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A new approach to theoretical modeling of heat transfer through fibrous layers incorporated with microcapsules of phase change materials

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ABSTRACT

In this study, a new approach is proposed to represent a model for heat transfer through a fabric containing microcapsules of phase change materials (micro-PCM). It is observed that the phase change phenomenon occurs within a melting temperature zone where the temperature is not constant. Based on this fact, during phase change process, the heat capacity of fabric which is comprised of constant and temperature dependent elements is changed. A variation function extracted from DSC results is applied to calculate the temperature dependent heat capacity of fabric. The model is applied to study the transient effect of PCM on a simulated skin temperature system once subjected to abrupt changes in environmental conditions from warm to cold. The values of T_{mean} are 0 and 4.6 for sample without PCM and sample containing maximum PCM with nominal melting point of 28 °C, respectively. $|G_T|$ are 32.51 and 139.2 for corresponding samples. The model was further verified by the effect of PCMs existence and PCM type on the temperature response of simulated skin.

1. Introduction

Phase change material is able to absorb, store and release large amounts of energy over a specific temperature range when undergoing phase or state changes. Such characteristics are valid only in the course of the phase change, and remain once the phase change in all of the PCMs is complete [1–3].

A fabric containing PCM can act as a transient thermal barrier by protecting its wearer from the effects of sudden temperature change in entrance in cold or hot environments. When a PCM fabric is heated, it absorbs its latent heat during the phase change from solid to liquid causing the temperature rise of the fabric to be prevented by maintaining it constant at the melting temperature of the PCM. Once the PCM has completely melted, its compensative effect would stop, and the temperature of the fabric would rise. In a similar manner, when a PCM fabric is cooled, the cooling effect of the fabric structure is interrupted by changing phase from liquid to solid. Once all the PCM has crystallized, the fabric temperature would be dropped imposing no effect on the fabric's thermal performance [4].

The magnitude and duration of PCM heating and cooling process which affect the clothing systems, are dependent on several textile and design-related factors. Each of these variables needs to be considered in relation to the type of temperature transient anticipated during the cloth usage (i.e., environmental temperature and/or skin temperature changes). Product variables, which are important determinates, include [5]: the transition temperatures (i.e., melting/freezing points) of the PCMs incorporated into each garment layer, the effect of mixing PCMs with different transition temperatures in one garment layer, the amount and purity of the PCMs in a garment layer (percent add-on), the number of PCM garment layers in a clothing ensemble, the placement order of PCM and non-PCM garment layers from the body surface to the environment, the amount of body surface area covered by garments with PCMs and the temperature gradient between skin and melting/solidification of PCM [5–11].

Usually, the PCMs are enclosed in a protective wrapping, or microcapsule, with a few microns in diameter. The microcapsule prevents leakage of the material during its liquid phase [12]. Microcapsules of phase change materials can be incorporated into the spinning dope of manufactured fibers (e.g., acrylic), and then, incorporated into the structure of foams, and finally, coated onto the fabrics [5].

Shim et al. investigated the effects of PCM on heat and moisture transfer in clothing during sensible temperature transients. They

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Nomenclature

A_{curve}	Area of DSC curve
c_f	Heat capacity of fibers (J/Kg °K)
c_{pcm-D}	Heat capacity of micro-PCM in dynamic state (J/Kg °K)
c_{pcm-S}	Heat capacity of micro-PCM in static state (J/Kg °K)
c_{t-D}	Total capacity of fabric in dynamic state (during phase change process) (J/Kg °K)
c_{t-s}	Total capacity of fabric in static state (without phase change process) (J/Kg °K)
h_{fu}	Heat of fusion of PCM (J/Kg)
K	Conductive heat transfer coefficient of fabric (W/m °K)
T	Local temperature (°K)
T_c	High amplitude point of phase change zone (°K)
T_{min}	Minimum point of phase change zone (°K)
T_{max}	Maximum point of phase change zone (°K)
T_{skin}	Simulated skin temperature (°K)
T_∞	Environmental temperature (°K)
u_∞	Heat transfer coefficient close to environment (W/m^2 °K)
q_{cons}	Heat flux generated from simulated skin
α	Core/shell ratio of micro-PCM
γ	Proportion of fibers in fabric
ρ_f	Density of fibers (Kg/m^3)
ρ_t	Total density of fabric (Kg/m^3)
ρ_{core}	Density of core of micro-PCM (Kg/m^3)
ρ_{pcm}	Density of micro-PCM (Kg/m^3)
ρ_{shell}	Density of shell of micro-PCM (Kg/m^3)
$\phi(T)$	Distributing function of temperature (dimension less)

