Monika Bogusławska – Bączek[1], Lubos Hes[2]
[1]Katowice School of Technology, Faculty of Architecture, Civil Engineering and Applied Art, Department of Design, 43 Rolna Street, 40-555 Katowice, Poland
[2]University of Liberec, Faculty of Textile Engineering, Department of Textile Evaluation, Studentská 1402/2, 461 17 Liberec 1, Czech Republic

Thermophysiological Properties of Dry and Wet Functional Sportswear Made of Synthetic Fibres

Toplotne lastnosti suhih in mokrih funkcionalnih športnih oblačil iz sintetičnih vlaken

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Abstract

In recent times, knitted fabrics made from synthetic fibres are being used increasingly for sportswear. This type of clothing should ensure thermal comfort in all weather conditions, regardless of the activity of the wearer. The most important thermal properties include thermal conductivity and resistance, as well as water vapour permeability. Sportswear often becomes wet (from sweat or due to a humid environment), which can have a significant effect on thermal properties, while most testing methods only perform measurements in a dry state. This paper therefore presents our study of the thermal properties of different types of knitted fabrics in both dry and wet states. The presented research proved that wet knitwear results in a significant loss of thermal comfort. This phenomenon is exacerbated when the moisture content of a material increases, and depends on the structure and filling of tested materials.
Keywords: thermal comfort, knitted sportswear, Alambeta, Permetest, relative water vapour permeability

Izvleček

V zadnjem času se za športna oblačila čedalje več uporabljajo pletiva iz sintetičnih vlaken. Športna oblačila morajo zagotavljati toplotno udobje v vseh vremenskih razmerah ne glede na aktivnost uporabnika. Med toplotnimi lastnostmi so najpomembnejše toplotna prevodnost in toplotna upornost ter prepustnost vodne pare. Čeprav športna oblačila pogosto postanejo mokra (znoj, vlažno okolje), kar lahko bistveno vpliva na njihove toplotne lastnosti, pa večina metod predvideva njihovo preizkušanje le v suhem stanju. Zato je v članku predstavljena raziskava toplotnih lastnosti različnih vrst pletiv v suhem in mokrem stanju, s katerimi je bilo potrjeno, da se mokrim pleteninam močno poslabšajo toplote lastnosti. Poslabšanje toplotnih lastnosti je povezano z večanjem vsebnosti vlage v materialu in je odvisno od strukture in polnil preskušenih materialov.
Ključne besede: toplotno udobje, pletena športna oblačila, Alambeta, Permetest, relativna prepustnost vodne pare

1 Introduction

Sportswear comprises special garments intended for the practice of a variety of sports, for ensuring appropriate sports movements and for providing an adequate thermal microclimate. It affects the ability to practice a particular sport and the quality thereof. It is meant to provide athletes comfort of use and to facilitate improvements in their sporting activities. Because of the multitude of sports and the specific nature thereof, the assortment of sportswear is very broad and diversified to meet the expectations

Correspondent author/*Korespondenčni avtor:*
Prof. Lubos Hes, PhD, DSc, Dhc, FTI (hon)
E-mail: lubos.hes@gmail.com

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of all athletes. Comfort in the use of clothing is directly related to the body's thermal comfort. Thermal comfort shapes the conditions in which a person lives, the type of activity in which they participate, and the type and characteristics of clothing. The amount of energy (heat) produced varies and depends on the activity of a person. It can vary from 45 Wm^{-2} at rest in a lying position to over 200 Wm^{-2} walking at a speed of 5 kmh^{-1}. In addition to producing heat, athletes produce a significant amount of sweat, which can reach as high as 2 lh^{-1} during extreme labour [1]. This is why thermal and water vapour resistance, and thermal contact are so important in the case of modern sportswear. These properties are most frequently studied in dry conditions and thus do not exhibit major differences. The advantages of functional, modern sportswear made from high-tech synthetic fibres over traditional sportswear made from cotton fibres arise when sportswear is used under real wearing conditions involving the presence of sweat. The parameters of good comfort near the skin can then be unbalanced and the well-being of the wearer may be lost. Comfort is defined as "the absence of displeasure or discomfort" or "a neutral state compared to the more active state of pleasure" [1]. There is general agreement that the transfer of heat, moisture and air through a fabric are the major factors of thermal comfort. Many authors have pointed out that the major factors affecting heat transfer through a fabric are thickness and entrapped air [2–5]. Contrary to a commonly accepted theories, garments are often used in a wet state due to sweat sorption or because of a humid, rainy climate, which affects their comfort properties [6–9]. In the case of sportswear, this is a very important issue, as it not only results in poorer sports results, but it can also cause health problems in athletes and, in extreme cases, break or end of their career or even result in death.

