Experimental Study of the Thermo-Regulating Property of Clothing Systems Contained Different Melting Point Microencapsulated PCMs

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***Abstract*—This study has been carried out in order to investigate the effects of type of phase change materials on the thermo-regulating performance of clothing. Three systems of clothing with the same construction are chosen and their effects on the temperature response of the body (skin temperature changes) during the activity under a defined scenario are investigated. One of the clothing systems is normal (without PCM, i.e. phase change material), the other one is incorporated with PCM with a melting point of 18°C and the third one is incorporated with PCM with a melting point of 28°C. The skin temperature which is mainly affected by the physiological response of the human body is recorded by an on-line measuring system in the field room. Experimental results showed that PCM can affect the thermo-regulating performance of clothing. Furthermore, PCM with a melting point of 28°C shows a more significant effect than PCM with a melting point of 18°C. On the other hand, under cold environmental conditions (-5°C) and during activity of body, PCM with a melting point of 28°C decreases the fluctuations of temperature more than PCM with a melting point of 18°C. Finally, results of this research show that the type of PCM affects the skin temperature of the body. By this method, it is possible to design smart protective clothes with desired level of comfort.**

Keywords: PCM (phase change material), temperature change rate, activity level, temperature response

I. INTRODUCTION

Fluctuations in body temperature are detected by a specific system in the human body. After detection, the human body keeps fluctuations in balance by such means as shivering, the flow of cutaneous blood, sweat production, and respiration, which can be called autonomic regulation. The most comfortable skin temperature is 34°C. If the fluctuation in the temperature of the skin is more than ± 2.5°C, the human body will feel discomfort. However, temperature fluctuations in the body core of more than 1.5°C, at around 36.5°C, can be deadly. Therefore, the temperature of the human body must be controlled and regulated at a safe limit. Wearing clothing is one of the most important ways to keep the temperature of the human body within safe limits. The clothing layers provide static insulation via air between layers [1].

When the skin is cooled enough to lower the body temperature and consciousness is lost, hypothermia occurs. The human body will lose the ability to spontaneously return to the normal temperature when the rectal temperature reaches as low as 28°C. On the other hand, if heat loss from the human body is less than heat production, the inner temperature of the human body will increase. Insufficient heat loss leads to overheating, also called hyperthermia. Therefore, the careful regulation of body temperature is critical to comfort and health [2].

Although, clothing layers provide superior insulation effects, they are insufficient in keeping the temperature of the body constant during outdoor sports and some activities in which working conditions are extreme. PCM regulates temperature according to the environment and body temperature. In fact, PCM creates a dynamic insulation in clothing layers.

Textiles containing PCMs react immediately with changes in environmental temperatures, and the temperatures in different areas of the body. When a rise in temperature occurs, the PCM reacts by absorbing heat and storing this energy in the liquefied phase. When the temperature falls again, the PCM releases this stored heat energy and the phase change materials solidify again. Before applying PCM's to the textile structure, they should be capsulated in very small spheres to protect them against environmental forces. The microcapsules are resistant to mechanical action, heat and most types of chemicals. When the temperature rises due to a higher ambient temperature, the microcapsules react by absorbing heat. In fact, the PCMs in the microcapsules melt and absorb heat from their surroundings and store it. When the temperature falls due to a lower ambient temperature, they release the previously stored heat [3-8].

The encapsulated PCMs can increase the capacity of materials to store energy by creating a dynamic insulation in traditional insulation layers of clothing. They help the body to keep the temperature at a comfort limit across hot and cold environments and during high and low activity levels [4].

Most of the published research that is available in the scientific literatures have been conducted on effect of the PCM level treated on a fabric on temperature regulation. On the other hand, the magnitude and duration of the phase change heating and cooling effects on a clothed body (no fabric layer) have not been documented. There are very

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few reports on the effect of PCM on physiological response of the human body. This study focuses on the effect of an application of PCM on skin temperature which is mainly affected by the physiological response of the human body in a cold protective clothing system and under different activity levels of the human body. Also, the effect of type of PCM on skin temperature changes of the human body has been investigated. This research is conducted based on a triple model of body-clothing-environment. Interaction of body conditions, clothing and environment is very important for designing suitable clothing systems.

II. Experiments

Five male subjects were selected and asked to participate in the experiments. Table I shows the mean of the physical characteristics of the participants.

TABLE I
PHYSICAL CHARACTERISTIC OF PARTICIPANTS

Average age (year)	Average height (m)	Average height(Kg)	Average A_{DU} value
27 ± 0.5	1.78 ± 0.03	70.5 ± 3.6	1.93 ± 0.03

A_{DU} is the surface area of the human body and was calculated by DuBois formula as shown by Equation (1) [10]:

$$A^{o}_{DU} = 0.007 \times W^{0.425} \times H^{0.725} \quad (1)$$

where, W is the weight of body (Kg) and H is the height of human (cm).

