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Clothing Temperature Changes of Phase Change Material-Treated Warm-up in Cold and Warm Environments

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Abstract: The purpose of this study was to investigate the appropriate amounts of phase change materials to give objective and subjective wear sensations. Vapor-permeable water-repellent fabrics with (WR-PCM) and without (WR) octadecane containing microcapsules were obtained by wet-porous coating process. Then, calculating the area of the WR-PCM treated clothes, we estimated the total calories of the clothing by multiplying the heat of fusion and heat of crystallization of PCM to the calculated area. Wear tests were conducted in both warm environment (30 °C, 65 % RH) and cold environment (5 °C, 65 % RH) with sports warm up style experimental garments made with WR and WR-PCM fabrics. Rectal, skin, and clothing microclimate temperatures, saliva and subjective evaluation measurements were done during the wear test. There was no difference of rectal and mean skin temperatures between WR and WR-PCM, but the clothing microclimate temperature of WR-PCM under warm environment was slightly lower than that of WR. In cold environment, WR-PCM showed much higher temperature than in WR. Saliva change did not appear between clothes, but did between two environments. Although subjective sensation between WR and WR-PCM was not significantly different, WR-PCM was rated as cooler than WR in warm environment and as warmer than WR in cold environment. The results of this study indicated that octadecane containing microcapsules in water-repellent fabric provide cooling effect.

Keywords: Phase change materials, Microcapsule, Microclimate, Subjective evaluation

Introduction

Phase change materials (PCMs) by themselves are able to absorb, store, and release large amount of latent heat according to temperature change of external environment [1]. Thermal storage or release of microcapsules containing PCMs endows cooling and heating effect to the treated fabric and consequently improves wearer's thermal comfort. The microencapsulated PCMs absorb excess heat and release the absorbed heat as phase change occurs and a temporary cooling and warming effect in clothing layers takes place. That is, PCMs-treated clothing is expected to help maintaining a thermal equilibrium from overheat or chilliness heat quickly [2]. In order to manufacture high performance fiber materials that maintain optimum body temperature, it is necessary to quantify how the amount of calories can change the clothing microclimate temperature and as the results, how the wearer feels his/her subjective comfort sensation.

Nevertheless, previous studies [3,4] have just confirmed the phase changing effect through measuring rising and descending rate of clothing microclimate, and have not presented any definite relations between calories and microclimate temperature human sensation. Therefore, through the estimation of total heat capacity which the clothes can produce and the assessment of the wear sensation, we can understand how many microcapsules we need to treat fabric in order to provide ultimately comfortable garments for a given environment as outdoor activity garments. It may be able to manufacture clothes that react with external environment spontaneously. Vapor-permeable water-repellent fabrics are now widely used to sports and leisure garments. If the vapor permeable water repellent fabrics are treated with PCMs, it will be able to upgrade the garment's thermophysiological comfort, and it might expand the area of comfort-zone of the garment

Here, a vapor-permeable water-repellent fabric was treated with PCM microcapsules containing octadecane. And two sets of garments were made with the same design and size specification; one is a vapor permeable water repellent garment (WR) and the other is a PCM treated vapor permeable water repellent garment (WR-PCM). The objectives of this study were to investigate the relationship between the calories and the objective temperature change, and to examine the relationship between the objective temperature change and the subjective thermal comfort. By doing so, it aimed to provide the fundamental data for developing thermally comfortable dual functional clothing.

Experimental

Clothing

The experimental garments were made of two 100 % nylon fabrics: one was a vapor-permeable water-repellent fabric without PCMs (WR) finished with wet coating process, the other was a vapor-permeable water-repellent fabric with PCMs (WR-PCM) finished with the same wet coating process. PCM ratio against polyurethane was 10 %. Table 1 shows

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Table 1. Characteristics of specimens

Specimen	Fiber content	Yarn type	Finish	Thickness (mm)	Weight (g/m^2)	Add-on (%)
WR*	Nylon 100 %	filament	wet, porous, polyurethane coated	0.26	162.2	-
WR-PCM**	Nylon 100 %	filament	wet, porous, polyurethane with microcapsules coated	0.31	169.7	4.63

*: vapor-permeable water-repellent fabric, **: vapor-permeable water-repellent fabric with PCM containing microcapsules.

the characteristics of specimens for experimental clothing. Experimental garments for the wear performance test consisted of long-sleeved, loose fitted jacket and long pants. All subjects wore 100 % cotton knit under pants, long sleeve shirts, ankle length socks, and experimental jacket and pants.

