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Effects of Fiber Cross Sectional Shape and Weave Pattern on Thermal Comfort Properties of Polyester Woven Fabrics

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Abstract
Thermal comfort properties, i.e. thermal conductivity, thermal absorption and thermal resistance, and the water vapour and air permeabilities of fabrics woven from different cross sectional shaped polyester fibres were investigated. A total of eight woven fabrics were produced in two different weave patterns (plain and twill) from polyester yarns of four different fibre cross sectional shapes (round, hollow round, trilobal and hollow trilobal). The fabrics consisting of hollow fibres had higher thermal conductivity and thermal absorption values but lower thermal resistance, water vapour and air permeability values than their counterparts of solid fibres. The twill fabrics produced from trilobal fibres showed the lowest thermal conductivity and thermal absorption but the highest thermal resistance, water vapour and air permeability.

Key words: *polyester, cross sectional shape, weave pattern, thermal properties, water vapour permeability, air permeability.*

Introduction

Synthetic fibres can be engineered to provide a high level of thermal insulation, not only by bulking or texturing the yarn but also by introducing a modified fibre cross section. Some synthetic fibres have been produced with a hollow core or channel. Hollow fibres have many unique properties and have found numerous applications as well. For example, hollow fibres can provide great bulkiness with less weight and are often used to make insulated clothing materials. The heat and moisture transport properties of hollow fibre products are better than those of conventional fibres [1 - 3].

The requirement for fabrics is not only mechanical and dimensional properties but also comfort properties. The thermal comfort of clothing as determined by the movement of heat, moisture and air, is a large portion of the total clothing comfort [4 - 7].

The heat transfer mechanisms through fabrics are complex. When a temperature potential is developed across such a material which is normal for its surface, heat is transferred by conduction through the solid fibres as well as by a combination of conduction, convection, and radiation through the air trapped. However, the mechanism of heat transfer depends mainly on thermal conduction, with radiation and convection losses within the fabric being negligible. Therefore, the total heat transmitted through a fabric is the combination of the amount of heat conducted through the air gaps and through the content of fibres [8 - 10].

Static thermal properties are characterised by thermal conductivity, thermal resistance and thermal absorption. Thermal conductivity is an important property of a material that indicates its ability to conduct heat. Thermal resistance expresses the difference in temperature across a unit area of a material of unit thickness when a unit of heat energy flows through it in a unit of time [11 - 17]. Thermal absorption is a surface property which allows the fabric's character to be assessed with regard to its 'cool/warm' feeling, i.e. the feeling obtained when the human skin briefly touches any object, such as the textile material. Hes [18] introduced the term 'thermal absorption'' as a measure of the 'warm-cool feeling'' of textiles. Fabrics with a low value of thermal absorption give a 'warm' feeling, whereas those with a high value of thermal absorption give a 'cool' feeling.

The thermal properties of textile fabrics are influenced by many factors, which can be studied at three levels: (1) the microscopic level (chemical composition, morphological characteristics, fineness, cross section, porosity and water content of component fibres), (2) the mesoscopic level (yarn structure and properties), and (3) the macroscopic level (the fabric's physical and structural characteristics and finishing treatments) [6, 8, 15, 19 - 21].

One of the comfort measures that greatly affects the wearer is air permeability, defined as the volume flow rate per unit area of a fabric when there is a specified pressure differential across two faces thereof [7, 14]. Many factors may affect air permeability, such as the fabric cover factor, thickness, porosity, yarn twist, yarn crimp, fabric weave, fibre cross section, and the amount of finish and coating applied to the fabric. Thermal properties are essentially influenced by air permeability [11, 22].

Water vapor transport properties of textile fabrics are of considerable importance in determining the thermal comfort properties of clothing systems. Water vapor permeability is the ability to transmit vapour from the body [15, 23]. Water vapour diffusion in fabric could be realised through inter-fibre spaces, inter-yarn spaces, and through the fibre substance itself. Fibre content, thickness, percentage fibre volume and fabric geometry are the main factors that may affect the water/moisture vapor transmission of textiles. Water vapour resistance mainly depends on the air permeability of the fabric and is the most important parameter in determining thermal comfort [22, 24, 25].

