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Article

Development of Microencapsulated Phase Change Material based Comfort Pads for Fighter Aircraft Pilot Helmets

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ABSTRACT

The present study deals with the sustainability of various helmet comfort pads incorporated with microencapsulated phase change material (MPCM) under simulated extreme hot (+45°C) and extreme cold (−30°C) weather conditions. Thermal management is one of the important factors in tropical climates wherein the temperature may go beyond 48°C and has a significant influence on the operations and overall efficiency of the fighter aircraft pilot. Hypothesizing a situation wherein a fighter aircraft pilot may be exposed to very hot or frigid temperature while ejecting out in tropical or temperate zones, respectively, the extent to which the comfort pads that is in contact with the scalp of the pilot helps in addressing many issues related to thermal management is studied. PCM based comfort pads have been found to be effective in bringing down the temperature to the extent of 17–18°C under dynamic weather condition from 0°C to +45°C. However, the pads have very limited effect beyond sub-zero climatic conditions. The thermal storage/release properties and sustainability of the MPCM fabric to multiple heating and cooling cycles were evaluated using differential scanning calorimetry. Based on the results, the comfort pads containing MPCM fabric and combination of MPCM fabric and MPCM foam is observed to exhibit good thermal stability.

Key words: Microencapsulated phase change material, Comfort pads, Thermal management, Differential scanning calorimetry, Environmental simulation.

1. INTRODUCTION

Latent heat storage is one of the most efficient ways of storing thermal energy due to its property of higher storage density with a narrow temperature difference between storing and releasing heat [1]. Phase change materials (PCMs) are latent heat storage materials that change phase from solid to liquid and vice versa by absorbing or emitting heat energy with a slight change in temperature [2]. Thermal storage by latent heat has long been recognized as an alternate to sensible heat storage to enhance the thermal comfort when subjected to extreme hot and cold weather conditions. To prevent their leakage during their liquid phase, PCMs are entrapped in a microcapsule and are called as microencapsulated phase change materials (MPCMs) [3,4]. PCM in a broad sense is considered as smart textiles as they are able to sense, adapt, and react when subjected to temperature stimuli. The potential applications were further explored as PCM can be incorporated during the extrusion of fibers or at the fabric stage (printing, impregnating by coating, or finishing).

Development of technology to incorporate MPCM into textile structures was initiated by NASA in the early 1980s with an intention to use these fabrics in the astronauts' space suits for improved thermal protection against the extreme temperature fluctuations observed in outer space [5,6]. From the original application of astronaut suits to establishing the marketplace of consumer apparel products, development of thermo-regulated textiles using MPCMs has gained tremendous interest worldwide and is also used in various engineering applications that include batteries, steel, and cement industries. Of late, MPCMs have been explored for addressing thermal stress and are increasingly being used in personal protective clothing in defense sector. The performance of defense personal protective clothing (activewear) is increasingly being judged based on the sensorial comfort and tactile properties. MPCMs have attracted the researchers for enhancing the functional performance of the product.

A wide range of organic MPCMs is available for various applications. However, MPCMs that can be explored for next to skin temperature applications are limited. Caution needs to be exercised before selecting any MPCM for personal protective clothing due to poor efficacy of MPCMs when subjected to combined effects of time, microclimate, absolute relative humidity (RH), and textile structure. The *n*-Octadecane is the most suitable MPCM that satisfies the major requirement of thermoregulation for application in textiles because its melting temperature is very close to the comfort temperature of the human body (around 28–29°C) [7,8].

One of the main challenges is to obtain a proper balance between the amount of MPCM that needs to be incorporated into the clothing and thermal comfort achieved. DEBEL in pursuit of developing the state-of-the-art personal protective clothing for the hot weather and extreme cold weather conditions has developed an array of clothing that is

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presently explored for use in combat paratrooper protective clothing, heated gloves, and fighter aircraft helmets for pilots. This article presents the incorporation of MPCM on the fabric and foam pads that are used on the inner side of fighter aircraft helmet shells.

