Textile
Research
Journal

Original article

Textile Research Journal
83(2) 148–159

DOI: 10.1177/0040517512460299
trj.sagepub.com
SAGE

Analysis of thermoregulation properties of PCM garments on the basis of ergonomic tests

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Abstract

Work in impermeable protective clothing leads to a significant thermal load on its user. Limited heat and moisture transport, which is an effect of using air- and moisture-impermeable coated fabrics in protective clothing, causes a significant increase of the temperature and relative humidity in the undergarment microclimate and, as a consequence, a rise of the skin and core temperature. To protect a worker from the thermal load, three types of garments with phase change materials designed to be worn under impermeable clothing have been developed and tested. The research, conducted with the participation of volunteers in a microclimatic chamber, has proved a statistically significant positive effect of the phase change materials, in the form of macrocapsules contained in the garment, on the undergarment microclimate underneath the barrier protective clothing.

Keywords

phase change materials, thermal comfort, thermoregulation effect, protective clothing

The necessity to protect the worker against hazardous and dangerous factors in the working environment imposes the obligation to use protective clothing. However, such clothing is often a source of additional and significant thermal load of its user during the work. This concerns in particular barrier (impermeable) protective clothing made of coated fabrics, designed for protection against chemicals. Owing to the fact that this kind of clothing constitutes a barrier between the man and the hazardous working environment, it is also an obstacle for heat and moisture exchange between the body and the environment. The heat produced by the human organism during work cannot be fully transferred to the environment, which leads to an imbalance between body heat production and heat loss. Then, a fast increase in the values of temperature and relative humidity of the undergarment microclimate occurs, which consequently causes an increase of the body and skin temperatures.[1,2]

Working in impermeable protective clothing increases the thermal stress of its user and his cardiovascular system.[3] Unfavorable changes in the values of the human physiological parameters (heart rate, core and skin temperatures) and the physical parameters of the microclimate under impermeable protective clothing are the reason for thermal stress of its user. As a consequence, it contributes to reduction of the permissible working time and impairs the performance of the garment user. Using coated protective clothing in hot environment is particularly burdensome for the human organism. Even low work intensity in impermeable protective clothing in heat allows only short exposure times and requires long rest periods.[4]

There are activities undertaken with the aim to lower thermal discomfort connected with working in impermeable protective clothing. A certain reduction of the thermal discomfort associated with wearing impermeable protective clothing can be obtained by using properly designed two-layer underwear (with a synthetic

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diffusion layer and a hygroscopic sorptive layer), superabsorbent inserts underneath this kind of clothing or underwear produced by modified fibers.[5,6] However, in the case of using them under the impermeable protective clothing that leads to the significant thermal discomfort of the user, they may not be sufficient. Thus, research works showed that such underwear constructions, despite providing moisture management, should be additionally supported by cooling solutions.

One of such solutions involves introducing cooling systems to the clothing structures,[7,8] including systems with forced liquid and air circulation.[9] Despite the generally positive assessment of their influence on the decrease of the thermal load imposed on the clothing user, they do have some shortcomings, such as their mass and lack of full mobility of the worker. These shortcomings can be avoided by the application of appropriately selected phase change materials (PCMs) implemented into the protective clothing structure or textiles worn underneath it.[10–13] PCMs are able to change their physical state in a particular temperature range. During this change they can absorb, store or release large amounts of energy in the form of latent heat.[14]

In the present study, it was assumed that the garment with PCM content designed to be worn underneath impermeable protective clothing should remove the excess heat generated by the user during work. Such a solution with PCMs was a basis for the development of new garment types with PCM content that can regulate the microclimate underneath impermeable protective clothing.

The aim of this study was to assess the effectiveness of the developed garments with PCMs in absorbing excess body heat generated during exercise in impermeable protective clothing.

Characteristics of the garments used in the study

Phase change materials selected for garment structures

While designing clothing structures with PCM content, the following criteria of appropriate PCM selection were adopted: high melting heat (high enthalpy) of the material; a possibility to use the PCM in clothing; a phase change within the temperature range close to the temperature comfortable for the skin. On that basis, two kinds of PCMs were selected: fibers with PCMs in the form of microcapsules introduced to their structure and PCMs in the form of macrocapsules. The details concerning the selected PCMs, including the analysis of enthalpy by the Differential Scanning Calorimetry (DSC) method,[15] are presented in Table 1.

smartcel™ clima fibers with PCM microcapsules produced by SmartfiberAG feature the highest latent heat of fibers with PCM available on the market (own market survey). smartcel™ clima fibers are Lyocell fibers (about 47% of cellulose content), which means that they are characterized by high sorption of liquids. That is why it was assumed that smartcel™ clima fibers have an ability to regulate both the temperature and the relative humidity in the undergarment microclimate underneath impermeable protective clothing.[16]

The second type of the selected PCMs are macrocapsules: MacroPCM (MPCM) 28 C made of paraffin wax (octadecane), about 4 mm in diameter, produced by Mikrotek Laboratories Inc.[17] This kind of PCM was selected because of much higher enthalpy in comparison to other PCMs and the form of beads that may be introduced to the fabric of the channel structure, saving its textile character.

Characteristics of fabric structures with PCM

Three kinds of knitted fabrics with PCM content were designed and produced during the described study:[15,18]

1. a two-layer knitted fabric made of a yarn with smartcel™ clima fibers – mS3;
2. a three-layer knitted fabric with a roving made of smartcel™ clima fibers – mS2;
3. a three-layer knitted fabric with a canal structure filled with MPCM 28 macrocapsules – mK1.

