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Evaluation of dynamic thermal behavior of fibrous layers in presence of phase change material microcapsules

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ABSTRACT

In this work, a dynamic system has been developed to evaluate the thermal behavior of fibrous layers containing PCM[1]. The system is able to concurrently resemble the triple condition of 'human body–clothing layers–environment'. The system hotplate, acting as the metabolic heat generator of human body, is able to self-adjust depending on the activity level of body section. An adjustable layering unit has been placed on the hotplate to simulate clothing layers. The environmental condition was rapidly changed from 0 to beyond 60 °C and from 5 to 100% relative humidity in order to prepare a transient condition. On-line data acquisition software has been designed to record and monitor data of the upper hotplate (skin) and spaces between the fibrous layers. Two indices were introduced and extracted to represent the thermal behavior of body skin/layers in the presence of PCMs at different environments. The system was further verified by studying the effect of PCMs presence and their increase on the thermal behavior of body skin/fibrous layers. The effect of PCMs' melting point, during thermal transient, was finally presented by the system.

1. Introduction

Thermal comfort in protective clothing has been a critical problem because protection increases by increasing clothing layers which can act as a barrier against heat and water vapor transfer from the skin to the environment. Accordingly, improvement of comfort in protective clothing has recently been studied. Clothes with built-in thermo-regulating functionality can help the wearer to maintain thermal comfort under varying ambient conditions and physical activity [1,2].

Introducing PCM as thermo-regulating materials and its application into textiles can be thought as a way to solve the challenge regarding comfort and protective clothing, and hence, increase the comfort in clothing [3].

Phase change material is able to absorb, store and release large amounts of energy over a defined temperature range when the material undergoes phase or state changes. These materials absorb energy when heated as phase change takes place; otherwise this energy can be transferred to the environment in the phase change range when cooled. The cooling/warming effect, reached by the PCM, is dependent on temperature and time, which takes place only during the phase change (within the temperature range of the phase change) and terminates when the phase change is complete in all of the PCMs [5–9,11].

When thermal comfort is considered, the investigation of dynamic cooling or warming properties is more important than static ones (insulation). The time dependent properties should be usually considered in thermal comfort or thermo-physiological studies [9–12]. On the other hand, environmental conditions of the wearer, structural properties of the clothing and body conditions (activity level) are very important as well. This issue becomes more significant when PCMs are applied in clothing as thermo-regulating materials. Phase change materials increase the comfort and maintain the body temperature by cooling or warming the human body.

The magnitude and duration of PCM heating and cooling, which affect the clothing systems, are dependent upon several textile and design-related factors. Each of these variables needs to be taken into account with respect to the type of temperature transient which was anticipated during use (i.e., environmental temperature and/or skin temperature changes). Product variables include [1]: 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

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[1] Phase change material.

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Table 1
Properties of microcapsules.

Microcapsule name	Core material	Melting point (°C)	Diameter of microcapsule (μm)	Core/shell ratio (%)
MPCM 28D	*n*-Octadcane	28	17–20	85–90
MPCM 18D	*n*-Hexadecane	18	17–20	85–90

layers from the body surface to the environment, and the amount of body surface area covered by garments with PCMs [1–3,13]. In addition to factors mentioned above, the temperature gradient between skin temperature and melting/solidifying temperature of PCM is also an important parameter [9,12].

In order to evaluate the performance of PCM containing fabrics, some studies have been documented which are now briefly reviewed as follows.

Dynamic heat transfer measurement is a method that simplifies the thermal effect of phase change as a resistance of heat transfer, called dynamic thermal resistance. The total thermal resistance of the PCM fabrics is assumed to be the sum of the basic thermal resistance (thermal resistance of the textile without activating the phase change) and the dynamic thermal resistance [15].

Measurement of the thermal regulating factor (TRF) is a method which was conducted under sinusoidal boundary conditions. The sample is sandwiched between hot and cold plates, and TRF is determined by the hotplate temperature amplitude divided by the flux amplitude and the steady-state thermal resistance of the fabric [16].

