THERMO-PHYSIOLOGICAL COMFORT PROPERTIES OF DIFFERENT WOVEN FABRICS USED IN SPORTSWEAR FOR OUTDOOR ACTIVITIES

by

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Original scientific paper
https://doi.org/10.2298/TSCI2203707L

In this study, the thermo-physiological wear comfort is mainly characterized by the thermal and water vapor resistance performance of the woven fabrics used as sportswear for outdoor activities. The commonly used twill woven fabric with different thicknesses, weight, and density are selected for the experimental analysis, and it finds that fabric weight and thickness have crucial effects on the thermal resistance, and the water vapor resistance depends linearly on density and thickness. The present study gives an optimal design of sportswear for outdoor activities with low thermal and water vapor resistance.

Key words: *thermo-physiological comfort, thermal resistance, sportswear, water vapor resistance, comfort, optimal design*

Introduction

Thermal comfort is the ability to maintain a constant body temperature through the thermal balance of the heat generated by a person’s body and to transfer it to the atmospheric environment [1-3]. The thermo-physiological comfort of the clothing is mainly affected by its water evaporation and thermal resistance. This is due to the clothing comfort sensation is mainly determined by a balance process of moisture and heat exchange between the human body and the environment through the clothing system [4, 5]. Generally, the low thermal resistance and water vapor resistance represent the high thermal conductivity property and efficient breathability of the woven fabrics that are preferred in making sportswear for outdoor activities.

The sweating guarded hot plate method [6] has been widely used to simulate the heat and moisture transfer process that occurs between the skin and fabric by testing their thermal and moisture vapor resistances, respectively. The thermal and water vapor resistance of clothing generally depends on the thermal conductivity of the fibers, the thickness and porosity of the fabrics. In recent years, fabric comfort has been studied and evaluated with different influencing parameters. Yanılmaz *et al.* [7] investigated the effects of wicking, wetting, and drying properties on the comfort of acrylic knitted fabrics, and they concluded that the high wicking height and the low drying time could increase the comfort level of clothing. Troynikov *et al.* [8] analyzed the moisture management properties of wool/polyester and wool/bamboo knitted fabrics for sportswear and revealed the corrections between the blend

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ratio and the water transport property. However, there were limited studies on the thermal resistance and water vapor resistance of the textiles used as sportswear.

Thus, this study aims to determine the thermo-physiological comfort properties of several polyester woven fabrics used for making sportswear by obtaining measurements through the sweating hot plate. In particular, this test device is suitable to investigate the thermal and water vapor resistances that are related to the thermo-physiological comfort properties of the fabrics.

Experimental

Materials

In this study, five types of commercially available fabrics used in producing sportswear were selected. The structure, weight, thickness, and yarn of these fabrics are listed in tab. 1. Before the test, all fabrics were placed in a conditioned room with a temperature of 20±2 °C and relative humidity (RH) of 65% ±5% for 24 hours.

Table 1. Description of the test materials

Sample Number	Woven structure	Thickness [mm]	Density [warp/weft per centimeter]	Weight [gm^{-2}]
S1	Twill	0.25	147/198	94.37
S2	Twill	0.26	153/196	212.38
S3	Twill	0.16	418/474	90.59
S4	Twill	0.28	148/202	136.44
S5	Twill	0.17	269/253	87.09

Measuring methods

The basic physical properties test

The thickness of the fabric was determined using a clothing thickness tester according to ASTM D1777 under a pressure of 17.5 ±1 kPa. The fabric weight per unit area was measured according to the ISO 3801:1977 standard using an electronic balance AL104. The warp and weft densities were measured with the Y511B counting glass. For the determination of the fabric physical properties, each sample was tested three times, and the mean was obtained.

Thermal resistance and water vapor resistance test

The sweating guarded hot plate apparatus was used to simulate the heat and moisture transfer process that occurs between the skin and fabric according to the ISO 11092 standard under a plate surface temperature of 35 °C [7]. Two main parameters involved thermal and water vapor resistance of the fabric were measured with the sweating guarded hot plate apparatus to evaluate its thermal comfortability. From fig. 1, the sweating hot plate could be used to simulate the transfer processes of the moisture and heat between the skin and fabric. Specifically, the fabric samples with a size of 500 mm × 500 mm were placed on the surface of the hot plate to test their thermal and water vapor resistance.

Thermal resistance represents the temperature difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. In this study, the sweating guarded hot plate apparatus was placed in an air-conditioned chamber with a temperature of 20 °C and an RH of 65%. The airspeed in this chamber was controlled at 1 ±0.05 m/s. For the thermal resistance test, the fabric specimen was placed on the porous metal plate surface. Consequently, the thermal resistance of the samples was achieved using:

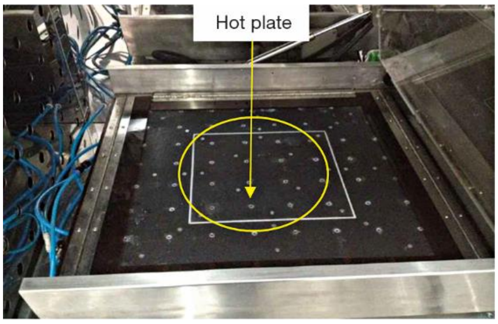

Figure 1. Sweating guarded hot plate apparatus

$$R_{ct} = \frac{(T_m - T_\mathrm{a})A}{H_c} - R_{ct0} \tag{1}$$

where R_{ct0} [m^{2}KW^{-1}] is the thermal resistance without a sample, R_{ct} [m^{2}KW^{-1}] – the thermal resistance of the sample, (T_m – T_a) [°C] – the temperature difference between the plate surface, T_m, and the temperature of the ambient air in the air-conditioned chamber, T_a, and H_c – the power required to maintain a constant plate surface temperature at 35 °C.

