Effect of Phase Change Materials on Temperature and Moisture Distributions in Clothing during Exercise in Cold Environment

Shu-Xiao Wang, Yi Li*, Hiromi Tokura, Jun-Yan Hu, Yi-Lin Kwok, Raymond Au

Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, People's Republic of China

Abstract: This paper reports a study on the effect of phase change material (PCM) in design of cold protective clothing. Two clothing systems with the same structural design, one was smart clothing (clothing C) was treated with PCM, the other one was moisture management clothing (clothing B), were tested in a climate chamber where was controlled at -15°C. Eleven young male students volunteered to take part in wear trial experiments. The experimental results showed that the ear canal temperature when subjects wearing clothing treated with PCM was significantly higher that when subjects wearing moisture management clothing. The results also indicated that subjects wearing the clothing treated with PCM felt more comfortable than wearing the clothing untreated with PCM.

Keywords: PCM, cold protective clothing, cold environment, temperature distribution, humidity distribution

1. Introduction

Wearing different clothing humans can live in different environments, normal, hot, cold and even outer space. The core temperature of humans is tightly steady, and is maintained by a number of temperature regulation mechanisms at 37°C [1]. Heat exchanges between human body with environment by conduction, convection, radiation and evaporation [2] [3]. In a cold environment, if heat loss from human body is larger than heat production, the inner temperature of human body will be decreasing. When the skin is cooled enough to lower the body temperature and consciousness is lost, hypothermia happens. Human 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 human body is less than heat production, the inner temperature of human body will be increasing. Insufficient heat loss leads to overheating, also called hyperthermia. Therefore, the careful regulation of body temperature is critical to comfort and health.

When human enters a cold environment from a warm environment, the temperature of the clothing microclimate decreases, if the heat loss is too fast, he feels cold. Reversible to the above, when human enters a warm environment from a cold environment, if the heat loss is too slow, he feels hot. In order to improve textile fibers' thermal performance, in 1987, scientists developed and patented the technology for incorporating microencapsulated phase change materials (PCM) inside textile fibers [4]. Material usually has three states, solid, liquid, and gas. There are four kinds of phase change, including solid to liquid, liquid to gas, solid to gas, solid to solid. Heat is absorbed or released during the phase change process. When phase change material is heated, its temperature increases and reaches the melting point, the PCM absorbs heat and changes from solid to liquid, during this process, the temperature is kept constant at the melting point until all material changes into liquid. When temperature decreases and reaches the crystallization point, the liquid phase change material releases heat and changes from liquid to solid, in this process, the temperature is kept constant at the crystallization point.

Different PCMs have different transition temperatures and latent heat. The ideal PCM would have the features such as high heat of fusion,

* Corresponding author's email: tcliyi@inet.polyu.edu.hk

reversible solid-to-liquid transition, high thermal conductive, high specific heat and volume change during phase change transition, low vapor pressure, etc [5]. According to the phase change material handbook, paraffins are ideal PCM used in textiles. Paraffins have a high heat of fusion per unit weight, a wide range of melting points (-5 to 66°C) and they are flammable, nontoxic, noncorrosive, chemically inert, stable below 500°C, and predictable. They also have properties of negligible super cooling behavior, low volume change on melting, low vapor pressure in the melt, reasonable cost, and high wetting ability. The density of paraffins ranges from 700 to770 kg/m^3 [5].

When PCMs are applied in textile, PCMs have to be put into microcapsules. Otherwise they will eventually drip off clothing when they melt. Microencapsulation is the process of enveloping microscopic sized droplets or particles in a shell material for the purposes of protection or controlled release, because PCM-containing microcapsules must be durable and safe through the finishing process [6].

Unlike traditional insulation that simply traps air, the encapsulated PCMs can dramatically increase the capacity of materials to store energy. The PCMs interactively respond to each individual's unique physiological condition, absorb, store and release heat to help the body remain comfortable. The PCMs help the body to maintain its natural temperature across hot and cold environments and during high and low activity levels.

Shim et al. (2001) reported that heat released by a PCM in a cold environment decreases body heat loss by an average of 6.5W for a one-layer suit and 13.2W for a two-layer suit compared with non-PCM counterparts [7]. Ying et al reported a study on the assessment of temperature regulating performance of textiles incorporated with phase change materials [8].

In summary, much research has been conducted on the relation between the temperature regulating effect and the level of PCM treated on a garment. There are very few reports on the effect of PCM on temperature distribution in a clothing system. This study focuses on the effect of an application of PCM on temperature distribution in a cold protective clothing system.

2. Methodology

2.1 Participants

11 healthy male students volunteered as subjects and gave informed consent to participate in the research. Their characteristics are provided in Table 1.

Table 1. Physical characteristics of participants (M±SD)

Age (years)	Height (m)	Weight (Kg)
21.4±0.8	1.73±0.04	61.9±6.7

Each subject was informed about the general purpose, procedure and possible risk involved with experiments.

2.2 Climate

In experiments, one climate chamber was used. The temperature of the climate chamber was controlled at -15.0±0.5°C. The air velocity was less than 0.1m/s. Before entering into the climate chamber, subjects changed clothing in a room in which temperature was about 23.0±1.0°C. The relatively humidity was about 65±5%.

2.3 Measurements

Heart rate was continuously measured by a chest electrode belt with a heart rate meter (S810i, Polar Electro Oy, Finland) for every 5 seconds. Blood pressure was measured for every 10 minutes in the right arm (DynaPulse® 5000AUTO).

Ear canal temperature was measured with a thermocouple probe (LT8A, Gram Co, Japan) for every 2 seconds. Skin temperature was measured on the left chest, left forearm, left thigh and left calf.

Thermistors (HEL-700-T-1-A, Honeywell, USA) were used for temperature measurement of each layer of the clothing system. Humidity sensors (HIH-3610-001, Honeywell, USA) were used for relative humidity measurement of the clothing system.

