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Modeling the heat transfer in a PCM cooling vest

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Cooling garments containing phase change materials (PCM) is one of practical techniques used for improving thermal comfort and worker's performance in hot environments. The efficiency of these garments and their ability in cooling the body has been the subject of much research. In this study, it has been attempted to investigate the way in which heat is transferred from the body to the cooling garment and examine its resulting effect on one's comfort. So, the three-part system of body–garment–environment has been simulated through the finite element method, and the problem of heat exchange between these three parts has been solved with the help of thermal analysis of ANSYS software. The results of modeling indicated that absorbing body's excessive heat through PCMs could decrease skin's temperature to at least 2.6°C. The average of heat absorption by phase change bags was 215.4 W/m^2 at the beginning of the process and 128.7 W/m^2 within one hour. The accuracy of the model was also verified with the results of subjective tests, and a good agreement between the experimental and model results was shown.

Keywords: cool vest; heat transfer; PCM

Introduction

Working in a warm or hot environment is in general more stressful for the worker than doing a similar work in a neutral environment. The physical load accompanying heat exposure can increase the risk of danger to the worker's safety and health (Havenith, Holmér, & Parsons, 2002). Heat stress can also result in reduced working endurance and performance in works such as fire-fighting, industrial activities, military drills, and sports (Gao, Kuklane, & Holmér, 2010). One measure intended to reduce such adverse effects, increase work performance, and possibly create thermal comfort is the use of personal cooling garments to improve the microclimate around the human body (Crockford & Lee, 1967; Duncan & Konz, 1975; Nunneley, 1970). Cooling garments absorb the body's excessive heat and help the body reach thermal comfort situation by reducing the heat content of the body in hot environments. A number of prototype microclimate cooling systems employing either air-cooled or liquid-cooled vests have been shown to be effective in reducing the workers' heart rate, skin temperature, and sweat rate (Barr, Gregson, & Reilly, 2010; Barwood, Davey, House, & Tipton, 2009; Reinertsen et al., 2008). Phase change garment (PCG), which absorbs the body's excessive heat through the melting process of the phase change material (PCM), is also another type of cooling garment known as a more practical cooling device for outside activities compared to other types such as air or liquid cooling garments (Bendkowska, Kłonowska, Kopias, & Bogdan, 2010; Gao et al., 2010). PCG, which uses PCM, consists of a torso garment containing pockets surrounding the chest cavity that holds the PCM packs. Body heat carried to the surface of the skin is absorbed by the PCM packs. PCMs absorb the latent heat of fusion in the melting point in order to reduce the body's excessive heat. Latent heat storage is one of the most efficient ways to store thermal energy. Unlike the sensible heat storage method, the latent heat storage method provides a much higher storage density, with a smaller temperature difference between storing and releasing heat (Farid, Khudhair, Razack, & Al-Hallaj, 2004). Today, many kinds of PCM such as paraffin waxes (linear hydrocarbons), frozen gels, and hydrated salts are used in the cooling garments.

The technology for incorporating PCM (Nelson, 2001) into textile structure to improve their thermal performance was developed in the early 1980s under NASA research program. PCMs are usually used in microcapsules for textile applications. PCM microcapsules are coated on the textile surface. But microcapsules of PCMs in clothing have been reported to provide a small, temporal heating/cooling effect during environmental transients between warm and cold chambers (Shim, McCullough, & Jones, 2001). When the PCM is used in the form of microcapsules, a limited weight of the material can be coated on the garment and so, only a little capacity of heat absorbing (around 15 W) is achieved. This little amount of excreted heat is not enough to support the wearer with thermal comfort in hot environments. Therefore, there is a need for at least