2. EXPERIMENTAL

2.1. Materials

In the present study, two different types of fabric (100% polyamide knitted fabric and MPCM coated fabric) and two varieties of foams (100% polyurethane foam and MPCM foam) are used to design the comfort pads for use in fighter aircraft pilot helmets. The knitted fabric (180 g/m^2) is used as an outer layer in all the comfort pads. The 410 g/m^2 MPCM fabric is designed by coating 200 g/m^2 of MPCM onto the knitted fabric with the help of 30 g/m2 adhesive. Here the total dry add-on of MPCM is 65% wherein 130 g/m^2 of *n*-Octadecane is encapsulated in 70 g/m2 acrylate. The foam used is RG29 which is 100% polyurethane foam. The MPCM foam is a three layer ensemble weighing 315 ± 5 g/m^2 with a thickness of 2.5 ± 0.3 mm wherein the first layer is 100% polyamide knitted fabric, second layer is 100% polyurethane foam (RG29), and the third layer is MPCM. The comfort pads used in the present study are fabricated by M/s. Natroyal Industries Pvt. Ltd., India, against design requirements of DEBEL. The active component *n*-Octadecane with microencapsulation was sourced from M/s. Outlast Technologies LLC, U.S.A.

2.2. Preparation of Comfort Pads

Four different Comfort pads were prepared by stitching the material layers as mentioned in Table 1 to fit into the inner side of a helmet with dimensional Length of 230 mm across the forehead region and 300 mm from forehead to the back portion of the head. The Velcros (4 Nos. each having a diameter of 50 mm) are attached to the outer layer of the comfort pad that helps in fixing it to the inner portion of the helmet shell attached with the expanded polystyrene liner. For comparison, a control pad (Sample A) is also studied which contains only knitted fabric and foam.

2.3. Methods

The thermal storage/release properties of the MPCM fabric were determined by differential scanning calorimetry (DSC; Mettler Toledo DSC-1 STAR^e System). The melting temperature (T_m) and heat of fusion (ΔH_f) on heating and crystallization temperature (Tc) and heat of crystallization (ΔH_c) on cooling were measured for 50 heating and cooling cycles in a temperature range of 10–40°C using a heating rate of 10°C/min.

All the four comfort pads were subjected to extreme weather conditions in an environmental simulation chamber. The pads were introduced into the chamber (maintained at 0°C) from room temperature and dynamically subjected to temperatures +25°C, +35°C and +45°C at 65% RH as well as at sub-zero temperatures −5°C, −10°C, and −30°C to study the functional performance in both hot and cold conditions. On reaching the set environmental temperatures, the temperature in the comfort pads were recorded at the instant of time when the chamber reaches the set temperature (Table 2) as well as the time taken by the pads to reach the set temperature when they were isothermally maintained at that set temperature (Table 3). For recording the temperature in the pads, the temperature probe was placed at the inner layer of the pads. The comfort pads were subjected to 65% RH in accordance with the standard atmospheric condition for testing of textile materials [9].

3. RESULTS AND DISCUSSION

The DSC measurements were carried out on the PCM (*n*-Octadecane), MPCM, and MPCM coated fabric and the values of Tm and ΔH_f on heating and the T_c and ΔH_c values on cooling are given in Table 4, and the respective thermograms are shown in Figures 1-3.

The pure *n*-Octadecane (PCM) shows a sharp endotherm with Tm at around 29°C with a ΔH_f value of 196.3 J/g. On cooling a sharp exotherm with Tc at around 25°C with a ΔHc value of 196.8 J/g is observed. Thus, it can be inferred that the complete heat that is utilized by the material for melting has been released when it is crystallized on cooling (Figure 1) indicating the effectiveness of PCMs when they undergo a transition from solid to liquid and liquid to solid. The nature of endo-exo curve is also observed to be similar except for a pointed configuration observed in endothermic transition.

