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Investigation of Moisture Transport Properties of Knitted Materials Intended for Warm Underwear

Abstract
The main functional purpose of knitted materials intended for warm underwear is to vouchsafe the comfort property while composing and maintaining a satisfactory microclimate on the human skin. This research seeks to investigate the liquid moisture management properties of knitted fabrics of different fibre blends of different ratios suitable for the base layer of underwear. Two groups of fabrics were knitted in combined and plain and plated single jersey with laid-in yarn patterns, and their moisture management properties were assessed using a moisture management tester. The usage of fleecy yarn in knitted fabric structure has improved the moisture management properties of fabrics in comparison to combined pattern fabrics. Out of ten fabrics studied, three were classified as moisture management fabrics that are suitable for the base layer of underwear.

Key words: *comfort properties, moisture transport, knitted underwear.*

Introduction

Clothing comfort is dependent upon the low-stress mechanical, thermal and moisture transfer properties of fabrics [1]. Clothing must also assist the body's thermal control function under changing physical loads in such a way that the body's thermal and moisture management is balanced, and a microclimate is created next to the skin [2]. There is a general agreement that moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body, which is maintained by perspiring both in vapour and liquid form. Therefore there are various methods to investigate the thermo-physiological properties of the body-textile medium in steady state conditions, e.g. sweating guarded hot plate apparatus, manikin tests; a moisture management tester is also used to characterise the liquid transfer properties of fabrics. However, it was found in previous studies [3, 4] that steady state vapour transport and moisture liquid transport through textile fabrics are two independent behaviours, as there was no significant correlation between the steady state vapour resistance and overall one-way transport capacity.

The human body produces heat during all its activities, and the production of sweat is started by the cooling system of the body in order to remove extreme heat from the body. It is very important that the body should keep a suitable temperature and moisture balance according to different environmental conditions [5]. If the sweat produced cannot be removed from the body, it will cause people to feel cold because of wet and cool skin. There are two forms of perspiration: insensible (in this form perspiration is transported as a vapour and it passes through the air gaps between yarns in a fabric) and liquid (this form occurs at higher sweating rates and it wets clothing that is in contact with the skin). Wetting starts after an amount of liquid which will fill the capillary pores between fibres and yarns is accumulated. The liquid transport mechanism depends on the effect of capillary forces and surface characteristics. Therefore the garment should evaporate the liquid before causing its accumulation [6, 7], as well as act as a barrier to heat and moisture loss. If over-heating is to be avoided, thermoregulation and moisture management are key functions of clothing designed for use as sportswear or underwear. Textiles with high liquid sorption abilities could be used for applications in direct contact with human skin in order to help cool the body by readily absorbing moisture or perspiration. Absorption and permeability properties as well as moisture transmission through textiles are important for textile design and especially relevant for the comfort of clothing [8].

The interaction of liquids with textile could involve some fundamental physical phenomena: wetting of the fibre surface, the transport of liquid into assemblies of fibres, the adsorption of the fibre surface, and the diffusion of liquid into the interior of the material [9, 10]. The mechanism by which moisture is transported in textiles is similar to the wicking of a liquid in capillaries. Capillary action is determined by two fundamental properties of the capillary: its diameter and surface energy of its inside face. The smaller the diameter or the greater the surface energy, the greater the tendency of a liquid to move up the capillary. In textile structures, the spaces between fibres effectively form capillaries. Hence the narrower the spaces between these fibres, the greater the ability of the textile to wick moisture. Fabric constructions, which effectively form narrow capillaries, pick up moisture easily. The surface energy in a textile structure is determined largely by the chemical structure of the exposed surface of the fibre, and therefore therefore hydrophilic fibres have a high surface energy.

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Knitted fabrics are the most common fabric structures for underwear garments. Knitted fabric generally possesses good stretch and recovery, providing good freedom of movement, shape retention, and tailored fit. With the possibility of various combinations of fabric constructions and yarns used, knitted fabric appears to be the ideal base for functionally adaptive sportswear. And commonly a knitted double-layer construction is selected to obtain a functional fabric design because of its flexibility of fibre selection and properties [11, 12]. In double-layer fabric structures, the connecting yarn acts as a bridge between the two layers of fabric [13] and improves the biophysical value of double-layer knitted materials [14]. There are a number of textile fibres that are currently used in underwear and sportswear garments, both natural and synthetic, but polyester is the single most popular and common fibre used in active wear and sportswear [15]. On the other hand, some other researchers have focused their attention on the geometric distribution of capillaries in synthetic fibre assemblies, which affects the volume of liquid and the wicking time of capillary action [16]. Profiled fibres are very useful fibres for such applications that need to have good water transfer instead of water absorption. The fibres profiled have a bigger surface area, which increases wick-ability [17]. It has been established that fabrics composed of fibres of cruciform cross section are more hydrophobic than those with a round one [18].

Today's underwear clothing is highly engineered to maximise comfort through enhanced moisture management and temperature regulation. Special properties are built into garments using specialised fibres, yarns, fabric structures and fabric finishes [19 - 21]. A garment that is worn next to the skin should have [22, 23] a good sweat absorption and sweat releasing property to the atmosphere, as well as a fast drying property for getting more tactile comfort. Experimental studies published have shown that the raw materials and structural properties of fabrics are important in the determination of moisture management properties of fabrics [24 - 28].