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*Corresponding author. Email: m.sh110@cc.iut.ac.ir several kilograms of PCM on the garments for long staying in hot environments. This is obtained with the use of macro pockets of PCM in the form of a cool vest (Mokhtari Yazdi & Sheikhzadeh, 2014). So, the idea of using PCMs in macro pockets of a garment was first suggested by Colvin and Bryant in 1995. Macro pockets can contain a larger amount of PCM than microcapsules. So, a larger amount of heat is absorbed, the efficiency of the cooling garment is increased, and the cooling period is lengthened. Numerous studies have investigated the cooling effects of PCM personal cooling devices used in severe hot environments, such as air temperatures at 50°C by Epstein, Shapiro, and Brill (1986), 49°C by Shapiro et al. (1982), 45°C by Smolander, Kuklane, Gavhed, Nilsson, and Holmer (2004), and 40°C by Hadid, Yanovich, Erlich, Khomenok, and Moran (2008). Evaluating the amount of heat extracted by a personal cooling system (cooling power) has been the goal of numerous studies in the literature (Gao et al., 2010; Smolander et al., 2004; Webster, Holland, Sleivert, Laing, and Niven, 2005). Cooling power is generally determined using either human tests or a thermal manikin. Conducting the human tests is the most accurate way to evaluate the cooling effect of the cooling garments. But human tests are expensive and time-consuming. Manikin testing reduces the cost and health risks of human testing (Gonzalez, Berglund, Kolka, & Endrusick, 2006). But thermal manikins have their own limitations too, such as the absence of vasoconstrictor response initiated in human skin when cooled. Bogerd, Psikuta, Daanen, and Rossi (2010) concluded that the heat transfer between the cooling systems and the human trial was lower than that measured with the thermal manikin. This must be due to the absence of vasoconstrictor response on the thermal manikin. Furthermore, thermal manikins are not able to simulate realistic thermophysiological responses, such as the change in body core and skin temperatures. Considering the limitations of the common ways used for evaluating the cooling power of cooling garments, it seems that modeling the heat transfer of a cooling garment can be useful in assessing the cooling performance of such devices. But, what has been addressed less in the previous studies relates to modeling the heat transfer from the PCM pockets to the body or the surrounding environment. If a proper modeling of the body and the cooling garment is done, and the physiological responses of the body are included in the model, a good simulation of the cooling performance of the cooling garment can be achieved.

Mathematical modeling of a PCM cooling garment can be also used for the optimum material selection and also to assist in the optimal designing of the systems. Li and Zhu (2004), for example, worked on a mathematical modeling of PCM microcapsules incorporating textiles. They reported the development of a mathematical model of moisture and heat transfer coupled with PCMs in porous textiles. On the basis of a finite volume difference scheme, the thermal buffering effect of PCM was simulated in their study.

A thermal mathematical modeling of heat transfer in a PCM cooling vest has also been attempted by Yifen, Nan, Wei, Guangwei, and Baoliang (2011) based on the human thermoregulation model. In this study, the uniform energy equation was constructed for the whole domain, and the equation was implicitly discrete by control volume and finite difference method. Then the enthalpy in each node was solved using the chasing method to calculate the tridiagonal equations, and the inner surface temperature of PCM was obtained. According to the human thermoregulation model of the cooling vest, the dynamic temperature distribution and sweat of the body were solved. This study showed that wearing the cooling vest could reduce the body heat load significantly.

Mathematical modeling has been done in both studies mentioned. But considering the fact that mathematical modeling is more complex and time-consuming than software modeling, and also paying attention to the higher repeatability and reproducibility of software modeling, the problem was solved through software modeling in this paper. Moreover, Software modeling is more appropriate in quickly investigating the effect of different factors in the model.

With the help of finite element analysis, it is possible to generate a simulation of any design concept and determine its real-world behavior under almost any imaginable environments. Also, when the appropriate software is used to analyze and simulate the phenomena, more acceptable and faster results can be achieved. So the aim of this study was to simulate the three-part system of body-garment-environment through the finite element method and solve the problem of heat exchange between these three parts with the help of thermal analysis of ANSYS software. In this study, the potential cooling contribution provided by a PCM cooling garment was evaluated as part of the total heat exchange mechanism of the body and also, the heat transfer occurring in the packets of PCM was modeled.

Modeling

To simulate the effects of using the cooling vests on human's body in this study, we used the ANSYS Workbench 14.5 finite element software. For modeling phase change phenomenon in this model, the enthalpy method was used. As the literature review shows, the most popular methods used to model the phase change process are the enthalpy method and the effective heat capacity method (Miroslaw, 2006). The relationship between the enthalpy and temperature can be defined in terms of the latent heat release characteristics of the PCM in enthalpy method. This relationship is usually assumed to be a step function for isothermal phase change problems – which change their phase in a fixed temperature – and a linear function for non-isothermal phase change cases (Hu & Argyropoulos, 1996). Using the available resources, we defined the enthalpy relation depending on the temperature for the PCM in the model (Marin, Zalba, Cabeza, & Mehling, 2003). Therefore, when the material reached its phase change temperature, it began to absorb body's heat without increasing the temperature.