JFBI Vol.1 No. 1 2008 doi:10.3993/jfbi06200805

2.4 Clothing system

In this study, two kinds of clothing systems were tested, one clothing system was moisture management function clothing system (clothing B), and the other one was smart clothing system (clothing C). The structures of two clothing systems were similar. Each clothing system consisted of 4 layers, the first one was underwear; the second one was the vest; the third one was coat; and the forth one was jacket. The first layer of two clothing systems consisted of one layer wool-cotton blend knit fabric which had moisture management function [9] [10]. The second layer (vest) consisted of 3 sub layers; the first sub layer was wool-cotton blend fabric with MMF; the second sub layer was nonwoven polyester; and the third sub layer was woven nylon which had water proof but breathable function. The second layer of the vest in clothing C was treated with PCM. The third part (coat) included 3 sub layers; the first one was wool-cotton blend knitted fabric with MMF function; the second sub layer was nonwoven polyester fabric; the third sub layer was woven nylon which had water proof but breathable function. The second layer of the coat in clothing C was treated with PCM. The forth layer (outer jacket) was made two layers. The first sub layer was wool-cotton blend knitted fabric with MMF function; the second sub layer was woven nylon fabric which had water proof but breathable function. The basic properties information of Clothing B system and clothing C system are shown in Table 2.

Table 2 The basic properties of two kinds clothing systems

			Material	Weight (g/m^2)	Thermal conductivity ($w\ m^{-1}\ k^{-1}$)	Air Permeability ($ml\ s^{-1}\ cm^{-2}$) at 100Pa	OMMC	Thickness (mm) At 0.6KPa
1. Underwear			Wool/cotton (40/60)	221.7±1.7	0.075±0.005	>78.70	0.86±0.01	0.99±0.01
2. Vest	1		Wool/cotton (40/60)	221.7±1.7	0.075±0.005	>78.70	0.86±0.01	0.99±0.01
	2	Clothing B	Polyester	166.3±15.2	0.051±0.008	>78.70	0.00	4.79±0.01
		Clothing C	Nonwoven Polyester treated with PCMA	260.1±5.5	0.061±0.003	>78.70	0.25±0.02	4.79±0.01
	3		Nylon	126.2±0.1	0.085±0.003	<0.02	0.00	0.37±0.01
3. Coat	1		Wool/cotton (40/60)	221.7±1.7	0.075±0.005	>78.70	0.86±0.01	0.99±0.01
	2	Clothing B	Polyester	166.3±15.2	0.051±0.008	>78.70	0.00	4.79±0.01
		Clothing C	Nonwoven Polyester treated with PCMB	244.9±8.6	0.047±0.002	>78.70	0.22±0.02	4.79±0.01
	3		Nylon	126.2±0.1	0.085±0.003	<0.02	0.00	0.37±0.01
4. Jacket	1		Wool/cotton (40/60)	221.7±1.7	0.075±0.005	>78.70	0.86±0.01	0.99±0.01
	2		Nylon	126.2±0.1	0.085±0.003	<0.02	0.00	0.37±0.01

OMMC: overall moisture management capability

2.5 Experimental protocol

All experiments began on 8:30 AM and ended on 11:30 AM. In the beginning, subjects were provided with breakfast and one bottle of distilled water (430ml). After breakfast, subjects were requested to go to toilet and make his bladder completely empty. Urine was poured into two small tubes. Each tube included 1.5 ml of urine. These two tubes were immediately stored in a deep freezer of -40^{o}C for later analysis of catecholamine. Then, total urine volume was measured using messcylinder and its value was recorded. The subject's heat rate and blood pressure were also measured. Before entering the chamber, the sensors for the measurements of ear canal temperature, skin temperatures and clothing microclimate (temperatures, humidities) at different layers were attached with adhesive surgical tape at thermoneutral room. Subject wore the experiment garment and filled out a questionnaire and entered the chamber. Subject took a rest for 30 minutes on a stool. Then subject was requested to walk on treadmill at a speed of 6.4 km/hour for 30 minutes. Subjects were requested to take a rest for 30 minutes on a stool. In the process, blood pressure was measured and questionnaire was filled every ten minutes. In the end of the experiment, the subject was allowed to go out of the chamber. All sensors were taken off. The subject went to toilet again, where he must make the bladder empty. All urine volumes were measured. The procedure was same as described previously. Before and after the experiment, the weight of each part of the clothing is measured with a balance (Sartorius, EA150FEG-1, German).

The experimental protocol was approved by the Hong Kong Polytechnic University Human Subjects Ethics Sub-committee.

2.6 Statistical analysis

The experimental data is analyzed by the software of Spss 12.0. A value of P<0.05 was taken as the limit for statistical significance.

3. Results

Statistical analyses were applied to the experimental data to reveal the effects of PCM on the temperature and moisture distributions at different layers by using SPSS 12.0. The result of analysis of the ear canal temperature is shown in Table 3. Stage has significant effect on ear canal temperature at P<0.001 (Greenhouse-Geisser). However, the interaction of the clothing and stage has no significant influence on the ear canal temperature.