In the present study, the liquid moisture transport performance of eight knitted

Table 1. *Characteristics of knitted fabric tested; * - in the inner layer of the combined pattern knitted material (1st group) ThermoºCool™ yarns were used, which are made with a unique combination of different engineered fibre cross-section types: multi – channel and round hollow; and in the middle layer Thermolite® yarns were used: polyester textured filament yarns from round hollow fibre; in the inner layer of the plain and plated single jersey with laid-in yarn knitted material (2nd group) tetrachanel Coolmax® yarns were used; and in the middle layer Thermolite® yarns were used: polyester textured filament yarns from round hollow fibre.*

Group of fabrics	Sample No.	Type of separate layer	Type of yarn*, linear density, tex	Pattern	Pattern courses (Figure 1)	Number of stitches per unit length and unit area, cm^{-1}		Mass per unit area, g/m	TF, tex$^{1/2}$/mm
						Courses, P_V front side/back side	Wales, P_H		
1st group	**F1**	I- inner	PES spun yarns (multi – channel + round hollow profile), 20	combined	E3, E6	9/18	10	295	26.1
		II-middle	PES textured yarns (round hollow profile, f100), 8.4		E1, E4				
		III-outer	Wool yarns, 25.0		E2, E5				
	F2	I-inner	PES spun yarns (multi – channel + round hollow profile), 20		E3, E6			268	22.6
		II-middle	PES textured yarns (round hollow profile, f100), 8.4		E1, E4				
		III-outer	Cotton/PES spun yarns (67/33%) with carbon fibre, 20.0		E2, E5				
	F3	I-inner	PES spun yarns (multi – channel + round hollow profile), 20		E3, E6			259	26.0
		II-middle	PES textured yarns (round hollow profile, f100), 8.4		E1, E4				
		III-outer	PES spun yarns with carbon fibre, 20.0		E2, E5				
	F4	I-inner	PES spun yarns (multi – channel + round hollow profile), 20		E3, E6			233	21.9
		II-middle	PES textured yarns (round hollow profile, f100), 8.4		E1, E4				
		III-outer	Bamboo viscose spun yarns, 14.8		E2, E5				
2nd group	**F5**	I- inner	PES spun yarns (4 channel profile), 50.0	plain and plated single jersey with laid- in yarn	-	9	14	278	34.5
		II-middle	PES textured yarns (round hollow profile, f100), 8.4						
		III-outer	Wool yarns, 25.0						
	F6	I- inner	PES spun yarns (4 channel profile), 50.0					245	34.0
		II-middle	PES textured yarns (round hollow profile, f100), 8.4						
		III-outer	Cotton/PES spun yarns (67/33%) with carbon fibre, 20.0						
	F7	I- inner	PES spun yarns (4 channel profile), 50.0			8		235	33.2
		II-middle	PES textured yarns (round hollow profile, f100), 8.4						
		III-outer	PES spun yarns with carbon fibre, 20.0						
	F8	I- inner	PES spun yarns (4 channel profile), 50.0					208	33.7
		II-middle	PES textured yarns (round hollow profile, f100), 8.4						
		III-outer	**Bamboo viscose** spun yarns, 14.8						

fabrics developed was assessed and fabric moisture management properties determined.

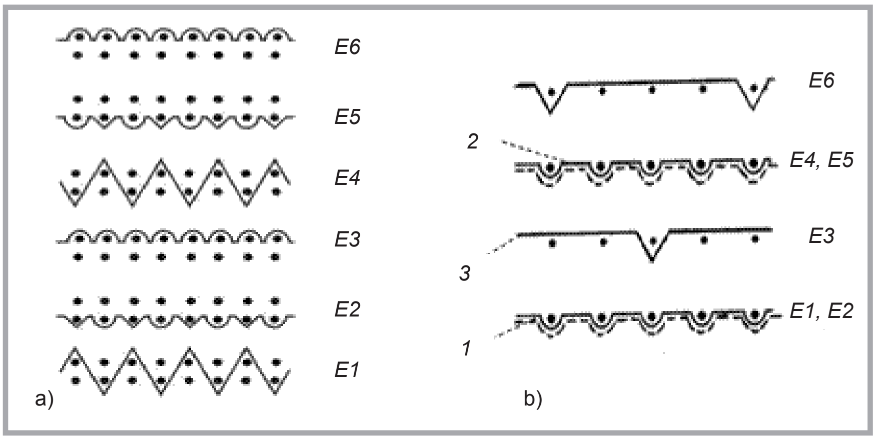

***Figure 1.** Structure of knitted fabrics: a) a combined pattern of three layer weft knitted fabrics investigated, b) structure of three-thread fleecy knitted fabric: 1 – plating yarn (outer layer), 2 – binding yarn (middle layer), 3 – fleece yarn (inner layer).*

Experimental

Fabrics description

In the first stage four combined pattern knitted fabrics intended for base layer underwear were produced on a 20E gauge METIN NOV circular interlock knitting machine of 30-inch (76 cm) diameter. A detailed description of the fabrics tested is given in ***Table 1***, and the knitting structure is shown in ***Figure 1.a***.

