Transfer of liquid and water vapour through knitted materials

Antonija Petrov[1], Goran Čubrić[1] and Ivana Salopek Čubrić[2]

[1]*University of Zagreb Faculty of Textile Technology, Department of Clothing Technology, Zagreb, Croatia*
[2]*University of Zagreb Faculty of Textile Technology, Department of Textile Design and Management, Zagreb, Croatia*

ORIGINAL SCIENTIFIC PAPER

UDC: 677.075:676.017.62:796.022.7

Hem. Ind. **77(3)** 211-221 (2023)

Abstract

Active sportswear has certain functions that should meet the expected properties and improve the performance of athletes. In addition to functionality, an important aspect of sportswear is thermal and physiological comfort. By choosing the right clothing for athletes, the dynamic and thermal load can be significantly reduced because sports require unhindered mobility, and clothing must be adapted to the body and absorb sweat. Proper vapour and liquid flow in textile materials are important from a comfort point of view. Therefore, in this research, seven representative samples were selected that are used for clothing intended for sport and leisure. Using an infrared thermal camera, the transfer of liquid on the surface of the material was precisely monitored, until the final stage when the material is completely dry. The obtained results show that fabric made of 100 % polyester has the shortest drying time, while the highest vapour permeability was exhibited by fabric made of viscose and elastane yarn. Those fabrics should be considered as the most suitable for sportswear because they do not cause discomfort when worn. Infrared thermography is a very useful method in research because it provides reliable data, especially when it comes to the drying time of the material.

Keywords: knitted fabric; wetting; thermography; drying; sportswear.

Available on-line at the Journal web address: http://www.ache.org.rs/HI/

1. INTRODUCTION

Clothing is a basic human need, and since ancient times people have made clothes and adapted them to their needs. Man is exposed daily to various unfavourable, difficult working and living conditions. In such conditions, the function of clothing has always been to protect the body from external influences. According to the defined use and special characteristic, clothing can be divided into several categories such as work wear, protective clothing, uniforms, casual wear, special purpose clothing, sportswear, etc. Sportswear plays an important role in daily life. When buying or designing sportswear, one should be paying close attention to the comfort properties, either thermophysiological or sensorial [1–6], which are expected to be adequate during material use as long as possible [7]. There are three types of sportswear: clothes that are worn during leisure time, clothes that serve as fashion items, and clothes for active participation in sports activities. Clothes that are worn during leisure time are sports clothes that are most often worn at home when increased physical activity or sweating are not expected. Sports clothes that serve as fashion items were created through the cooperation of fashion houses, fashion designers, and sports brands, with professional athletes, and the most attention is paid to fashion design and the aesthetic appearance of the clothes. Active sportswear is often expected to be very light so that it does not hinder the athlete in his activities. This type of clothing must not interfere with or restrict movement and often is required to meet additional conditions that are in line with the specifics of the particular sport. By providing physical protection and comfort to the wearer, clothing can have a significant impact on the performance of professional and non-professional athletes during competition or training sessions. Extreme and dangerous sports require protective and durable clothing that have to protect the body from various weather conditions such as wind, rain, snow, and sun. The performance of sportswear is also influenced by the thermodynamic, aero-

Corresponding author: A. Petrov, University of Zagreb Faculty of Textile Technology, *Zagreb, Croatia*
E-mail: antonija.petrov@ttf.unizg.hr; Tel. +385 1 3712 555
Paper received: 21 October 2022; Paper accepted: 24 April 2023; Paper published: 16 May 2023.
https://doi.org/10.2298/HEMIND221021012P

dynamic, and hydrodynamic properties of the material used, as well as by the material structure, design, and finishing [8–12]. For the performance evaluation, the textile industry uses a variety of quality tests. Among the most used instruments that determine the transfer of water vapour and liquid through materials are a sweating guarded hotplate, moisture management tester, and permetest. Still, in order to complement those results or to get insight into the specific behaviour, different additional instruments and methods may be used. One of these is based on the use of infrared thermal camera for evaluation of the material transfer properties, more precisely the material wetting time, the wetting speed of a liquid on the material, and the time required for drying of the material [13]. Infrared thermography is a non-contact method of measuring temperature, and it is based on measuring the intensity of infrared radiation [14-17]. The term thermography comes from the Greek words therme - heat and graphene - to write [16]. This means that after the thermographic measurement, a permanent record of the measured quantities remains, and this record is called a thermogram [17].

The thermographic system consists of a thermographic camera and a thermogram processing unit (software). The sensor in a thermographic camera measures the amount of energy that falls on its surface and corresponds to the radiation intensity of a defined part of the infrared spectrum. The amount of thermal energy emitted from the surface is directly proportional to the surface temperature. Changes in temperature result in changes in emissive power, which is shown by the Stefan-Boltzmann's equation:

$$E = \varepsilon \sigma T^4 \quad (1)$$

where E is the emitted energy, ε is the emissivity coefficient, σ is the Stefan-Boltzmann constant [5.67×10^{-8} W m^{-2} K^{-4}], and T is the body temperature. This relationship is very important as it is very sensitive in calculating temperature from the radiant power and can distinguish areas with different temperatures due to different emissivities. The Stefan-Boltzmann's law is considered the basic law governing infrared thermography [18,19].

