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Innovative PCM-desiccant packet to provide dry microclimate and improve performance of cooling vest in hot environment

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ABSTRACT

A novel combination of phase change material (PCM) and a solid desiccant layer is proposed for the aim of maintaining dry cool microclimate air adjacent to wet warm skin and hence improve PCM performance in cooling vests used in hot humid environment.

A fabric-PCM-Desiccant model is developed to predict the temperature and moisture content of the microclimate air layer in the presence of a PCM-Desiccant packet. The developed model is validated through experiments conducted on a wet clothed heated cylinder for the two cases of using (i) a PCM only packet and (ii) a PCM-Desiccant packet. Microclimate air temperatures and humidity content as well as PCM and desiccant temperatures were measured experimentally and were compared with predicted values by the fabric-PCM-Desiccant model. Good agreement was attained with a maximum relative error of 7% in measured temperatures. A decrease is observed in the humidity content of the microclimate air in the presence of the solid desiccant from 21.23 g/kg dry air to 19.74 g/kg dry air and an increase in the melted fraction of the PCM at the end of the experiment from 0.24 to 0.5.

1. Introduction

Personal passive cooling systems have been increasingly used to cool the human body during outdoor activities in hot environment. Phase change material (PCM) cooling vests are an example of body passive cooling means that can be worn by human workers outdoors [1]. PCM vests are available in the market as commercial products with PCM packets of different shapes, weights and PCM melting temperatures. The PCMs used in textiles, due to their thermal energy storage in the form of latent heat, have the advantage of protecting workers against the harsh hot conditions by absorbing the heat from the workers and the hot ambient [2]. In addition, there is a wide range of PCM melting temperatures that can be selected to provide comfort and suit the conditions and the duration of use of the PCMs [2]. The cooling vests among other microclimate cooling systems are known to be the cheapest, most portable, and the easiest to be worn [3–5].

The performance of the PCM cooling vest has been assessed in previous studies via experiments on human subjects and on thermal manikins [6–10]. The main findings include that the cooling rate of the vest depends on the temperature gradient between the skin and the PCM packet, on the PCM mass and on the coverage area. It was found that PCM packets with lower melting temperatures are better for effective cooling in hot conditions. In addition, modeling of the PCM in the cooling vest has been used for performance assessment, where it was found that a lower melting temperature is recommended for a fast cooling effect and increasing the PCM mass would increase mainly the cooling duration [11–13]. It was also established that the PCM cooling vest decreases the core temperature of people working in construction or in firefighting thus reducing their heat stress and extending their work duration in hot environment [14–16].

However, PCM cooling vest effectiveness is constrained in hot humid environment due to reduced moisture transport from the vest and the consequent risk of sweat and condensation on the PCM packet surface. In a study by Dotti et al. [17], three back protectors were evaluated for comfort through experiments done on human subjects performing intermittent physical activity. They reported that the back protector with the highest breathability and lowest microclimate humidity ranked the first among other protectors in terms of thermal sensation and that moisture management played the major role in the acceptance of back protectors. Houshyar et al. [18] also indicated that using clothing that prevent air and water vapor transport would result in saturation of the microclimate humidity near the skin layer and condensation of water vapor due to sweating leading to heat stress and reduction of the work efficiency. Wang and Hu [19] also showed that the

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Nomenclature

A	area (m^2)
C_p	thermal capacitance (J/kg K)
e	thickness (m)
f	volume fraction
g	gravitational acceleration (m/s^2)
h_{fg}	heat of evaporation (J/kg)
h_{sf}	latent heat of fusion (J/kg)
h_m	mass transfer coefficient of inner fabric (kg/m^2 kPa s)
h_c	convective heat transfer coefficient (W/m^2 K)
h_{des}	mass transfer coefficient (m/s)
h_r	radiative heat transfer coefficient (W/m^2 K)
HD	hot dry
HH	hot humid
k	thermal conductivity (W/m K)
m	mass (kg)
$\dot{m}_a$	mass flow rate triggered by buoyancy forces
P	vapor pressure (kPa)
PCM	phase change material
q	heat flux (W/m^2)
Q	desiccant heat of adsorption (J/kg)
r	radius
R	thermal resistance (m^2 K/W)
R_{tot}	total thermal resistance (m^2 K/W)
R_e	evaporative resistance of the fabric (m^2 kPa/W)
t	time (s)
t_{adh}	thickness of adhesive tape (m)
t_{DM}	thickness of desiccant membrane (m)
T	temperature (°C)
w	humidity ratio (kg_w/kg_{air})

Greek symbols

α	fraction of melted PCM
β	volumetric thermal expansion ($°C^{-1}$)
ρ	density (kg/m^3)
ν	kinematic viscosity of air (m^2/s)

Subscripts

adh	adhesive tape
air	macroclimate air between the PCM and the environment
aj	microclimate air between PCM and skin
con	conduction
des	desiccant
DM	desiccant membrane
env	environment
of	outer fabric
i	index indicating the body segment number
if	inner fabric
liq	liquid
PCM	phase change material
skin	skin layer
Tot	total

mean thermal sensation of humans in hot conditions was related to sweating sensation.

Reinertsen et al. [7] assessed experimentally the effect of covering the whole trunk or part of it with PCM packets on sweat evaporation through the vest in hot environment. They reported that thermal sensation was better when decreasing the number of PCM packets in the vest due to improved sweat transport through the vest. However, reducing the number of PCM packets in the vest may decrease the vest cooling duration. Zhoa et al. [10] performed experiments on a thermal manikin in a hot and humid (HH) environment and in a hot and dry (HD) environment to test the PCM vest cooling performance when sweat evaporation from the manikin skin is restricted. Results showed that the PCM cooling capability in the HD environment did not compensate for the restricted cooling by evaporation and led to lower torso heat losses. Itani et al. [16] modeled the fabric-PCM performance taking into consideration the heat of condensation and indicated that condensation speeded up the PCM melting and decreased the vest cooling duration. They reported that in order to avoid condensation in the vest, the PCM cooling vest at a melting temperature of 28 °C can only be used at humidity levels below 53% and 31% in the hot conditions at 35 °C and 45 °C, respectively. This means that performance and usability of the PCM vest are compromised if relative humidity exceeded the threshold values for onset of condensation in hot and humid weather.

A novel solution is proposed in this work to overcome the deterioration of the PCM performance due to condensation and sweat accumulation on the skin layer. Keeping the skin and microclimate air dry can be done by utilizing a thin solid desiccant packet covering part of the PCM packet surface. The solid desiccant such as silica gel can decrease the moisture content of the microclimate air between the PCM packet and the inner fabric layer of the cooling vest through an adsorption process. However, the released heat of adsorption might increase the temperature of the microclimate air if the PCM mass is insufficient for absorbing both the generated heat by the desiccant and the heat lost from the torso of the human body. It is of interest to determine whether the PCM-Desiccant packet combination is capable of enhancing the cooling performance of the vest. The placement of the PCM-Desiccant packet in the cooling vest could target torso areas that contain high distribution of sweat glands like the chest and upper back segments [20–22]. To the authors' knowledge, the combination of PCM and desiccant for use in the cooling vest has not been modeled or tested in previous studies.

The aim of this work is to develop a fabric-PCM-Desiccant model to identify design parameters that affect the heat and mass transfer taking place through the cooling vest. An experimental setup including a heated clothed vertical wet cylinder will be used to validate the developed fabric-PCM-Desiccant model. Experiments will be performed to verify the accuracy and applicability of the developed model.

