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Assessment of the Thermoregulation Properties of Textiles with Fibres Containing Phase Change Materials on the Basis of Laboratory Experiments

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Abstract

The problem of thermal discomfort affects thousands of people. One of the ways of reducing this problem is introducing phase change materials, which have an ability to absorb the excess heat in protective clothing. In this research two kinds of knitted fabrics with phase change materials were designed and produced for use in under-barrier protective clothing. These products were tested for their biophysical properties ie. thermal resistance, water vapour resistance, air permeability and hygroscopicity, thermoregulation properties: a measurement of the enthalpy by the DSC method and measurement of the TRF factor on a device simulating human skin, and the sorptive properties. On the basis of the results1), the impact of the clothing designed containing phase change materials, on the underwear microclimate, with an indication of their ability of taking off excess heat was assessed.

Key words: *phase change materials, thermal comfort, thermoregulation properties, underwear, protective clothing.*

Introduction

In recent years, significant technical progress in textiles has been observed. Besides multifunctional textiles and fabrics of high efficiency, there have appeared on the market a new class of fabrics and clothing - so called smart textiles, which are also named as active, interactive or adaptive. An important part of this group are textiles which can receive stimuli directly from the human body and the environment, and react to them through significant physical, chemical and biological changes that are often reversible. This group of textiles is used to support a human's thermoregulation process, especially in such conditions where the withdrawal of excess heat from the organism is necessary. As an example of such innovative products are the textiles mentioned with phase change materials (PCM).

The development of textiles intended to improve the thermal comfort of its user is closely connected with the trend of providing optimal working and life conditions, which can be achieved by physiological comfort. According to the WHO (World Health Organization) criteria, the internal temperature should be kept between (37 ± 1) °C to make the human organism function normally and for a longer period of time [1].

The features of textiles that support the thermoregulation process of their users allow them to be employed in protective clothing construction intended for use in difficult working environment conditions, including tight clothing impervious to water vapour, made of coated materials used for protection against aggressive chemicals which causes significant thermal stress for the human organism. Such clothing limits or even disenables heat exchange with the environment, leading to a rapid rise in the relative humidity and temperature in the underclothing microclimate [2]. Thus, working in such a type of protective clothing can be classified as very onerous. The problem of excessive heat stress concerns tens of thousands people working in barrier protective clothing protecting against chemical and biological factors, as well as water.

In the project conducted at the Central Institute for Labour Protection – National Research Institute (CIOP-PIB), the thermoregulation property of textiles with Phase Change Materials (PCM) was used to provide the considerable effect of removing excess heat generated while working in barrier protective clothing.

Phase Change Materials (PCM) selected for the research

As a solution to control the microclimate underneath hermetic protective clothing, research was begun aimed at designing new, active garments containing Phase Change Materials (PCM). PCM are able to change their phase (e.g. from solid to liquid and back to solid) in a certain temperature range known as phase change temperatures. During such changes, they can absorb, store and release energy as latent heat. Textiles with PCM compounds are described as being of the regulation or enthalpy type as they absorb or release heat depending on the parameters of their surroundings and level of physical activity of their user [3, 4].

The properties which were decisive when choosing an appropriate PCM were as follows: a high enthalpy per unit weight, large thermal capacity, possibility of use in clothing, low weight, and a phase change temperature similar to the human body temperature. Based on literature and data from PCM producer SmartCel^{TM} clima, fibre with PCM content was selected.