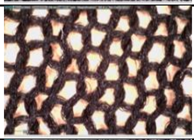
Thermography is divided into qualitative and quantitative in terms of the information it provides, and into passive and active in terms of motivation. Qualitative thermography aims to provide the basic information about the temperature distribution on the surface of the studied object, while quantitative thermography is used to provide accurate temperature values on the surface of the examined object [20,21]. Thermography is used in sports to find various traumas within the human body and to determine temperature changes in an active athlete depending on the type and intensity of training [22,23]. Back in 1975, the first research study was published in the field of sports using infrared thermography [24]. Thermography allowed trainers and athletes to observe changes in the body temperature in specific parts of the body to prevent muscle injuries and to get an insight into the health of athletes [19,24,25]. Infrared thermography may be successfully used in different areas of sport: sports medicine, physical therapy, sports performance, and research [26]. In research papers, experiments are mainly based on thermoregulation in a cold or warm environment and sweating during exercise [27-31]. For example, thermography, using an infrared thermographic camera, provided insight into the change in body temperature in active futsal athletes before and after indoor training, in order to perform detailed body mapping. The developed body maps would further be used to design ergonomic sportswear for futsal players. The results showed that infrared thermography is an extremely useful method for adjusting the construction of clothing and certain types of training. This is very important because of the athlete's performance and his comfort in wearing these clothes [32]. Mijović and co-workers chose a research objective to investigate whether thermography can be used to assess heat and moisture transfer within clothing systems used by police officers in the field [33]. An infrared imaging system was used to identify the body temperature pattern of healthy adult men engaged in controlled physical activity in a temperature-controlled environment. Research results have shown that thermography is an effective tool for assessing skin temperature and perspiration evaporation from clothing. The information gathered can be applied in the design of new clothing systems to maximize the body's cooling effect through evaporation of perspiration [33]. Similarly in another study [34], the aim was to show possibilities of using infrared thermography for determining the heat transfer in protective clothing with four different sets. The kits were carefully designed to ensure optimal wearing comfort in temperate and cold climates with the focus on functionality. The obtained thermographic measurements assembled in thermograms showing temperature distribution on the surface of the subject's body and of protective clothing by color coding. Temperature distribution indirectly provides information about different states of the surface itself or if it reflects the structure and internal state of the observed object. By measuring temperature distribution on subjects working outdoors at low temperatures, thermal insulation of protective clothing can be assessed [34]. From this short literature review, it is clear that infrared thermography has a great potential for research and experiments in the field of clothing evaluation [26,35,36]. Still, the use of this technique for evaluation of mass transfer properties (especially liquid and moisture transfer) is to be expanded. Therefore, the present research focuses on aspects of thermography application for evaluation of liquid transfer through textile materials. To assess the advantages of the additional measuring methods, this research also includes evaluation of water vapour transfer characteristics by using the Absolute Moisture Meter PCE-MA. The PCE-MA device provides weighting of the material to determine the moisture content.

2. EXPERIMENTAL

2. 1. Materials and material characterization

For the experimental part of this research, seven representative single jersey knitted fabrics were selected so to cover a wide range of available materials at the market (in terms of the raw material and knitted structure). All those materials are specifically produced to be used for the production of leisurewear or fashion sportswear that is in direct contact with the skin (*i.e.* for the production of T-shirts and short trousers). Characteristics of the materials are shown in Table 1.

Table 1. Characteristics of the materials

Sample ID	Micrograph	Raw material	Mass per unit area, g m^{-2}	Yarn count, tex	Knitting density (horizontal / vertical), stitches cm^{-1}	Thickness, mm	Porosity factor
M1		100 % PA 6	111.61 (St.dev. 2.524)	18	11/15 (St.dev. 0.5)	0.800 (St.dev. 0.017)	0.93
M2		100 % PES	73.42 (St.dev. 0.552)	18	9/11 (St.dev. 0)	0.465 (St. dev. 0.007)	0.67
M3		100 % PA 6.6, recycled	109.02 (St.dev. 1.192)	18	11/13 (St.dev. 0.5)	0.478 (St.dev. 0.0079)	0.89
M4		4.5 % Lycra 38.2 % wool 57.3 % viscose	162.88 (St.dev. 1.277)	28	10/14 (St.dev. 0.5)	0.798 (St.dev. 0.010)	0.97
M5		3.2 % EA Lycra 29.0 % linen 67.8 % viscose	225.32 (St.dev. 6.774)	28	10/14 (St.dev. 0.5)	0.940 (St.dev. 0.022)	0.97
M6		93 % viscose 7 % elastane	248.49 (St. dev. 0.060)	22	16/35 (St.dev. 0.5)	0.651 (St. dev. 0.032)	0.99
M7		91 % cotton 9 % elastane	209.56 (St. dev. 0.050)	12	16/30 (St.dev. 0.5)	0.682 (St. dev. 0.017)	0.97

*The standard deviation is given in parenthesis.
**The standard deviation of the porosity factor for all samples is < 0.015 %.

The mass or materials per unit area was measured by using an analytical scale with a 4-digit accuracy (0.1 mg). Round samples with the area of 1 dm^2 were used, and for each material 10 measurements were performed. The yarn count was determined by weighing a skein of yarn in the length of 10 m. A total of 20 measurements for each yarn was made. The fabric horizontal and vertical densities were determined by counting the number of stitches in the length of 1 cm and for each specimen, 10 repetitions were performed. Thickness of the material was measured by using a thickness gauge meter DM-2000 (DM 2000 – Wolf, Germany). The specimen was conditioned in the standard testing atmosphere before testing, and for each specimen, 10 replicate measurements were performed. Structure of the materials was visualized by using a Dino-Lite Edge AM7915MZT digital microscope (AnMo Electronics Corporation, Taiwan) and further used for calculation of the porosity factor using the MATLAB software (MathWorks, MA).

2. 2. Determination of material transfer properties

Two methods of testing the selected knitted fabrics were performed relevant for the textile industry. The first method aimed at evaluation of moisture transfer properties of the material, more precisely, wetting time of the material, speed of liquid spreading through the material, and the time required for the material to completely dry. The wetting time of the material is observed along the material, while the speed of liquid expansion is the time required for a certain amount of liquid to spread in the directions of the x- and y-axes (mm/s). In this manuscript, artificial sweat was used as liquid. Sweating of athletes was simulated by using diluted acidic sweat (AS) pH 5.5 prepared according to the ISO 105-E04:2013 standard [37].

