Energy and Buildings 155 (2017) 533–545

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Experimental study on using PCMs of different melting temperatures in one cooling vest to reduce its weight and improve comfort

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A R T I C L E I N F O

Article history:
Received 20 July 2017
Received in revised form
17 September 2017
Accepted 20 September 2017
Available online 21 September 2017

Keywords:
Passive cooling vest
Phase change material
Local and mean skin temperatures
Thermal comfort and sensation

A B S T R A C T

This study aims at evaluating experimentally phase change material (PCM) cooling vest performance when incorporating two types of PCM with different melting temperatures with varied PCM placement on the lower, upper, front and back of the torso. Experiments on a thermal manikin were conducted to assess cooling rate observed with the various PCM arrangements while experiments on six male subjects were conducted to assess associated physiological and comfort votes after exercising for 45 min.

The main findings of manikin testing were that an improved cooling effect can be achieved by covering the upper torso with PCM packets at 28 °C melting temperature while covering the lower torso with the 18 °C packets. Human subject testing established that similar improvements in thermal comfort and sensation levels could be attained when covering the back or lower torso segments with 18 °C instead of covering all the torso. In addition, a maximum reduction in local skin temperatures of 5.45 ± 1 °C was achieved accompanied with a reduction of 64 W in body heat storage. Covering the chest and upper back segments with the 18 °C packets suppressed sweat production and improved wetness sensation. Finally, 16% lower vest weight might be possible with prolonged working periods of two hours at 35 °C.

1. Introduction

The need to provide comfortable working spaces in warm or hot conditions requires cooling these spaces and thus consuming energy. In the presence of global warming, the ability to provide comfort is becoming more challenging and the need for cooling is increasing while accompanied with an increase in energy consumption [1]. Different types of personal and local cooling methods have been used in previous studies to reduce thermal stresses on outdoor workers [1–9] and improve comfort of indoor workers in office and commercial buildings [10]. Local cooling allows for having elevated macroclimate air temperatures, since the microclimate of the workers is cooled and thus less energy is required by space air conditioning systems [1]. Moreover, thermal comfort in transitional spaces can be improved through the use of local passive cooling techniques [11].

One type of local cooling includes phase change material (PCM) cooling vests, which incorporate ice packets, paraffin or even salt-based packets used to cool the human torso [12–17]. Such a system allows for exploiting the latent heat storage effect without consuming additional energy unlike active refrigeration systems that cool the whole occupied space and unlike active cooling vests with ventilation fans. Previous studies have investigated the performance of PCM cooling vests under a wide range of PCM melting temperatures from relatively low values of 0 °C such as ice to relatively high values of 32 °C like salt-hydrates and Glauber's salt [12,15,16,18]. Some manufacturers of salt-hydrate PCMs [19–21] and researchers in previous studies [15,21,23], reported ranges of PCM melting temperatures from 6 °C to 32 °C, with an increasing trend in the latent heat of fusion as the melting temperature increases [24–26]. As the environment gets warmer, it is advantageous to use lower PCM melting temperature rather than higher ones because they result in higher body cooling rates due to the significant temperature gradient between the human skin and the PCM surface [15–17]. However, there are some shortcomings of the low melting temperature PCM: i) it can last for a short period of time before complete melting due to its low latent heat of fusion at higher body cooling rate and ii) it requires storage at low temperature which consumes energy and adequate transport for end use. On the other hand, PCM packets with higher melting temperatures have relatively high latent heat of fusion so they can last for longer durations when worn. In addition, they can be regenerated or solidified at room temperatures or in conditioned spaces without the need for

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http://dx.doi.org/10.1016/j.enbuild.2017.09.057

Nomenclature

Age	Age of the human subject (years)
BWL	Body weight loss (g)
C_{body}	Body specific heat (J/kg·°C)
ISO	International organization for standardization
IRTT	Infrared tympanic thermometer
m_{body}	Human body mass (kg)
MET	Metabolic equivalent for task
PE	Perceived exertion
PCM	Phase change material
QU	Qatar university
S	Change in body heat storage (W)
SD	Standard deviation
t	Time (s)
T	Temperature (°C)
TC	Thermal comfort
TTS	Torso thermal sensation
WBGT	Wet bulb globe temperature (°C)
WBTS	Whole body thermal sensation
WSSC	Wetness of skin and clothing
18F-18B	PCMs of 18 °C melting temperature cover front and back
18F-28B	PCMs of 18 °C melting temperature cover front and 28 °C melting temperature cover back
28F-18B	PCMs of 28 °C melting temperature cover front and 18 °C melting temperature cover back
28F-28B	PCMs of 28 °C melting temperature cover front and back
28U-18L	PCMs of 28 °C and 18 °C melting temperature cover upper torso and lower torso, respectively
18U-28L	PCMs of 18 °C and 28 °C melting temperature cover upper torso and lower torso, respectively

Subscripts

b	Body
cr	Core
initial	Initial state
final	Final state
mean	Mean
sk	Skin layer

refrigeration, thus providing local cooling without consuming any additional energy. Conversely, they have lower cooling rates due to the lower temperature gradient as reported in previous studies [15–18].

Establishing that PCM packets with lower melting temperatures have lower latent heat than those with higher melting temperatures, then the melting period duration of the lower temperature packets would be shorter. For example, if a situation is considered where a clothed human is working at moderate activity level of 3 METs in hot humid conditions of 35 °C for two hours [24,25,27], heat storage occurs in the body accompanied with a rise in core, T_{cr}, and mean skin temperatures, $T_{sk,mean}$. The amount of heat stored in the human body, S, [17,29] would be about 52 W with a 1.5 °C increase in the body temperature [13]. Using a uniform melting temperature in the cooling vest, which was consistently done in previous studies [12,15–17], the resulting mass of PCM needed to alleviate that amount of heat would be about 3.31 kg when using 18 °C PCM melting temperature having a latent heat of 113 kJ/kg and about 2.35 kg when using 28 °C PCM melting temperature having a latent heat of 159 kJ/kg. Thus, a substantial PCM weight difference by about 41% is present in that case when using low melting temperatures which would increase the metabolic rate of the human and thus affect the working endurance [30]. But selecting a relatively high melting temperature PCM with lower mass results in slower cooling rate. Clearly, a tradeoff may exist by using different melting temperature PCMs in the same vest to make use of the advantages of both high and low melting temperature PCMs; the ones with high latent heat of fusion and lower energy use for regeneration and the ones with lower melting temperature.

Combining two different melting temperatures in the same vest would have to be in such a manner that is responsive to human physiology to target body areas that are sensitive to cooling. It was reported that local cooling of the back torso segment affects significantly the thermal perception of humans and thus, using low PCM melting temperatures on this segment might improve sensation levels and reduce heat stress [13,31,32]. Therefore, there is a viable option of using two different melting temperatures of PCM packets, a relatively low and a relatively high one, in the same vest to result in a significant, fast, and lasting cooling effect at lower mass of the vest and regeneration energy use. The research question would then be: Is it possible to combine the advantage of the low melting PCM temperature (more comfort) and the advantage of higher melting temperature (larger heat of fusion and lower regeneration energy consumption)?

In this study, the objective is to find the right arrangement of PCM packets with different melting temperatures of 18 °C and 28 °C that results with the desired cooling effect, by either targeting the most comfort sensitive segments or by investigating different PCM placements on the upper and lower torso segments. The PCM cooling effect will be first measured on a thermal manikin and then on human subjects to get physiological data and subjective comfort and sensation votes.

2. Material and methods

The experiments in this study were limited to the situation where the PCM coverage area is fixed and the placement of the PCMs with lower and higher melting temperatures is varied on either the frontal or back torso segment or both. Experiments on a thermal manikin were done to first answer what arrangement is better when used on a thermal manikin and second to test that arrangement on human subjects while conducting physiological and thermal comfort assessments.

In the coming subsections, a description of the proposed cooling vests is done first, then a description of the tests performed on a thermal manikin with main conclusions. After that, the descriptions of human subject experiments and measurements are presented.

2.1. Description of cooling vest arrangements tested on thermal manikin

A commercially available PCM cooling vest made of polyester with 20 inner pockets to hold the PCM packets is used in this study. Good fitting of the vest to the body of the manikin and participants was ensured through Velcro fasteners. All the PCM packets were cooled overnight to have an initial temperature of 15 °C at the start of every experiment.