2. System description

The purpose of the PCM-Desiccant packet proposed in this study is to provide cooling for the human body doing work in hot conditions and to adsorb the water vapor from the microclimate air, thus enhancing the evaporation of sweat from the skin layer and improving cooling of the human body. The PCM-Desiccant packet is made up of three main components, the PCM, the desiccant and the water vapor permeable membrane that holds the desiccant inside it. A 3-D schematic of the PCM-Desiccant packet showing its different components and placed inside a cooling vest is shown in Fig. 1. The packet will be placed in the microclimate air layer near the skin with the desiccant directed toward

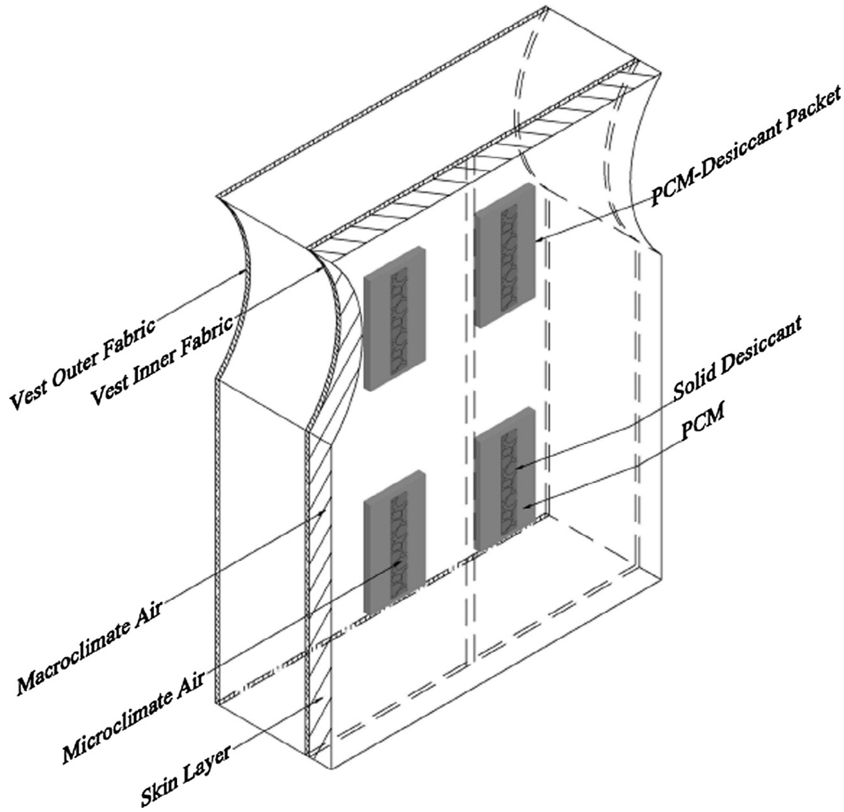

Fig. 1. A 3-D schematic of the PCM-Desiccant packet placed in a cooling vest.

the skin layer so that water vapor adsorption takes place effectively.

The selected PCM of the packet is made up of a salt mixture of sodium sulfate and water known as Glauber's salt [23], while the selected desiccant is solid silica gel granules. The PCM is placed in its own aluminum wrapping, while the desiccant is placed in another wrapping represented by a water vapor permeable membrane. The placement of the PCM and the desiccant in different wrappings does not allow the mixing between the PCM in its melted form and the desiccant to happen. However, the water vapor permeable membrane allows the desiccant to adsorb the water vapor from the microclimate air layer between the packet and the inner fabric layer of the vest and prevents any liquid transport to the desiccant. The desiccant surface area is smaller than that of the PCM in order to allow the PCM to absorb heat from the microclimate air near the skin of the human and to absorb the bulk of the heat released by the desiccant during adsorption process of water vapor. Care should be taken in the design of the PCM-Desiccant packet so that the addition of the desiccant does not increase the mass of the packet considerably. The bulk density of the desiccant is about 60% of that of the PCM [24,25,13], which indicates that the desiccant occupies more space than the PCM if a higher desiccant mass is needed to adsorb the moisture. A relatively high surface area of contact is needed between the PCM and the desiccant with the microclimate air so that the PCM can extract heat for cooling purposes and the desiccant can extract moisture for decreasing the moisture content of the microclimate air. The PCM and the desiccant surfaces should have a good adhesive contact area at low thermal resistance so that heat is transferred to the PCM effectively. This is achieved by using a thermally conductive double-sided adhesive tape between the two wrappings of PCM and desiccant. Regeneration of the solid desiccant can be simply done by placing it in a hot medium to release its moisture content and bring it to its initial state [24,25].

3. Research methods

3.1. Mathematical formulation of fabric-PCM-Desiccant model

A model that predicts the conditions of the microclimate and macroclimate air in the presence of the PCM-Desiccant packet placed near the human skin would be a significant tool for improving the performance of a PCM cooling vest in situations where moisture transport is hindered. The presence of a solid desiccant will adsorb, through the water vapor permeable membrane holding the solid desiccant, moisture from the microclimate air layer released due to sweat secretion and prevent condensation from happening at the packet surface. Meanwhile, the PCM will absorb the heat of adsorption released by the desiccant so that no excess heat is released to the microclimate air. Thus, the fabric-PCM model developed by Hamdan et al. [12] has been modified to include the effect of a solid desiccant added to the PCM packet as shown in Fig. 2(a). The solid desiccant in the model is considered to be lumped with a surface area A_{des}, which in addition to the surface area of the PCM, A_{PCM}, form the total area, A_{Tot}, of the PCM-Desiccant packet shown in Fig. 2(b).

The desiccant present between the microclimate air layer and the PCM will adsorb moisture from the microclimate air layer as shown in Fig. 3(a). In addition, mass transfer will take place between the different layers of the cooling vest due to the pressure differences between the different air and fabric layers and the environment. The PCM as well as the desiccant are both assumed to

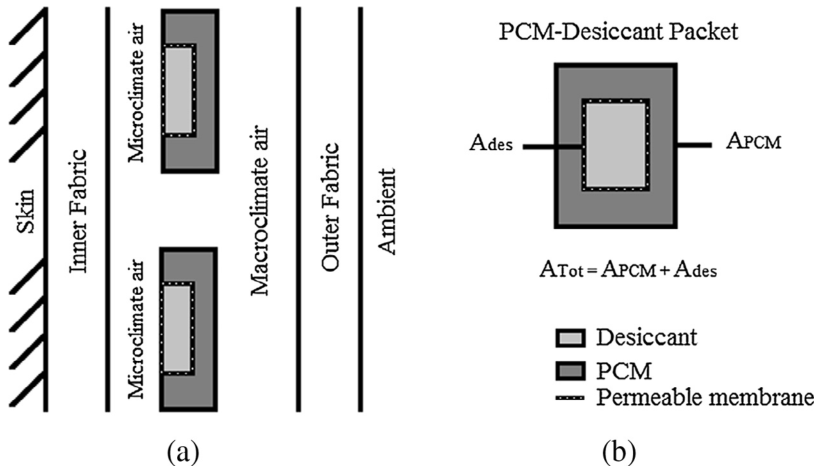

Fig. 2. Schematic of the (a) cooling vest side view with different fabric and air layers sandwiching the PCM-Desiccant packet and (b) area fraction of PCM and desiccant in the packet.