Table 3 Effects of clothing and stage on the ear canal temperature

Tests of Within-Subjects Effects

Measure: Ear_canal_temperature

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Clothing	Sphericity Assumed	1.072	1	1.072	1.408	.263
	Greenhouse-Geisse	1.072	1.000	1.072	1.408	.263
	Huynh-Feldt	1.072	1.000	1.072	1.408	.263
	Lower-bound	1.072	1.000	1.072	1.408	.263
Error(Clothing)	Sphericity Assumed	7.618	10	.762		
	Greenhouse-Geisse	7.618	10.000	.762		
	Huynh-Feldt	7.618	10.000	.762		
	Lower-bound	7.618	10.000	.762		
Stage	Sphericity Assumed	6.749	9	.750	14.379	P<0.001
	Greenhouse-Geisse	6.749	2.413	2.797	14.379	P<0.001
	Huynh-Feldt	6.749	3.235	2.086	14.379	P<0.001
	Lower-bound	6.749	1.000	6.749	14.379	.004
Error(Stage)	Sphericity Assumed	4.694	90	.052		
	Greenhouse-Geisse	4.694	24.133	.194		
	Huynh-Feldt	4.694	32.354	.145		
	Lower-bound	4.694	10.000	.469		
Clothing * Stage	Sphericity Assumed	.309	9	.034	1.258	.271
	Greenhouse-Geisse	.309	2.891	.107	1.258	.307
	Huynh-Feldt	.309	4.191	.074	1.258	.301
	Lower-bound	.309	1.000	.309	1.258	.288
Error(Clothing*Stage	Sphericity Assumed	2.457	90	.027		
	Greenhouse-Geisse	2.457	28.906	.085		
	Huynh-Feldt	2.457	41.912	.059		
	Lower-bound	2.457	10.000	.246		

The error bar chart of the ear canal temperature for two kinds clothing systems is shown in Figure 1

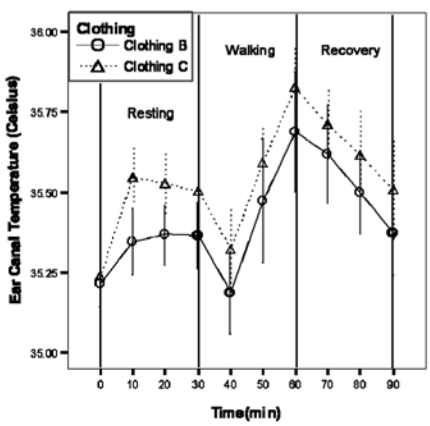


Figure 1 A comparison of the ear canal temperature under the influence of clothing B and C

Figure 1 compares the ear canal temperature when participants wore clothing B and clothing C. The trends of the ear canal temperature when clothing B and C were worn are similar. In the whole experimental process, the ear canal temperature when clothing C was worn was higher than that when clothing B was worn.

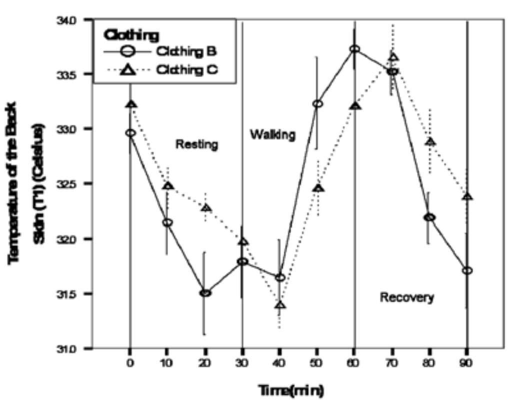
JFBI Vol.1 No. 1 2008 doi:10.3993/jfbi06200805

The temperatures at different layers of the clothing systems were analyzed by the same method. The results are summarized in Table 4 in terms of statistical significances. Table 4 shows that stage had a significant influence on temperatures of different locations with $p<0.001$. Clothing had a significant influence on the temperature of the outside of the underwear, the temperature of the outside of the vest and the temperature of the outside of the coat with $P<0.001$. Clothing had a significant influence on the temperature of the back skin with $P<0.05$. The interaction between clothing and stage also had significant influences on the temperature of the back skin, the temperature of the outside of the vest, the temperature of the outside of the coat with $P<0.005$.

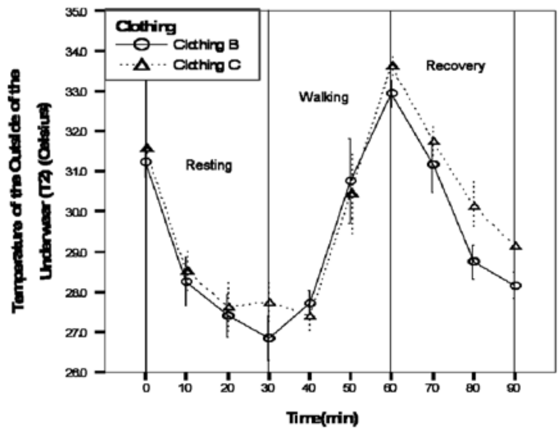
Table 4 Effects of clothing, stage and their interaction on temperatures

Temperature	Clothing	Stage	Clothing* Stage
Temperature of the back skin	0.015	0.000	0.000
Temperature of the outside of the underwear	0.000	0.000	0.077
Temperature of the outside of the vest	0.000	0.000	0.002
Temperature of the outside of the coat	0.000	0.000	0.000

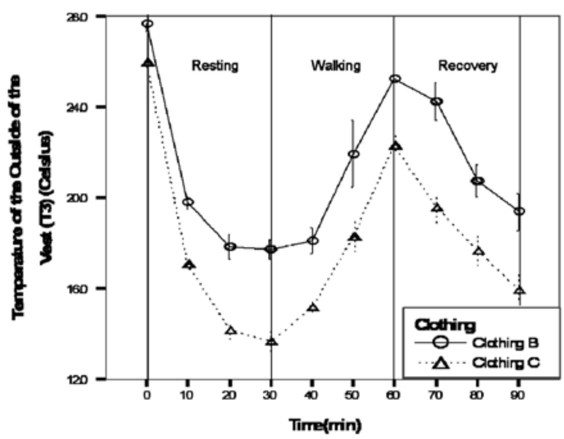
The comparisons of temperatures of different layers are shown in Figure 2



