(REFEREED RESEARCH)

ANALYSIS OF THERMO-PHYSIOLOGICAL COMFORT AND MOISTURE MANAGEMENT PROPERTIES OF FLAT KNITTED SPACER FABRICS

DÜZ ÖRME SANDVİÇ KUMAŞLARIN TERMO-FİZYOLOJİK KONFOR VE NEM İLETİM ÖZELLİKLERİNİN ANALİZİ

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ABSTRACT

This study aims to investigate the effect of surface material type, monofilament yarn diameter and inclination angle on the thermal comfort and moisture management properties of the flat knitted spacer fabrics. For this purpose, seven different spacer fabrics were knitted by using different type of surface materials (Multifilament polyester and Coolmax®) and by varying the monofilament yarn parameters (yarn diameter of 0.28, 0.38, 0.48 mm and connecting distances of spacer yarns (three, five, seven needles shifting). The thermo-physiological comfort (air permeability, water vapour permeability and thermal resistance) and liquid moisture transport capabilities of these fabrics were tested and evaluated statistically. The results indicated that, the most effective factor on the thermo-physiological comfort and moisture management properties is the raw material. Due to their channelled structure, fabrics containing Coolmax® yarns with higher air permeability, water vapour permeability index, thermal resistance and OMMC values provide better thermo-physiological comfort and liquid moisture transfer properties.

Keywords: Flat knitted spacer fabric, Surface material, Monofilament yarn diameter, Monofilament yarn inclination angle, Thermal comfort, Moisture management

ÖZET

Bu çalışmada düz örme sandviç kumaşların ısıl konfor ve nem iletim özelliklerine kumaş yüzeyinde kullanılan iplik tipi, monofilament iplik çapı ve monofilament iplik yerleşim açısının etkisi incelenmiştir. Bu amaçla farklı iplik tipleri (multifilament polyester ve Coolmax®) kullanılarak ve monofilament iplik parametreleri (0.28, 0.38 ve 0.48 monofilament iplik çapı ve monofilament iplik yerleşim açısı (askının 3, 5, 7 iğne kaydırılması)) değiştirilerek yedi farklı sandviç kumaş üretilmiştir. Kumaşların hava geçirgenliği, su buharı geçirgenliği ve ısıl direnç gibi termo-fizyolojik özellikleri ile sıvı nem iletim yetenekleri test edilmiş ve istatistiksel olarak değerlendirilmiştir. Çalışmanın sonucunda termo-fizyolojik konfor ve nem iletim özelliklerine etki eden en önemli faktörün yüzeyde kullanılan iplik tipi olduğu tespit edilmiştir. Kanallı yapısı sayesinde Coolmax® içeren kumaşların yüksek hava geçirgenliği, su buharı geçirgenliği indeksi, ısıl direnç ve OMMC değerleri ile daha iyi ısıl konfor ve sıvı nem iletim özelliklerine sahip olduğu belirlenmiştir.

Anahtar Kelimeler: Düz örme sandviç kumaş, Yüzeyde kullanılan iplik tipi, Monofilament iplik çapı, Monofilament iplik yerleşim açısı, Isıl konfor, Nem yönetimi

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INTRODUCTION

Spacer fabrics are 3D textiles consisting two surface layers connected by a yarn layer called as spacer yarn. It is possible to produce these fabrics by weaving or nonwoven techniques besides warp and weft knitting processes (1). Weft knitting machines with two sets of needles have the ability to create two individual layers of fabric that are held together by tucks. Weft knitted spacer fabrics can be produced with different types of fibres on both double jersey circular knitting machine or electronic V-bed flat knitting machine. Two types of products can be created when flat knitting technology used for the spacer fabric production: a) two independent structures connected by cross-threads which is the focus of this paper and b) two independent fabric structures connected by fabric layers (2). On flat knitting machines, the distance between the outer layers is limited by the distance between the needle beds and also the stitch length of the spacer yarn (2,3). 3D spacer fabrics can be used in thermal insulation applications due to their higher thickness compared to 2D woven and knitted fabrics. These fabrics produced with monofilament spacer yarn have found applications in apparels and medical products. They have special properties such as compression, breathability, high elastic recovery, high water vapour transmission characteristic, etc. that are provided by spacer yarn (1, 4-7). These properties play an important role for improving the clothing comfort of spacer fabrics used in apparels and medical products (7).

Comfort which can be determined as satisfactory of physical and psychological harmony between body and environment, is considered as a fundamental property when a clothing is evaluated. Three main parameters such as thermo-physiological, sensorial and psychological comfort mainly influence clothing comfort. Thermo-physiological comfort is the most important parameter of clothing especially designed for physical activities and is closely related to the thermal balance of the body. Thermal balance of the body should be provided by heat, moisture and air transfer management (8-10).