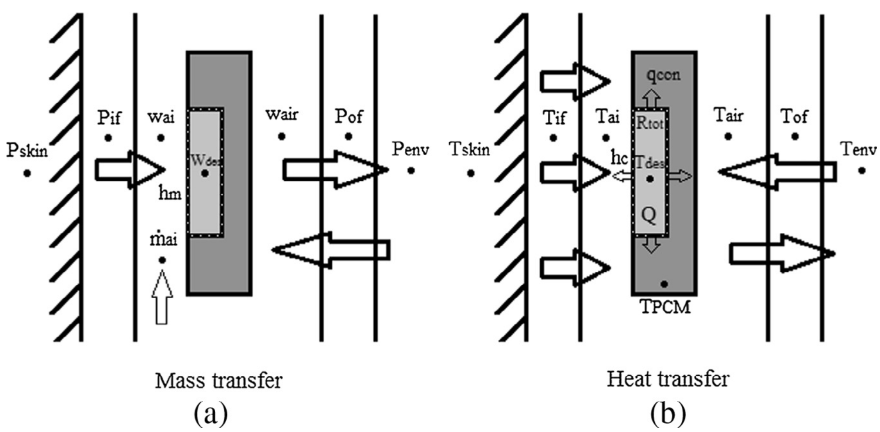

Fig. 3. Schematic of the (a) mass transfer and (b) heat transfer at the different layers of the cooling vest.

have a lumped temperature since the packet is thin. In addition, the thermal resistance between the PCM and the desiccant is assumed to be minimal due to the high thermal conductivity of the wrappings of the PCM and the desiccant and the thermally conductive double-sided tape used to join the PCM and the desiccant into one packet. Resistances to the aforementioned mass transfer are represented as evaporative resistances for the fabric layers and reciprocals of the mass transfer coefficients. Furthermore, the PCM in contact with the desiccant will exchange heat with the microclimate and macroclimate air layers and with the desiccant as shown in Fig. 3(b). Heat transfer will also take place between the different layers of the cooling vest and the hot environment. Thermal resistances to heat flow are represented as dry resistances for the fabric layers and reciprocals of the convective heat transfer coefficients.

The PCM and the solid desiccant, which are present in one packet, are considered to have distinct temperatures. The temperature of the PCM, $T_{PCMi,j}$, can be found using Eq. (1) if no melting is taking place, through an energy balance in which the PCM exchanges convective heat with the macroclimate and microclimate air layers, radiative heat with the inner and outer fabrics and exchanges heat with the desiccant through a contact surface of thermal resistance, R_{tot}, found using Eq. (2). During melting, the PCM melted fraction, $\alpha_{i,j}$, can be found as given in Eq. (3), where the PCM temperature is fixed at the melting temperature.

The PCM packet energy balance when there is no melting is given by

$$\begin{aligned} f_{PCM,i,j} m_{PCMi,j} C_{PCMi,j} \frac{dT_{PCMi,j}}{dt} &= h_c \times A_{Tot,i,j} \times (T_{air,i} - T_{PCMi,j}) \frac{r_{air,i}}{r_{PCMi,j}} \\ &+ A_{Tot,i,j} \frac{(T_{desi,j} - T_{PCMi,j})}{R_{tot}} \\ &+ h_c A_{PCM,i,j} (T_{ai,j} - T_{PCMi,j}) \frac{r_{if,i}}{r_{PCMi,j}} \\ &+ h_{r,PCM,if} A_{PCM,i,j} (T_{if,i} - T_{PCMi,j}) \frac{r_{if,i}}{r_{PCMi,j}} \\ &+ h_{r,PCM,of} A_{Tot,i,j} (T_{PCMi,j} - T_{of,i}) \frac{r_{PCMi,j}}{r_{of,i}} \end{aligned} \quad (1)$$

The thermal resistance between PCM and desiccant is given by

$$R_{tot} = \frac{t_{adh}}{k_{adh} \times A_{adh}} + \frac{t_{DM}}{k_{DM} \times A_{DM}} \quad (2)$$

The PCM packet energy balance during melting is given by

$$\begin{aligned} f_{PCM,i,j} h_{sf} m_{PCMi,j} \frac{d\alpha_{i,j}}{dt} &= h_c \times A_{Tot,i,j} \times (T_{air,i} - T_{PCMi,j}) \frac{r_{air,i}}{r_{PCMi,j}} \\ &+ A_{Tot,i,j} \frac{(T_{desi,j} - T_{PCMi,j})}{R_{tot}} + h_c \\ &\times A_{PCM,i,j} (T_{ai,j} - T_{PCMi,j}) \frac{r_{if,i}}{r_{PCMi,j}} \\ &+ h_{r,PCM,if} A_{PCM,i,j} (T_{if,i} - T_{PCMi,j}) \frac{r_{if,i}}{r_{PCMi,j}} \\ &+ h_{r,PCM,of} A_{Tot,i,j} (T_{PCMi,j} - T_{of,i}) \frac{r_{PCMi,j}}{r_{of,i}} \end{aligned} \quad (3)$$

The mass flow rate, $\dot{m}_{ai,j}$, of the microclimate air in the small gap width between each PCM-Desiccant packet and the clothing layer on each segment of the human torso can be found using Eq. (4), assuming a Poiseuille flow [26] as follows:

$$\dot{m}_{ai,j} = \rho_{air} \times g \times \beta \times \frac{T_{air,i} - T_{ai,j}}{12\nu} \times d^3 \times l \quad (4)$$

The symbols d and l represent the gap width and the width of the PCM packet, respectively.

In addition, mass and energy balances are used to predict the segmental humidity ratio of the microclimate air, $w_{ai,j}$ and the temperature of the lumped microclimate air, $T_{ai,j}$, using Eqs. (5) and (6), respectively. The segmental macroclimate air humidity ratio, $w_{air,i}$ and temperature, $T_{air,i}$, can also be found using the mass and energy balances developed by Hamdan et al. [12]. The mass balances consider water vapor transport between the fabric layers and the microclimate and macroclimate air layers as well as the moisture loss due to adsorption. The energy balances consider heat exchanges between the fabric layers, the desiccant, the PCM and the microclimate and macroclimate air layers, as follows:

Mass balance of microclimate air

$$\rho_{air} d \frac{dw_{ai,j}}{dt} = \sum \frac{P_{if,i} - P_{ai,j}}{\frac{R_{e,if} \times h_{fg}}{2} + \frac{1}{2 \times h_m}} \frac{r_{if,i}}{r_{ai,j}} + \dot{m}_{ai,j}(w_{air,i} - w_{ai,j}) \frac{1}{d \times l} - \rho_{air} h_{des}(w_{ai,j} - w_{desi,j}) \frac{r_{ai,j}}{r_{des,i,j}} \quad (5)$$

Energy balance of microclimate air

$$\rho_{air} \times d \times A_{Tot,i,j} \times \left(C \times \frac{dT_{ai,j}}{dt} - h_{fg} \times \frac{dw_{ai,j}}{dt} \right) = h_c A_{des,i,j}(T_{desi,j} - T_{ai,j}) \frac{r_{ai,j}}{r_{des,i,j}} + A_{PCM,i,j} h_c (T_{PCMi,j} - T_{ai,j}) \frac{r_{ai,j}}{r_{PCM,i,j}} + A_{Tot,i,j} h_c (T_{if,i} - T_{ai,j}) \frac{r_{if,i}}{r_{ai,j}} + \dot{m}_{ai,j} C_{air} (T_{air,i} - T_{ai,j}) \frac{r_{air,i}}{r_{ai,j}} \quad (6)$$

Mass and energy balance equations are also used to find the inner and outer fabric regains and temperatures [12].