Subjects

Nine healthy females between 20-25 years old participated for the wear test and the time reported to the laboratory at the same time of the day to minimize circadian effects on the body temperature. They were all at the early follicular phase of their menstrual cycle.

Pretest

In order to decide the experimental temperature by checking the phase change materials' release and absorb phenomena, a pretest was performed. A participant put on the experimental garment treated with microcapsules and sensors were attached on the surface of the garment and inside of the garment. After adaptation for 10 minutes at 20 °C, the participant moved to a chamber controlled at 5 °C (cold environment) and stayed for 60 minutes. And moved to a warm chamber controlled at 28 °C (warm environment) for 60 minutes after exposure at 20 °C for 30 minutes again. Figure 1 shows the changes of clothing microclimate and surface temperature at chest. In cold environment, after passing about 17 minutes, the clothing surface temperature raised drastically as the temperature reached to the crystallizing temperature. We decided to shorten the duration time at cold temperature from 60 minutes to 50 minutes because it was to long. In warm environment, the clothing temperature slightly decreased after 35 minutes passed when the temperature reached to the fusing temperature. But, because the fusing occurred faintly, we decided to raise the chamber temperature of warm environment to 30 °C for the main test.

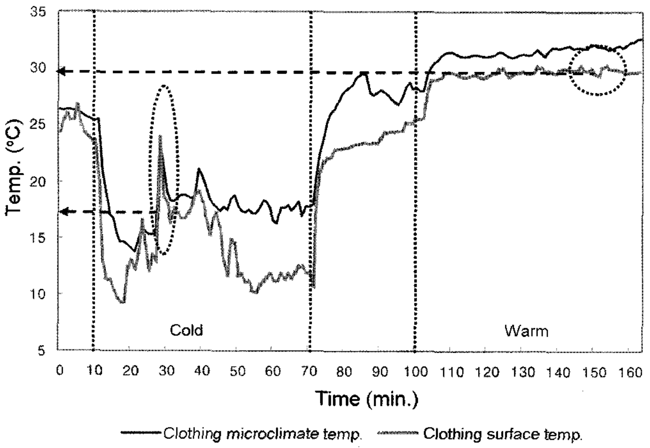

Figure 1. Pretest results for clothing surface temperature at chest.

Chamber Condition and Experimental Protocol

For the main test, the environmental temperature transient was achieved by using three chambers with different conditions. The first chamber simulated a standard environment: 20 °C air temperature, 65 % RH, 0.1 m/s air velocity. The second chamber represented a warm environment: 30 °C air temperature, 65 % RH, 0.1 m/s air velocity. The third chamber represented a cold outdoor condition: 5 °C air temperature, 65 % RH, 0.1 m/s air velocity.

Participants sat on a chair for 10 min at 20 °C, and their saliva was collected after 3 minutes passed. They moved to warm chamber, and sat on a chair for 50 minutes. In warm chamber, they rated their subjective sensations with 5 minutes intervals, and their saliva was collected again after 35 minutes passed. After 50 min, they changed underwear, and adapted at 20 °C chamber for 20 minutes. At that time, the saliva was collected again. In cold chamber, they rated their subjective sensations with 5 minutes intervals and saliva was collected again after 35 minutes passed. Then, they rested at 20 °C for 10 minutes.

Temperature and Humidity Measurement

Rectal temperature, mean skin temperature, clothing microclimate temperature, humidity, and clothing surface temperature were measured by the thermohygrometer (LT-8A Gram Corporation) every minute throughout the experiment at period. Skin temperatures were obtained at forehead, chest, forearm, hand, thigh, shin, and foot. Mean skin temperature (*MST*) was calculated using the following formula: *MST*(°C) = 0.07 (forehead) + 0.35(chest) + 0.14(forearm) + 0.05(hand) + 0.19 (thigh) + 0.13(shin) + 0.07(foot) [5]. The microclimate temperature and humidity inside clothing was measured at the chest and forearm.