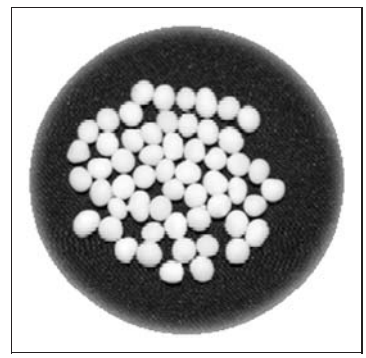
Symbols correspond to our previous publications and result from the order of conducted knitting process. All knitted fabrics were produced on the rip knitting machine. Detailed characteristics of fabric structures were presented in previous papers.[15,18]

The inner side of the two-layer knitted fabric (mS3) is made of textured polyester (PES). The task of this layer is to draw up and transport moisture to the external layer, which is made of the smartcel™ clima yarn 20 tex. The material content in the two-layer knitted fabric is: 30% PES, 62% smartcel™ clima and 8% PA 6.6.

To ensure relatively high content of PCMs in the designed textile products, a new three-layer knitted fabric with extended inner layer in the form of roving containing smartcel™ clima fibers (mS2) has been introduced. Such three-layer knitted fabric consists of 5% PES, 25% smartcel™ clima yarn and 70% smartcel™ clima roving.

Within the framework of this study, a unique fabric construction was also developed: a two-layer knitted fabric with canals that creates a three-layer structure after filling with PCM macrocapsules (mK1).

Table 1. Characteristics of phase change materials (PCMs) selected for the research

No.	Kind of PCM	Manufacturer	Phase change temperature [°C]	Enthalpy (DSC method) [J/g]	Photo
1	smartcel™ clima fibers with PCM microcapsules (>33% of active component paraffin) in a form of yarn[11]	SmartfiberAG	28	33	
2	MPCM 28 macrocapules[12]	Microtek Laboratories Inc.	28	154	

DSC: Differential Scanning Calorimetry.

Such fabric construction is a subject of the patent application no. P-396551 dated 5 October 2011 – the inner layer is made of PES and the external layer is made of smartcel™ clima yarn.

Characteristics of the developed knitted fabric with PCM content are presented in Table 2.[13,14] As mK1 is not a typical textile structure, thermal resistance, water vapor resistance, hygroscopicity and air permeability have not been tested for this material.

Construction of the new garments with PCM content

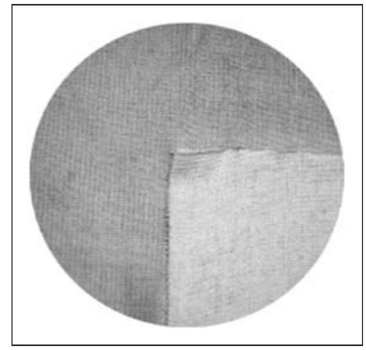
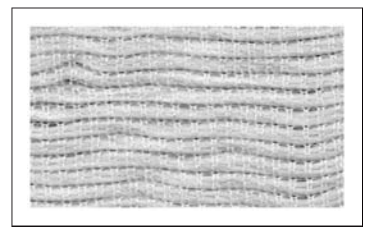
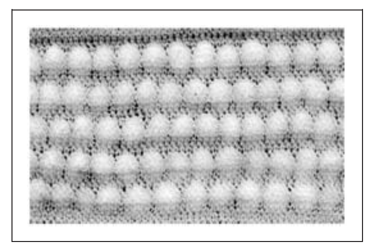
New types of knitted fabrics with PCM content were designed for the underwear and two kinds of vests. The main task of the garments with PCM is to remove the excess heat produced under barrier protective clothing, and at the same time not to limit heat transfer from the body to the environment.

Two-layer underwear made of the smartcel™ clima yarn. The two-layer knitted fabric made of yarn with smartcel™ clima (mS3), due to two-layer structure supporting liquid transport, was adopted for producing the underwear, which consists of a T-shirt with long sleeves (Figure 1(a)) and pants with long legs (Figure 1(b)). Such underwear is designed for wearing under the vests with PCM and barrier protective clothing and is marked with the S3 symbol in the further part of the paper.

Three-layer vest with smartcel™ clima rovings. The three-layer knitted fabric filled with smartcel™ clima rovings (mS2) was intended for a vest in the form of slipover worn on the PCM underwear underneath impermeable protective clothing. Such garment construction with three-layer structure characterized by high content of rovings with PCM microcapsules in fibers was proposed to maximize the ability to remove excess heat from the user's body during work. The vest is marked as S2 in the further part of the paper and is presented in Figure 1(c).

Three-layer vest with MPCM 28 macrocapsules. The three-layer knitted fabric, characterized by a canal structure

Table 2. Characteristics of the developed knitted fabric with phase change material (PCM) content[15,18]

Symbol	Thickness[a] [mm]	Mass per square meter[b] [g/m²]	Enthalpy [J/g]	Photo
mS3	0.96	162	18	
mS2	1.99	450	20	
mK1	4.8	1259	150	

[a]EN ISO 5084:1996. Textiles – determination of thickness of textiles and textile products (ISO 5084:1996).[19]
[b]ISO 3801:1977. Textiles – woven fabrics – determination of mass per unit length and mass per unit area.[20]