The mass and energy balances of the desiccant are used to predict the moisture content, $w_{desi,j}$ (kg water/kg dry desiccant) and the temperature of the desiccant, $T_{desi,j}$, using Eqs. (7) and (8), respectively. The mass balance considers water vapor transport between the desiccant and the microclimate air layer due to adsorption. The energy balance considers heat exchanges between the desiccant, the microclimate air layer and the PCM. In addition to the heat released due to the adsorption process, as shown below:

Mass balance of solid desiccant

$$\rho_{des} \times e_{des} \times \frac{dw_{desi,j}}{dt} = \rho_{air} h_{des}(w_{ai,j} - w_{desi,j}) \frac{r_{ai,j}}{r_{des,i,j}} \quad (7)$$

Energy balance of solid desiccant

$$f_{des,i,j} \times \rho_{des} \times e_{des} \times A_{desi,j}(C_{p,des} + w_{desi,j} C_{p,liq}) \frac{dT_{desi,j}}{dt} = h_c A_{des,i,j}(T_{ai,j} - T_{desi,j}) \frac{r_{ai,j}}{r_{des,i,j}} - A_{Tot,i,j} \frac{(T_{desi,j} - T_{PCMi,j})}{R_{tot}} + f_{des,i,j} \times \rho_{air} \times Q \times h_{des} \times A_{desi,j}(w_{ai,j} - w_{desi,j}) \frac{r_{ai,j}}{r_{des,i,j}} + h_{r,des,if} A_{desi,j}(T_{if,i} - T_{desi,j}) \frac{r_{if,i}}{r_{des,i,j}} \quad (8)$$

3.2. Numerical solution of fabric-PCM-Desiccant model

The mass and energy balance equations of the fabric-PCM-Desiccant model are solved using the explicit Euler forward method. Initial temperatures of the air layers, fabric layers and PCM-Desiccant packets are defined. The initial conditions of the pressures of the different clothing layers as well as the humidity ratios of the air layers are set. Initially, the inner and outer fabric regains are found at the new time step followed by finding their temperatures and values of the relative humidity [27]. Also, the new temperatures found are used to calculate the fabric saturation pressures [28] and the corresponding vapor pressures.

The mass flow rate of the microclimate air layer due to buoyancy is found and used to calculate the humidity ratios and temperatures of the microclimate and macroclimate air layers at the new time step. The temperature of the PCM and the desiccant can also be found, where the PCM temperature is compared to its melting temperature at each time step to check whether the PCM started melting and to find its corresponding melted fraction. It should be noted that the heat of adsorption of the desiccant is found using the formula developed by Pesaran and Mills [29] which depends on the moisture content of the desiccant. The major thermo-physical properties of air, PCM, desiccant and fabric taken as model inputs are presented in Table 1. A flow chart showing the fabric-PCM-Desiccant model sequence of operation is shown in Fig. 4.

3.3. Validation of fabric-PCM-Desiccant model

Validation of the fabric-PCM-Desiccant model is done by conducting experiments on clothed heated cylinder with a solid desiccant packet placed in contact to the PCM packet on the inner side of the clothing. The data collected from the experiment, which include the microclimate and macroclimate air temperatures, the temperature variation of the PCM packet and the desiccant and the moisture content of the microclimate air layer are compared with their equivalent predicted by the model to validate it for certain environmental conditions, wind speed, clothing permeability and thermal properties and geometry. The thermal resistance between the PCM and the desiccant in the PCM-Desiccant packet is also found by using Eq. (2).

3.3.1. PCM-Desiccant packet

The PCM-Desiccant packet used in the experiments has dimensions of 118 mm × 50 mm × 15 mm and a total mass of the PCM and the solid desiccant of 100.47 g, of which 15.64 g are for the desiccant. The material used for the PCM in the experiment constitutes of a salt mixture of sodium sulfate and water and has a melting temperature of 28 °C and a density of 1239 kg/m^3 [23,30]. The desiccant used in the experiment is silica gel granules of Type A,

Table 1
Major thermo-physical properties of air, PCM, desiccant and fabric taken as model inputs.

Parameter	Property	Value	Unit
A_{PCM}	PCM area	36	cm^2
C_{PCM}	PCM thermal capacitance	3100	J/kg·K
h_{sf}	PCM latent heat of fusion	126	kJ/kg
ρ_{PCM}	PCM density	1239	kg/m^3
T_{PCM}	PCM melting temperature	28	°C
A_{Des}	Desiccant area	23	cm^2
e_{Des}	Desiccant thickness	9.1	mm
ρ_{Des}	Desiccant density	750	kg/m^3
β	Volumetric thermal expansion	3.26E−3	°C^{-1}
ρ_{air}	Air density	1.2	kg/m^3
C_{air}	Air thermal capacitance	1005	J/kg K
ν	Kinematic viscosity of air	16.5E−6	m^2/s
R_{tot}	Total thermal resistance	0.11	m^2 K/W
R_{dry}	Fabric dry thermal resistance	0.023	m^2 K/W
R_e	Fabric evaporative resistance	1.677	m^2 kPa/W
e_{Fabric}	Fabric thickness	1	mm

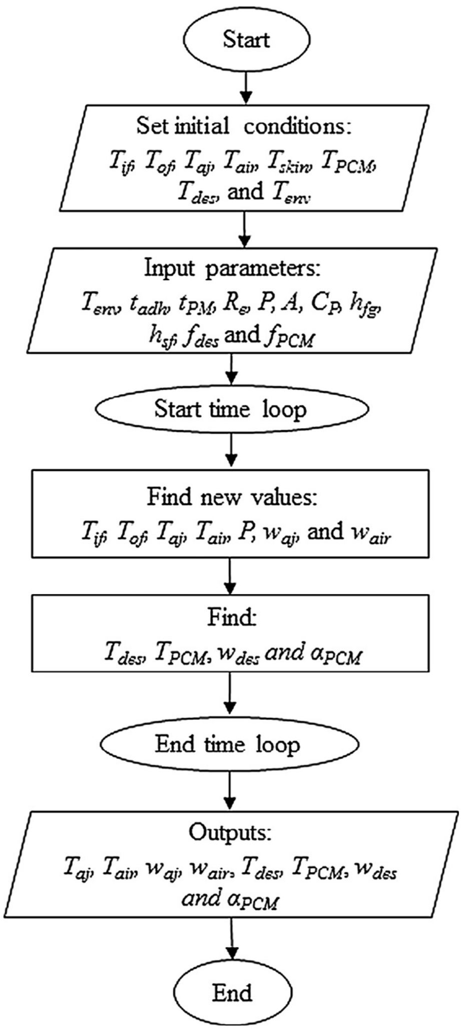

Fig. 4. Flow chart of the fabric-PCM-Desiccant model sequence of operation.

with a bulk density of 750 kg/m^3 placed inside a water vapor permeable membrane made up of polypropylene. The volume fraction of the desiccant in the PCM-Desiccant packet was 18%, covering 39% of the total surface area of the packet.