A lot of researches [6, 9, 10, 13, 26 - 30] on the thermal comfort behaviour of textiles investigated the effects of different materials and fabric constructions on the thermal properties of knitted and woven fabrics. There have been a limited number of studies [7, 8, 24, 31, 32] in which all the thermal comfort properties i.e. thermal properties, air permeability and water vapour permeability were tested. Many researchers have tried to obtain the effects of different fibre properties

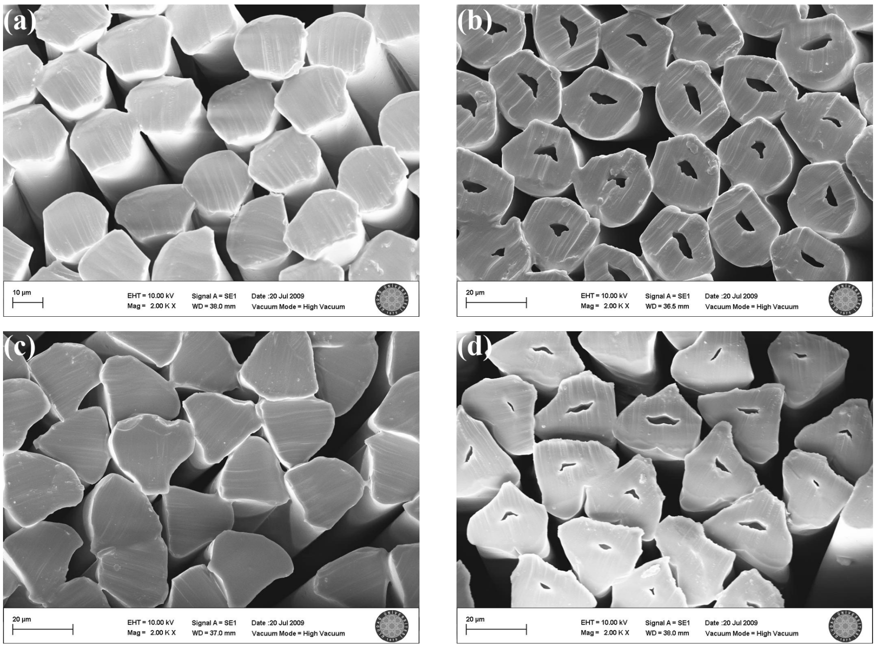

Figure 1. *SEM photographs of the fibres; a)Round; b)Hollow Round; c)Trilobal; d)Hollow Trilobal.*

Table 1. *Fabric construction properties and codes.*

Fabric code	Fibre cross sectional shape	Fabric pattern	Warp density, 1/cm	Weft density, 1/cm	Fabric weight, g/m^2	Fabric thickness, μm
R-P	Round	Plain	52	35	161	270
HR-P	Hollow round			36	168	310
T-P	Trilobal			35	160	250
HT-P	Hollow trilobal			36	166	280
R-T	Round	Twill		34	156	292
HR-T	Hollow round			35	162	330
T-T	Trilobal			33	154	273
HT-T	Hollow trilobal			35	159	310

[4, 6, 7, 9 - 11, 14, 15, 31 - 33] and different fabric parameters [11, 13, 15, 19, 24, 26 - 30, 34] on the thermal comfort properties of textile materials. A number of researchers [7, 14, 17, 24, 31, 34] have worked on the effects of different yarn properties on thermal comfort behaviour. Some of researchers investigating fibre parameters considered the significance of fibre cross sectional shapes on the thermal comfort behaviour of fabrics. Varshney et.al. [8] reported the effect of profiles of polyester fibres of four different cross sectional shapes (circular, scalloped oval, tetrakelion and trilobal) on the physiological properties of their fabrics. Manish et.al. [35] determined the effect of using a tetra channel cross section polyester fibre in place of cotton in a polyester/cotton blended yarn on various handle and thermal properties. Tyagi et.al. [7] studied the thermal comfort behaviour of fabrics produced from polyester/viscose and polyester/cotton ring and air jet yarns. In the study, the polyester yarns had circular and trilobal cross sectional shapes. Paul et.al. [27] aimed to determine the impact of a varying fibre cross section and fibre orientation on the effective thermal conductivity of fibrous insulations by using numerical simulations. The three fibre constructions tested were a round fibre, a round fibre with four holes and a fibre with deep grooves. Lin et.al. [28] investigated the thermal conductivity of nonwoven fabrics with different processes. Nonwoven fabrics were manufactured using FR-polyester hollow fibres and low melting temperature polyester fibres. It did not coincide with any study investigating the thermal comfort properties of woven fabrics produced from hollow filaments.