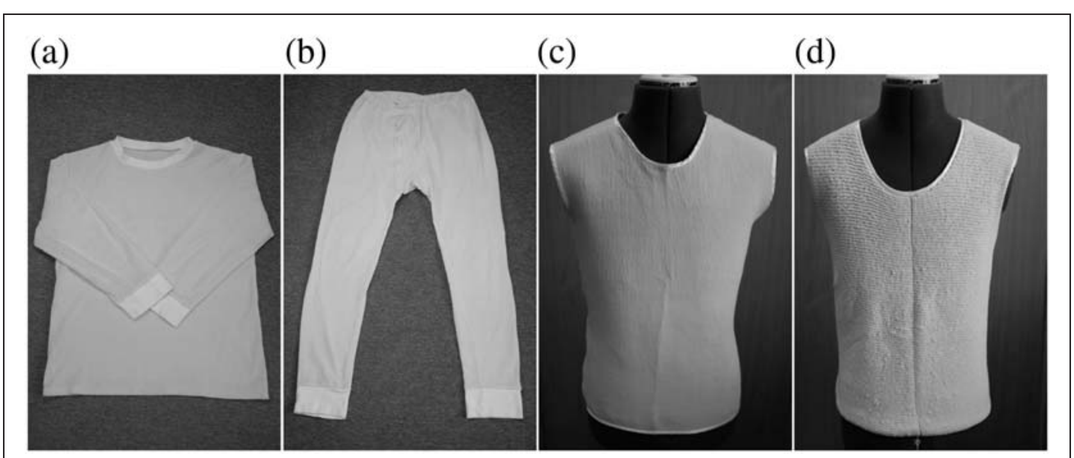


Figure 1. Photos of the designed garments with phase change material (PCM): (a) T-shirt of the two-layer underwear with PCM content (S3); (b) pants of the two-layer underwear with PCM content; (c) three-layer vest with smartcel™ clima rovings (S2); (d) three-layer vest with MPCM 28 macrocapsules (K1).

filled with PCM macrocapsules (mK1), was also intended for a vest, similarly as in the case of the three-layer vest with smartcel™ clima rovings. High content of PCM macrocapsules – 1067 g/m^2 – and their high enthalpy of 154 J/g should support human thermoregulation processes during work that requires wearing impermeable barrier protective clothing. This vest is marked as K1 in the further part of the paper and is presented in Figure 1(d).

As opposed to the known solutions where PCMs are introduced to the clothing structure in the form of isolated packs, such clothing construction where PCMs are in direct contact with the skin is unique, as there is lower thermal resistance between the skin and PCM so it can provide better thermal comfort. Introducing PCMs directly in the fabric structure ensures high flexibility of the garment and also good biophysical properties, such as air permeability or water vapor permeability, which may be limited by the pocket material proposed in other solutions.[12,13,21]

Other types of clothing used in the study

Cotton underwear. For the comparative variant, cotton underwear was selected as it is traditionally used under the barrier chemical protective clothing. It consists of a T-shirt with long sleeves and pants with long legs that are made of 100% cotton interlock knitted fabric, characterized by mass per square meter of 164 g/m^2 and thickness of 0.88 mm. For this cotton knitted fabric, the basic parameters that characterize its biophysical properties were measured: thermal resistance – 0.040 m^{2}K/W, water vapor resistance – 7.43 m^{2}Pa/W and hygroscopicity – 13.21%.[15,18]

L2 barrier chemical protective clothing. For research purposes, the L2 overalls were selected as the impermeable protective clothing. This kind of suit is intended for protecting the user against liquid chemical substances, especially concentrated acids or alkalis. It is made of polyamide fabrics coated by a gum mix based on butyl rubber on both sides. Its mass per square meter is 300 ± 20 g/m^2. The L2 suit features permanently fixed wellingtons and a hood.

Study of the designed PCM garments on the volunteers

To assess the impact of the developed garments with PCM content on human physiological parameters and the undergarment microclimate while working in impermeable protective clothing, the following research methodology was applied. The analysis was based on tests of PCM garments worn by volunteers walking on a treadmill in the microclimatic chamber, under specific environmental conditions. The proposed garment testing methodology applied to the volunteers gained the approval of the Research Ethics Committee.

Variants of clothing sets selected for the study

For further research, two sets of clothing were composed from the developed PCM garments. The first one consisted of two-layer underwear made of smartcel™ clima yarn (S3), a three-layer vest with smartcel™ clima rovings (S2) and impermeable protective clothing (L2). The second set of garments included two-layer underwear made of smartcel™ clima yarn (S3), a three-layer vest with MPCM 28 macrocapsules (K1) and impermeable protective clothing (L2).

To assess the effectiveness of the proposed PCM garments, a comparative variant was taken into account. It consisted of commonly used cotton underwear (BB) and impermeable protective clothing (L2).

Characteristics of the garment variants selected for the measurements on volunteers in the microclimatic chamber are presented in Table 3.

The volunteers participating in the study wore all different kinds of clothing, assigned on a random basis.

Characteristics of the volunteers

All the volunteers underwent medical and physical examinations. The aim of these initial examinations was to select five healthy men with similar characteristics and physical performance. The medical examination included an interview and electrocardiogram (ECG) analysis, while the physical performance examination included a maximal effort test conducted on a cycloergometer with an increasing load – beginning with the load of 50 W and increasing it by 50 W increments at each further level. Each load was set for 3 min and the test was conducted until exhaustion.

As the result of the medical and physical examinations, five men (22.6 ± 2.6) years old were chosen. They had similar physical performance and physique parameters. They were (181.2 ± 1.1) cm tall, weighed (77.7 ± 4.4) kg and their mean physical capacity was equal to (41.2 ± 2.4) ml $VO_2 \cdot kg^{-1} min^{-1}$.

The test methodology

The volunteers had sensors affixed and were dressed in an appropriate set of garments in a laboratory where the atmospheric conditions were as follows: air temperature (23 ± 1)°C and relative humidity (35 ± 5)%. This procedure lasted about 30 minutes.

