Elena Tomovska[1,*], Lubos Hes[2]

Thermophysiological Comfort Properties of Polyamide Pantyhose

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[1] **University Ss Cyril and Methiodus, Faculty of Technology and Metalurgy, Department of Textiles,** Skopje, Macedonia
* e-mail: etomovska@tmf.ukim.edu.mk

[2] **Technical University of Liberec, Faculty of Textile Engineering, Department of Textile Evaluation,** Liberec, Czech Republic

Abstract
In this paper, the thermophysiological characteristics of low weight knitted polyamide and polyamide/elastane fabrics for pantyhose differing in terms of filament count were studied. Alambeta and Permetest devices were used to measure the thermal conductivity, thermal resistance, thermal absorptivity, evaporative resistance and relative water vapour permeability. The results indicated that fabrics made of finer filaments have lower thermal conductivity, thermal resistance, thermal absorptivity and evaporative resistance values.

Key words: *polyamide, knitted fabrics, thermophysiological comfort.*

Introduction

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]. Thermal comfort, a subset of clothing comfort, pertains to two basic properties: thermal resistance (or insulation), and water vapour resistance (or permeability) [2].

Thermal properties are among the most important features of textiles [3]. Most of the studies carried out have been devoted to measuring thermal properties such as thermal conductivity, thermal resistance, and thermal absorptivity. Thermal conductivity indicates the ability of a material to allow the passage of heat from one side to another. Thermal conductivity is anisotropic in nature and largely depends upon the structure of the material. The thickness of a material determines its resistance to the passage of heat through it. Thermal resistance has an inverse relationship with thermal conductivity. Thermal absorptivity indicates whether a user feels 'warm' or 'cool' upon the first brief contact of the fabric with human skin. The smoother the fabric surface, the cooler the fabric feels to the touch, because conduction between the skin and fabric is maximised and thermal changes taking place in the fabric are rapidly passed onto the skin [4].

The heat and fluid transmitting properties of textiles are influenced by various structural fabric characteristics such as fibre type, yarn properties, fabric structure, finishing treatments and clothing conditions.

The influence of raw material on the thermal insulation of clothing results from the different thermal properties of fibres and polymers. The thermal comfort properties of fabrics from different types of fibres and yarns have been researched. Oglakcioglu and Marmarali studied polyester and cotton fibres [5], as well as the characteristics of single jersey knitted structures produced from channelled and hollow polyester fibres [6]. Ozcelik et al. investigated the effect of yarn bulkiness obtained via different texturing processes on the thermal properties of polyester yarns [4]. Sampath et al. [7, 8] showed that knitted sportswear of spun polyester and polyester/cotton fabrics provided better thermal insulation and warmer feeling on initial touch compared to micro-denier and filament polyester. Fabrics from cellulose fibres, such as cotton, regenerated bamboo, flax and rayon [9, 10], or protein fibres such as wool [11, 12] were also investigated. It can be observed that research mostly concentrates on the more common types of fibre, such as polyester or cotton.

Other researchers concentrated on the influence of fabric structure on thermal properties [13]. In the case of knits, research concentrates on the effect of different knitting patterns. When comparing cotton and polyester knitted fabric with different structures, single jersey fabrics showed remarkably lower thermal conductivity and thermal resistance values as well as higher relative water vapour permeability values than 1 × 1 rib and interlock fabrics [5]. Amber et al. [11] investigated the thermal and moisture transfer properties of single jersey, half terry and terry sock fabrics with various types of fibre and yarn structure. Ucar and Yilmaz [14] analysed the natural and forced convective heat transfer characteristics of 1 × 1, 2 × 2 and 3 × 3 rib knitted fabrics produced from acrylic yarns. In addition to investigating different knitted patterns (plain, rib and interlock), Erdumlu and Saricam [15] varied the yarn tightness in fabrics.

The objective of this study was to determine the effect of yarn count and fibre content on the thermal comfort of polyamide and polyamide blend pantyhose with different yarn counts, as well as their moisture transport properties. Insight into the comfort properties of pantyhose can help towards the development of specific fabrics for warm/cold weather conditions and increase consumer choice by allowing adequate labelling of pantyhose for various climate conditions.