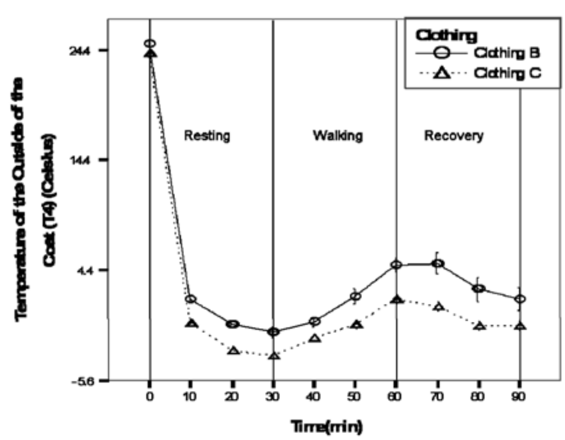
2a. Temperature of the back skin



2b. Temperature of the outside underwear



2c. Temperature of the outside vest

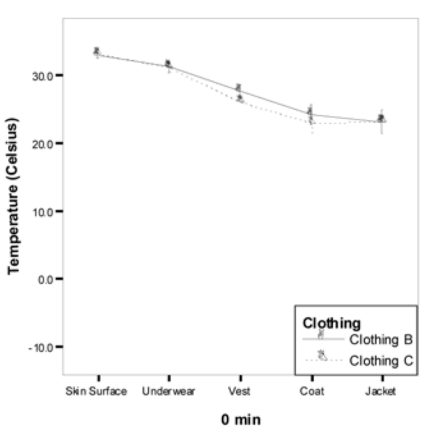


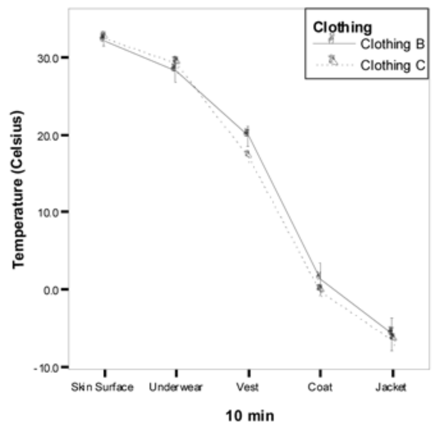
2d. Temperature of the outside coat

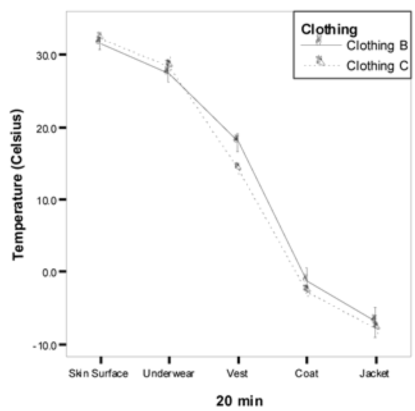
Figure 2 Error bar charts of temperatures at different clothing layers

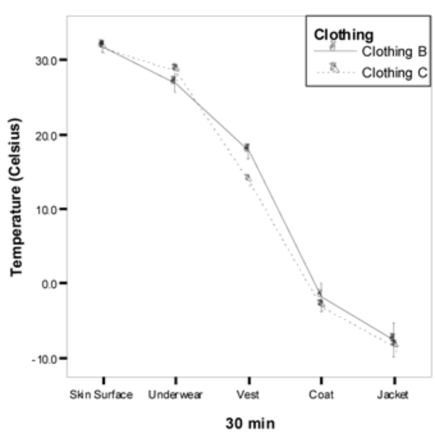
Figures 2a and 2b show that in the first 30-minute-resting period, temperatures of back skin and the outside of the underwear when clothing C was worn were higher than those when clothing B was worn. When participants entered the chamber, temperatures of the back skin when participants wore clothing B and clothing C decreased. However, the temperature decrease rate when clothing B was worn was higher than that when clothing C was worn. In the 30-minute-walking period, the back skin temperature when clothing C was worn was lower than that when clothing B was worn. The temperature increase rate when clothing C was worn was lower than that when clothing B was worn. The peak temperature value of the back skin when clothing C was worn was also lower than that when clothing B was worn. In the recovery period, temperatures of back skin and the outside of the underwear when clothing C was worn were higher than those when clothing B was worn. The temperature decrease rate of when clothing C was worn was lower than that when clothing B was worn. In the end of the experiment, the back skin temperature of participants wore clothing C was higher that that of participants wore clothing B. Figures 2c and 2d show that temperatures of the outside of the vest and the outside of the coat when participants worn clothing B were higher than those when participants worn clothing C in the whole experimental period. In the end of the 30-minutes-resting, the temperature of the outside of the vest difference between clothing B and C was about 4.0^{o}C.

In order to confirm this observation, the temperature distributions at different layers in different stages were plotted in Figure 3