In this study, polyester fibres of different cross sectional shapes, i.e. round, hollow round, trilobal and hollow trilobal, were produced using the same production parameters. The thermal comfort properties, including thermal conductivity, thermal resistance, thermal absorption, air and water vapour permeability, of fabrics woven from these fibres were investigated.

Experimental

The polyester multifilament yarns used in this study were produced from semi-dull poly(ethylene terephthalate) (PET) polymer via the melt spinning process. Only the spinneret cross sectional shape was changed and all the other parameters were constant during the production stages. Details of the production parameters were given in our previous paper [36]. Four different polyester multifilament yarns (fully drawn yarn) of 135 dtex and 48 filaments with round, hollow round, trilobal and hollow trilobal cross sectional shapes were manufactured. Photographs of the cross sectional shapes, taken by a Jeol 840 Model Scanning Electron Microscope (SEM), are presented in ***Figure 1.***

All the polyester multifilament yarns were twisted 300 turns per meter on a two-for-one yarn twisting machine. The twisted polyester yarns were then woven on an air jet weaving machine while keeping all production parameters the same except the weave pattern. Two different patterns, plain and twill (2/1 Z), were used for the woven fabrics. A total of eight woven fabrics were produced in two different weave patterns from polyester yarns of four different fibre cross sectional shapes. After weaving, the fabrics were pretreated under mill conditions and prepared for dyeing. Afterwards the fabrics were heatset in a stenter (180 °C for 60 sec.), and then they were dyed tied end-to-end in mill conditions on a sample jet dyeing machine with a black disperse dye (4% owf). After dyeing and reduction clearing, the samples were neutralised, hot and cold rinsed, and then dried. Further details were given in the former paper [37]. The codes and constructional properties of the finished fabrics are presented in ***Table 1***.

The thermal properties of the fabrics were measured by an Alambeta Instrument which enables the quick measurement of both steady-state and transient-state thermal properties [38]. The instrument directly measures the stationary heat flow density, the temperature difference between the upper and bottom fabric surface, and the fabric thickness [39]. The values of thermal conductivity, thermal absorption, thermal resistance and fabric thickness under a 200 Pa contact pressure were determined.

Water vapour permeability was measured on a Permetest Instrument working on a similar skin model principle [40]. The instrument measures the dynamic heat flow caused by the evaporation of water passing through the specimen tested by a similar procedure to that given by BS EN 31092. Relative water vapour permeability is defined as the ratio of the heat loss measured with a sample and that measured without one [5, 25].

The air permeability of the fabrics was measured on a Textest M821A Air Permeability Tester according to TS 391 EN ISO 9237. The pressure differential was set to 100 Pa.

All the measurements were made under standard atmospheric conditions. The tests of thermal properties and water vapor permeability were repeated three times, and the air permeability test was repeated ten times. The means and standard deviations (SD) of data were calculated for all the tests. The results were evaluated statistically according to two-way variance analysis (ANOVA), and the factors were the 'fibre cross sectional shape' and 'weave pattern'. The means were compared with each other according to the Student-Newman-Keuls (SNK) Test by using a statistical package program separately for every thermal comfort test. $P < 0.05$ was regarded as statistically significant.

Results and discussion

Thermal properties

The results of thermal properties, i.e. thermal conductivity, thermal absorption, and thermal resistance, for the fabrics are presented in ***Table 2***. The values of the thermal conductivity are compared in graphic form in ***Figure 2*** (see page 70).