Materials and methods

In this study, the effects of filament count and the addition of elastane on the thermophysiological properties of polyamide pantyhose were investigated. Samples were knitted from commercially available yarns on an industrial circular knitting machine with four systems, a diameter of four inches and 400 needles. The filament composition of the pantyhose was pure nylon, with standard and microfibre filaments, as well as blends of polyamide with bare elastane and covered elastane. The filament density ranged from 8/2 dtex to 2 × 44/13 dtex. Filaments were knitted at three different tightness levels, resulting in various stich densities of the finished fabric. As a result, 42 pantyhose structures were obtained. The pure polyamide knits were single jersey, while the addition of elastane was through a knitted hopsack structure. Physical and structural properties of the samples are presented in ***Table 1***. The samples were made of fine filaments, with low weight and a high cover factor.

Thermal properties of the fabrics were measured by an Alambeta instru-

Table 1. Sample specifications. **Sample code:** Number – yarn count, P – pure polyamide, M – microfiber polyamide, E – polyamide-bare elastane blend, CE – polyamide-covered elastane blend.

Sample	Yarn count, dtex	Stitch density, cm^{-2}			Weight, g/m^2			Cover factor, %		
	T_t	D_1	D_2	D_3	M_1	M_2	M_3	CF_1	CF_2	CF_3
8CE	8/2	990	540	360	31.7	33	27.4	79.7	76.6	72.6
17P	17/3	1050	810		57.7	56		88.9	89.1	
17E	17/3	945	720	420	55.7	56.3	45.5	94.4	96.4	94.1
22P	22/5	810	675	540	60.9	56.6	61.4	86.0	88.1	89.9
22E	22/5	675	600	420	58.8	55.4	50.5	93.8	94.3	94.6
22CE	22/4	945	720	480	55.7	50.1	39.7	84.1	73.6	68.2
33P	33/10	525			81.7			88.5		
33M	33/10+44/34	840			83.6			86.3		
44E	44/13	1350	840		143.9	125.7		94.2	97.1	
44P	44/13	720	720	630	89.5	83.1	83.2	94.4	92.0	96.2
44M	22/20x2	735	525	450	133.4	108.4	103.8	97.7	97.4	98.2
66M	33/34x2	630	525	360	136.4	118.4	109.2	98.1	98.4	98.0
78P	78/24	630	540	450	144.6	140	135.8	94.9	95.8	95.1
78CE	78/24	630	525	360	99.52	91.7	88.5	88.3	85.0	81.2
88CE	44/13x2	360	320	240	164.2	143.6	119.7	89.2	89.1	89.5

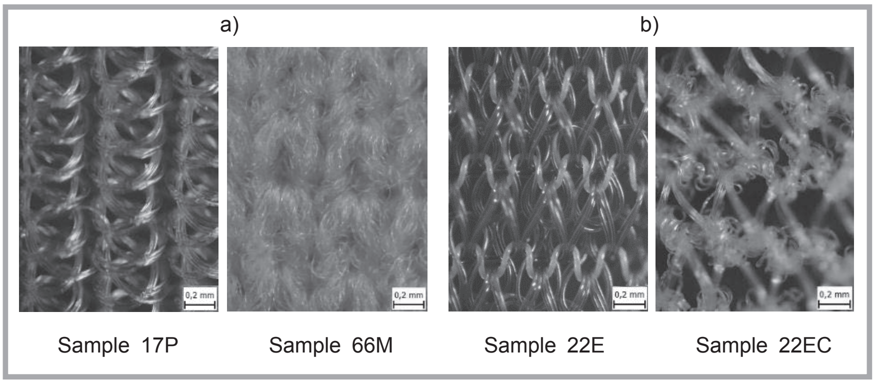

Figure 1. Optical microscopy images (5x) of the surfaces of samples B: a) single jersey and b) knitted hopsack with bare and covered elastane.

ment according to Standard ISO 8301. The measurements were repeated 5 times on randomly chosen parts of the fabrics, and average values and standard deviations were calculated. Permatest apparatus determined the relative water vapour permeability (RWVP) and evaporative resistance (Ret) of the textile fabrics according to the Czech equivalency of Standard ISO 11092. The measurement was repeated 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 cover factors of the samples were calculated using an image analysis technique, in which photos were taken with an Olympus BX51 microscope at a magnification of 5 ×, and the macro porosity was analysed with the "R" programme. ***Figure 1*** shows microscopic images of selected samples.