After that, they went to the Climatic-Walk-in-Test Chamber, a Weiss System (Germany) microclimatic

Table 3. Variants of the garments selected for the measurements on volunteers in the microclimatic chamber

No.	Symbol	Set of garments	Total weight [g]	Mean effective thermal insulation [°Cm^{2}W^{-1}]
1	BB/L2	Cotton underwear + L2 overalls (a comparative variant)	3483 g	0.133
2	S3 + S2/L2	Underwear made of two-layer knitted fabric with Smartcel™ clima yarn (S3) + vest made of three-layer knitted fabric filled with the roving of Smartcel™ clima fibers (S2) + L2 overalls	3290 g (where the vest S2: 334 g)	0.146
3	S3 + K1/L2	Underwear made of two-layer knitted fabric with Smartcel™ clima yarn (S3) + vest with MPCM 28C macrocapsules (K1) + L2 overalls	3986 g (where the vest K1: 1021 g)	0.144

chamber, in which the climatic conditions during all of the experiments were as follows:

- air temperature (22.1 ± 0.1)°C;
- air flow velocity (0.15 ± 0.03) ms^{-1};
- relative air humidity (44.9 ± 0.6)%.

Such test conditions were selected according to the authors' survey to imitate real conditions of working in the L2 impermeable chemical protective clothing in the selected chemical plant. Even in the case of low level of effort, while working in the L2 impermeable protective clothing workers confirmed thermal discomfort.

The participants' task was to walk on a treadmill with the constant speed of 2 kmh^{-1} and the inclination of 5% for 60 min. The mean load of the tested subjects of the individual VO_2max was equal to 16.8% (ranging from 15.6 to 18.3% in the individual cases). A view of the person taking part in the tests is presented in Figure 2.

Achieving one of the following values of the volunteers' physiological parameters – body core temperature of 38.0°C, heart rate reaching 85% of the individual maximum heart rate, 100% relative humidity measured at least at two sites (under the protective clothing) – and objective or subjective signs of fatigue provided a basis discontinuation of the measurements. However, nobody quit before the intended time of the experiment.

During the test, the following parameters were recorded:

- heart rate, using an HR S-810 monitor (Polar Electro Oy, Finland);
- body core temperature in the external ear canal sealed by a soft plastic ear stopper to avoid the influence of ambient temperature and eight local skin temperatures according to the ISO 9886:2004 standard[22] with an FX 2000 cardio monitor (Emtel, Poland), the measurement accuracy was 0.1°C;
- three locations of the temperature and relative humidity underneath the underwear (two locations in the front area – chest and abdomen – and in the middle of the back at the height of the shoulders) with a HygroLab 2 (Rotronic AG, Switzerland) connected to the FX 2000 cardio monitor to obtain results of the measurements at the same time; the temperature measurement accuracy was 0.1°C and

Figure 2. A view of the volunteer taking part in the tests.

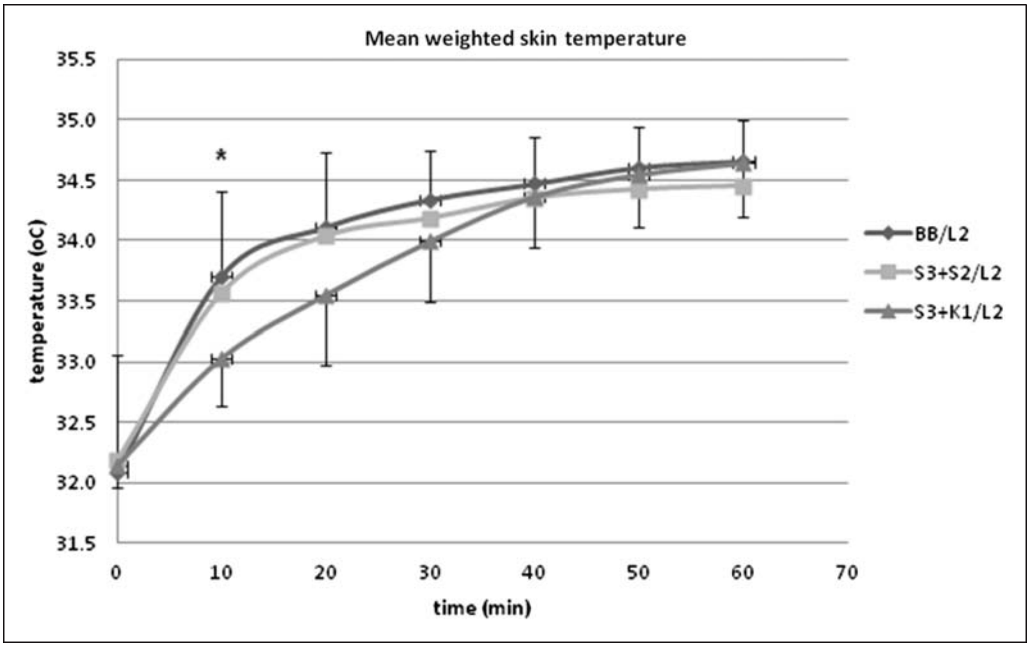


Figure 3. Mean-weighted skin temperature results.
*Statistically significant difference for $\alpha = 0.05$.

