Design of the cooling system based on organic PCMs for thermal comfort of an EOD suit

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An EOD suit is designed to shield personnel from the effects of explosions, such as those caused by improvised explosive devices. Beside ballistic protection, it must ensure thermal comfort of the operator. Here we demonstrate the efficiency of a subvestimentar cooling system based on 1-teradecanol as phase change material macro-encapsulated in aluminized polypropylene. DSC studies prove the thermal stability of the system during 10 heating/cooling cycles, maintaining the temperature in the range 23.83 °C – 45.77 °C with a mean enthalpy of transformation 224.78 - 229.27 J/g and mean thermal conductivity measured with the planar hot disk method 0.30165 W/mK.

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1. Introduction

An EOD suit is a specialized piece of protective gear designed to shield personnel from the effects of explosions, such as those caused by improvised explosive devices. These suits are crucial for bomb technicians and other personnel involved in explosive ordnance disposal, providing protection against blast overpressure, fragmentation impact heat, and flames. These suits impose excess heat and cardiovascular strain and practical methods for planning safe working during extremely hazardous and unique activities are required [1].

The EOD protective suit must ensure the thermal comfort of the operator for a minimum of 30 min. The actual methods for the commercial subvestimentar cooling system include: i) air, preferably from 2 adductions from two battery-powered electric ventilators; ii) water and ice, the cooling water being powered from a vessel by means of a battery-operated pump; iii) thermostatic water powered with similar system as for water and ice. The main disadvantage of these methods is the reduced manoeuvrability of the suit, making difficult for the operator to move independently. The use of phase change materials (PCMs) to store the heat accumulated in the EOD suit during operation may highly improve the comfort of the operator and reduce the weight of the suit.

Phase change materials (PCMs) are functional substances enabling storage and release significant latent heat during phase transitions via reversible melting and cooling processes in the thermal management of different systems [2-4].

PCMs capture and store substantial thermal energy during phase transitions, providing a stable temperature environment. Various compounds may be used as PCMs for different applications based on their specific physical and chemical properties [5]. PCMs are generally classified into three main categories: inorganic, organic, and eutectic PCMs [6].

Organic PCMs are composed of hydrocarbons and comprise paraffin, fatty acids, polyethylene glycol, fatty alcohols, and fatty esters [7, 8]. The phase transition temperature depends on the hydrocarbon chain length.

Inorganic PCMs include salt hydrates and metals, possessing high latent heat, superior thermal conductivity, and low volume change during phase transitions [9, 10].

Eutectic PCMs combine organic, inorganic, or both in certain ratios, leading to organic-organic, inorganic-inorganic, and mixed organic-inorganic eutectics. The advantage of this approach is the ability to obtain PCMs with pre-design transition temperature and latent heat [11-13].

Encapsulation of organic, inorganic, and eutectic PCMs, including macro-encapsulation, micro-encapsulation and nano-encapsulation may enhance their functional properties, durability, and environmental impact by reducing the degradation and leakage [14-16].

In this paper we investigate the transformation temperature and phase transformation enthalpy of four different organic PCMs to design a reliable subvestimentar cooling system for EOD suite. Following the studies performed 1-tetradecanol was selected as optimal PCM for the proposed application and its thermal behaviour after macro-encapsulation in aluminized polypropylene envelopes was studied by DSC and thermal conductivity, demonstrating the viability of the cooling concept.

2. Experimental part

The following commercial organic PCMs have been used in experiments:

- 1-tetradecanol, purity 99%, density 0.82 gcm^{-3}, melting temperature 33.9^{o}C
- 1-dodecanol, purity 97%, density 0.82 gcm^{-3}, melting temperature 37.7^{o}C
- Paraffin C20 (n-Eicosane C20), purity 93%, density 0.7886 gcm^{-3}, melting temperature 47.8^{o}C
- C18 (Normal Octadecane), purity 99%, density 0.777 gcm^{-3}, melting temperature 41.9^{o}C

The main criteria for their selection were a transformation temperature as close as possible to the human body normal temperature (36-37^{o}C) to avoid thermal stress of the operator during using the EOD suit and a low density to reduce the weight of the EOD suit.

