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The role of the enhanced moisture absorption of regenerated cellulose fibers (MMCF) in textile comfort and the thermoregulation of the body

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Abstract

The role of cellulosic fiber (TENCEL™ lyocell and modal) content in fabrics is to improve thermo-physiological and sensorial comfort attributes in apparel and bedding applications. This paper presents some important studies investigating moisture management and the surface properties of TENCEL™ and its role in supporting body cooling mechanism.

Introduction

Comfort is one of the main functions of clothing, since humans began to cover their bodies. Humans optimized their clothing throughout times according to functional and climatic needs and the availability of the materials, whereas protein-based fibers like wool and silk and cellulosic fibers like cotton, linen and flax were widely used to make fabrics. The mainly used natural fibers have in common the ability to absorb water, in vapor and in liquid form.

Thermo-physiological comfort is the result of the interrelationship between fiber material, yarn structure, fabric structure, transmission characteristics (air, heat and moisture) and tactile aspects of textile materials on thermo-physiological and neurophysiological processes [1].

Thermo-physiological and sensorial comfort are especially essential requirements for fabrics used in contact with skin, as it is essential for the body cooling mechanism to remove moisture generated on the skin by perspiration. Under “comfort condition” (before the body comes to a sensation of sweating caused by liquid sweat on the skin surface), vapor uptake is a key performance factor of fabric, while liquid uptake, transportation and evaporation are the mechanism required for performance textiles involved in more intensive activity, leading to liquid sweat on the skin surface. At higher physical effort, or in hot and humid climates, the temperature control of the human body mainly relies on the production and evaporation of sweat, whereas the water evaporation carries heat away from the skin.[2-8] This requires either evaporation on the skin and a transportation of the vapor through the covering fabric. Excess liquid must be transferred away from the skin to the fabric, where it should evaporate. If the sweat cannot be transported through the fabric, the cooling effect will be too low, the body temperature would raise and hence the physical performance drop [9].

The regenerated cellulose fibers lyocell and modal, like cotton, take up moisture from the ambient air, but in higher quantity than cotton. [10]. Moisture absorption has also an effect on the sensorial perception of the surface. Hygroscopic materials are known to provide a cool touch [11], and even on non-absorbing fabrics, the moisture content can influence the cool/warm perception [12].

An important thermo-physiological term is the “breathability index”, meaning the ratio between the thermal insulation and the vapor permeability. While the required thermal insulation depends on the ambient conditions and the level of body activity, a high vapor permeability always desired, as the removal of moisture is essential for the skin function in body cooling. Both parameters are often assessed by the hotplate test. However, a hotplate measurement is performed under equilibrated conditions, with constant climate and after the device has reached the steady state. This does not yield information related to transient conditions, meaning fast changes in temperature and moisture development between skin and textile, especially when hygroscopic fibers are involved [13,14]. Under transient conditions (for example sleep, change of physical surrounding temperature, change of activity mode), studies recommended considering moisture buffering function as an additional comfort characteristic [15-17].

This paper presents demonstrative examples from earlier works, showing the contribution of moisture absorption of lyocell and modal fibers to wear comfort in different textile applications, in single materials and in blends with synthetic fibers.

Regenerated cellulose fibers – enhanced moisture absorption

TENCEL™ fibers regenerated cellulose fibers (also called man-made cellulosic fibers, MMCF) are produced by dissolving cellulose pulp (originating from wood, recycled cotton or other sources) and re-shaping (spinning) it into fibers. While the modal process is based on transforming the cellulose into soluble cellulose-xanthogenate and regenerating it to cellulose after the fiber spinning, the lyocell process dissolves the fiber directly in N–Methylmorpholine–N–Oxide (NMMO) and the solvent is removed after the fiber spinning. Regenerated cellulose fibers lyocell and modal, like cotton, take up moisture from the ambient air, but in higher quantity than cotton have the same chemical composition as cotton: cellulose. They only differ in fiber structure which depends on the process applied to dissolve and regenerate the cellulose. In their detailed work on the properties of regenerated cellulose fibers, Bredereck et al showed also the vapor absorption and the water retention of the main types in comparison to cotton(Table 1) [10].

