ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 21, No.3. 2015

Investigation of Thermo-regulating Properties of Multilayer Textile Package

Julija BALTUŠNIKAITĖ [1, 2] *, Lina VALASEVIČIŪTĖ [1], Audronė SANKAUSKAITĖ [1], Kristina DUBINSKAITĖ [1]

[1] *Textile Institute, Center for Physical Sciences and Technology, Demokratų str. 53, Kaunas LT-48485, Lithuania*
[2] *Kaunas University of Technology, Department of Materials Engineering, Studentų str. 56, Kaunas LT-51424, Lithuania*

crossref http://dx.doi.org/10.5755/j01.ms.21.3.6920

Received 11 April 2014; accepted 08 November 2014

Thermal comfort of a clothing system is one of the important goals of the clothing manufacturers that require an engineering approach. In this research work a thermo-regulating textile packages were developed and a wearing comfort of protective clothing consisting from those packages was improved. The organic microcapsules of phase change materials that have different binding to the fibre mechanisms were padded on the fabric surface by pad-dry-cure method. The thermal properties and stabilities were measured using differential scanning calorimetry. The results demonstrate that 20% higher values of thermal resistance were obtained after incorporation of fabric, coated by PCMs into lining layer of multilayer textile package. By using such multilayer fabric systems with incorporated phase change material for military protective garments, the wearer's comfort can be enhanced substantially and the occurrence of heat stress can be prevented.

Keywords: multilayer textiles, microcapsules of phase-change materials, heat resistance, thermo-regulating properties.

1. INTRODUCTION

Thermal regulating textiles play a very important role in providing thermal comfort for human beings in temperature changing environments. The level of thermal comfort depends on the heat exchange between the human body and the environment that surrounds it. The thermoregulatory effect can be achieved with the presence of microcapsules of phase change materials (PCMs) into textiles.

Research studying the thermoregulatory effects of PCM treated textiles and their multi-layer assemblies are fundamental for the effective use of such smart thermal functional textiles [1]. Besides wearing comfort is one of the main requirement for the nowadays defense personnel military clothing [2 – 4] and the comfort depends on the materials ability to transport heat and moisture from inner layers to outer layer.

Clothing manufacturers are now seeking ways to maintain actively the clothing microclimate within the comfort zone through heat emission or heat absorption by the garment. Such characteristics can be implemented by using microcapsules of phase change materials made of an organic polymer shell and paraffin core [5, 6] that can detect temperature changes within the fabric. Phase-change textile materials are materials that can regulate the thermal comfort of the wearer [2, 4 – 8]. The heat absorbing temperature of PCMs, used for textile applications, is within the temperature range 20 to 40°C [7]. PCMs can be applied to the textiles in a variety of processes [7 – 10]. To modify textile materials, different techniques of microcapsules of PCM incorporation into their structure are used. The incorporation of microcapsules of PCMs can be made by melt spun method inside the fibres [11]. Most of published research work are about enhancing the thermal properties of textiles with PCM by printing and lamination [7 – 10, 12 – 14], but the most common and technically easier method of textiles modification is the coating with paste containing microcapsules of PCM [5, 9, 14 – 18].

The treated fabrics with PCMs enhanced the capacity of thermo-regulated property compared to untreated fabric [12, 19]. It should be mentioned that the heat storage capacity increases as the concentration of the microcapsules increases [14] and the latent heat storage capacity and the amount of retained PCMs depends on the kind of used textile [13]. Also it is important to keep stability of PCMs during mechanical processes.

In actual use, clothing undergoes many environmental changes according to the movement of the wearer and, with the exception of clothing typically worn in warm or hot environment; garments are usually composed of several layers.

Most of published research works [7, 9, 10, 12 – 14, 18, 20] study the thermo-regulating properties of textile materials incorporated with PCMs, other part of the investigations are performed with the clothing having the PCM fabric in the middle layer, however some part of investigations are done with the PCM encapsulated fabrics that are used in different clothing layers [8, 21 – 23]. Summarizing results of above mentioned investigations [8, 21 – 23], it could be stated that the magnitude of the effect depends on the number of layers of PCM in the garment, the orientation of the PCM layer to the body, and surface area of the body covered by PCM garments. As Celcar [8] refers, by clothing systems in combination with PCM of the wearer in warm environment, when fabric with PCM is in the lining layer, thermal effect is reflected in rising of mean skin temperature during activity changes.