In all experiments, a climate chamber was used. The temperature of the climate chamber was controlled at -5.0±0.5°C. The air velocity was less than 0.1m/s.

A. Measurements

The heart rate was continuously measured by a measuring system installed on a treadmill. Skin temperature was measured on the back and left armpit. A PLC2B Sensor System with ±0.1°C accuracy (manufactured by TamKar Co, Iran) was used for temperature measurements on the participants' skin.

B. Clothing system

In this research, three kinds of clothing systems were tested, the first was normal clothing (without microcapsules containing PCM) (clothing A), the second was incorporated with microcapsules containing PCM with 18°C melting point (clothing B) and the third was with microcapsules containing PCM with 28°C melting point (clothing C). The structure of these clothing systems was similar. Each clothing system consisted of 3 layers, the first one was underwear, the second one was a nonwoven fabric as insolation layer, and the third layer was a coat. The only difference between samples A, B and C was the second layer that contained PCMs with 18°C and 28°C melting points for samples B and C and without PCM for clothing A.

C. Preparation of nonwovens containing PCM

PES nonwoven fabrics with 60gr/m^2 weight were prepared and microcapsules containing phase change materials were added to fabrics with the impregnation method. Two types of microPCM from Microtek were applied to fabrics. The properties of microPCMs are listed in Table II.

The impregnation of the fabric was made in baths containing the binder and the microcapsules. It was carried by immersion of the fabric in the different formulation baths and the extra solution was removed using a padding device. Then, the treated fabrics were dried and baked at 100°C and 150°C for two 4 minutes respectively.

Details of nonwoven layers are presented in Table III.

D. Experimental protocol

Before entering the chamber, the sensors for measuring the skin temperatures were attached to participants' skin with surgical adhesive tapes. The subject wore the experiment garment and took a rest on a stool for 20 minutes. Then he was asked to walk on a treadmill at the speed of 5 km/hour for 20 minutes. After that, he was asked again to take a rest for 20 minutes. At the end of the experiment, the subject was allowed to exit the chamber. Each participant was tested with three clothing systems under this protocol.

E. Statistical analysis

SPSS.16.0 software was used to statistically analyze the experimental results. The value of $P<0.05$ was taken as the limit for statistical significance. Results of analysis of the temperature in the armpit are shown in Table IV. Results showed that clothing (B and C) has a significant effect on skin temperature.

F. Results

The temperatures in back and armpit were recorded by the same method and the results are summarized in Figures 1 to 4.

Figures 1 and 3 show the temperature change against time in the armpit. As shown in these figures, in the first 20 minute period (resting period), the trend of temperature change in clothing B (with pcm18) and clothing C (with pcm28) are similar and approximately constant. In this period, the temperature of clothing C is higher than clothing B. The temperature decreases significantly, when clothing A (without PCM) was worn.

In the walking period, the temperature change rate of clothing C was very low and close to zero while the temperature increased significantly when clothing B and clothing A were worn.

TABLE II
PROPERTIES OF MICROCAPSULES CONTAINING PCM

Particle size (µm)	Capsule composition	Core material	Melting point (°C)	Sell material	Heat of fusion (J/gr)	Form
17-20	85-90% wt.% PCM 10-15 wt.% polymer shell	Paraffin (n-Hexadecane)	18 and 28	Melamine- formaldehyde	135-140	Powder

TABLE III
PROPERTIES OF NONWOVENS

Property	Pure weight (gr/m2)	PCM percentage (%)	Type of fiber content	Melting point of PCM microcapsules
nonwoven without PCM for clothing A	100	0	PES	-
nonwoven with PCM for clothing B	100	30	PES	18°C (pcm18)
nonwoven with PCM for clothing C	100	30	PES	28°C(pcm28)

However, the temperature decrease rate was higher when clothing A was worn. In the recovery period, in all samples, the trend of temperature change was similar as in all of them, in which temperatures decrease. As indicated by Figure 3, when clothing C was worn, the rate of temperature changes in all periods was lower than that when clothing B was worn. As shown in Figure 1, these changes in rates when clothing B was worn were lower than that when clothing A was worn.

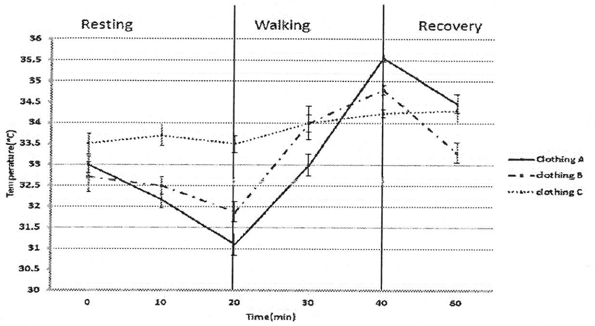

Fig. 1 Error bar chart of temperature-time curve in armpit.