With measurement of the thermal transient process, four indices are derived, namely static thermal insulation (Is), phase change duration time (td), the mean heat flux delayed by the phase change (Id) and thermal psycho-sensory intensity (TPI) [17].

Wang et al. developed a method in which the sample was placed onto the simulated skin surface controlled at a constant temperature of 33 °C. After it was balanced in a warm condition, the system was moved into a cold environment. The reduction of heat flux at the skin surface when covered with a PCM fabric was taken as a measure in comparison with the situation in which the skin surface is covered with the non-PCM counterpart [4].

Wan and Fan applied the hotplate system to a simulation of human body. The hotplate, covered by the PCM fabric, is exposed to a thermal transient. From the measured temperature and heat loss at the upper surface of the hotplate, they proposed four parameters for characterizing the thermal regulatory effects of PCM containing fabrics [18].

In this work, an attempt is made to simulate the triple conditions of human body (metabolic heat rate)–clothing layers–environment conditions in a unit system. The layer placement frame has been devised into evaluating the system to simulate the clothing layers. Moreover, by designing and applying a system for simulating the actual body and clothing layers situation under transient conditions, the dynamic thermal evaluation of layers incorporated with PCM has been studied. The environmental condition changes in a short duration have been devised into the system. This system can evaluate thermal behavior of different layers of clothing, activity level of the body, environmental conditions and changes of condition activity. From measurements of simulated skin temperatures, new indices were extracted for evaluation of the layer containing PCM.

2. Experiments

2.1. Preparation of layers

PP nonwoven fabrics with mass of 40 g/m^2 were prepared, and microcapsules containing phase change materials were added to the fabrics through the impregnation method. Two types of micro-PCM, were made in Microtek Company, were applied to the fabrics. The properties of micro-PCMs are listed in Table 1.

The impregnation of the fabric was conducted in different baths containing the binder and the microcapsules at different concentrations (Table 2). This process has been carried out by immersion of the fabric in baths with different formulations, and pressed by a padding device. Then, the drying treatment step was done for 4 min at 100 °C to evaporate the water, and for 4 min at 150 °C to ensure adequate binder crosslinking. Structural and technical properties of samples have been given in details in Tables 2 and 3.

The add-ons for treated fabrics were calculated according to Eq. (1) [14]:

$$\frac{\text{Add}-\text{on}(\%) = (b-a)}{b} \tag{1}$$

where b and a are the weights of specimen after and before treating, respectively.

2.2. Thermal evaluating system

In this work, a dynamic heat evaluating system has been developed to evaluate the thermal behavior of fabric layers. The results were applied for assessing the performance of fabrics containing PCM. Fig. 1 shows the apparatus schematically, which is comprised of four sections as follows:

1. Environmental condition control chamber: it consists of a double stainless steel wall container which has been filled by foam insulation materials. This system controls temperature from 0 to 60 °C and humidity from 5 to 95 percent. Air velocity was controlled at 0.1 m/s. The precision of temperature and humidity in chamber are 0.1 °C and 1%, respectively. The dimensions of the chamber are 1200 mm × 800 mm × 600 mm.
2. Hot plate system – simulated body skin: this part includes a hot plate containing the heating element, and produces heat similar

Table 2
Structural properties of samples.

Sample code	weight of sample (g/m^2)	Add-on (%)	Mass binder to massmicro PCM ratio	Type of PCM
101	93.76	57%	1	Octadcane
102	104.55	62%	1	Octadcane
103	119.82	67%	1	Octadcane
201	93.88	57%	1	Hexadcane
202	106.25	62%	1	Hexadcane
203	120.32	67%	1	Hexadcane

Table 3
Technical properties of samples.

Sample code	Thickness (mm)	Static thermal resistance (°Cm^2 W^{-1})
101	1.13	0.04
102	1.15	0.038
103	1.15	0.039
201	1.13	0.038
202	1.1	0.041
203	1.12	0.037
Without PCM	1.05	0.039