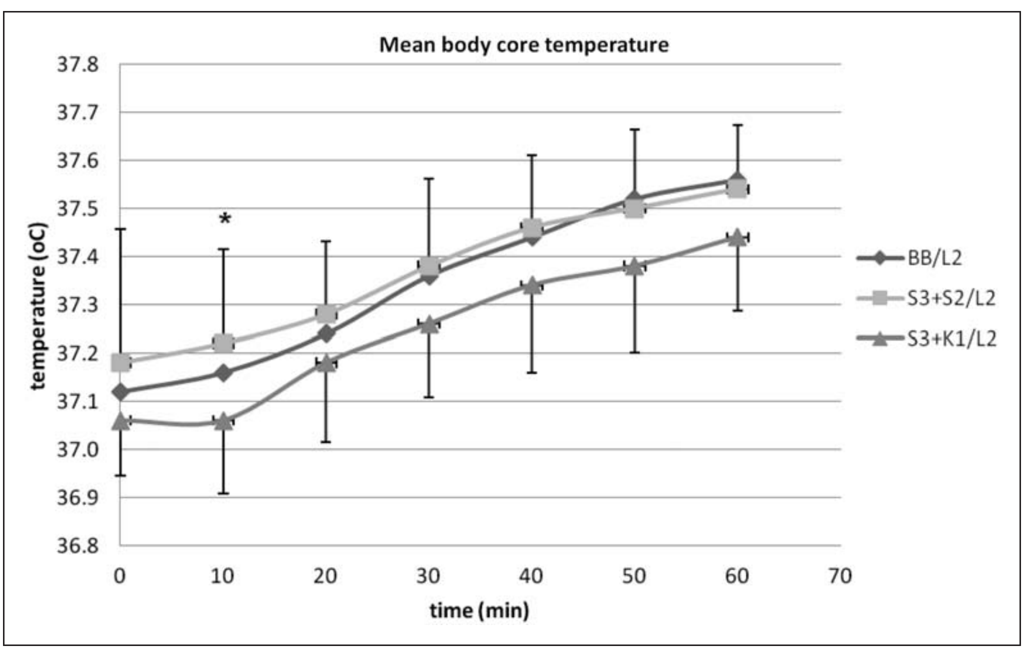


Figure 4. Mean body core temperature results.
*Statistically significant difference for $\alpha = 0.05$.

the relative humidity measurement accuracy was 5%.

The data were recorded every 4 seconds, but the interval was assumed to be 10 minutes for the analysis. Moreover, every 10 minutes volunteers were asked about their subjective sensations: thermal and skin wetness sensations; perceived exertion; thermal sensations; skin and clothing wittedness.

On the basis of the recorded local skin temperatures, the mean-weighted skin temperature was calculated according to the ISO 9886:2004 standard.[22]

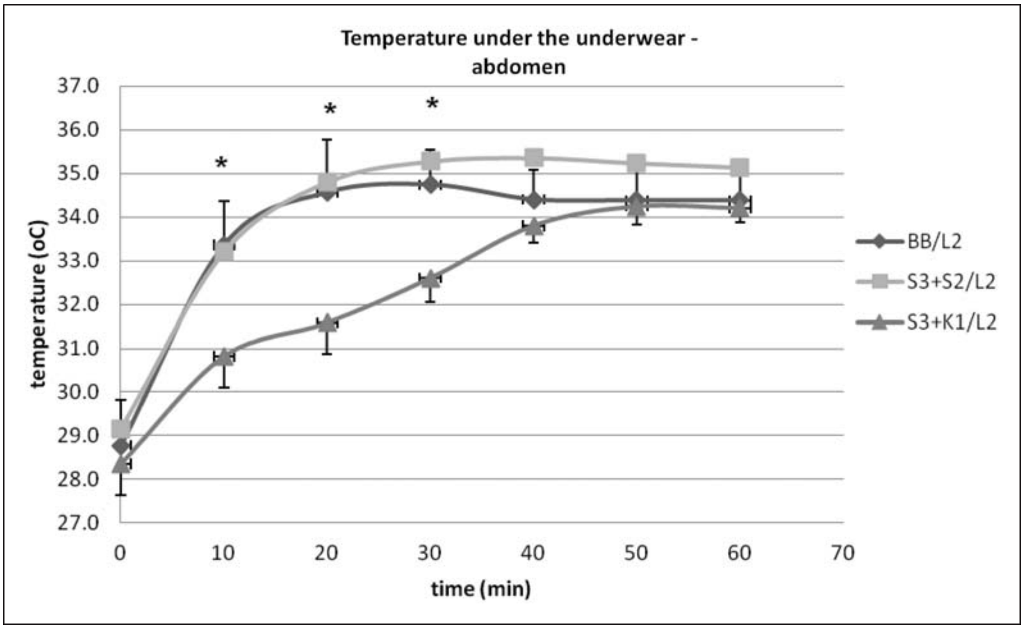


Figure 5. Undergarment temperature results obtained on the abdomen.
*Statistically significant difference for $\alpha = 0.05$.

