class2: Lapped seam; Stitch class: 607 (Flatlock stitch)	1.79	3.10
Seam 3	Class1: Superimposed seam; Stitch class: 514 (Overlock stitch)	1.75	1.38
	Class2: Lapped seam; Stitch class: 607 (Flatlock stitch)	1.66	1.38
Seam 4	Class1: Superimposed seam; Stitch class: 514 (Overlock stitch)	1.63	1.04
	Class2: Lapped seam; Stitch class: 607 (Flatlock stitch)	1.62	1.04
Seam 5	Class1: Superimposed seam; Stitch class: 514 (Overlock stitch)	1.58	0.52
	Class2: Lapped seam; Stitch class: 607 (Flatlock stitch)	1.50	0.52

3. RESULT AND DISCUSSION

3. 1. Thermal conductivity

Thermal conductivity values of seams made of sewing threads with different filament fineness are shown in Figure 1. The results show that the thermal conductivity of the seamed fabric is increased when using finer sewing thread filaments. Finer fibre allows heat enters the fibre quickly helping the garment to maintain the heat balance [10]. The seams made of threads with fine filaments have thus better heat conductivity when compared to those made of threads with coarser filaments so that the overall increase in thermal conductivity from seem 1 to 5 is significant (Fig. 1). However, the differences between the values determined for seams 1 and 2 as well as for 3 and 4 are not as pronounced as differences in values determined for seams 2 and 3 and seams 3 and 5. These results correspond to differences in filament finenesses (*e.g.* the fineness difference for the seams 1 and 2 is 0.86 dpf, while for seams 2 and 3 it is 1.7 dpf). When comparing the overlock and flatlock seams, the latter shows higher thermal conductivity for all filament finenesses. This may be due to the slight differences in the seam thickness as well as in the stitch patterns.

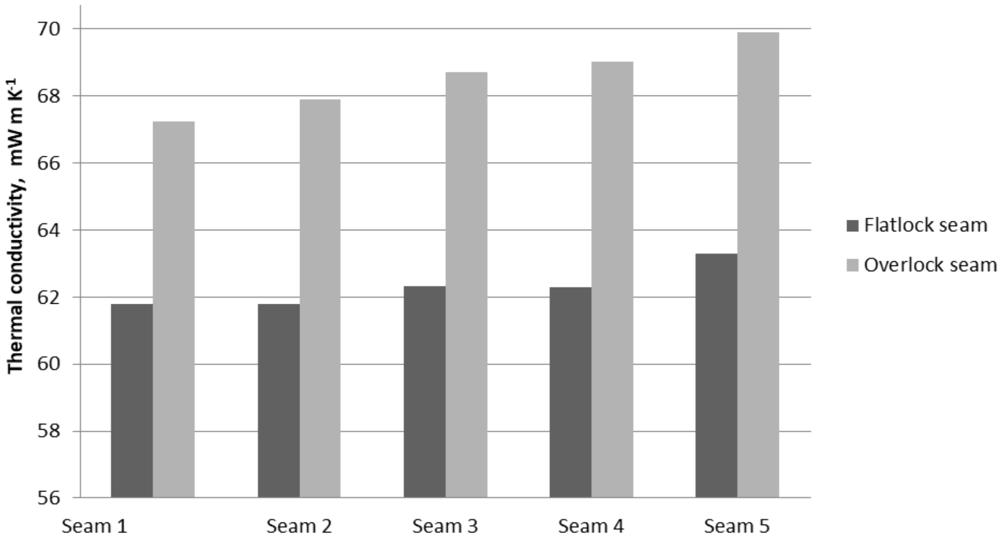

Figure 1. Thermal conductivity of seams made of sewing threads with different filament finenesses

3. 2. Thermal resistance

Thermal resistances of seamed fabric made with sewing threads with different filament finenesses are shown in Figure 2. Seam thermal resistance is determined by the seam thickness and the seam thermal conductivity. The amount of heat-insulated by the seam is decreased with the increase in the sewing thread filament fineness. Finer fibres conduct heat easily and quickly [10]. Thus, the heat transfer is faster in seams made of finer filaments. A decrease in the thermal resistance is seen from the seam 2 to 3 possibly due the decrease in the seam thickness (Table 1) and the increase in the thermal conductivity (Fig. 1). Though there are significant changes in thermal conductivity from the seam 1 to 5 (Fig. 1), there is an only slight change in the seam thickness (Table 1). This is the reason why there is a lower impact on the thermal resistivity for the seam range 3 to 5 (Fig. 2).

