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To cite this article: Jialin Ye *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **563** 042041

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3D-Finite Element Analysis for Influences of PCM Inserted in Garment on Body Temperature Responses

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Abstract. To investigate the influences of the PCM micro-capsules in the garment on the body temperature responses, a mathematical model of heat and moisture transfer in garments inserted PCM micro-capsules is developed. The model is solved by the finite element method. Then, this garments model is interfaced with the thermal regulatory model of the human body based on the 3D FEM. Furthermore, the temperature distribution of garment and human body is simulated by using the model. The results show that garment with PCM can significantly delay the temperature rise compared with garment without PCM.

1. Introduction

In recent years, the study of phase change material (PCM) has become more attractive especially in the area of garments. PCM has the ability to absorb and store a large amount of latent heat during heating and release this energy during cooling. So the garments added with PCM could efficiently improve thermal protective function of textiles and garments. A large number of solid-liquid PCM have been investigated for heating and cooling applications[1]. Nuckols[2], Hittle and Andre[3] established the analytical models of the dry fabrics with micro-capsules PCM and investigated the influence of PCM on the dry fabrics. To consider the dynamic heat and moisture transfer in the clothing with PCM and influence of the PCM micro-capsules on the body temperature, Wang and Li [4] developed a heat and moisture model for pilot-anti G suit-environment system. However, the model is limited by large temperature gradient because of its one-dimensional structure. In order to provide guidance for quantitative design of the PCM in the garments and consider the effect of the large temperature gradient on heat transfer, this paper developed a 3-D heat and moisture transfer model of the garment with PCM micro-capsules, that is combined with the 3-D FEM model of the human thermal regulation to obtain garment and body temperature distribution. The simulating results show the advantages of PCM in thermal protection clothing.

2. Mathematical models

2.1. Governing equation

The passive system of the entire body can be divided into the following four subsystems: human tissue system, circulatory system, respiratory system and garments system. The governing equations for first three subsystems can be found in the Ref.[5]. Coupling the garments subsystem based on the above equations and adding PCM material item, we get four basic equations: water vapor mass balance equation, the mass balance equation of liquid water, the energy balance equation of the garment after adding the PCM, and the relationship between variable volume fraction:



$$\begin{cases} \frac{\partial(C_a \varepsilon_a)}{\partial t} = \bar{\nabla} \cdot \left(\frac{D_a \varepsilon_a}{\tau_a} \bar{\nabla} C_a \right) - \varepsilon_f \xi_1 \Gamma_f + \Gamma_{lg} \\ \frac{\partial(\rho_l \varepsilon_l)}{\partial t} = \bar{\nabla} \cdot \left(\frac{D_l}{\tau_l} \bar{\nabla}(\rho_l \varepsilon_l) \right) - \varepsilon_f \xi_2 \Gamma_f - \Gamma_{lg} + a \frac{\partial \varepsilon_l}{\partial z} \\ c_v \frac{\partial T_{cl}}{\partial t} = \bar{\nabla} \cdot (k_{mix} \bar{\nabla} T_{cl}) + \varepsilon_f \Gamma_f (\xi_1 \lambda_v + \xi_2 \lambda_l) - \lambda_{lg} \Gamma_{lg} + q \\ \varepsilon = \varepsilon_l + \varepsilon_a + \varepsilon_m = 1 - \varepsilon_f \end{cases} \quad (2.1)$$

Where, $q = h_e \frac{3\varepsilon_m}{R_m} \{T_m(x, R_m, t) - T_{cl}\}$ represents the heat flux delivered to the garments by the PCM

micro-capsules in the unit volume micro-element; h_e is heat transfer coefficient combined conduction convection and radiant; ε_m is the volume fraction of PCM; T_m is the temperature of the PCM, which is the function of position x of the phase change micro-capsule in the garments, the radial position r of the micro-capsule and the time t ; R_m is the radius of PCM; T_{cl} is the garments temperature. The other terms can be found in the Ref.[5].