In the next stage a 20E gauge FIHN (“Orizio”, Italy) circular knitting machine of 30-inch (76 cm) diameter was used for manufacturing three-thread fleecy fabrics. A detailed description of the fabrics tested is given in ***Table 1***, and the knitting structure is shown in ***Figure 1.b***.

For construction of knitted fabric for warm underwear clothing, plain and plated single jersey with laid-in yarn was chosen. Every line of this knitting consists of three kinds of threads (plating, binding and fleece), each of which forming a separate layer in the knitting structure: outer, middle and inner. Fleece yarn in the knitting periodically structures only tuck loops, while the floating of the yarn shape embossed the surface of the inner side, forming a three-layer knitted material (***Figure 1.b***), the inner layer of which is usually napped.

Overall, two groups consisting of four particular variants of knits with special four and round hollow channel profile polyester, wool, bamboo viscose, cotton-polyester and polyester (with carbon fibres) yarns were investigated. The cross section fibres profiled were chosen for sample manufacturing due to their significant improvement in sweat transferring power as well as other moisture management properties [13].

Moreover for enhancement of the liquid water transfer capacity of knitted double-layer fabrics, polyester type fibres for the inner surface (as well as connecting yarns) of the knitted fabrics were chosen [29]. Another main property that might be most effective than others in the case of liquid transferring is the cross-sectional geometry, like multi-channels on the surface of fibres. It can be seen that the sample with Coolmax fibres knitted into the reverse side has the highest wicking ability when compared to others, due to the physical cross-sectional geometry enabling water transfer in the channels on the surface of fibres [18].

The knitted fabrics were washed to remove dirt and to relax yarn tension in the fabric specimens. The samples were washed according to Standard EN ISO 6330:2012 using procedure 6N (60 ºC) and dried in a free state.

Test methods

Prior to testing all fabrics samples were conditioned and tested in a standard atmosphere according to Standard EN ISO 139:2005. Structure parameters of the knitted samples were analysed according to Standard EN 14971:2006. The mass per unit area was calculated as the mean mass per unit area, as indicated in Standard EN 12127:1997. Five tests per sample were performed.

The number of wales and courses in an accurately measured length were counted along a line at right angles to the course or wale being considered. Five counts in each direction were made at positions evenly spaced along or across the fabric; selvedge was avoided. The measurements were made according Standard EN 14971:2006.

Since different tightness properties are attributed to different samples, different

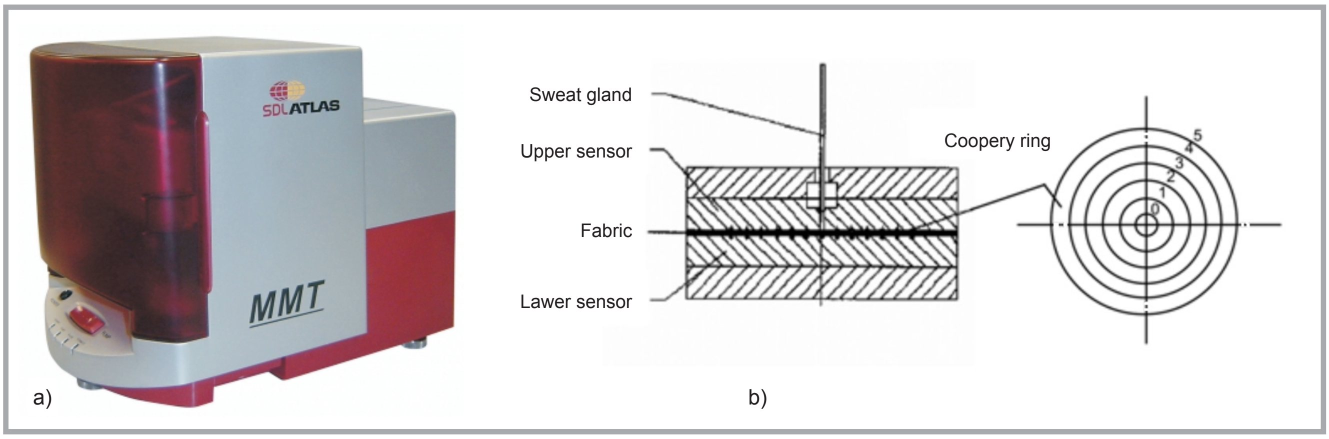

***Figure 2.** Moisture management tester, model M290, SDL Atlas: a) view of a device, b) schematic view of tester sensors [3].*