The PCM melting temperatures are chosen such that a good temperature gradient exists between the skin and the PCM temperature as well as a substantial difference between the two melting temperatures themselves accompanied with high latent heats of fusion. The melting temperatures used in this study were 18 °C and 28 °C, as shown in Fig. 1a and b and similar to the ones used in previous studies [12–15,17,18]. It should be noted that the packets used are not custom-made and their physical dimensions are provided by the manufacturer [33,34]. The cooling area and weight of each PCM packet with a melting temperature of 18 °C are about 102 cm^2, and 155 g, respectively. The cooling area and weight of each PCM

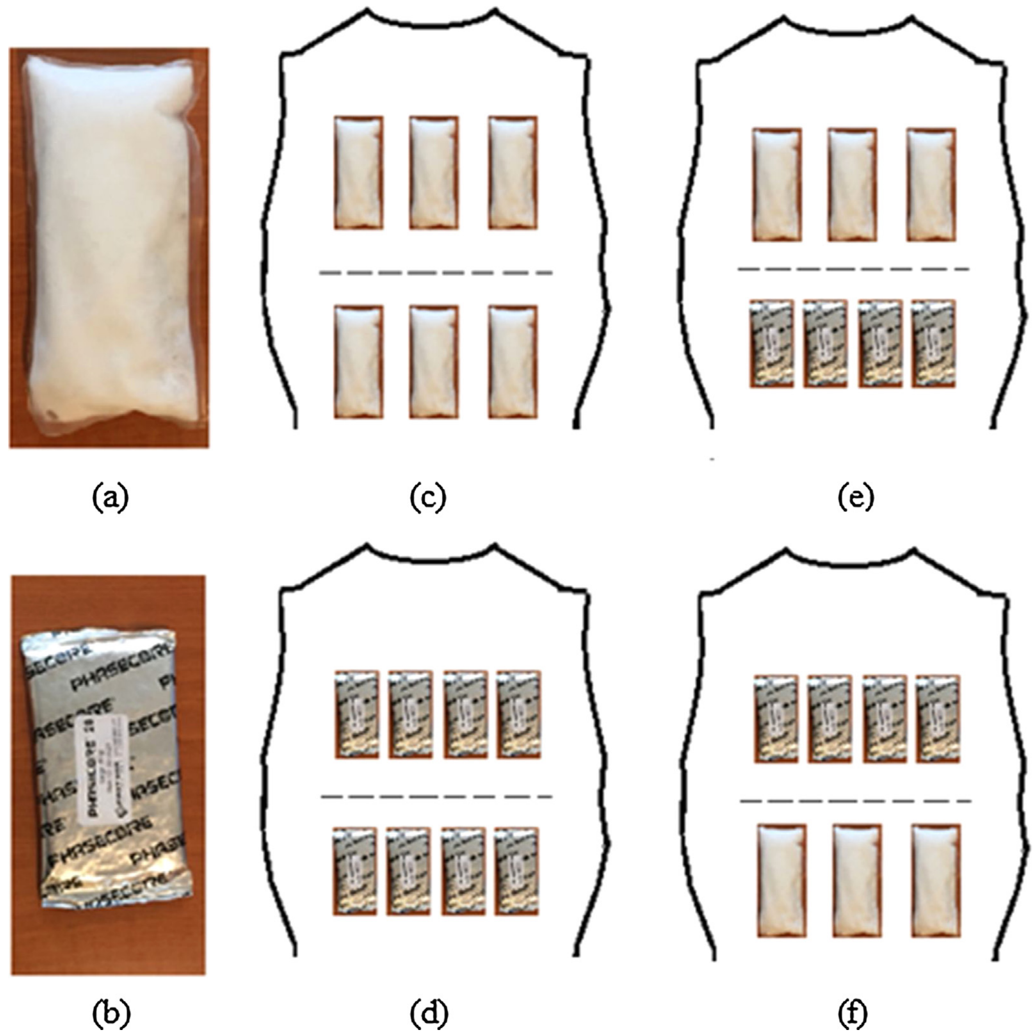

Fig. 1. Picture showing (a) the PCM packet of 18 °C melting temperature and (b) the 28 °C packets and schematics of the different possible arrangements showing (c) all 18 °C on upper and lower segments, (d) all 28 °C on upper and lower segments, (e) 18 °C on upper segments and 28 °C on lower segments and (f) 28 °C on upper segments and 18 °C on lower segments.

packet with a melting temperature of 28 °C are about 80.24 cm^2, and 87.5 g, respectively. It is noted that a difference in the weight is present, where each packet of 18 °C weighs 67.5 g more than the 28 °C packets.

Many variables should be controlled when using two melting temperatures in the same vest. The choice of the coverage area and the number of packets in the vest for the different experiments is based on having enough packets to cover a good portion of the torso. The total coverage area in all the vests will be fixed at 1224 cm^2 and divided equally on the front and back torso segments with 612 cm^2 covering each, while varying the position of the two PCM types on the torso (chest, abdomen, lower back and upper back). In the cases using two melting temperatures simultaneously, 6 packets of 18 °C melting temperature are equivalent in coverage area to 8 packets of 28 °C melting temperature. In addition, total melting did not happen with PCM packets of 28 °C melting temperature after an exercise period of 45 min [15–17]. However, a maximum weight difference of 0.46 kg is present when considering all packet of 18 °C or all packets of 28 °C. The added weight, if worn by a human would have a slight effect on his metabolism; however, on a thermal manikin weight is irrelevant in this case.

Experimentation on a thermal manikin will be first done to test the cooling power of the different PCM arrangements either with one or with two melting temperatures simultaneously and conclude the best arrangements among them. However, for complete vest assessment for comfort and cooling, experiments on human subjects are performed to obtain physiological and thermal response data and subjective comfort and sensation votes. The different PCM arrangements corresponding to thermal manikin testing are described in Table 1 and shown in Fig. 1c–f. The experiments that were performed on a thermal manikin were repeated twice. The description of the different experiments performed on a thermal manikin with their results and those performed on human subjects are discussed in the following sections.

Table 1
Different PCM arrangements tested on thermal manikin.

PCM Arrangement	PCM coverage on front/back (cm^2)	Number of 18 & 28 °C packets used	Total PCM weight (kg)
28U–18L	612/612	6 & 8	1.63
18U–28L	612/612	6 & 8	1.63
28F–28B	612/612	0 & 16	1.40
18F–18B	612/612	12 & 0	1.86

2.2. Thermal manikin clothed with cooling vest at constant temperature mode

The aim of the manikin experiments is to investigate the significance of the arrangement on the cooling effect when using two

Fig. 2. Picture showing Newton thermal manikin clothed with the PCM cooling vest.

different melting temperatures in the vest against using only one melting temperature. Random mixing between the two types of PCM packets in the vest will not be considered, however, the criteria will be placing each PCM type on either the upper or lower torso segments. Placing the packets with the higher melting temperature on the upper torso segments, might enhance the microclimate air flow rate and thus affect the vest cooling performance. It should be kept in mind that the total PCM coverage area in all the vests will be fixed and divided equally on the front and back torso segments, while varying the position of the two PCM types on the torso. Since the PCM vest covers only the torso segments of the thermal manikin, the shoulders, chest, abdomen and back segments were included in the assessment of the vest cooling effect by finding their average heat flux.

2.2.1. Experimental procedure

The cooling power of the PCM vest under four different PCM arrangements was initially measured on the 20-zone "Newton" thermal manikin shown in Fig. 2 [35]. A constant thermal manikin skin temperature at 35 °C was used to record the cooling power of the different PCM packets on the torso segments. The different cooling vest arrangements tested have the same PCM coverage area of 1224 cm^2 and have either a uniform melting temperature in the vest or two temperatures simultaneously, as was shown in Fig. 1.

Table 2
Results of the thermal manikin experiments.