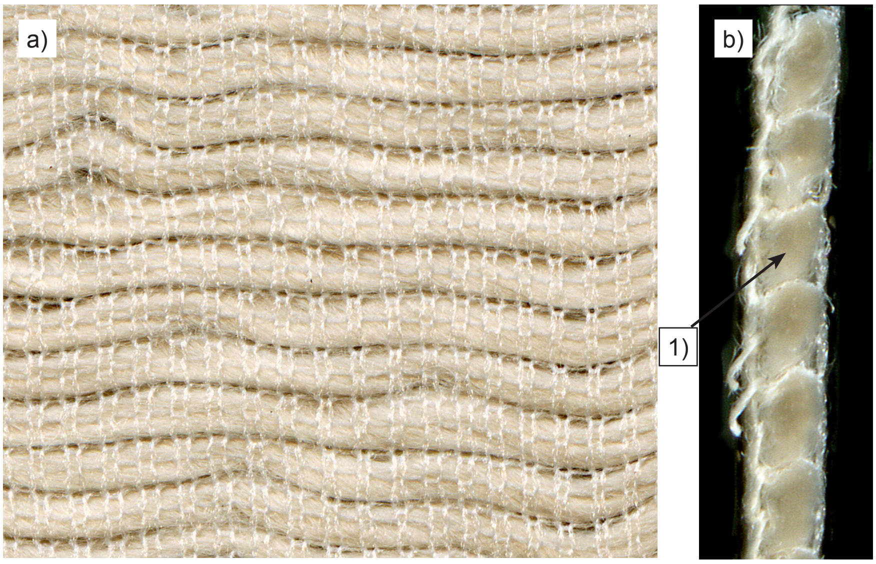

***Figure 1.** Photograph of a three-layer knitted fabric with PCM compound: a) view, b) cross-section along the course; 1 - roving.*

SmartCel^{TM} clima [5] is a cellulose fibre with the addition of PCM microcapsules. This product features higher latent heat than other fibres with PCM. On the basis of own research with the use of Differential Scanning Calorimetry (DSC), it was proved that their enthalpy is equal to 33-35 J/g and its phase change occurs at 29 °C. Their important feature is the content of Lyocell fibres, which have a high sorption of liquids. For the research, fibres characterised by a weight per length unit equal to 1.7 dtex were chosen. The fibres were used to make a yarn to produce a two-layer knitted fabric and a roving for application in a three-layer knitted fabric.

Textiles with phase change materials

Within the project [6, 7], two types of knitted fabrics with SmartCel^{TM} clima fibres were designed and produced:

- two-layer knitted fabric made of yarn with SmartCel^{TM} clima fibres, for an undergarment worn under protective clothing,
- three-layer knitted fabric with SmartCel^{TM} clima fibres, for a vest worn under protective clothing [4].

Because of the fact that there wasn't either yarn or roving available on the market which met the requirements of the project to produce above-mentioned knitted fabrics, it was necessary to design and produce those products from Smartcel^{TM} clima fibres selected to the project. The weight per unit length of SmartCel^{TM} clima roving was 630 tex and the yarn was 20 tex.

The roving and yarn were prepared in the experimental plant of the Department of Spinning Technology, Faculty of the Material Technologies and Textile Design at the Technical University of Lodz.

The two-layer knitted fabric was intended for underwear with an internal layer made of polyester and an external layer made of SmartCel^{TM} clima fibres with PCM. It was proved that such a construction of two-layer underwear is the most appropriate solution for shaping the microclimate under barrier protective clothing [8, 9]. The material contents of the knitted fabric, named S3 were as follows: PES 30%, Smartcel^{TM} clima 62%, and PA 8%. The thickness of the knitted fabric was 0.96 mm and its mass per square meter - 162 g/m^2 [4].

***Table 1.** A list of indicators characterizing the biophysical properties of the textiles*

Indicator	Symbol	Unit	Measurement method
Thermal resistance	Rct	m^{2}K/W	PN-EN 31092:1998 [11]
Water vapor resistance	Ret	m^{2}Pa/W	PN-EN 31092:1998 [11]
Air permeability	AP	mm/s	PN-EN ISO 9237:1998 [12]
Hygroscopicity	H	%	PN-P-04635:1980 [13]

For a vest to be worn under protective clothing, to ensure a relatively high content of phase change materials in the textile products, a new type of knitted fabric was developed based on a three-layer knitted fabric with extended inner layer roving containing SmartCel^{TM} clima fibres. This type of knitting fabric with other material filling – high-sorption fibres has been patented [10].