The objective of this study was to determine the above-mentioned thermal comfort properties of selected knitted fabrics intended for sportswear, both in a dry state and under simulated real conditions of use, as provided for by the application of the so-called sweat impulse. Measurements of thermal insulation, thermal contact properties and water vapour permeability were made using fast-working Alambeta and Permetest testing instruments (manufactured by SENSORA, Czech Republic).

2 Theoretical approach

2.1 Thermal properties of textile

The thermal properties of textiles, such as thermal resistance, thermal conductivity and thermal absorptivity, are affected by fabric properties, such as structure, density, humidity, the material and properties of fibres, type of weave, surface treatment, filling and compressibility, air permeability, surrounding temperature and other factors.

The **thermal conductivity coefficient** λ [$Wm^{-1}K^{-1}$] is given by the amount of heat that passes through 1 m^2 of material over a distance of 1 m within time 1 second, creating a temperature difference of 1K, according the Equation 1:

$$\lambda = \frac{Q}{t}\,\frac{h}{S\Delta T} \qquad (1),$$

where Q is the amount of heat (thermal energy) [J] lost or received by the body through the area S [m^2], t is time [s] and ΔT is the temperature difference in the thickness h [m^2] in the direction of heat conduction.

The highest thermal conductivity is exhibited by metals, while polymers have a low thermal conductivity that ranges from 0.2–0.4 $Wm^{-1}K^{-1}$. The thermal conductivity of textile structures generally reaches levels from 0.033–0.10 $Wm^{-1}K^{-1}$. The thermal conductivity of steady air at 20 °C is 0.026 $Wm^{-1}K^{-1}$, while the thermal conductivity of water is 0.6 $Wm^{-1}K^{-1}$, which is 25 times greater. This is the reason that the presence of water in textile materials is undesirable.

Thermal resistance (*R*) [m^2KW^{-1}] depends on fabric thickness, h [m] and the thermal conductivity coefficient, λ [$Wm^{-1}K^{-1}$] [10]:

$$R = \frac{h}{\lambda} \qquad (2).$$

The concept of the **thermal absorptivity (*b*)** of fabrics was introduced by Hes and Dolezal [11] to characterise the thermal feeling (heat-flow level) during brief contact between the human skin and the surface of a fabric. Provided that the time of heat contact (τ) between the human skin and a fabric is shorter then several seconds, the measured fabric can be simplified into a semi-infinite homogenous mass with a certain thermal capacity (ρc [Jm^{-3}]) and initial temperature of T_2. An unsteady temperature field between the human skin (with a constant temperature of T_1) and a fabric, with respect to boundary conditions, offers a relationship that enables us to determine the heat flow (q [Wm^{-2}]) that passes through a fabric:

$$q = b\,(T_1 - T_2) \,/\, (\pi\tau)^{1/2} \tag{3}$$

and

$$b = (\lambda\rho c)^{1/2} \tag{4},$$

where q is heat flow [Wm^{-2}], b is the thermal absorptivity of a fabric [Ws$^{1/2}$m^{-2}K^{-1}], ρc is thermal capacity [Jm^{-3}], τ is the time of heat contact [s], T_1 is skin temperature [K], T_2 is the initial temperature [K], and λ is the thermal conductivity coefficient [Wm^{-1}K^{-1}].