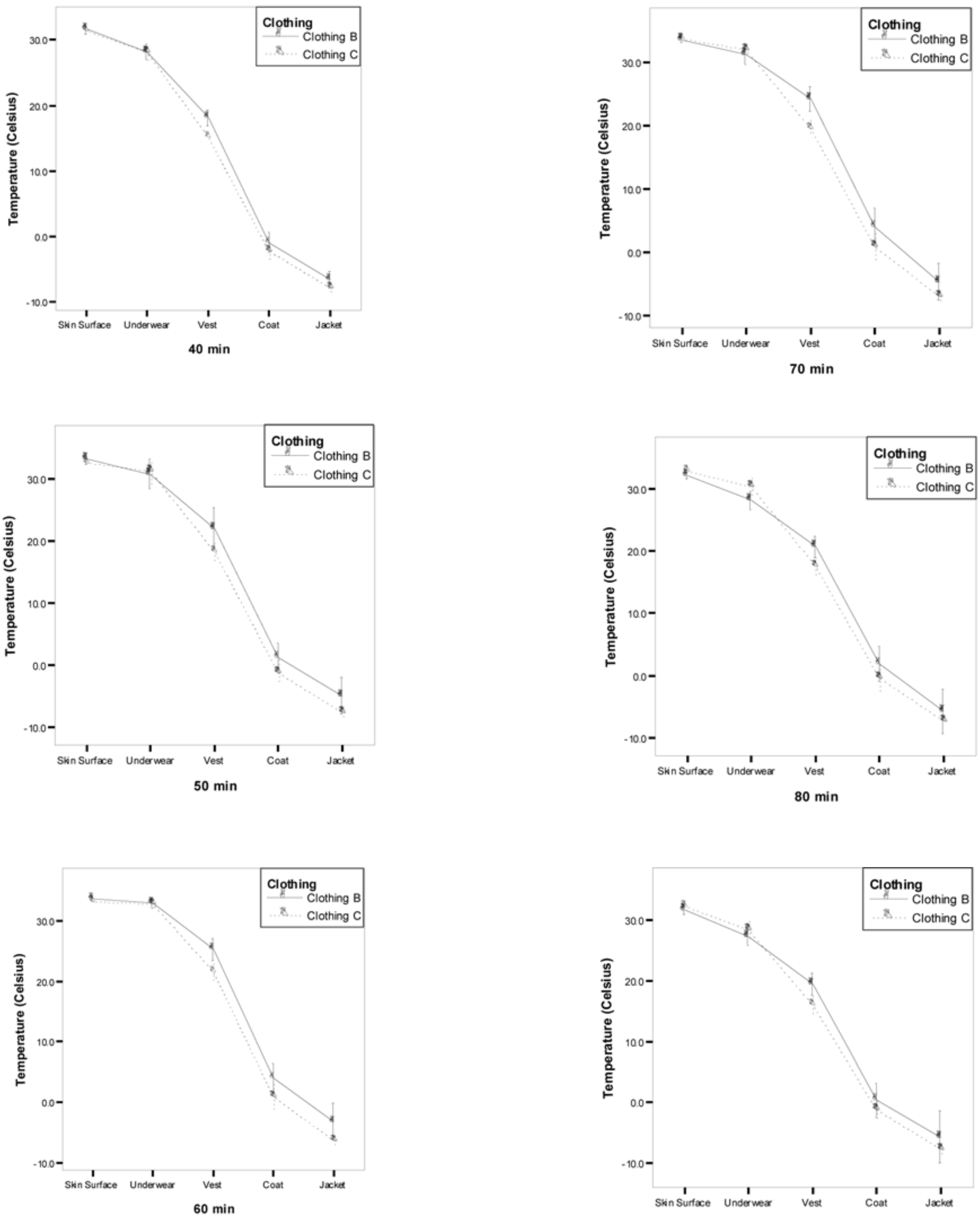


Figure 3 Temperature distributions in clothing B and C systems

Figure 3 shows that in the beginning of the experiment, the temperatures of the back skin and the outside of the underwear when participants wore clothing B and clothing C were similar, there was no significant difference. After participants entered the cold chamber, both temperatures of the back skin when participants wore clothing B and C decreased, however, the temperature of the back skin when participants wore clothing C was higher than that when participants wore clothing B. When participants walking on the treadmill, the temperature of the back skin when participants wore clothing B increased and at the 50th minute was larger than that when participants wore clothing C. From the 70th minute to the end of the experiment, the temperature of the back skin when participants wore clothing B decreased quickly and lower than that when participants wore clothing C.

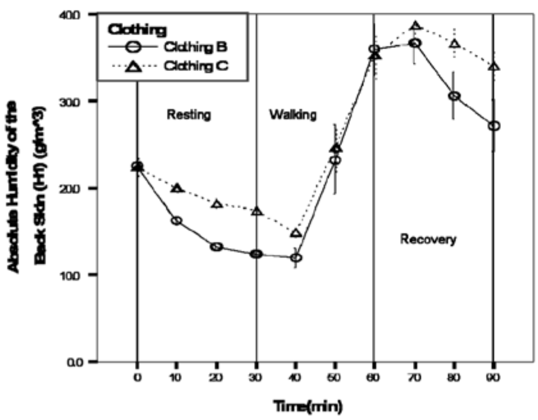
The humidities in different layers are also analyzed by SPSS 12.0 and summarized in Table 5.

Table 5 Effects of clothing, stage and their interaction on humidities

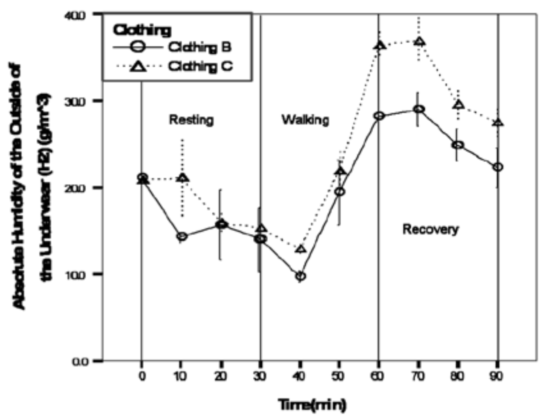
Humidity	Clothing	Stage	Clothing*Stage
The absolute humidity at the back skin	0.029	P<0.001	0.017
The relative humidity at the back skin	0.017	P<0.001	------
The absolute humidity of the outside underwear	0.045	P<0.001	------
The relative humidity of the outside underwear	0.042	P<0.001	------
The absolute humidity of the outside vest	P<0.001	P<0.001	0.006
The absolute humidity of the outside coat	0.003	P<0.001	------

Note: All the p-values greater than 0.05 are not listed in the table.