Tabele 2. *Grading of MMT indices.*

Grade Index		1	2	3	4	5
Wetting time	Top	≥ 120 No wetting	20 - 119 Slow	5 - 19 Medium	2 - 5 Fast	< 3 Very fast
	Bottom	≥ 120 No wetting	20 - 119 Slow	5 - 19 Medium	2 - 5 Fast	< 3 Very fast
Absorption rate	Top	0 - 10 Very slow	10 - 30 Slow	30 - 50 Medium	50 - 100 Fast	> 100 Very fast
	Bottom	0 - 10 Very slow	10 - 30 Slow	30 - 50 Medium	50 - 100 Fast	> 100 Very fast
Max wetted radius	Top	0 - 7 No wetting	7 - 12 Small	12 - 17 Medium	17 - 22 Large	> 22 Very large
	Bottom	0 - 7 No wetting	7 - 12 Small	12 - 17 Medium	17 - 22 Large	> 22 Very large
Spreading speed	Top	0 - 1 Very slow	1 - 2 Slow	2 - 3 Medium	3 - 4 Fast	> 4 Very fast
	Bottom	0 - 1 Very slow	1 - 2 Slow	2 - 3 Medium	3 - 4 Fast	> 4 Very fast
AOTI		< - 50 Poor	- 50 to 100 Fair	100 - 200 Good	200 - 400 Very good	> 400 Excellent
OMMC		0 - 0.2 Poor	0.2 - 0.4 Fair	0.4 - 0.6 Good	0.6 - 0.8 Very good	> 0.8 Excellent

sizes of inter-loop voids are expected for each sample, and thus the influence of only inter-loop voids on liquid transfer characteristics is to be considered. This property influences the porosity of knitted fabrics [30], which in turn has an effect on moisture transport performance. The tightness of knitted fabrics is characterised by the tightness factor [31]:

$$TF = \sqrt{T}/l \tag{1}$$

where T – actual linear density of the yarn in tex, l – stitch length in cm.

A Moisture Management Test (MMT) device, model M290, *SDL Atlas* (schematic view of the instrument is presented in ***Figure 2***) was used to determine multi-directional liquid moisture transport capabilities and distribution properties of the knitted fabric samples. The investigations were carried out according to the AATCC Test Method 195-2012. Five specimens with dimensions of 8 × 8 cm were prepared for each type of fabric. The specimens were then conditioned in a conditioning atmosphere. MMT properties of knitted fabrics are evaluated by placing a fabric specimen between two horizontal (upper and lower) electrical sensors, each with seven concentric pins. A pre-defined amount of test solution (synthetic sweat) is introduced onto the upper side of the fabric.

The results obtained with this test method are based on water resistance, water repellency and water absorption characteristics of the fabric structure, including the fabric's geometric and internal structure and the wicking characteristics of its fibres and yarns. The MMT method assumes that the value of the electrical resistance change depends on two factors: the components of the water and its content in the fabric, and thus when the influence of the water components is fixed, the electrical resistance measured is only related to the water content in the fabric [6, 32].

The test solution is free to move in three directions after dropping onto the fabric's top surface: spreading outward on the top surface of the fabric, transferring through the fabric from the top to the bottom surface, and spreading outward on the bottom surface of the fabric and then evaporating. During the test, changes in electrical resistance of specimens are measured and recorded. A summary of the measurement results is used to grade the liquid moisture management properties of a fabric tested using predetermined indices.

In the present study, the back of the fabric samples was always the top surface (facing the top sensor) when the sample was tested, imitating the case in which the reverse side is in direct contact with the skin.

MMT indices used in investigation:
Bottom surface – the side of a specimen that when placed down against the lower electrical sensor is that of the fabric that would be the outer exposed surface of a garment when it is worn or a product when it is used. *Top surface* – the side of a specimen that when placed on the lower electrical sensor is facing the upper sensor. This is the side of the fabric that would come in contact with the skin when a garment is worn or when a product is used.

Wetting Time (WT_T – top surface and WT_B – bottom surface) – the time in sec-

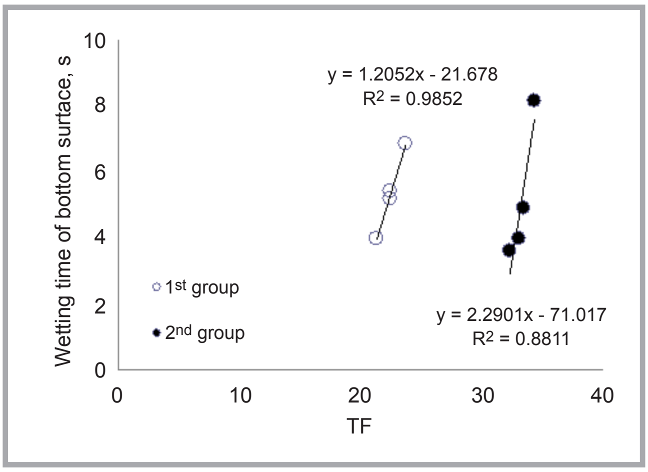

Figure 3. *Relationship between the wetting time of the bottom surface and tightness factor.*

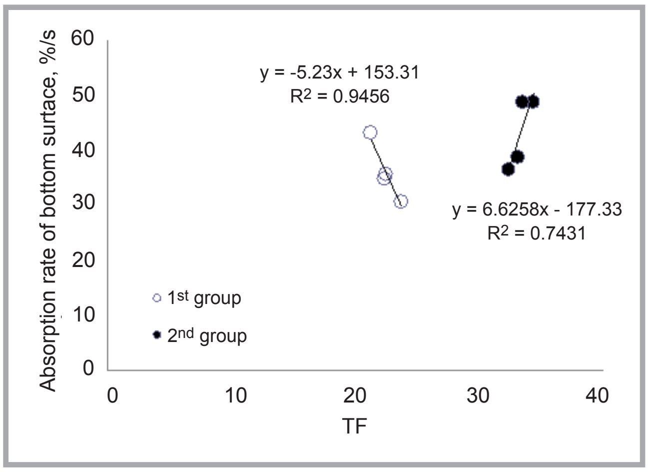

Figure 5. *Relationship between the absorption rate of the bottom surface and tightness factor*

onds when the top and bottom surfaces of the specimen begin to be wetted after the test is started.