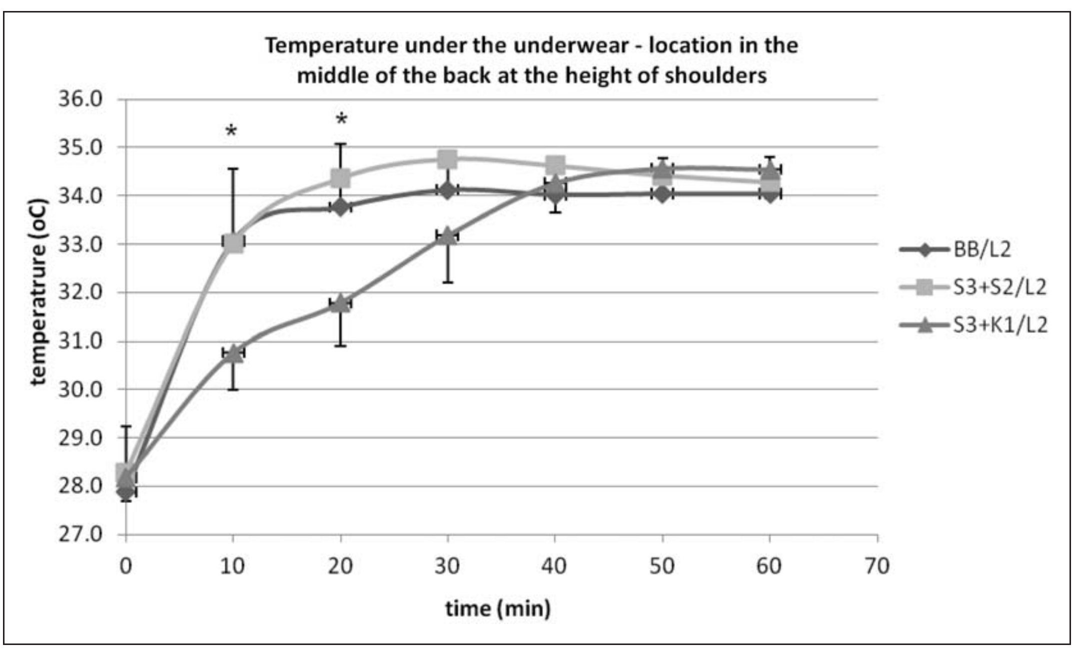


Figure 6. Undergarment temperature results from the middle of the back at the height of shoulders.
*Statistically significant difference for $\alpha = 0.05$.

Statistical differences between the obtained results were calculated by the analysis of variation for the 0.05 significance level. Analysis was conducted for all tested variants of garments. The homogeneity of variance was checked using the Levene test.

Results of the measurements

From the performed tests, the results concerning the physiological reactions of five young men, as well as the parameters of the undergarment microclimate,

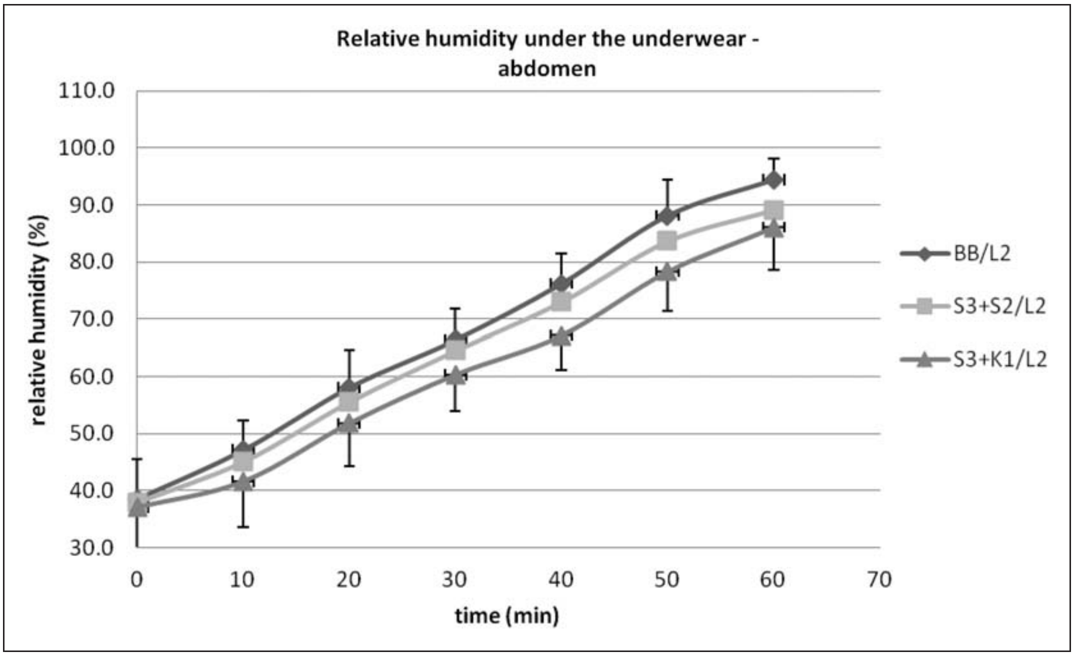


Figure 7. Relative undergarment humidity results on the abdomen.