Results and discussion

Thermal properties

Thermal properties of the samples are given in ***Table 2***. Due to the low thickness of material and structure of the knits, the variation coefficient of the thickness is higher than usual. ***Table 3*** lists the correlation coefficients between thermal and strucrtural properties of the samples.

Thermal conductivity (λ) is a phenomenon which indicates the capability of material to conduct heat from one point to another. Lower thermal conductivity indicates that the material has better thermal insulation properties. The thermal conductivity of samples correlates with the linear density of the constituent yarns of the fabric. Two groups of samples were analysed – samples P made of pure polyamide with filaments of 17, 22, 33, 44, and 78 dtex linear density, and samples CE made of polyamide and covered elastane blends with filaments of 8, 22, 78, and 88 dtex linear density. Both sample groups had three densities, as seen in ***Table 1***. Pearson correlation coefficients between the thermal conductivity and filament yarn count are given in ***Table 3***. ***Figure 2.a*** presents the regression curves for both sets of samples. It is noticeable that in both cases finer filaments contribute to lower thermal conductivity of the pantyhose.

The thermal conductivity of dry fabrics depends on the structure and properties of the yarns. The thermal conductivity of fabrics is due not only to the polymers but also to the air trapped inside the fabric, which has a thermal conductivity of 0.024 W/mK. The macro porosity and inter-yarn spaces depend on the filament count. Coarser filament yarns are composed of more filaments as compared to finer filament yarns, leaving fewer macro pores in the fabric. Thus, pantyhose made of coarser filaments have higher thermal conductivity values.

Covered elastane yarns consist of an elastane core wrapped in textured polyamide filament. The addition of covered elastane yarns adds more air to the knitted structure, particularly with coarser filaments. Therefore, the influence of elastane is more visible for knitted fabrics of coarser yarns, which have lower thermal conductivity compared to pure polyamide samples. In addition, the inlayed covered elastane yarn disrupts the laminar flow of air between the knit courses, which would add to the thermal insulation effect.

Macro-porosity can also be expressed through the cover factor (CF) of yarns. Pantyhose made of coarser yarns have a higher cover factor. As the thermal conductivity of all fibres is lower than that of air, it will decrease with an increase in the cover factor, as can be seen in ***Figure 2.b***. The Pearson correlation coefficients are listed in ***Table 3***. The cover factor of a fabric depends on the knitted structure, hence the correlation coefficient of the overall set is low; however, when the same structures are considered as one set, it increases drastically. Covered elastane yarns entrap more air and will have the same thermal conductivity as pure polyamide even if their cover factor is lower.

When it comes to pantyhose made with the addition of bare elastane, the results given in ***Table 2*** for samples 17P & 17E and 44P & 44E show that the thermal

Table 2. Thermal properties of samples.