PCMs are encapsulated in a core-sheath configuration using a compatible resin generally made out of urea formaldehyde/melamine formaldehyde/acrylic. The melting endotherm in MPCM becomes slightly broad but melts at the same temperature (29°C). However, the crystallization occurs at two steps; the major crystallization starts at around 23°C having its Tc value around 18°C while the second step commences immediately after the first one having its Tc at around 13°C. Such a delayed two-step crystallization is attributed to the presence of acrylic microencapsulation around *n*-Octadecane moieties (Figure 2).

For the MPCM coated fabric, the melting endotherm is also observed to be a two-step transition, where along with the main endotherm at around 28°C, another weak endotherm appears at around 34°C. On cooling, the sample starts to crystallize very early as the weak exotherm starts to appear at around 32°C itself. This infers that the fabric acts as nucleating sites for the crystallization process. The major crystallization starts at around 25°C having its peak value at around 21°C, and the third step of crystallization is slightly broad and completes at around 11°C with its peak value at around 15°C. Thus, the presence of acrylic capsule delays the crystallization of *n*-Octadecane while on coating it on fabric, slightly makes the crystallization process fast.

The DSC thermograms of MPCM fabric subjected to repeated heating and cooling cycles (50 cycles) is represented in Figure 4. It is evident from the figure that on each heating and cooling cycle, the resultant thermogram overlaps with the previous cycle which reveals that the associated latent heat storage in *n*-Octadecane remains almost the same. This reveal that even after incorporation into the comfort pads and on exposure to repeated hot and cold environments, the efficacy of MPCM would remain essentially same within the comfort pad.

The graphs of each comfort pad subjected to a simulated environmental temperature from 0°C to +45°C and isothermal environmental

Table 1: Layers of materials used in comfort pads.

Layer position	Sample A	Sample B	Sample C	Sample D
Outer layer	Knitted fabric	Knitted fabric	Knitted fabric	Knitted fabric
Middle layer	PU foam	MPCM PU foam	PU foam	MPCM PU foam
Inner layer	-	Knitted Fabric	MPCM coated fabric	MPCM coated fabric

Table 2: Temperature recorded when comfort pads were subjected to selected simulated environmental temperatures.

Temperature of chamber (°C)	Temperature in the comfort pad (°C)			
	Sample A	Sample B	Sample C	Sample D
Hot				
+25	19.2	16.7	15.5	17.8
+35	32.8	24.7	24	23.8
+45	40.6	35.6	26.2	27.9
Cold				
−5	4	15	21.6	22.8
−10	-4.8	2	13.7	6.4
−30	-28.4	−25.7	−23.9	−24

Table 3: Time taken by comfort pads to reach equilibrium chamber temperature from first recorded temperature.

Iso-thermal condition of chamber (°C)	Time recorded (min)			
	Sample A	Sample B	Sample C	Sample D
+25	6	17	50	18
+35	6	33	24	27
+45	9	17	29	27
−5	4	9	15	18
−10	7	5	13	10
−30	1	6	6	5

Table 4: DSC results of PCM, MPCM, and MPCM fabric.

Material	T_m (°C)	T_c (°C)	ΔH_f (J/g)	ΔH_c (J/g)
n-Octadecane (PCM)	29	25.1	196.3	196.8
MPCM	29	13.0, 18.5	153.3	153
MPCM fabric	27.9	15.9, 21.4	90.7	90.4

PCM: Phase change materials, MPCMs: Microencapsulated phase change materials, DSC: Differential scanning calorimetry