2.2. Boundary conditions

On the inner surface of the garments subsystem:

$$\begin{cases} -\frac{D_l}{\tau_l} \bar{\nabla}(\rho_l \varepsilon_l) \cdot \bar{n} \Big|_{\Gamma_1} = \kappa_2 h_{lg} (C_a^*(T_{cl,0}) - C_{ask}) \\ -\frac{D_a \varepsilon_a}{\tau_a} \bar{\nabla} C_a \cdot \bar{n} \Big|_{\Gamma_1} = -m'' \\ -k_{mix} \bar{\nabla} T \cdot \bar{n} \Big|_{\Gamma_1} = (H_{t1} (T_{cl,0} - T_{skin})) - \lambda_{lg} m'' + \kappa_2 \lambda_{lg} h_{lg} (C_a^*(T_{cl,0}) - C_{ask}) \end{cases} \quad (2.2)$$

Where H_{t1} is heat transfer coefficient combined conduction, convection and radiant; λ_{lg} is evaporation latent heat; m'' is moist evaporation rate on the surface of the human skin system; $\kappa_2 = \varepsilon_l / \varepsilon$ is evaporation mass transfer ratio; C_a^* is saturated water vapor concentration; C_{ask} is the water vapor concentration on the surface of the human skin; h_{lg} is the evaporation coefficient of the liquid water.

On the outer surface of the garment subsystem:

$$\begin{cases} -\frac{D_a \varepsilon_a}{\tau_a} \bar{\nabla} C_a \cdot \bar{n} \Big|_{\Gamma_2} = \kappa_1 H_{m2} (C_{acl,L} - C_{env}) \\ -\frac{D_l \rho_l}{\tau_l} \bar{\nabla} \varepsilon_l \cdot \bar{n} \Big|_{\Gamma_2} = \kappa_2 h_{lg} (C^*(T_{cl,L}) - C_{env}) \\ -k_{mix} \bar{\nabla} T \cdot \bar{n} \Big|_{\Gamma_2} = \lambda_{lg} \kappa_2 h_{lg} (C_a^*(T_{cl,L}) - C_{aenv}) + H_{t2} (T_{cl,L} - T_{env}) \end{cases} \quad (2.3)$$

Where subscript 'env' is the environment; H_{t2} is the overall heat transfer coefficient on the outer surface of the garment; $\kappa_1 = \varepsilon_a / \varepsilon$ is the volume fraction of water vapor condensed on the outer surface of the garments in the gap of the garments structure; Subscript 'L' is the outer surface of the garment; H_{m2} is mass transfer coefficient on the outer surface of the garments.

2.3. Temperature determination of micro-capsule surface

In general, PCM is in a certain temperature range when a phase change process occurs. We use the sensible heat capacity method. At time t , the micro-capsule containing the PCM, where the position x

with surface temperature $T_m(x, R, t)$ can be solved while being in a heat conducting state. The equation of the micro-capsule is:

$$\tilde{C} \frac{\partial T_m(x, r, t)}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(\tilde{k} r^2 \frac{\partial T_m(x, r, t)}{\partial r} \right) \quad (2.4)$$

Where \tilde{C}, \tilde{k} is equivalent heat capacity and thermal conductivity of the phase change process. According to the PCM properties in the experiment, the equivalent heat capacity can be expressed as:

$$\tilde{C} = \begin{cases} C_s & T_m < T_a \\ \frac{2\rho_m \Delta H}{(T_c - T_a)(T_b - T_a)} (T_m - T_a) + \varepsilon_{ms} C_s + \varepsilon_{ml} C_l & T_a \leq T_m \leq T_b \\ \frac{2\rho_m \Delta H}{(T_c - T_a)(T_c - T_b)} (T_c - T_m) + \varepsilon_{ms} C_s + \varepsilon_{ml} C_l & T_b < T_m \leq T_c \\ C_l & T_m > T_c \end{cases} \quad (2.5)$$