3.3.2. Thermal resistance between PCM and desiccant

The total thermal resistance between the PCM and the desiccant packet is due to the adhesive tape that bonds the PCM packet to the desiccant one as well as the desiccant membrane that holds the desiccant. The adhesive is thermally conductive, with a thermal conductivity of 0.6 W/m K and thickness of 1.27E−4 m, to ensure good contact between the PCM and the desiccant by removing air gaps that would increase the thermal resistance. The desiccant membrane has a thermal conductivity of 0.2 W/m K and thickness of 1E−5 m. The thermal storage or capacity in the thermally conductive adhesive and the desiccant membrane is considered negligible. Thus the resultant total thermal resistance, R_{tot}, has a value of 0.11 m^2 K/W, which is required as input to the fabric-PCM-Desiccant model.

3.3.3. Experimental setup

The experiment is conducted on a wet clothed heated cylinder, similar to the one used in the study of Ghaddar and Ghali [31], and placed in a climatic chamber with ambient conditions maintained at 28 ± 0.5 °C and relative humidity of 50 ± 2% and wind speed at 0.3 m/s, as shown in the schematic in Fig. 5 and actual experimental setup in Fig. 6. The wind speed was measured using 731A anemometer with an accuracy of 3%.

The heated cylinder used is made up of copper and has a diameter of 0.104 m and a length of 0.215 m. The copper cylinder is wrapped with Omega-KH-1012 highly conductive metallic resistance heaters to produce a constant heat flux condition per heater at the cylinder surface. Independent regulation of the heat fluxes from the different strip heaters is done to ensure a uniform mean steady surface temperature of 34 °C ± 0.5 °C for each strip heater. The copper heated cylinder is wrapped by a wet stretch fabric completely wetted before being placed around the heaters. It is ensured that no water is dripping from the wet stretch fabric and that no dry areas appear on its surface through monitoring the wet fabric temperature. After about 30 min, the wet fabric temperature reached a uniform mean steady temperature of 33 °C ± 0.5 °C. Then, two concentric thin metallic screens (0.215 m long each) are used to guard the wet clothed heated cylinder and hold the PCM-Desiccant packet (inner and outer guards), as shown in Fig. 5. The diameters of the concentric inner and outer guards are 0.108 m and 0.128 m, respectively. A third 0.215 m long guard with a 0.14 m diameter, the outer fabric guard, made up of a metallic mesh is used to hold the outer fabric layer. The wet clothed cylinder and its guards are fixed on an insulated support platform made up of Styrofoam material at the bottom of the cylinder so that minimal heat and mass transfer take place at the bottom.

The cotton fabric used in the experiment is obtained from Testfabrics Inc. (Middlesex, NJ 08846) [32], and is made of knitted cotton, style #473 of thickness of 1 mm. The permeability of the clothing is measured by SDL MO2IA air permeability tester with a percent deviation in repeated measurements of ±0.9% and an accuracy of 10^{-4} m^3/(m^2 s) and is found to be 0.65 m^3/(m^2 s). The tester is characterized by fast, simple, and accurate determination of the air permeability of all kinds of flat materials. The cotton fabric dry thermal resistance and evaporative resistance are measured using the sweating guarded hotplate (Model 306-200/400) and

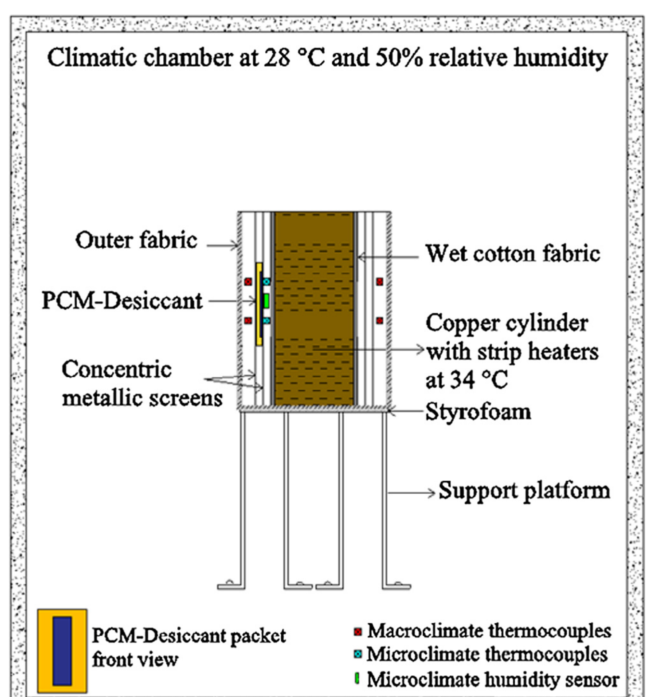

Fig. 5. Schematic of the experimental setup of the wet clothed inner heated cylinder.

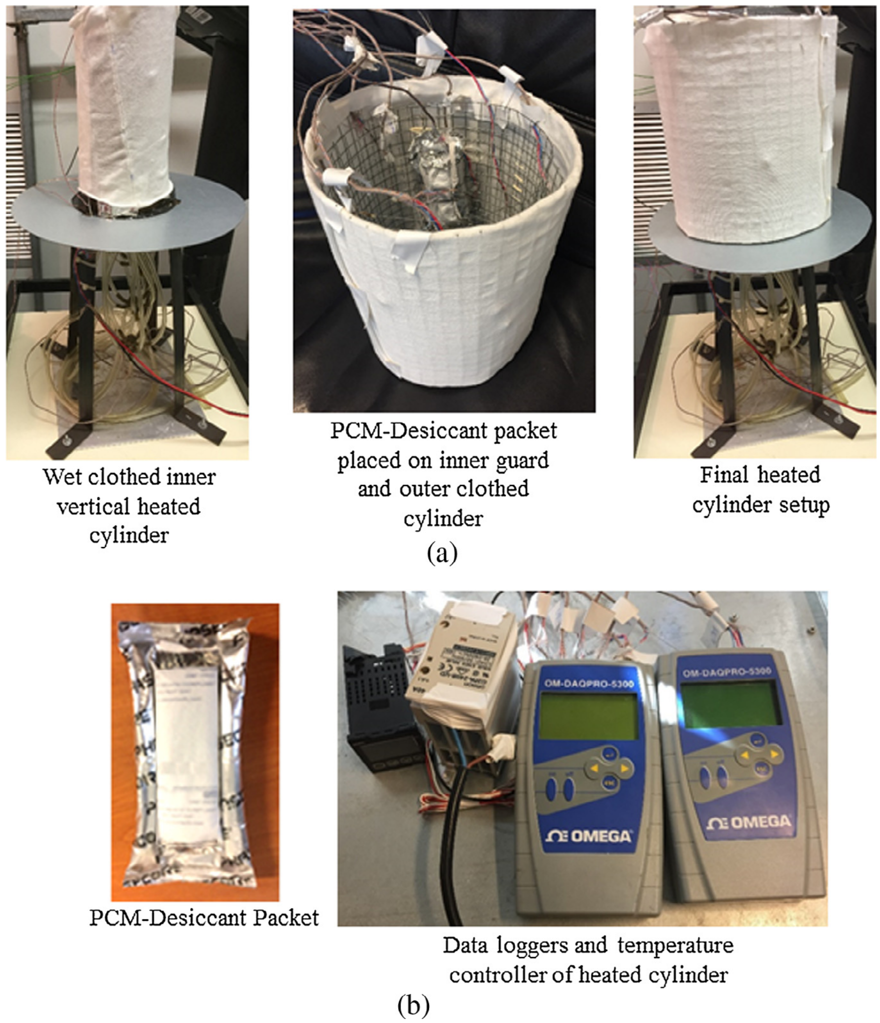

Fig. 6. Pictures of (a) the experimental setup of the wet clothed inner heated cylinder in the climatic chamber and (b) the PCM-Desiccant packet, data loggers and temperature controller for heated cylinder.

found to be 0.023 m^2 K/W and 1.677 kPa m^2/W, respectively, with an error less than 0.1%.