Sample	λ (10^{-3} W $K^{-1}m^{-1}$), CV%			R (10^{-3} Km^2/W), CV%			h (mm), CV%			b ($Ws^{1/2}$ $K^{-1}m^{-2}$), CV%		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
8CE	37.48	37.05	36.25	5.34	5.64	4.41	0.20	0.21	0.16	75.0	63.0	63.5
	(2.9)	(1.2)	(1.2)	(2.9)	(0.8)	(1.1)	(0.0)	(1.2)	(0.0)	(9.0)	(7.6)	(7.2)
17P	39.75	37.37		7.36	6.23		0.28	0.23		76.9	70.1	
	(2.7)	(6.1)		(1.2)	(11.1)		(7.2)	(5.2)		(5.3)	(5.3)	
17E	37.69	39.57	37.60	8.27	7.11	5.45	0.31	0.28	0.20	89.8	80.2	82.7
	(3.3)	(1.5)	(5.0)	(1.3)	(6.0)	(3.9)	(4.3)	(7.2)	(7.6)	(5.6)	(5.9)	(3.4)
22P	37.25	38.83	37.65	8.06	8.31	8.64	0.30	0.32	0.33	88.1	89.1	86.1
	(1.7)	(3.4)	(1.7)	(0.7)	(3.0)	(6.1)	(2.4)	(3.0)	(4.4)	(1.6)	(5.7)	(4.8)
22E	38.78	39.54	38.78	5.06	5.56	5.26	0.22	0.22	0.20	103.1	90.9	95.1
	(1.9)	(1.0)	(2.1)	(3.0)	(1.6)	(2.2)	(4.4)	(2.8)	(2.3)	(3.2)	(2.4)	(4.2)
22CE	40.23	37.63	37.70	7.51	8.21	8.24	0.30	0.31	0.31	98.6	84.6	72.2
	(1.5)	(3.6)	(4.4)	(7.4)	(1.7)	(6.3)	(8.5)	(5.2)	(7.5)	(7.1)	(1.9)	(7.5)
33P	43.49			8.95			0.39			114.5		
	(4.4)			(4.3)			(1.5)			(9.2)		
33M	44.43			9.96			0.44			102.4		
	(2.9)			(3.7)			(3.0)			(1.7)		
44E	42.83	41.05		11.75	13.12		0.50	0.54		135.7	117.6	
	(1.8)	(1.9)		(3.6)	(2.6)		(2.1)	(2.5)		(4.2)	(8.6)	
44P	45.50	44.04	42.18	9.64	10.22	10.38	0.44	0.45	0.44	105.0	101.1	97.3
	(1.9)	(2.0)	(1.0)	(1.6)	(2.1)	(4.1)	(1.4)	(1.3)	(4.2)	(4.1)	(5.6)	(6.9)
44M	46.70	42.75	38.02	9.98	11.03	13.01	0.47	0.47	0.49	134.8	116.6	98.41
	(1.1)	(1.5)	(2.4)	(1.4)	(1.0)	(1.5)	(2.0)	(2.8)	(2.4)	(5.4)	(5.6)	(7.3)
66M	51.35	49.85	45.93	9.50	9.93	10.92	0.49	0.50	0.50	143.6	128.1	119.7
	(1.9)	(0.1)	(2.6	(2.8)	(1.6)	(1.0)	(1.4)	(1.4)	(2.1)	(6.5)	(4.4)	(1.2)
78P	52.52	48.90	45.08	9.33	11.40	12.75	0.49	0.56	0.57	155.0	131.3	118.4
	(0.8)	(2.0)	(2.3)	(1.8)	(0.1)	(3.0)	(2.2)	(1.9)	(1.5)	(5.2)	(1.4)	(5.1)
78CE	45.27	42.50	41.23	9.39	10.42	11.52	0.43	0.44	0.48	137.2	123.1	102.7
	(1.5)	(2.3)	(2.3)	(1.4)	(1.2)	(4.0)	(0.0)	(2.3)	(5.2)	(4.7)	(6.2)	(3.1)
88CE	46.84	45.23	42.50	14.16	15.41	16.60	0.66	0.70	0.71	141.4	128.8	123.6
	(2.8)	(3.5)	(1.0)	(3.5)	(2.6)	(2.7)	(2.6)	(1.7)	(2.3)	(8.0)	(8.3)	(8.1)

Table 3. Correlation of structural and thermal properties of samples.

Parameter	Set	Thermal conductivity λ, 10^{-3} W $K^{-1}m^{-1}$			Thermal resistance R, 10^{-3} Km^2/W			Thermal absorptivity b, $Ws^{1/2}$ $K^{-1}m^{-2}$		
		D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
Yarn count Tt, tex	Whole set	0.85	0.84	0.83	0.72	0.82	0.88	0.90	0.93	0.90
	Set P	0.97	0.99	0.97	0.74	0.91	0.99	0.96	0.97	0.99
	Set CE	0.99	0.98	0.99	0.90	0.91	0.94	0.99	0.99	0.98
Cover factor CF, %	Whole set	0.34	0.52	0.47	0.21	0.29	0.40	0.34	0.48	0.62
	Set P	0.88	0.97	0.85	0.74	0.85	0.71	0.68	0.91	0.65
	Set CE	0.98	0.97	0.90	0.89	0.87	0.88	0.99	0.89	0.95

