Functional and Comfort Properties of Textiles from TENCEL® Fibres Resulting from the Fibres' Water-Absorbing Nanostructure: A Review

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Summary: The comfort in wear of textiles has been studied extensively on the level of textile construction. The influence of the fibre material is present in the experience of textile consumers, but objective assessment is rather difficult. Some recent works are reviewed here. TENCEL® is a man-made cellulosic fibre of the generic fibre type lyocell. The background of the special comfort in wear of textiles made from TENCEL® fibres is explained as a consequence of the fibres' water-absorbing nanostructure. The basis for these properties are found in the high absorption of water and water vapour, which leads to high heat capacity and heat balancing effect for thermoregulation, comparable with the action of phase change materials. The thermal wear properties resulting are the cool and dry touch, the active cooling effect in sports wear, and the warming properties when used as an insulation layer. These effects are to a certain extent adaptive to the environment, providing comfort in a wide range of climatic conditions. Moreover, neutral electric properties, retarded bacterial growth and good skin sensory perception add to the overall skin friendly properties, which were also shown in wear studies with patients suffering from skin diseases.

Keywords: absorbent; cellulose; comfort in wear; skin sensory perception; thermoregulation

Introduction

During human history, the functions of textiles were for a long time a self-evident part of the cultural and technological development in textile making, side by side with fashion aspects. The necessity to keep the human body warm and dry has been the main purpose in cold climates. In warm climates, protection from heat and sun has been particularly important. For long historic periods, performance and comfort of textiles were based on the material properties and variety of the available natural fibres, which are all more or less hydrophilic and hygroscopic or water-absorbing. With the inventions of man-made fibres, new properties became feasible. One important difference in properties is that the man-made fibres from synthetic polymers are more or less hydrophobic, and not water-absorbing, hence their properties are not altered when fibres are wetted. In the first decades of man-made fibre use, the textile world was very simple when it came to the function of textiles: hydrophilic natural fibres like cotton and wool and the man-made cellulosic fibres stood for absorbency and breathability and the synthetic fibres stood for strength and easy care.

With increasing use of the term ''functional textile'', the situation has become more complex. The synthetic fibre industry has been developing new products and marketing approaches claiming enhanced ''physiological function in textiles'' for

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sportswear and other fields. Consumers have accepted these arguments and there is a general belief that synthetic fibres are the product of choice for active sportswear, even where the hydrophilic fibres may be superior.

Lenzing AG is a leading producer of three man-made cellulosic fibres types, viscose, modal, and lyocell under the brands of Lenzing Viscose®, Lenzing Modal®, and TENCEL®, respectively.[1,2] In order to redress the situation explained above, Lenzing AG decided that a deeper insight into the ''inherent physiological properties and functions'' of hydrophilic fibres was needed. A research program was started to look at the inherent properties of fibres using new methods and approaches. The objective is to produce the evidence needed to make customers aware of the excellent ''inherent functionality'' of cellulosic fibres and that in many cases there is no need to use highly sophisticated functional synthetic fibres and finishes to achieve a ''functional textile''.

There are two ways of developing the physiological functions of a textile product. Properties can be modified or enhanced by work on the fabric and textile construction level.[0] On the other hand, fibres can be used, which offer physiological functions on the fibre level; it is known qualitatively that the interaction between hydrophilic fibres and water can play an important role for the comfort of clothing.[4] The best products will result from a combination of the two approaches.

However, this paper does not consider specific textile product development possibilities; it presents statements of the ''inherent physiological fibre properties'' of hydrophilic fibres. For each physiological function that is described, evidence is presented.

Cellulose and Water – A Natural Couple Leading to Special Properties for Textile Fibres

To help understand the origins of the ''inherent physiological functions'' of textile fibres it can be postulated that:

1. When hygroscopic or hydrophilic fibres come into contact with water, they absorb it into the fibre structure.
2. A cellulosic fibre of a certain type will not handle/absorb water in the same way as another cellulosic fibre type; there are significant differences between different types of cellulosic fibres.
3. The combination of a cellulosic fibre material with water gives interesting inherent physiological functions on the fibre level.
4. The combination of TENCEL® with water gives enhanced physiological properties
5. Hydrophobic synthetic fibres do not absorb water into the fibre structure; they can only adsorb water onto the fibre surface.
6. Therefore the combination of synthetic fibres with water normally will not result in added physiological properties (or only to a very low extent).

To demonstrate visually the difference between cellulosic fibres and synthetic fibres, samples of fibre were placed in the specimen chamber of an environmental scanning electron microscope. The atmosphere surrounding the fibres was saturated with water.

Figure 1 shows the result.[5] The fibre on the left is polyester; the fibre on the right is a TENCEL® fibre. Water droplets have condensed on the surface of the polyester fibre. The TENCEL® fibre does not show any water on the surface. This is the major difference between synthetic fibres and cellulosic fibres. Synthetic fibres such as polyester are non-absorbing, non-hygroscopic and therefore not breathable on the fibre level (textile constructions from polyester fibres are breathable on a textile level, if they show sufficient air permeability). They will only adsorb water on the fibre surface. Cellulosic fibres like TENCEL® are hygroscopic, water absorbing and breathable on the fibre level. Water is absorbed into the fibre structure.

The ability to absorb water into the fibre structure is a common feature of all

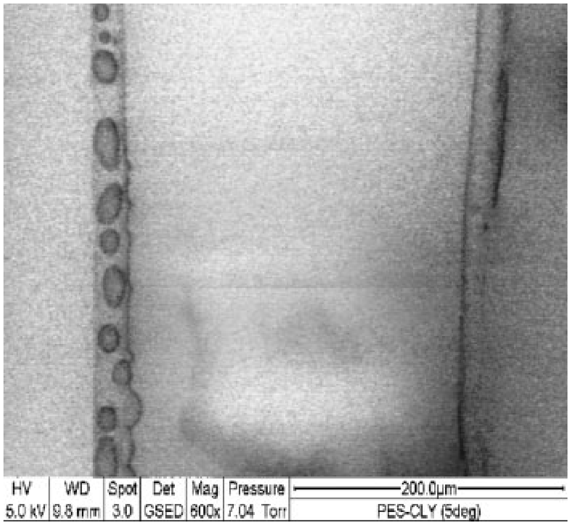


Figure 1.
A single fiber of polyester (8 dtex; left) and a single TENCEL® fibre (6.7 dtex; right) in saturated water vapour atmosphere in the environmental SEM. Bar, 200 μm. (image: Dr. Peter Pölt, from:[5]).

cellulosic fibres, is the prerequisite for the "natural intelligence" of natural cellulosic fibres, and forms the basis of some very important physiological properties in textile applications. All cellulosic fibres show the following eight physiological properties to a certain extent:

Absorbency for water vapour and liquid water
High heat capacity and heat buffering
Cool and dry to the touch
Active temperature reduction
Warm and dry as an insulation layer
Reduced static electricity
Retarded bacterial growth
Gentle to the skin

The inherent physiological properties depend on the amount of water, which is absorbed, and on the way it is distributed within the swollen fibre structure. TENCEL® has a very high absorption capability, a unique nano-fibril structure and a very smooth surface. As a result, all these physiological functions are much more pronounced for TENCEL® than for other cellulosic fibres.