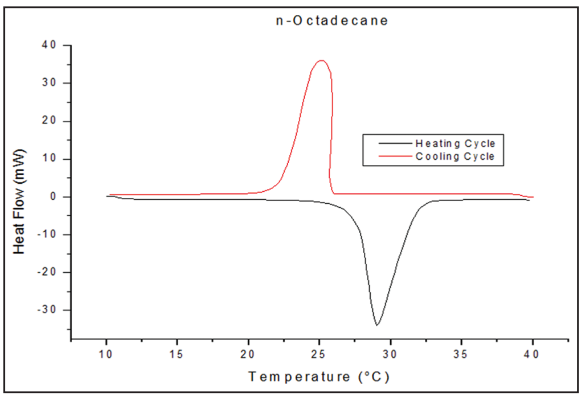

Figure 1: Differential scanning calorimetry thermogram of *n*-Octadecane (phase change materials).

simulation at +45°C at 65% RH is shown in Figure 5. It can be seen that on abrupt exposure to 0°C from room temperature, there is a slight dip in temperature of the comfort pads and then gradually raises and stabilizes at the set temperature at approximately 20 mins. From the graph, it can be observed that Sample C and Sample D can maintain a cooler temperature for a slightly long duration than the other two pads due to the presence of MPCM at the inner layer. These two samples also maintain relatively cooler temperature for the experiments conducted at the simulated temperature of +25°C and +35°C (Tables 2 and 3).

The results of comfort pad subjected to simulated environmental temperature from 0°C to −30°C and isothermal environmental simulation at −30°C is shown in Figure 6. It can be seen that on abrupt exposure to 0°C from room temperature, the comfort pads exhibit a drastic dip in temperature in 5 mins and reaches 0°C. This could be due to the Tm of MPCM being at a relatively higher temperature (29°C). Similar experiments were carried out at −5°C and −10°C. It could be observed that Sample C and Sample D provides comfortable temperature only for 15–18 min when exposed to −5°C. This is again due to the presence of MPCM in the inner layer of the pad. Thus, it can be inferred that MPCM can be effectively used to a sub-zero temperature of −5°C for a short duration and not beyond −5°C.

The results prove that Sample A (without any MPCM) has shown little or no effect as the temperature of the comfort pad was increased or decreased (Table 2). Although there is MPCM coated foam in Sample B, since it is in the middle layer and has a knitted fabric layer before the thermal probe, the comfort pad has been less effective in helping to regulate the temperature. Both Samples C and D provide considerable comfort in extreme hot conditions (+45°C) and to some extent at temperature slightly below zero (−5°C). This is attributed to

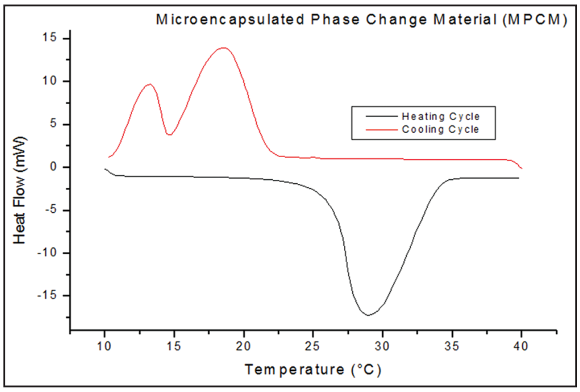

Figure 2: Differential scanning calorimetry thermogram of microencapsulated phase change materials.

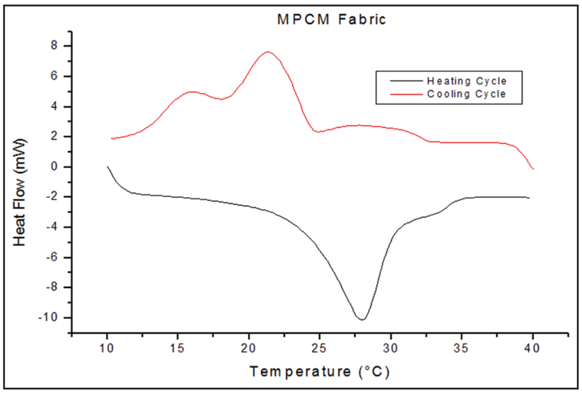

Figure 3: Differential scanning calorimetry thermogram of microencapsulated phase change materials coated fabric.