The PCM studied in this model was a linear paraffin called Hexadecane. It is made of 16 molecules of carbon and 34 molecules of hydrogen ($C16H34$). Thermal properties of this material are shown in Table 1.

Figure 1 shows the diagram related to the temperature changes of this material during the process of phase change, in comparison with the ambient air temperature and water according to the data of the study conducted by Marin et al. (2003). As can be seen, the decrease in temperature was continued until this material reached the phase change point. After reaching the phase change point (18°C), the temperature of the material, in spite of heat loss, was fixed and this was continued until the whole volume of the material was converted to the solid state. After this, the decrease in the temperature again led to heat loss.

Assuming water as the reference material, with a comparison of both curves, using a mathematical description of the heat transfer makes it possible to determine the heat capacity, c_p, and the enthalpy, h, of the PCM from the known c_p of the reference material. Accordingly, the enthalpy of PCM in terms of temperature was obtained (Marin et al., 2003), as can be seen in Figure 2.

As can be seen, after the material reached the phase change temperature, about 240 kJ was absorbed by the material (320–80). All this was used for changing the phase of material without any effect on its temperature. Therefore, according to the law of energy conservation, the heat absorbed by the material did not increase the temperature, but increased the enthalpy of the material.

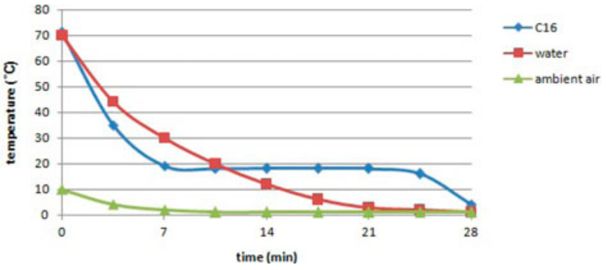

Figure 1. Temperature–time curve obtained for paraffin C16.

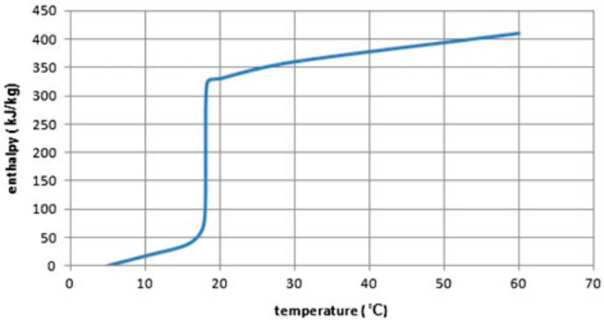

Figure 2. Enthalpy–temperature curve of paraffin C16 obtained from the data in Figure 1.

This enthalpy diagram was used for defining the phase change phenomenon in the model, with some modifications. The modification was related to changing the phase change temperature to the range of 18–20°C. This change could be due to the impurities present in paraffin obtained from the market, leading to the increase in phase change temperature.

Model hypotheses and boundary conditions

The cooling vest simulated in this model contained 2.4 kg of PCM and its cooling effect on a person of average height was investigated. The heat generated in the person's body was selected as the metabolic activity of a person having a metabolism (M) equal to 1.4 met (81.2 W/m^2).

Heat transfer of the torso can be by conduction (K), convection (C), radiation (R), and evaporation (E). When combined together, all of the rates of heat production and loss provide a rate of heat storage (S). For the body to be in heat balance (i.e. constant temperature), the rate of heat storage is zero ($S = 0$). If there is a net heat gain, storage will be positive and body temperature will rise (as the situation in this model). The conceptual heat balance equation is based on Parsons (2003):

Table 1. Defined properties of PCM in the model.

Type of PCM	Density (kg/m^3)	Latent heat of fusion (J/g)	Melting point(°C)
Hexadecane	770	240	18–20

$$M - W = E + R + C + K + S, \tag{1}$$

where external work (W) and conduction are equal to zero for most activities.

The rate of evaporative heat loss (E) and dry heat loss (R + C) was calculated based on the ASHRAE standard (2005):

$$E = \frac{\omega(P_{sk,s} - P_a)}{Re + \frac{1}{f_{cl}h_e}}, \tag{2}$$

$$C + R = \frac{\bar{t}_{sk} - t_o}{I_{cl} + \frac{1}{f_{cl}h}}, \tag{3}$$

where ω is the wettedness of the skin, $p_{sk,s}$ and p_a are the saturated water vapor pressures at the skin and the ambient air pressure, R_e is the evaporative resistance of the clothing, f_{cl} is the cover factor of the clothing, I_{cl} is the thermal resistance of the clothing, and t_{sk} and t_o are the mean skin temperature and operative temperature of the environment, respectively.