During the test, liquid was transferred to the sample surface by using a pipette, that is 0.5 cm^3 of artificial sweat was applied to each sample (Fig. 1). Prior to testing, materials were left for 24 hours on a flat surface in the standard atmosphere (20±2 °C and 65±2 % of relative humidity).

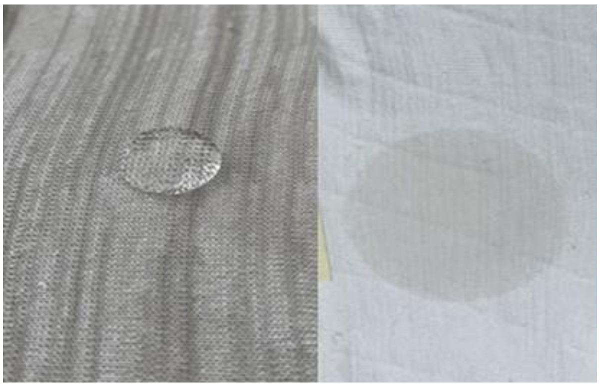


Figure 1. Application of a liquid drop and absorption in the material

After applying the liquid to the selected material, the TESTO 872 infrared thermal camera (TESTO, Germany) supplied with additional TESTO IRSoft v4.8 software (Fig. 2) was used to detect the breakpoints that mark the beginning and end of different process phases. The combination of a thermal camera and efficient image processing methods allows precise monitoring of the wet area of the material during the wetting and drying phases. The used thermal camera has the possibility of measuring in the temperature range from -30 to +650 °C with an accuracy of ± 2 %. Images were processed with the correction of emissivity for parts of the image up to individual pixels. This method allowed determination of critical points in the thermal image, as well as recording of hot and cold points.

Three important phases were observed in this experiment: the wetting, the static, and the drying phase throughout which the infrared camera was used. The wetting phase is represented by the time required for the applied liquid to spread completely over the surface of the material. The static phase begins immediately after the wetting phase ends and the main moment characterizing the material is when the wet area begins to shrink (Fig. 3).

During the measurement process, the wetting diameter (in the *x* and *y* directions), surface area and the wetting speed of the material were determined. The wetting speed was calculated, as the ratio of the wetting diameter to the wetting time.