The thermal behaviour of each organic PCM was studied using a DSC F3 Maia from Netzch, Germany, working in the temperature range -40^{o}C to 600^{o}C in Ar using alumina crucibles. For each set of experiments the baseline was established. The results were registered and processed using the software Proteus Analysis.

For macro-encapsulation process the PCM was melted and poured in a polymeric alveolar material (SPATIATO SF0606B, China). After solidification, the resulting pellets are placed in aluminized polypropylene envelopes. The sachets are closed by heat sealing after removing the air from the packages. The DSC curves of macro-encapsulated PCM was measures on 30 mg samples collected using the same procedure described for organic PCMs.

The determination of thermal conductivity, thermal diffusivity and specific volumetric heat were performed by the transient plane source method using a TPS-2200 system from Hot Disk, Sweden, model 5082. In the laboratory determinations, a cylindrical sample with a diameter of 20 mm was cut, using a mica temperature sensor for measuring the temperature of the sample.

3. Results and discussions

The DSC curves for the 4 selected PCMs were registered for 5 heating / cooling cycles and are presented in Figs. 1-4.

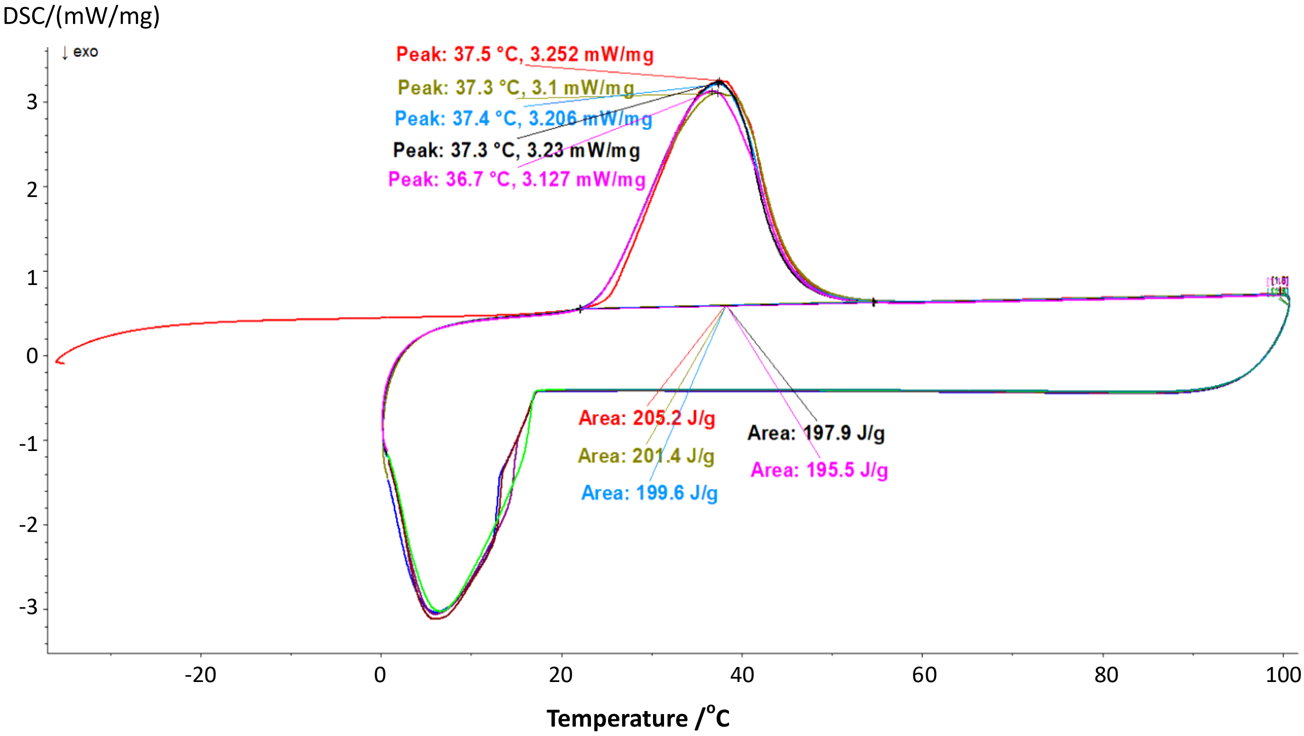

Fig. 1. DSC spectra for 5 heating and cooling cycles of 1-tetradecanol (colour online)