Transmission electron microscopy can be used to show the location of water in a fibre. For imaging, water-containing pores are filled and stained with a contrasting substance. The water-containing pores show up black, but the cellulose without stain shows up white. Figure 2 shows the cross-sections of four types of cellulosic fibres[6] in the water swollen state.

Cotton absorbs much less water than TENCEL®, modal or viscose. The crystalline skin of modal contains less water than the core. The water distribution of TENCEL® is very uniform over the whole fibre cross section. Modal and viscose have a rather coarse pore system with a wide range of pore size distribution from nanometer to micrometer size dimensions. The voids in TENCEL® are very small and quite uniform, in the nanometer range.

Structure Model for TENCEL® Fibres: A Nanofibrillar – Nanoporous Structure

TENCEL® fibres are man-made cellulosic fibres produced by Lenzing AG, Austria, through a direct dissolution spinning process with regeneration from the organic solvent

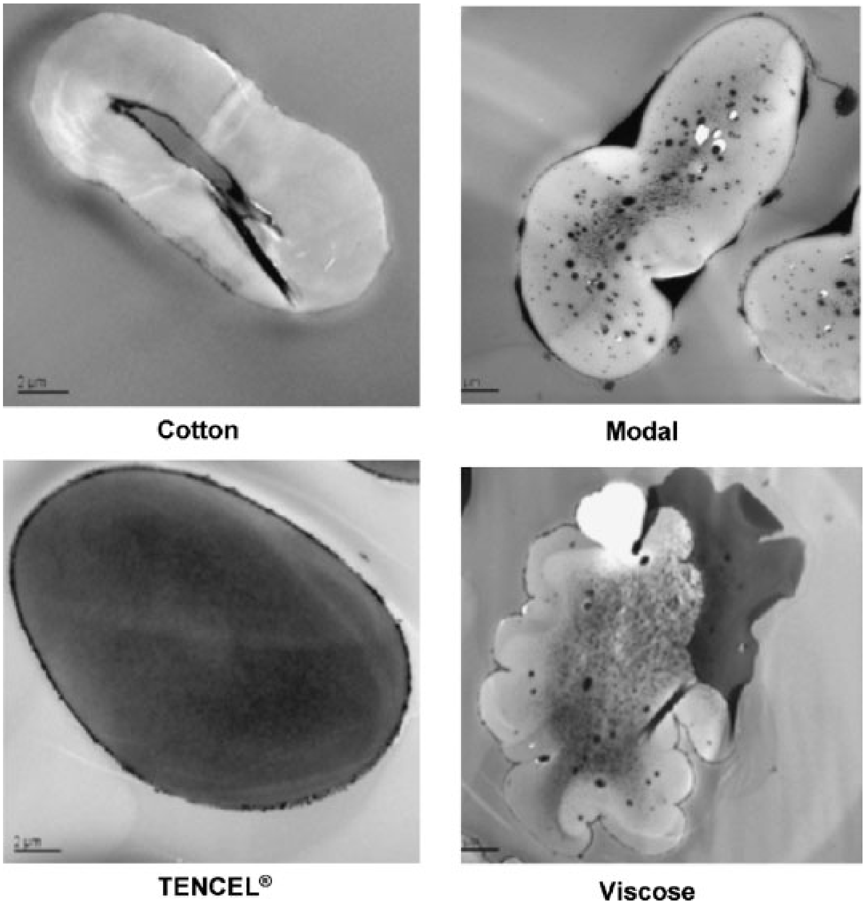


Figure 2.
Position of absorbed water in cellulosic fibres. Transmission electron micrographs. Water appears dark (electron-dense), cellulose bright. Bars, 2 μm. (from[6]).

N–Methylmorpholine–N–Oxide.[1,2] The generic fibre type name according to BISFA (Bureau International pour la Standardisation des Fibres Artificielles) is lyocell.

Fibres spun according to this process differ from other man-made cellulosic fibres primarily in their mechanical properties resulting from higher orientation and crystallinity. For a review of man-made fibre properties characterised by physical-chemical methods and with respect to textile dyeing and finishing see.[4] Recent approaches to visualise the fibre structure have shown a nano-fibrillar cellulose structure, which consists of countless, non–swelling, crystalline microfibres. The fibrils can be visualized in dry fibres by scanning electron microscopy of broken fibres (Figure 3, left inset).

The surface of TENCEL® fibres is very smooth, as the fibrils are covered by the fibre skin. Scanning electron micrographs do not show any distinct surface features. At the resolution of atomic force microscopy, only nanometer size roughness can be detected. In phase contrast mode, regular softer and harder structures in the shape and size of nano-fibrils at dimensions of ca. 20 nm width were detected.[7]

In high magnification transmission electron micrographs of wet, water–swollen fibres

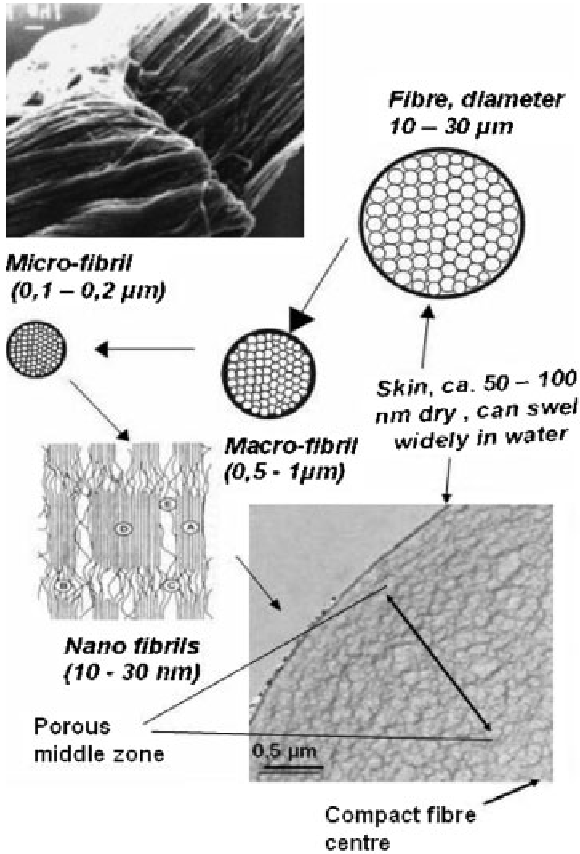


Figure 3.
Model of the TENCEL® fibre structure. Left Inset: Scanning electron micrograph of a broken dry fibre inside; bar, 1 μm; Right inset: TEM micrograph of a wet, water –swollen fibre (bar: 0.5 μm).[8]