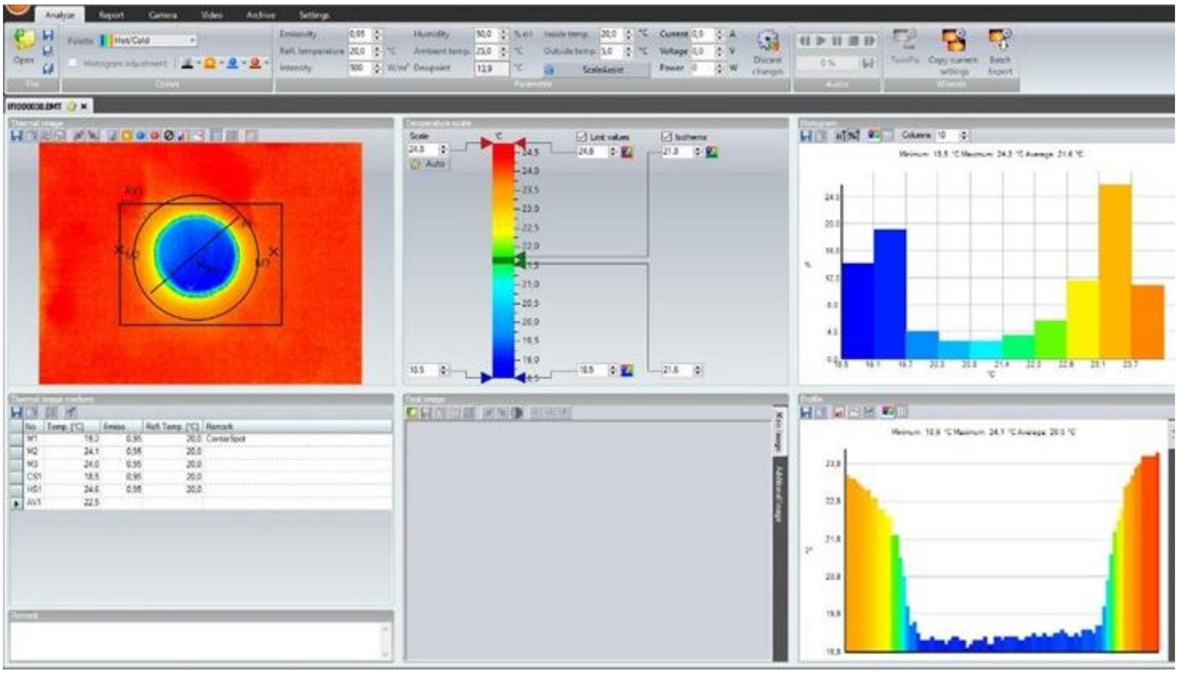


Figure 2. Example of processing of a thermogram

a b

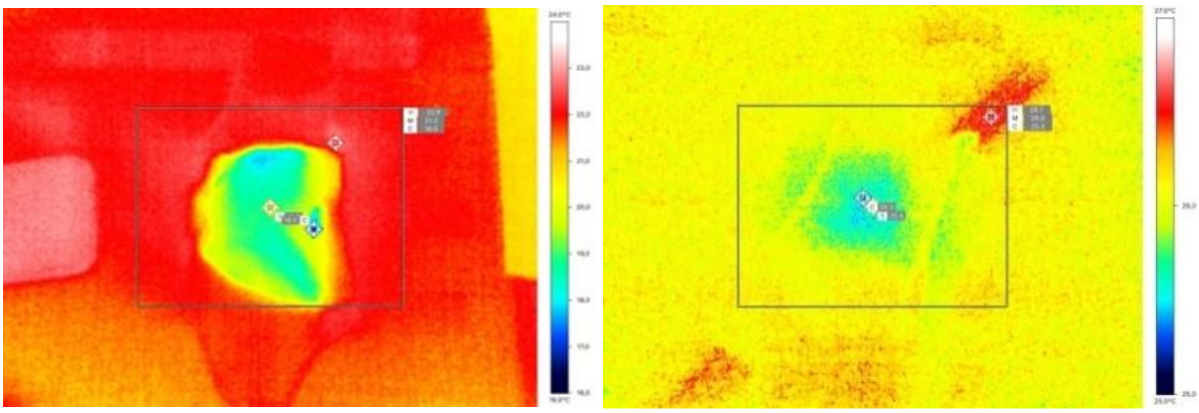


Figure 3. Example of thermograms during material drying: a - wet material; b - drying phase

Drying time is the time required for a certain amount of water to evaporate from the surface of the material. The drying phase begins after the end of the wetting process, including the static phase. This time is determined as duration from the first breakpoint to the end of drying. All measurements were carried out indoors, at a temperature of 20±2 °C and relative humidity 60±5 %. During the measurements, materials were placed on a dry flat surface. The measurements were performed in triplicates.

In the second method, an Absolute Moisture Meter PCE-MA (PCE Instruments, Germany) was used to determine the water vapour permeability. The PCE-MA device provides weighting of different materials and determination of their moisture contents. A heating chamber is heated by halogen lamps up to 199 °C. The material is dried and moisture meter calculates moisture content from the mass difference. As an additional modification of the method, a semi-permeable cellophane sheet was placed between the liquid and the dry material to simulate transfer of water vapour. The principle is adapted from the international standard ISO 11092 [38]. The device is set to a temperature of 41 °C and a time of 15 min. Three measurements were performed for each sample and the average value and coefficient of variation were calculated. Based on the data obtained in the experimental part of the work, a statistical analysis of the data, *i.e.* correlation, was made using the Statistica 14.0. program.

3. RESULTS AND DISCUSSION

Results of all conducted measurements are provided in Tables 2 to 4, and Figures 4 and 5. As could be seen from the data presented in the experimental part (Table 1), the selected fabrics differ regarding to the raw material as well as the mass per unit area ranging from an average of 73 g m^{-2} (sample M2, 100 % polyester) to 248 g m^{-2} (sample M6, 93 % viscose and 7 % elastane).

Table 2 shows the correlation between the mass, knitting density, thickness, and porosity factor of the material. The porosity factor is defined as the ratio between the volume of the fibres in a unit cell and the volume of the unit cell of the knit and ranges from 0 to 1. As can be seen from the results, the correlation between the fabric mass and porosity factor is positive and moderate (0.77). Furthermore, the correlation between the knitting horizontal density and knitting vertical density is positive and strong (0.97). Porosity has a significant influence on the physical properties and comfort properties of the fabric. It can be noticed that the porosity factor is the smallest in sample M2 (0.67), confirmed also visually at the micrograph showing significantly larger pores than in the other materials. This automatically affects the mass per unit area, which is the lowest for this material. Sample M6, which has the highest mass per unit area, as well as the highest knitting density, also has the highest value of the porosity factor (0.99). This material is very densely knitted, and its pores are very dense, barely visible in the micrograph (Table 1).

Table 2. Fabric properties correlation

Variable	Mass	Knitting density Dh	Knitting density Dv	Thickness	Porosity factor
Mass	1.000000				
Knitting density Dh	0.664513	1.000000			
Knitting density Dv	0.736102	**0.974121**	1.000000		
Thickness	0.473108	-0.103492	-0.099253	1.000000	
Porosity factor	**0.765153**	0.520324	0.503044	0.736641	1.000000

Marked correlations are significant at p <0.05000

Results of drying and wetting times are presented in Table 3 showing relatively short wetting time. Sample M6 (93 % viscose and 7 % elastane) had the longest wetting time (22 s), followed by sample M1 (15 s) and M3 (9 s). The material M2 (100 % PES) had the shortest wetting time (0.9 s only), which was expected considering the porosity factor. Due to the very large pores in M2, liquid applied at the surface passes through the material very quickly.

Table 3. Test results

Sample		Wetting time, s	Wetting diameter, mm		Wetting surface area, mm^2	Wetting speed, mm s^{-1}		Drying time, h
			x - axis	*y* - axis		*x* - axis	*y* - axis	
M1	Avg.	15.20	29.00	34.33	778.85	2.07	2.33	2.29
	CV, %	27.06	13.79	14.95	16.89	44.40	19.43	6.93
M2	Avg.	0.88	32.00	33.67	844.83	42.74	42.69	0.91
	CV, %	37.65	15.63	6.18	14.94	60.41	40.81	5.66
M3	Avg.	8.80	31.67	34.33	853.47	3.73	4.11	1.74
	CV, %	25.77	11.96	1.68	11.33	22.41	29.14	8.68
M4	Avg.	2.15	53.33	50.67	2138.90	27.13	25.42	1.97
	CV, %	31.47	14.32	9.33	22.88	42.64	35.69	6.77
M5	Avg.	1.81	51.33	51.33	2073.19	29.61	29.24	2.20
	CV, %	25.54	6.84	13.82	16.48	23.89	18.06	8.42
M6	Avg.	21.89	33.67	34.67	914.20	1.64	1.63	2.25
	CV, %	26.71	3.43	13.01	10.20	34.30	17.09	3.83
M7	Avg.	2.43	67.00	64.67	3413.34	30.53	29.12	1.69
	CV , %	36.68	5.38	8.93	13.88	40.19	35.82	4.27

Avg. – Average value, CV - Coefficient of variation

On the other hand, the time required for drying of the selected set of materials was in the range 0.91 to 2.29 h. The fastest drying material is M2 (100 % PES) as expected, exhibiting up to 2.5-fold shorter drying time than those of the rest of the investigated materials. Considering the composition and the structure of the knitting fabric (mass, thickness, and porosity factor), polyester proved to be the most suitable when it comes to drying clothes intended for athletes.