Absorption Rate (AR_T – top surface and AR_B – bottom surface) – the average speed of liquid moisture absorption for the top and bottom surfaces of the specimen during the initial change of water content during a test.

Maximum wetted radius (MWR_T – top surface and MWR_B – bottom surface) – the greatest ring radius measured on the top and bottom surfaces.

Spreading Speed (SSi) – the accumulated rate of surface wetting from the centre of the specimen, where the test solution is dropped to the maximum wetted radius.
Accumulative one-way transport capability (AOTI) – the difference between the area of the liquid moisture content curves of the top and bottom surfaces of the specimen with respect to time.

Overall moisture management capacity (OMMC) – an index to indicate the overall capability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance: the moisture absorption rate on the bottom side, the one way liquid capability, and the moisture drying speed on the bottom side, which is represented by the accumulative spreading speed.

According to AATCC Test Method 195–2012, the indices are graded and converted from a value to grade based on a five grade scale. ***Table 2*** shows the range of values converted into grades.

The coefficients of variation of values of the parameters tested do not exceed 5.8%.

Results and discussion

The liquid transport properties of two groups of knitted fabrics differing in the raw material of the outer-layer were investigated. The results of moisture management properties, converted into the grades, of the fabrics used are visualised in diagrams. As the tightness property influences the porosity of knitted fabrics [30], which in turn has an effect on the moisture transport performance, the possible relationships between the *TF* and moisture management properties of the double-layer knitted fabrics tested were found and scatter plots with regression lines of *MMT* indices and *TF* established. In ***Figure 3*** the relationship between the wetting time of the bottom surface of both groups of fabrics tested and *TF* is presented (as the moisture management properties of the inner layer of the samples tested do not vary significantly, this side of the fabrics was not taken into further consideration when analysing the above-mentioned relationship). The wetting time of the bottom is the time period in which the bottom surface of the fabric tested begins to be wetted after the test is started.

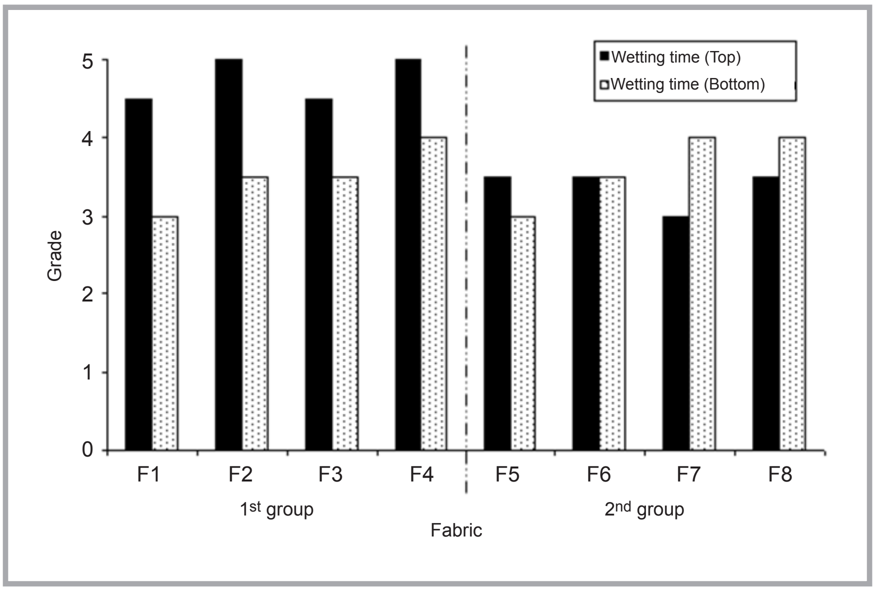

Figure 4. *Top and bottom wetting time grades of the fabrics tested.*

As is seen from ***Figure 3***, the wetting time of the bottom surface increased with an increase in the tightness factor of the samples tested, and a strong linear relationship exists between the wetting time and *TF*.

After the conversion of wetting time values into grades (see ***Figure 4)*** it can be seen that fabrics of the 1st group have a very good wetting time on the top surface (fabrics No. F1-F4), showing that when the test liquid was dropped onto the fabric surface, all the kinds of fibres absorbed liquid and transported it to bottom surface fast, having a medium wetting time on the bottom surface, while fabrics knitted in plain and plated single jersey with a laid-in yarn pattern (2nd group) have a medium wetting time in both the top and bottom directions. Many studies [7, 10, 16, 20] on the wicking behaviour of textile materials assumed that the liquid flows through inter-fibre spaces in the yarn by means of the interfacial tension between the liquid and fibre surfaces; therefore the rate of wicking should depend on the surface energy of the fibre and the separation between fibres in the yarn.