Although several investigations have been performed to exploit the applications of weft knitted spacer fabrics, systematic studies on these fabric's characteristics especially thermal comfort and moisture management properties are still very limited. The effects of structural parameters such as fibre/yarn combinations, weft knit patterns, spacer yarns, density, tightness, etc. on the thermal comfort (thermal conductivity, air permeability, water vapour permeability) and also compression properties of flat knitted spacer fabrics were investigated by Crina et al. (3) and Liu and Hu (7). Delkumburewatte and Dias created theoretical models to predict porosity and capillarity of the weft knitted spacer fabrics depending on their geometrical parameters (11). Yip and Ng studied the physical and mechanical properties of elastic weft-knitted spacer fabrics used for intimate apparels (12). Pereira, Anand, Rajendran, and Wood investigated the structures and properties of weft-knitted spacer fabrics for knee braces and compared them with commercial products (13). Arumugam investigated the thermo-physiological comfort and compression properties of 3D circular knitted spacer fabrics by varying the fabric parameters (i.e. raw materials, type of spacer yarn, density, thickness, and tightness of surface layer) (6). Among these studies, it is determined that, thermo-physiological comfort and mechanical properties of these fabrics are significantly affected by the fabric parameters of spacer fabric.

In this study, the effect of structural parameters of flat knitted spacer fabrics, (type of surface materials, monofilament yarn diameter and monofilament yarn inclination angle) on thermo-physiological properties particularly on heat, air and water vapour permeability were investigated. Additionally, the effects of the above-mentioned parameters on the moisture management characteristics of flat knitted spacer fabrics were also discussed.

MATERIAL AND METHOD

Seven different spacer fabrics were manufactured by using E 7 gauge, 2 systems, Shima Seiki NSSG 122-SV electronically computerized flat knitting machine with a single stitch cam position, adjusted in correlation with yarns and structure. While the surface layers were knitted by using multifilament polyester and Coolmax® (8 Ne), polyester monofilament of 0.28, 0.38, 0.48mm in diameters were used as spacer yarn. In knitting process, four single yarns (8Ne) were fed for the production of one surface layer, in order to obtain proper structure according to machine gauge. The details of each fabric samples are illustrated in Table 1.

The weight values are determined according to the TS EN 12127 standard. Fabric density is calculated by dividing fabric weight to fabric thickness. The porosity characteristic of the fabrics is calculated by using Equation (1):

$$\varepsilon = 1 - \frac{\rho_a}{\rho_b} \qquad (1)$$

where Ɛ is the fabric porosity (%), ρ_a is the fabric density (g/cm^3) and ρ_b is the fibre density (g/cm^3). Fabric characteristics are given in Table 2.

Three different structures (denoted as A, B, C in Figure 1) were produced with different connecting distances of spacer yarns. Tuck stitches are used to connect the two outer layers together with the monofilaments. Different tuck connecting methods can result in different monofilament (spacer yarn) inclination angles. Here, the inclination angle of a spacer yarn is defined as the angle formed between the outer layer and the monofilament. The inclination angle decreases when the connecting distance of two tuck stitches increases. The term of "needle shifting" mentioned in Table 1 and also in Figures 2 to 7 corresponds to connecting distance of the spacer yarns between the two tucks.

Table 1. Details of the fabric samples

Fabric Code	Outer Layer (Face side)	Inner Layer (Back side)	Monofilament yarn diameter (mm)	Monofilament yarn inclination angle
S1	Coolmax®	Coolmax®	0.28	Three needles shifting
S2	Coolmax®	Polyester	0.28	Three needles shifting
S3	Polyester	Polyester	0.28	Three needles shifting
S4	Polyester	Polyester	0.38	Three needles shifting
S5	Polyester	Polyester	0.48	Three needles shifting
S6	Polyester	Polyester	0.28	Five needles shifting
S7	Polyester	Polyester	0.28	Seven needles shifting

Table 2. Fabric characteristics

Fabric Code	Course/cm (cpc)	Wale/cm (wpc)	Fabric Thickness (mm)	Weight (g/m^2)	Fabric density (g/cm^3)	Porosity (%)
S1	6	4	9.718	1291.67	0.1329	90.4
S2	6	4	9.218	1327.29	0.1440	89.6
S3	6	4	8.217	1478.65	0.1799	87.0
S4	6	4	8.450	1703.49	0.2016	85.4
S5	6	4	9.339	1733.91	0.1857	86.5
S6	6	5	9.754	1686.09	0.1729	87.5
S7	6	5	11.293	1643.23	0.1455	89.5

Within the study, air permeability tests were performed according to standard ISO 9237 using a Textest FX-3300 air permeability tester with a pressure of 100 Pa on the sample area 5 cm^2. Thermal resistance property and thickness were determined by Alambeta instrument at a pressure of 200Pa (14). The water vapor permeability test was performed on SDL Shirley M–261 Water Vapor Permeability Tester, according to standard BS 7209-1990. For testing the liquid moisture transport capabilities of the fabrics, the SDL Moisture Management Tester (MMT) which is designed to sense, measure, and record the liquid moisture transport behaviours in multiple directions was used (15). In order to combine the special characteristics of different fibres for achieving high level of comfort, spacer fabrics were designed by Coolmax® and polyester yarns as Coolmax®/Coolmax®, Coolmax®/polyester, polyester/polyester) and thermo-physiological comfort properties of Coolmax®/polyester structure were tested on both sides (outer and inner layers) in order to decide the optimum side that would be used next to skin.