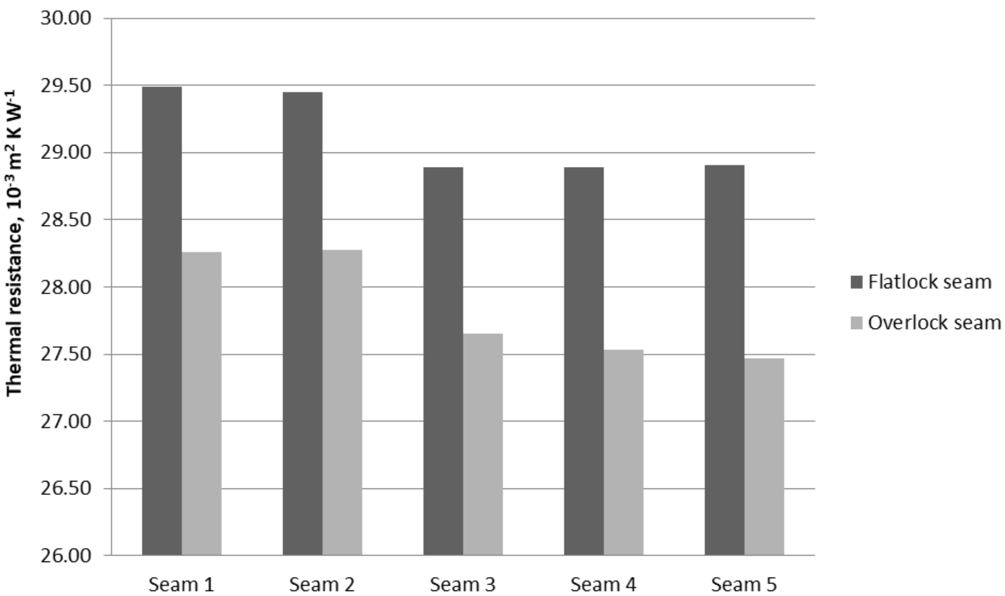

Figure 2. Thermal resistance of seams made of sewing threads with different filament finenesses

3. 3. Moisture vapour transmission rate

Figure 3 presents the water vapour permeability of seams made of micro-denier polyester sewing threads with different filament finenesses showing that the sewing thread fineness plays a vital role in moisture vapour transmission on the seam line. The seam 1 made of coarser filament sewing threads was characterized by the lowest moisture vapour transmission rate, whereas the seam 5 had the highest moisture vapour transmission rate. When the sewing thread becomes finer and the number of filaments is increased, gaps are establishes through which moisture vapour passes from one to the other side of the seam line. The sewing thread is not tightly packed since it has lower number of twists per length (TPI 3 to 4) than the standard sewing thread (TPI 24 to 26) which is also a major factor for creating the gaps among filaments. There are more gaps between finer filaments through which the moisture escapes easier when compared to the coarser filaments.