The task of this research is to improve a wearing comfort of protective clothing, applying different textile

* Corresponding author. tel.: +370-37-308661; fax.:+370-37-308668.
E-mail address: *julija.baltusnikaite@ftmc.lt* (J. Baltušnikaitė)

materials treated with two types of microcapsules of PCMs, whereof can be embedded on the material by cross linking resin, the other type demonstrates the functional reactivity to all kinds of fibres without the use of binder, for lining layer of multilayer clothing packet. Only lining fabric was treated with PCMs whereas treatment of whole assembly with the large amount of PCMs could typically enhance stiffness and roughness of the garment. The assessment of the effect of PCMs on the thermo-regulating properties of multilayer clothing system was performed on the basis of thermal analysis obtained by the differential scanning calorimetry (DSC) technique and thermal resistance obtained in steady state conditions. Furthermore, scanning electron microscopy (SEM) technique was applied to analyse the presence and distribution PCMs into the textile.

2. EXPERIMENTAL

For the investigation of thermal resistance experimental processes the textiles fabrics, which are used for the manufacturing of winter military (from the first to the fifth clothing layers) clothing, were selected. The lining of clothing system was alternated seeking to improve the thermal resistance properties. The description of fabrics used for investigation is presented in Table 1 (the layers of clothing are indicated in receding order starting from the body). The fabric assemblies were combined from the materials described in Table 1 and sets of materials in the textile package are presented in Table 2.

Due to improving the thermo-regulating properties of multilayer protective clothing, two types of commercially available microcapsules of organic phase change materials were used. The first type of PCMs (type I – *PCM-I*) can be embedded on textile by cross linking resin. On the contrary, the second type of PCMs (type II – *PCM-I*) demonstrates the chemical activity to all kinds of fibres without the use of binder.

For fabric samples intended for lining, the type I PCMs (LJ Specialities LTD, UK) [24] by using acrylic binder by pad-dry-cure was applied. Another samples intended for the same purpose were padded with type II PCMs (Devan Chemicals, Belgium) [25].

Table 2. The arrangement of materials in the textile package

Code letter of Sample	Set of materials in the textile package (material numbers are taken from Table 1)
A	1.1+2.1+3.1+(4.1 or 4.1.1 or 4.1.2)+5.1
B	1.1+2.1+3.1+(4.2 or 4.2.1 or 4.2.2)+5.1
C	1.1+2.1+3.1+(4.3 or 4.3.1 or 4.3.2)+5.1
D	1.1+2.1+3.1+(4.4 or 4.4.1 or 4.4.2)+5.1
E	1.1+2.1+3.1+(4.5 or 4.5.1 or 4.5.2)+5.1

Table 1. The assortment and characteristics of the textile materials used for investigation of protective clothing

Clothing layer	Material No.	Fibre content	Mass per unit area, g/m ^{2}	Material thickness, mm	Description of the material
1 – near the body, innermost	1.1	Cotton – 100 %	120	0.8	Knitted material (rib 1/1)
2	2.1	Cotton – 32 % Polyester (PES) – 68 %	187	0.7	Multi-fibre material of Rip-stop weave
3	3.1	PES –100 %	287	4.8	Double sided knitted duvet material
4	4.1	Cotton – 34 % PES – 66 %	173	0.9	Multi-fibre material of plain weave
	4.1.1				Multi-fibre material of plain weave (with PCM finishing, PCM-I)
	4.1.2				Multi-fibre material of plain weave (with PCM finishing, PCM-II)
	4.2	Cotton – 34 % PES – 66 %	201	0.9	Multi-fibre material of plain weave
	4.2.1				Multi-fibre material of plain weave (with PCM finishing, PCM-I)
	4.2.2				Multi-fibre material of plain weave (with PCM finishing, PCM-II)
	4.3	Cotton – 100 %	203	1.1	Woven material of twill weave
	4.3.1				Woven material of twill weave (with PCM finishing, PCM-I)
	4.3.2				Woven material of twill weave (with PCM finishing PCM-II)
	4.4	Cotton – 85 % PES – 15 %	218	1.2	Woven multi-fibre material of twill weave
	4.4.1				Woven multi-fibre material of twill weave (with PCM finishing, PCM-I)
	4.4.2				Woven multi-fibre material of twill weave (with PCM finishing, PCM-II)
	4.5	PES – 100 %	217	0.9	Woven material of twill weave
	4.5.1				Woven material of twill weave (with PCM finishing, PCM-I)
	4.5.2				Woven material of twill weave (with PCM finishing, PCM-II)
5 – outer	5.1	I – PES 100 % II – Polyurethane 100 % III – Polyamide 100 %	219	0.8	Three layer material with micro pore membrane

For each fabric sample which was used in fourth clothing layer, both wet treatments were done on Laboratory Padder EVP-350 (Roaches International, UK). Drying and drying-curing processes of all samples were carried out on Laboratory oven and steamer machine TFOS IM 350 (Roaches International, UK).