Experiment	28U–18L	18U–28L	28F–28B	18F–18B
Average torso heat flux at the start ± SD (W/m^2)	65 ± 0.6	53 ± 0.7	51 ± 1.2	65 ± 2.1
Average torso heat flux at steady state ± SD (W/m^2)	22 ± 0.4	19 ± 0.5	12 ± 1.4	30 ± 1.9

Table 1 shows the four different experiments done on the thermal manikin.

The manikin was clothed with a long sleeved cotton shirt and trousers as shown in Fig. 2. The experiments were conducted in a climatic chamber at the moderate ambient temperature of 32 ± 0.5 °C and 45 ± 3% relative humidity. The thermal manikin divides the torso into 4 segments, which include the shoulders or upper back, chest, stomach or abdomen and back. The segmental heat fluxes were recorded every minute using the ThermDAC control software [36] and then used to find the average torso heat flux. The thermal manikin, which was present in the climatic chamber over the night, was turned on after the room conditions as well as the thermal manikin reached steady values of 32 ± 0.5 °C. The manikin was turned on to reach a constant skin temperature of 35 °C and the cooling vest was put on once the skin temperature was attained. The PCM packets at initial temperature of 15 °C were placed inside the vest pockets adjacent to the upper and lower torso segments. The whole process of placing the packets in the vest and clothing the manikin took around two minutes and the duration of the experiment was 200 min. The experiments on the manikin were repeated twice and average values were used for analysis.

2.2.2. Results of manikin testing

After applying the constant skin temperature mode at 35 °C on the thermal manikin, the average torso heat flux was recorded for 200 min after clothing the manikin with the cooling vest. Table 2 presents the average torso heat fluxes with their standard deviations recorded at the start and after steady state was attained for the different vests. The results indicated highest values of heat flux at the beginning of the experiments to reach after that stable levels due to the fixed temperature of the PCM packets while melting. Among the four experiments, the highest heat fluxes recorded are those of experiment **18F-18 B** since all the segments were covered with packets of the lower melting temperature of 18 °C. It should be noted that during all the experiments, total melting of either the 28 °C or 18 °C packets did not happen after 200 min have passed. After attaining steady state in experiment **18F-18B**, the average torso heat flux was 30 ± 1.9 W/m^2, which was the highest value recorded among the different experiments. However, it was noticed that the steady average torso heat flux of **28U-18L** was lower than that of **18F-18 B** by about 27% but higher than **28F-28 B** by about 83% due to mixing of two PCM types in the same vest. When comparing the results of experiment **28U-18L** and **18U-28L**, it was noticed that **28U-18L** had higher heat losses by about 16% with a maximum deviation of 5%. Thus, placing the PCM packets with the lower melting temperature on the lower torso segments resulted in better cooling effect on the torso. The reason behind that could be attributed to the effect of enhancing the microclimate air flow rate by placing the higher PCM temperature on the upper side. In other words, having the higher PCM temperature on the upper torso induces better circulation of microclimate air so that the hotter air rises upward and out of the vest more efficiently.

The improvement in cooling effect on the manikin when placing the higher PCM temperature on the upper torso justifies the need to test it further on human subjects and check if similar conclusions can be drawn on thermal comfort and sensation votes. Manikin testing provided information about the heat losses from the torso

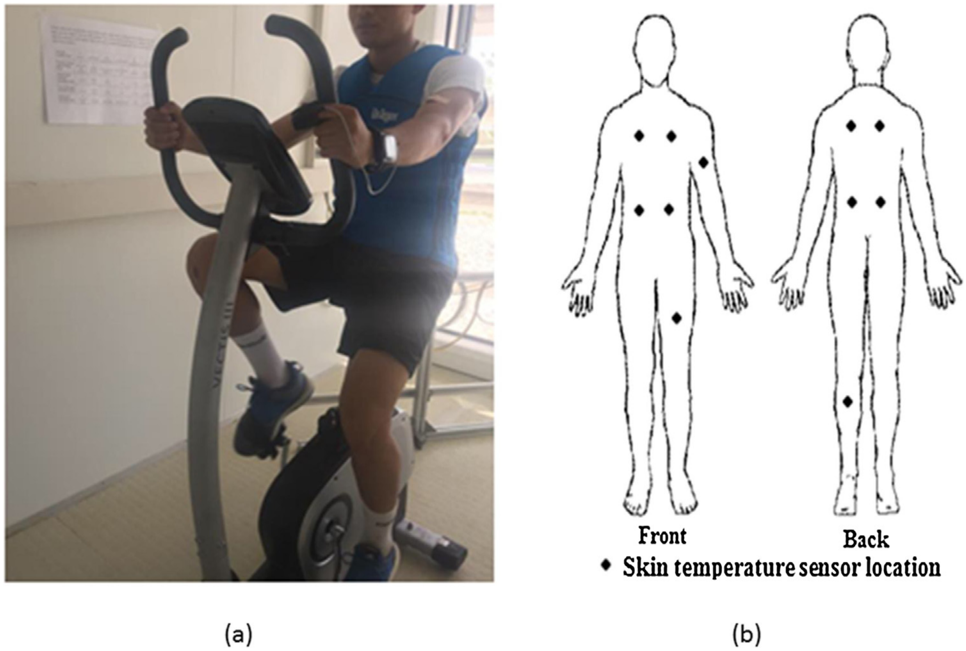

Fig. 3. Pictures showing (a) one participant doing exercise while wearing a vest at QU and (b) skin temperature sensor locations on body segments.

Table 3
Characteristics of the male subjects participating in this study.

Subject	Age (year)	Height (m)	Weight (kg)
1	21	1.71	72
2	25	1.80	89
3	23	1.72	71
4	21	1.79	70
5	23	1.64	64
6	21	1.72	90

Table 4
Different PCM arrangements tested on human subjects.

PCM Arrangement	PCM coverage on front/back (cm^2)	Number of 18 °C and 28 °C packets used	Total PCM weight (kg)
No vest	0	0 & 0	0
28U–18L	612/612	6 & 8	1.63
18U–28L	612/612	6 & 8	1.63
28F–28B	612/612	0 & 16	1.40
18F–18B	612/612	12 & 0	1.86
28F–18B	612/612	6 & 8	1.63
18F–28B	612/612	6 & 8	1.63

without physiology being considered in the assessment and without subjective comfort and sensation votes. In addition, the issue if total melting of one packet happened is not present since total melting of either the 28 °C or 18 °C packets did not happen after 200 min have passed.

2.3. Human subject experimentation

After conducting experiments on a thermal manikin, the results showed that in the presence of two melting temperatures in the same vest, improvement in PCM vest cooling effect can be achieved by proper placement of packets with different melting temperatures on upper and lower torso segments. Thus, extending the assessment of different PCM arrangements in the vest on human subjects would provide closure on the selection of the optimal tested arrangement. In this section, the descriptions of the human subjects, cooling vest arrangements, the experimental protocol and measurements taken are presented.

2.3.1. Subjects

Ethical approval to carry out the study on six male subjects was obtained from the Institutional Review Board at Qatar University, QU. Similar studies have been conducted with the same sample size of participants or even lower [16,31,37,38]. The average age of the participants was 22.33 ± 1.49 years (mean ± SD), the average height was 1.73 ± 0.05 m and average weight was 76 ± 9.8 kg. Table 3 shows the characteristics of the six male participants of this study.

All the human subjects wore a 50% cotton-50% polyester t-shirt, briefs, shorts, shoes and socks with a 0.46 clo dry thermal resistance. Each subject was asked not to drink alcohol or coffee 24 h prior to the experiment time and eat or smoke for at least two hours before the experiment. The subjects arrived to the research laboratory via personal vehicles and upon arrival they were briefed about the experiment and signed a consent form. The experiment was conducted under the surveillance of a nurse. Fig. 3a shows a picture at QU for one participant doing exercise while wearing a vest. Each participant was asked to do seven experiments at the same time of the day with at least two days between them; one without a PCM cooling vest and six with the vest but with different PCM arrangement at a randomized order. Experiments were conducted in the months April and May in the afternoon, where average outdoor ambient temperature and relative humidity during that period and at that time are about 34 °C and 45%, respectively.