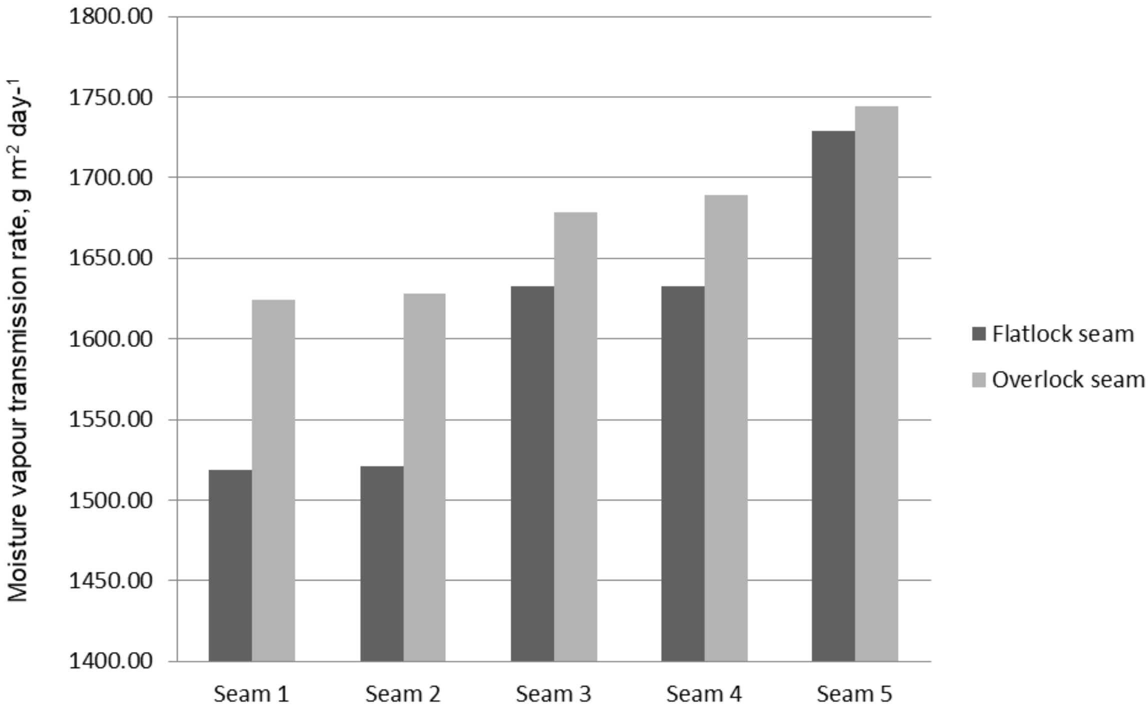

Figure 3. Moisture vapour transmission rate of seams made of sewing threads with different filament finenesses

3. 4. Air permeability

Air permeability of the seamed fabric was determined by measuring the airflow rate passing through the series of seams of a specified area under the standard air pressure. Figure 4 clearly shows that the airflow through the seamed fabric is significantly influenced by the sewing thread characteristics. Airflow increases with an increase in the sewing thread fibre fineness from the seam 1 to 5. A fabric which is allowing moisture transport will usually allow the air transport, too, since air and water vapour permeabilities are closely connected. Air permeability as well as the water vapour permeability of the fabric were improved by the increase in the yarn fineness (Figs. 3 and 4), which provides a less dense structure [11]. This increased airflow may be due to the gaps between the increased number of polyester filaments in the sewing thread for the same sewing thread size. There is no significant change between the seams 1 to 2 due to only slight changes in the sewing thread filament fineness.

3. 5. Wicking

Figure 5 shows wicking properties of the investigated seams. It is evident that the wicking height is increased with the increase in the sewing thread filament fineness on the seam line. Micro-fibres are absorbing water amounting to more than seven times the fibre weight and dry in one-third of the time required for drying of ordinary fibres. Capillary action in the micro-filament sewing thread is better than in a normal denier fibre [10]. This action can be apparently improved by increasing the sewing thread fineness.

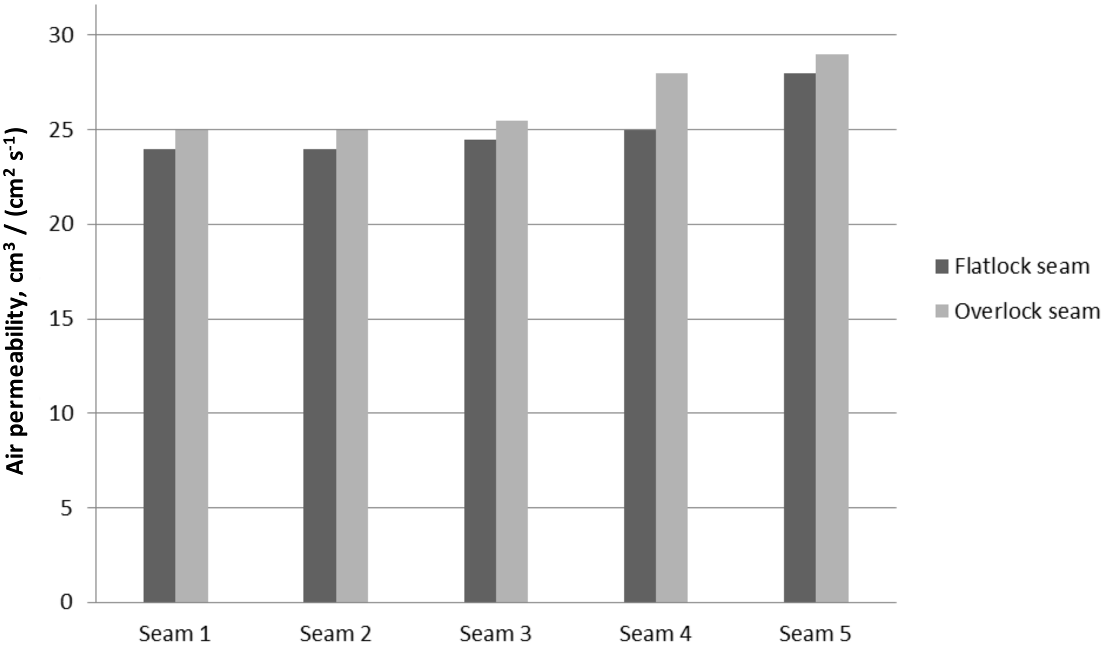

Figure 4. Air permeability of seams made of sewing threads with different filament finenesses