The higher the level of thermal absorptivity, the cooler the feeling provided. Practical values of this parameter for dry textile fabrics range from b = 30–300 Ws$^{1/2}$m^{-2}K^{-1}. For wet fabrics, thermal absorptivity can exceed as much as b = 1000 Ws$^{1/2}$m^{-2}K^{-1} due to the high thermal conductivity and thermal capacity of water. The level of thermal absorptivity of fabrics not only depends on the fabric's composition and water content, but also on the surface structure. It is thus possible to alter the level of thermal absorptivity by means of both mechanical and chemical treatment, such as raising, brushing, enzymatic treatment and coating. A relatively dry contact feeling can be achieved by covering the super-absorbent interior of diapers with hydrophobic fabrics made, for example, of polypropylene [12].

2.2 Semi-empirical model of the thermal resistance of fabrics in a wet state

This original mathematical model for the thermal resistance of single-layer woven wet fabric presented by Mangat et al. [13] includes the thermal resistance of dry fibre polymer segments:

$$R_f = \frac{h}{\lambda_f} \tag{5},$$

the thermal resistance of air segments:

$$R_a = \frac{h(1-\varepsilon)}{\lambda_a(1-\mu)} \tag{6},$$

the thermal resistance of moisture (water) segments:

$$R_w = \frac{h(1-\varepsilon)}{\lambda_w \mu} \tag{7},$$

where λ_f is the thermal conductivity of dry fibre polymer segments [Wm^{-1}K^{-1}], λ_a is the thermal conductivity of the air segment [Wm^{-1}K^{-1}], λ_w is the thermal conductivity of the moisture segment [Wm^{-1}K^{-1}], h is fabric thickness [m], ε is the geometrical porosity of the fabric, and μ is the relative moisture content of the fabric.

The described thermal resistance values can be connected in real fabric, either in a series or in parallel, or in any combination of those connections. The original idea developed by Mangat et al. [13] depends on a comparison of all possible connections with real experimental results, the statistical evaluation of those results and the selection of the resistance connection with the best correlation. For single-layer woven fabrics, this thermal resistance model takes the following form:

$$R_t = \frac{R_a(R_f + R_w)}{R_a + R_w + R_f} \tag{8}.$$

The objective of the presentation of this structural model of the thermal resistance of fabrics in this paper is merely to demonstrate the theoretical effect of porosity and moisture content on the thermal resistance of the studied fabric. As this model is based on heat conduction only, the effect of heat transfer was not take into account. Fortunately, the proportion of total heat flow that passes through compact fabrics accounted for by heat flow through radiation for the most part does not exceed 10%. It should be emphasised that the following results of the experimentally determined λ also take into account the minor effect of heat transfer through radiation.

2.3 Water vapour permeability of wet fabrics

The heat flow generated due to sweat evaporation determines heat lost by the body and the cooling effect thereon. Heat flow due to moisture, which evaporates from the surface of a fabric (Figure 1), also influences the cooling effect. However, this cooling effect may not be sufficient to cool the body because the heat flow caused by a drop in temperature on a fabric's surface is reduced by the effect of the thermal resistance of that fabric and the thermal resistance of the air gap between the fabric and the skin

[14, 15]. The effect of contact thermal resistance is not taken into account in this study. Figure 2 shows a series of all evaporation resistances *Ret* [Pam^{2}W^{-1}] encountered during the passage of heat flow caused by the evaporation of sweat into the environment.