As there is no gap between the body and the clothing, it has been assumed that thermal transfer from the body to the vest is only through thermal conductivity. It has also been assumed that a cotton T-shirt is the first layer covering the surface of the skin with the cooling vest coming immediately after it. Environment temperature and the initial temperature of the skin have been assumed to be 30 and 33°C, respectively. The initial temperature of the PCM, upon contact with the body has been assumed to be 10°C. Therefore, given that the start of melting in materials was 18°C, the PCMs were solid at the beginning of the process.

Model geometry and material definition

The geometry of the system in the model consisted of four major parts: torso, cotton T-shirt, polyethylene packets containing PCM, and PCM. The torso considered for the model included back, breasts, and belly, collectively covering a surface of 0.65 m^2 (ISO 8996, 2004). The vest covering the surface of the torso contained 14 PCM packets with the size of 12 × 10 × 2 cm; six bags were in front of the torso and eight at the back (Figure 3). The surface covered by PCM packets was 0.168 m^2, which was 26% of the torso. To mesh the system, 57,331 thermal solid elements were used. These elements were of two types: hexahedral solid90 and tetrahedral solid87, which had 10 and 20 nodes, respectively (Figure 4). PCM packets were regularly meshed, but the meshing of skin and T-shirt layers was irregular due to the complex geometry of them.

Properties of skin layer and cotton T-shirt were defined as given in Table 2. Insulation of the T-shirt layer was turned to Conductive coefficient with the help of the following equation (ISO 5085-1, 1989) and used in the model for material definition.

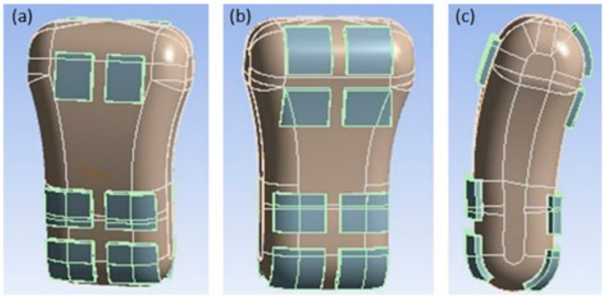

Figure 3. (a): front view, (b): back view, and (c) side view of the model geometry.

$$k\left(\frac{W}{m,K}\right) = \frac{d(mm) \times 10^{-3}}{R_f\left(m^2 \cdot \frac{K}{W}\right)}, \tag{4}$$

where k is the conductive coefficient of the layer, d is the thickness of the layer, and R_f is the insulation of the textile layer. The insulation of the cotton T-shirt was defined as 0.318 clo and its thickness was estimated to be 1 mm according to ISO 9920 (1995).

As the best efficiency of the cooling garments can be achieved with the close contact of the garment to the body, the contact between the different parts of the model was defined as perfect contact. Also, no ventilation effect and air flow were assumed between the skin and the garment.

Results and discussion

The results of modeling can be studied in some phases as follows:

- mean skin temperature variation throughout the process;
- temperature distribution graph for the system;
- Temperature distribution graph for the PCM bags;
- The curve of heat flux from the body to the PCM bags.

Mean skin temperature variation

Figure 5 shows the mean skin temperature variations from the start of contact between the body and the cooling vest. The control model curve also shows the changes in the mean skin temperature of the body without the use of the cooling vest. The properties of the control model were set completely the same as the model with the cool vest, and the only difference was due to the non-use of the PCM packets on the body.

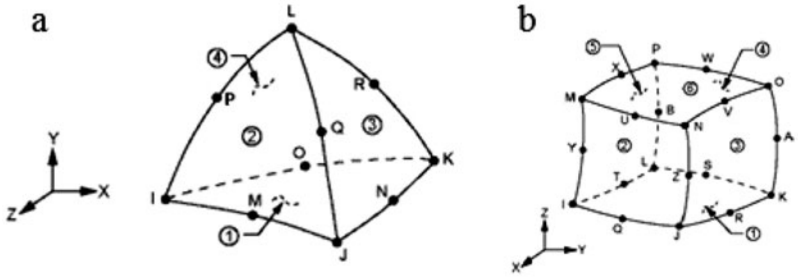

Figure 4. Elements used for meshing the model ((a) solid87 and (b) solid90).