Water vapor resistance refers to the vapor pressure difference between the two faces of a material divided by the resultant heat flux per unit area in the direction of the gradient. The sweating guarded hot plate apparatus can simulate the water vapor transport through textiles when they are worn next to human skin. This particular process is an indirect means for measuring the vapor transmission property of the fabric. In this study, the porous plate was firstly covered by a water vapor permeable, and a liquid-water impermeable polytetrafluoroethylene membrane was used to measure the water vapor resistance of the specimen. Subsequently, the distilled water was fed into the porous heated plate and then passed through the membrane as vapor. In this case, no liquid water could contact the test specimen. Finally, the test samples were placed above the membrane. For the water vapor resistance test, T_m and T_a were both set at 35 °C, while the RH and wind speed of the air-conditioned chamber were controlled at 40% and 1 m/s, respectively. After reaching the steady-state, the water vapor resistance of the test fabric was achieved based on:

$$R_{et} = \frac{(P_m - P_\mathrm{a})A}{H_c} - R_{et0} \tag{2}$$

where R_{et} [m^{2}PaW^{-1}] is the water vapor resistance of the sample, P_m [Pa] – the water vapor pressure at the surface of the heat plate, P_a [Pa] – the air in the conditioned chamber, R_{et0} [m^{2}PaW^{-1}] – the water vapor resistance without a sample, and H_c – the electrical power required to keep the plate surface's temperature at 35 °C.

Results and discussion

Comparison of the thermal resistances of the fabrics

As we know, thermal resistance is related to the fabric thickness, weight, and structure. Figure 2 demonstrated the thermal resistances of the five different fabric samples with diversely inherently physical characteristics listed in tab. 1. Clearly, the thermal resistances of

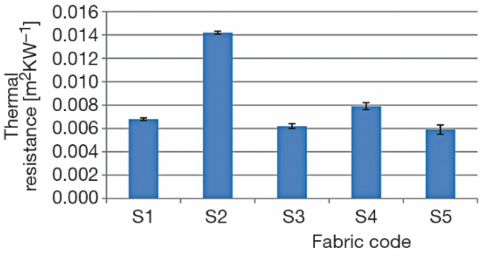

Figure 2. Thermal resistance values of the woven fabrics used as sportswear

all woven fabrics ranged from 0.0059 m^{2}K/W to 0.0142 m^{2}K/W, and were disparate for each woven fabric due to the different constructional parameters. Notably, woven fabric S2 had the highest thermal resistance value, whereas that of woven fabric S3 was the lowest among all samples. Such a difference in the thermal resistance performance of the fabrics was caused by the fabric weight and thickness.

To further elaborate on the effects of fabric thickness and fabric weigh on thermal resistance, all the data were fitted. From fig. 3, a low association between the thermal resistance and thickness of the five examined fabrics was obtained. The relationship could be explained with the model $y = 0.034X + 0.006$, where y is the thermal resistance and X – the thickness of the woven fabric. The corresponded regression coefficient was 0.3, indicating that the effect of the fabric thickness on their thermal resistance was slight. Figure 4 demonstrated that thermal resistance was strongly associated with the fabric weight, along with the regression coefficient 0.9665. Compared with the fabric thickness, the fabric weight is a more important factor that affects the properties of thermal resistance because that the thermal resistance values of these five samples were positively correlated with the weight of the samples. It was why fabric S3 had a slightly larger thermal resistance than that of fabric S5 owing to the higher weight, although it had a lower thickness. These results were consistent with that in fig. 2. Both twill woven fabric S3 and S5 exhibited the best thermal comfort in this section.