(Figure 3, right inset) it can be seen clearly that the pore structure of TENCEL® is a true nano–structure. This is unique amongst all man–made cellulosic fibres. TENCEL® consists of countless, very hydrophilic, crystalline nano–fibrils, which are arranged in a very regular manner. In cross-sections of fibres prepared by filling the pores with polyisoprene as for the TEM images (Figure 3), repeat units of fibrils and pores in sizes of 20 to 60 nm could be seen.

The fibrils themselves do not absorb water; water absorption only takes place in the capillaries between the fibrils. A single TENCEL® fibre, therefore, will behave like an ideally wetting nano–multifilament, something which does not exist in the synthetic fibres world.[8,10] The pore structure is accessible to water vapour and liquid water; this is the background for the special water management and the good comfort in wear of textiles containing TENCEL®.[5] The pore structure is also accessible to larger dissolved molecules, like neutral molecular size probes in inverted size exclusion chromatography[4,11], salt ions[12], textile dyes[13] and fluorescent dyes[14], which is important in textile dyeing and finishing technology, and can be used for characterisation purposes. Although some viscose types have higher absorption of water, in a general trend the TENCEL® structure is more accessible to various molecules than other man-made and natural cellulosic fibres. (The correlations with water absorption parameters, especially when comparing charged and neutral molecules, are not always simple[14]).

The Properties of TENCEL® for Function and Comfort in Textiles

Absorbency of Water and Water Vapor

As shown above, due to its supramolecular structure, a single TENCEL® fibre will behave like an ideally wetting bundle of nano-fibrils with pores in nanometer range in between, something which does not exist in the synthetic fibre world. This is the reason for the water management properties, resulting in the special comfort in wear of textiles containing TENCEL®.[5]

Figure 4 shows the water vapour absorption isotherms of some fibres[15] at 20 °C. Polyester fibre absorbs only negligible amounts of water; cotton absorbs much more. TENCEL® and also Lenzing Modal® absorb up to 20% water at 90% relative humidity, which is approximately the same water vapour absorption capacity as wool or down.

Not just the quantities of water absorbed are interesting. The hysteresis between the adsorption and the desorption curve is an indicator for the structural changes when moisture is adsorbed or desorbed. These relative changes are much more pronounced in TENCEL® compared to cotton (Figure 5, from:[16]), indicating a generally higher response to environmental conditions and as such a higher adaptation to the climate in use and wear.

The **absorption** capacity and rate **of liquid water** absorbency is another important feature of textile fibres. Good water vapour absorbency does not necessarily mean also a high rate of liquid water absorption; the wicking properties of a fabric greatly influence the absorption rate.

One way to measure the absorbency of a fabric for liquid water is the ‘‘gravimetric absorbency testing system’’, the ‘‘GATS’’ test[17] (Figure 6). In this test, the sample is exposed to liquid water from below without any hydrostatic pressure. Therefore the sample will only take up water as it ‘‘demands’’ it. The test allows measurement of the total water absorption and the absorption rate.

Results with polyester and TENCEL® fabrics of comparable weight, which had been washed once before testing, have been reported previously. The TENCEL® jersey clearly outperformed the hydrophobic polyester (PES) fabric in absorption rate and the amount absorbed.[19]

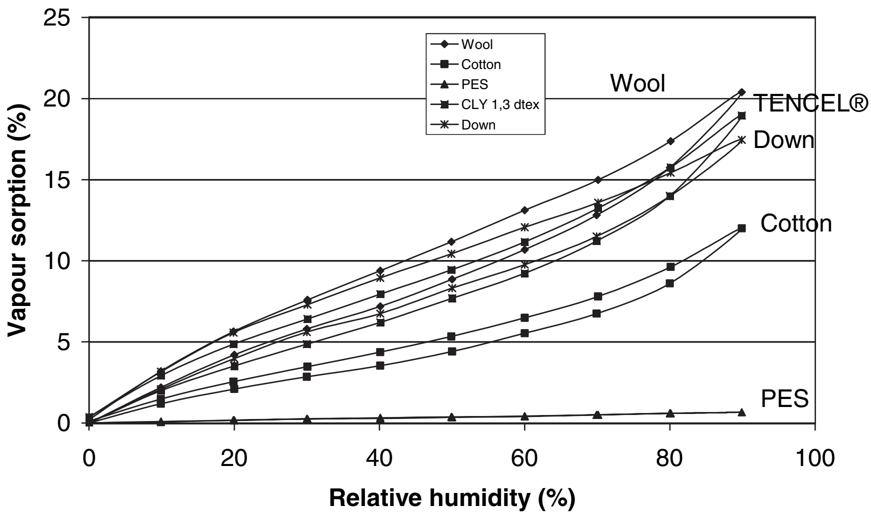


Figure 4.
Water vapour absorption isotherms of various textile fibres at 20 °C.

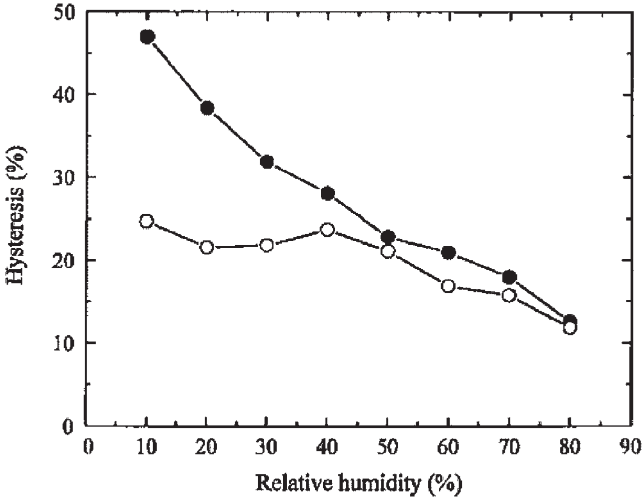


Figure 5.
Effects of relative humidity on hysteresis between sorption and desorption isotherms for TENCEL® (full dots ●) and cotton (empty circles ○). Relative differences in % of the sorption values are drawn (from:[16]).