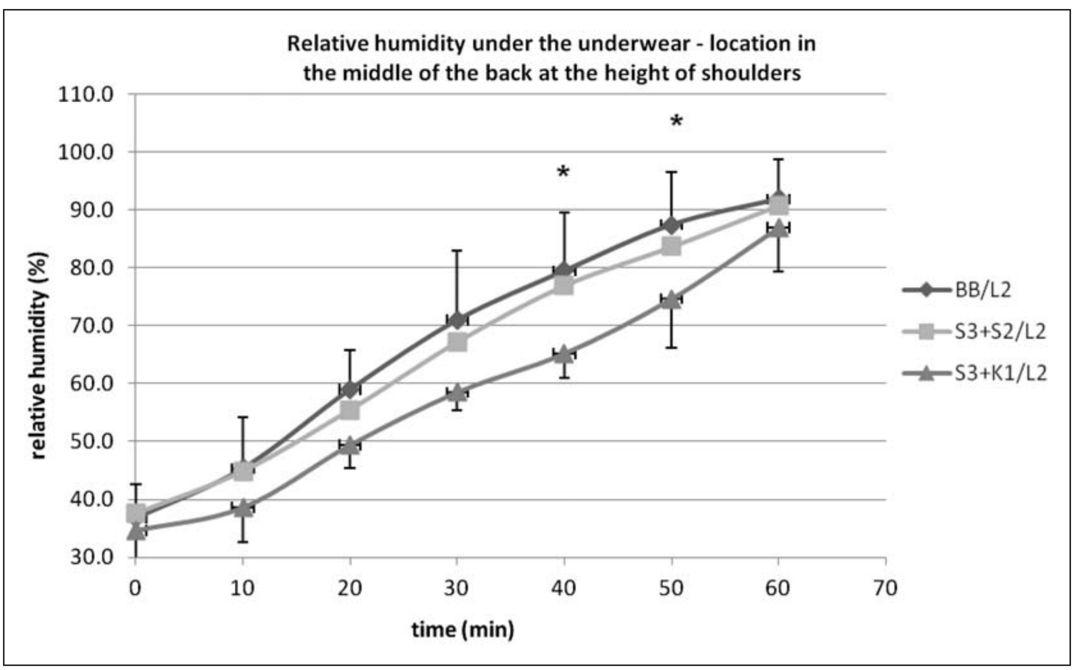


Figure 8. Relative undergarment humidity results from the middle of the back at the height of the shoulders. Statistically significant difference for $\alpha = 0.05$.

were obtained. The analysis of those results was used in the further part of the research to assess the effectiveness of working conditions improvement obtained with the new PCM garments in comparison with the traditionally worn cotton underwear.

Physiological parameters measurements

During the tests, measurements of the mean heart rate were conducted. However, obtained results for all tested variants were similar and achieved differences were not statistically significant.

The results of the mean-weighted skin and mean body core temperatures are presented in Figures 3 and 4. In the case of both parameters, lower values of the temperature almost for the whole time of the test were obtained for the S3 + K1/L2 set of clothing with PCM garments.

In the case of the S3 + S2/L2 set of clothing, the shape of the mean-weighted skin temperature curve is quite similar to the shape of the curve obtained for the BB/L2 variant. The highest difference between the obtained mean-weighted skin temperature results for those clothing variants approximated 0.3°C, and conducted tests showed that it had no influence on human thermal sensations.

It should be also pointed out that in the case of mean-weighted skin temperature, a statistically significant difference was observed in the 10th minute of the experiment for the variant with a three-layer vest filled with PCM macrocapsules. Moreover, the influence of PCM macrocapsule (S3 + K1/L2) content is highly visible between the beginning of the experiment and the 40th minute, when the values for both variants almost equalized.

In the case of mean body core temperature, plotting of the temperature curves for all variants was quite similar during the whole time of the experiment; however, the values obtained for the S3 + K1/L2 variant were lower by about 0.1°C.

Undergarment microclimate parameters

Results of the measurements of the parameters characterizing the undergarment microclimate obtained from the sensor located on the abdomen and in the middle of the back at the height of the shoulders are presented in Figure 5–8. The results from these locations were selected to present the most visible influence of the PCM content in the developed garments on the undergarment microclimate.

On the basis of the results of the temperature changes in the undergarment microclimate (Figure 5), it can be said that in the first 20 minutes of the experiment there were no differences in the results concerning the microclimate temperature between the S3 + S2/L2 and BB/L2 variants. After that time, temperature values of the undergarment microclimate obtained for the S3 + S2/L2 set of clothing slightly increased in relation to the results for the comparative variant with cotton underwear. Such temperature increase was probably a result of the finished melting process of PCM microcapsules contained in the S3 and S2 garments and higher thermal insulation in the steady state of the knitted fabrics made of smartcel^{TM} clima fibers than in case of the cotton underwear.

In the case of the garment variant with PCM macrocapsules (S3 + K1/L2), highly noticeable differences in comparison with the variant without PCMs (BB/L2) could be observed in the 10th, 20th and 30th minutes. They were statistically significant and even reached 3°C in the 20th minute. Such a good result proved that the proposed three-layer vest filled with PCM macrocapsules influenced the undergarment microclimate and can be used to improve these microclimate conditions during approximately 40 min of work. After that time, the temperature under the underwear rose and was similar to the values obtained for the variant without PCM. On the basis of the results of the temperature measurements in the undergarment microclimate, it can be established that temperature changes in the space underneath the underwear were similar in all of the considered sensor locations (Figure 6).

In the case of changes of relative humidity in the undergarment microclimate (Figure 7), almost a linear increase of values was observed for all clothing variants and each sensor location. The obtained results proved a high ability of the designed garment with smartcel^{TM} clima fibers to remove the moisture from the body, better than in the case of cotton underwear. Despite higher thermal insulation and thickness of the S3 + S2/L2 variant, there was less moisture underneath the underwear, which causes differences in the relative humidity values between the BB/L2 and S3 + S2/L2 variants, even reaching 5% on the abdomen.

However, the lowest relative humidity values in the undergarment microclimate were obtained for the S3 + K1/L2 variant. At the beginning of the experiment, the relative humidity values were almost equal; however, the initially small differences were gradually increasing, to achieve about 10% in favor of the S3 + K1/L2 variant on the abdomen.