Two types of three-layer knitted fabrics were prepared (S1, S2) differing in the quantity of rovings introduced. In the S1 and S2 knitted fabrics, a roving of 640 tex linear density was used. In the S1 knitted fabric, 35 rovings per 1 dm were introduced, while in the S2 knitted fabric – 50 rovings per 1 dm. The mass per square meter of the S1 knitted fabric was 322 g/m^2 and its thickness – 1.58 mm, while the mass per square meter of the S2 knitted fabric was 450 g/m^2 and the thickness – 1.99 mm. The material composition of S1 was as follows: PES 5%, SmartCel™ clima yarn 25%, SmartCel™ clima roving 70% and for S2: PES: 5% Smartcell™ clima yarn 17%, SmartCel™ clima roving 78%; in total, for both three-layer knitted fabrics, the fibre composition was PES 5% Smartcell™ and clima 95% [4]. In ***Figure 1***, there is a view of the S2 knitted fabric and its cross-section.

The knitted fabrics with phase change materials were produced at the Department of Knitting Technology, Faculty of Material Technologies and Textile Design at the Technical University of Lodz.

Methodology of measuring the properties of textiles with PCM which could have an influence on the underclothing microclimate

While establishing the methodology, the fact that the knitted fabrics produced were intended for use under barrier protective clothing was taken into account. As the main property influencing the microclimate, the ability to draw excess heat and moisture generated by the human body while working in barrier protective clothing was chosen.

The methodology proposed included tests of the standard biophysical properties of clothing materials such as the thermal resistance, water vapour resistance, air permeability and hygroscopicity, which have an influence on the underclothing microclimate and thermal comfort of the clothing user, as well as tests of properties characterising the activity of the materials designed towards taking off excess heat and sweat generated by the body in dynamic conditions: the enthalpy, the TRF factor and dynamics of the sorption capacity.

Measurement of biophysical properties

Measurements of the biophysical properties were conducted according to standardised methods.

The value of the **thermal resistance** of materials not intended for protection against the cold is a very important parameter while taking into account the drawing of excess heat from the human body. **Water vapour resistance** is considered as a basic parameter characterising the biophysical properties of clothing materials because it has an influence on removing water vapour from the underclothing microclimate. Then it supports the evaporation of sweat produced by the organism. Of similar importance is the **air permeability** of clothing materials. Materials intended for clothing worn close to the body should be characterised by low values of water vapour resistance and air permeability. A high value of **hygroscopicity** of materials intended for clothing worn under barrier protective clothing (not permeable to water vapour) has positive significance because of the possibility to absorb excess water vapour in the underclothing microclimate. The clothing used under barrier protective clothing should be characterised by a high value of hygroscopicity; however, under condition that the layer close to the body is made of hydrophobic fibres that do not absorb moisture (eg. PES). Then the skin has contact with a dry layer of the underwear.

In ***Table 1***, the methods of measuring the biophysical properties of clothing materials are presented.

Measurement of the enthalpy by Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry allows for the observation and quantity assessment of the thermal effects occurring while either heating or cooling the material tested. This method is very useful for testing materials characterised by physical or chemical transformation during heating or cooling. The group of physical phenomena that can occur during the heating or cooling process includes melting, evaporation, sublimation or crystallization, while the group of chemical phenomena is thermal decomposition or oxidation.

The measurement principle is based on simultaneous heating and cooling in the same conditions of the tested substance and the standard substance. As the standard substance, a material which is not subject to any physical or chemical transformation during heating or cooling was chosen. A test sample and standard sample are put directly on very sensitive thermoelements. Those thermoelements allow for precise measurement of the voltage difference, which corresponds to the temperature difference of the test sample or standard sample. If during the heating or cooling of the test or standard sample, there are no physical or chemical changes in which absorbing or generating heat occurs, the temperature of the test and standard sample is the same.

In the case of the occurrence of a transformation during the heating, a process of heat absorbance can be observed, in which case the temperature of the sample is lower than that of the standard sample, with the measuring system showing this difference. An analogous situation is when the generation of heat can be observed, in which case the temperature of the sample is higher than that of the standard sample.

In this research the measurement of thermoregulation properties by the DSC method was conducted on:

- Smartcel^{TM} clima fibres,
- Three-layer knitted fabrics with rovings of Smartcel^{TM} clima fibres - S1 and S2,
- Two-layer knitted fabrics with Smartcel^{TM} clima fibres in a yarn - S3.