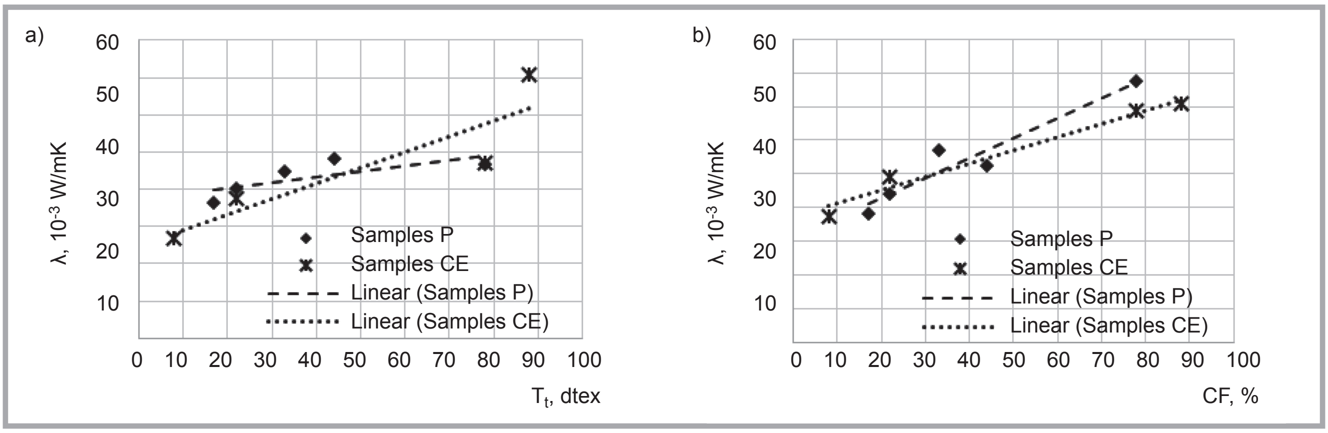

***Figure 2.** Correlation of thermal conductivity of samples D_1 of pure polyamide (P) and polyamide with covered elastane (CE): a) with linear density of filaments and b) with cover factor of knitted fabrics.*

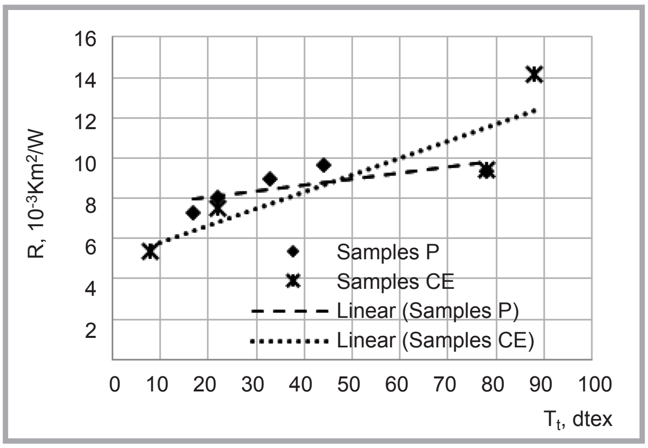

Figure 3. *Thermal resistance of samples D_1 of pure polyamide (P) and polyamide with covered elastane (CE) with linear density of filaments.*

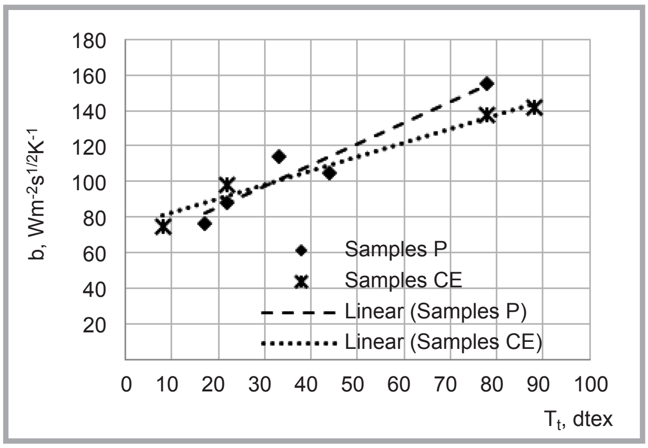

Figure 4. *Thermal absorptivity of samples D_1 of pure polyamide (P) and polyamide with covered elastane (CE) with linear density of filaments.*