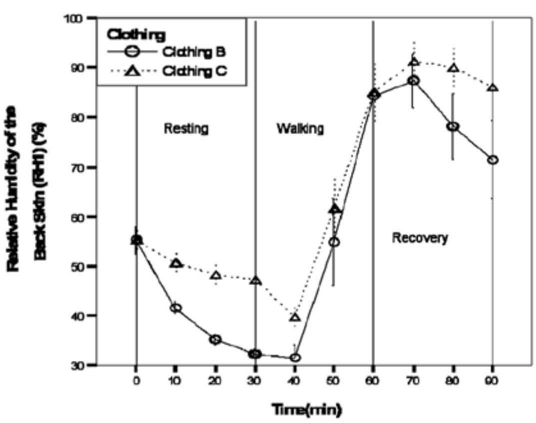
The comparisons of humidities of different layers are shown in Figure 4



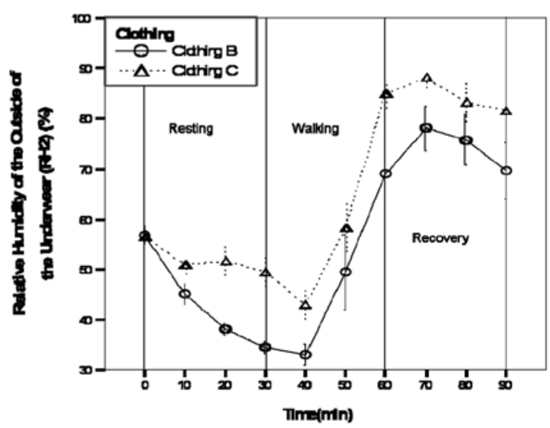
4a. Absolute humidity of the back skin



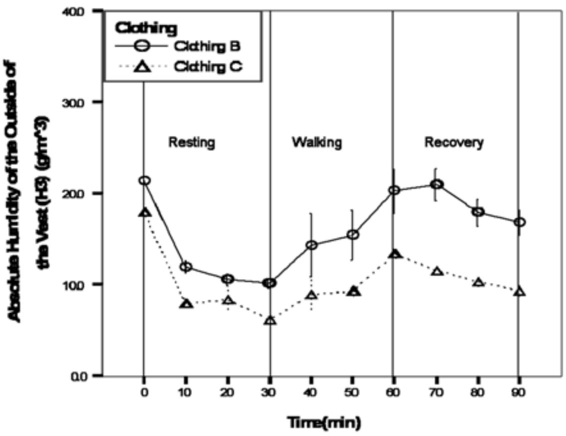
4c. Absolute humidity of the outside underwear



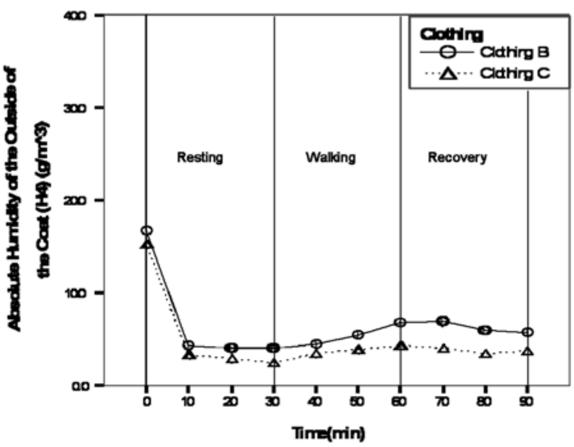
4b. Relative humidity of the back skin



4d. Relative humidity of the outside underwear



4e. Absolute humidity of the outside vest



4f. Absolute humidity of the outside coat
Figure 4. Error bar charts of humidity at different clothing layers

Figures 4a-4d show that the absolute humidities and the relative humidities of the back skin and the outside of the underwear when participants wore clothing C were higher than those when participants wore clothing B in the whole experimental period. Both the relative humidities of participants wore clothing B and C did not reach 100%, this result indicated that there was no liquid sweat appearing on the skin surface. Figures 4c and 4d show that the absolute humidities of the outside of the vest and the coat when participants wore clothing B were higher that those when participants wore clothing C. These results indicated that much more moisture diffused from the inside of the clothing B to the environment than clothing C.

Table 6 shows that clothing, and stage produce significantly different effects on the thermal sensation (P<0.05).

Table 6 Effects of clothing and stage on the thermal sensation

Tests of Within-Subjects Effects

Measure: Thermal_sensation

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
clothing	Sphericity Assumed	2.618	1	2.618	6.115	.033
	Greenhouse-Geisser	2.618	1.000	2.618	6.115	.033
	Huynh-Feldt	2.618	1.000	2.618	6.115	.033
	Lower-bound	2.618	1.000	2.618	6.115	.033
Error(clothing)	Sphericity Assumed	4.282	10	.428		
	Greenhouse-Geisser	4.282	10.000	.428		
	Huynh-Feldt	4.282	10.000	.428		
	Lower-bound	4.282	10.000	.428		
stage	Sphericity Assumed	274.364	9	30.485	43.456	P<0.001
	Greenhouse-Geisser	274.364	2.345	116.994	43.456	P<0.001
	Huynh-Feldt	274.364	3.109	88.259	43.456	P<0.001
	Lower-bound	274.364	1.000	274.364	43.456	P<0.001
Error(stage)	Sphericity Assumed	63.136	90	.702		
	Greenhouse-Geisser	63.136	23.451	2.692		
	Huynh-Feldt	63.136	31.086	2.031		
	Lower-bound	63.136	10.000	6.314		
clothing * stage	Sphericity Assumed	4.018	9	.446	1.431	.187
	Greenhouse-Geisser	4.018	4.517	.890	1.431	.235
	Huynh-Feldt	4.018	8.697	.462	1.431	.190
	Lower-bound	4.018	1.000	4.018	1.431	.259
Error(clothing*stage)	Sphericity Assumed	28.082	90	.312		
	Greenhouse-Geisser	28.082	45.168	.622		
	Huynh-Feldt	28.082	86.967	.323		
	Lower-bound	28.082	10.000	2.808		

The error bar chart of the thermal sensation is shown in Figure 5

The error bar chart of the thermal sensation is shown in Figure 5

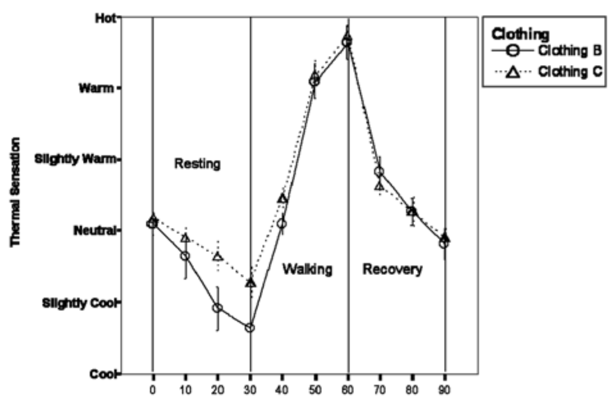


Figure 5 The error bar chart of the thermal sensation

Figure 5 shows that participants felt much warmer when clothing C was worn than when clothing B was worn in the first 40 minutes. Figure 2a shows that in this period, the back skin temperature when participants wore clothing C was higher than clothing B. In the next 50 minutes, the thermal sensations of participants wore Clothing B and clothing C was similar.