The concentration of microcapsules of the type I PCMs was 200 g/l, concentration of acrylic binder – 50 g/l, wet pick up – 70 %, drying – 100 °C, 2 min, curing – 150 °C, 2 min. The concentration of microcapsules of the type II PCMs was 200 g/l, concentration of fixing agents – 42 g/l, concentration of softeners – 70 g/l, wet pick up – 70 %, drying – 140 °C, 1 min.

To characterize the thermal behaviour of PCMs, the measurements of phase change temperatures and energy storage capacities of microcapsules were performed in a differential scanning calorimetry model DSC Q10 (TA Instruments, USA) equipped with a refrigerated cooling system and under nitrogen atmosphere at a flow rate 20 ml/min.

During DSC analyses, test specimens were heated and cooled within a certain temperature interval ranging from 10 °C to 50 °C at 10°min^{-1}, which is commonly used in the experiments of polymer microcapsules.

Scanning electron microscopy was used to analyse the morphology, fixation and integrity of PCMs into the textile fabrics. Samples were observed by using SEM Quanta-200 (FEI, Netherlands).

Afterwards the evaluation of heat insulation properties of five layers fabric assemblies with different lining was performed according to ISO 11092:2014 standard method [26] with Sweating Guarded Hotplate M259B, produced by SDL International Ltd., England. Before testing, the specimens were conditioned for a minimum of 24 h at a temperature 35 °C and relative humidity 65 % in Controlled Humidity Test Chamber (JCI 191-192, UK). During the investigation temperature of measuring unit was 35 °C and air temperature in the test enclosure was 20 °C with a relative humidity of 65 %. The air speed was hold at 1 m/s. The tested fabrics assemblies were placed so that they lie flat across the measuring body towards the measuring unit.

Thermal resistance (R_{ct}), in m^2 K/W, was calculated from equation [26]:

$$R_{ct} = \frac{(T_m - T_a) \cdot A}{H - \Delta H_c} - R_{ct0}, \quad (1)$$

where: T_m is the temperature of the measuring unit, in °C, T_a is the air temperature in the test enclosure, in °C, A is the area of the measuring unit, in m^2, H is the heating power supplied to the measurement unit, in W, ΔH_c is the correction term for heating power for the measurement of thermal resistance R_{ct}.

3. RESULTS AND DISCUSSION

For the thermal protection, the important task of clothing is to create a stable microclimate next to the skin in order to support the body's thermoregulatory system. When a textile product is incorporated with thermally active materials, it can provide enhanced thermal capacity to keep the body in the comfort level.

In order to select the fabric structure more suitable for the winter military clothing system different textile fabrics were employed. For this purpose, the appropriate structure of multilayer textile package was selected and the thermal resistance of materials multilayer systems was evaluated. Multilayer packages were constructed from 5 layers and in forth (lining) layer the fabric finished with different PCMs and without finishing was used. Such a selection was determined according to the results of previous research [23], where is indicated that seeking to obtain bigger effect of heat regulation, the phase change materials should be used in the middle layer of multilayer package.

At the first stage the thermal performance of the multilayer textile package containing unfinished lining was investigated. The obtained results of thermal resistance values of tested packages are presented in Fig. 1.