Table 2. *Thermal properties of the fabrics (mean ± SD).*

Fabric code	Thermal conductivity, $Wm^{-1}K^{-1}$	Thermal absorption, $Wm^{-2}s^{1/2}K^{-1}$	Thermal resistance, $Km^{2}W^{-1}$
R-P	0.0320 ± 0.0004	173 ± 3	0.00844 ± 0.0002
HR-P	0.0363 ± 0.0007	175 ± 15	0.00840 ± 0.0001
T-P	0.0301 ± 0.0015	163 ± 13	0.00821 ± 0.0004
HT-P	0.0343 ± 0.0002	167 ± 8	0.00808 ± 0.0009
R-T	0.0318 ± 0.0008	170 ± 10	0.00919 ± 0.0002
HR-T	0.0361 ± 0.0003	175 ± 14	0.00914 ± 0.0002
T-T	0.0292 ± 0.0016	161 ± 10	0.00935 ± 0.0002
HT-T	0.0337 ± 0.0005	165 ± 12	0.00930 ± 0.0000

The fabrics produced from solid fibres and twill fabrics had lower thermal conductivity and thermal absorption values, but higher thermal resistance values than those produced from hollow fibres and plain fabrics, respectively. Thus these fabrics provided a higher thermal insulation than those produced from hollow fibres and plain fabrics. Among all the fabric types, the twill fabrics produced from solid trilobal fibres (T-T) had the lowest values for thermal conductivity and thermal absorption, and the highest value for thermal resistance.

Statistical analysis results of the effects of the fibre cross sectional shape and weave pattern on thermal properties of the woven fabrics are presented in ***Table 3***. The thermal conductivity values were statistically affected only by fibre cross sectional shapes, while the thermal resistance results were affected only by the weave pattern. Statistical differences were not observed among the thermal absorption values of the fabrics in terms of the factors.

A basic weave structure can be represented as repeated units consisting of air of lower thermal conductivity (0.025 W/mK) and solid fibre of higher thermal conductivity (e.g. 0.141 W/mK for polyester) [8]. The amount of air entrapped in the fabric is related to the inter-yarn pores in the fabric and inter-fibre pores in the yarns. When it is geometrically considered, the pore volume in yarns produced from hollow fibres will be greater than that in yarns produced from solid fibres of the same fibre count because of the greater outer dimension of the hollow fibres. Because of the same reason, the yarns produced from hollow fibres will have greater diameters than their counterparts produced from solid fibres with the same production parameters. This situation caused higher crimp formation in the yarns produced from hollow fibres as well as a higher unit weight and thicker fabric structure in the fabrics produced from these fibres (***Table 1***). Thermal insulation is affected by both fabric thickness and porosity [41]. The thermal conductivity of the fabrics produced from hollow fibres was expected to decrease because of increases not only in fabric thickness but also in the pore volume within the yarns. On the other hand, as the yarn densities were the same in all the fabrics produced, the greater diameters of the yarns produced from hollow fibres caused decreases in the distance between the yarns and, as a result, decreased porosity. This was an effect which increased the thermal conductivity of the fabrics produced from hollow fibres. The results showed that the thermal properties of the fabrics were mainly affected by inter-yarn pores in the fabric rather than inter-fibre pores in the yarns.

According to the results obtained in this study, the thermal conductivity and thermal absorption values of the fabrics produced from trilobal fibres were lower

Table 3. *Statistical analysis results for thermal properties; * - statistically significant (P < 0.05), ^{ns} - non-significant, (a), (b), (c), (d) represent the statistical difference ranges.*

Factors	Thermal conductivity			Thermal absorption			Thermal resistance		
	F value	P value	SNK*** Range	F value	P Value	SNK Range	F Value	P value	SNK Range
Fibre cross sectional shape (F)	63.711	0.000*	HR(a), HT(b), R(c), T(d)	1.539	0.243ns	HR(a), R(a), HT(a), T(a)	0.130	0.94ns	R(a), T(a), HR(a), HT(a)
Weave pattern (W)	1.746	0.205ns	P(a), T(a)	0.173	0.683ns	P(a), T(a)	41.221	0.000*	T(a), P(b)
Interaction (F X W)	0.229	0.875ns	HR-P(a), HR-T(a), HT-P(a), HT-T(a), R-P(a), R-T(a), T-P(a), T-T(a)	0.021	0.996ns	HR-P(a), HR-T(a), R-P(a), R-T(a), HT-P(a), HT-T(a), T-P(a), T-T(a)	0.729	0.549ns	T-T(a), HT-T(a), R-T(a), HR-T(a), R-P(a), HR-P(a), T-P(a), HT-P(a)