The relationship between the absorption rate of the bottom side of both groups of fabrics tested and *TF* is presented in ***Figure 5***. The absorption rate of the bottom is the average speed of liquid moisture absorption for the bottom surface of the specimen during the initial change in water content during a test.

As is seen from ***Figure 5***, the absorption rate of the 2nd group of knitted fabrics increases with an increase in the tightness factor of the samples tested, whereas that of the bottom surface of the 1st group of fabrics decreased with an increase in the tightness factor. This tendency could be attributed to the different inner surfaces of the fabrics investigated, as the inner side of the second group's fabrics is slightly raised. However, strong linear relationships exist between the wetting time and *TF*.

In terms of absorption rate indices, it was seen (***Figure 6***, see page 98) that all fabrics tested had medium to slow values for the top surface, meaning that the liquid passed quickly through the fabric and accumulated on the bottom surface. Such a tendency is due to profiled PES fibre existence on the inner surface of knitted fabric. While fabrics F1 and F5 have a very slow absorption rate on the bottom surface with a quite fast absorption rate on the top, fabrics F7 and F8 have

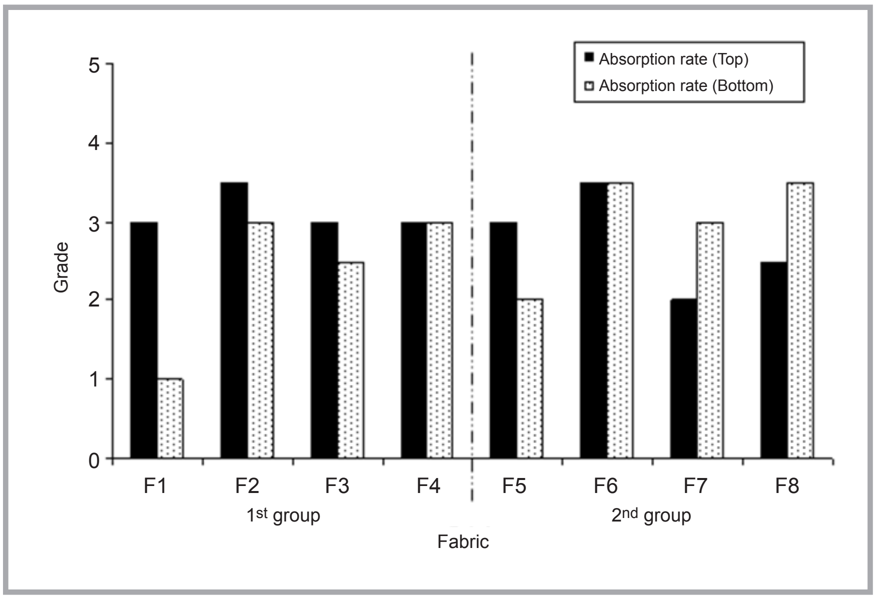

***Figure 6**. Top and bottom absorption rate grades of fabrics tested.*

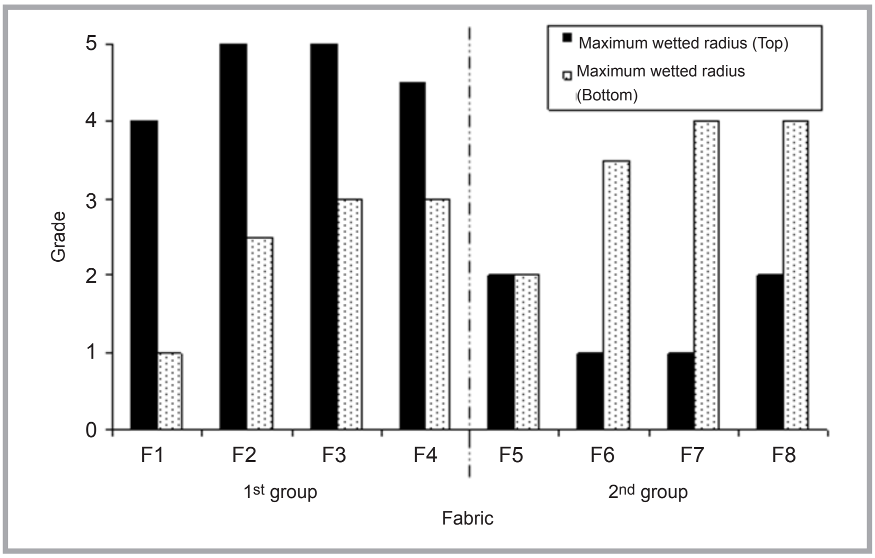

***Figure 7.** Top and bottom maximum wetted radii grades of fabrics tested.*

a higher top absorption rate grade than the other fabrics tested, which may be because of the liquid water accumulating on the top layer surface for a very short while, causing an obvious increase in the water content of the top surface.