2.3.2. Description of cooling vest arrangements tested on human subjects

The different PCM arrangements corresponding to the human subject testing are described in Table 4 and shown in Fig. 1**c**–**f**. Six different PCM arrangements and a no vest case will be tested while the subjects are doing moderate activity for 45 min in a climatic chamber at 35 °C and 50% relative humidity. It should be noted that two additional vest cases were tested on the human subjects that were not tested on the manikin, which are 18F–28 B and 28B-18F. The former two cases would result in the same heat flux if tested on the manikin, however, if tested on human subjects, then

Table 5
Exercise protocol.

Time (min)	Activity	Location
0–10	Signing of consent form, participant & clothing weighing, preparation of sensors & start of T_{cr} and heart rate recording	Research laboratory
11–40	Participant rests while seated	Research laboratory
41–85	Participant exercises on a magnetic upright bike at about 3 METs while wearing PCM vest	Climatic chamber
86–96	Participant & wet clothing weighing, then participant resting	Research laboratory

Table 6
Reference scales for subjective ratings.

Thermal Comfort Scale		Wetness of Skin and Clothing Scale		Whole Body/Torso Thermal Sensation Scale		Perceived Exertion Scale	
0	*neutral*	**1**	*more dry than normal*	**−4**	*very cold*	**0**	*extremely light*
				−3	*cold*		
1	*comfortable*	**2**	*normal dryness*	**−2**	*cool*	**1**	*very light*
2	*slightly uncomfortable*	**3**	*chest and back slightly wet*	**−1**	*slightly cool*	**2**	*fairly light*
				0	*neutral*		
3	*uncomfortable*	**4**	*chest and back wet*	**1**	*slightly warm*	**3**	*somewhat hard*
4	*very uncomfortable*	**5**	*body wet*	**2**	*warm*	**4**	*hard*
5	*extremely uncomfortable*	**6**	*body wet, clothing sticks to the skin*	**3**	*hot*	**5**	*very hard*
				4	*very hot*		

physiology due to different segmental sensitivity to cooling may influence subjective votes and result in additional factors affecting the selection of the best cooling vest. Each arrangement described in Table 4 was repeated six times on the six male subjects.

2.3.3. Experimental protocol

The experiments are conducted at moderate ambient conditions of 35 °C and 50% relative humidity and air speed of 0.2 m/s. Table 5 shows a brief description of the experimental protocol followed in this study.

Each participant was asked to sign a consent form upon arrival. The participant, clothing, towel and cooling vest were then weighed separately and sensors and other equipment were prepared. After the briefing, signing and preparation period have elapsed, the participant rested in the research laboratory for 30 min to reach a thermo-neutral state (steady core temperature and heart rate) as similarly done in previous studies [17,28,39,40]. After that, the participant wore the PCM cooling vest and entered the conditioned chamber. The participant performed cycling for 45 min on a magnetic upright bike at about 3 Mets, while wearing the vest. Readings of core temperature were taken at the start and every 15 min by a nurse to stop the experiment if it exceeded 38 °C and avoid any injury to the ear. Subjective votes were taken to assess thermal comfort and sensation at the start and every 5 min during exercise. After finishing the exercise and exiting the climatic chamber, the participants clothed with their wet clothing were first weighed. Then the cooling vest, wet clothing, participant after toweling off the sweat remaining on his skin and wet towel were separately weighed to determine the body weight loss. Finally, the participants rested for 10 min in the laboratory as shown in Table 5.

To avoid any risk of harm on the participants, a criterion was implemented for stopping the experiments if any of the three conditions occurred [37]. The first, if the core temperature reached 38 °C [41], the second if the heart rate reached 95% of the age predicted maximum heart rate (220-Age) and the third if the participant wished to stop any time during the experiment. However, all experiments were carried out till the end of their allocated time. A similar experimental protocol was followed to conduct the experiments without the cooling vest.

2.3.4. Physiological and physical measurements

The participant, clothing and cooling vest were weighed using a digital bench scale (Quartzell™ Bench Scale 3600SC, Avery Weigh-Tronix – USA, 1 g resolution). Temperature iButton sensors (iButton® DS1922L, Maxim Integrated, CA, USA, 0.0625 °C resolution) were taped on seven human body segments at 11 positions as shown in Fig. 3b (left and right chest, left and right upper back, left and right abdomen, left and right lower back, left upper arm, left thigh, and left calf) and were taking a measurement every 5 min throughout the 45 min exercise. The average accuracy of the iButton temperature sensors is ± 0.09 °C when used at the environmental conditions of 34.9 ± 0.1 °C with a maximum deviation of 0.4 °C [42]. In order to ensure proper contact with the skin, a surgical tape was used to place the sensors on the different segments [42,43]. In addition, temperature variation of four PCM packets placed on the upper and lower back, chest and abdomen segments were recorded every 5 min using temperature iButton sensors. The variation of the PCM temperatures would show the times melting started and if total melting of any of the packets occurred after 45 min of exercise. Heart rate and change in core temperature from the initial state, ΔT_{cr}, were recorded every 5 and 15 min, respectively, through a wristband pulse oximeter (CMS-50F, accuracy ± 2%) and using an infrared tympanic thermometer, IRTT, (Braun ThermoScan® 7 IRT6520, Braun, Kronberg, Germany, accuracy ± 0.2 °C), respectively. The core temperature was measured twice in the left ear to ensure accurate data collection. Since the eardrum shares blood supply with the hypothalamus (temperature control center in the brain), unlike other body sites, measuring the core temperature by the ear can reflect the core body temperature [44,45]. In addition, a recent study on new generations of IRTTs showed their good reliability in reflecting core temperature, which is the optimal method to represent body temperature, if disposable shields are used and frequent cleaning is applied [43]. Moreover, IRTT is time efficient, easy to use, more hygienic and acceptable in consideration to patients or participants than rectal and was used in recent studies [46,47]. In this study, the same IRTT was used for all participants as an indication for stopping the experiment, and it was assumed that any potential measurement error was the same for all subjects, while applying all precautions recommended for taking the readings.

The change in mean skin temperature from the initial state, $\Delta T_{sk,mean}$, is found with $T_{sk,mean}$ calculated using the formula $T_{sk,mean} = 0{\cdot}3T_{chest} + 0.3T_{arm} + 0.2T_{thigh} + 0.2T_{leg}$ [48]. The frontal and back torso skin temperatures were found by averaging the left and right chest and abdomen segments and left and right upper and lower back segments, respectively [31,49–52]. The temperatures were found via measurements on eight locations on the torso as presented in Fig. 3c to accurately represent the torso

Table 7
Experimental results for PCM initial and final states (mean ± SD) during exercise and the time melting started for the different PCM arrangements.

Case/Arrangement	PCM Location on Torso	$T_{initial}$ (°C)	T_{final} (°C)	Start of melting (min)
28F–28B	Front	14.8 ± 1.1	29.3 ± 0.6	10 ± 0.6
	Back	14.5 ± 0.8	29.6 ± 0.5	13 ± 0.4
28F–18B	Front	15.2 ± 1.9	29.2 ± 0.9	10 ± 0.8
	Back	15.6 ± 1.0	19.6 ± 1.0	5 ± 0.6
18F–28B	Front	15.9 ± 0.8	18.9 ± 0.3	5 ± 0.5
	Back	15.5 ± 0.6	29.7 ± 0.2	16 ± 0.3
18F–18B	Front	15.1 ± 2.0	18.6 ± 0.3	6 ± 0.3
	Back	14.9 ± 1.5	19.0 ± 0.5	7 ± 0.7
28U–18L	Upper	15.3 ± 1.9	29.9 ± 0.9	9 ± 0.8
	Lower	14.9 ± 2.0	19.1 ± 1.0	4 ± 0.6
18U–28L	Upper	15.4 ± 0.8	19.4 ± 1.2	6 ± 0.5
	Lower	15.7 ± 2.0	29.3 ± 1.0	10 ± 0.9

parts that are either covered or not by the PCM packets. The change in mean body temperature, ΔT_b, found using the formula $\Delta T_b = 0.8\Delta T_{cr} + 0.2\Delta T_{sk,mean}$ and the change in body heat storage, S, found using the formula $S = (\Delta T_b \times m_{body} \times C_{body})/t$, were used to assess the cooling effect of the different vests [8,17]. Body weight loss or sweat production was found by the difference in the weight of the clothed subject before and after the exercise after correcting it for the sweat absorbed in the clothing [53].

