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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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):

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

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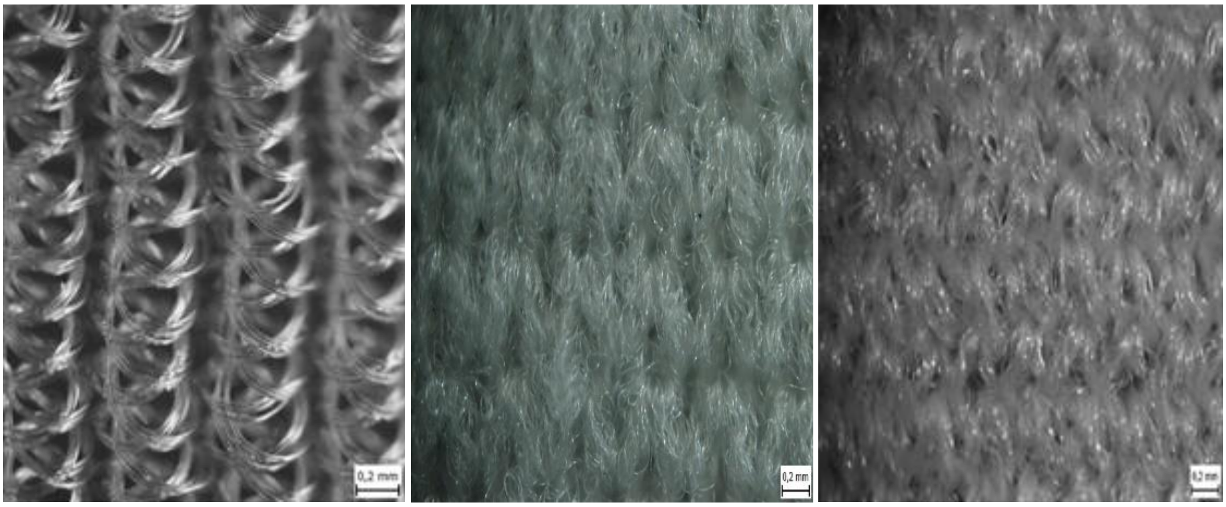
Standard fibre densities for polyamide (ρ_0 = 1.14 g cm^{-3}) and elastane (ρ_0 = 1.15 g cm^{-3}) were used for the calculation. The fabric density (ρ) was calculated by using the fabric mass per unit area (M) and thickness (t), Equation (2):

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

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:

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

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

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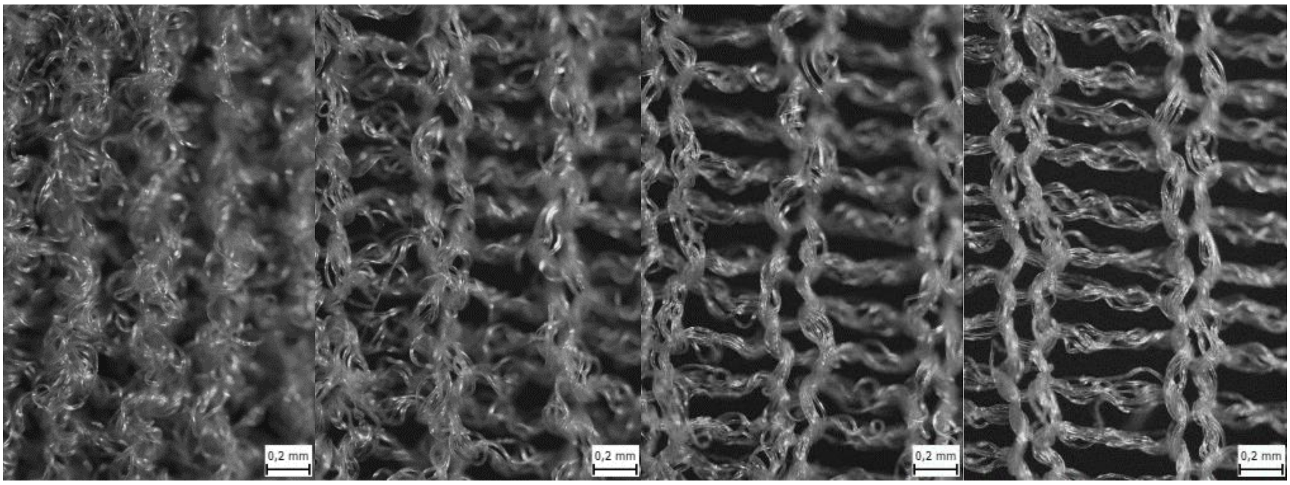
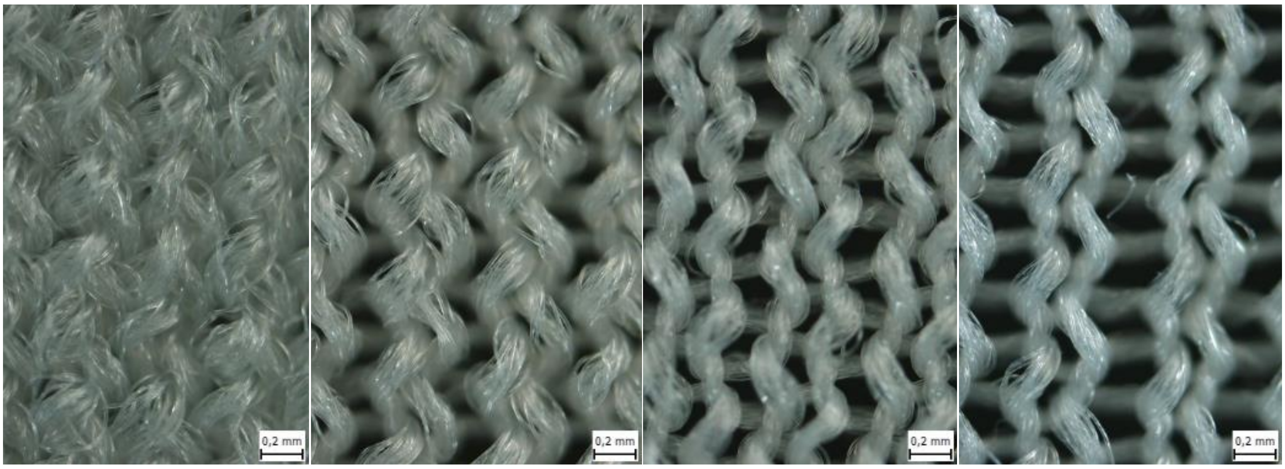
19.6 cm^2), 5.5 cm in diameter (area 23.7 cm^2), and 6 cm in diameter (area 28.3 cm^2). The extensions correspond to 100, 121 and 144 % of the original dimensions.