Table 2. Properties of skin and cotton T-shirt defined in the model.

Layer name	K (W/m°k)	Density (kg/m^3)	Thickness (mm)
Skin	0.5	1010	10
Cotton T-shirt	0.02	1540	1

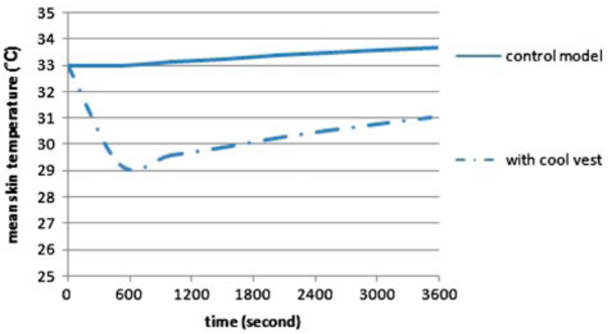

Figure 5. Mean skin temperature variation curves with and without the cooling vest.

As can be seen in the figure, it can be inferred that if the body is in a hot environment, mean skin temperature is gradually increased. The skin temperature in control condition can reach to 33.67°C without the use of cooling vest. The increase in skin temperature will be higher if the worker is doing a higher level of activity. This is due to a much more level of heat produced through the metabolism.

In the second curve, it is observed that the use of PCM packets on the skin could greatly reduce mean skin temperature by absorbing the body's excessive heat. Mean skin temperature fell very fast in the first minutes of the contact with the PCM packets due to the low temperature of the PCM (10°C) and then gradually increased. This resulted in a reduction of 2.58°C in mean skin temperature after one hour (33.67–31.09). This reduction in the mean skin temperature could result in increasing endurance threshold and individual's performance in hot working conditions.

Of course, the decrease of skin's temperature, which was due to wearing cooling vests, depends on different factors such as the vest design, the kind of PCM applied, the environmental condition, and the person wearing the garment. In this model, just one situation was examined. But, as the software model was used, it is possible to change each of these conditions and examine their resulting effects.

Temperature distribution graph of the system

The distribution graph for temperature of all parts of the system could be achieved at any time during the process with the software modeling. Figure 6 shows the temperature distribution after 20 min. The reduction in skin temperature in points of contact with the phase change packets could be easily seen. Increase in other parts of the body was the result of hot environment and the internal metabolism of the body. The parts that have the highest temperature were the contact areas with the arms, neck, and legs. These parts were selected to have a fixed temperature of 37°C during the process, which is the same as the internal temperature of the body.

As the PCM packet's temperature shows, after 20 minutes, a great deal of PCM at the outer surface of

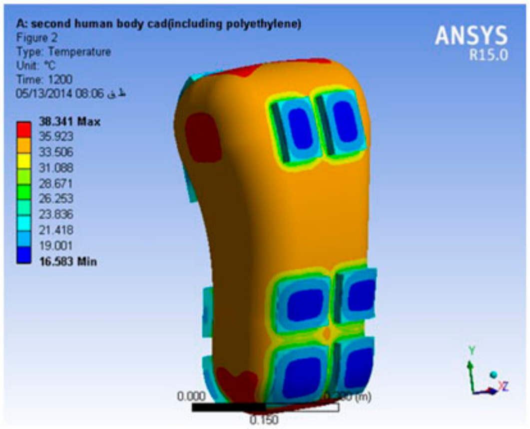

Figure 6. Total temperature diagram after 20 min.

PCM packets did not reach the phase change temperature, thus remaining in the solid phase. As only the edges had been melted in the external layer, so the cooling effect of these packets was maintained as far as the remained PCM was still in the solid phase.

Temperature distribution graph for the PCM bags

A fast increase in the temperature of PCM bags occurred in the first minutes of the contact between the PCM bags and the body. This increase was merely due to the temperature difference between two faces and within two minutes, the melting process got started in the PCM bags. This can be observed using a diagram showing the temperature distribution in the PCM bags (Figure 7). This figure represents the temperature distribution in the PCM bags at the time of one and two minutes. It can be understood from this graph that phase change first occurred in the internal layers of PCM bags that were close to the body. These layers, because of being closer to the skin and having a high temperature difference with it, experienced a fast increase in temperature and therefore, reached the phase change temperature sooner than other parts of the bags. Part (a) shows that in the first minute, when bags were in contact with the body, a few points in the internal layer of the bags (which are brighter) reached the temperature of 18°C. But, after 2 minutes, the melting phenomenon was propagated almost everywhere in the internal layer (part b). However, the external layers in both graphs showed a marginal increase in the temperature when compared with the initial temperature (10°C). So, much more time was needed for the external and middle layers in bags containing PCM to start their phase change.