Microclimate and macroclimate air layers are formed by arranging the outer clothed cylinder and the metallic guards around the clothed heated cylinder. The temperature of the microclimate air layer is measured via two T-type thermocouples placed on the metallic guards in the layer neighboring the PCM-Desiccant packet (Fig. 5). Furthermore, the temperature of the macroclimate air layer was measured using six T-type thermocouples placed at different positions in the layer neighboring the outer clothed cylinder. The humidity ratio of the microclimate air layer was measured using OM-EL-USB-2 sensor with an accuracy ±3% in reading the relative humidity. In order to measure the temperatures of the PCM and the desiccant, T-type thermocouple are also used and placed inside each one of them. The PCM and desiccant packets are well-sealed using epoxy to prevent any leakage. Regeneration of the solid desiccant to restore its adsorption capacity was done by placing it in a hot oven at 75 °C for six hours and then placed in a plastic bag to cool down in the ambient room air.

3.3.4. Experimental protocol

At the start of the experiment, the heated vertical cylinder was turned on and kept for about 30 min to reach a steady wet fabric surface temperature of 33 °C ± 0.5 °C. After that, the PCM with the desiccant membrane packet, initially at 26 °C was brought and covered with a removable plastic cover. The regenerated solid desiccant, initially at 26 °C, was inserted in the desiccant membrane shielded with a plastic cover to avoid moisture transport to the desiccant while preparing the PCM-Desiccant packet. Then, after ensuring a uniform thickness of the desiccant layer, sealing the packet and removing the plastic cover, the PCM-Desiccant packet was inserted in its allocated position on the metallic guards. Thus the PCM-Desiccant packet together with the metallic guards and the outer clothed cylinder can be then placed around the heated cylinder. The previous step took about 2 min while data about the different parameters started logging. The thermocouples reading the microclimate and macroclimate temperatures and the PCM and desiccant temperatures were connected to OM-DAQPRO-3500 data logger set to take a reading every 10 s (Fig. 6(b)). Another experiment was also performed with a PCM packet (without the desiccant packet). The PCM packet had the same weight of about 85 g compared to the weight of the PCM in the PCM-Desiccant packet.

4. Results and discussion

In this section, a comparison is done between the results of the two experiments conducted on clothed wet heated cylinder and (i) using only a PCM packet and (ii) using a PCM-Desiccant packet. The reason for doing the two experiments is to compare the conditions of the microclimate air (temperature and humidity content) and PCM temperature when a solid desiccant is used. The main inputs to the fabric-PCM-Desiccant model are the PCM melting temperature, ambient conditions, PCM-Desiccant mass and surface area, PCM-Desiccant thermal properties, and the total thermal resistance between the PCM and the desiccant.

Fig. 7 shows the comparison between the measured and the predicted PCM and microclimate air temperatures as well as the simulated PCM melted fraction in the case when no desiccant is used. The experimental PCM temperature rises from its initial condition at about 26 °C after it gains heat to reach its melting temperature of 28 °C after 35 min. The initial condition of the PCM packet is taken as input to the model and the results showed a later start of melting (after about 39 min). The predicted melted fraction of the PCM packet was 0.24 after 60 min have passed. The microclimate temperature shows a sharp increase in the first few minutes due to subjecting the microclimate air to a high temperature of 34 °C of the heated cylinder. After 15 min have passed, the microclimate temperature reached a stable value of about 32 °C. The recorded humidity ratio of the microclimate air at the beginning of the experiment was 16.8 g/kg dry air and reached a value of 21.23 g/kg dry air at the end of the experiment. The results show a good agreement between the measured and the predicted temperatures, where the maximum relative error is 3% and 4% for the PCM and microclimate air temperatures, respectively. The under-estimation of the fabric-PCM model of the PCM temperature could be related to the fact that the PCM did not show a constant melting temperature at 28 °C in the experiment, but rather a higher one at about 28.5 °C.

Fig. 8 shows the comparison between the experimental and the simulation results of the PCM and solid desiccant temperatures as well as the simulated PCM melted fraction in the case when a PCM-Desiccant packet is used. The PCM temperature rises from its initial condition at about 26 °C to reach its melting temperature of 28 °C after 22 min while the model predicts a slightly later start of melting after about 24 min. The predicted melted fraction of the PCM packet was 0.5 after 60 min have passed. The results indicate that a faster start of PCM melting by about 15 min was observed due to the presence of the solid desiccant in contact with the PCM, which justifies also the higher melted fraction of the PCM. A higher desiccant temperature than that of the PCM is evident during the time when the PCM is in the transient phase in the first 24 min. The desiccant temperature showed higher values than that of the PCM due to the thermal contact resistance between the PCM and the desiccant, in addition to the adsorption process that releases heat of adsorption. Consequently, the maximum relative error in predicting the PCM and desiccant temperatures is 3% and 4%, respectively.

Fig. 9 shows the comparison between the measured and predicted results of the microclimate and macroclimate air temperatures in the case when a PCM-Desiccant packet is used. Both measured temperatures had a similar trend similar throughout the duration of the experiment. A sharp increase in the temperatures occurred in the first few minutes due to the exposure to the relatively high surface temperature of the heated cylinder and the temperatures started stabilizing after 20 min of the experiment have passed. However, the microclimate air temperature had higher values than the macroclimate one due to the exposure to the heated cylinder maintained at a surface temperature of

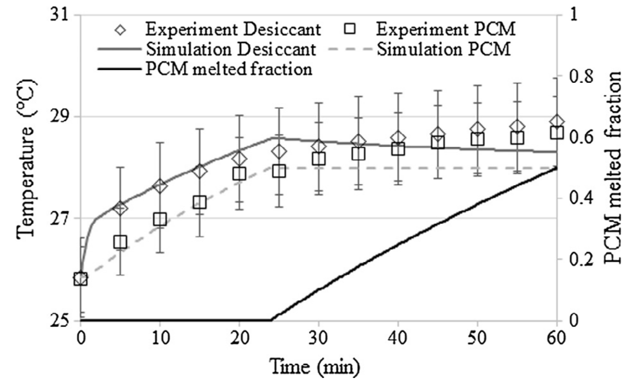

Fig. 8. Plot showing the variation with time of experimental and simulation results of the PCM and desiccant temperature as well as the PCM melted fraction corresponding to the experiment on the PCM-Desiccant packet.