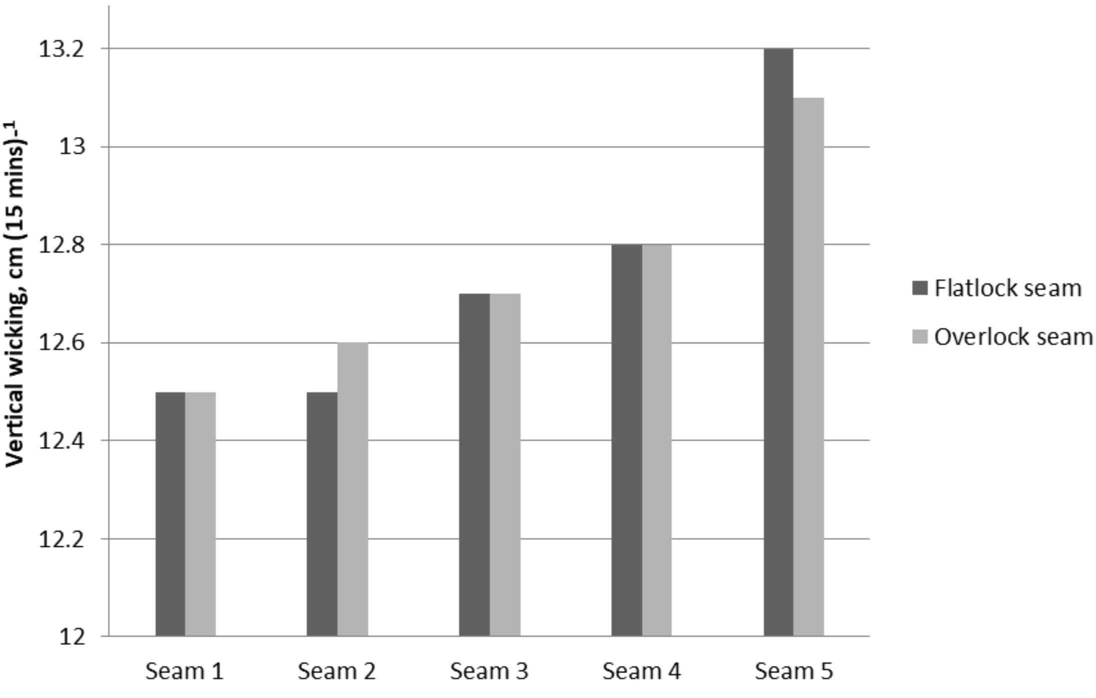

Figure 5. Vertical Wicking of seams made of sewing threads with different filament finenesses;

3. 6. Statistical analysis

One-way analysis of variance (ANOVA) has been performed at 0.05 significant level and the results are shown in Table 2. For all the responses it was obtained that $F_{critical} < F_{actual}$, which means that the sewing thread fineness significantly affects the investigated thermal comfort properties of the seam. Even a slight change in the sewing thread filament fineness is significantly affecting the thermal comfort properties of seams and obviously it will affect the garment's overall comfort. The results of thermal conductivity and thermal resistance are tested by using the Tukey's

HSD (Honestly significant difference) test, too (Table 3). It is evaluated which pairs of the results among all the results are significantly different with respect to each other. The p-value of the given result corresponding to the *F*-statistic of one-way ANOVA, lower than 0.01 strongly indicates that one or more pairs of samples are significantly different. The *Q* critical value ($Q_{(5,40)}$= 4.93) is lower than the *Q* actual value for all the pair comparisons. This analysis strongly confirmed that the sewing thread filament fineness greatly influences the thermal comfort properties of seams.

Table 2: Statistical analysis using one-way ANOVA

Seam type	Thermal conductivity, mW m K^{-1}		Thermal resistance, 10^{-3} m^2 K W^{-1}		Moisture vapour transmission rate, g m^{-2} day^{-1}		Air permeability, cm^3 / (cm^2 s^{-1})		Vertical wicking, cm (15 min)$^{-1}$	
	F value	*P* value*	*F* value	*P* value*	*F* value	*P* value*	*F* value	*P* value*	*F* value	*P* value*
Flatlock seam	1954.42	1.1102	381769.21	1.1102	2273.21	1.1102	4267.66	1.1102	1162.70	1.1102
Overlock seam	9720.68	1.1102	1,740.11	1.1102	1339.79	1.1102	4541.91	1.1102	129.71	1.1102