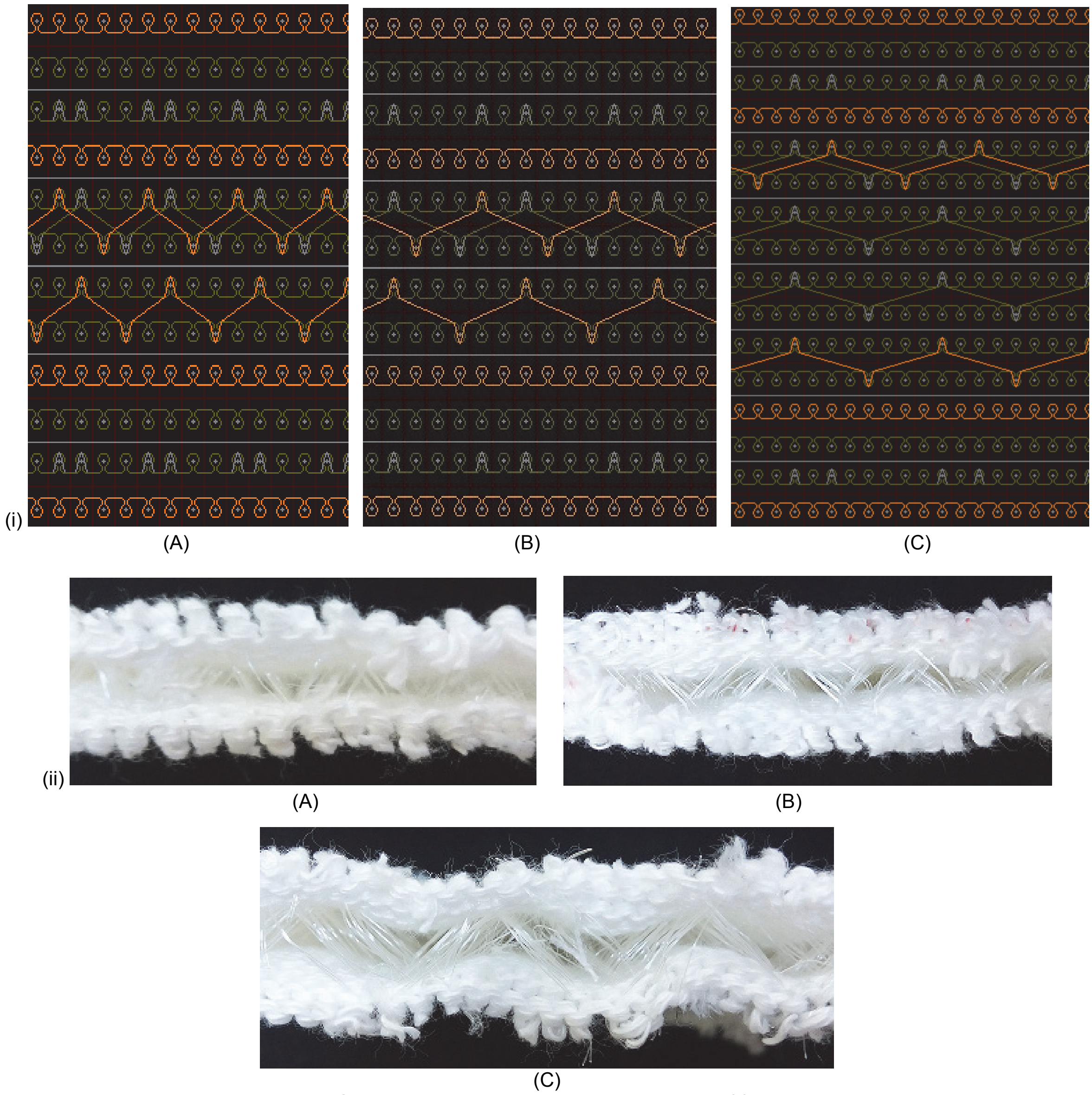

Figure 1. (i) Stitch diagram and (ii) cross-sectional view of fabric samples

RESULTS AND DISCUSSION

Air Permeability

Air permeability, which is accepted as one of the most important factors often used in evaluating and comparing the breathability characteristic, is the rate of air flow through the fabric when there is a differential air pressure on either surface of the fabric. This parameter is mainly affected by fabric structure and yarn properties and the most effective parameter is the porosity for air permeability character. (9, 16, 17).

As it can be observed in Figure 2 and was confirmed by variance analysis (Table 3), there is a significant influence of the investigated structural parameters (type of surface materials, monofilament yarn diameter and monofilament yarn inclination angle) on the air permeability of the fabric samples.

When type of materials is compared, spacer fabrics containing Coolmax® yarns (S1 and S2) have higher air permeability values than polyester/polyester fabric. This may be due to the lower fabric density and higher porosity of the fabric samples containing Coolmax® yarns (Table 2).

As the diameter of the monofilament yarn increases the air permeability values of the fabric samples increase, as well. Within the group, fabric sample produced with monofilament yarn diameter of 0.48 mm (S5) have higher air permeability due to its lower density and higher porosity properties.