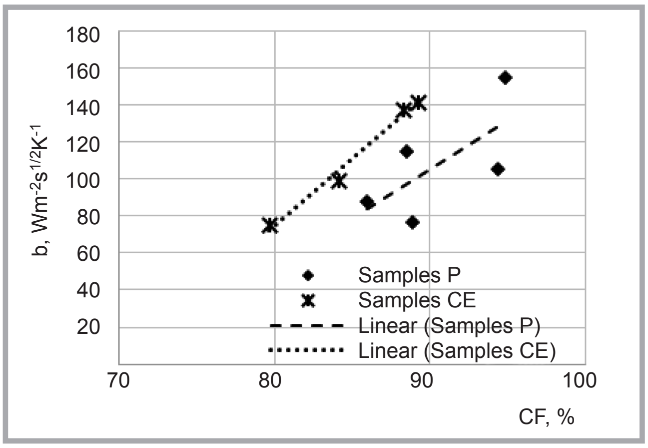

Figure 5. *Thermal absorptivity of samples D_1 of pure polyamide (P) and polyamide with covered elastane (CE) with cover factor of knitted fabrics.*

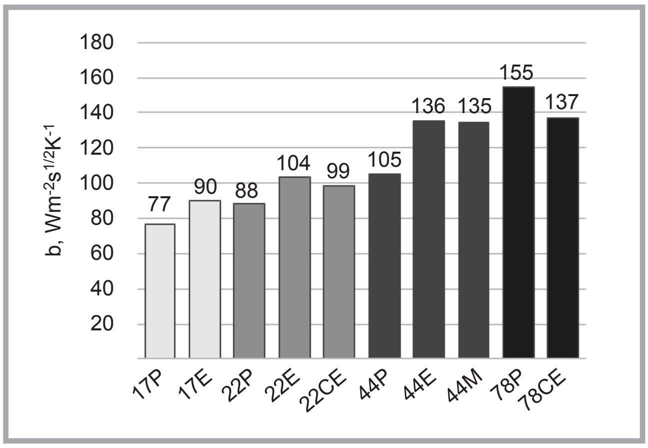

Figure 6. *Thermal absorptivity of samples D_1.*

conductivity of pantyhose with added elastane is slightly lower. Similar to pure and covered elastane yarns, finer microfibre (samples 44M) has lower thermal conductivity values compared to coarser (sample 66M).

The thermal resistance of the knitted polyamide filament fabrics is relatively low, as shown in ***Table 2***. Thermal resistance is directly proportional to fabric thickness and increases as the fabric thickness increases. Although the samples made of finer filaments show lower thermal conductivity, they are very thin, with a thickness ranging from 0.16 mm to 0.32 mm. As an end result, thickness overrides the significance of low thermal conductivity, and they have lower thermal resistance values. Coarser yarns produce fabrics with a thickness of 0.5-0.7 mm, providing increased thermal resistance, despite having higher thermal conductivity. Correlation coefficients of the thermal resistance with the yarn count and cover factor are given in ***Table 3***.

The thermal absorptivity (b) values depend on the thermal capacity and conductivity of the fabric as well as on the contact area of the skin and surface. Similar to the thermal conductivity, the thermal absorptivity of samples increases with the growth of linear density and the cover factor, as shown in ***Figures 4*** and ***5***. The surface character of the fabric greatly influences this sensation. A smoother surface increases the area of contact and the heat flow, thereby creating a cooler feeling. Coarser filaments distribute more evenly on the fabric surface, making the knitted fabrics cooler at touch. The presence of elastane increases the cool feeling. Along with bare elastane yarns contributing to a smoother fabric surface, the thermal absorptivity also significantly increases, as can be seen from the comparison of samples 17P, 22P and 44P with 17E, 22E and 44E (***Figure 6***). Blends of polyamide and covered elastane yarns did not show a constant trend. Microfibre yarns (44M) provide a cooler touch in comparison to standard yarns, which is consistent with previous results for polyester knits [6].

Relative water vapour permeability and water vapour resistance

Water vapour permeability (RWVP) is the ability of fabrics to transmit water vapour from one side to the other. The evaporative resistance, Ret, is the reciprocal quantity of water vapour permeability. The higher the *RWVP*, the lower the *Ret,* and the better the thermal comfort of the garment.