*All *P* values should be multiplied by 10^{-16}

Table 3: Post hoc Tukey HSD multiple comparisons

Dependent variable	Comparisons between samples	Standard error	Significant difference	95 % confidence interval	
				Lower bound	Upper bund
Thermal conductivity	SEAM4 *vs*. SEAM5	0.798758	0.000	-8.82174	-4.37926
	SEAM3 *vs*. SEAM5	0.798758	0.000	-11.06474	-6.62226
	SEAM3 *vs*. SEAM4	0.798758	0.000	-4.46424	-0.02176
	SEAM2 *vs*. SEAM5	0.798758	0.000	-11.82524	-7.38276
	SEAM2 *vs*. SEAM4	0.798758	0.003	-5.22474	-0.78226
	SEAM2 *vs*. SEAM3	0.798758	0.000	-2.98174	1.46074
	SEAM1*vs*. SEAM5	0.798758	0.000	-15.82724	-11.38476
	SEAM1 *vs*. SEAM4	0.798758	0.000	-9.22674	-4.78426
	SEAM1 *vs*. SEAM3	0.798758	0.000	-6.98374	-2.54126
	SEAM1 *vs*. SEAM2	0.798758	0.000	-6.22324	-1.78076
Thermal r esistance	SEAM4 *vs*. SEAM5	0.722149	0.000	068330	3.33309
	SEAM3 *vs*. SEAM5	0.722149	0.000	-0.01646	3.99994
	SEAM3 *vs*. SEAM4	0.722149	0.000	-1.34135	2.67504
	SEAM2 *vs*. SEAM5	0.722149	0.000	1.74120	5.75760
	SEAM2 *vs*. SEAM4	0.722149	0.001	0.41631	4.43270
	SEAM2 *vs*. SEAM3	0.722149	0.000	-0.25054	3.76586
	SEAM1 *vs*. SEAM5	0.722149	0.000	2.91111	6.92751
	SEAM1 *vs*. SEAM4	0.722149	0.000	1.58622	5.60262
	SEAM1 *vs*. SEAM3	0.722149	0.001	0.91937	4.93577
	SEAM1 *vs*. SEAM2	0.722149	0.001	-0.83829	3.17811

*The mean difference is significant at the 0.01 level

5. CONCLUSIONS

Increase in the sewing thread filament fineness leads to the higher thermal conductivity and lower thermal resistance in seams. Increase in the filament fineness induces also the increase in air and moisture vapour permeabilities attributable to the enhanced availability of free voids in the seam structure. Vertical wicking of the seams made of different fibre finenesses are slightly influenced by the fibre fineness in both overlock and flatlock seams. Overall thermal comfort properties of overlock seams were better when compared to the flatlock seam due to the larger seam thickness and bulkiness in the latter case. The conclusion is that the seams made of micro-denier polyester sewing thread provide better thermal comfort than overclock seam. The study concludes that the thermal comfort properties of seams can be improved by reducing sewing thread filament fineness.

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Toplotni komfor šavova formiranih upotrebom šivaćeg konca od poliestarskih mikrofilamenata namenjenih za profesionalnu sportsku odeću

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(Naučni rad)

Izvod

Cilj ovog rada je ispitivanje svojstava toplotnog komfora poliestarske pletenine sa šavovima izrađenim od poliestarskih šivaćih konaca različite finoće filamenata. Primenjene su dve vrste iz dve različite klase šavova – 514 i 607. Konci za šivenje iste finoće 16,66 tex izrađeni su od različitog broja teksturiranih poliestarskih filamenata (38, 48, 108, 144 and 288). Na taj način, eksperimentalni materijal je obuhvatio ukupno 10 različitih uzoraka sa šavovima svrstanim u pet grupa (različita finoća filamenata) sa po dve vrste šava. Uočeno je da se termička svojstva, propustljivost vazduha i vodene pare, i kapilarno kvašenje šava mogu poboljšati upotrebom poliestarskog šivaćeg konca izrađenog od finijih (mikro) filamenata. Takođe, utvrđeno je da se sa povećanjem finoće filamenata šivaćeg konca povećava propustljivost vazduha i vodene pare, kapilarno kvašenje i sposobnost prenosa toplote na liniji šava. Uticaj finoće filamenata šivaćeg konca na toplotni komfor šavova potvrđen je statističkom analizom.

Ključne reči: udobnost odeće; šavovi i ubodi; termičko ponašanje šavova; konac za šivenje; mikro-dener filamenti