Where T_a, T_b, T_c is the temperature of the PCM; T_a, T_c is lower and upper limits of phase change interval; T_b is the peak temperature; ΔH is the total latent heat of the interval from T_a to T_c ; C_s, C_l is solid and liquid heat capacity of PCM; $\varepsilon_{ml}, \varepsilon_{ms}$ is decided by specific temperature and current temperature; \tilde{k} is the equivalent thermal conductivity which is expressed by the following formula:

$$\tilde{k} = \begin{cases} k_s & T_m < T_a \\ \varepsilon_{ms} k_s + \varepsilon_{ml} k_l & T_a \leq T_m \leq T_c \\ k_l & T_m > T_c \end{cases} \quad (2.6)$$

Where k_s, k_l is the conducting rate at solid and liquid.

On the outer surface of the PCM micro-capsule:

$$-\tilde{k} \frac{\partial T_m(x, r, t)}{\partial r} \Big|_{r=R_m} = h_e \{T_m(x, R_m, t) - T_{cl}\} \quad (2.7)$$

A constraint is applied to the inner center point of the PCM micro-capsule, so symmetric boundary conditions are used:

$$-\tilde{k} \frac{\partial T_m(x, r, t)}{\partial r} \Big|_{r=0} = 0 \quad (2.8)$$

Initial conditions for PCM micro-capsules:

$$T_m(x, r, 0) = T_{m0} \quad (2.9)$$

Through formula (2.4) to (2.9), we can get temperature value at any position inside the PCM micro-capsule, and the temperature value at any position on the surface of the micro-capsule can be calculated according to the internal temperature.

3. Simulation and validation

The Eqs.(2.4),(2.7-2.9) are solved by the control volume method and Eqs(2.1-2.3) are solved by finite element method. The basic model is validated in Ref. [5]. Here we use the model to simulate the temperature distribution of the garments with or without PCM. The simulation was under two room with different environment of 28°C, 65% RH and 43°C, 80%RH. People who wear garments with or without PCM separately stand into each room initially at 28°C,65%RH. And when the temperature and skin temperature tend to stabilize about 30°C at 5 minutes, the environment of both room suddenly turn to 43°C,80%RH. Then we predicted the temperature distribution changes of the garments and skin by the next 9 minutes. As for the materials of the garments, we use eicosane as PCM and the range of its melting temperature is: $T_a=35^\circ\text{C}$, $T_b=36^\circ\text{C}$, $T_c=38^\circ\text{C}$. The rest physical parameter of eicosane is shown on the table 1. The cotton trousers will be used as garments without PCM and the physical parameter of the cotton fabric can be found in the Ref.[6].

Table 1. Physical parameter of eicosane^[4].

Type of PCM	Coefficient of heat transfer cal/s.cm.°C	Capacity J/kg.k	Latent heat J/kg	Density kg/m ³	Micro model radius μm
Eicosane	3.85×10^{-4}	2210	247×10^3	856	5

The results of the predicted simulation are shown on the following figures. The figure 3.1 display separately the temperature distribution changes of human body and the garments without PCM when being put into 43°C, 80%RH. Figure3.2 separately shows the temperature distribution changes of human body and garments with PCM after being put into 43°C, 80%RH.