The results revealed that, fabric produced with seven needles shifting (S7) has higher air permeability and the decrease in the monofilament yarn inclination angle leads to an increase in air permeability property. This situation might be explained by the fabric density and porosity. Lower fabric density and higher porosity can result in air passing easily through the fabric surfaces. Fabrics produced with seven needles shifting has higher weight and thickness values. Normally, increasing the inclination angle also results in an increase in the fabric thickness (7). However, in the present study this situation becomes quite different. Instead of decreasing the fabric thickness, it increases as the connecting distance of tuck stitches increases. The reason is that the increase in connecting distance causes an increase in wpc values. The wales on the surface layers become closer after the relaxation and this can lead to higher thickness of these fabric samples.

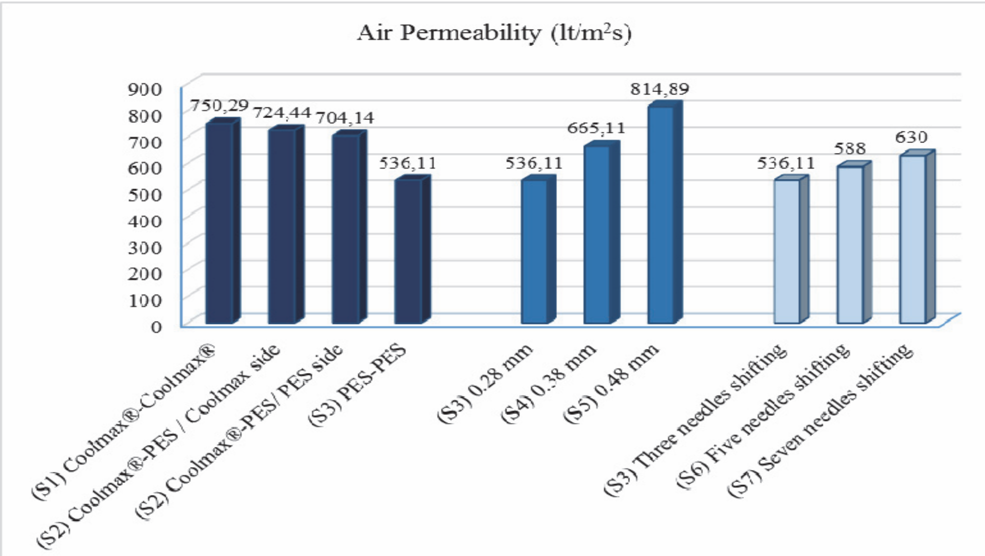

Figure 2. Air permeability values of the fabrics

Table 3. Variance analysis of air permeability values

Fabric codes	N	Subset for alpha = 0.05						
		1	2	3	4	5	6	7
S3	10	536.11						
S6	10		588.00					
S7	10		630.00	630.00				
S4	10			665.11	665.11			
S2- Polyester side	10				704.14	704.14		
S2- Coolmax side	10					724.44	724.44	
S1	10						750.29	750.29
S5	10							814.89
Sig.		1.000	.051	.102	.070	.341	.226	.070

Water Vapor Permeability

Water vapor permeability is one of the key properties affecting clothing comfort, as it represents the ability of transferring perspiration (18). The human body cools itself by sweat production and evaporation during periods of high activity. Clothing must be able to remove this moisture in order to maintain comfort (16, 17, 19). To permit evaporation of water, the outer layer should have a high water vapor permeability and low vapor resistance. The water vapor permeability of fabric depends upon a number of factors including thickness and density of fabrics, wetting and wicking behaviour of yarns, and the relative humidity and temperature of the atmosphere (6). According to the BS 7209-1990 standard, the water vapor permeability index (Equation (4)) is calculated by expressing the water vapor permeability (WVP) of the fabric (Equation (2) and Equation (3)) as a percentage of the WVP of a reference fabric which is tested alongside the test specimen.

$$WVP = \frac{24M}{At}(g/m^2/day) \tag{2}$$

where M is loss in mass (g), t is time between weightings (h) and A is the internal area of the dish (m^2).

$$A = \left(\frac{\pi d^2}{4}\right) x10^{-6}(m^2) \tag{3}$$

where d is the internal diameter of the dish (mm).

$$I = \left\{\frac{(WVP)_f}{(WVP)_r}\right\} x100 \tag{4}$$

where $(WVP)_f$ is the water vapor permeability of the test fabric and $(WVP)_r$ is the water vapour permeability of the reference fabric. The higher the calculated WVP values of the samples, the higher the water vapor permeability of the fabrics.

The results indicated that Coolmax®-Coolmax® fabrics provide higher water vapour permeability due to its structured surface. Coolmax® fabrics are made from specially engineered tetra channel polyester fibres. These four external channels create a capillary effect and form a larger surface area over which moisture can be rapidly transferred away (20). Three mechanisms can be considered for water vapor transfer through the fabric: one is through fabric pores; the second is through absorption by fabric and then evaporation from fabric surfaces and the third is transferring the vapor (liquid) through the fibres constituted the fabric. In the case of spacer fabrics and with respect of Coolmax® fibres with high wicking properties, the third mechanism is much more effective in this mass transfer situation, as mentioned by Bagherzadeh et.al. (21).