As PCM bags were also involved in heat exchange with the surrounding environment, the next part in which phase change occurred was related to the external layers of the bags. As can be seen, the edges of the bags, after two minutes, started to increase the temperature. It is natural that the middle layers melted in the final stage and changed their phase. The less the speed of phase change progression in the bags, the more is the duration of cooling in the garment. The speed of phase change depends on different factors such as the temperature difference between PCM melting point and the skin surface, the weight of PCM used in the garment, the environment temperature, PCM thermal conductivity, and the material of which the garment is made.

Curve of heat flux from the body to the PCM bags

PCMs absorb the heat required to increase the temperature and change the phase from solid to liquid from both the body and the surrounding environment. The software model makes it possible for us to study the amount of heat exchanged from each side. Figure 8 shows the diagram representing the intensity of heat absorbed by PCM bags from the body. As can be seen, in the initial moments when the bags were in touch with the body, a large volume of heat was absorbed by the bags due to the large temperature difference between the body and the material in the bags; also, it led to the initiation of phase change in the internal layers of such bags. After a short while, heat exchange was decreased due to the decrease in large temperature difference between the two surfaces and the relative elimination of sensible heat in the exchange. After an hour, heat loss reached a stable state which was continued until the complete melting of PCM.

This process of variation in heat loss, which was increased intensely at the beginning, was then decreased, finally reaching a stable state. It showed a good agreement with the results obtained by Bendkowska et al. (2010), who had estimated heat loss resulting from the use of PCM vests through thermal manikins.

The volume of total heat flux vs. sensible heat absorbed by the PCM packets can be distinguished in Figure 8. Sensible heat loss of the body was due to the temperature difference between the body surface and PCM packets. The latent heat of PCM melting was not

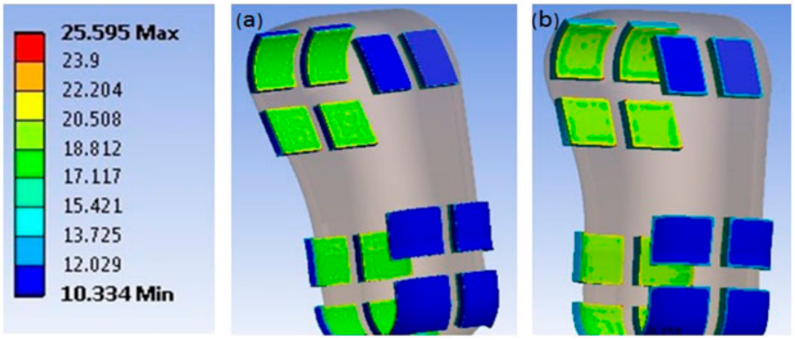

Figure 7. Temperature distribution in PCM packets in (a) 60 and (b) 120 s.

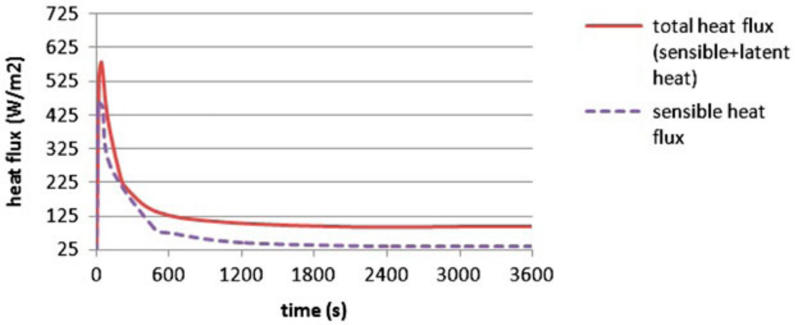

Figure 8. Heat flux of the body to the PCM packets.

included in the sensible heat flux curve. Average amounts of heat loss during the process can also be seen in Table 3 for only sensible heat and total heat loss of the body.

As it is clear, most absorbed heat (around 72%) in the first minutes of placing the PCM packets on the body was related to sensible heat due to the high temperature difference between the two surfaces. In these times, only a limited part of the material in the packets near the skin surface had reached the melting point. So, only 28% of the exchanged heat was due to the latent heat of melting. Along with the time, melting phenomena reached to other parts of the bags and so, the latent heat portion of the total was increased. Inasmuch as an hour, one half of the total heat exchange was allocated to each sensible and latent heat.