Table 7 indicates that clothing and stage also produce significantly different influences on the moisture sensation ($P<0.05$).

Table 7 Effects of clothing and stage on the moisture sensation

Tests of Within-Subjects Effects

Measure: Moisture_sensation

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
clothing	Sphericity Assume	1.314	1	1.314	5.179	.046
	Greenhouse-Geiss	1.314	1.000	1.314	5.179	.046
	Huynh-Feldt	1.314	1.000	1.314	5.179	.046
	Lower-bound	1.314	1.000	1.314	5.179	.046
Error(clothing)	Sphericity Assume	2.536	10	.254		
	Greenhouse-Geiss	2.536	10.000	.254		
	Huynh-Feldt	2.536	10.000	.254		
	Lower-bound	2.536	10.000	.254		
stage	Sphericity Assume	115.768	9	12.863	46.527	P<0.001
	Greenhouse-Geiss	115.768	3.181	36.397	46.527	P<0.001
	Huynh-Feldt	115.768	4.838	23.931	46.527	P<0.001
	Lower-bound	115.768	1.000	115.768	46.527	P<0.001
Error(stage)	Sphericity Assume	24.882	90	.276		
	Greenhouse-Geiss	24.882	31.807	.782		
	Huynh-Feldt	24.882	48.375	.514		
	Lower-bound	24.882	10.000	2.488		
clothing * stage	Sphericity Assume	1.550	9	.172	1.099	.372
	Greenhouse-Geiss	1.550	3.261	.475	1.099	.367
	Huynh-Feldt	1.550	5.026	.308	1.099	.373
	Lower-bound	1.550	1.000	1.550	1.099	.319
Error(clothing*stag	Sphericity Assume	14.100	90	.157		
	Greenhouse-Geiss	14.100	32.611	.432		
	Huynh-Feldt	14.100	50.263	.281		
	Lower-bound	14.100	10.000	1.410		

The error bar chart of the moisture sensation is shown in Figure 6

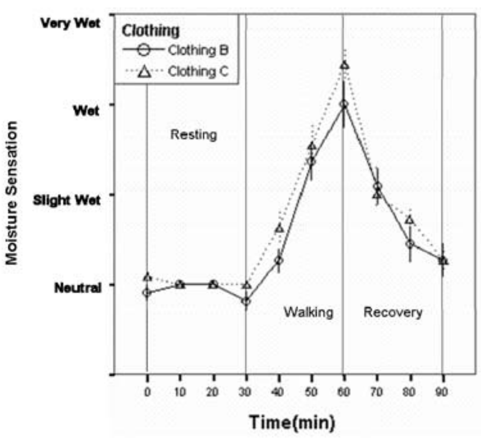


Figure 6 shows that both the moisture sensations when clothing B and C were worn are similar in the first 30-minutes-resting and recovery period. In the 30-minutes-walking period, the moisture sensation when clothing C was worn was higher than that of when clothing B was worn. These results are confirmed that the observations in Figures 4a and 4b.

Table 8 indicates that clothing and stage also produce significantly different effects on the perception of overall comfort with $P<0.05$.

Table 8 Effects of clothing and stage on overall comfort

Tests of Within-Subjects Effects

Measure: Overall_comfort

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
clothing	Sphericity Assumed	1.473	1	1.473	17.802	.002
	Greenhouse-Geisser	1.473	1.000	1.473	17.802	.002
	Huynh-Feldt	1.473	1.000	1.473	17.802	.002
	Lower-bound	1.473	1.000	1.473	17.802	.002
Error(clothing)	Sphericity Assumed	.827	10	.083		
	Greenhouse-Geisser	.827	10.000	.083		
	Huynh-Feldt	.827	10.000	.083		
	Lower-bound	.827	10.000	.083		
stage	Sphericity Assumed	46.909	9	5.212	11.333	P<0.001
	Greenhouse-Geisser	46.909	3.197	14.675	11.333	P<0.001
	Huynh-Feldt	46.909	4.874	9.624	11.333	P<0.001
	Lower-bound	46.909	1.000	46.909	11.333	.007
Error(stage)	Sphericity Assumed	41.391	90	.460		
	Greenhouse-Geisser	41.391	31.965	1.295		
	Huynh-Feldt	41.391	48.742	.849		
	Lower-bound	41.391	10.000	4.139		
clothing * stage	Sphericity Assumed	1.164	9	.129	.628	.771
	Greenhouse-Geisser	1.164	2.982	.390	.628	.602
	Huynh-Feldt	1.164	4.389	.265	.628	.659
	Lower-bound	1.164	1.000	1.164	.628	.447
Error(clothing*stage)	Sphericity Assumed	18.536	90	.206		
	Greenhouse-Geisser	18.536	29.820	.622		
	Huynh-Feldt	18.536	43.890	.422		
	Lower-bound	18.536	10.000	1.854		

The error bar chart of the overall comfort is shown in Figure 7

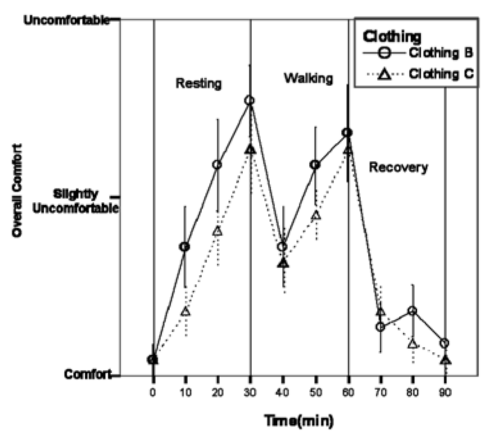


Figure 7 shows that participants felt more comfortable when clothing C was worn than clothing B. The feeling differences were larger in the first 30-mintues-resting period and in the walking period.