Fabric produced with 0.48 mm monofilament yarn diameter (S5) has higher water vapour permeability index and additionally an increase of monofilament yarn inclination angle causes an increase in water vapour permeability index. Although there have been statistically significant differences between the water vapor permeability index values of some samples (Table 4), these values are very similar to each other as shown in Figure 3.

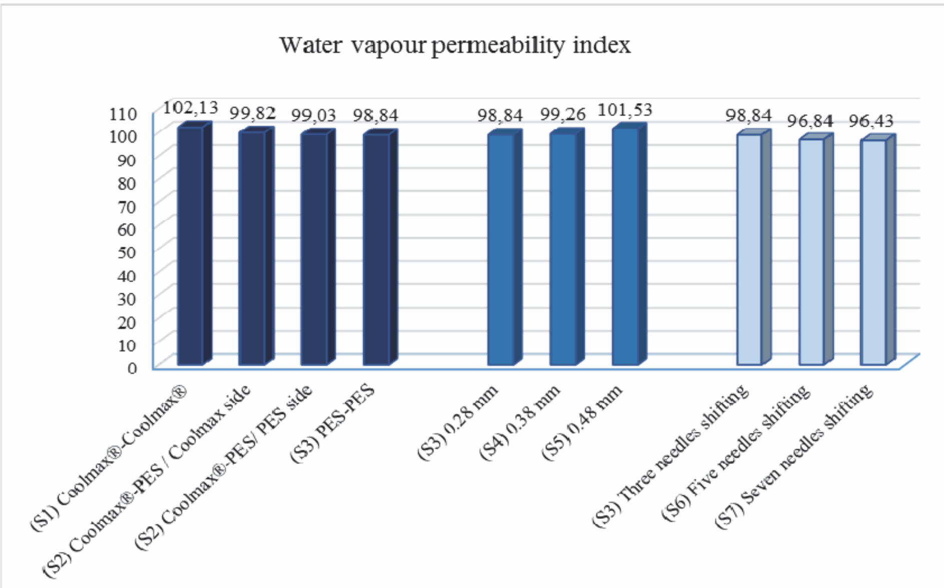

Figure 3. Water vapour permeability index values

Table 4. Variance analysis of water vapour permeability index values

Fabric codes	N	Subset for alpha = 0.05			
		1	2	3	4
S7	3	96.43			
S6	3	96.84			
S3	3		98.84		
S2- Polyester side	3		99.03	99.03	
S4	3			99.26	
S2- Coolmax side	3			99.82	
S5	3				101.53
S1	3				102.13
Sig.		.284	.129	.138	.344

Thermal Resistance

The insulation value of a fabric is measured by its thermal resistance which is the reciprocal of thermal conductivity and it is defined as the ratio of the temperature difference between the two faces of fabric to the rate of heat flow per unit area normal to the faces (17, 18). The entrapped air is the most significant factor in determining thermal insulation. Generally, due to the low thermal transmittance of air, more still air in the textile structure can improve the thermal resistance value of the textile and keep the body warm. However, the characteristics of fibres, yarns, fabrics, and garments also have a major contribution towards thermal comfort. Thermal resistance can be expressed as:

$$R = \frac{h}{\lambda}(m^2 K / W) \quad (5)$$

where R is thermal resistance, h is fabric thickness (m) and λ is thermal conductivity (W/mK). It has been seen from Equation (5) that higher thickness leads to higher thermal resistance.

The statistical analysis (Table 5) illustrated that thermal resistance values of the samples are significantly affected by the surface material type, monofilament yarn diameter and monofilament yarn inclination angle.

As material type for surface layers, Coolmax®-Coolmax® fabric (S1) provides higher thermal resistance characteristics because of their higher thickness values. The increase in the diameter of monofilament yarn and decrease in the monofilament yarn inclination angle lead to an increase in the thermal resistance characteristics of the fabric samples. Both situation can be explained by thickness values of the samples. Fabrics produced with 0.48 (S5) monofilament yarn diameter and fabrics produced with seven needles shifting (S7) have higher thickness values within their individual groups (Figure 4).

For these fabric groups, thickness property determines the thermal resistance characteristic, because the thermal conductivity values of all samples are very close to each other and there isn't any statistically significant different between the thermal conductivity values of the fabric samples within their individual groups (0.62, 0.58, 0.51 of p values for the first, second, third groups, respectively).