It is interesting to observe the differential behaviour of the top and bottom surfaces of fabrics F1 and F5: the top's absorption and wetting rate grades are substantially higher than the bottom's absorption and wetting rate grades (***Figures 4*** and ***6***). Such a tendency could be due to the fact that moisture diffusion into a fabric through air gaps between yarns and fibres is a fast process, while moisture diffusion into fibres is coupled with the heat-transfer process, which is much slower and is dependent on the ability of fibres to absorb moisture. Thus the difference in the top and bottom surfaces' behaviour for S1 and F5, as compared to other fabrics, is probably due to the wool having lower fibre surface energy than polyester, viscose and cotton: as the liquid is initially introduced to the top layer of F1 and F5 it diffuses more quickly through the air gaps from the top to the bottom layer without being absorbed into the top layer, and then, as it accumulates on the bottom layer, it is absorbed into the wool fibres that form the bottom layer.

Figure 7 shows the mean grades of the maximum wetted radius of the top and bottom of the sample fabrics tested. Each maximum wetted radius (MWR_T and MWR_B) is defined as the greatest wetted ring radius on the top and bottom surfaces, respectively.

Analysing data presented in ***Figure 7***, it can be noticed that the samples can be divided into two groups: the first group (F1 - F4) has a large and very large maximum wetted radius on the top surface, indicating that liquid sweat can be easily transported with a large wetted area by capillary forces, while the second group of fabrics (F6 - F8) has a large maximum wetted radius on the bottom surface, suggesting that all three kinds of fabric had transferred and distributed more liquid water in the bottom layer than in the top layer, indicating that all three fabrics had a moisture management ability. The results show that fabrics F6, F7 and F8 have the largest bottom wetted area and the smallest top wetted area, indicating that the usage of fleecy yarn can increase the liquid moisture spreading capacity of the bottom layer.

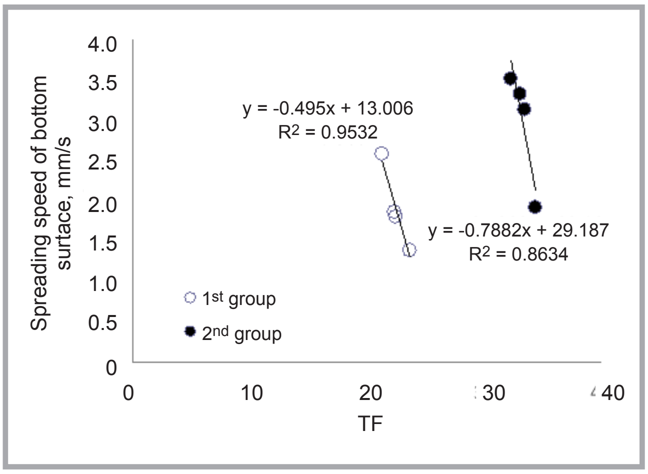

***Figure 8**. Relationship between the spreading speed of the bottom surface and tightness factor.*

In ***Figure 8*** the relationship between the liquid spreading speed of the bottom side of both groups of fabrics tested and *TF* is shown. The SS_B are defined as the accumulated rate of surface wetting from the centre of the specimen where the test solution is dropped to the maximum wetted radius.

As is seen from ***Figure 8***, the spreading speed of the bottom surface of the fabrics decreased with an increase in the tightness factor of the samples tested. A high determination coefficient improves the relationship between those two parameters. A decrease in the spreading speed is caused by a decrease in porosity. Besides, the solution spreads faster on the fabrics that have the highest rates of surface energy, i.e. knitted fabrics from viscose fibre.

In ***Figure 9*** the mean grade of the liquid spreading speed of the top and bottom of all fabrics tested is shown. The SS_T and SS_B are defined as the accumulated rate of surface wetting from the centre of the specimen where the test solution is dropped to the maximum wetted radius. As is seen from ***Figure 9***, the first group of fabrics (S1 - S6) has from a fast to very fast spreading speed grade on the top surface, while the spreading speed grade on the top of the second group of fabrics is very slow.

Figure 10 shows the mean grade of the accumulative one-way transport index AOTI, which shows the cumulative moisture difference between the two surfaces of fabric, and the overall moisture management capacity OMMC, which shows all performance of liquid moisture obtained by calculating other indexes for the fabric, therefore ***Figure 10*** gives a general idea of the moisture comfort of the fabric investigated.

A comparison of the accumulative one-way transport index (AOTI) of all kinds of fabric is shown in ***Figure 10***, indicating that the AOTI of the first group's fabrics (except fabric F4) was dramatically lower than that of the second group of fabrics (except fabric F5). The results indicate that with respect to the liquid water transfer speed and water content, fabrics F6, F7 and F8 have higher differences between the two layers and a better moisture management ability, while fabrics without fleecy yarn in the structure have the poorest AOTI.

In order to give a direct overall evaluation and result for the liquid moisture management properties, each of the fabrics is classified by fabric type based on the grades and values of indices (***Table 2***) [32]. ***Figures 4, 6, 7, 9*** and ***10*** reveal that fabrics F6, F7 and F8 have the highest liquid moisture management capacity (OMMC is very good) and accumulative one-way transport index (AOTI is excellent), showing that liquid sweat can be easily and quickly transferred from next to the skin to the outer surface to keep the skin dry. These fabrics also had relatively large spreading rates (SS_B is very good) and a more than medium wetted radius (MWR_B is large) on the bottom surface, indicating that liquid can spread on the bottom surface and dry quickly.