Method of Saliva Measurement [5]

We collected the saliva using 2 pieces of sponge at the sublingual site and 2 other pieces at sites between the inner cheek and teeth with 50 min intervals. After 5 minutes passed, we filled the sponge case by taking out saliva sponges from mouth.

Subjective Evaluation

The subjective ratings of the thermal, humidity, and overall comfort sensation were obtained during experiments in warm and cold environment. The participants answered their subjective sensations with 5 minutes intervals according to the ASHRAE 7 point scales.

Data Analysis

Data were statically analyzed using SPSS 11.0 program. A paired samples t-test used to determine the difference between the two experimental garments in terms skin temperature, clothing microclimate temperature and humidity, saliva change, and of subjective sensation.

Results and Discussion

Expected Calories from PCM Treated Garment

We calculated the expected calories of WR-PCM clothes by obtaining the total weight of textiles:

Total Weight of Textiles (g) = Clothing Surface Area (m^2) × Weight per Unit Area of Textile (g/m^2)

Where, clothing surface area of Jacket was 1.37 m^2, and that of pants was 11 m^2, and weight per unit area of textile is 169.7 g/m^2. Therefore, total weight of textile used on jacket and pants were 232.5 g and 188.4 g respectively.

Then, the total calories of clothes were calculated by the following equation:

Total Calories (J) = Calories per Unit Textile Weight (J/g) × Total Weight of Clothing (g)

Heat of fusion of PCM treated textiles is 14.02 J/g, and heat of crystallization is 13.05 J/g. Therefore, results of expected calories calculation, heat of fusion of jacket is 3259.7 J (782.3 cal), and one of pants is 2641.4 J (634.0 cal). Also, heat of crystallization of jacket and pants are 3138.75J (753.3 cal) and 2543.4 J (610.42 cal) respectively (To see Table 2).

Rectal Temperature Changes During Wear Test

Rectal temperature, one of body core temperature, changes in a regular range. The mean rectal temperatures of subjects for the WR-PCM clothes were slightly higher than those measured for the WR clothes (To see Figure 2). WR clothes descended averagely 0.26 °C and WR-PCM clothes decreased about 0.42 °C as compared with rectal temperature at 20 °C (general environment). Also, in cold environment, WR and WR-PCM clothes decreased 0.37 °C and 0.42 °C respectively in comparison with rectal temperature at 20 °C (general environment). As a result, the difference between two clothes was not seen under warm and cold environment.

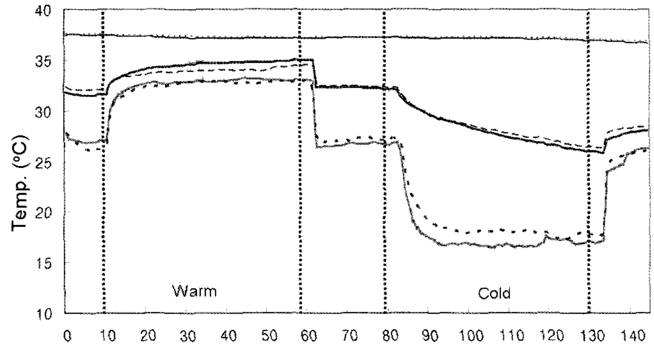

Figure 2. Comparison of changes in rectal, mean skin and clothing microclimate temperature between WR and WR-PCM.

Mean Skin Temperature Changes

The trend of *MST* (mean skin temperature) was similar both WR and WR-PCM clothes. But *MST* of WR clothes was increased about 1.57 °C and *MST* of WR-PCM clothes was increased about 1.21 °C as compared with general environment. This could be expected the cooling effect resulted from the thermal storage of microcapsules containing octadecane. That is, PCMs-treated clothes help maintaining a thermal equilibrium from overheat. On the other hand, in cold environment, WR and WR-PCM clothes were lower 4.08 °C and 5.08 °C respectively than *MST* at 20 °C (general environment). This is thought because temperature of cold environment was so low.