Figures 2 and 4 show the temperature distribution in the back of the body. As shown in these figures, in the first 20 minute period (resting period), the trend of temperature change in clothing B, C and A are similar. However, the decrease in the rate of temperature when clothing A was worn was higher than that when clothing B and C were worn. In the walking period, the rate of temperature change for clothing C was lower than that when clothing B and A were worn. When clothing C was worn, the minimum and maximum values of temperature in this period were respectively higher and lower than that when clothing B and C were worn. Also, in the recovery period, the rate of temperature change when clothing C was worn was lower than that when clothing B and A were worn. As indicated in Fig. 4, in the entire period of the test protocol, the fluctuations of temperature when clothing C was worn were lower than clothing B. Figure 2 shows that the highest fluctuations of temperature are related to the case when clothing A was worn.

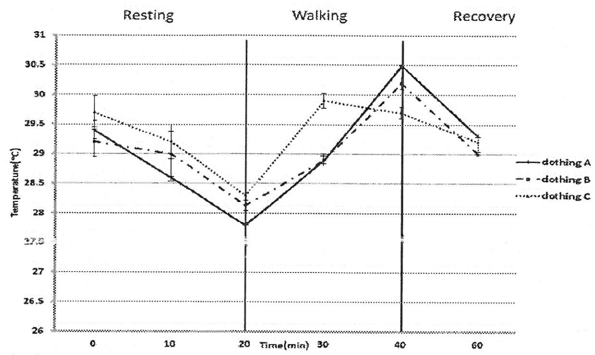

Fig. 2. Error bar chart of temperature-time curve in back.

Figures 5 and 6 show the temperature distribution of different activities based on the protocol test versus the clothing system that was worn.

As Figure 5 shows, when clothing C was worn, the dispersal of temperature in the armpit and in different periods of the experiment was significantly less than that when clothing B and C were worn. Also, when clothing A was worn, the dispersal of temperature was broader than that when clothing B and C were worn.

Figure 6 shows temperature distribution of the back for different clothing systems. This figure confirms the results of Figure 5.

As indicated in figures 5 and 6, both in the back and

TABLE IV
EFFECTS OF CLOTHING TYPES ON SKIN TEMPERATURE IN ARMPIT

Multiple Comparisons

Dependent Variable:temperature

	(I) clothing	(J) clothing	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Tukey HSD	clothing A	clothing B	-.76667	.33110	.129	-1.7826	.2493
		clothing C	-2.40000*	.33110	.001	-3.4159	-1.3841
	clothing B	clothing A	.76667	.33110	.129	-.2493	1.7826
		clothing C	-1.63333*	.33110	.006	-2.6493	-.6174
	clothing C	clothing A	2.40000*	.33110	.001	1.3841	3.4159
		clothing B	1.63333*	.33110	.006	.6174	2.6493

*. The mean difference is significant at the 0.05 level.

armpit, the temperature after the resting period when clothing C was worn was greater than that when clothing B and A were worn. Also, after the walking period, when clothing C was worn the temperature was significantly less than that when clothing B and A were worn. Overly, Figures 1 and 6 show that the fluctuations of temperature in the entire period of experiments (for different activities of the body), was significantly less when clothing C was worn.

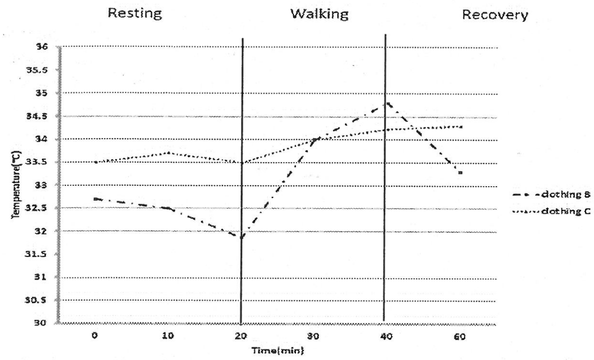

Fig. 3. Comparison of skin temperature between clothing B and C (affected by PCM type) in armpit.

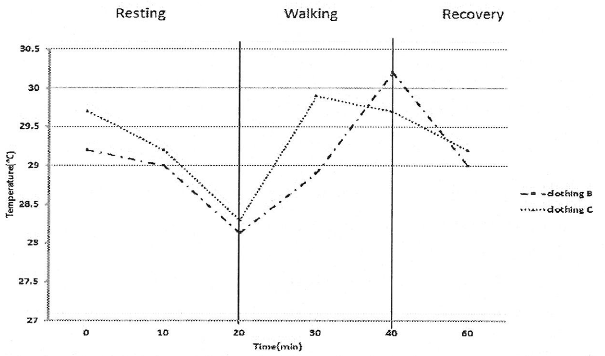

Fig. 4. Comparison of skin temperature between clothing B and C (affected by PCM type) in back.