2.3.5. Subjective evaluation and statistical analysis

The participants were asked to report their subjective ratings every 5 min using different reference scales shown in Table 6 [28,31,49,54–56]. Recorded ratings were for overall thermal comfort, TC, torso thermal sensation, TTS, whole body thermal sensation, WBTS, wetness sensation on skin and clothing, WSSC and perceived exertion, PE.

The effect of wearing a cooling vest with different melting temperatures was investigated using paired-samples *t*-test, since each subject participated in all the proposed arrangements, with statistical significance set at $p < 0.05$ [16,57].

3. Results of human subject experiments

In this study, cooling vests that incorporate PCM packets of two different melting temperatures, simultaneously, with different arrangements are considered. In order to analyze the skin temperature variations and psychological responses of the participants, the different PCM packets should be during their melting periods when their temperatures are fixed and not in their initial transient period. The transient period is defined as the time the temperatures of the packets need to increase from their initial state at 15 °C to their melting temperatures (either 18 °C or 28 °C). It should be noted that when packets of melting temperature 18 °C and 28 °C are considered simultaneously, the 18 °C packets has a shorter transient period than the 28 °C ones. After that, the packets are in their melting state at a stable temperature till the end of the exercise period of 45 min.

Comparisons of the different cases are done with respect to the three reference cases: i) the no vest case; ii) the uniform melting temperature PCM arrangement 18F-18B; and iii) and the uniform melting temperature PCM arrangement 28F-28B. The remaining arrangements are divided into (a) front and back cases (18F–28 B and 28F-18B) and (b) upper and lower cases (18U-28L and 28U-18L) to ease the comparison.

3.1. PCM different states during exercise

The experimental results for PCM initial and final temperatures (mean ± SD) and the time melting started for the different vest arrangements are presented in Table 7. In all the cases, a similar trend of variation was found, where the PCM temperatures increased from their initial values of about 15 °C to reach a stable temperature after some time indicating the start of melting. Moreover and in all the cases, the PCM temperatures remained stable near their melting temperature till the end of the exercise indicating that they were still in the melting phase and did not completely melt. It can be concluded from Table 7 that the transition period for the PCM packets to increase from their initial temperature to their melting one at 28 °C was about 9 ± 0.8 min to 16 ± 0.3 min and those with melting temperature of 18 °C, their transition period was about 4 ± 0.6 min to 7 ± 0.7 min only. The variations in the start of melting between the different cases with the same type of PCM could be related to the higher temperature gradient between the skin temperatures and the PCM temperature; the higher the gradient is the earlier the melting starts. Thus, typically the packets with 28 °C melting temperature need more time to reach their melting phase but that was limited to the first 15 min of exercise. It was noted that the final temperature of the 18 °C and 28 °C packets was not at their exact melting temperatures (reported by the manufacturer) even though they were in their melting phase and that could be due to having different types of additives in one packet rather than having a pure substance [18,22]. The remaining 30 min of exercise was the main focus to analyze the results of the skin temperatures and subjective votes in the following sections.

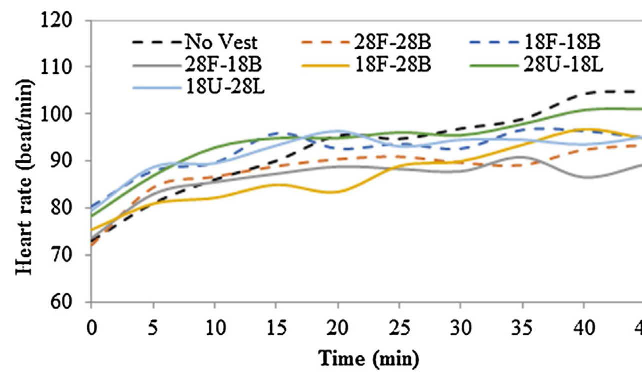

Fig. 4. Mean values of heart rate during 45 min exercise (dotted lines represent the reference cases of no vest and vests with uniform packets of 28 °C and 18 °C melting temperature).

3.2. Heart rate

During the 45 min of exercise in the warm conditions of 35 °C, the variation of the mean heart rate for the different cases is shown in Fig. 4. At the onset of the exercise, the initial value of the heart rate for all participants was about 76 ± 10 bpm, which is simi-

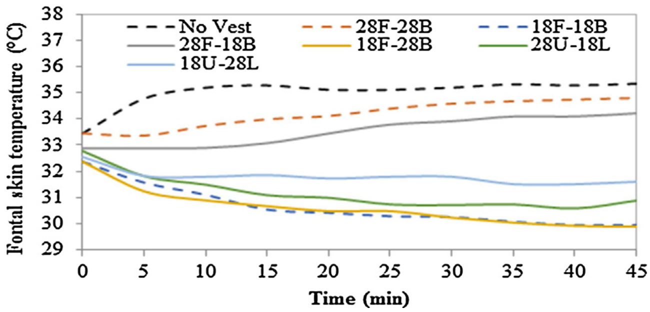

Fig. 5. Frontal local skin temperature for the different cases during exercise for 45 min (dotted lines represent the reference cases of no vest and vests with uniform packets of 28 °C and 18 °C melting temperature).

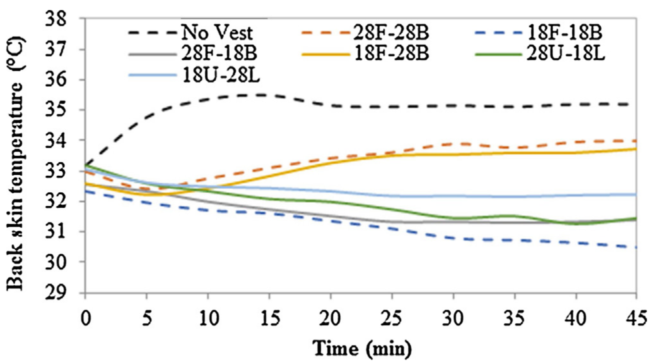

Fig. 6. Back local skin temperature for the different cases during exercise for 45 min (dotted lines represent the reference cases of no vest and vests with uniform packets of 28 °C and 18 °C melting temperature).

larly found in previous studies [13,34]. Then, the heart rate had an increasing trend up to the end of the PCM transient period (about 15 min) in all the vest cases. During the PCM melting period, the heart rate has almost stabilized till the end of the 45 min of exercise. The corresponding stable heart rates for PCM arrangements 28F-28B, 28F-18B, 18F-28B, 18F-18B, 28U-18L and 18U-28L were 93.5 ± 15 bpm, 89 ± 15 bpm, 92 ± 15 bpm, 95 ± 13 bpm, 99 ± 4 bpm and 95 ± 9 bpm, respectively. However, in the no vest case, the heart rate kept on increasing till it reached 105 ± 22 bpm at the end of exercise. Moreover, no significant difference ($p > 0.05$) was found between the no vest case and all the other cases or among any of the vest cases at all times of exercise.

3.3. Local skin temperatures

The variations of the frontal and back local skin temperatures during the 45 min exercise are shown in Figs. 5 and 6, respectively, for the different cases. It can be noticed that in the no vest case, the local skin temperatures of the front and the back kept on increasing from their initial thermo-neutral state till their final states of 35.34 ± 0.5 °C and 35.1 ± 1 °C, respectively, at the end of exercise. Under the influence of the cooling vest in the remaining cases, a different trend of variation is noticed. At the time the cooling vests with 28 °C packets covering the front or back were worn, the skin temperatures had an initial drop due to the relatively lower PCM initial temperature of 15 °C. After about 15 min of exercise, the PCM packets entered their melting phase and the skin temperatures started increasing to reach stable values. However, for the cooling vests having 18 °C packets covering the front or the back, there was a drop in skin temperature during the transient period of the PCMs to reach after that almost stable values till the end of exercise.