Measurement of the enthalpy was performed on a Perkin - Elmer DSC-6 (US Instrument Division Norwalk, CT) in a range of temperatures from -5 to 50 °C in a dry nitrogen atmosphere (the flux was equal to 20 ml/min) with a heating speed of 5 °C/min. Measurements of the enthalpy were carried out at the Department of Man-Made Fibres, Faculty of Material Technologies and Textile Design at the Technical University of Lodz. Because of the fact that knitted fabrics S1, S2 and S3 mainly consist of cellulose fibres characterised by a high water sorption, the decision was made to perform enthalpy measurements after the initial drying [14]; otherwise, the water contained in the samples could evaporate, changing their weight and characteristics of thermal effects observed. The method of drying involves heating the sample to 105 °C for 20 – 30 minutes so that the water contained in the sample is removed.

In the DSC method a very important aspect is to prepare samples which are appropriate for the analysis. The measurement device is a very sensitive apparatus which allows to analyse samples whose weight is about 3-5 mg. Powdered samples of the knitted fabrics with PCM designed were heated in closed aluminum cells from a starting temperature of -5 °C to a final temperature of 50 °C at a constant speed equal to 5 °C/min, and after reaching 50 °C, the samples were cooled with the same speed.

Dynamic tests of thermoregulation properties on a device simulating human skin

Tests were conducted on a measurement stand that simulates the skin – clothing – environment relation. Its basic element is a hot plate with the possibility of regulating the heat flux delivered, which is sinusoidally changed, imitating changes in the generation of heat by a human in clothing during physical activity [15, 16], and allows to designate the thermal regulation factor (TRF).

A sample of the material tested covers the hot plate on both sides. On both sides of the hot plate there are also cold plates of constant temperature which imitate the environment. As a result of the test, temperature changes in the hot plate are measured, which can be identified as the response of the system tested for heat flux changes.

In a steady-state, the device measures the thermal resistance of fabrics, which is defined as a quotient of the difference between the temperatures of the hot plate and cold plates and the heat flux delivered to the hot plate.

The thermal regulation factor TRF defined by Hittle [17] is as follows:

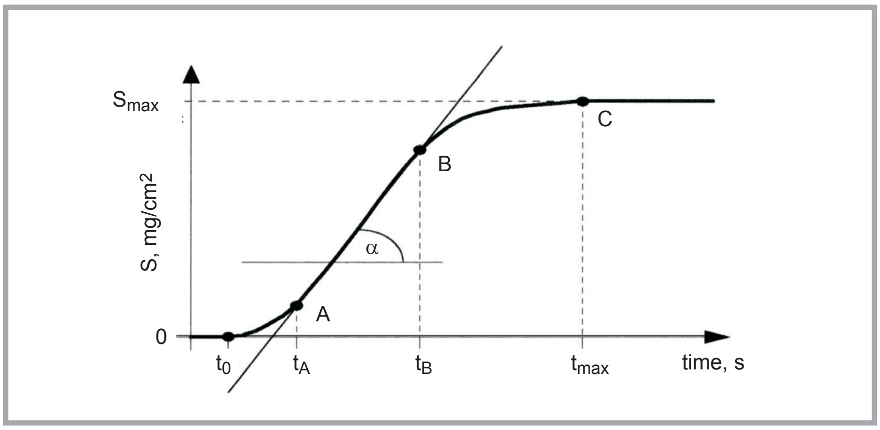

***Figure 2.** Typical sorption curve.*

***Table 2.** Results of measurements of the biophysical properties of knitted fabrics with PCM.*

Variant	Thermal resistance - R_{ct}, $m^2 \times K/W$	Water vapor resistance - R_{et}, $m^2 \times Pa/W$	Air permeability - A_p, mm/s	Hygroscopicity - H, %
S1	0.062	3.98	335	21.0
S2	0.052	5.43	178	20.3
S3	0.034	2.71	2367	15.2

$$TRF = \frac{T_{max} - T_{min}}{q_{max} - q_{min}} \frac{1}{R} \qquad (1)$$

where:

$(T_{max} - T_{min})$ – amplitude of temperature changes on the hot plate,

$(q_{max} - q_{min})$ – amplitude of heat flux changes,

R – thermal resistance in a steady-state.