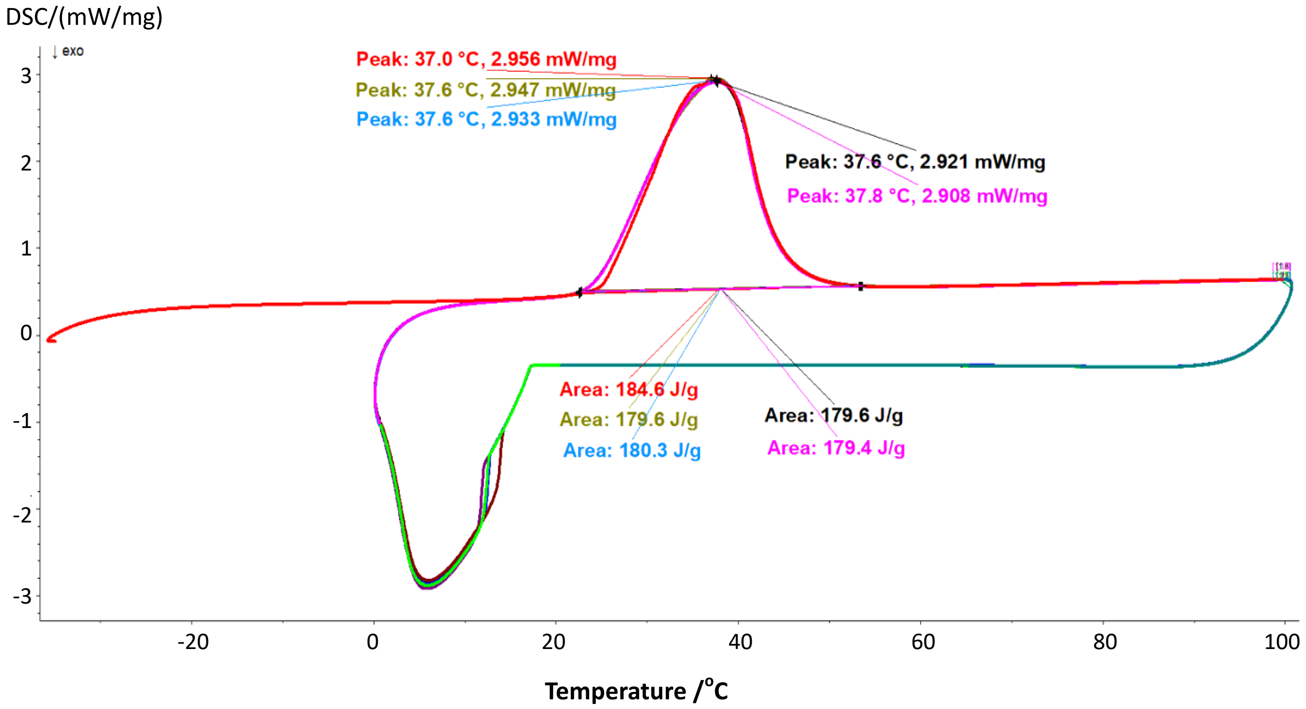

Fig. 2. DSC spectra for 5 heating and cooling cycles of 1-dodecanol (colour online)