Table 1: moisure absorption of cellulosic fibers

	Moisture Regain (%)	Water Retention (%)	Volume Swelling
Lyocell	11.9	65-70	67
Modal	13	50-53	63
Viscose	14.1	70-80	88
Cotton	7.1	45	35

The reason for these differences in the water absorption is the structural differences among the fibers, whereas the water is absorbed in the accessible amorphous zones inside the fiber. The study of Abu-Rous et al. (2006) visualized the water distribution within the fiber cross-section [18].

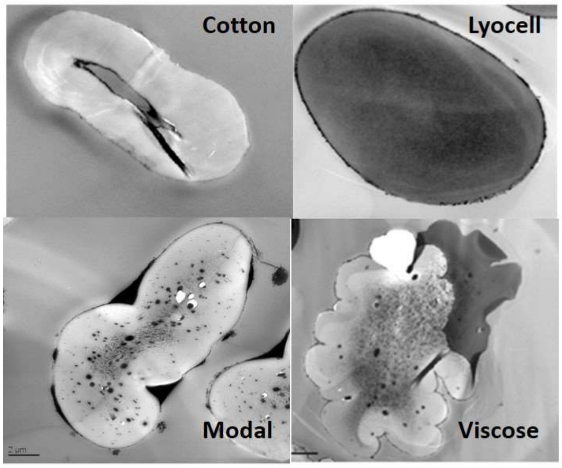


Figure 1: Transmission electron microscopy (TEM) of cross-sections of cotton, lyocell, viscose and modal fibers, showing the water (black) distribution inside the fiber.

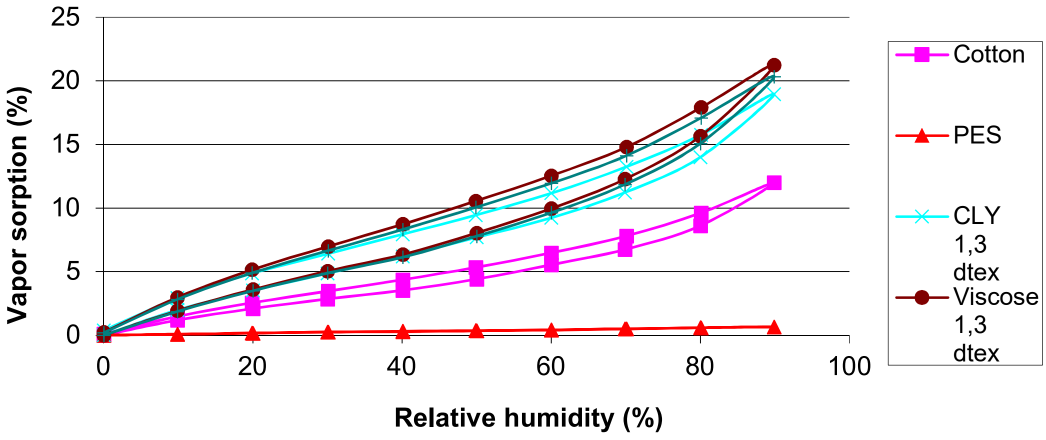


Figure 2: Moisture sorption isotherms of cellulosic fibers under absorption and desorption by varying the relative humidity at 20°C