TRF is used for the assessment of multilayer clothing systems and for comparing fabrics with PCM. TRF is a dimensionless number from (0,1); TRF = 1 means that the test material does not have thermoregulation properties, while TRF = 0 means that the test material has an infinite thermal capacity, and the heat in contact with it will maintain a constant temperature.

In this research, because of the intended use of the fabrics with phase change materials, the following test conditions were adopted:

- temperature of the hot plate: 33 °C,
- temperature of the cold plates: 20 °C,
- periods of heat flux changes: 240 s, 480 s, 600 s, 720 s, 900 s, 1200 s,
- amplitude of heat flux changes: 50 W/m^2.

***Table 3.** Results of the TRF measurements.*

Period of the heat flux changes, s	TRF factor	
	Sample S1	Sample S2
240	0.60	0.51
480	0.77	0.70
600	0.82	0.77
720	0.86	0.80
900	0.90	0.84
1200	0.94	0.92

Measurements of the thermoregulation factor TRF were conducted at the Textile Research Institute of Lodz.

Measurement of the sorption capacity

To evaluate the knitted structures produced for their capacity to absorb and drain liquid sweat, the method of determining indices of sorption in superficial contact with liquid was applied. The method reflects the actual conditions of use [18] of a garment in contact with sweating human skin and allows to assess the sorption phenomenon over time. A sample of the textile product rests upon the porous plate of a Schott's funnel, whose top surface is the liquid level, kept constant by automatic control. The liquid absorbed by the sample is refilled continuously by the hydraulic system. A quantity of the liquid refilled, in the form of impulses regulated in the time function, is recorded and processed to be expressed on a sorption curve graph. The graph of the quantity of water absorbed by a unit surface of the sample in the time function [S] is the basis for an analysis of the indices determining a course of the sorptive process [14]. A typical sorption curve graph obtainable by applying the method under discussion is depicted in ***Figure 2***.

The proper sorption time is characterised by a rapid (rectilinear) increase in the liquid mass of the sample volume. The tangent of the inclination angle of the AB segment to the X-axis defines the **sorption velocity** V_{30-70} in mg/(cm^2·s).

The saturation stage begins at the moment of an abrupt decrease in the sorption velocity and lasts until the complete cessation of the liquid mass increase. At that point, the maximum sorption - S_{max}, expressed as the mg of the absorbed liquid per cm^2 of the sample, is determined. The time corresponding with that point is defined as the total sorption time t_{max} in s.

Assuming that during the use of tight protective clothing, acontinuous, intensive sweat secretion takes place and that the undergarment and vests with PCM will be used under the pressure of the outer barrier clothing layer, the following measurement conditions were adopted:

- pulsative liquid supply – 0.2423 mg,
- pressure exerted on the sample – 0.5 kPa,
- range of AB curve interval used for determination of the sorption velocity 30 - 70% S_{max},
- pre-set time - 20 s – time of termination of the measurement, after which, if no subsequent liquid supply is absorbed, the hydraulic system switches off.

In order to approximate the actual conditions associated with sweat secretion, tests were carried out using an acid sweat substitute according to PN-P-4913:1996 [19], based on literature data concerning the chemical composition of sweat [4].

Results of measuring the impact of textiles with PCM on the underclothing microclimate

Results of measurements of the biophysical properties

Results of measurements of the thermal resistance, water vapour resistance, air permeability and hygroscopicity of the knitted fabrics produced are presented in ***Table 2***.

Results for enthalpy from the DSC method

Results of the measurement of enthalpy for PCM fibres and knitted fabric with

PCM carried out by the Differential Scanning Calorimetry (DSC) method were obtained in the form of thermograms. On the basis of their analysis for Smartcel™ clima fibres, it was found out that phase change materials, which are in the fibres, change their phase at a temperature of 28.8 °C and that those fibres are characterised by a phase change heat equal to 33-35 J/g. The shape of the pick connected with the melting shows that the substance introduced to the fibres most likely consists of two different components, and the melting temperature established may suggest that those components are two alkanes: n-octadecane (whose melting temperature is 28.2 °C) and n-nonadecane (melting temperature - 32.1°C).