As the PCM temperature was not changed during the melting process and remained at 18–20°C, the sensible heat exchange continued due to the 13° difference existing in temperature. The latent heat exchange was also continued until the whole PCM was melted. After the complete melting of PCM, latent heat contribution reached to zero and sensible heat transfer from the skin was continued until two surfaces became isothermal. At this time, the cooling process came to an end. Duration of the cooling process in this model was estimated to be more than 3 h.

The average heat loss obtained by modeling using PCM bags was 215.4 W/m^2 in the first 15 min after wearing the vest, reaching 128.71 W/m^2 after one hour. By multiplying these values by the area occupied by PCM bags on the body (0.168 m^2), for average energy received, the values of 36.2 and 21.6 W were obtained in the first 15 min and an hour, respectively. Comparison of the heat absorbed by PCM macro bags in this kind of cooling vest with the results obtained in garments with microcapsules of PCM showed the higher efficiency of the macro PCM garments. In a study conducted by Shim et al. (2001), microcapsules of PCMs in clothing were reported to provide a small, temporal heating/cooling effect (about 15 min) during environmental transients between warm and cold chambers. Also, the whole heat received by the garment during this time, if it was made of one layer, was 6.5 and 13 W if it was made of two layers (Shim et al., 2001). Meanwhile, the cooling vest containing the macro bags of PCM (the same as this study), absorbed 3 to 6 times more heat compared to the microcapsules of PCM in the first 15 min. Also, the cooling effect of macro bags of PCM could continue for more than 3 h in spite of the micro PCM vest.

Model verification with the experimental tests

Results of a series of subjective tests were used to verify the accuracy of the model. The experiments were conducted in a climatic chamber conditioned at a temperature of 30°C and the relative humidity of 37%. Four college-age subjects participated in the wear trial tests. They were healthy, moderately physically active, with all having a normal blood pressure. Their mean age, height, and weight, with standard deviations were 22 years (3.4), 168.5 cm (3), and 68.5 kg (9.2), respectively.

The subjects wore working clothes consisting of their own undershorts, a cotton T-shirt, trousers, and socks. This clothing ensemble was estimated to be 0.88 clo by

Table 3. Average heat flux from the body to the PCM packets.

Parameter	First 15 min	First 30 min	First one hour
Total heat flux (latent heat + sensible heat) (W/m^2)	215.4	157.45	128.71
Sensible heat flux (W/m^2)	154.7	106	68.43
Percent of the sensible heat	72%	67%	53%

measurement with thermal manikin. PCM cooling vest with properties similar to those of the model was designed and worn on the working clothes. The control condition tests were also employed without the use of cooling vests. Before entering the test chamber, the participants stayed in a room with a lower temperature than the test chamber at 24.5°C, without any activity. After 10 minutes of entering the climatic chamber, every subject was asked to go 25 steps up and down, each for 10 min, during the 60-min experimental test. This activity was estimated to be 1.4 met (81.2 W/m^2), the same as the metabolic heat assumption of the model (Tanabe, Imamura, Shou, & Suzuki, 1995). Skin temperature at chest and back was measured and stored each 4 min. For each subject, only one test was conducted during one day. The order of testing was randomized.

Figure 9 shows the variation of skin temperature with and without the use of cooling vest. The results of the model were also added to estimate the degree of correspondence between the two curves.

The data recorded in 60 min was used for the calculation of the mean skin temperature. Normality of the data was analyzed under the Kolmogorov–Smirnov Test, and as the asymp. Significance (2-tailed) was more than 0.05, so it was concluded that the two groups of data were normal and finally, the independent T-test was used to analyze the equality of mean values between experimental and modeling results. Data were analyzed using SPSE 20.0 for Windows and Statistical significance was set at $p < 0.05$. Table 4 shows the statistical data used for analyzing the mean skin temperatures.

As can be seen, the values obtained for skin temperature for the control condition in the experimental tests and modeling showed a good agreement. As the significance level in T-test for the equality of means was 0.462, the experimental and model results in control condition did not show a significant difference. This good agreement revealed that the heat exchanges between the body and the environment have been correctly simulated in the model.