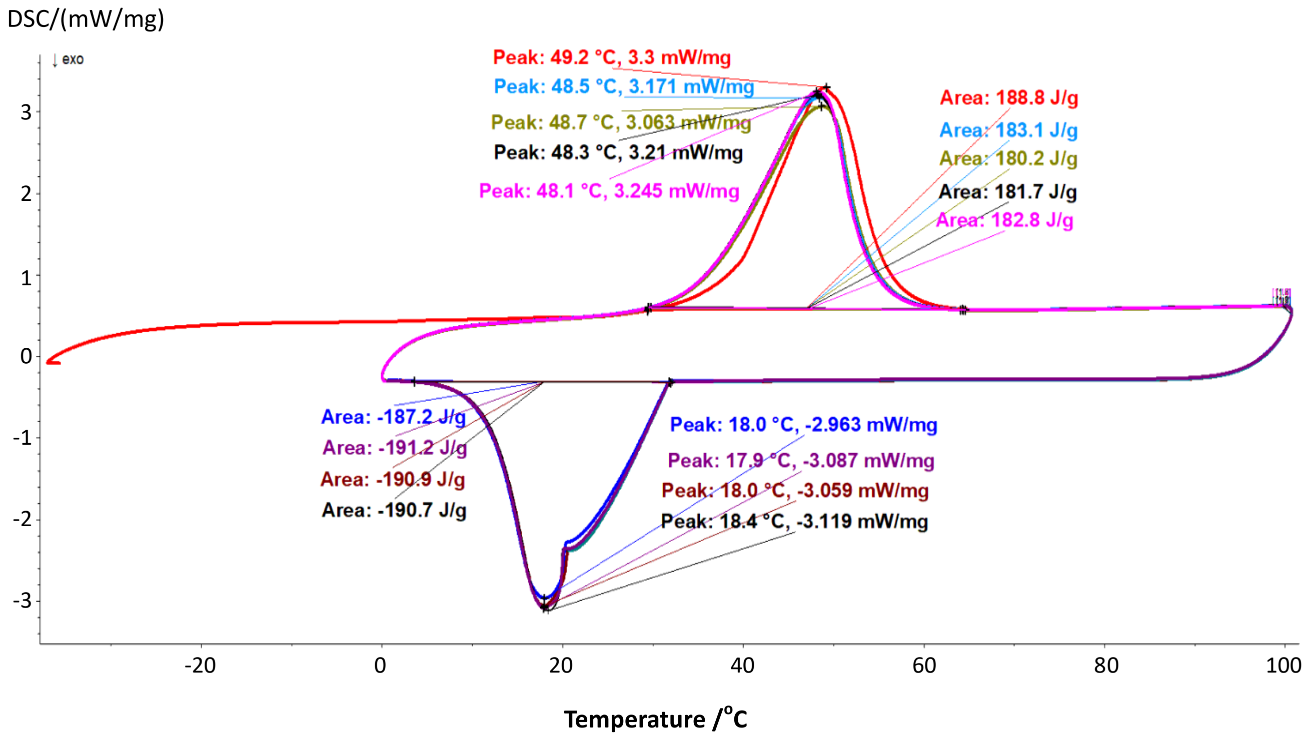

Fig. 3. DSC spectra for 5 heating and cooling cycles of n-Eicosane (colour online)