Clothing Microclimate Temperature

In warm environment, clothing microclimate temperature of WR-PCM was significantly lower 027 °C than that of WR. And in cold environment, clothing microclimate temperature of WR-PCM was higher 0.78 °C than WR. But difference of

Table 2. Expected calories from PCM treated experimental garment

Garment	Total weight of textile (g)	Heat of fusion (J/g)	Total calories from Hf (J)	Heat of crystallization (J/g)	Total calories from Hc(J)
Jacket-WR-PCM	232.5	14.02	3259.7	13.05	3138.8
Pants-WR-PCM	188.4	14.02	2641.4	13.05	2543.4
Total	420.9		5901.1		5682.2

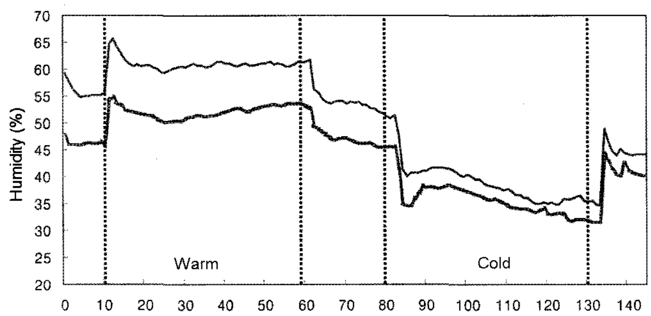

Figure 3. Comparison of changes in clothing microclimate humidity at chest between WR and WR-PCM.

clothing microclimate temperature between WR and WR-PCM began to be descent from about 35 minutes. As a result, we can find that effect of PCMs attached on clothes was continued for about 35 minutes.

Clothing Microclimate Humidity

Clothing microclimate humidity at chest of WR and WR-PCM clothing were showed in Figure 3. According to results, humidity of WR-PCM was higher about 2.77 % than that of WR in warm environment. This may be due to the higher evaporative resistance of the PCMs fabric as compared to WR. And humidity of WR-PCM was lower about 0.12 % than that of WR in cold environment.

Saliva Changes

There was no main effect in changes of saliva volume, s-IgA concentration and s-IgA secretion rate between WR and WR-PCM clothing. But shown in Figures 4, 5, there was effect both change of saliva volume ($p<0.01$) and change of s-IgA concentration ($p<0.05$) in t environment temperature change. That is, participants not suffered from stress by PCM treated clothing, but they were affected by environment temperature.

Results of Subjective Evaluations

The difference of thermal sensation, humidity sensation, and overall sensation were not significant at $p<0.05$. But, they showed slightly different patterns from those of skin temperature and clothing microclimate (To see Figure 6). In warm environment, participants felt WR-PCM clothing was less warm than WR one from 15 minutes to 35 minutes. And microclimate temperature was showed the highest value at 25 minutes. On the other hand, humidity sensation was that WR-PCM clothing was wetter than WR in warm environment. The overall sensation was affected by humidity sensation rather than thermal sensation, thus WR-PCM clothing was more uncomfortable. In cold environment, overall sensation was that WR-PCM clothing was less uncomfortable by 35 minutes. After 35 minutes, WR-PCM was more uncomfortable than WR. This is result that phase change effect maintained for 35 minutes.

Conclusions

In our study to investigate clothes treated with PCM-containing microcapsule, we calculated expected calories of WR-PCM clothes, and evaluated experimental clothings worn by human subjects based on the measurements including rectal temperature,

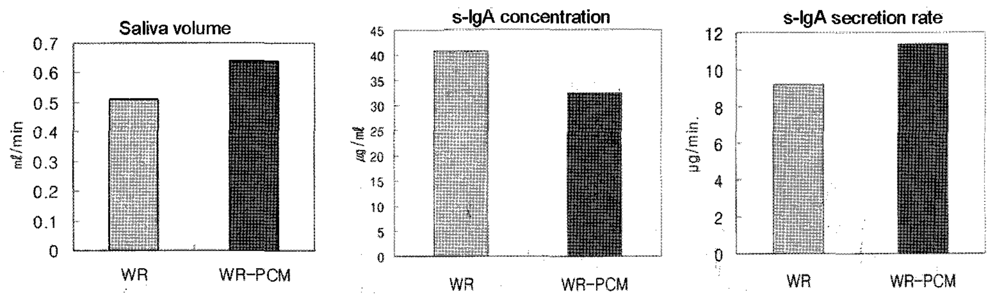

Figure 4. Changes of saliva measurements in warm environment.