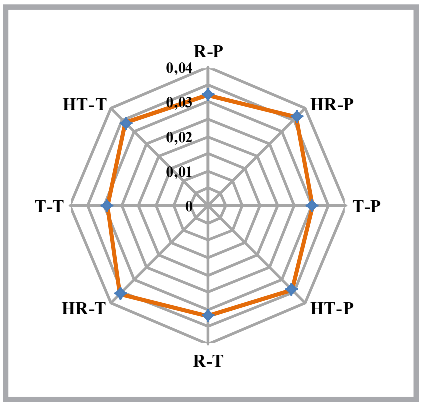

Figure 2. Thermal conductivity values of the fabrics.

than corresponding values of the fabrics produced from round fibres. As the fabrics produced from trilobal fibres had lower unit weights and thicknesses than those produced from round fibres (***Table 1***), the trilobal fibres could have been packed densely in the yarn structure. Although it is pointed out in literature [8] that the edges of the trilobal fibres restrict the compact packing of these fibres in the yarn structure, the difficulty of the dense packing of trilobal fibres in the yarn structure because of their edges may not be always true because of the effects of yarn tension and twist levels during the yarn twisting. The edges of the trilobal fibres could create an effect which enables the dense packing of fibres in the yarn structure, especially at high twist levels and high yarn tensions. The denser packing of trilobal fibres in the yarn proposed led to a compact yarn structure on the one hand, and an increase in inter-yarn pores on the other . The compact yarn structure displayed an effect which increased the thermal conductivity while the increase in the distance between the yarns showed an effect which decreased the thermal conductivity. The results in this study implied that the inter-yarn pores had a greater effect on the thermal properties of the fabrics produced from trilobal fibres. As the thermal conductivity values of the fabrics produced from trilobal fibres were lower than their round counterparts, the thermal resistances of these fabrics would be expected to be higher.

This result was revealed in the thermal resistance values of the twill fabrics, but not in those of the plain fabrics. This situation could have been due to the effect of fabric thickness on the determination of thermal resistance.

The fabric with a twill pattern has lower cross over points, higher yarn floats and, as a result, lower yarn crimps than the fabric with a plain pattern when the warp and weft densities are the same. This results in a looser and more open structure with lower unit weights in twill fabrics. Consequently, as also mentioned in literature [24, 29], the thermal conductivity and thermal absorption values of the plain fabrics were higher and the thermal resistance values lower than corresponding values of the twill fabrics. But the differences obtained were statistically meaningful only for the thermal resistance, not for the thermal conductivity and thermal absorption.

Water vapor permeability

The relative water vapour permeability values of all the fabrics were presented in ***Table 4*** and compared in ***Figure 3***.

The relative water vapour permeability values of the fabrics woven from hollow fibres were lower than those of the fabrics woven from solid fibres. The twill fabrics had higher relative water vapour permeability values than the plain fabrics. Similarly the fabrics produced from solid and hollow trilobal fibres had higher relative water vapour permeability values than those produced from solid and hollow round fibres, respectively. Among all the fabric types, the twill fabric woven from trilobal solid fibres (T-T) had the highest relative water vapour permeability value.

Differences observed among the relative water vapour permeability values of the fabrics produced from fibres having different cross sectional shapes were statistically significant (***Table 5***). Also there was a statistical difference between the relative water permeability values of the twill and plain fabrics.

*Table 5. Statistical analysis results for relative water vapor permeability; * - statistically significant (P < 0.05), ns - non-significant, (a), (b), (c), (d) represent the statistical difference ranges.*

Factors	F value	P value	SNK Range
Fibre cross sectional shape (F)	60.539	0.000*	T(a), R(a), HT(b), HR(b)
Weave pattern (W)	195.232	0.000*	T(a), P(b)
Interaction (F X W)	0.782	0.521ns	T-T(a), R-T(a), HT-T(a), HR-T(a), T-P(a), R-P(a), HT-P(a), HR-P(a)

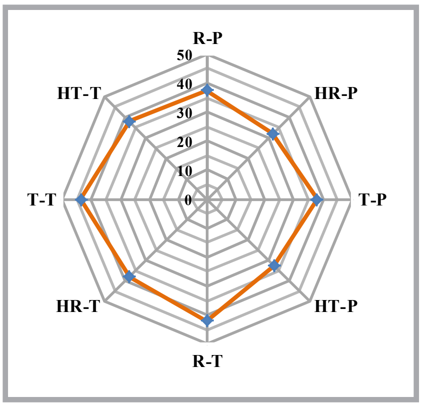

Figure 3. Relative water vapour permeability values of the fabrics.