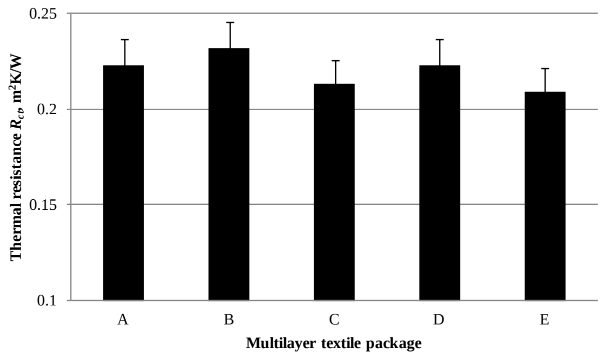


Fig. 1. Thermal resistance of different multilayer fabric packets when inner layer of the system is not treated with PCMs (the arrangement of materials in the textile packages is given in Table 2: A – when middle layer is from material No.4.1, B – when middle layer is from material No.4.2, C – when middle layer is from material No.4.3, D – when middle layer is from material No.4.4; E – when middle layer is from material No.4.5

Fig. 1 shows that changing fourth layer of 5th layers fabric package the thermal resistance values varied fractionally. It could be seen from Fig. 1 that thicker lining layer in the assembly (Sample B) imparted higher thermal resistance compared to the assembly of fabric consisting of the lining layer from the same fibre content (Sample A).

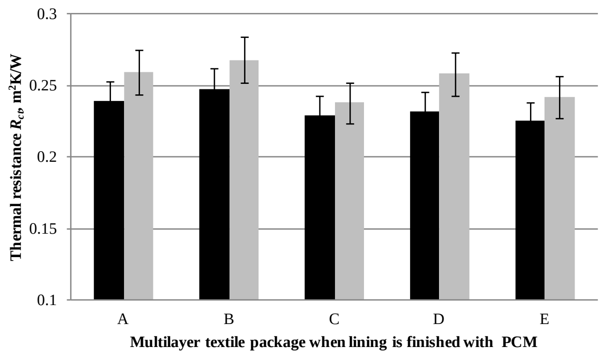


Fig. 2. Thermal resistance of different multilayer fabric packets when inner layer of the system is treated with PCMs; *PCM-I* ■, *PCM-II* ■

For the further investigations of heat insulation improvement, the appropriate structure of multilayer textile package was selected, in which the material finished with different PCMs, were used as a lining in the personal protective jacket (see description of the chosen materials in Table 1 and the arrangement of materials in the textile package – in Table 2). The obtained results of thermal resistance values of tested packages containing PCM treated lining layer (4^{th} layer) are presented in Fig. 2.

Afterwards the thermal properties of both types of PCM microcapsules were analysed with DSC instrument. DSC curves of *PCM-I* and *PCM-II* microcapsules are shown in Fig. 3 and Fig. 4.