All samples examined showed very high RWVP and had low *Ret* values, given in ***Table 4***. Due to the larger porosity, open fabrics, like knitted ones, naturally offer much higher water vapour permeability. Samples of all densities were highly correlated to the fabric weight and filament count (***Figures 7*** and ***8***). The presence of elastane in either form did not influence the moisture transport properties of the fabric. Samples containing micro fibres

Table 4. Relative water vapour permeability and water vapour resistance. ***Note:*** *a) Correlation with samples mass M, g/m^2; b) Correlation with filament linear density Tt, dtex.*

Sam.	Ret (Pa m^2/W)						RWVP (%)					
	D_1		D_2		D_3		D_1		D_2		D_3	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
8CE	1.3	3.9	1.3	3.9	1.2	4.9	80.8	0.4	80.7	0.5	82.0	0.5
17P	1.0	0.0	1.0	8.2			85.1	0.4	84.9	0.7		0.7
17E	1.5	3.9	1.3	13.9	0.9	0.0	78.4	0.5	80.6	0.9	86.7	0.9
22P	1.4	4.3	1.6	3.7	1.4	0.0	79.7	1.0	78.2	0.8	79.4	0.5
22CE	1.3	4.3	1.4	4.2	1.3	4.3	80.8	0.4	80.5	0.0	80.6	0.5
33P	1.5	3.8					78.2	1.1				
33M	1.9	11.5					73.8	0.9				
44E	2.5	4.6	2.8	2.1			68.5	0.6	65.4	0.5		
44P	1.7	3.3	1.9	2.9	1.7	7.7	77.8	0.9	74.5	0.9	77.2	0.9
44M	2.7	3.7	2.4	2.4	2.5	4.7	67.3	1.7	68.0	2.6	67.5	2.6
66M	2.7	5.6	2.6	2.2	2.4	4.2	67.2	1.3	66.4	1.4	68.2	1.4
78P	2.5	4.0	2.6	4.5	2.4	2.4	67.6	2.4	66.3	2.3	67.8	2.3
78CE	2.1	3.0	2.0	5.9	2.0	4.8	72.2	1.7	73.5	1.9	73.3	1.9
88CE	2.9	3.9	3.0	0.0	3.1	3.7	64.7	2.0	64.2	2.5	63.9	2.5
a)	0.96		0.96		0.90		-0.94		-0.96		-0.91	
b)	0.83		0.83		0.87		-0.83		-0.82		-0.85	

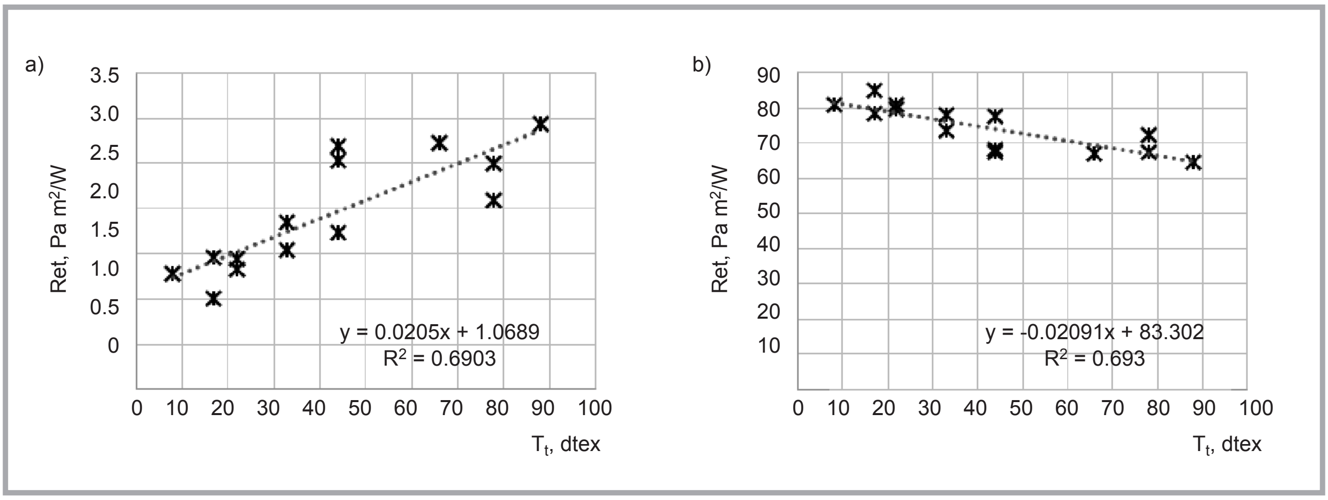

Figure 7. Correlation of a) Ret and b) RWVP with yarn count.