Lower relative humidity values in the undergarment microclimate and the volunteers' assessment of the skin wetness sensation on the lowest level obtained for the S3 + K1/L2 variant suggested that, in addition to better thermal conditions in the underwear microclimate, as a consequence, using the designed garments with PCM can cause better humidity conditions for the user. The analysis of the relative humidity results in the undergarment microclimate allowed one to conclude that the curve shapes obtained for all sensor locations were very similar. It can also be stated that differences in relative humidity values for both locations on the front torso were not statistically significant, whereas the measurements carried out on the back showed statistically significant differences ($\alpha = 0.05$) between the BB/L2 and S3 + K1/L2 variants in the 40th and 50th minutes (Figure 8). For the S3 + K1/L2 variant (a vest with PCM macrocapsules), 80% humidity, regarded as causing discomfort for the user, was obtained maximally about 15 min later than for the BB/L2 variant (the reference variant with cotton underwear).

Analysis of the results

In the presented research, it was assumed that a decrease of thermal discomfort connected with using impermeable protective clothing can be obtained by applying PCMs to the garment structure worn underneath. Moreover, it was also assumed that the designed garments should be characterized by good sorptive properties and should transport moisture away from the skin. Hence, the aim of this analysis was to assess the effect of using PCM garments underneath the impermeable protective clothing on the physiological parameters and the undergarment microclimate parameters in comparison with the set of clothing, in which impermeable protective clothing was used with cotton underwear.

During the experiments, an increase of all the measured parameters was observed. However, the limit values of the recorded parameters required to stop the experiment were not achieved.

An analysis of the results demonstrated that the values of physiological parameters, such as body core temperature and skin temperature, reached the lowest and the most desirable level in the case of the S3 + K1/L2 variant with a three-layer vest filled with PCM macrocapsules. Throughout almost the whole experiment, the body core temperature for this variant was about 0.1°C lower than for the BB/L2 variant. Much higher differences between the tested clothing variants were obtained for the skin temperature: until the 40th minute of the experiment the values were lower for the S3 + K1/L2 variant and the obtained differences were statistically significant. It was also noticed that after the 40th minute of the experiment the skin temperature course for the variant with PCM garment was similar to the values obtained for the variant with the cotton underwear, what could be a result of completing the PCM melting process.

The most significant influence of the PCMs in the form of macrocapsules was observed in the analysis of the undergarment microclimate parameters. Using the vest filled with PCM macrocapsules has an influence on undergarment microclimate temperature decrease of 2–4°C, depending on the sensor location; these differences were statistically significant. A similar correlation was observed in the case of undergarment microclimate relative humidity, where the differences between variants reached 10–15%. The use of underwear made of smartcel™ clima fibers under the vest filled with PCM macrocapsules exerted a positive influence on keeping the relative humidity of the microclimate underneath the protective clothing at a lower level than in the case of the cotton underwear. The S3 underwear is characterized by an ability to absorb the sweat. Because of the fact that the layer next to the skin is made of PES, which does not absorb moisture, this kind of garment stays in a dry contact with the skin and ensures the most proper microclimate near the skin of the impermeable protective clothing user.[23] Such positive influence of the vest with PCM macrocapsules on decreasing the physiological parameters and the underwear microclimate parameters is a result of high enthalpy of this garment equal to 164 kJ/m^2.

As far as the S3 + S2/L2 set of clothing is concerned, it can be said that such PCM garments do not ensure reduction of the thermal load on the impermeable protective clothing user at about 22°C. Body core temperature, mean-weighted skin temperature and undergarment microclimate temperature reached in that case comparable or higher levels than in the case of the variant with cotton underwear. A positive influence of the clothing variant with the three-layer vest with smartcel™ clima fibers in the form of rovings on the thermal load of the impermeable protective clothing user was noticed only for the relative humidity in the undergarment microclimate. Because of high Lyocell fiber content in this variant, the undergarment microclimate relative humidity remained at a lower level (to 5%) for each sensor location and was more favorable for the user of the barrier protective clothing than for the comparative variant with the cotton underwear.

Because of high content of PCM in the fibers and relatively high thermal resistance, this clothing variant may be more appropriate for use at lower temperatures, for example 10°C. The above hypothesis will be verified in the next experiment.

Conclusions

In the presented study, it was proved that specially designed garments with PCM content, intended for using under impermeable protective clothing can reduce thermal discomfort associated with using such kind of clothing.

Tests of the garments with PCM content – underwear with smartcel™ clima fibers and the three-layer vest filled with MPCM 28C macrocapsules – conducted on the volunteers under moderate climatic conditions demonstrated its positive influence on modification of the microclimate underneath the impermeable protective clothing. In comparison with the clothing variant without PCM, a decrease of the undergarment microclimate temperature equal to 2–4°C and a decrease of the relative humidity reaching 10–15% were observed. A reduction of the thermal stress on the impermeable protective clothing user while working in the underwear and the vest filled with PCM macrocapsules is also proved by observed changes in the physiological parameters, such as body core temperature and skin temperature, which reach a lower level than for the variant with the cotton underwear. The proposed solution can be an alternative for the known solutions with PCM introduced to the clothing in a form of isolated packages.

The performed tests showed that garments made of three-layer knitted fabric with smartcel^{TM} clima fibers in rovings are characterized by insufficient ability to eliminate excess heat from the microclimate under the impermeable protective clothing under moderate climatic conditions, despite the highest enthalpy of fibers with PCM microcapsules commercially available.

Acknowledgment

The authors would like to thank Department of Spinning Technology and Department of Knitting Technology, Faculty of the Material Technologies and Textile Design at the Technical University of Lodz for a cooperation during the project realization.

Funding

This publication has been based on the results of Phase I of the National Programme "Safety and working conditions improvement", funded in the years 2008–2010 in the area of scientific research and development works by the Ministry of Science and Higher Education/The National Centre for Research and Development.

The Programme coordinator: Central Institute for Labour Protection – National Research Institute.

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