For athletes who run and produce large amounts of sweat, it is very important to keep the heat balanced. If the material causes discomfort when worn, especially during physical activities, the human body automatically resists it. Athletes feel uncomfortable, concentration decreases, and most importantly, the athlete performance is affected.

Wetting diameters (Table 3) were measured at the moment when acidic sweat as completely distributed over the material. As can be seen from the results presented, the smaller the diameter, the longer the wetting time is. An example of this can be seen in sample M6, which has a wetting time of 22 s, and wetting diameters along the *x*- and *y*-axes of 34 and 35 mm, respectively. By measuring the wetting diameter in the direction of the *x*-axis and the *y*-axis, it was possible to calculate the surface area (Table 3). The material M1, which had a relatively long wetting time, has a minimum wetted surface of 779 mm^2, while the sample with the largest wetting surface, M7 (3413 mm^2) had a fairly short wetting time of 2.4 s.

The wetting speed of the liquid in the x and y directions was then calculated showing the highest values in both directions for the sample M2, which showed the shortest wetting time and the lowest values for the sample M6.

To investigate the strength of the relationship between material characteristics defined in Table 1 and measured properties related to sweat management (*i.e.* the wetting time, wetting surface, wetting speed and drying time) correlation coefficients are given in Table 4. As can be seen from the results presented, the correlation between the drying time and the fabric mass per unit area is positive and moderate (correlation coefficient is 0.60). Correlation between the fabric mass per unit area and the other observed properties (wetting time, wetting surface, and wetting speed) is weak. As already mentioned in the paper, the porosity factor significantly affects the drying time of the material. It is evident that the correlation coefficient between the drying time and porosity factor has a high value (0.88), and this indicates a high degree of linear dependence. The relationship between the other observed properties is relatively weak.

Table 4. Correlations of wetting parameters with the material properties

Variable	Mass	Yarn count	Knitting density direction of wales	Knitting density direction of courses	Porosity factor
Wetting time	0.234206	-0.084231	0.493905	0.524861	0.336889
Wetting surface	0.507821	-0.085781	0.358170	0.308215	0.437805
Wetting speed, x-axis	-0.106434	0.063257	-0.337963	-0.286365	-0.466929
Wetting speed, y-axis	-0.127209	0.056356	-0.355022	-0.302841	-0.496658
Drying time	**0.595548**	0.411127	0.298055	0.315297	**0.877540**

Marked correlations are significant at p <0.05000

Figure 4 shows wetting and drying (W-D) profiles of all seven tested materials. Wetting duration presents the time required for the liquid to reach its maximum distribution on the material (area), while the drying duration presents the time required for the liquid to completely evaporate from the surface of the material. It can be said that the drying duration begins at the moment when the wetting duration ends, which also includes the static period.

For each sample in this study, the changes in behavior can be seen. It can be seen that the curve of sample M7 shows the largest area of the wet part. When the wetting surface reaches its maximum (approx. 43.5 cm^2), the drying duration begins, which in this sample is relatively short compared to the remaining samples. Sample M1 shows the curve that has the longest drying duration, but also the smallest wet area, while the sample M2 has the shortest drying duration. Based on the presented results (Figure 4), It can be concluded that specimen M2 is the most suitable material for sportswear. Due to its short drying time and the relatively small wetted surface of the material, it does not cause wearing discomfort. For top athletes, it is very important that the material dries quickly when sweating, so that it does not spread to the skin and cools the body, reducing the performance of active athletes.

Water vapour permeabilities (Figure 5) were in the range from 314 to 499 g cm^{-2} h^{-1} with the mean value for all seven samples of 388 g cm^{-2} h^{-1}. The highest water vapour permeability was exhibited by the sample M6 (499 g cm^{-2} h^{-1}), which in the previous method showed the longest wetting time, the lowest speed of liquid expansion on the surface and a relatively small diameter of the wetted surface.