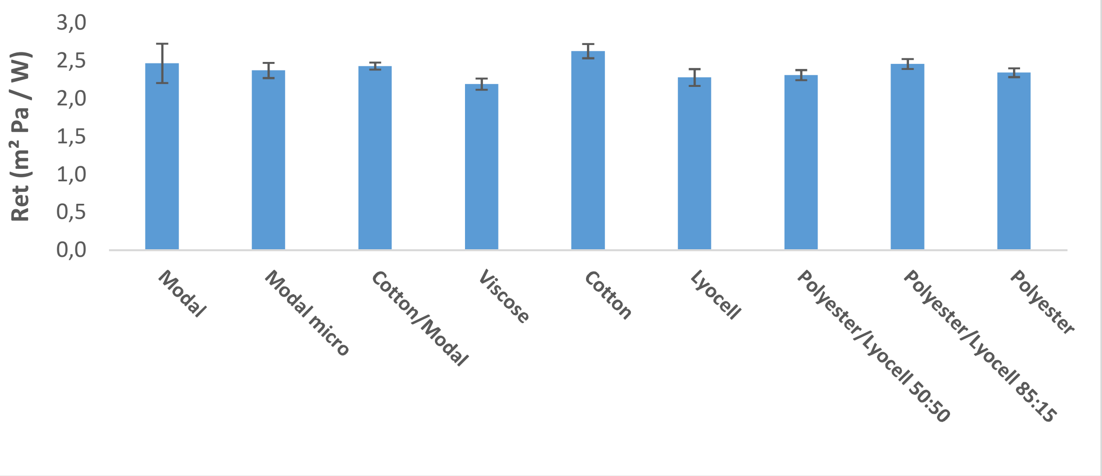


Figure 3: Evaporative resistance (Ret) of single jersey knits made of different fiber materials

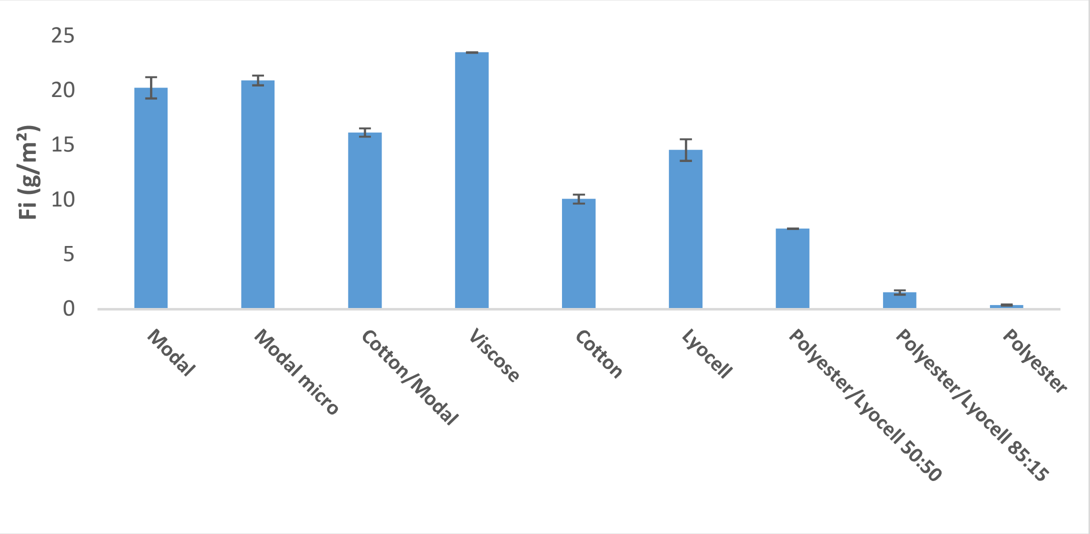


Figure 4: Moisture buffering (vapor uptake) of single jersey knits made of different fiber materials