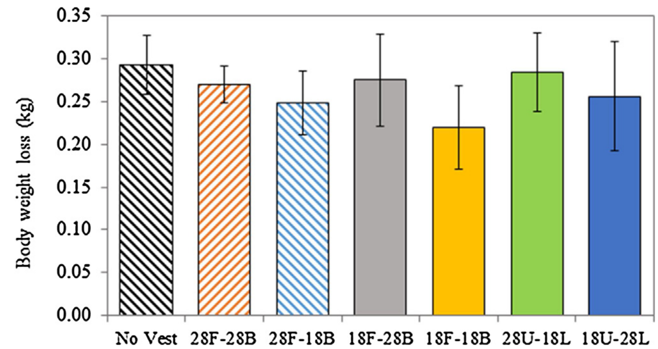

Fig. 7. Sweat production or body weight loss after exercise (Mean values and SD) (with hatched columns representing the reference cases of no vest and vests with uniform packets of 28 °C and 18 °C melting temperature).

Uniform melting temperature vest arrangements 28F–28 B and 18F–18 B showed the highest and lowest local skin temperatures among the different vest cases, respectively. After the end of the PCM transient period in about 13 ± 0.4 min and 7 ± 0.7 min in cases 28F–28 B and 18F-18B, respectively, the front skin temperature became stable at 34.79 ± 1.2 °C and 29.89 ± 1.1 °C, respectively, while those of the back became stable at 33.99 ± 0.9 °C and 30.48 ± 1.9 °C, respectively. Note that the front skin temperature is consistently higher than the back skin temperature for vest using uniform melting temperature for all PCM packets in the vest.

The cases that showed a significant difference ($p < 0.05$) from the no vest case in frontal skin temperature at all times during exercise were 18F-28B, 18F-18B, 28U-18L and 18U-28L. Moreover, cases 18F-28B, 18F-18B, 28U-18L and 18U-28L showed a significant difference ($p < 0.05$) from the no vest case at all times in back skin temperature. In case 28F-18B, there was a significant difference from the no vest case in the last 30 min of exercise only in back skin temperature.

3.4. Mean skin and core temperatures and body weight loss

The experimental results of the change in mean skin, core and body temperatures from initial state (mean ± SD) and heat storage reported every 15 min during the 45 min of exercise for the different cases are shown in Table 8. In general, the temperatures of the different cases kept on increasing with time from their initial value reaching a maximum value at the end of exercise. The cooling vests reduced the rate of increase of the different temperatures in comparison to the no vest case, however, at different significance levels.

Cooling vest 18F-18B, while the PCM packets are in their melting phase, recorded significantly lower $\Delta T_{sk,mean}$, ΔT_{cr}, and ΔT_b than the no vest case by 1.66 °C, 0.37 °C and 0.65 °C, respectively, at the end of exercise. In addition, arrangements 28F–18 B and 28U-18L showed significant reductions in the different temperatures by the end of the exercise. Thus it can be noticed that no significant difference of $T_{sk,mean}$ is present in the former cases, where the 18 °C packets were placed on back or lower torso segments. In the last 15 min of exercise, all cases except 28F–28 B and 18U-28L had significantly lower T_b [17,58] from the no vest case.

The results for the calculated change in body heat storage [8,17], S, show that the no vest case at the end of exercise had the highest value among the different cases at 100 W, which is justified since no cooling is applied. The arrangements that showed a significant decrease in heat stored after 45 min of exercise were 18F-18B, followed by 28U-18L, 28F–18 B and 18U-28L. The arrangements placing the 18 °C packets on the back segment or on the lower torso segments resulted in a similar cooling effect.

Table 8
Change in mean skin, core and body temperatures from initial state (mean ± SD) and heat storage reported every 15 min during exercise for the different cases.

Time (min)	Case/Arrangement	$\Delta T_{sk,mean}$ (°C)	ΔT_{cr} (°C)	ΔT_b (°C)	Calculated S (W)
0	All cases	0.00 ± 0.0	0.00 ± 0.0	0.00 ± 0.0	0
15	No vest	+2.63 ± 1.0	+0.30 ± 0.2	+0.78 ± 0.2	229
	28F–28B	+3.08 ± 0.9	+0.15 ± 0.2	+0.74 ± 0.3	217
	28F–18B	+2.10 ± 0.9*	+0.05 ± 0.1	+0.46 ± 0.1*	135
	18F–28B	+2.35 ± 0.8	+0.05 ± 0.2	+0.51 ± 0.1*	149
	18F–18B	+1.44 ± 1.0*	+0.10 ± 0.1	+0.36 ± 0.2*	105
	28U–18L	+1.30 ± 0.6*	+0.10 ± 0.1	+0.34 ± 0.1*	100
	18U–28L	+1.29 ± 1.2	+0.32 ± 0.2	+0.52 ± 0.5	152
30	No vest	+2.57 ± 0.4	+0.37 ± 0.2	+0.83 ± 0.2	122
	28F–28B	+3.37 ± 0.9	+0.20 ± 0.1	+0.84 ± 0.3	123
	28F–18B	+2.12 ± 0.9	+0.10 ± 0.1*	+0.50 ± 0.2	73
	18F–28B	+2.39 ± 1.1	+0.20 ± 0.2	+0.63 ± 0.3	92
	18F–18B	+1.48 ± 0.8*	+0.12 ± 0.1*	+0.39 ± 0.2*	57
	28U–18L	+1.50 ± 0.5*	+0.14 ± 0.1	+0.41 ± 0.1*	72
	18U–28L	+1.25 ± 1.1*	+0.38 ± 0.2	+0.56 ± 0.3	82
45	No vest	+2.74 ± 0.4	+0.57 ± 0.2	+1.02 ± 0.2	100
	28F–28B	+3.50 ± 0.7	+0.22 ± 0.2*	+0.88 ± 0.3	86
	28F–18B	+2.16 ± 0.7*	+0.12 ± 0.1*	+0.53 ± 0.1*	52
	18F–28B	+2.40 ± 1.0	+0.25 ± 0.2*	+0.68 ± 0.3*	66
	18F–18B	+1.08 ± 0.8*	+0.20 ± 0.1*	+0.37 ± 0.2*	36
	28U–18L	+1.58 ± 0.4*	+0.26 ± 0.1*	+0.52 ± 0.1*	51
	18U–28L	+1.29 ± 0.9*	+0.40 ± 0.2	+0.58 ± 0.4	57

* Significant statistical differences ($p < 0.05$) between the vest case and the no vest one.

Body weight loss or sweat production, shown in Fig. 7, was measured for the different experiments at the end of the 45 min of exercise. The body weight loss was maximum in the no vest case with 0.29 ± 0.03 kg, and it decreased under the influence of the cooling vest. Following the no vest case, the sweat rates in descending order for cases 28U-18L, 18F-28B, 28F-28B, 18U-28L, 28F–18 B and 18F–18 B were 0.28 ± 0.05 kg, 0.275 ± 0.05 kg, 0.27 ± 0.02 kg, 0.26 ± 0.06 kg, 0.25 ± 0.04 kg and 0.22 ± 0.05 kg, respectively. All the vest cases showed no statistical significant difference ($p > 0.05$) in the sweat produced from the no vest case except 18F-18B. In addition, there was no statistical significant difference between the vest cases.

3.5. Thermal comfort and sensation, wetness of skin and clothing and perceived exertion

The experimental mean ratings of overall thermal comfort, TC, and torso thermal sensation, TTS, during exercise for the different cases are presented in Figs. 8 and 9, respectively, while focusing on the comparison between (a) front and back cases and (b) upper and lower cases.