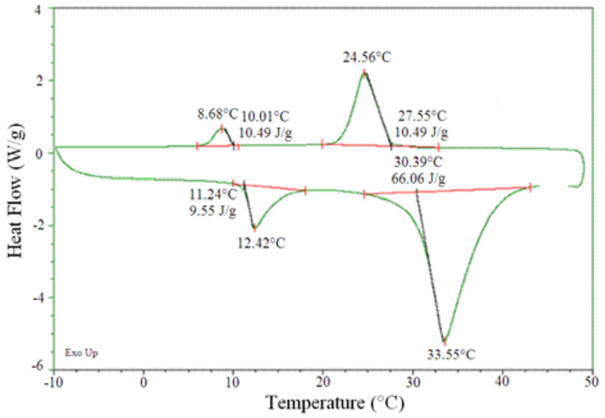


Fig. 3. DSC thermogram of *PCM-I*

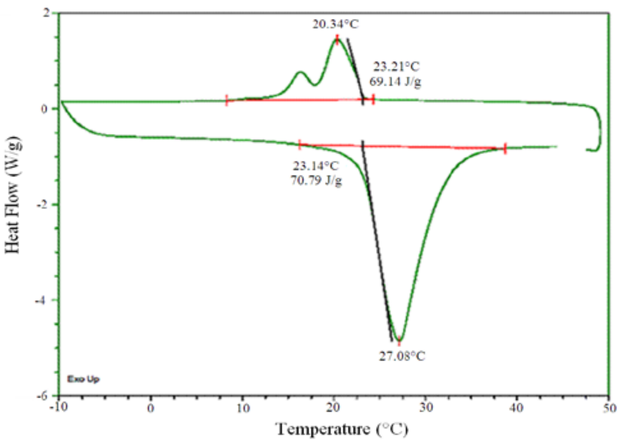


Fig. 4. DSC thermogram of *PCM-II*

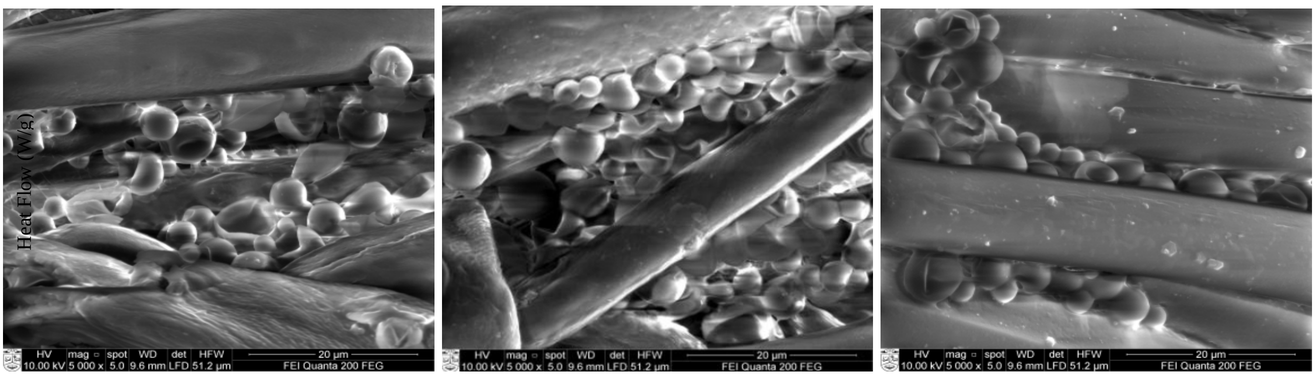
From Fig. 3 and Fig. 4, the melting temperatures of both microcapsules can be seen: the melting temperature (T_M) of pure *PCM-I* is 12.4 °C and 33.6 °C and of pure *PCM-II* is 27.1 °C. The latent heats of melting and freezing of *PCM-I* and *PCM-II* microcapsules were measured to be 70.59, 71.25 and 70.79, 69.14 Jg^{-1}, respectively. However analysing the obtained results it is seen (Fig. 3 and Fig. 4) that both PCMs rise in close values of investigated parameters.

Whereas the different results of thermal analysis were gained for fabrics finished with PCMs: the values of enthalpy (ΔH) are between 0.170 ÷ 0.465 Jg^{-1} for different fibre content fabrics finished with *PCM-I* and 1.175 ÷ 3.617 Jg^{-1} for the same fabrics finished with *PCM-II*, it means that much more higher comparing with fabrics incorporated with *PCM-I*. This may lead to the conclusion made by Shin [27] that the treated fabric is capable of absorbing till 4.44 Jg^{-1} of heat if the microcapsules on the fabric undergo a melting process.

This phenomenon could be explained by different linkage mechanism to fibre of above mentioned PCMs. New generation microcapsules of PCM (*PCM-II*) that have active functional groups which reacts with fibre, characterize higher ability of heat accumulation. However *PCM-I* microcapsules that are embedded on textile by cross linking resin, have two phase change temperature intervals. For intensify of PCM temperature conversion bigger amount of heat is required.

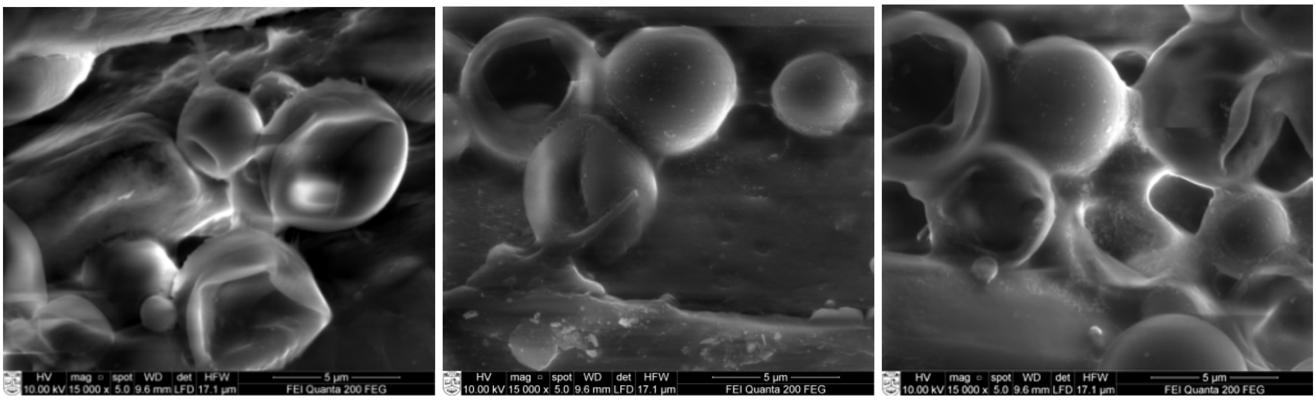
When SEM photos are taken into consideration both the general characteristics of the microcapsules and the differences between the various finished fabric types become prominent. Fig. 5 –Fig. 7 show morphology of fabrics finished with *PCM-I* and *PCM-II* respectively. SEM images show microcapsules distributed homogenously over different locations on the cotton, cotton/PES and PES fabrics. The coated microcapsules have a smooth and regular surface and spherical shape that coated the surface of the fabric. It can also be seen from the SEM images that capsules are partially agglomerated. In addition, SEM images can give an idea about the different distribution characteristics of the fabric tested.