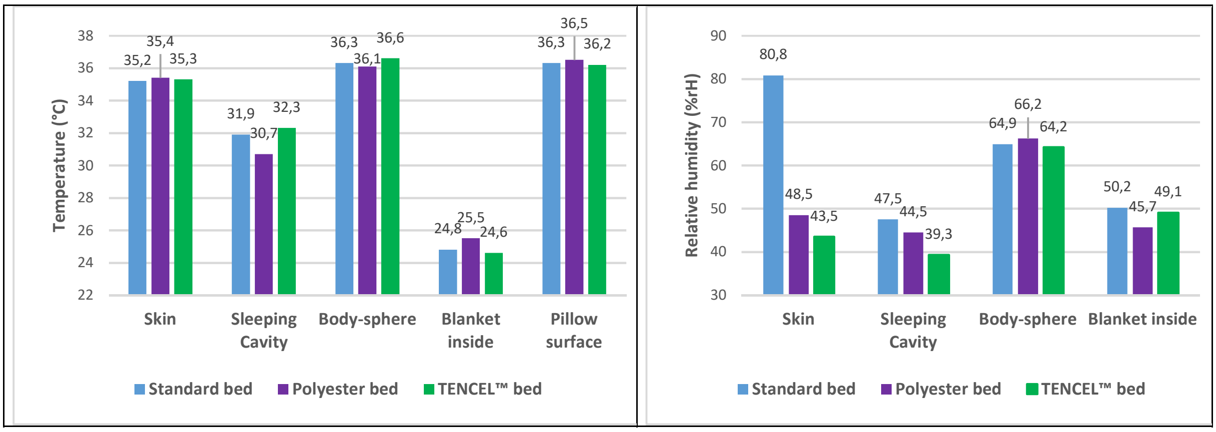


Figure 5: Average values of bed microclimate as assessed by Helbig et al.

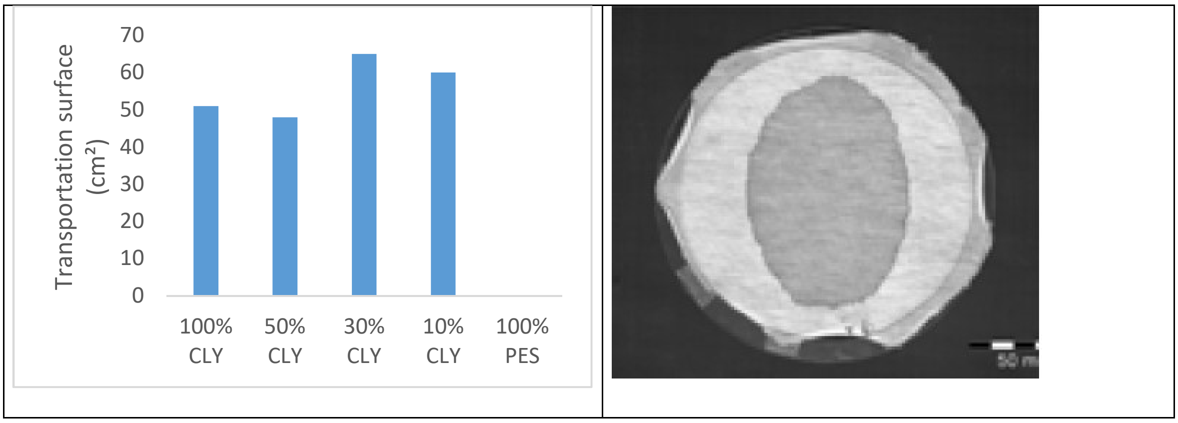


Figure 6: water transportation rate in lyocell (CLY) and regular polyester (PES) single jersey knits