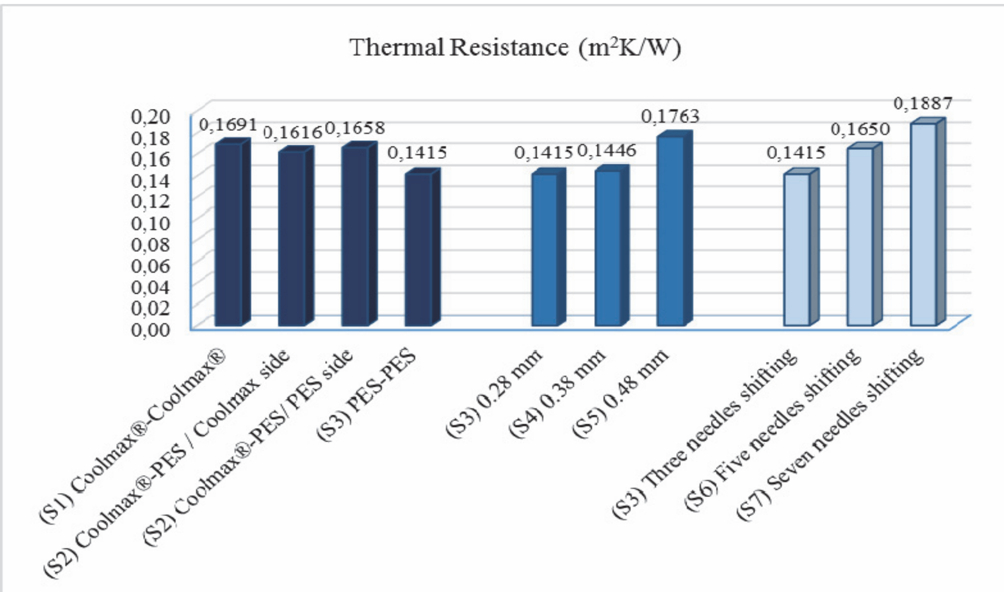

Figure 4. Thermal resistance values

Table 5. Variance analysis of thermal resistance values

Fabric codes	N	Subset for alpha = 0.05				
		1	2	3	4	5
S3	3	.1415				
S4	3	.1447				
S2- Coolmax side	3		.1616			
S6	3		.1650	.1650		
S2- Polyester side	3		.1658	.1658		
S1	3			.1691		
S5	3				.1763	
S7	3					.1887
Sig.		.244	.129	.138	1.000	1.000

Liquid Moisture Transport Capability

The process of liquid moisture transport through clothing under transient humidity conditions is an important factor that influences the comfort of the wearer in practical use. Moisture management of fabric draws moisture away from the skin, disperses it over a large surface area away from the skin where it evaporates, reducing the humidity at the skin and improving comfort (22). Moisture transport property of the fabrics can be determined by the indexes including top and bottom wetting time in second, top and bottom absorption rate in %/sec, top and bottom max wetted radius in mm, top and bottom spreading speed in mm/s and overall moisture management capacity (OMMC).

The results of the variance analysis (Table 6) revealed that, the structural parameters like monofilament yarn diameter and monofilament yarn inclination angle have not any significant effect on the moisture transport properties of the samples. Only the raw material factor is found to be significant for all moisture transport parameters except absorption rate.

Wetting time

The wetting time of top surface (WTT) and bottom surface (WTB) are the time periods in which the top and bottom surfaces of the fabric just start to get wetted, respectively, after the test commences, which are defined as the time in second (s), when the slope of total water content at the top and bottom surfaces become greater than Tan (15^0) (15).

As can be seen in Figure 5, the lowest wetting time values for both surfaces were obtained from Coolmax® containing fabrics (S1 and S2). Due to the four-channelled structure, Coolmax® yarns create a capillary effect and form a larger surface area over which moisture can be rapidly transferred away. Because of the hydrophobic character of the polyester fibre, the water molecules were not absorbed or only a comparatively small amount of moisture can be absorbed. For this reason, fabric with polyester inner surface and polyester/polyester fabric have higher wetting time.

Absorption rate

Absorption rate on the top and bottom surfaces (%/sec) are the average moisture absorption ability of the specimen, in the pump time (15). These parameters were not significantly affected by the surface material combination (Table 6). This means that the initial slopes of water content curves are similar for all fabric samples.

Table 6. The p values of the variance analysis of moisture management properties

Parameter	Top Surface*				Bottom Surface			
	Wetting time	Absorption rate	Max. wetted radius	Spreading speed	Wetting time	Absorption rate	Max. wetted radius	Spreading speed
Surface materials (S1-3)	**.032***	.635	**.010***	**.047***	**.016***	.095	**.003***	**.011***
Monofilament yarn diameter (S3-5)	.457	.488	.914	.710	.218	.565	.252	.234
Monofilament yarn inclination angle (S3,6,7)	.236	.368	1.000	.884	.218	.396	.252	.257

*statistically significant according to α=0.05

*Top surface refers to inner surface that is in touch with the skin and test liquid is dropped on it.