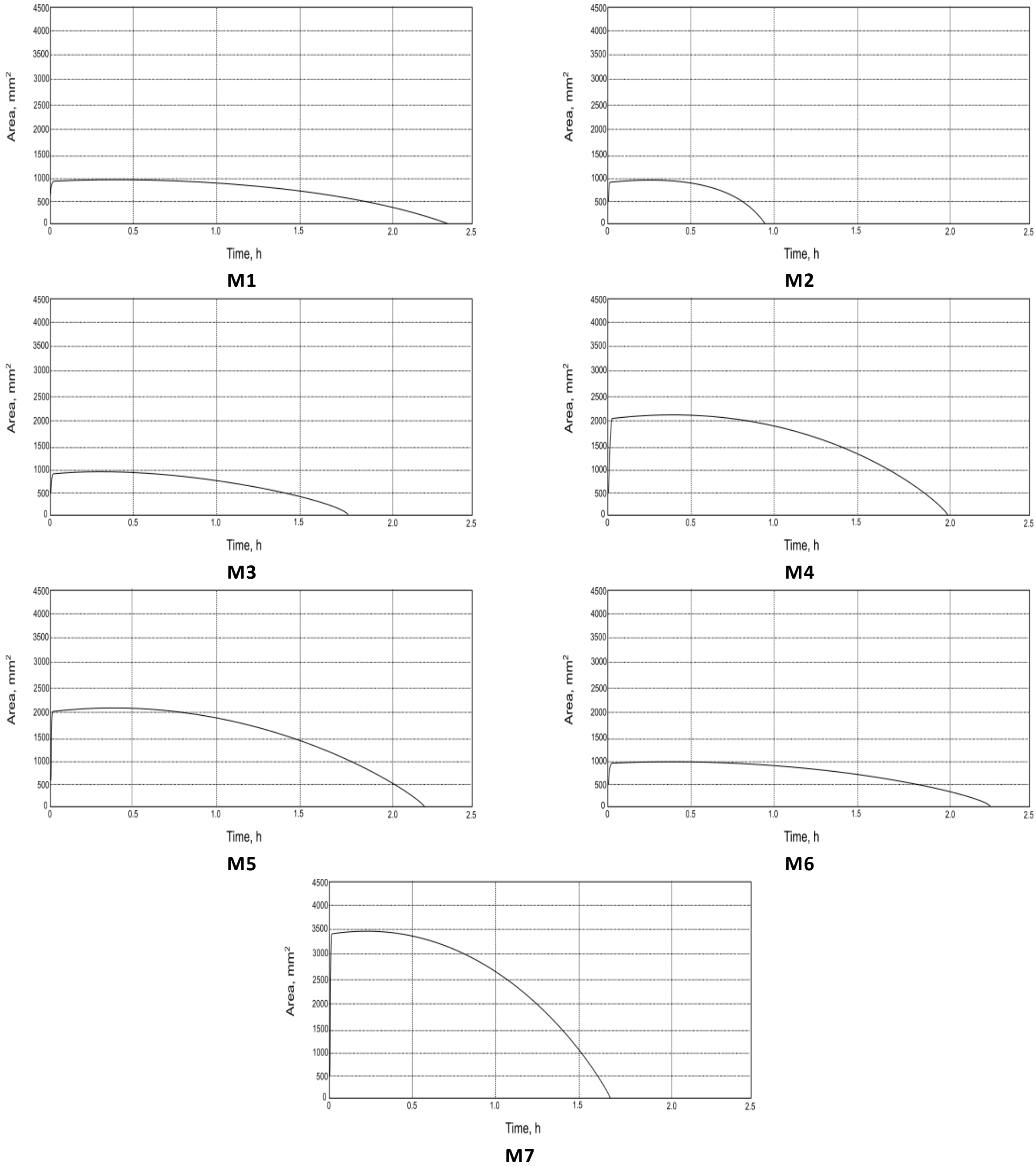


Figure 4. W-D profiles of the investigated materials as the wet area over time

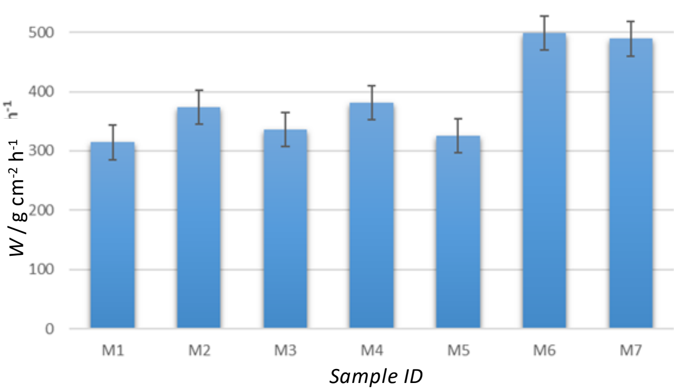


Figure 5. Water vapour permeability

4. CONCLUSION

This paper focuses on the investigation of liquid moisture properties by using thermography to observe changes in temperature that are associated with the amount of moisture on the surface of fabrics. The obtained results indicate that polyester is the most suitable material when it comes to drying clothes intended for athletes. For athletes who run and produce large amounts of sweat, it is very important to maintain an even temperature. Of all seven tested samples, we can highlight 3 materials. The 100 % PES (M2) material has the highest porosity and dries very quickly. The other two are materials with elastane (M6 and M7) that have high water vapour permeability. All three materials can be considered suitable for sportswear. Nowadays, a single sportswear garment is made of several different materials, *i.e.* different materials are combined in the construction of the garment itself. In some parts of the garment, a material that dries faster is needed, while in other parts, the used material that has to be more elastic withstanding the stresses (stretching) that occur every day when playing, while at the same time having higher water vapour permeability. The obtained results confirmed previous research in this field. Due to its short drying time and its smallest spreading wetting area on the surface of the material, it does not cause wearing discomfort, and athletes can perform physical activity without any hindrance. Likewise, infrared thermography has proven to be a useful method for research because it provides reliable data, especially when observing drying time.

Acknowledgements: This work has been supported in part by the Croatian Science Foundation under the project IP-2020-02-5041 „Textile Materials for Enhanced Comfort in Sports“ – TEMPO.