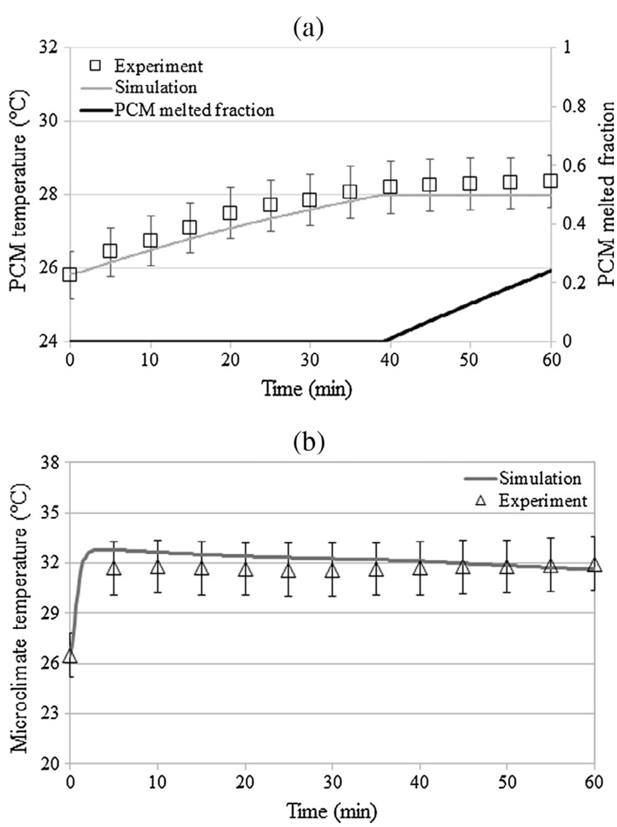

Fig. 7. Plots showing the variation with time of the (a) experimental and simulation results of the PCM temperature and simulated PCM melted fraction and (b) the microclimate air temperature corresponding to the experiment on the PCM packet only.

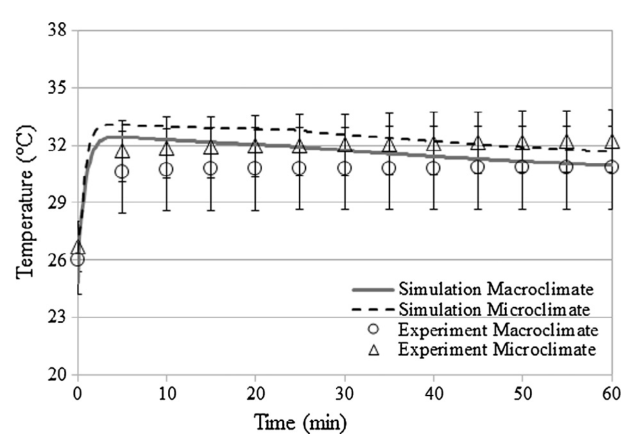

Fig. 9. Plot showing the variation with time of experimental and simulation results of the microclimate and macroclimate temperatures corresponding to the experiment on the PCM-Desiccant packet.

34 °C. The recorded humidity ratio started initially at 16.9 g/kg dry air and ended at 19.74 g/kg dry air. Thus, comparing the humidity ratio of the two experiment cases, it can be deduced that the presence of the desiccant caused a reduction in the humidity content of the microclimate air as desired. Good agreement was found between the measured and the predicted results with a maximum relative error of 5% and 7% corresponding to microclimate and macroclimate temperatures, respectively. Comparing the microclimate temperature in the case when a PCM-Desiccant packet was used to that when only a PCM packet was used, it can be deduced that higher values by an average of about 0.6 °C were attained when using the PCM-Desiccant packet. Thus, the presence of the desiccant increased the microclimate temperature to reach higher values than those reached when no desiccant was used.

Fig. 10 shows the comparison between the measured and predicted results of the microclimate relative humidity for the two cases: (i) using only a PCM packet with no desiccant and (ii) using a PCM-Desiccant packet throughout the experiment. The trend of the relative humidity showed a slight decrease with time, accompanied with an increase in the moisture content of the microclimate air. The results also show a higher reduction in the relative humidity when a desiccant was added to the PCM packet, where a sharp decrease was noticed in the first 10 min of the experiment. The relative humidity at the end of the experiment when no desiccant was used reached about 70% and about 65% when a desiccant was used. The corresponding humidity ratio of the microclimate air at the end of the experiment, where no desiccant was used, was 21.23 g/kg dry air and 19.74 g/kg dry air when a PCM-Desiccant packet was used. Thus, the desiccant caused a reduction in the humidity content of the microclimate air as desired.

The analysis of the experimental and predicted results shows that the problem of blockage of water vapor transport associated with the PCM packets can be solved. Using a PCM-Desiccant packet to provide a dryer microclimate region would improve the performance of cooling vests by increasing the coverage area of the PCM on the skin without causing undesired moisture accumulation and discomfort for the wearer, especially in hot environments. In the study of Itani et al. [16] constrictions on the applicability of the PCM cooling vests at certain environmental conditions to avoid condensation in the vest were set. It was stated that at the ambient temperatures of 28 °C, 35 °C and 45 °C there exist upper limits of the ambient relative humidity at which the cooling vest can be used, which are at 80%, 53% and 31%, respectively. The proposed PCM-Desiccant packet can be used to improve the performance of the cooling vest and widen the region of its applicability without the risk of condensation. Thus, the combined PCM-Desiccant packet can be utilized for providing a similar performance to a PCM only cooling vest by possibly adding a number of PCM packets

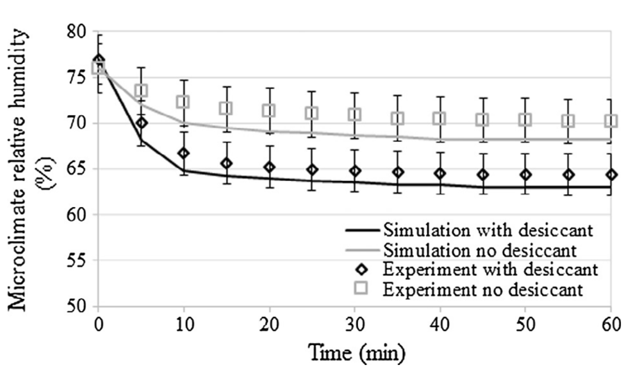

Fig. 10. Plot showing the time variation of the experimental and predicted microclimate air relative humidity when using only the PCM packet and when using the PCM-Desiccant packet.

with a slightly higher mass in the vest. Another possibility could be by introducing a combination of PCM-Desiccant packets and PCM only packets to maintain acceptable performance in HH environment through controlling both temperature and humidity within the trunk microclimate. These design possibilities would be addressed in future work for optimizing a PCM-Desiccant cooling vest for best combination, weight, and duration of melting.

5. Conclusion

A novel idea is proposed, modeled and validated experimentally to find the state of the microclimate air and its moisture content under the influence of using a PCM-Desiccant packet. The idea entails using a solid desiccant in addition to a PCM packet to maintain dry skin and macroclimate air layers, prevent condensation and enhance sweat evaporation from the skin. Experiments are conducted on a clothed wet heated cylinder with two cases considered to show the effect of adding the desiccant to the PCM packet. Microclimate air temperatures and relative humidity as well as PCM and desiccant temperatures were measured experimentally and predicted by the developed fabric-PCM-Desiccant model with a maximum relative error of 7%. The results showed a desired effect, which is the decrease in the humidity content of the microclimate air from 21.23 g/kg dry air to 19.74 g/kg dry air in the presence of the solid desiccant. The melted fraction of the PCM at the end of the 60-min experiment increased from 0.24 in the absence of the solid desiccant to 0.5 in the presence of the desiccant. Higher microclimate temperature by 0.6 °C was attained when using the PCM-Desiccant packet instead of the PCM packet.