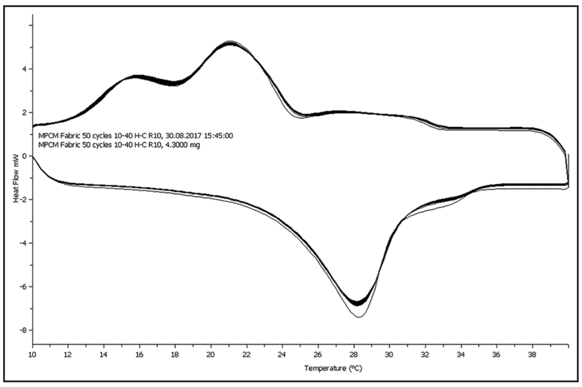

Figure 4: Differential scanning calorimetry plot of microencapsulated phase change materials fabric subjected to 50 heating and cooling cycles.

the presence of MPCM coated fabric at the inner layer which is in close proximity to the thermal probe.

In the actual scenario, the pilots of fighter aircrafts may eject out both in extremely hot climatic regions such as Sri Ganganagar, Rajasthan, or cold regions like Siachen. From the present study, we propose that use of MPCM incorporated comfort pads in the helmet would provide comfortability of around 30 min in extreme hot conditions and approximately 15–18 mins in cold environments.

4. CONCLUSIONS

The present work attempts to study the effect of MPCM incorporated helmet comfort pads on maintaining the comfortability at the inner

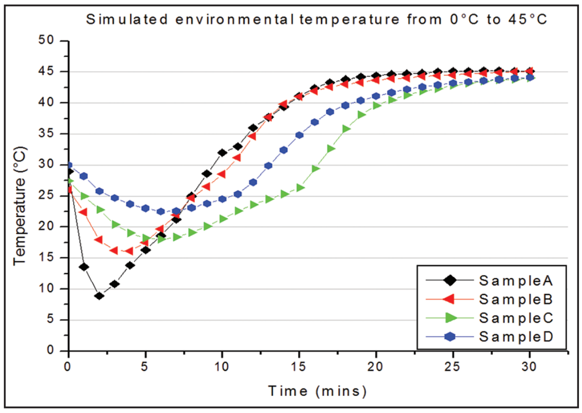

Figure 5: Temperature of the comfort pads when subjected to simulated environmental temperature from 0°C to +45°C at 65% relative humidity.

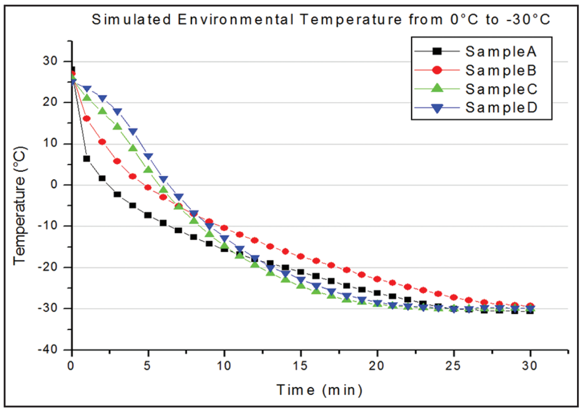

Figure 6: Temperature of the comfort pads when subjected to simulated environmental temperature from 0°C to −30°C

portion of the helmet shell of a fighter aircraft pilot. The DSC results indicate that the efficacy of heat storage and release in the MPCM fabric is unaffected by 50 continuous heating and cooling cycles. The environmental simulation temperature tests reveal that when the MPCM coated fabric is in close proximity to the scalp, it can be effective in providing comfortable temperature to the wearer from extreme heat by about 17–18°C for a duration of 30 min. The protection offered by MPCM incorporated comfort pads was endurable to the frigid temperature for about 15 min only.

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***Bibliographical Sketch**

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