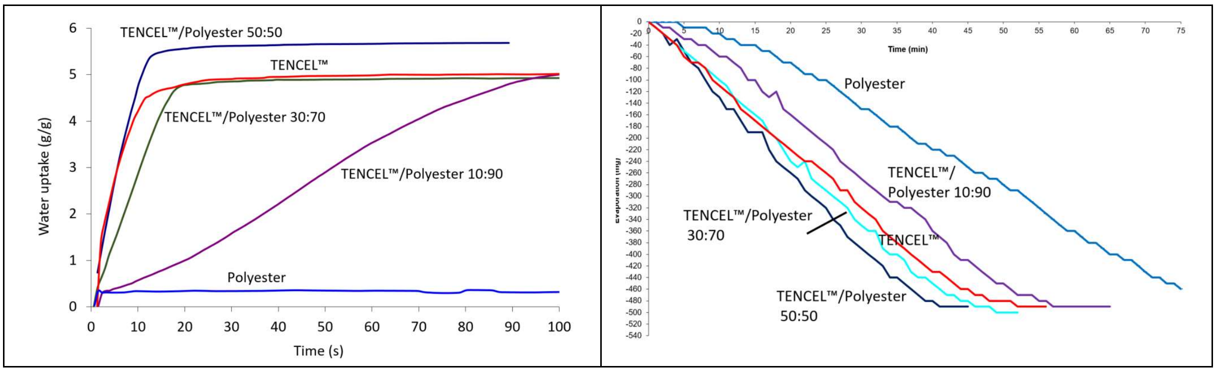


Figure 7: GATS demand wettability test (left) and drying rate (right) of fabric single jersey knits made of lyocell, polyester and their blends

Table 2: Energetic cost of done physical work and time of restitution for volunteers worn the sportswear

average energetic cost (kcal)	Without garment	TENCEL™/Polyester	TENCEL™	Polyester
Physical effort (10min)	129.87	126.06	128.40	130.64
Restitution (5min)	14.85	14.28	15.37	16.14
Physical effort + restitution	145.02	140.34	143.87	146.81

Vapor sorption isotherm

Vapor sorption isotherms of lyocell fiber in comparison to cotton was assessed by Okubayashi et al [19], and the same method was applied by Varga et al to assess the vapor sorption of other regenerated cellulose fibers. [20].

The moisture absorption was measured gravimetrically using a multi-sample moisture sorption analyzer SPS 11 (Project–Messtechnik, D–Ulm), where the atmosphere was conditioned at 25± 0.1 °C changed in 10% intervals from RH 0 to 90% (± max.1%) and back, and the mass change registered at equilibrium condition. The resulting hysteresis is shown in Figure 2.

Fabric „breathability" and vapor uptake

An important measure for fabric breathability is the hotplate test according to ISO 110921 [21], where the fabric breathability is given as the relation between the thermal resistance (R_{ct}) and the vapor transfer resistance (R_{et}). As the measurement takes place under steady-state condition, the result depends mostly rather on the fabric thickness and its permeability than on the fiber type. An example is shown in Figure *3* with the results of single jersey ~ 120 g/m² fabrics knitted with the same knitting parameters from Nm50 ring yarns of different fiber content. The results show that R_{et} values of all fabrics are close lay within the range of "very breathable" (R_{et}<6) as defined by Hohenstein Institute [17].

Fabrics containing absorbing fibers show slightly higher vapor transfer resistance, as the test typically does not consider the amount of vapor absorbed inside the fabric.

Figure 4 shows the moisture buffering capacity (Fi), which describes the vapor uptake (absorption) inside the fabric. It is obtained from the weight difference of the fabrics before and after R_{et} measurement. Other than the evaporative resistance measurement, Fi considers the vapor removal of the moisture from the sweating surface by the absorption in fabric, which already takes place in the transient condition from the first development of moisture and before the steady condition is reached.

Vapor uptake is under non-sport conditions and the absence of sensation of sweating a decisive parameter for thermo-physiological comfort, as discomfort and body heating appear in times shorter than the time needed for the steady state.