III. Discussion

Figures 1 and 4 show that clothing C and B could decrease the fluctuation of temperature during the whole period of the experiment. This improvement was more significant when clothing C was worn. As mentioned earlier and indicated in Table III, the structures of all clothing systems were similar. The only difference between clothing A, B and C was on the second layer that contained PCM with 18°C for clothing B and PCM with 28°C for clothing C and without PCM for clothing A. When the participant entered the cold room (the first 20 minutes of the experiment), the body heat was generally lost during this period and the temperature of the body skin decreased. Here PCM may change from a liquid state to solid state and during the phase change process the heat was released. Therefore PCM played a temperature regulation role and decreased the temperature decrease rate of the body skin. Figures 5 and 6 show that after resting, the temperature of clothing C was greater than clothing B and A. Therefore, clothing C that contained PCM with a melting point of 28°C was more effective than clothing B that contained PCM with a melting point of 18°C. On the other hand, in the walking period (see Figures 3 and 4), the metabolism of the body increased and more heat was produced and released. Therefore, the temperature of the body increased. In this case, PCM may change from a solid to liquid state and during this process, heat is stored. Therefore, PCM decreased the temperature increase rate of the body skin. Figures 3 and 4 show that clothing C regulated the temperature in the walking better than clothing B. Furthermore, as indicated in Figures 5 and 6, the temperature after walking in clothing C was significantly less than that in clothing B. Finally, during the last 20 minutes of the experiment (recovery), the metabolic rate decreased. Thus, the temperature decreased and PCM may change from liquid to solid when the heat is released.

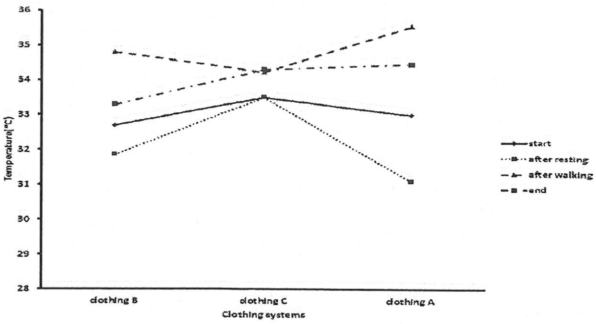

Fig. 5. Temperature-clothing system curve in armpit.

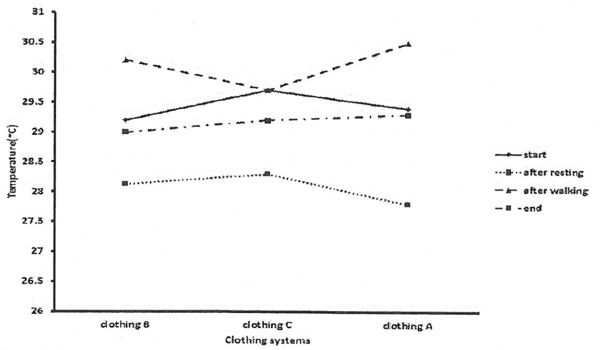

Fig. 6. Temperature-clothing system curve in back.

As discussed above, clothing C containing PCM with a melting point of 28°C, regulated temperature better than clothing B containing PCM with a melting point of 18°C and decreased the fluctuations of temperature. Figures 5 and 6 clearly show this issue. In Figure 5, dispersal of temperature in clothing C is significantly less than clothing B. Therefore, it may be concluded that PCM with a melting point of 28°C can regulate the skin body temperature in cold environments and at different levels of human body activities better than PCM with a melting point of 18°C. The clothing systems studied in this work, had an insulation layer and protected the body from cold weather, therefore PCM may exchange heat with body skin more than that with cold environment. So, the PCM that had a melting point close to skin temperature range may be active faster and start to change its phase. Therefore, the PCM with a melting point of 28°C may regulate the body skin temperature better than one that with the melting point of 18°C. In fact, PCM could be probably more greatly affected by the physiological condition of the body than environmental conditions. Therefore, under this condition, because the melting temperature of PCM in clothing C (28°C) was closer to the body's skin temperature than temperature of PCM in clothing B (18°C), the role of clothing C would be more significant than clothing B. Thus, clothing C had a greater thermo-regulating effect than clothing B.

IV. Conclusion

In this study, three systems of clothing, without PCM, with PCM with melting points of 18°C and 28°C were applied and their effect on the temperature response of the body (skin temperature changes) during activity under a defined scenario was investigated. Experimental results showed that PCM can be effective on thermo-regulating performance of clothing. Furthermore, PCM with a melting point of 28°C had a more significant effect than PCM with a melting point of 18°C. These results can be beneficial for smart protection clothing designers when they apply PCM in protective clothing.

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