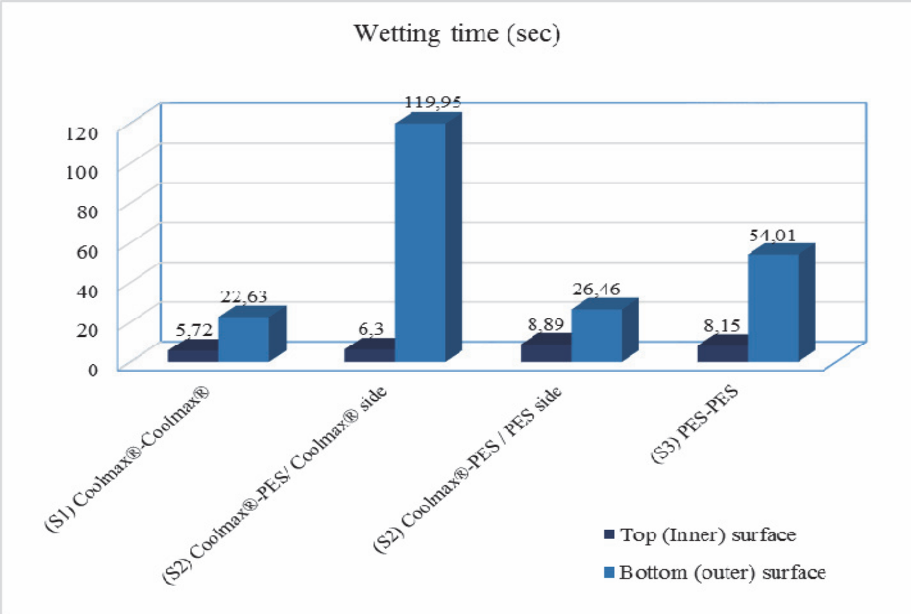

Figure 5. Wetting time values of the fabrics

Max wetted radius

Maximum wetted radius MWR_{top} and MWR_{bottom} (mm) are defined as the maximum wetted radius (MWR) at the top and bottom surfaces, respectively, where the slopes of total water content (U_{top} or U_{bottom}) become greater than Tan (15^0) for the top and bottom surfaces, respectively (15).

According to Figure 6, Coolmax®(inner)-PES(outer) fabric (S2) has the highest maximum top wetted radius value due to good capillary transfer property of Coolmax®. In addition, PES (inner)-Coolmax®(outer) fabric (S2) has the lowest top and the highest bottom wetted radius. This situation might be explained by hydrophobic character of polyester and larger surface area of Coolmax®. Since PES (inner)-Coolmax®(outer) fabrics have the lowest top wetted radius value, which also indicates its good moisture transport property, it will give a dry feeling than Coolmax®(inner)-PES(outer) fabric.

Spreading speed

Spreading speed (SS; mm/sec) is defined as the accumulative spreading speed from the centre to the maximum wetted radius. The accumulative SS is calculated according to the following equation:

$$SS_{top} = \frac{MWR_{top}}{t_{wrt}} \quad \text{and} \quad SS_{bottom} = \frac{MWR_{bottom}}{t_{wrb}} \qquad (6)$$

where t_{wrt} and t_{wrb} are the times to reach the maximum wetted rings on the top and bottom surfaces, respectively (15).

As it can be observed from Figure 7, the highest top and bottom SS values were obtained from Coolmax®(inner)-PES(outer) fabric and PES (inner)-Coolmax®(outer), respectively. As it is expressed in Equation 6, MWR and SS have direct relationship and an increase in MWR leads to an increase in SS.