Table 4. Relative water vapour permeability results of the fabrics (mean ± SD).

Fabric code	Relative water vapor permeability, %
R-P	37.57 ± 1.76
HR-P	32.10 ± 0.53
T-P	37.88 ± 0.52
HT-P	32.74 ± 0.88
R-T	41.99 ± 1.11
HR-T	37.93 ± 0.01
T-T	43.75 ± 1.04
HT-T	38.01 ± 0.51

Fibre content and fabric geometry are two main factors that may affect the water vapour transmission of textiles [22]. Fibre content consists of parameters such as material type, fibre count, fibre cross sectional shape etc. In this research, as all the fibre parameters, except the fibre cross sectional shape, were the same, the water vapour permeability of the fabrics produced were affected by only the cross sectional shape of the fibre related parameters. The transportation of water vapour through a thick and tight fabric would be harder than the opposite case, the reason for which being that the water vapour diffusion through the air portion of the fabric is almost instantaneous (the diffusion coefficient of water vapour through air is 0.239 $cm^2 s^{-1}$), whereas the diffusion through a fabric system is limited due to the lower water vapour diffusivity of the textile material [8]. For the fibres produced with the same fibre fineness, the hollow fibres were thicker and, as a result, the inter-yarn pores in the fabrics produced from these fibres were smaller than those in the fabrics produced from solid fibres. The decrease in inter-yarn pores together with the increase in fabric thickness caused a decrease in the water vapour permeability of the fabrics produced from hollow fibres. Similarly the fabrics produced from thinner yarns of solid fibres had lower thickness, a more porous structure for the same warp and weft densities, and higher water vapour permeability values.

The water vapour permeability results of the fabrics produced from trilobal fibres were slightly higher than the corresponding results of the fabrics produced from round fibres, the reason for which could be explained by the compact structure of the yarns spun from trilobal fibres, which caused the fabric thicknesses to decrease and inter-yarn pores to increase for the same yarn densities.

Woven fabric geometry consists of parameters such as the yarn count, yarn density, weave pattern etc. In this research, as all the fabric parameters, except the weave pattern, were the same, the water vapour permeability of the fabrics produced were affected by only the weave pattern of the fabric geometry related parameters. Because of the lower number of cross over points and longer yarn floats, the twill fabrics had a looser and more open structure, as a result of which they had higher water vapour permeability values than the plain fabrics.

Air permeability

Air permeability values of all the fabrics are presented in ***Table 6*** and compared in ***Figure 4***.

The results showed that the twill fabrics had higher air permeability values than the plain fabrics, and the fabrics made from solid fibres were more permeable to air as compared to those made from hollow fibres. The highest air permeability value was observed in the fabric of twill weave and trilobal solid fibre (T-T).

When the statistical analysis results in ***Table 7*** were considered, it was observed that the fibre cross sectional shape, weave pattern and interaction of these factors were statistically significant for the air permeability values.

Studies on the structural factors influencing the air permeability of fabrics assume that airflow takes place in the spaces between yarns. Therefore the inter-yarn pore is an important parameter influencing the openness of the fabric structure. The intra-yarn pore also contributes to the total pore volume of the fabric, but the total airflow is not affected much by pores enclosed within the yarn [6]. As the thicknesses of the hollow fibres were higher when compared to their solid counterparts for the same fibre count, the pores in the yarns consisting of hollow fibres were larger, but the space between the yarns decreased for the same warp and weft density. As a result, the fabric woven from hollow fibres had a closer and more impermeable structure.

In the experimental part, the fabrics produced from trilobal fibres had lower unit weights and thicknesses than those produced from round fibres for the same yarn and fabric parameters. The inter-yarn pores were higher in the fabrics produced from trilobal fibres than corresponding fabrics produced from round fibres for the same warp and weft densities, as a result of which the air permeability values of these fabrics were higher than corresponding values of the fabrics produced from solid fibres.