In the case where no vest is worn, TC and TTS had similar increasing trends throughout the exercise period and reached the highest values of 3.67 ± 0.8 and 3.83 ± 0.9, respectively, among the different cases at the end of exercise with an uncomfortable TC level and a hot TTS (Table 6). In general, it was noticed in all the vest cases that the rate of increase of the TC level was slower than the no vest case and reached stable values in the last 15 min of exercise due to the packets being in their melting phase at an almost constant temperature. The different PCM arrangements were able to lower TC and TTS from the no vest case, however, not all cases showed a statistically significant difference from the no vest case at all times of exercise. Arrangement 28F–28 B reduced the TC and TTS to 2.5 ± 1.2 (slightly uncomfortable) and 2.5 ± 1 (warm), respectively, in comparison to the no vest case at the end of exercise with no significant difference at all times during exercise. However, arrangement 18F–18 B showed a significant difference from the no vest case at all times reaching TC and TTS values of 2 ± 0 (slightly uncomfortable) and 1.75 ± 0.5 (slightly warm), respectively, at the end of exercise. Moreover, in the last 30 min of exercise, the TC for arrangements 28F–18 B and 28U-18L showed significant differences from the no vest reaching 2 ± 0.8 (slightly uncomfortable) and 2.2 ± 0.8 (slightly

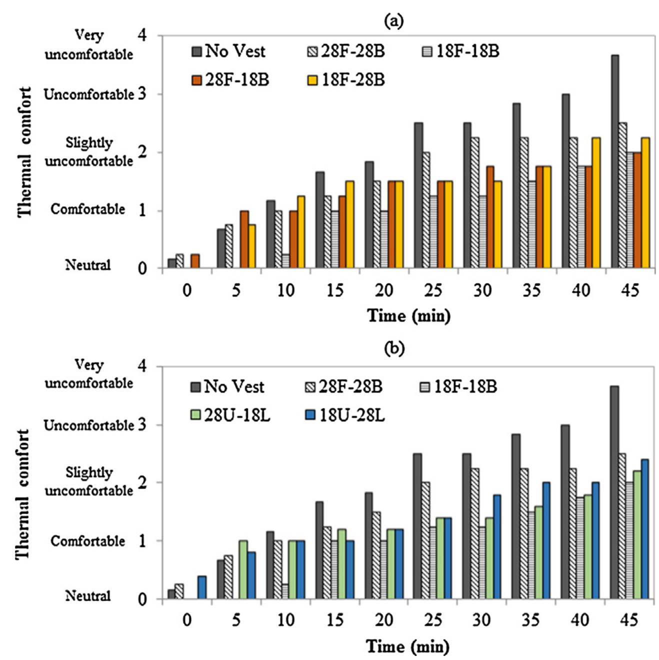

Fig. 8. Experimental mean ratings of overall thermal comfort during exercise showing (a) front and back cases and (b) upper and lower cases (hatched columns represent the reference cases of no vest and vests with uniform packets of 28 °C and 18 °C melting temperature).

uncomfortable) at the end of exercise, respectively. Similarly, TTS for arrangements 28F–18 B and 28U-18L showed significant differences from the no vest at all times with values of 2 ± 0.8 (warm) and 2 ± 0.7 (warm) at the end of exercise, respectively. Thus, placing the 18 °C packets on the back segment resulted in slightly better TC levels, but similar TTS, than placing them on the lower torso segments. In addition, TC for case 18F–18 B was very similar to that of 28F-18B, where two types of PCM packets were used.

Table 9 summarizes the results of the instantaneous mean ratings (± SD) of whole body thermal sensation (WBTS), wetness of skin and clothing (WSSC) and perceived excretion (PE) during the 45 min of exercise. Regarding the WBTS, the no vest case had the highest values among the different cases, reaching 3.8 ± 1.0 (hot)

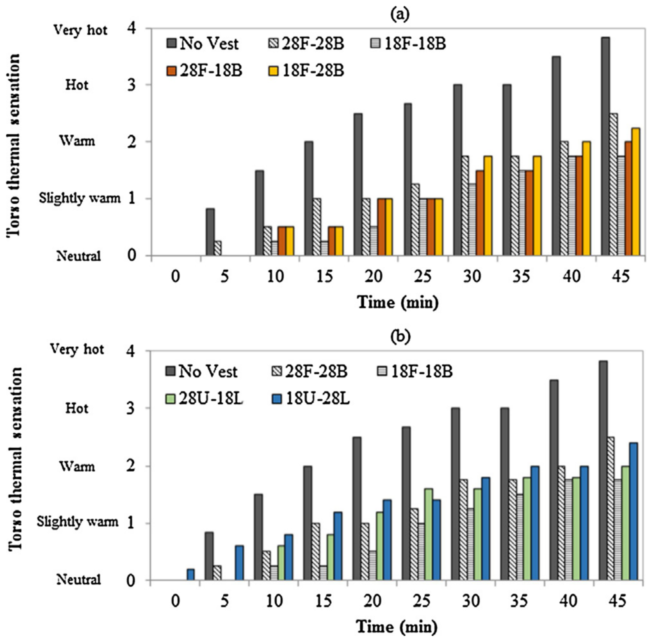

Fig. 9. Experimental mean ratings of torso thermal sensation during exercise showing (a) front and back cases and (b) upper and lower cases (hatched columns represent the reference cases of no vest and vests with uniform packets of 28 °C and 18 °C melting temperature).

Table 9
Instantaneous mean ratings (± SD) of whole body thermal sensation, wetness of skin and clothing and perceived exertion during 45 min exercise for the different cases.

Time (min)	Case/Arrangement	WBTS	WSSC	PE
0	No vest	0.0 ± 0.0	2.0 ± 0.0	0.0 ± 0.0
	28F–28B	0.0 ± 0.0	1.5 ± 0.6	0.0 ± 0.0
	28F–18B	0.0 ± 0.0	1.8 ± 0.5	0.0 ± 0.0
	18F–28B	0.0 ± 0.0	2.0 ± 0.0	0.0 ± 0.0
	18F–18B	0.0 ± 0.0	2.0 ± 0.0	0.0 ± 0.0
	28U–18L	0.0 ± 0.0	2.0 ± 0.0	0.0 ± 0.0
	18U–28L	0.0 ± 0.0	1.8 ± 0.4	0.0 ± 0.0
15	No vest	2.0 ± 0.6	3.7 ± 0.5	1.5 ± 0.8
	28F–28B	1.5 ± 1.0	2.5 ± 0.6*	1.3 ± 1.0
	28F–18B	1.0 ± 0.8	2.5 ± 0.6*	1.0 ± 0.8
	18F–28B	1.2 ± 1.0	2.5 ± 0.6*	0.8 ± 0.5
	18F–18B	1.0 ± 0.8	2.2 ± 0.5*	1.5 ± 0.6
	28U–18L	1.2 ± 0.5*	2.2 ± 0.5*	1.2 ± 0.8
	18U–28L	1.4 ± 0.6	2.4 ± 0.6*	1.2 ± 0.8
30	No vest	3.0 ± 0.6	4.8 ± 0.4	2.3 ± 1.2
	28F–28B	2.0 ± 0.8	3.0 ± 0.8*	1.8 ± 1.3
	28F–18B	1.7 ± 0.5*	3.5 ± 0.6*	2.0 ± 1.4
	18F–28B	2.0 ± 0.0*	3.5 ± 1.3	1.8 ± 0.5
	18F–18B	1.5 ± 0.6*	3.2 ± 0.5*	2.3 ± 1.0
	28U–18L	2.2 ± 0.5*	3.2 ± 0.8*	1.8 ± 0.8
	18U–28L	2.0 ± 0.0*	3.0 ± 0.7*	2.0 ± 0.7
45	No vest	3.8 ± 1.0	5.2 ± 0.4	2.8 ± 1.5
	28F–28B	3.0 ± 0.8	3.8 ± 1.3	2.5 ± 1.7
	28F–18B	2.5 ± 0.6*	3.7 ± 0.5*	2.5 ± 1.7
	18F–28B	2.7 ± 0.5	4.3 ± 1.3	2.5 ± 1.0
	18F–18B	2.5 ± 0.6*	3.5 ± 1.0*	2.7 ± 0.9
	28U–18L	2.6 ± 0.6*	4.0 ± 0.7*	2.4 ± 0.5
	18U–28L	2.8 ± 0.8	3.4 ± 0.9*	2.8 ± 0.8

* Significant statistical differences ($p < 0.05$) between the vest case and the no vest one.

at the end of exercise. There was a statistical significant difference ($p < 0.05$) from the no vest case especially in the last 15 min of exercise for some PCM arrangements. Those arrangements are 28F-18B, 18F–18 B and 28U-18L, where the WBTS reached similar values of 2.5 ± 0.6, 2.5 ± 0.6 and 2.6 ± 0.6 (warm) at the end of exercise, respectively. Moreover, even though there was no significant difference ($p > 0.05$) among all the cooling vest cases, arrangement 28F–18 B had better WBTS than 28U-18L. With respect to WSSC, the results showed that the no vest case had the highest value among the different cases reaching 5.2 ± 0.4 (body wet) at the end of exercise. The presence of the cooling vests reduced the WSSC to 3.4 ± 0.9, 3.5 ± 1.0, 3.7 ± 0.5 and 4.0 ± 0.7 in arrangements 18U-28L, 18F-18B, 28F–18 B and 28U-18L, respectively. In addition, for all the pre-mentioned cooling cases, there was a significant difference ($p < 0.05$) from the no vest case in the last 30 min of exercise. No significant difference ($p > 0.05$) in WSSC was found among all the vest cases. Finally, the results for the PE of the vest cases presented in Table 9 did not show any significant difference ($p > 0.05$) from the no vest case at all times during exercise.