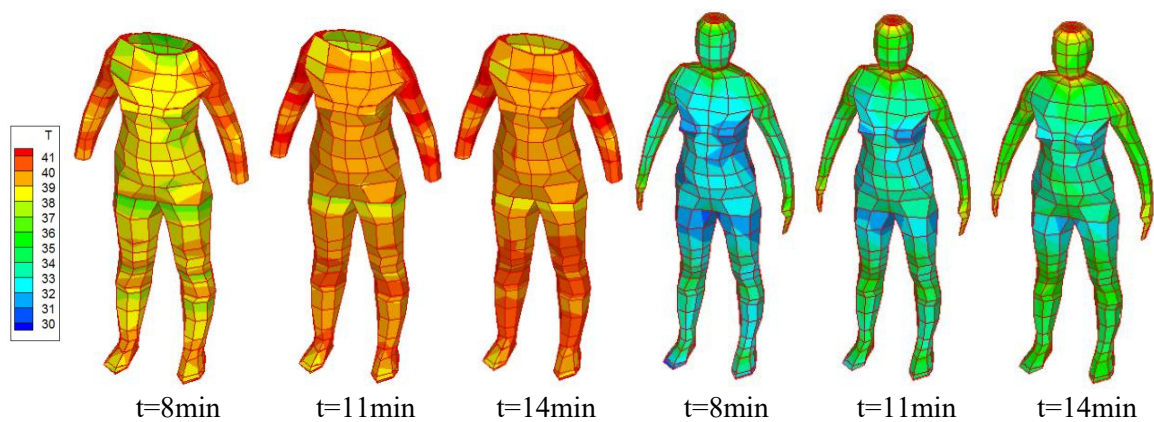


Figure 3.1 Garments without PCM

The figures show us that the temperature of skin and garments all has a growth trend, and the garments without PCM rise to about 41°C at 14 minutes and the temperature of skin rise to about 37°C. But the temperature of garments with PCM reaches about 38°C and 35°C for skin. As for the progress, it is clearly that the temperature of garments and skin under the condition with PCM rise slower than under the condition of non PCM at any time. And the total temperature rise of garments with PCM is not much, however, the temperature of garments without PCM rise obviously especially at the part of arms and legs.

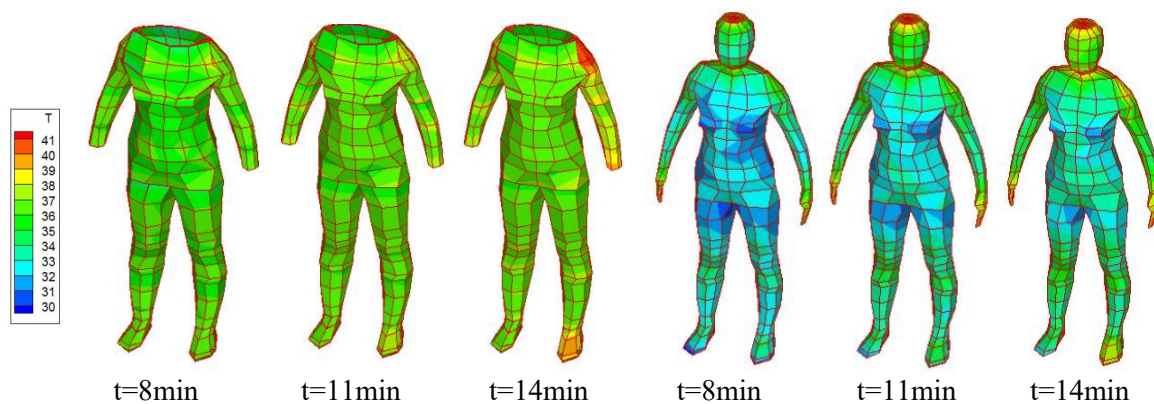


Figure 3.2 Garments with PCM

4. Conclusion

This paper developed a 3D clothed human body model, which considered the influence of PCM. The model can predict the thermal responses of human body who wear different garments. The conclusion shows that the addition of PCM can effectively reduce the increase of garments temperature and the increase of skin temperature. The proposed model is more suitable of the regulation for garments design. The user can flexibly choose the kind of fiber and PCM, the radius of fiber, the layers of fiber, as well as the temperature, moisture of the environment to predict the human body thermal responses with the time and get the information of the temperature and moisture of the garments. This has a significant meaning to be designed as a CAD system of thermal function of the garments.

Acknowledgments

This work was supported by the Key Laboratory of Aircraft Environment Control and Life Support (NUAA) , Ministry of Industry and Information Technology.

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