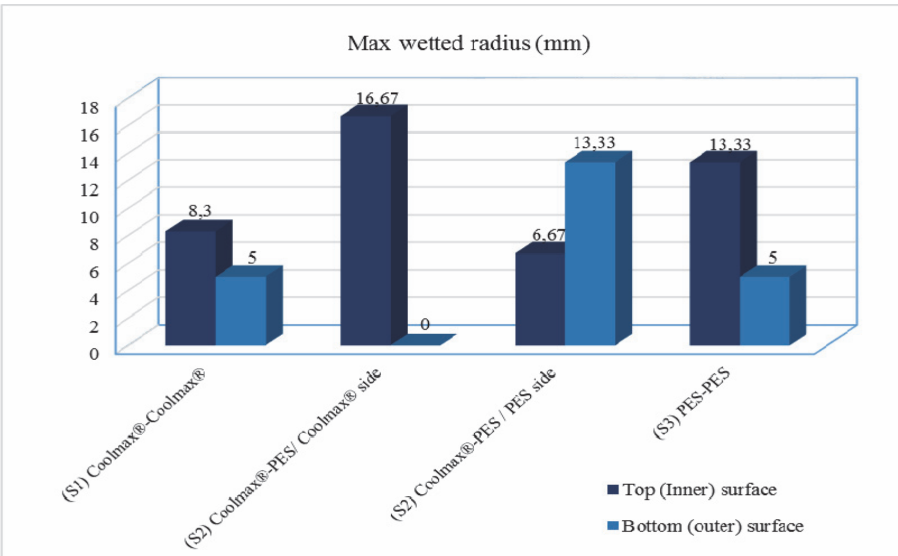

Figure 6. Max wetted radius values of the fabrics

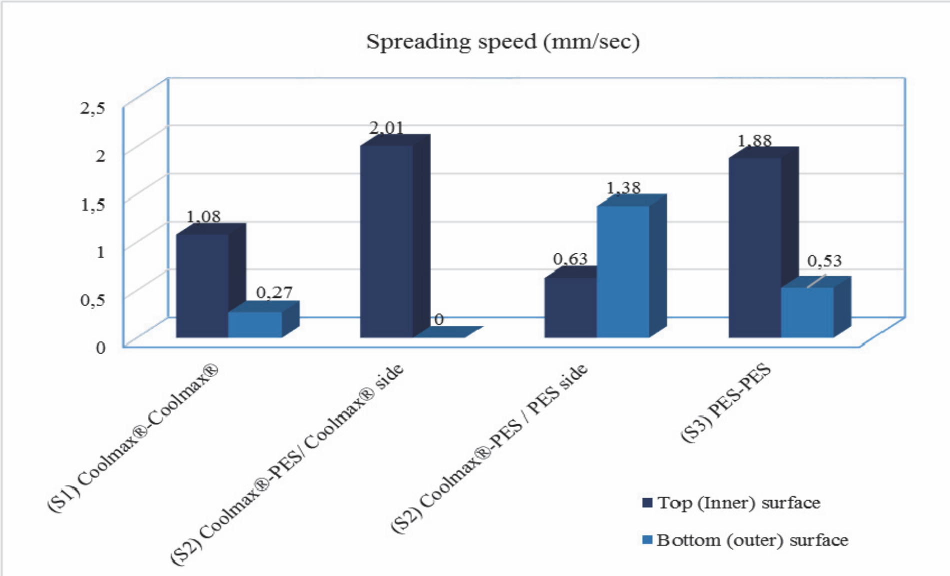

Figure 7. Spreading speed values of the fabrics

Overall moisture management capacity (OMMC)

The Overall moisture management capacity (OMMC) is an index to indicate the overall capability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance: moisture absorption rate of the bottom side (BAR), one-way liquid transport capacity (OWTC; the diffence of the cumulative moisture content between the two surfaces of the fabric), and the spreading/drying rate of the bottom side (SS_b), which is represented by the maximum SS. The OMMC is defined as (15,22-24):

$$OMMC = 0.25BAR + 0.5OWTC + 0.25SSb \qquad (7)$$

OMMC values are compared with the grading scale given by the manufacturing company. The higher the OMMC is the higher the overall management capability of the fabric.

Coolmax®(inner)-Coolmax®(outer) (S1) and PES(inner)-Coolmax®(outer) (S2) fabrics were categorized as 'good' according to grading (Table 7) due to the high OWTC value of Coolmax®(inner)-Coolmax®(outer) fabric (S1) and high SS value of the bottom side of PES (inner)-Coolmax®(outer) fabric (S2).

CONCLUSION

This study performs an investigation of the effect of monofilament yarn parameters (diameter, inclination angle) and surface materials on the thermal comfort and moisture management properties of the flat knitted spacer fabrics. For this purpose, seven different spacer fabrics were knitted by using different surface materials (Multifilament polyester and Coolmax®) and by varying the monofilament yarn parameters (yarn diameter of 0.28, 0.38, 0.48 mm and needle shifting (three, five, seven needles). The thermo-physiological comfort (air permeability, water vapour permeability and thermal resistance) and liquid moisture transport capabilities of these fabrics were tested and evaluated.

The following conclusions can be drawn from this study:

- When the type of surface material is compared, it can be stated that, due to their channelled structure, fabrics containing Coolmax® yarns, especially Coolmax®-Coolmax® fabric have higher air permeability and water vapour permeability index values than polyester/polyester fabric. In addition, Coolmax®-Coolmax® fabric provides higher thermal resistance characteristics because of its higher thickness value. For the evaluation of the moisture management property, it can be concluded that, OMMC values of Coolmax®(inner)-Coolmax®(outer) and PES (inner)-Coolmax®(outer) fabrics indicate that these fabrics have a good moisture management (liquid moisture transfer) property.

Table 7. OMMC values of the fabric samples

	Coolmax® (Inner) Coolmax (Outer)	PES (Inner) Coolmax® (Outer)	Coolmax® (Inner) PES (Outer)	PES (Inner) PES (Outer)
OMMC values	0.5131	0.4637	0	0.0833
Moisture management category	Good	Good	Very poor	Very poor
0-0.2: very poor, 0.2-0.4: poor, 0.4-0.6: good, 0.6-0.8: very good, >0.8: excellent (15)				

- Air permeability, water vapour permeability and thermal resistance properties of the flat knitted spacer fabrics were significantly affected by the diameter of monofilament yarn used as spacer yarn and the monofilament yarn inclination angle. On the other hand, the effect of these parameters on moisture management properties of the fabrics samples were found to be statistically insignificant.
- As the diameter of monofilament yarn increases, air permeability, water vapour permeability and thermal resistance characteristics of the fabric samples increase, as well.
- An increase in the monofilament yarn inclination angle (from three to seven needles shifting) leads to a decrease in air permeability and thermal resistance values and an increase in water vapour permeability index.

Along with these results, it is demonstrated that, the most effective factor on the thermo-physiological comfort and moisture management properties is the raw material. These properties can be improved by using profiled fibres such as Coolmax® on the surface layer of the spacer fabrics. High level of clothing comfort for flat knitted spacer fabrics can be established by using different yarn types and combination on the surface layers.

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