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.



Extension 0 % Extension 100 % Extension 121 % Extension 144 %

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



Extension 0 % Extension 100 % Extension 121 % Extension 144 %

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

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fabrics increases as porosity (and air permeability) increases. Therefore, there is a strong negative correlation between air permeability and water vapour resistance.

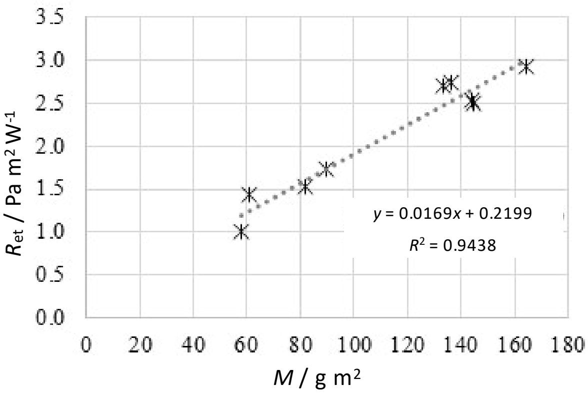

Figure 4. Correlation of R_{et} and speciffic mass

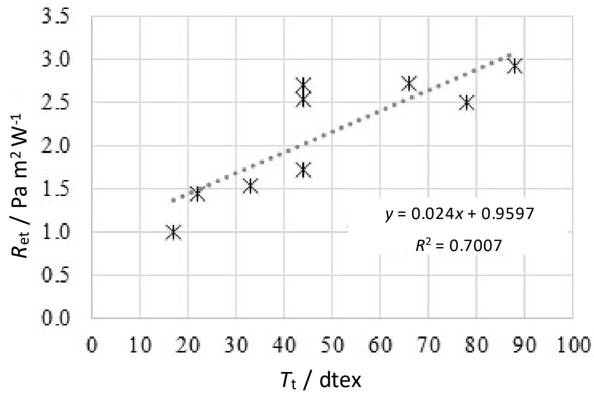

Figure 5. Correlation of R_{et} and yarn fineness

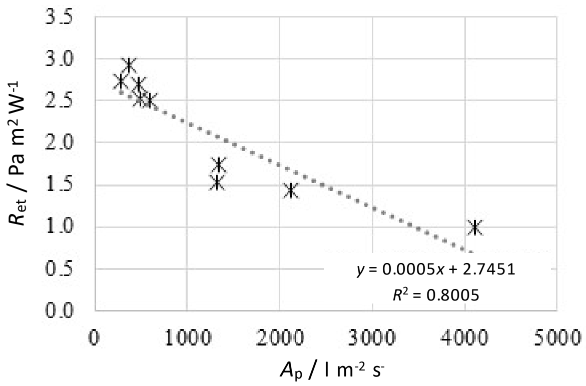

Figure 6. Correlation of R_{et} and air permeability

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.

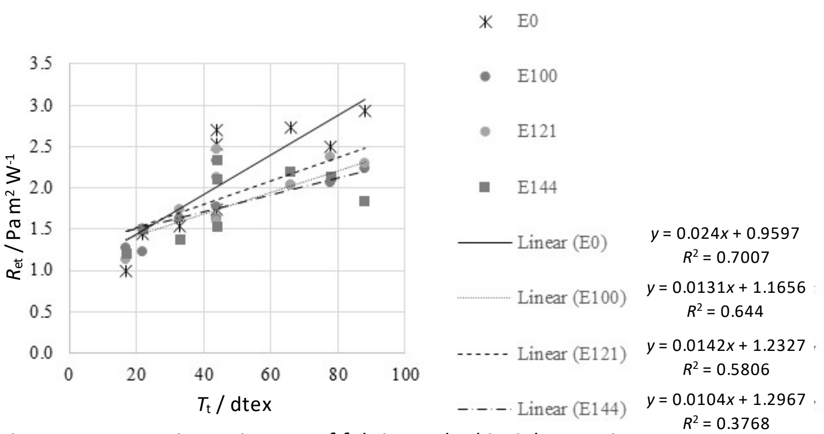

Figure 7. Evaporative resistance of fabrics under biaxial extension and the best linear fits

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

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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

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