From the thermogram of the knitted fabric S1, it can be stated that the pick connected with the melting is quite narrow and high (5.4 mW) and the thermal effect connected with the metling is equal to 20.5 J/g. Thermal measurements of the S2 three-layer knitted fabric showed that its behaviour is similar to that of S1 and its phase change heat is equal to 19.5 J/g. The thermogram of the knitted fabric S3 also has a similar curve shape, and its phase change heat is 18 J/g.

Results of measurements of thermoregulation properties conducted on a device simulating human skin

Results of dynamic tests of thermoregulation properties conducted on a device simulating human skin are presented in ***Table 3***.

Measurement of the TRF for the knitted fabric S3 could not be made because of its too small thickness, therefore it was decided to make a measurement only for knitted fabrics S1 and S2.

Results of liquid sorption

Results of the measurement of liquid sorption are presented in ***Table 4***.

Analysis of results of the thermoregulation and sorption properties of textiles with phase change materials

The results of measurements presented in ***Table 2*** allows to state that the materials produced are characterised by satisfactory biophysical properties.

Table 4. *Indicators of the liquid sorption of knitted fabrics with PCM.*

Symbol of the fabric	S1	S2	S3
Value of the sorption, S_{max}, mg/cm^2	171	170	115
Maximum speed of the sorption, V_{max}, mg/cm^{2}s	6.5	14.6	11.5
Mean spead of the sorption, $V_{30\text{-}70}$, mgl/cm^{2}s	5.0	13.8	9.5
Total time of the sorption, S_{max}, s (median)	83.5	23.8	24.5

Measurements of the thermal resistance of the knitted fabrics with PCM designed show that the lowest value of thermal resistance (0.034 $m^2 \cdot K/W$) and very low water vapour resistance R_{et} equal to 2.71 $m^2 \cdot Pa/W$ was obtained in the case of the knitted fabric S3 [4]. It is a satisfactory result because the intended use of this material is in underwear, and in accordance with literature data the thermal resistance of such materials should be at a level less than 0.040 $m^2 \cdot K/W$ and the water vapour resistance less than 6 $m^2 \cdot Pa/W$ [8].

In the case of knitted fabrics with PCM S1 and S2, the values of thermal resistance were higher than in the case of S3 but similar to each other. For the knitted fabric S1, it is equal to 0.062 $m^2 \cdot K/W$ and for S2 - 0.052 $m^2 \cdot K/W$. This value is a result of the high density of Smartcel™ clima fibres in their structure; however, those products are not intended for use in underwear, but for vests worn on the underwear. It should also be noted that those knitted fabrics are characterised by a low value of water vapor resistance (3.98 – 5.43 m^2PaW), suggesting that they will not be a barrier for sweat evaporation, which is also supported by the high value of air permeability of the knitted fabric S3 (2367 mm/s). Knitted fabrics S1 (335 mm/s) and S2 (178 mm/s) are also air permeable but much lower than the knitted fabric S1 because of the dense packing of Smartcel™ clima fibres.

Hygroscopicity characterises the ability of the test knitted fabrics to absorb sweat vapour. The high value of hygroscopicity for knitted fabrics S1 and S2 (about 21%) is because of the high content of sorptive Lyocell fibres. A high sweat vapour sorption, because of the Lyocell fibre content, was also observed for the knitted fabric S3 (hygroscopicity - 15.2%) under conditions described in [4]. The results achieved showed that the structures produced should provide good water vapor sorption during sweat evaporation under barrier protective clothing, where there is no possibility of removing the sweat outside the barrier [4].