4. Discussion

Many researches have concluded that providing a greater body cooling area would be more effective in reducing heat strain for humans [15,59]. However, in some applications like outdoor construction or field work, whole body cooling is not feasible, consumes a lot of energy and unnecessary as targeting certain body areas may result with the desired cooling effect [60]. Moreover, local cooling would contribute to energy savings in an increasingly energy demanding air conditioning systems in the presence of global warming [1,13].

In the current study, the cooling effect of the PCM vests was evaluated via both thermal manikin and human subject testing. The common use of thermal manikins is mainly focused on finding clothing thermal properties [61] and not on finding thermo-physiological effects. The results of the manikin experiments using two types of PCM packets of different melting points showed that an improvement in cooling effect with more heat losses can be achieved if the PCM packets with the higher melting temperature of 28 °C are placed on the upper torso segments, while placing the 18 °C packets on the lower torso segments. The improvement in cooling effect could be due to enhancing the microclimate air flow rate by placing the higher PCM temperature on the upper side, inducing better circulation of microclimate air so that the hotter air rises upward and out of the vest efficiently. However, further assessment was needed to include physiology and subjective votes through human testing.

The selection of the best cooling vest depends on how much heat is absorbed by the PCM and on how the participants perceive it. In cases of uniform melting PCM vest of 18F–18 B and 28F-28B, there was no specific PCM arrangement to specify which resulted in significant improvement in sensation, but rather only the assessment of how much heat was absorbed by the packets. In the remaining cases (18F-28B, 28F-18B, 28U-18L and 18U-28L), the arrangement of the packets was a factor that determined which torso segment is more sensitive to cooling and triggers better comfort and sensation than others. With further analysis on the results of human subject testing, the arrangement 18F–18 B significantly lowered the local skin temperatures of the frontal and back torso segments by a maximum of 5.45 ± 1 °C and 4.62 ± 1.6 °C, respectively. The findings confirm with what previous studies have concluded on reductions in local torso skin temperatures by about 3–5 °C in the presence of cooling vests [17,49,59].

The change in mean body temperature, found through the changes in mean skin and core temperatures, was significantly reduced in the last 15 min of exercise in most cooling vest cases. Thus, a significant cooling effect evaluated at the end of exercise [8,17] was found in cases 18F-18B, 28U-18L, 28F–18 B and 18U-28L with 64 W, 49 W, 48 W and 43 W of cooling, respectively. The uniform low melting temperature PCM vest case 18F–18 B absorbed the highest amount of heat from the participants. In addition, it was found that placing the 18 °C packets on the back segment resulted in a similar cooling effect with no significant difference to placing them on the lower torso segments when using two PCM types.

A reduction in sweat rate was observed in this study with the presence of a cooling vest, which is consistent with findings in previous experiments [16,17,38,39,59]. However, only arrangement 18F–18 B significantly reduced the body weight loss by about 24% from the no vest case at 35 °C ambient temperature. Similarly, in the study of Choi et al. [59], the sweat rate was reduced due to the cooling vest by 20% in comparison to the no vest case at 33 °C ambient temperature. It was also noted in previous studies that the torso areas that contain high distribution of sweat glands are the chest and upper back [62–64]. Thus, placing the PCM packets with the lower melting temperature of 18 °C on the chest and upper back segments suppressed sweat production, which lead to improved wetness sensation on skin and clothing in arrangements 18F-18B, 18U-28L and 28F-18B.

Both overall thermal comfort and torso thermal sensation were improved by wearing the PCM cooling vests and reached stable values in the last 15 min of exercise, but not all arrangements showed major changes from the no vest case. Moreover, participants of arrangement 28F–18 B had similar TC levels to 18F–18 B and slightly higher TTS values, which shows that cooling the back segment is an effective way to improve TC levels. When considering two PCM melting points in the same vest, placing the packets with lower melting temperature on the back segment (28F-18B) resulted in similar TC levels to placing them on the lower torso segments (28U-18L) with no significant difference between the two arrangements. The findings agree with previous conclusions, which stated that placing the PCM packets on the back improved thermal sensation votes [14,31,38]. Participants wearing cooling vests 18F-18B, 28F–18 B and 28U-18L had similar whole body thermal sensations that were significantly colder than the no vest case.

In this study, the proposed cooling vest with two PCM melting temperatures (18 °C and 28 °C) was tested at moderate ambient conditions and for a limited exercise period of 45 min. It is expected that at the same ambient conditions and for longer working durations, for example two hours, the proposed system would allow for reductions in vest weight to be carried by the workers. It is estimated that with arrangement 18F-18B, about 3.31 kg of the 18 °C packets would be needed to remove 52 W of body stored heat in two hours. However, using two PCM types (18 °C and 28 °C) in the same vest with equal coverage area of each type would require a total PCM weight of 2.77 kg. Thus, using arrangement 28F–18 B or 28U-18L would result in a vest 16% lighter than 18F–18 B with similar improvement in thermal comfort and sensation levels. However, such improvements need further investigation on human subjects doing a heavier activity level and in hotter environments. In addition, when considering the effect of wearing either cooling vest 28F–18 B or 28U-18L for a period of two hours, the weight distribution on the torso would be a factor that affects the comfort of the wearer. Previous studies reported that carrying the external load on the front and the back torso segments is the most physiologically efficient method than carrying the load on the back [65,66]. Thus, arrangement 28U-18L would result in the best arrangement choice in providing comfort for a working period of two hours.

Therefore, it can be concluded from the reduction in heat storage and improvement in comfort and sensation levels that using two PCM melting temperatures in one cooling vest can be implemented for a prolonged working duration. In addition, the proposed method was successful in making use of the advantages of both high and low melting temperature PCMs; the ones with high latent heat of fusion and lower energy use for regeneration and the one with lower melting temperature. It is recommended to select the arrangement that places the packets with lower melting temperatures on the lower front and back torso segments as a first option, followed by the arrangement that places them on the back torso segment, as in arrangements 28U-18L and 28F–18 B in this study.

5. Conclusion

A study to evaluate the cooling performance of PCM cooling vests having one or two PCM melting temperatures in the same vest simultaneously was conducted. The main conclusions that were obtained are as follows:

1) Using a PCM cooling vest that covers only the torso was effective in reducing local skin temperatures by a maximum of 5.45 ± 1 °C, body heat storage by a maximum of 64 W as well as improving subjective thermal comfort and sensation votes of subjects performing moderate work at 35 °C.
2) Placing the PCM packets with the lower melting temperature of 18 °C on the chest and upper back segments suppressed sweat production, which lead to improved wetness sensation on skin and clothing.
3) Reduction in sweat rate was observed in the presence of all tested cooling vests, but significant reduction was found when 18 °C PCM packets covered both frontal and back torso segments.
4) Similar improvements in thermal comfort and sensation levels to 18F–18 B would be obtained with arrangements 28F–18 B and 28U-18L with vest weights 16% lighter than that of 18F-18B.
5) Better cooling effect was found when covering the upper torso segments (chest and upper back) with PCM packets having a higher melting temperature than those covering the lower torso segments (abdomen and lower back) in both thermal manikin and human subject experiments.
6) For a prolonged working duration, it is recommended to select the arrangement that places the lower melting temperature packets on the lower front and back torso segments as a first option, followed by the arrangement that places them on the back.

Acknowledgements

This publication was made possible by NPRP grant# [NPRP 7 − 486–2 − 185] from the Qatar National Research Fund (a member of Qatar Foundation). The findings achieved herein are solely the responsibility of the authors.

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