Future work will address optimized design of PCM-Desiccant cooling vest for best combination and placement of PCM-Desiccant and PCM packets taking into consideration human thermal response to local cooling and dryness.

References

[1] Johnson JK. Evaluation of four portable cooling vests for workers wearing gas extraction coveralls in hot environments. Graduate Theses and Dissertations. United States: University of South Florida; 2013.

[2] Sharma RK, Ganesan P, Tyagi VV, Metselaar HSC, Sandaran SC. Developments in organic solid–liquid phase change materials and their applications in thermal energy storage. Energy Convers Manage 2015;95:193–228.

[3] Kamon E, Kenney WL, Deno NS, Soto KI, Carpenter AJ. Readdressing personal cooling with ice. Aihaj 1986;47:293–8. http://dx.doi.org/10.1202/0002-8894(1986) 047<0293:rpcwi>2.3.co;2.

[4] Coleman SR. Heat storage capacity of gelled coolants in ice vests. Aihaj 1989;50:325–9. http://dx.doi.org/10.1202/0002-8894(1989) 050<0325:hscogc>2.0.co;2.

[5] Kenny GP, Schissler AR, Stapleton J, Piamonte M, Binder K, Lynn A, et al. Ice cooling vest on tolerance for exercise under uncompensable heat stress. J Occup Environ Hygiene 2011;8:484–91. http://dx.doi.org/10.1080/15459624.2011.596043.

[6] Gao C, Kuklane K, Holmér I. Cooling vests with phase change materials: the effects of melting temperature on heat strain alleviation in an extremely hot environment. Eur J Appl Physiol 2010;111:1207–16. http://dx.doi.org/10.1007/s00421-010-1748-4.

[7] Reinertsen RE, Færevik H, Holbø K, Nesbakken R, Reitan J, Røyset A, et al. Optimizing the performance of phase-change materials in personal protective clothing systems. Int J Occup Safety Ergon 2008;14:43–53. http://dx.doi.org/10.1080/10803548.2008.11076746.

[8] Bendkowska W, Kłonowska M, Kopias K, Bogdan A. Thermal manikin evaluation of PCM cooling vests. Fibres Textiles Eastern Europe 2010;18(1):78.

[9] Gao C, Kuklane K, Holmér I. Cooling effect of a PCM vest on a thermal manikin and on humans exposed to heat. In: 12th International conference on environmental ergonomics, vol. 12. Ljubljana, Slovenia: Biomed doo; 2007. p. 146–9.

[10] Zhao M, Gao C, Wang F, Kuklane K, Holmer I, Li J. The torso cooling of vests incorporated with phase change materials: a sweat evaporation perspective. Textile Res J 2012;83:418–25. http://dx.doi.org/10.1177/0040517512460294.

[11] Qiu Y, Jiang N, Wu W, Zhang G, Xiao B. Heat transfer of heat sinking vest with phase-change material. Chinese J Aeronaut 2011;24:720–5. http://dx.doi.org/10.1016/s1000-9361(11)60084-8.

[12] Hamdan H, Ghaddar N, Ouahrani D, Ghali K, Itani M. PCM cooling vest for improving thermal comfort in hot environment. Int J Therm Sci 2016;102:154–67. http://dx.doi.org/10.1016/j.ijthermalsci.2015.12.001.

[13] Itani M, Ouahrani D, Ghaddar N, Ghali K, Chakroun W. The effect of PCM placement on torso cooling vest for an active human in hot environment. Build Environ 2016;107:29–42. http://dx.doi.org/10.1016/j.buildenv.2016.07.018.

[14] Shim H, Mccullough EA, Jones BW. Using phase change materials in clothing. Textile Res J 2001;71:495–502. http://dx.doi.org/10.1177/004051750107100605.

[15] Chou C, Tochihara Y, Kim T. Physiological and subjective responses to cooling devices on firefighting protective clothing. Eur J Appl Physiol 2008;104:369–74. http://dx.doi.org/10.1007/s00421-007-0665-7.

[16] Itani M, Ghaddar N, Ghali K, Ouahrani D, Chakroun W. Cooling vest with optimized PCM arrangement targeting torso sensitive areas that trigger comfort when cooled for improving human comfort in hot conditions. Energy Build 2017;139:417–25. http://dx.doi.org/10.1016/j.enbuild.2017.01.036.

[17] Dotti F, Ferri A, Moncalero M, Colonna M. Thermo-physiological comfort of soft-shell back protectors under controlled environmental conditions. Appl Ergon 2016;56:144–52. http://dx.doi.org/10.1016/j.apergo.2016.04.002.

[18] Houshyar S, Padhye R, Troynikov O, Nayak R, Ranjan S. Evaluation and improvement of thermo-physiological comfort properties of firefighters' protective clothing containing super absorbent materials. J Textile Inst 2015;106:1394–402. http://dx.doi.org/10.1080/00405000.2014.995930.

[19] Wang H, Hu S. Experimental study on thermal sensation of people in moderate activities. Build Environ 2016;100:127–34. http://dx.doi.org/10.1016/j.buildenv.2016.02.016.

[20] Randall WC. Quantitation and regional distribution of sweat glands in man. J Clin Invest 1946;25:761–7. http://dx.doi.org/10.1172/jci101760.

[21] Arens E, Zhang H. The skin's role in human thermoregulation and comfort. Thermal and moisture transport in fibrous materials;2006. doi:http://dx.doi.org/10.1201/9781439824351.ch16.

[22] Herrmann F, Prose PH, Sulzberger MB, Mandol L, Medoff G, Roth L. Studies on sweating: V. Studies of quantity and distribution of thermogenic sweat delivery to the skin. J Invest Dermatol 1952;18(1):71–86.

[23] Gao C, Kuklane K, Holmér I. Cooling vests with phase change material packs: the effects of temperature gradient, mass and covering area. Ergonomics 2010;53:716–23. http://dx.doi.org/10.1080/00140130903581649.

[24] Narayanan R, Saman W, White S, Goldsworthy M. Comparative study of different desiccant wheel designs. Appl Therm Eng 2011;31:1613–20. http://dx.doi.org/10.1016/j.applthermaleng.2011.01.043.

[25] JIAYOU Q. Characterization of silica gel-water vapor adsorption and its measurement facility, Master dissertation. Singapore: National University of Singapore; 2004.

[26] Bejan A. Convection heat transfer. New York: Wiley; 1984.

[27] Morton WE, Hearle JWS. Physical properties of textile fibres. Manchester: Textile Institute; 1975.

[28] Hyland RW, Wexter A. Formulations for the thermodynamic properties of the saturated phases of H_2O from 173.15 K to 473.15 K. ASHRAE Trans 1983;89:500–19.

[29] Pesaran AA, Mills AF. Moisture transport in silica gel packed beds—I. Theoretical study. Int J Heat Mass Transfer 1987;30(6):1037–49.

[30] Swedish Emergency & Disaster Equipment AB, <http://www.swedeproducts.se/econtent/140> [accessed 04.01.17].

[31] Ghaddar N, Ghali K. Effect of moisture transport on mixed convection in vertical annulus of a heated clothed vertical wet cylinder in uniform cross wind. In: 2010 14th International heat transfer conference, vol. 7; 2010. doi: http://dx.doi.org/10.1115/ihtc14-22342.

[32] Testfabrics. <http://www.testfabrics.com/products.php?catID1=TWpBPQ&%3BcatID2=1> [accessed 04.01.17].