For use in high performance sports wear, single jersey knitted fabrics from fibre blends of TENCEL® with polyester were prepared. Figure 7 shows the GATS test results. The 100% TENCEL® single jersey absorbs much more water than 100% Polyester (PES). TENCEL® / PES blended jerseys show a higher and faster demand

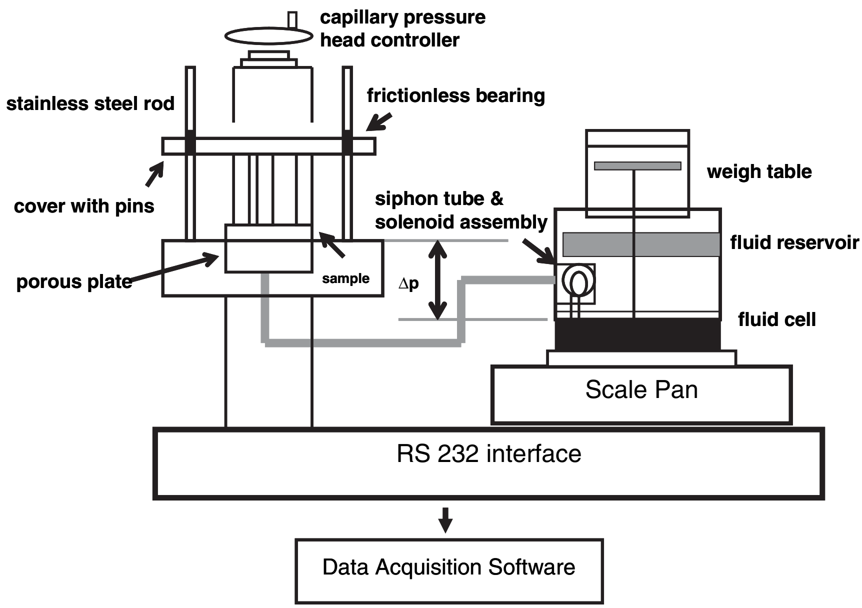


Figure 6.
Schematic drawing of the GATS (gravimetric absorbency testing) device (adapted from[18]).

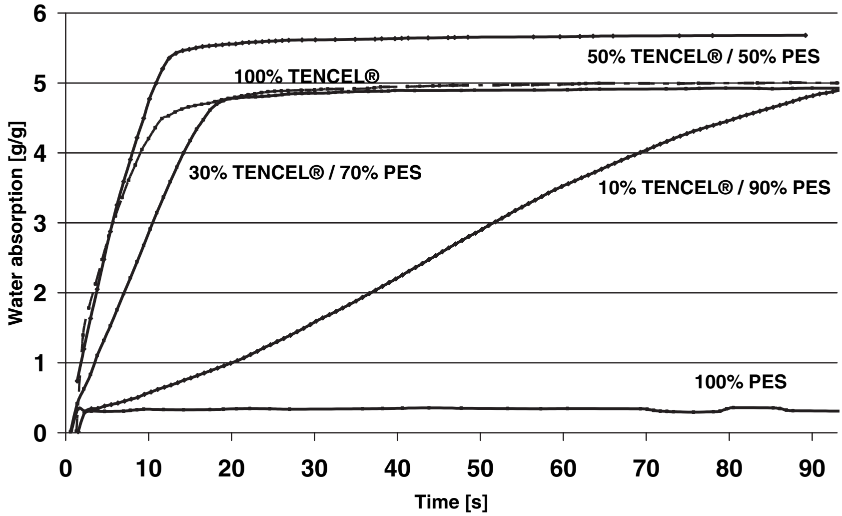


Figure 7.
Absorption of liquid water into fabrics. GATS test results on single jersey fabrics for sports wear applications. PES, polyester (from[20]).

wetability than 100% TENCEL®. The optimum absorption in quantity of water appears between 30% and 50% TENCEL®.

Heat Capacity for Thermoregulation

Due to the high heat capacity of water, it can be expected that fibres, which contain water will also have a high heat capacity. This can be an important factor to assist the human body's temperature regulation. Cellulosic fibres like TENCEL® will always contain water under practical use conditions.

Figure 8 shows a simple experiment to demonstrate the heat capacity of fibre fillings. A small sample of fibre fills with a defined water content sealed into plastic bags. The samples were placed in an oven at 50 °C until they had equilibrated. They were then taken out of the oven at the same time and the cooling rate was monitored with an infrared camera.

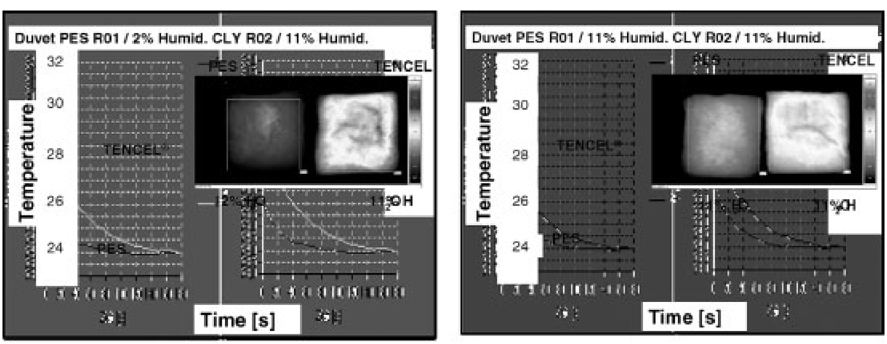


Figure 8.
Cooling of duvets. Duvet models were made by sealing fibres into plastic bags at different humidity conditions, then heated to 50 °C, then left at ambient to cool. The difference is shown by an infrared camera. Insets, IR camera views. Left, preparation under ambient conditions, so PES contained 2% humidity, TENCEL® contained 11%. Right, both fibre types set to 11% humidity.[5]

The first trial (Figure 8, left) used very realistic conditions with TENCEL® having a moisture content of 11% and polyester 2%. The brighter colours of the TENCEL® sample show that it is retaining heat much more effectively than the polyester sample.