In the case of using the cooling vest, the curves related to body's temperature in both modeling and experimental conditions showed the reduction of skin temperature in comparison to the control condition. But the results of modeling in the first minutes of wearing the vest were somewhat overestimated, so the reduction of skin temperature during this time was more than its real value. This can be attributed to the inability of the model to simulate skin cutaneous vasculature. Normally, body causes skin vasodilation to increase heat loss and vasoconstriction to reduce heat loss in hot and cold environments, respectively (Parsons, 2003). As reported, a cooling vest can cause skin vasoconstriction in the body (Cotter, Sleivert, Roberts, & Febbraio, 2001). As the cooling garment reduces the skin temperature, it can result in the constriction of the cutaneous vasculature.

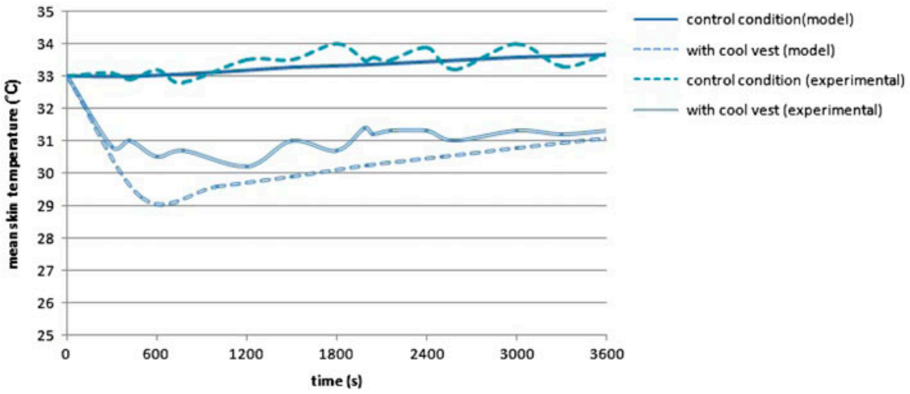

Figure 9. Skin temperature with and without cooling vest (experimental and model results).

Table 4. Statistical data.

Test condition	Group of data name	*N*	Mean	Std. Deviation	Sig. (2-tailed)In t-test for Equality of Means
With cooling vest	Model results	8	30.5400	1.16997	0.121
	Experimental results	16	31.1188	0.60467	
	Model results	8	33.3087	0.25453	0.426
	Experimental results	16	33.4188	0.37277	

Overcooling increases tissue insulation, decreases convective heat transfer from the body core, and reduces the cooling garment-to-skin temperature gradient, thereby theoretically reducing cooling garment operating efficiency (Cheuvront, Kolka, Cadarette, Montain, & Sawka, 2003). It is likely that vasoconstriction reduces cooling efficiency, which is defined as the ratio of the body core cooling and cooling provided by a cooling garment. In principle, vasoconstriction will increase the skin insulation and prevent the exchange of heat between the body core and the cooling garment (Kocjan, Perret, Bogerd, Rossi, & Daanen, 2009). And this effect cannot be simulated because of the lack of skin vasoconstriction in the model. But, this effect was decreased in the model by the decrease in temperature difference between skin and the cooling vest. Therefore, after one hour, the results of modeling and human tests were converged, showing a good agreement. The significance level in T-test for the equality of means was 0.121, so the experimental and model results, with the use of cooling vest, didn't show any significant difference with each other.

Conclusion

In this study, heat transfer from the body of a person with moderate activity to a cooling PCG was modeled. Also, the effect of heat transfer from the body to the garment on the body's temperature was studied. The results of modeling showed that the intensity of heat transfer from the body to the garment was more considerable in the initial minutes and then, in the course of time, it was decreased. Therefore, the decrease in skin temperature was considerable at the beginning and then it was gradually decreased. After one hour, the decrease in skin temperature in the sample model reached to about 2.6°C. The accuracy of the results obtained by modeling in sample conditions was verified by human tests employed, showing a good agreement between theoretical and practical results. The comparison of the amount of heat absorbed in cooling garments containing PCM microcapsules and the vest used in this study showed that these garments had a higher efficiency (2–4 times) in protecting the wearer against the unpleasant conditions of the hot environment.

Also, the investigation of temperature changes in the PCMs showed that the phase change present in the cooling bags first occurred in the internal layers of the bags, which were closer to the body and then reached the external layers and finally, the middle layers of the PCM bag. The speed of melting progression in the bags and the time during which garment cools depend on several factors. Therefore, investigating of efficiency of the cooling garment needs further studies.

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