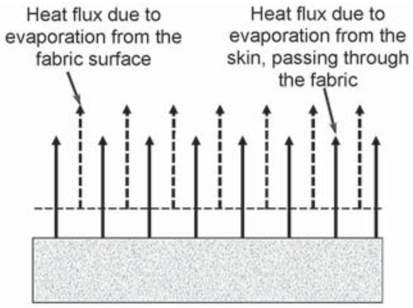

Figure 1: Heat flux generation due to sweat evaporation from the skin surface and moisture evaporation from a fabric's surface [14]

We first analysed the skin cooling effect caused by the evaporation of moisture from a fabric's surface. Despite the assumption of isothermal conditions, wet fabric becomes cooler than the surrounding air because the fabric surface is not maintained at the temperature of the instrument (skin model) measuring surface due to the effect of certain thermal resistance properties of a particular fabric. The flow of heat per unit of area (also referred to as heat flux in many studies) caused by the convection mass transfer from a fabric surface (q_{fabw}) can be described by Equation 9, under the condition that the fabric surface is covered by a continuous water film [7]:

$$q_{fabw} = L\,\beta_p(p_{sat.fab} - p_{air}) \tag{9}$$

The force that causes water vapour transfer can be expressed as the difference between partial pressures of water vapour, or as the difference between water vapour concentrations. In ergonomics, the use of partial pressures of water vapour (Equation 9) is more common [1, 6]. Except for dry and very dry fabric states, a continuous water film is present at any level of fabric moisture, and is referred to as the period of constant drying velocity and constant fabric surface temperature. During this period, the partial pressure of water vapour on the skin's surface reaches saturation. Heat flux (q_{fabw}) must be in equilibrium with thermal losses by convection into the atmosphere and heat conduction in the direction of the skin:

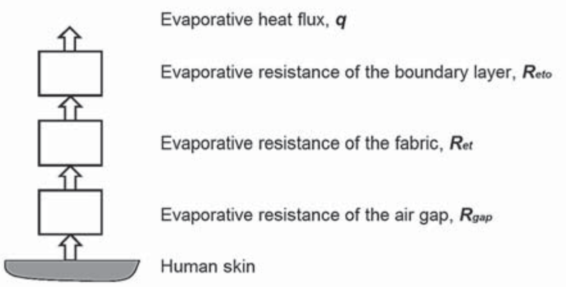

Figure 2: Evaporative resistances (connected in a series) during evaporative heat flux from the skin through a garment [14]

$$L\,\beta_p\,(p_{sat.fab} - p_{air}) = \alpha\;\Delta t_{air} + \Delta t_{air}/(R_{ctw} + R_{gap}) \tag{10}$$

The thermal resistance of a fabric in the wet state R_{ctw} can be expressed approximately as the linear function of the relative moisture of a fabric (U):

$$R_{ctw} = R_{ct}\,(1 - kU) \tag{11}$$

The heat flux that causes skin cooling can then be derived from the following Equations:

$$q_{fabw.sk.} = \Delta t_{air}\,/\,(R_{ctw} + R_{gap}) \tag{12}$$

$$q_{fabw.sk.} = \frac{\beta_p(p_{sat,\,fab} - p_{air})}{1 + \alpha R_{ct} + (1 - kU) + \alpha R_{gap}} \tag{13}$$

Equation 13 confirms that as fabric moisture increases, the thermal resistance of a fabric decreases, which causes an increase in the cooling flux conducted away from the skin. This explanation can be further simplified: an increase in the moisture content of a fabric will likely be followed by an increase in the mass transfer area, at least to some extent. The heat flux evaporated from the skin (q_{skin}) can be then described by [14, 15], provided that the partial pressure of water vapour at the skin's surface reaches a saturated level (this assumption is applied by many researchers [16, 17]):

$$q_{skin} = \frac{p_{sat} - p_{air}}{R_{gap} + R_{et} + R_{eto}} \tag{14}$$

The evaporative resistance of the relatively narrow air layer (R_{gap}), without taking into account free convection, can be described as:

$$R_{gap} = h/D_p \tag{15}$$

The evaporative resistance of the boundary layer (R_{eto}) yields the Equation 16:

$$R_{eto} = 1/\beta_\mathrm{p} \tag{16}$$

Thus, the total heat flux (q_{tot}) transferred through the boundary layer on the fabric surface is determined (with some simplifying assumptions, i.e. by neglecting heat transfer by radiation) by summing the heat flux that passes from the skin through a permeable fabric and the heat flux caused by the temperature gradient between the skin and fabric surface, which is cooled through the evaporation of water from a fabric's surface, as follows:

$$q_{tot} = \frac{p_{sat} - p_{air}}{R_{egap} + R_{et} + R_{eto}} = \frac{\beta_p(p_{sat,\,fab} - p_{air})}{1 + \alpha R_{ct} + (1 - kU) + \alpha R_{gap}}$$

3 Materials, methodology and devices

The tested samples were special knitted underwear for various sports, and consisted of polyester, polyamide and polyurethane elastane fibres. Their characteristics are presented in Table 1. They were measured in a laboratory at temperatures ranging from of 21–23 °C and at a relative humidity in the range of 50–55%. All fabrics were obtained from the laboratory of mountaineering equipment of Adam Malachowski, a manufacturer of high-performance thermoactive sportswear.

All fabrics were tested in various states of moisture content, in a "normal state", in an "ultra-dry state" and in a "wet state" (various). Initially, the samples were dried in an air conditioner at 105 °C ± 0.2 °C in order to remove all moisture. The samples were then soaked to their full volume of water to increase their humidity.

An Alambeta measuring device was used to determine thermal properties, while a Permetest device was used to determine water vapour permeability. The measurements took only a few minutes, which ensured reliable results for the wet fabric, as the sample's moisture during measurement remained at an almost constant level.

4 Results and discussion

4.1 Thermal conductivity, thermal resistance and thermal absorptivity properties

Figures 3 to 5 present the experimental results of the effect of the weight of samples and the type of raw material on the studied properties of thermal conductivity, thermal resistance and thermal absorptivity measured in dry and normal states.

It is evident from the results obtained that there were slight differences in dry and normal states for each tested knitted fabric. It is also evident that thermal resistance increases when the weight and thickness of fabric are increased. In the case of thermal conductivity, however, the effect of the type of raw material was clearly visible. Fabrics with similar compositions of polyester fibres demonstrated similar thermal conductivity, regardless of their weight or thickness, while knitted fabric comprised of polyamide fibres demonstrated the lowest thermal conductivity. Thermal absorptivity values, i.e. thermal feeling during brief contact between the human skin and a fabric's surface, were in the range of 95 to almost 160 $\mathrm{Ws^{1/2}m^{-2}K^{-1}}$ and from around 100 to over 170 $\mathrm{Ws^{1/2}m^{-2}K^{-1}}$ in a normal state. The highest values, and thus the coldest feeling, were obtained for knitwear comprised of polyamide fibres, while the lowest values, i.e. the warmest feeling, were obtained for knitwear comprising 87% polyester fibres and with the greatest thickness of the tested fabrics.

Table 1: Characteristics of knitted fabrics

No.	Raw material	Structure	Weight [g/m^2]	Thickness [mm]	Application
1	87% PES, 13% PU	Plain	335	1.09	underwear insulation layer
2	90% PES, 10% PU	Plain	205	0.81	underwear insulation layer
3	81% PES, 19% PU	Plain	155	0.59	underwear
4	75% PES, 25% PU	Plain	140	0.47	underwear
5	42% PA, 42% PES, 16% PU	Plain	115	0.35	underwear