An example of the relevance of vapor uptake under comfort condition is sleep/bedding application, where thermal insulation is accompanied by body temperature change during the night sleep, resulting in a high moisture level inside the bed cavity. The bedding materials need to react quickly to humidity development to ensure more comfortable sleep. A study by Helbig et al [22], showed the effect of the bedding material compositions on the microclimatic conditions. Temperature and humidity were measured between the laying test person and the surrounding (pillow, cover) over the span of 120 minutes, comparing a standard (cotton bed linen, polyester filling, polyester shell fabrics), and TENCEL™ lyocell bedding sets (TENCEL™ bed linen, TENCEL™ shell fabrics, TENCEL™ fillings). The results showed that under comparable temperature in all the measurement zones the measured humidity values were the lowest in the TENCEL™ bedding system, especially in the body near measurement positions (Figure 5).

A further study of the physical and microclimate properties of pillows by Cafuta et al. used a thermal sweating manikin in simulated sleeping conditions and compared pillow fillings made of polyester, down and a polyester/lyocell 70:30 and 50:50 blend. Although using an – absorbing – cotton/lyocell shell fabric in all pillows, the study showed that enhancing the moisture uptake by the lyocell fiber content in the carded filling did not only reduce the evaporative resistance of the shell fabric, but also measured a temperature reduction of at least one degree Celsius under the sweating head [23].

At more intensive body activity such as sport or hard work, the body begins to sweat and the transportation of the liquid away from the skin becomes more relevant to support the body cooling mechanism.

Drying rate

The drying rate of a fabric surface depends on the ability of the fabric to spread the liquid to obtain a larger evaporation surface. In their study on the performance of TENCEL™ lyocell in sportswear, Firgo et al [4] showed a synergy effect with lyocell added as a minority blending partner to polyester in sport-shirts. The presence of a hydrophilic component in the fabric seemed to accelerate the liquid transportation in the fabrics. The spreading speed and area were measured with a GATS [24] apparatus equipped with camera (Figure 6).

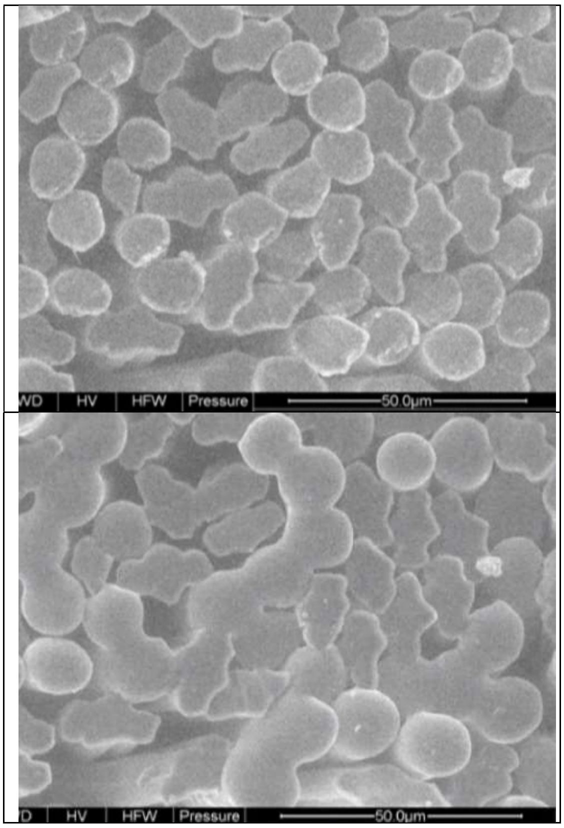


Figure 8: Environmental scanning electron microscopy (ESEM) imaging of a cross-section of a lyocell (round) and polyester (star shape) blended yarn in in dry (top) and wet (bottom) condition [source: Lenzing AG]

The drying speed was measured by placing the fabric on a scale connected to PC for digital weight registration. 500 mg deionized water were dropped on the fabric surface and the weight loss by evaporation was measured every minute. The relation between the water uptake and the evaporation speed Figure 7.

This synergy effect can be explained by the absorbing force of cellulose and the polyester fiber acting as spacer between the swelling cellulosic fibers and keeping the capillary transportation channels open. This phenomenon was visualized in the works of Ksenija Varga [20] with environmental scanning electron microscopy (ESEM) imaging of the swelling, as shown in Figure 8.