In the second trial (Figure 8, right) both fibre fills had a water content of 11%, but still TENCEL® shows a higher heat capacity and slower cooling rate. The combination of water absorbed with the cellulose fibre structure of TENCEL® leads to a higher heat capacity than the liquid water, which is only adsorbed on the surface of the polyester fibres.

TENCEL® fibre fill in duvets, therefore, acts like a hot water bottle and has a high heat capacity. It can help to smooth out the temperature fluctuations in bed and supports more restful sleep.

Heat Buffering: Comparison with Phase Change Materials

The so called Phase Change Materials (PCMs) are latent energy storage materials. A thermal energy exchange with the environment occurs at practically isothermal conditions when a material changes its state of aggregation, e.g. from the solid to the liquid state, or from a liquid to a solid.

PCM's containing textiles are said to be more comfortable by balancing the microclimate temperature. They are expected to store excessive body heat and release the stored heat when the body cools down.

Following these requirements, TENCEL® would act as a PCM because of its water content. The heat capacity of the fibre is high and proportional to its humidity content. Additionally, dry TENCEL® fibres produce energy by absorbing water vapour due to the heat of sorption, delivering a warming effect, while humid TENCEL® fibres deliver a cooling effect by the desorption (evaporation) of water.

To quantify the temperature balancing effect, the total heat absorbed by textile materials was measured in a differential scanning calorimeter (DSC) by heating the materials from 18 to 35 °C. Before, the materials were equilibrated at 20 °C and 65% relative humidity. These conditions simulate the temperature range and humidity inside duvets found by an *in vivo* trial with test persons.[21] Figure 9 shows some preliminary results[22] of the comparison of the heat absorption of pure TENCEL® fibres with other commercial PCM- containing fill fibres, and a realistic blend on PCM material and polyester fibres as used

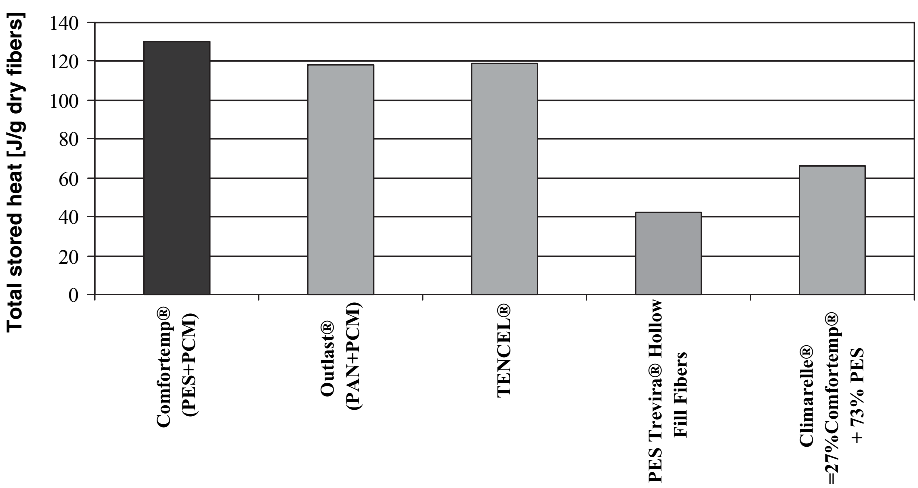


Figure 9.
A comparison of the total stored heat (J/g dry fibres) of TENCEL® with the same of different commercially available fill fibres containing PCM materials at 18–35 °C and 56% Humidity. The value for Climarelle® was calculated as a combination of PES and Comfortemp® in the practical ratio of 73% / 27%.[22]

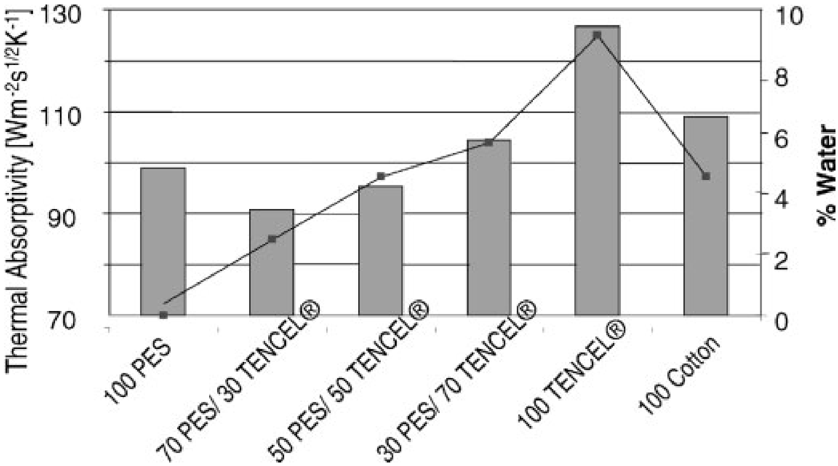


Figure 10.
Thermal absorptivity of knitted fabrics for sports wear applications, and moisture content at measurement conditions.

in duvets. The effect is the sum of the heat capacities of moist fibre and textile materials plus the heat of evaporation of water. It can be seen that a high amount of PCMs on textiles would be required to deliver a comparable warming/cooling effect like achieved by 100% TENCEL® fibres.

Note that these measurements are preliminary in quantification, as the heat flow due to the heat capacity of the polymers is near the limit of reliable quantification by the instrument used.

Cool and Dry Touch in Textiles

The thermal absorptivity of a fabric is a measure of the amount of heat conducted away from the surface of the fabric per unit time. A fabric, which does not conduct heat

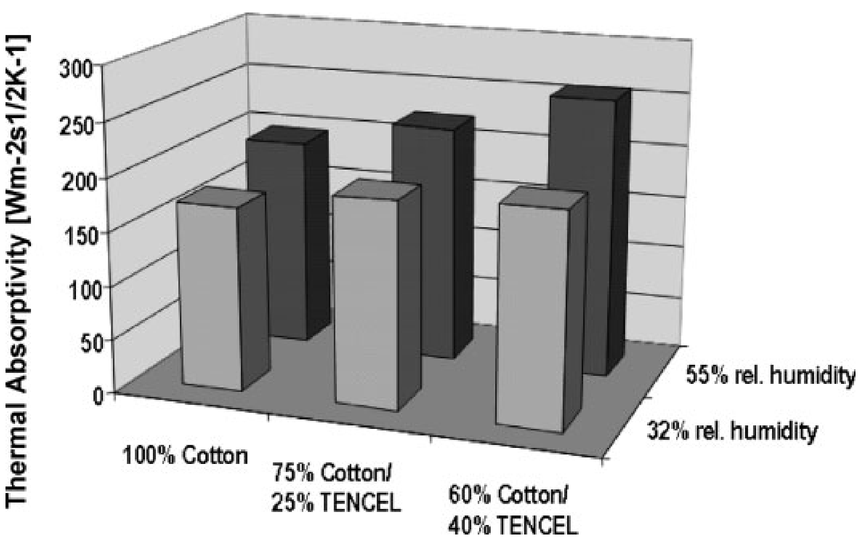


Figure 11.
Thermal absorptivity of shirt fabrics, TENCEL® / cotton blends.

away from its surface, will feel warm; one that does conduct heat away will feel cold.