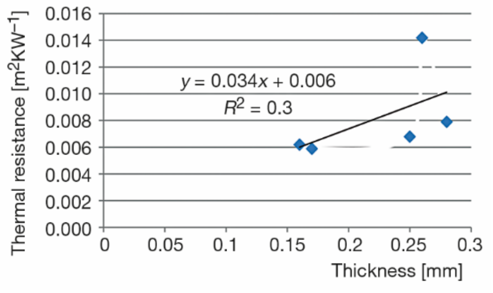

Figure 3. Relationship between thickness and thermal resistance of fabrics

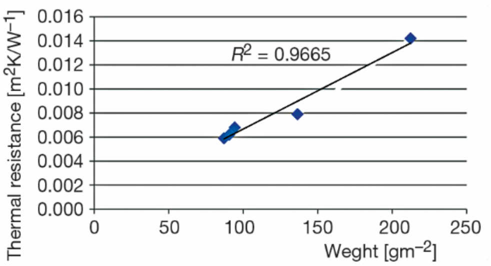

Figure 4. Relationship between weight and thermal resistance of fabrics

Comparison of the water vapor resistance

Wearing sportswear during sports activities, the sweat vapor can be transported from the fabric to the external environment to decrease the humidity and temperature on a human body's surface. Therefore, the water vapor permeability of sports clothing is one of the vital factors that affect thermo-physiological comfort, particularly under sweaty conditions. Water vapor resistance pertains to the ability of water vapor permeability. Hence, in this study, the water vapor resistance is used to assess the water vapor permeability of the samples through the sweating guarded hot plate. Figure 5 compared the water vapor resistance values of the tested fabrics and revealed that fabric S4 had the highest water vapor resistance among the fabrics because of its highest thickness and density. By contrast, fabric S3 displayed the lowest water vapor resistance among all tested fabrics because of its lowest thickness and secondly lowest density

The effects of the thickness or density on the water vapor resistance properties of the fabrics, were fitted, respectively. The results displayed that the water vapor resistance increased with the increase of fabric thickness and density as expressed by:

$$Y = 18.86X + 1.839, \quad R^2 = 0.890 \qquad (3)$$

where Y [m^{2}PaW^{-1}] is water vapor resistance and X [mm] – the fabric thickness.

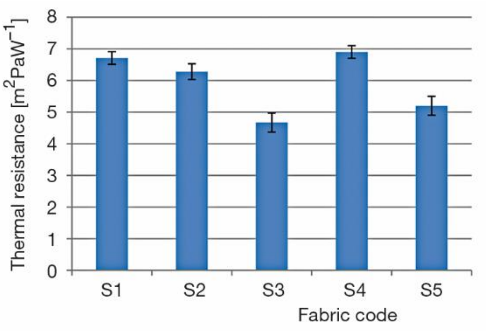

Figure 5. Water vapor resistance values of the woven fabrics used for sportswear

$$Y = 0.313X - 10.49, \quad R^2 = 0.965 \qquad (4)$$

where Y [m^{2}PaW^{-1}] is the water vapor resistance and X [mm] – the fabric density (warp/welt per cm).

Given that the high correlation coefficients, R^2, of 0.89 and 0.965, the relationship between the thickness or density and the water vapor resistance properties of the fabric were highly fitted, respectively. Obviously, both the thickness and density played a vital role in the water vapor resistance. When the difference in density or weight is very significant, it is easy to infer the decisive factor affecting the water vapor resistance. For example, the fabric S3 with the higher density and slightly lower thickness showed the lower water vapor resistance than the fabric S5 due to the major effect of fabric thickness and minor effect of fabric density. Notably, three test samples contained fabric S4, S2, and S1 showed the similar density and thickness, so their water vapor resistance was determined by the combined effects of density and thickness. Comparing the water vapor resistance values of these five twill woven fabrics, it can be inferred that fabric S3 exhibited the most thermal comfort property.

The method for improving the thermal conductivity and water vapor resistance properties of sportswear

Apart from the fabric structure involved thickness, weight, and density that influence the thermal resistance and permeability of the water vapor of sportswear, garment structure also plays an important role in total comfortableness. Figure 6 shows the main sweating area of a human body, which were depicted as lightly colored parts. In a human body, the armpit and crotch easily generate sweat, but can hardly release it into the atmosphere environment. If

Figure 6. The main sweating area of human body

the sweat or water vapor cannot be transported out from the skin, then it may cause serious discomfort to the human body during intense sports activities. This problem cannot be easily resolved by selecting and wearing strongly breathable fabrics alone. Therefore, the relational fabric garment structures should be controlled to achieve the desired effect.

Thus, considering only a single factor can not completely solve the issues encountered in wearing sportswear. Numerous factors, including the fabric properties and garment structure, should be considered to achieve high thermal conductivity and moisture permeability.

Discussion and conclusions

This paper gave an experimental analysis of the thermo-physiological comfort properties of different woven fabrics, and we thought the theoretical analysis might be more important.

In this study, the thermo-physiological comfort features of the woven fabrics commonly used in the production of sportswear for outdoor activities were compared and analyzed in terms of their thermal and water vapor resistance. Compared with fabric thickness, fabric weight is a more important factor in the thermal resistance of the fabrics used for sportswear. High moisture permeability is preferred for sportswear because this can facilitate the quick release of the water vapor from the inner garment to the atmosphere environment. The overall water vapor resistance of the tested fabrics is low. Moreover, the results reveal that both the density and thickness of the fabrics significantly influence their water vapor resistance. The regression coefficients are 0.89 and 0.96, signifying that the fabric thickness and density were linearly correlated with the thermal resistance of the tested fabrics. The results derived by this research may enable an individual to understand the factors that influence the thermal and water vapor resistance of sportswear.

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Paper submitted: October 1, 2020
Paper revised: January 22, 2021
Paper accepted: January 22, 2021

Published by the Vinča Institute of Nuclear Sciences, Belgrade, Serbia.