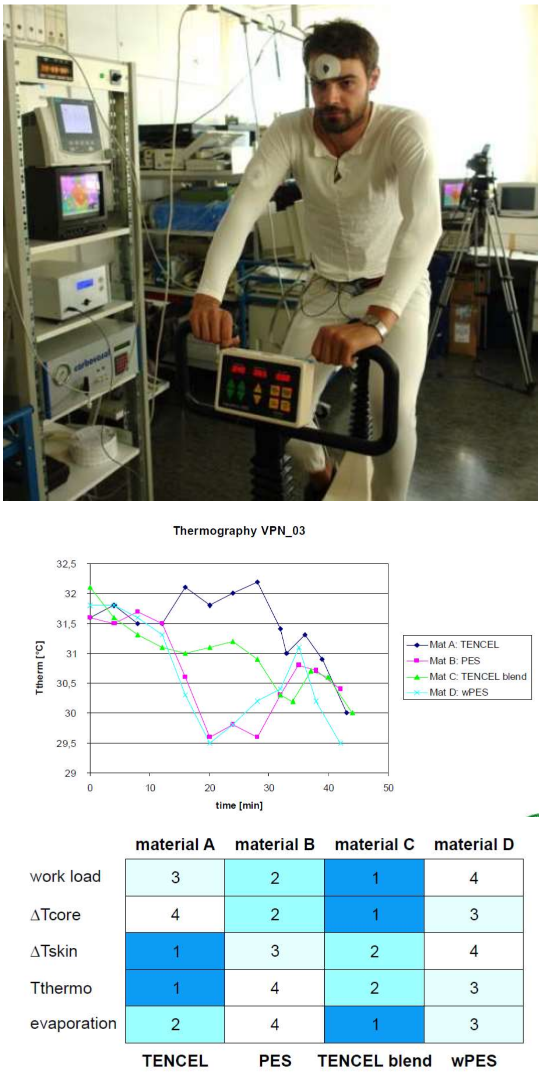
Moisture absorption, temperature reduction and body performance

The cooling effect of TENCEL™ in comparison to polyester was investigated by Schuster et al [8]. The study used an ergometer test, performed by subjects wearing T-shirts consisting of 2 halves. The left half was polyester, the right half TENCEL™, both made of single jersey fabric with same construction.

The test persons 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. Figure 9 shows the surface temperature on the T-shirt surface, resulting from the heat dissipation through during high sweat production. The TENCEL™ side shows a higher temperature difference of 0.5 to 1.8°C seems to be small, however, in physiological terms it is significant.

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 and evaporation of the sweat.



	material A	material B	material C	material D
work load	3	2	1	4
ΔTcore	4	2	1	3
ΔTskin	1	3	2	4
Tthermo	1	4	2	3
evaporation	2	4	1	3
	TENCEL	PES	TENCEL blend	wPES

Figure 9: experimental setting (top), thermographic monitoring (middle) and the ranking (bottom) of the mean results in Pessenhofer et al. [25] on the relation between textile and body performance parameters under physical work conditions

A similar outcome regarding the influence of fiber type and moisture transfer on body temperature was observed on the study of Pessenhofer et al., which also included a thermographic assessment of surface temperature (figure 9). The study also investigated the energy metabolism and heat balance during sportive performance [25]. The study also provides an aggregated assessment of various physiological parameters such as lactate concentration in the muscles, the heart rate, core and skin temperature, The trials resulted in the best ranking for the lyocell/polyester blend by the final sportive performance indicators, which were caused by the underlying better physiological state of the test persons, and correlating with the textile characteristics like the optimum of moisture storage and sweat spreading.