The thermal absorptivity can be measured using the "Alambeta Test".[23] Figure 10 shows test results on single jersey knitted fabrics from fibre blends of TENCEL® with polyester prepared for use in high performance sports wear (same as in Figure 7). In the 100% fabrics, TENCEL® fabric shows the highest indicator of cool feeling, followed by cotton. The polyester blends increase in coolness with the TENCEL® content. Overall, there is a certain correlation between coolness and moisture content of the fabrics due to ambient air humidity.

Even in minority blends TENCEL® will enhance the "cool feeling" of textiles. Blends of 25% to 40% TENCEL® with cotton in a shirting fabric will give a cooler feeling compared to 100% cotton - especially at higher air humidity (Figure 11). It shows that TENCEL® feels cooler to the touch and that the "cool feeling" increases with increasing air humidity because the moisture content of the fibres increases. With TENCEL®, this behaviour is much more pronounced than with cotton as the increase in water content with increasing air humidity is much steeper for TENCEL® than for cotton.

This represents a self-regulating, adaptive system. In warm and humid ambient conditions, when cooling is needed, the cool feeling is increased.

Active Body Temperature Reduction in Sportswear

At very high physical activity levels or in very hot and humid climates, the temperature control of the human body mainly relies on the production and evaporation of sweat.[3,20] As the sweat evaporates it carries energy away from the body in the form of the latent heat of vaporization. To do this, the sweat must either evaporate from the skin and pass through the covering fabric as vapour or it must be transferred from the skin to the fabric and subsequently evaporate. If the sweat cannot be transported through the fabric, the cooling effect will be too low and the physical performance will drop accordingly.

The ideal "active cooling" textile, therefore, has to have good water transport properties, however, it should allow water evaporation next to the skin in order to achieve maximum cooling of the human body. (Many of today's high performance 2 layer sports shirts evaporate the moisture from the surface of the fabric, rather than next to the skin. This results in a pleasant dry feeling on the skin, but reduces the effect of body cooling.).

To investigate the differences of the active cooling properties of TENCEL® and polyester fibres, ergometer tests were performed on subjects wearing T-shirts consisting of 2 halves. The left half was polyester, the right half TENCEL® - both single jersey with the same construction. The test subjects performed a strenuous exercise with the power output increasing in stages to 250 W, which guaranteed full sweat production. There was a relaxation stage after the first half of the experiment duration.

The surface temperature of the two halves of the T-shirts was monitored with an infrared camera. In Figure 12, the surface temperature on the right side of the T-shirt – the TENCEL® fabric – is higher.

This demonstrates the better heat dissipation through the TENCEL® fabric during high sweat production. The temperature difference of 0.5 to 1 °C seems to be small, however, in physiological terms it is significant.

The effect increases in an adaptive way, whenever there is more need for cooling. The heat dissipation increases with sweat production, first due to increasing heat conductivity with the increasing moisture content in the fabric up to the saturation point, and then by the wide spreading of liquid sweat (Figure 7) especially in optimized blends with hydrophobic synthetic fibres. On the other hand, when warming properties are needed, the quick drying behaviour of textiles from hydrophilic/hydrophobic fibre blends of TENCEL®

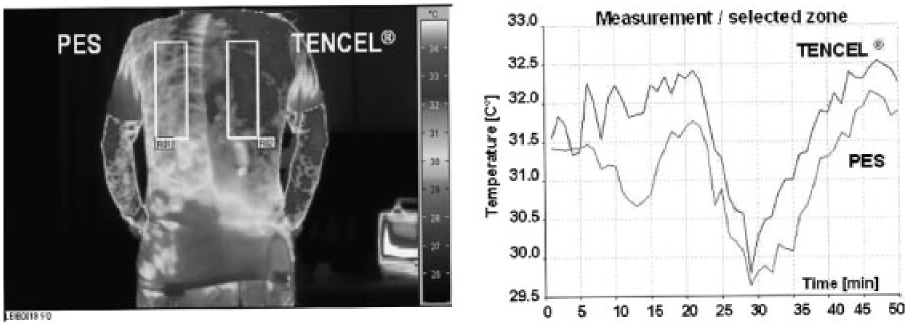


Figure 12.
Heat dissipation by a T-shirt in two halves during exercise. Left image, infrared camera view on the back of the test person. Left side, polyester. Right side, TENCEL®. The temperature measured on average over the boxes are 31.5 °C (left) and 32.3 °C (right). Right image, temperature course over the experiment.

and polyester ensures that the garment properties adapt quickly and return to a warming effect, especially when a double-layer construction is used. So, the body's temperature regulation is supported in an optimal way by the TENCEL® containing garment.

Warm and Dry as a Thermal Insulation Layer

TENCEL® FILL (a fibre specially designed for use as the filling in duvets) is used to make duvets with good thermal insulation combined with high water vapour transport, and high absorption of water[15], leading to a high overall comfort over a wide temperature range of cool and warm conditions compared to polyester fillings[15] and even compared to down fillings.[19,23]

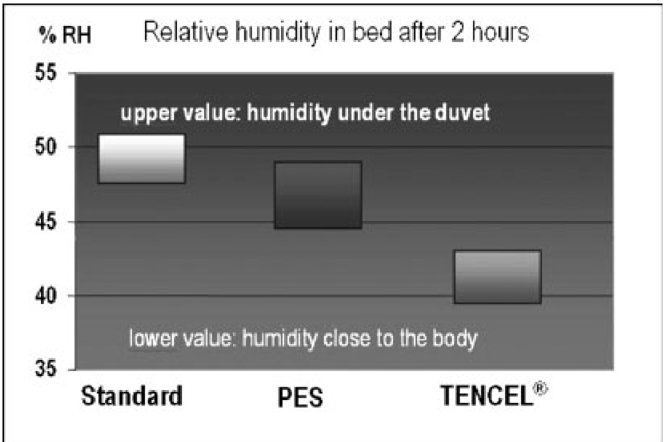
To compare the laboratory tests for bedding material with *in vivo* results, a study with test persons was reported by Helbig.[21] Briefly, a group of strongly sweating persons rested in beds with differing bedding materials. Three types of beds were used:

1) a "standard bed" with a mattress having a polyester fleece and a cotton cover. The bed linen was cotton, the duvet and pillow were polyester filled and had a cotton shell.
2) a "polyester bed" with all materials made from polyester and
3) a "TENCEL® bed" with all materials produced from TENCEL®.