Tests performed using the DSC method indicated that Smartcel™ clima PCM fibres are characterised by a lower value of latent heat from the phase change than that published in the product catalogue - 33 – 35 J/g [4]. Textile products S1, S2 and S3 show similarity in their thermal behaviour and enthalpy values not as high as for SmartCel fibres, due to other fibres (PES) present in their structures. The enthalpy of S1 equals 20.5 J/g and that of the knitted fabric S2 equals 19.5 J/g, while for the knitted fabric S3 it is 18.0 J/g [14]. Moreover, it should be noted that due to the large content of SmartCel™ clima fibres, the satisfactory effect of taking off heat by the underwear fabric should be achieved; this material is intended for use underneath any type of vest with PCM content, which would support the thermoregulation effect. Taking into account the mass per square meter of the knitted fabrics with PCM and also the body surface they cover, from which they take off heat (vest - 0.57 m^2, underwear – 0.95 m^2), the amount of heat that can be taken off from the body and absorbed by the knitted fabrics designed can be calculated. Then it can be assumed that a vest made of the three-layer the knitted fabric S1, whose mass per square meter is 322 g/m^2 and thermal capacity is 19 J/g, can absorb excess heat equal to 3.48 kJ, while a vest made of the knitted fabric S2 with a mass per square meter of 450 g/m^2 and thermal capacity of 20 J/g can accumulate excess heat equal to 4.3 kJ. Underwear made of the two-layer the knitted fabric S3, whose mass per square meter is equal to 162 g/m^2 and thermal capacity - 18 J/g, is able to absorb excess heat equal to 2.8 kJ.

On the basis of the result analysis of the TRF factor, it can be stated that both S1 and S2 are characterised by similar thermoregulation properties, but S2 with a higher PCM content (78% SmartCel™ clima roving) has a little higher value of the TRF factor. The measurements of the TRF for S1 and S2 showed that knitted fabrics with PCM roving feature thermoregulation properties; however, they are quite weak, especially over longer periods of heat flux changes. The high values of TRF (in a period of heat flux changes equal to 720 s and more) mean that there may not have been enough PCM contained in the S1 and S2 samples to achieve a satisfactory thermoregulation effect in all of the conditions chosen.

The measurement results from ***Table 5*** show that the knitted fabrics with Smartcel^{TM} clima fibres tested are characterised by a high value of sorption capacity because of the high content of cellulose fibres Lyocell. The maximal liquid sorption of the knitted fabric S3, which is intended for use in underwear, is equal to 115 mg/cm^2, which is a very good result. This knitted fabric is made of 38% polyester in the layer close to the body, which causes that moisture is transported to the external layer and the fabric stays in dry contact with the skin of the user. A higher value of liquid sorption is featured by both S1 and S2, where highly absorbent fibres in the rovings are surrounded by hydrophobic polyamide fibres, suggesting that the wet feeling occurring while using vests made of knitted fabrics S1 and S2 will be avoided.

Conclusions

In this research two kinds of knitted fabrics with phase change materials were designed and produced: two-layer knitted fabric with PCM in the yarn and three-layer knitted fabric with PCM in the roving to increase the thermoregulation effect. Those products were assessed in terms of their thermoregulation properties and the ability to transport moisture from the human body during use under barrier protective clothing.

On the basis of the results obtained from the measurements of the thermoregulation properties of the two-layer knitted fabric with PCM in the yarn and three-layer knitted fabric with PCM in the roving, it can be stated that those products are characterised by a very high enthalpy, and hence an ability to absorb heat, as compared to other textiles offered on the market. The satisfactory biophysical properties of the new textiles with PCM suggest that they can be used in clothing intended for use under protective clothing. Taking into account the significant thermal stress of the user of protective clothing, their thermoregulation properties may not be enough to take off excess heat during intensive physical effort in this type of protection. However, it can be assumed that those structures can be appropriate for use under other types of protective clothing as thermoregulatory textiles in colder conditions, as they are characterised by a high density of fibres, influencing thermal resistance.

Moreover, on the basis of the results from the liquid sorption measurements, it can be stated that because of the high content of Lyocell cellulose fibres, those products will provide the satisfactory drawing of liquid perspiration from the user's skin as well as appropriate relative humidity and temperature in the underwear microclimate while using tight (barrier) protective clothing.

The next article will present an assessment of the textiles with a Smartcel^{TM}-clima fibres containing PCM on the basis of ergonomic tests on volunteers in a microclimatic chamber.

Editorial note

1. *This publication presents the results of research conducting in the scope of the Long-Term Research Program: Improvement of Safety and Work Conditions - I stage*

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