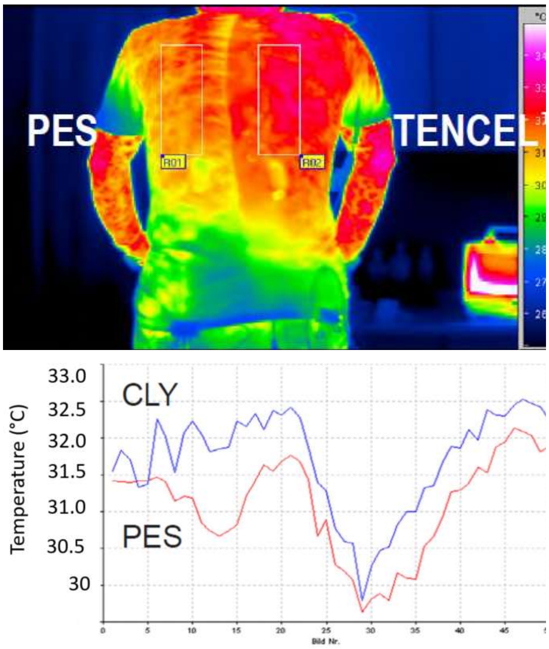


Figure 10: Heat dissipation by a T-shirt in two halves during exercise. Top image, infrared camera view on the back of the test person. The temperature measured on average over the boxes are 31.5°C on the polyester half (top) and 23.3°C on the TENCEL™ half (bottom). Image below shows the temperature course over the experiment

Similar results were obtained by the study of Zimniewska et al. [26] on the influence of the fiber material (100% polyester, 100% TENCEL™ and a 50:50 TENCEL™/polyester blend) in sportswear on the physiological parameters and energy consumption. The study included ten masculine test persons, who performed physical exercise (run with speed 8 - 12 km/h with using treadmill) for ten minutes under standardized conditions. Runs took place on four subsequent days in the order undressed, polyester/TENCEL™, polyester, TENCEL™. Physiological parameters as well as parameters of respiratory and circulatory systems were measured for the estimation of energetic cost of physical effort.

The moisture-related fabric properties of the TENCEL™/polyester blend seem to have a significant effect on microclimate in skin-clothes area. Although the changes in microclimate between skin and fabric were the same for all fiber types during the stimulus of physical effort, the results (table 2) show the TENCEL™/polyester blended fabric differs significantly from the 100% fabrics in terms of energetic cost of physical work, having a favorable effect, also on the time of restitution of volunteers and their endurance and efficiency. The 100 % TENCEL™ fabric was second best.

Another study on the influence of clothing on muscle activity came to a similar conclusion by applying electromyography to measure muscle tension of test persons during 5 hours moderate activity, wearing garments with similar fiber compositions as mentioned above (TENCEL™, polyester and their 30:70% blend). The findings showed that daily cloth might negatively influence the electromyographic records of muscle tension in the case of synthetic fiber (polyester), as these fabrics show a higher electrostatic charge. This phenomenon was not observed in the case of TENCEL™ fabric. The reason is the fact, that sweating increase and electrostatic charges accumulation do not occur in clothing made thereof (27).

Conclusions

The summary showed the effect of the moisture management of TENCEL™ fibers on comfort and performance under different conditions as emphasized in published studies on fiber and fabric moisture management performance and on studies on human-textile interactions. Removing moisture away from skin surface is essential for body thermal regulation under comfort as well as under high-activity conditions. Regenerated cellulose fibers, of which modal and lyocell (TENCEL™) are most relevant for consumer textile application, show higher moisture vapor absorption capacity than cotton, which makes them effective in managing moisture development in the skin. This results in dry feeling and enhanced comfort under normal conditions. Regenerated cellulose fibers show also a higher water absorption capacity than cotton. This property relevant under sport and physical work condition. The presented studies show how the water binding by the textile contributes to supporting the body cooling during the exercise and hence the muscle performance. In such cases, a blend of hydrophilic cellulosic fibers with non-swelling synthetic fibers would provide optimal construction for the versatile application fields and the requirements therein.

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