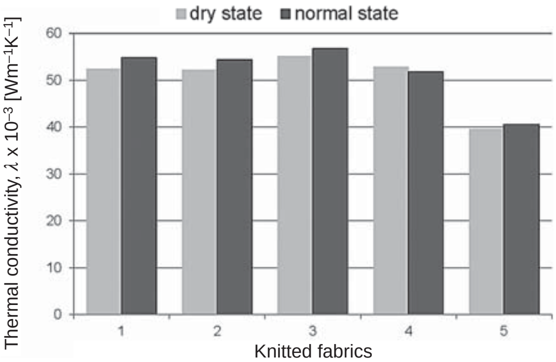

Figure 3: Thermal conductivity of knitted fabrics in dry and normal states

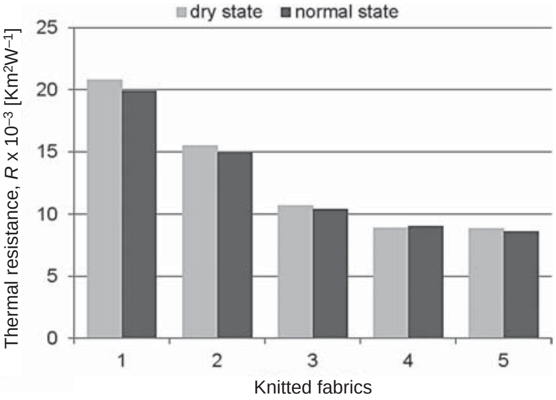

Figure 4: Thermal resistance of knitted fabrics in dry and normal states

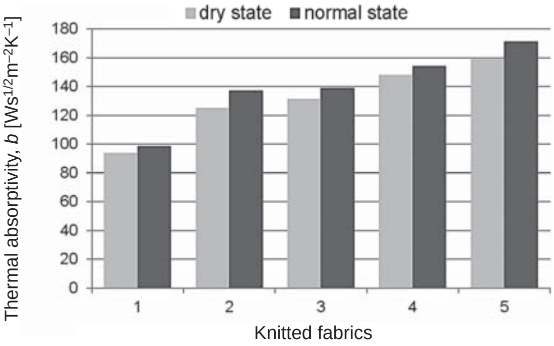

Figure 5: Thermal absorptivity of knitted fabrics in dry and normal states

The results of measurements in a wet state are presented in Figures 6 to 8. Our study identified a very significant negative effect of moisture on the thermal properties of the tested knitted fabrics. All relationships can be explained as linear trends. In the case of thermal conductivity, it was observed that increasing moisture content caused an increase in this value by as much as four times. In terms of thermal resistance, increasing moisture content resulted in a twofold decrease in obtained values. The effect of moisture content on a fabric is worst in terms of thermal absorptivity. Here, thermal absorptivity increased by up to nine times relative to the value from a dry state. We can conclude from the above facts that the moisture inside the tested fabrics greatly reduced the thermal properties of the tested materials. The increase in moisture content caused an increase in thermal conductivity and a decrease in thermal resistance, and resulted in a much cooler thermal feeling when a fabric was in contact with the human body.

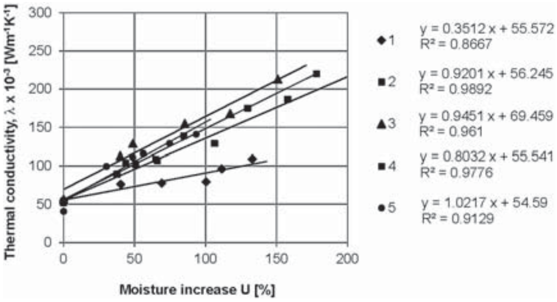

Figure 6: Effect of fabric moisture content on the thermal conductivity of knitted sportswear

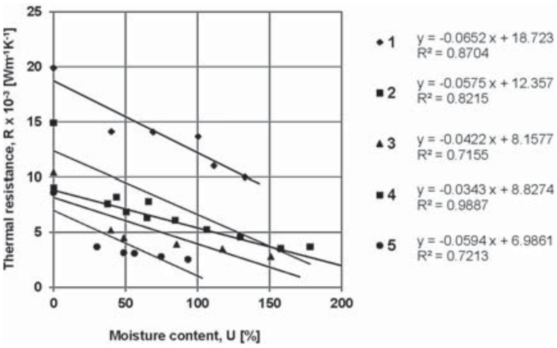

Figure 7: Effect of fabric moisture content on the thermal resistance of knitted sportswear