REFERENCES

[1] Shishoo R. Physiological comfort of sportswear. In: *Textiles in sports.* Cambridge: Woodhead Publishing Limited; 2005:177-203. https://www.elsevier.com/books/textiles-in-sport/shishoo/978-1-85573-922-2

[2] Ziemele I, Šroma I, Kakarane A. Comfort in sportswear. *Key Eng. Mater*. 2018; 762:402-407. https://doi.org/10.4028/www.scientific.net/kem.762.402

[3] Chowdhury P, Kartick KS, Basak S. Recent development in textile for sportswear application. *Int Res J Eng Technol*. 2014; 3(5):1905-1910. https://doi.org/10.17577/IJERTV3IS051844

[4] Salopek Čubrić I, Čubrić G, Majumdar A. Sensory attributes of knitted fabrics intended for next-to-skin-clothing. *J Text I.* 2022; https://doi.org/10.1080/00405000.2022.2075654

[5] Salopek Čubrić I, Čubrić G, Perry P. Assessment of Knitted Fabric Smoothness and Softness Based on Paired Comparison. *Fiber Polym*. 2019; 20(3): 656-667. https://doi.org/10.1007/s12221-019-1112-1

[6] Salopek Čubrić I, Skenderi Z. Evaluating Thermophysiological Comfort Using the Principle of Sensory Analysis. *Collegium Antropol.* 2013; 37(1):57-64. https://hrcak.srce.hr/99509

[7] Salopek Čubrić I, Čubrić G, Katić Križmančić I, Kovačević M. Evaluation of Changes in Polymer Material Properties Due to Aging in Different Environments. *Polym*. 2022; 14(9): 1682; https://doi.org/10.3390/polym14091682

[8] Stojanović S, Geršak J. Textile materials intended for sportswear. *Tekstil*. 2019; 68(4-6):72-88. https://hrcak.srce.hr/250867

[9] Chowdhury H, Alam F, Mainwaring D, Beneyto-Ferre J, Tate M. Rapid prototyping of high performance sportswear. *Procedia Eng*. 2012; 34:38-43. https://doi.org/10.1016/j.proeng.2012.04.008

[10] Priego Quesada JI. Assessment of sport garments using infrared thermography. In: *Application of Infrared Thermography in Sports Science*. New York: Springer, Cham; 2017:159-183. https://doi.org/10.1007/978-3-319-47410-6_7

[11] Salopek Čubrić I, Skenderi Z. Effect of finishing treatments on heat resistance of one-and two- layered fabrics. *Fiber Polym.* 2014; 15(8) 1635-1640. https://doi.org/10.1007/s12221-014-1635-4

[12] Krstović K, Potočić Matković VM, Salopek Čubrić I, Čubrić G. Physical-mechanical properties of knitted fabric for swimsuits. *Tekstilec*. 2022; 65(3): 181–193; https://doi.org/10.14502/tekstilec.65.2022048

[13] Petrov A. Perspective of infrared thermography and its application in sport. In: *PhD Students´ day 2022: Book of Proceedings*. University of Zagreb Faculty of Textile Technology, Zagreb, Croatia, 2022, pp. 274-276. https://www.bib.irb.hr/1184173

[14] Venegas P, Ivorra E, Ortega M, Sáez de Ocáriz I. Towards the automation of infrared thermography inspections for industrial maintenance applications. *Sensors*. 2022; 22(2):401-406. https://doi.org/10.3390/s22020613

[15] Tomita K, Yit Lin Chew M. A review of infrared thermography for delamination detection on infrastructures and buildings. *Sensors.* 2022; 22(2):423. https://doi.org/10.3390/s22020423

[16] Online Etymology Dictionary. Thermography, Origin and meaning of thermography. https://www.etymonline.com/word/thermography Accessed September 7, 2022.

[17] Grubišić I, Gjenero L, Lipić T, Sović I, Skala T. Medical 3D thermography system. *Period. Biol*. 2011; 113(4):401–406. http://fulir.irb.hr/3401/1/str_401_406.pdf

[18] Šišić R, Hodžić A, Kevilj A, Hrustić O. Thermography and energy efficiency of dwelling structures. *Electronic Journal of the Faculty of Civil Engineering.* Osijek-e-GFOS. 2013; 4(7):24-31. https://doi.org/10.13167/2013.7.3

[19] Priego Quesada JI, Cibrián Ortiz de Anda RM, Pérez-Soriano P, Salvador PR. Introduction: Historical Perspective of Infrared Thermography and Its Application in Sport Science. In: Priego Quesada JI, ed. Application of Infrared Thermography in Sports Science. Biological and Medical Physics, Biomedical Engineering. Springer, Cham; 2017:1-23. https://doi.org/10.1007/978-3-319-47410-6_1

[20] Glavaš H, Barić T, Stojkov M. Application of infrared thermography in technical systems. In: *Processing of the 8th International Natural Gas, Heat and Water Conference PLIN*. Osijek, Croatia, 2017, pp. 33-50. https://www.bib.irb.hr/895216

[21] Haka AT. Thermography. In: Joseph DM, Cyrus CMM, ed. *Between Making and Knowing. Tools in the History of Materials Research.* Singapore: World Scientific Publishing Co; 2020:539-551. https://doi.org/10.1142/9789811207631_0047

[22] Bandeira CFC, Kenedi PP, Castro JTP. On the use of thermographic method to measure fatigue limits. *Lat. Am. J. Solids Struct*. 2018; 15(10):1-15. https://doi.org/10.1590/1679-78254331

[23] Aywin P, Racinais S, Bermon S, Lloyd A, Hodder S, Havenith G. The use of infra-red thermography for the dynamic measurement of skin temperature of moving athletes during competition; methodological issues. *Physiol Meas*. 2021; 42(8):1-20. https://doi.org/10.1088/1361-6579/ac1872

[24] Keyl W, Lenhart P. Thermography in sport injuries and lesions of the locomotor system due to sport. *MMW Fortschr Med*. 1975; 93(3):124–126. https://pubmed.ncbi.nlm.nih.gov/1173237/

[25] Salopek Čubrić I, Čubrić G. Body-mapping based on thermographic measurements under different influencing factors, Sigurnost: časopis za sigurnost u radnoj i životnoj okolini. 2021; 63(2):143-154. https://doi.org/10.31306/s.63.2.2