The humidity and the temperature were measured in the middle of the duvet filling, under the duvet and close to the body. In Figure 13, the graph shows the humidity under the duvet and close to the body. The TENCEL® bed gave the lowest air humidity both under the duvet (the upper value of the bar) and close to the body (the lower value of the bar).

The insulation properties of TENCEL® fibres in waddings of outdoor jackets were tested under wear conditions. A volunteer cycled on an ergometer in a cooled climate room at −20 °C. The jacket she used contained an insulation fleece of TENCEL® / Polyester on the left side and polyester on the right side. The outside surface temperature on the back was measured by an infrared camera. The sides showed a temperature difference of around 1 °C. Figure 14 shows the situation after 15 minutes cycling.

Table 1 shows the textile data of the wadding fleeces and the textile physiological measurements taken by the sweating guarded hot plate instrument.[3] This instrument measures the thermal resistance, R_{ct}, , and the water vapour resistance, $R_{et.}$. The ratio, i_{mt}, is the water vapour permeability index. The higher the i_{mt}, the better the comfort in otherwise identical textiles. It can be seen by the infrared image and by the R_{ct}



	Standard	PES	TENCEL®
Mattress			
Fabric	Cotton	PES	CLY blend
Filling	PES	PES	CLY blend
Bed linen	Cotton	PES	µ CLY
Duvet /Pillow			
Filling	PES	PES	CLY Fill
Cover	Cotton	PES	µ CLY

Figure 13.
Humidity in bed after two hours experiment time, and composition of test beds.[21]

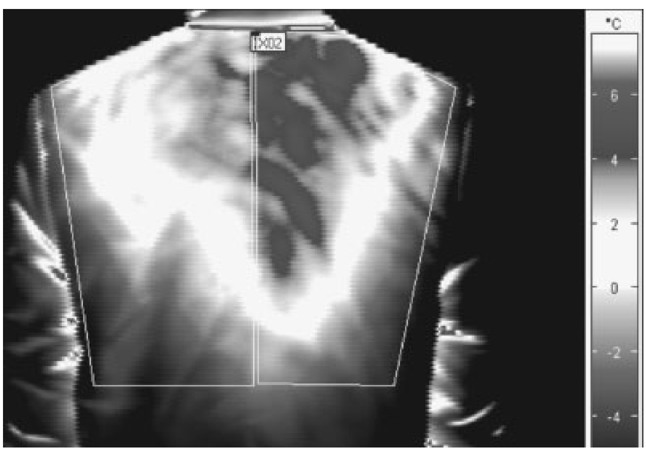


Figure 14.
Infrared image of the surface temperature of an outdoor jacket in wear trial at (minus)−20 °C ambient temperature. Left, TENCEL®/polyester wadding, 0.08 °C average in the marked box. Right, polyester wadding, 1.23 °C average in box.

Table 1.
Textile physical and physiological data of the waddings used. R_{ct}, thermal resistance; i_{mt}, water vapour permeability index.

Wadding	Area weight [g/m2]	Fleece thickness [cm]	R_{ct}	i_{mt}
100% PES	120	1.5	0.287	0.73
70% TENCEL®30% PES	120	1.7	0.430	0.68

-value that with basically the same textile properties, the fleece containing TENCEL® fibres shows better insulation. A temperature difference of more than 1 °C on the outside of the jacket will lead to a marked difference in heat loss.

The findings mean that for a certain target insulation property, the TENCEL® containing blend fleece can be made thinner, and will give better water vapour transport. This opens new design possibilities for warm jackets with good wear comfort and avoiding a bulky appearance.

Neutral Electric Properties – Reduced Static Electricity

Measurements have shown (Table 2) that even at a very low air humidity of 25%, the TENCEL® fabric has a surface resistance, which is three orders of magnitude lower than for the polyester fabric. At higher air humidity (65%), the surface resistance of the TENCEL® fabric is six orders of magnitude lower. A surface resistance of higher than 10^{10} Ohm will cause electrostatic charging when friction is applied to the fabric. A high level of electric charge on textiles can be very unpleasant when the static charge is suddenly discharged and can even cause the sparks. Figure 15 shows the effect of contact between the human body and fabrics when a person stood on an isolated rubber matt and pulled various textiles from his naked shoulders. Polyester and polypropylene cause very high charging of the body in this test (>2.5 kV) while TENCEL® and cotton gave a neutral result. Polyamide was much better than the other synthetic fibres, but still worse than the other cellulosic fibres. An electrostatic charge of more than 1800 Volts is felt.

According to newer findings, discomfort in charged textiles is not just caused by the well-known unpleasant sparks in sudden discharge. Sensitive individuals can feel a pronounced discomfort in charged textiles even without sparks occurring. As an objective measure, the assessment by electromyography has been established.

This method, developed by orthopaedics for the diagnosis of muscle coordination problems, can detect the excitation status of the muscles beneath the skin. In healthy individuals, at the resting state of the muscles sometimes extra potentials of muscle activity can be detected. This has been related to stress situations. It could be shown that textiles can cause such stress-related muscle tension signals.[25–27] When healthy individuals were wearing 100% polyester textiles leading to electric body charge, the spontaneous signals in rest were higher and more frequent than when wearing natural cellulosics (linen)

Table 2.
Electric contact resistance according to DIN 54345 for TENCEL® and polyester fabrics, at different humidity levels.

	Absolute humidity @ 22 °C/65% RH (as % water to 100 % fabric)	Electric contact resistance [RDT] Ω	
		23 °C/25% RH	22 °C/65% RH
TENCEL®	13%	4.5×10^{10}	6.8×10^{7}
Polyester	1%	5×10^{13}	5×10^{13}

Table 3.
Results of wearing trials with TENCEL® textiles, as compared to the patient's usual textiles as the reference.[15]

	Acceptance of TENCEL® Textiles compared to the patients' personally optimised textiles			
Patients with:	Total	Worse	Equal	Better
Atopic Dermatitis	14	0	2	12
Psoriasis	19	1	1	17

or man-made cellulosics (TENCEL®). Blends of polyester with linen or TENCEL® performed better than 100% polyester.