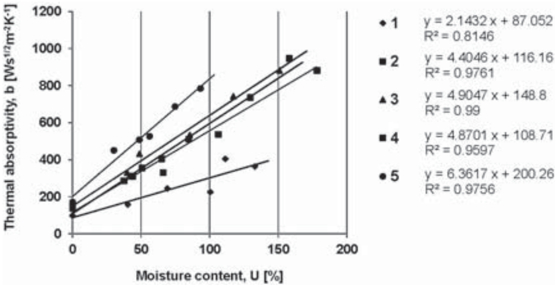

Figure 8: Effect of fabric moisture content on the thermal absorptivity of knitted sportswear

4.2 Relative water vapour permeability and absolute water vapour permeability.

In terms of water vapour permeability, all tested knitwear demonstrated a good level of relative water vapour permeability (RWVP, %) in a normal state, as well as an appropriate level of absolute water vapour permeability (AWVP, Pam^{2}W^{-1}).

In the case of relative water vapour permeability (Figure 9), we observed the effect of the weight of the knitted sportswear on this property. Relative water vapour permeability increased when the weight of the samples was decreased. Moreover, the composition of the samples also met an important rule. Fabric to which polyamide fibres were added (even fabric of the lowest weight) demonstrated nearly the lowest level of relative water vapour permeability.

A similar phenomenon was seen for absolute water vapour permeability (Figure 10). Here, we noted an even more significant effect of the weight and composition of samples on this property. When weight was decreased, absolute water vapour permeability also decreased, while the addition of polyamide fibres resulted in an increase in the absolute water vapour permeability of the tested samples.

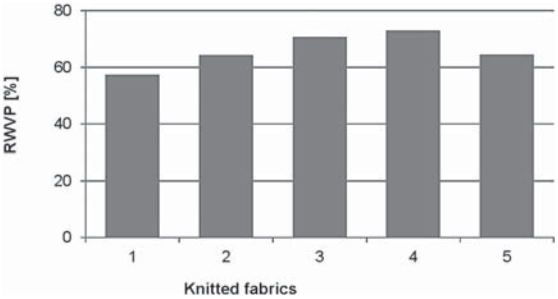

Figure 9: Relative water vapour permeability (RWVP, expressed in %) of knitted sportswear

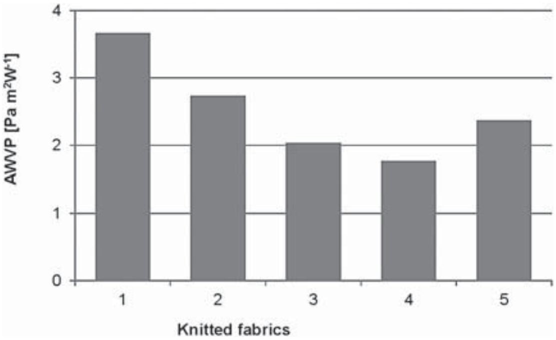

Figure 10: Absolute water vapour permeability (AWVP) of knitted sportswear

5 Conclusion

It is evident from the presented study that the weight and composition of tested knitted fabrics affected thermal properties, as well as heat and water transfer, in both dry and normal states. It can also be concluded that increasing moisture content in knitted sportswear leads to a significant deterioration in their thermal properties and their ability to transfer heat. A decrease in these values in a wet state was achieved even for 70% when comparing dry or normal states. This was caused by the substitution of air in fabric pores with water, which has a higher thermal conductivity. Thus, the physiological properties of fabrics that become increasingly wet as a result of use are subjected to sudden changes that have an adverse effect on the quality of worn apparel. Knowledge of these phenomena is very important in terms of clothing design and technology, particularly in the case of protective sportswear garments, which are often used in extreme weather conditions at a high humidity. The deterioration of thermal properties in this case can result in a significant reduction in the performance of athletes and have an adverse effect on their health.

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