The great differences observed between the air permeability values of the plain and twill fabrics were due to differences in their characteristic covering properties. For equivalent weaving parameters, 2/1 twill fabrics had a lower unit weight and higher porosity, resulting in a looser structure because of having longer yarn floats than the plain fabrics. Thus the twill fabrics were much more permeable to air than the plain fabrics.

Conclusions

In this study, the thermal comfort properties of woven fabrics produced from polyester fibres with different cross sectional shapes were investigated. From the results, the following conclusions can be made:

1. The thermal conductivity increased in the fabrics woven with hollow fibres when compared with those woven with solid fibres. As a result, the thermal insulation property of the fabrics produced from hollow fibres was lower.
2. Hollow fibres have a greater outer dimension than those with the same fibre count. It is well known that when hollow fibres are used as insulating materials in a non-orderly form, they exhibit high insulation properties. However, the current research showed that when the hollow fibres were spun into yarns and later these yarns were used in woven fabric production, the covering and total porosity properties of the woven fabrics surpassed the effects of inter-fibre pores in the yarn. As a result, the insulation properties of the hollow fibres expected were not observed, and even contrary results of thermal properties were obtained.
3. The fabrics woven from trilobal fibres had lower thermal conductivity and thermal absorption values than those woven from round fibres because of the compact yarn structure and consequently numerous inter-yarn pores.
4. In the twill fabrics, the thermal conductivity and thermal absorption values were lower and the thermal resist-

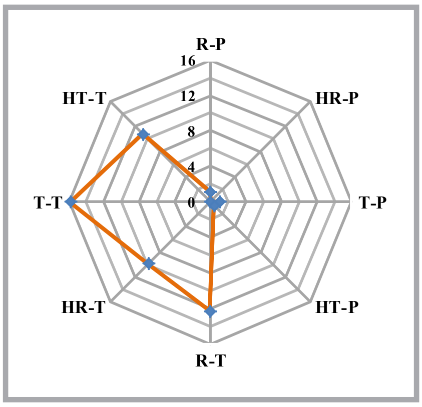

Figure 4. *Air permeability values of the fabrics.*

Table 6. *Air permeability results of the fabrics (mean ± SD).*

Fabric code	Air permeability, $m^3m^{-2}min^{-1}$
R-P	1.12 ± 0.06
HR-P	0.06 ± 0.01
T-P	1.14 ± 0.13
HT-P	0.63 ± 0.06
R-T	12.34 ± 0.59
HR-T	9.87 ± 0.64
T-T	15.84 ± 0.90
HT-T	10.75 ± 0.58

Table 7. *Statistical analysis results for air permeability; * - statistically significant ($P < 0.05$), ns: non-significant, (a), (b), (c), (d) represent the statistical difference ranges.*

Factors	F value	P value	SNK Range
Fibre cross sectional shape (F)	193.0	0.000*	T(a), R(b), HT(c), HR(d)
Weave pattern (W)	10871.7	0.000*	T(a), P(b)
Interaction (F X W)	103.7	0.000*	T-T(a), R-T(b), HT-T(c), HR-T(d), T-P(e), R-P(e), HT-P(e), HR-P(f)

ance values higher than corresponding values of the plain fabrics.

5. When compared with the fabrics woven from solid fibres, the water vapour and air permeabilities of the fabrics woven from hollow fibres were lower because of their greater thickness, lower porosity and closer structure.
6. The water vapour and air permeability results of the fabrics produced from trilobal fibres were higher than corresponding results of the fabrics produced from round fibres because of the compact structure of the yarns spun from these fibres.
7. The twill fabrics showed higher values of water vapour and air permeabilities than the plain fabrics due to their higher porosity.
8. The twill fabrics produced from solid trilobal fibres (T-T) had the lowest value of thermal conductivity and the highest values of relative water vapour and air permeability.

Acknowledgment

The authors would like to thank TUBİTAK (The Scientific and Technical Research Council of Turkey) for its financial support in the research project (No. 105M089 (MAG-HD-19)) and Korteks Corp. (Bursa), İsko Corp. (Bursa) and Berke Corp. (Bursa) for their cooperation at the various production stages.

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Received 23.09.2011 Reviewed 14.11.2011