Thought, the images of *PCM-I* in Fig. 6 indicate that some of the microcapsules were formed distinctly, and it could be the reason of the lower thermal resistance of fabrics tested.



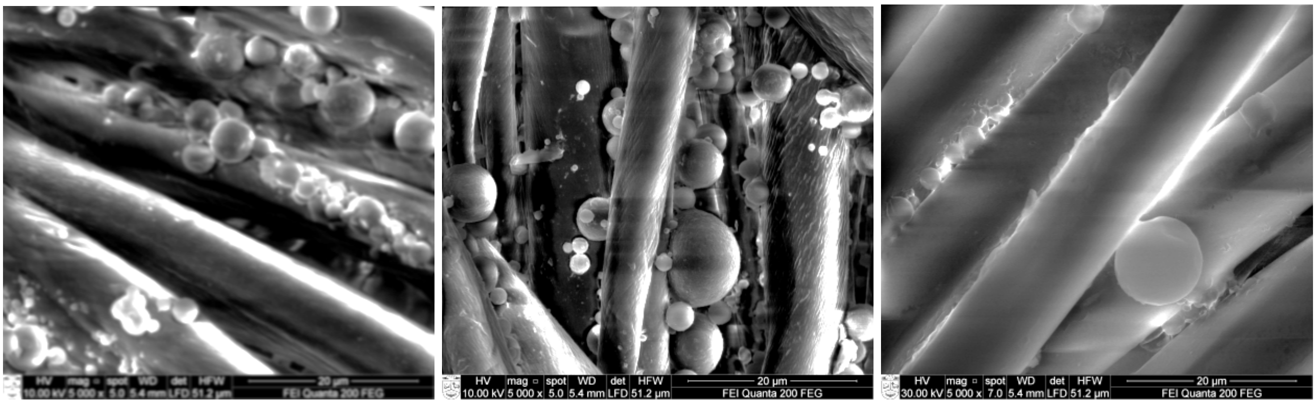
a b c

Fig. 5. Views of fabrics treated with *PCM-I* microcapsules: a – cotton fabric; b – cotton/PES blended fabric c – PES fabric



a b c

Fig. 6. Views of fabrics treated with *PCM-I* microcapsules: a – cotton fabric; b – cotton/PES blended fabric; c – PES fabric



a b c

Fig. 7. Views of fabrics treated with *PCM-II* microcapsules: a – cotton fabric; b – cotton/PES blended fabric; c – PES fabric

4. CONCLUSIONS

Concluding the results it is estimated that up to 20% higher values of thermal resistance are obtained when microcapsules of phase change materials are incorporated into the multilayer fabric system. Thermal resistance values gained 7 – 10 % higher for fabrics treated with *PCM-II* microcapsules that form chemical linkage with fibres, and this type of microcapsules provides better thermo-regulating properties for textiles, also those PCMs are quite satisfactory to suit thermal comfort requirements of many textile products as well as clothing. Their latent heat of fusions in terms of ΔH values (Jg^{-1}) are between 1.175 ÷ 3.617 Jg^{-1} for cotton, cotton/PES and PES fabrics, i.e., all quite large, and thus, compatible.

Analysis of morphology of microcapsules showed that *PCM-I* capsules where damaged during the technological process and it influenced on lower thermal resistance of multilayer systems tested, however the initial melting temperatures and enthalpy values of both PCMs were very close. Furthermore, the latent heat capacity of treated fabrics was enhanced compared to untreated fabrics.

Acknowledgments

This research was funded by a grant (No. MIP-120/2012) from the Research Council of Lithuania.

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