4. Discussion

The experimental results showed that the clothing C system could significantly improve the ear canal temperature (Figure 1). These results indicated that the body temperature when participants wore clothing C was higher than that when participants wore clothing B. Table 2 shows that the structures of Clothing B and clothing C are similar. All materials are also similar except the second sub layer of the vest and the second sub layer of the coat. The second sub layer of the vest and the second sub layer of the coat were treated with PCM in the smart clothing. Figure 2a shows that in the first 30-minutes-resting period, the temperature change rate when clothing C was worn was lower than that when clothing B was worn. PCM has the temperature regulation function. When participants entered the cold chamber, the PCM treated on the clothing C may change from liquid state to the solid state, heat was released, and retarded the temperature change rate. So, participants wearing clothing C should feel much warmer than wearing clothing B. The observations shown in Figure 5 are confirmed these results were correct. When participants were walking on the treadmill (from the 30^{th} minute to the 60^{th} minute), the metabolism increased and more heat was produced and released. The skin temperature began to increase. Figure 2 shows that the skin temperature when participants wore clothing B increased quicker than when participants wore clothing C. In the recovery period, the skin temperature when participants wore clothing C decreased slower than when participants wore clothing B. The reason maybe PCM treated on the clothing C absorbed heat released by human body and changed from solid to liquid. PCM acted as heat buffer and reduced the temperature change rate in the microclimate of clothing system. Participants also reported that they felt more comfortable when clothing C was worn than when clothing B was worn (Figure 7).

The humidity distributions in different layers are shown in Figures 4a~4f. It can be found that the absolute humidities and the relative humidities of the back skin and the outside of the underwear when participants wore clothing C were higher than those when participants wore clothing B. Figure 6 shows that participants reported that they felt a little wetter when wore clothing C than clothing B. The relative humidities of the back skin and the outside of the underwear no matter participants wore clothing B or C did not reach 100%. The absolute humidities of the outside of the vest and the coat when clothing C was worn were lower than those when clothing B was worn (Figures 4e, 4f). These results indicated that the moisture in clothing B was much more easily diffusion than in clothing C. The observations shown in Figures 2c and 2d (the temperatures of the outside of the vest and the coat when clothing B was worn were higher than those when clothing C was worn) also indicated that the more moisture diffused from the clothing B and improved the outer layers' temperature. These results were consonant with the reports by Chung et al.(2004) [11]. Generally, participants reported that in the whole experimental period they felt more comfort when clothing C was worn than clothing B. The PCM treated in clothing C can significantly improve the temperatures and the humidities of the back skin and the outside of the underwear, decrease the temperature change rate and make the wears more comfort.

5. Conclusion

Experimental results showed PCM treated in clothing system temperature regulating effect and improved the temperatures and humidities of inner layers. The ear canal temperature when participants wearing clothing C was higher than that when participants wearing clothing B. PCM treated in clothing system also decreased the temperature change rate of the back skin, and decreased the temperature impact induced by the environment temperature change and activity level change. The water resistance of clothing system decreased when fabrics treated with PCM. In experiment process, no condensation water was found in two kinds of clothing system. Participants still felt comfortable even the absolute humidities of the clothing system increasing when clothing C were worn. Participants felt more comfortable when wearing clothing C than wearing clothing B.

Acknowledgements

The authors would like to thank the Hong Kong Research Grant Council, the Hong Kong Polytechnic

University and Hong Kong Innovation Technology Commission ITS-023-03 for funding this research through the project PolyU 5281/03E, ITP-002-TP-07.

References:

[1] Rutishauser S. Physiology and anatomy: A basis for nursing and health care. Churchill Livingstone, 1994.

[2] Ingram DL, Mount LE. Heat exchange between animal and environment. In: Schaefer KE (ed). Man and animals in hot environment. Springer, Berlin Heidelberg, New York, 1975.

[3] Fanger PO. Thermal comfort: Analysis and applications in environmental engineering. New York, McGraw-Hill, 1972.

[4] Bryant YG, Colvin DP. Fibers with enhanced reversible thermal energy storage properties. Techtextile Symposium, 1992. p. 1-8.

[5] Hale DV, Hoover MJ, O'Neill MJ. Phase change materials handbook. Marshall Space Flight Center, Alabama, 1971.

[6] Brown RC, Rasberry JD, Overmann SP. Microencapsulated phase-change materials as heat transfer media in gas-uidized beds. Powder Technol 1998;98:217-222.

[7] Shim H, McCullough EA, Jones BW. Using phase change materials in clothing. Textile Research Journal 2001;71(6):495-502.

[8] Ying BA, Kwok YL, Li Y. Thermal regulating functional performance of PCM garments. International Journal of Clothing Science and Technology 2004;16(1/2):84-96.

[9] Li Y, Wong ASW. Clothing bio-sensory engineering for comfort. Woodhead Publishing Limited, 2006.

[10] Hu JY, Li Y, Yeung KW, Wong ASW. Moisture management tester: A method to characterize fabric liquid moisture management properties. Textile Research Journal 2005;75(1):57-62.

[11] Chung H, Cho G. Thermal properties and physiological responses of vapor-permeable water-repellent fabrics treated with microcapsule-containing PCMs. Textile Research Journal 2004;74(7):571-575.