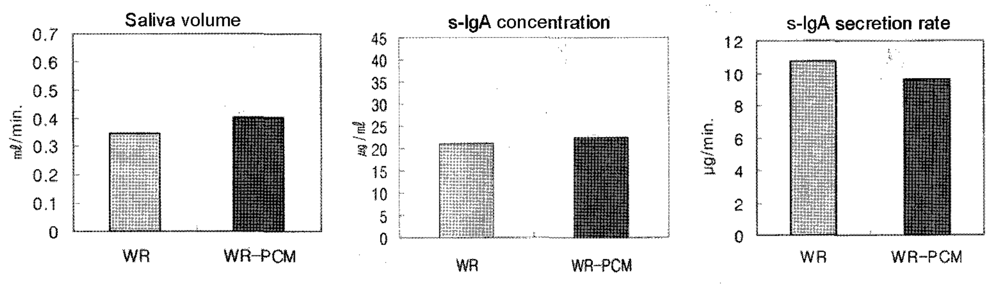

Figure 5. Changes of saliva measurements in cold environment.

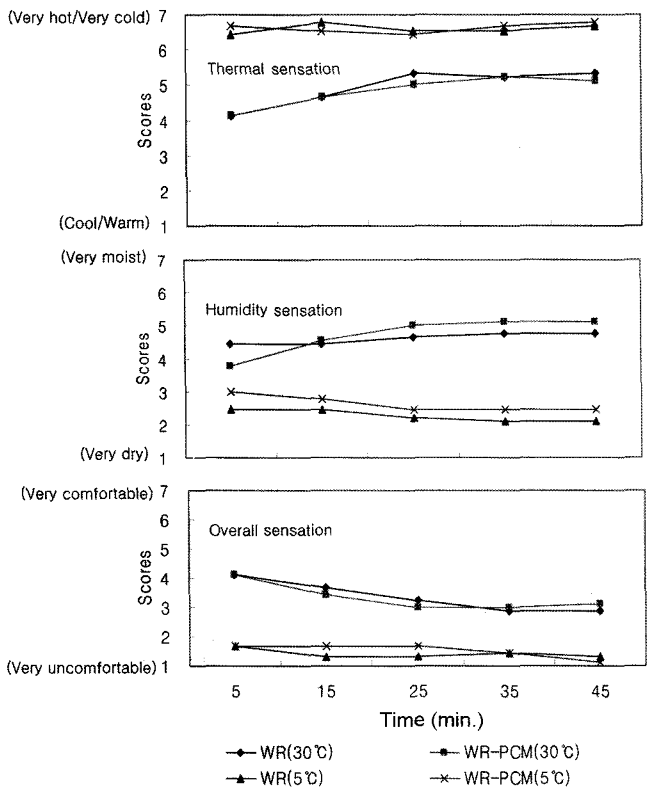

Figure 6. Changes of subjective sensation in warm (30 °C) and cold (5 °C) environment.

mean skin temperature, clothing microclimate, and saliva change.

We calculated the expected calories of WR-PCM clothes. We got expected calorie of clothes by weight of textile, heat of fusion and heat of crystallization of WR-PCM clothes. Therefore, results of the calculation of expected calories, were that heat of fusion of jacket is 3259.7 J (782.3 cal), and heat of fusion of pants is 2641.4 J (634.0 cal), heat of crystallization of jacket is 3138.75 J (753.3 cal), and heat of crystallization of pants is 2543.4 J (610.42 cal).

The rectal temperature and mean rectal temperatures of subjects for the WR-PCM clothes were slightly higher than those measured for the WR clothes. In warm environment, clothing microclimate temperature of WR-PCM was significantly lower than that of WR. And in cold environment, clothing microclimate temperature of WR-PCM was higher than WR. Saliva changes were not influenced on factor of clothes, but were influenced in environment temperature. In subjective sensation, WR-PCM clothing was more uncomfortable. in warm environment. And in cold environment, overall sensation was that WR-PCM clothing was less uncomfortable by 35 minutes. This is result that phase change effect maintained for 35 minutes.

In this study, we confirmed phase change of vapor-permeable water repellent and thermal storage/release properties. And WR-PCM has better thermal property than WR. In further studies, by applying various microcapsule concentrations, higher than 10 %, on vapor-permeable water-repellent fabrics, we may be able to find optimum condition for multi-functional fabric.

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