Retarded Bacterial Growth on Textiles

When clothing textiles are worn next to the skin, they are in permanent contact with skin flora bacteria. Under many circumstances, the skin flora bacteria are important symbionts on the human skin and pose neither an odour nor a health problem. However, excessive growth of skin flora bacteria on textiles can lead to odour formation and to discolouring of textiles.

Growth of bacteria on textiles can be simulated by various *in vitro* tests, e.g. the Japanese standard JIS 1902 L. Figure 16 illustrates the results of the bacteria growth in a laboratory test on samples of knitted fabrics from various fibres.

All cellulosic fibres perform well this test. The bacteria growth on synthetic fibres can be higher by some orders of magnitude. However, within the family of cellulosic fibres, TENCEL® fibres show ten times lower bacterial growth than cotton.

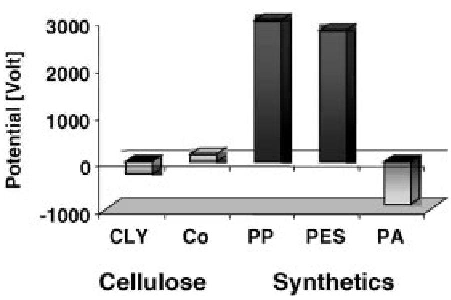


Figure 15.
Voltage generated by fabric rubbing against skin.[19]

The trend could be confirmed by *in vivo* tests performed as wear trials with left/right comparisons using divided T-shirts.[28,29]

Bacteria and fungi require liquid water for optimum growth. When a dry TENCEL® fabric absorbs 60% water, all the water will be absorbed into the fibre, which will cause swelling of the fibre. However, if synthetic fabric absorbs 60% water; all of this water will be located on the surface of the fibres as a water film and/or droplets on and between the fibres or fabrics. Thus explains why micro–organisms would be more likely to grow rapidly on moist synthetic fibre than on moist TENCEL® fibre.

Additionally, the smooth surface of TENCEL® as compared to cotton (Figure 17) may hamper biofilm formation.[19,28] So, the combination of the high water absorption of TENCEL® fibres with its smooth surface leads to retarded bacterial growth.

Skin Sensory Perception and Skin Friendly Properties

Fibres with poor water absorption capacity result in textiles, which cling to the skin when they are wet. Wet skin is much more sensitive to irritation than dry skin. The coarseness, the stiffness and the surface character of the fibres will also have an impact on the skin's sensory perception. Both cotton and wool have rather good water absorbency, however, they have a rather rough fibre surface (Figure 17), which can cause an irritation of the skin. Cotton fibres are not as rough as a wool, but

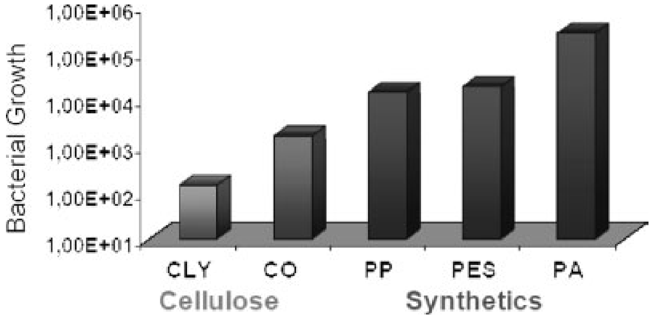


Figure 16.
Bacterial growth in 24 hours for knitted fabrics from various fibre types. Modified "Challenge test" similar to JIS 1902 L. Average of 3 assays each.[19] Growth is given as the multiplication factor relative to the initial number of bacteria.

still much rougher that the TENCEL® fibres.

TENCEL® combines good water absorbency with a smooth fibre surface, which makes it a fibre, which is very gentle to the skin. An objective measure for the friction between a textile and the skin is the wet cling index.[3] It was shown that TENCEL® shows a low wet cling index. Blends of polyester and TENCEL® in the same knitwear construction and varied fibre composition were improved by increasing share of TENCEL®.[20]

A clinically observed wear study on textile comfort was done with adult patients suffering from atopic dermatitis. Uncomfortable textiles are one of the important aggravating factors for these patients. Results of the examination of 33 patients at Heidelberg University Hospital show that TENCEL® textiles help nearly 90% of the patients to a great improvement of skin disease symptoms like itching.[31,32] Another study with children showed a similar trend.[30,31]

The outcome of this study is summary of the sensorial and thermoregulatory properties of TENCEL® textiles. Approximately 80% of the patients suffering from atopic dermatitis or psoriasis prefer TENCEL® products over their normally used textiles. As the main comfort factors, the thermoregulatory properties, the cool, smooth and dry feeling, and the overall excellent skin compatibility were noted by the patients.

Conclusion

The background of the special comfort in wear of textiles made from TENCEL® fibres is beginning to be explained as a consequence of the fibres' water-absorbing nanostructure. The basis for these properties are found in the high absorption of

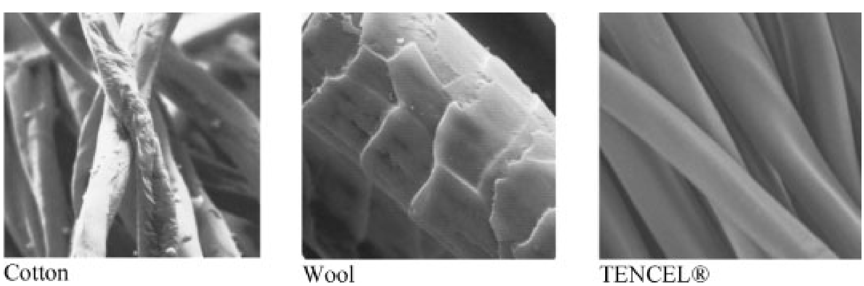


Figure 17.
SEM micrographs showing fibre surfaces: left – cotton, middle – wool, right – TENCEL®.[5]

water and water vapour, which leads to high heat capacity and heat balancing effect for thermoregulation, comparable with the action of phase change materials. The thermal wear properties resulting are the cool and dry touch, the active cooling effect in sports wear, and the warming properties when used as an insulation layer. Moreover, neutral electric properties, retarded bacterial growth and good skin sensory perception add to the overall skin friendly properties, which were also shown in wear studies with patients suffering from skin diseases.

More effects of textiles on human physiology are currently under investigation applying modern (bio-) medical approaches.

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