Fabrics F1 - F3 & F5, on the other hand, have poor liquid moisture management properties with a very low wetted radius and spreading rates on the bottom surface, as well as negative accumulative one-way transport capacities, indicating that the liquid (sweat) cannot diffuse easily from the next-to-skin surface to the opposite side and will accumulate on the top surface of the fabric.

Fabric F4 has medium one-way transfer abilities, higher spreading rates, and larger wetted areas, indicating that the liquid (sweat) can transfer from the surface next to the skin to the opposite surface and spread quickly on the fabric's bottom surface with a large wetted area, where it evaporates into the environment. Such fabric has fast absorbing and quick-drying abilities.

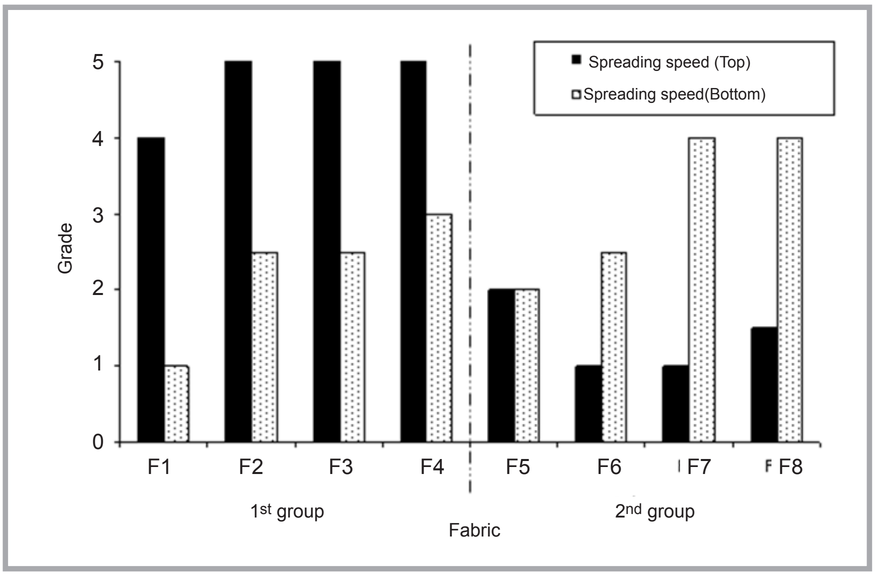

Figure 9. *Top and bottom spreading speed grades of fabrics tested.*

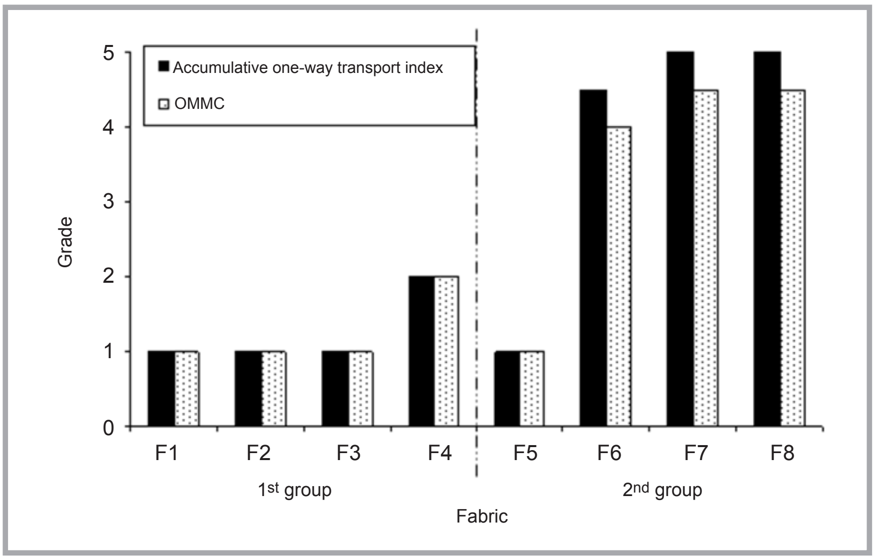

Figure 10. *Accumulative one-way transport index and overall moisture management capacity grades of fabrics tested.*

Conclusions

Knitted fabrics of combined construction and in plain and plated single jersey with laid-in yarn construction of different fibre content in the outer-layer have different moisture management properties and performance attributes, thus potentially it is possible to engineer fabrics of such a construction as to achieve the moisture management performance required by varying their fibre content. The most influential factors for moisture transport were the fabric structure: fleecy fabrics can transport moisture more effectively compared to plain knitted fabrics, and with respect to the fibre‘s surface energy, fabrics with a higher surface energy value are characterised by better moisture management properties. Also it was estimated that moisture management properties linearly depend on the tightness factor.

Fabrics constructed from cellulose and polyester and pure polyester in the outer-layer (F6, F7 and F8) were classified into moisture management fabrics according to the possible commercial classification; these fabrics are suitable for warm underwear. The knitted materials produced in a combined pattern could be used as fast absorbing and quick drying fabrics, except those made from wool fibre in the outer-layer.

Based on the tests conducted in this study, in comparison with three layer weft knitted combined structures, it was evident that fabrics made of a fleecy structure (samples F6, F7, F8) possess a significantly greater initial water absorption rate and one-way transport capacity, which are highly beneficial to the moisture comfort of outerwear or underwear.

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