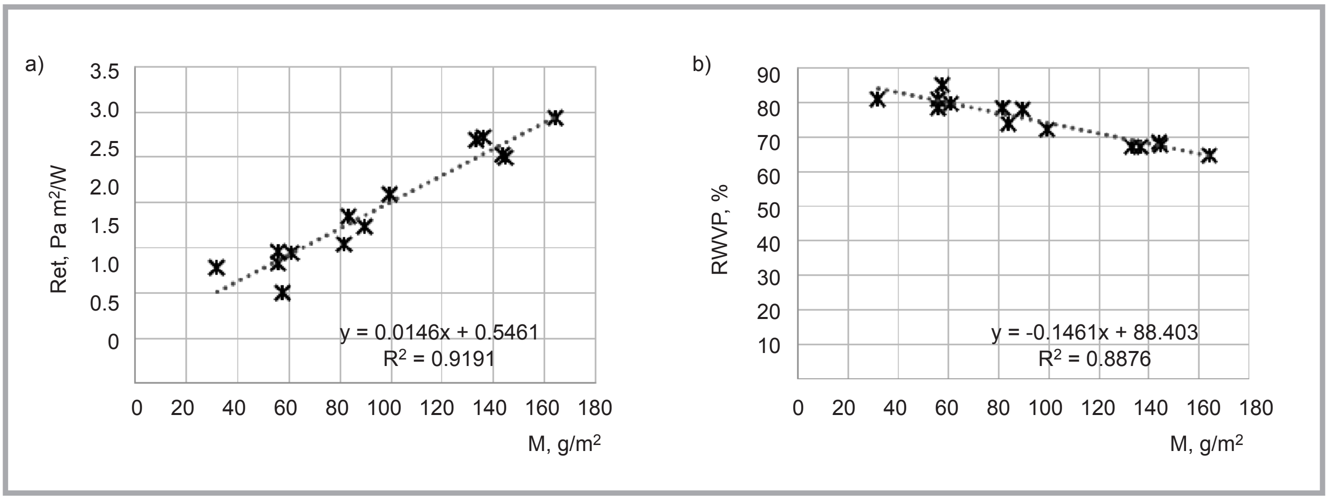

Figure 8. Correlation of a) Ret and b) RWVP with fabric weight.

show the lowest RWVP, as microfibres have more micro pores, which present big barriers against moisture transfer.

Conclusions

In this paper, the thermophysiological comfort properties of polyamide pantyhose were investigated, as well as the influence of incorporating elstane into the fabric structure. A total of 42 pantyhose structures were used in the experiment. In order to study the thermophysiological properties of the pantyhose, the thermal conductivity, thermal resistance and thermal absorptivity were measured, as well as the relative water vapour permeability and evaporative resistance.

The thermal conductivity of pure polyamide ranges from 0.037 W/(m.K) to 0.045 W/(m.K), increasing proportionally with the yarn count. The addition of elastane slightly decreases the thermal conductivity. Although the thermal conductivity of finner filament pantyhose is better, the overall thermal resistence depends on the thickness of the material Coarser yarns produce fabrics with increased thickness, resulting in increased thermal resistance.

The thermal absorbtivity of the fabrics ranges from 70,1 $Ws^{1/2} K^{-1}m^{-2}$ to 155,0 $Ws^{1/2} K^{-1}m^{-2}$. Surprisingly, fabrics made of fine filaments show a warmer hand, as they have lower thermal absorbtivity. The addition of elastane makes the surface cooler, lowering thermal absorbtivity. Thus, the incorporation of elastane in pantyhose with a lower filament count will make them more suitable for warm environmental conditions.

All fabrics investigated showed very high relative water vapour permeability and had low evaporative resistance. The high values of relative water vapour permeability are an indicator of good thermophysiological comfort. As the yarn count grows, the evaporative resistance increases, and the relative water vapour permeability decreases. Microfibre polyamide pantyhose have lower relative water vapour permeability than those of standard polyamide and polyamide with elastane.

Pantyhose are a wardrobe staple, yet the low price of these clothing articles often means that their properties are seldom optimised. As thermophysiological comfort is only one of the contributors to overall comfort, further research into comfort properties, hand values and aesthetics can help improve the product.

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