measured the effect of one and two layers of PCM clothing materials on reducing the heat loss or gain from a thermal manikin as it moved from a warm chamber to a cold chamber and back again. The results indicated that the heating and cooling effects lasted approximately 15 min, and that the heat release by micro-PCM in a cold environment depended on the number of PCM layers, their orientation to the body and the amount of body surface area covered by PCM garments [13].

Li and Zhu presented a mathematical model for heat and moisture transfer in porous textiles containing micro-PCM. On the basis of a finite difference scheme, the thermal buffering effect of PCM was simulated. Upon specification of initial and boundary conditions, the distributions of temperature, moisture concentration and water content in the fibers could be numerically computed for different amounts of PCM in the textiles. They also considered micro-PCM as a sphere consisting of solid and liquid phases during the transient processes of the phase change of a PCM. The total rate of energy loss from the microspheres was derived, and then, the governing differential equations for the temperature in two regions of core and spherical shell around the core of microcapsules were solved. It was observed that the transient period is about 10 min to reach equilibrium [14].

Ghali et al. incorporated PCMs in a numerical three-node fabric ventilation model to study their transient effect on body heat loss during exercise when subjected to sudden changes in environmental conditions from warm indoor air to cold outdoor air. The reported heating effect duration was approximately 12.5 min

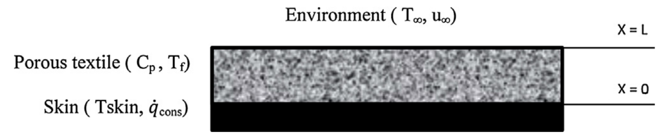

Fig. 1. Skin–fabric–environment system.

depending on the PCM percentage and cold outdoor conditions. Moreover, they reported the reduction of about 40–55 W/m^2 for clothed-body heat loss, for a one-layer suit, depending on the frequency of ventilation and crystallization temperature of the PCM [4].

Ghali et al. also analyzed the effect of micro-PCM on the thermal performance of fabric during periodic ventilation. The obtained results indicated that the presence of micro-PCMs in fabric causes a temporary heating effect once subjected to a sudden change from a warm environment to a cold environment. Such effect is revealed as a decrease in the sensible heat loss during the phase change process as compared to a fabric without micro-PCM. The duration interval of the phase change process decreases with increased frequency of ventilation while duration increases with an increased percentage of PCM in the fabric together with an increased environmental temperature [4,15–16].

In almost all the studies mentioned above, there is a basic problem. They all assumed that PCM is melted at a single temperature point which might not be accurate. As shown in DSC curves of micro-PCM, phase change process always takes place within temperature range of temperature. The experimental reports from Wan and Fan [17] and Safavi et al. [11] also confirm the abovementioned hypothesis, that is, phase change process takes places within a range of temperatures. The results indicate the PCM affects the temperature response as a decrease in temperature change rate. In this process, heat is transferred both as sensible and latent heat state simultaneously. The proportion of sensible and latent heat is variable during the phase change process.

In this study, a new approach is developed to represent a simple model of heat transfer through a fabric containing phase change materials. It is considered that phase change takes place in a range of temperatures (not at a single point), which is extracted from DSC[1]. In the phase change process, specific heat of micro-PCM is a function of temperature. In the outside of phase change range, the specific heat is a constant value calculated from the properties of fabric layer and micro-PCM.

2. Mathematical model

The porous fabric layer incorporated PCM was considered in the current study. Herein, x denotes the coordinate across the porous fabric layer, and $x = 0$ and $x = L$ indicate the positions at the lower and upper surfaces of the layer, respectively. Porous fabrics are assumed to be a nonwoven polyester layer and PCM microcapsules are embedded in these porous textiles. Fig. 1 shows this layer and the skin–fabric–environment system schematically. Table 1 presents the physical properties and conditions of systems used in simulation. For achieving more reliable results from the proposed model, a hypothetical system, close to real situation, was utilized.

[1] Differential scanning calorimetry.