[26] Marins JCB, Fernández-Cuevas I, Arnaiz-Lastras J, Fernandes AA, Sillero-Quintana M. Applications of infrared thermography in sports. A review. *Rev Int Med Cienc Ac.* 2015; 15(60):805-824. https://www.researchgate.net/publication/286935481_Applications_of_Infrared_Thermography_in_Sports_A_Review

[27] Puszkarz AK, Wojciechowski J, Krucinska I. Analysis of the Thermal Insulation of Textile Using Thermography and CFD simulation Based on Micro-CT Models. *Autex Res. J.* 2020; 20(3):344-351. https://doi.org/10.2478/aut-2020-0003

[28] Nemcokova R, Glombikova V, Komarkova P. Study on liquid moisture transport of knitted fabrics by means of MMT, thermography and microtomography systems. *Autex Res. J.* 2015; 15(4):233-242. https://doi.org/10.1515/aut-2015-0022

[29] Salopek Čubrić I. Approach Towards Design and Functional Sportswear for Improved Human Performance. In: *Proceedings of the 8th International Ergonomics Conference*. Advances in Intelligent Systems and Computing. Springer, Cham. Zagreb, Hrvatska, 2020, pp. 3-11. https://doi.org/10.1007/978-3-030-66937-9_1

[30] Wang F, Del Ferraro S, Molinaro V, Morrissey M, Rossi R. Assessment of body mapping sportswear using manikin operated in constant temperature mode and thermoregulatory model control mode. *Int J Biometeorol.* 2014; 58(7):1673-1682. https://doi.org/10.1007/s00484-013-0774-4

[31] Salopek Čubrić I, Čubrić G, Potočić Matković VM. Behavior of polymer materials exposed to aging in the swimming pool: focus on properties that assure comfort and durability. *Polym.* 2021; 13(15): 2414. https://doi.org/10.3390/polym13152414

[32] Salopek Čubrić I, Čubrić G, Potočić Matković VM. Development of Ergonomic Sportswear Based on Thermal Body Mapping. In: *Proceedings of the 8th International Ergonomics Conference*. Advances in Intelligent Systems and Computing. Springer, Cham. Zagreb, Hrvatska, 2020, pp. 49-56. https://doi.org/10.1007/978-3-030-66937-9_6

[33] Mijović B, Salopek Čubrić I, Skenderi Z, Reischl U. Thermographic Assessment of Sweat Evaporation inside Clothing Systems. *Fibres Text. East. Eur*. 2012; 20(5):81-86. http://fibtex.lodz.pl/article787.html

[34] Pejnović N, Frančević B. Ispitivanje prijenosa topline kod zaštitne odjeće primjenom termovizijske kamere. *Sigurnost: časopis za sigurnost u radnoj i životnoj okolini.* 2019; 61(3):209-216. https://doi.org/10.31306/s.61.3.7

[35] Abreu MJ, Catarino AP, Haeussermann N. Comfort Effects of Weft-knitted Structures on Rowing Shirts Using IR Thermography. In: *Fiber Society Spring Conference 2016.* Haute Ausace, Mulhouse, France, 2016. https://www.researchgate.net/publication/312578026

[36] Korman P, Zielinski J, Kusy K, Straburzynska-Lupa A. Possible use of infrared thermography in sport. *Trends in Sport Sciences*. 2016; 2(23):57-62. https://www.researchgate.net/publication/305395742

[37] ISO 105-E04:2013 Textiles — Tests for colour fastness — Part E04: Colour fastness to perspiration.

[38] ISO 11092 Textiles — Physiological effects — Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test).

Prijenos tekućine i vodene pare kroz pletene materijale

Antonija Petrov[1], Goran Čubrić[1] i Ivana Salopek Čubrić[2]

[1]*Sveučilište u Zagrebu Tekstilno-tehnološki fakultet, Zavod za odjevnu tehnologiju, Zagreb, Hrvatska*

[2]*Sveučilište u Zagrebu Tekstilno-tehnološki fakultet, Zavod za projektiranje i menadžment tekstila, Zagreb, Hrvatska*

(Naučni rad)

Izvod

Sportska odjeća danas je bitan element za sve vrste sportskih aktivnosti diljem svijeta. Aktivna sportska odjeća je odjeća određenih funkcija koja zadovoljava očekivana svojstva i pruža odgovarajuću pomoć sportašima u postizanju sportskih rezultata. Osim funkcionalnosti, važan aspekt sportske odjeće je toplinska i fiziološka udobnost pri nošenju. Pravilnim odabirom odjeće, sportašima se značajno može smanjiti dinamičko i toplinsko opterećenje jer sport zahtijeva nesmetanu pokretljivost, a odjeća mora biti prilagođena tijelu i upijati znoj. Odgovarajući protok vodene pare i tekućine u tekstilnim materijalima važan je s gledišta udobnosti. Stoga je u ovom istraživanju odabrano sedam reprezentativnih uzoraka koji se koriste za odjeću namijenjenu sportu i slobodnom vremenu. Za ispitivanje su korišćeni infracrvena termalna kamera i uređaj za mjerenje apsolutne vlage. Pomoću infracrvene termalne kamere bilo je moguće precizno pratiti prijenos tekućine na površini materijala, sve do završne faze kada je materijal potpuno suh. Rezultati pokazuju da je poliester najprikladniji materijal za izradu sportske odjeće jer ne izaziva nelagodu pri nošenju, a infracrvena termografija je vrlo korisna metoda u istraživanju jer daje pouzdane podatke, posebice kada je u pitanju vrijeme sušenja materijala.

Ključne reči: Pletivo; močenje; termografija; sušenje; sportska odjeća