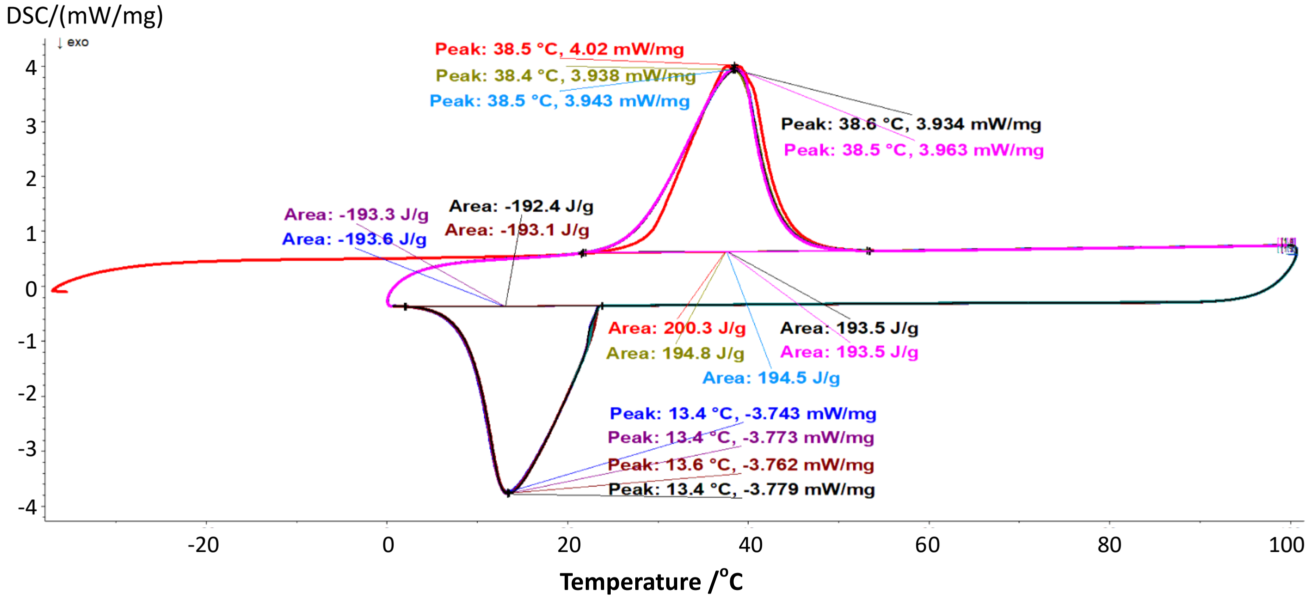

Fig. 4. DSC spectra for 5 heating and cooling cycles of C18 n-octadecane (colour online)

The results on melting temperatures T_m and enthalpies of melting (ΔH_m) are summarized in Table 1.

Table 1. Thermal behaviour of the 4 selected organic PCMs

Compound/ No. of cycles	***T_m ^0C***	***ΔH_m Jg^{-1}***	***Compound/ No. of cycles***	***T_m ^0C***	***ΔH_m Jg^{-1}***
1-tetradecanol			**n-Eicosane C20**		
Cycle 1	*37.5*	*197.9*	*Cycle 1*	49.2	188.8
2	*37.3*	*205.2*	*2*	48.5	183.1
3	*37.4*	*201.4*	*3*	48.7	180.2
4	*37.3*	*196.6*	*4*	48.3	181.7
5	*36.7*	*195.5*	*5*	48.1	182.8
Mean values	*37.24*	*199.32*	*Mean values*	48.56	183.32
Standard deviation	*0.28*	*3.55*	*Standard deviation*	0.38	2.92
1-dodecanol			**C18 n-octadecane**		
Cycle 1	*37.0*	*179.6*	*Cycle 1*	38.5	193.5
2	*37.6*	*184.6*	*2*	38.4	200.3
3	*37.6*	*179.6*	*3*	38.5	194.8
4	*37.6*	*180.3*	*4*	38.6	194.5
5	*37.8*	*179.4*	*5*	38.5	193.5
Mean values	*37.52*	*180.7*	*Mean values*	38.5	195.32
Standard deviation	*0.27*	*1.97*	*Standard deviation*	0.06	2.54

The mean melting temperatures increase in the order T_m (1-tetradecanol) ~ T_m (1-dodecanol) < T_m (C18 n-octadecane) < T_m (n-Eicosane C20). The mean enthalpies of melting increase in the order ΔH_m (tetradecanol) > ΔH_m (n-octadecane) > ΔH_m (n-Eicosane C20) > ΔH_m (1-dodecanol). Corroborating the results obtained, the organic PCM material selected for macro-encapsulation tests is 1-tetradecanol possessing a melting temperature close to the normal human body temperature and the highest transformation energy.

Thermal behaviour of the 1-tetradecanol pellets macro-encapsulated in aluminized polypropylene envelopes was studied by performing 10 heating and cooling cycles. DSC curves obtained are presented in Fig. 5 and Table 2.

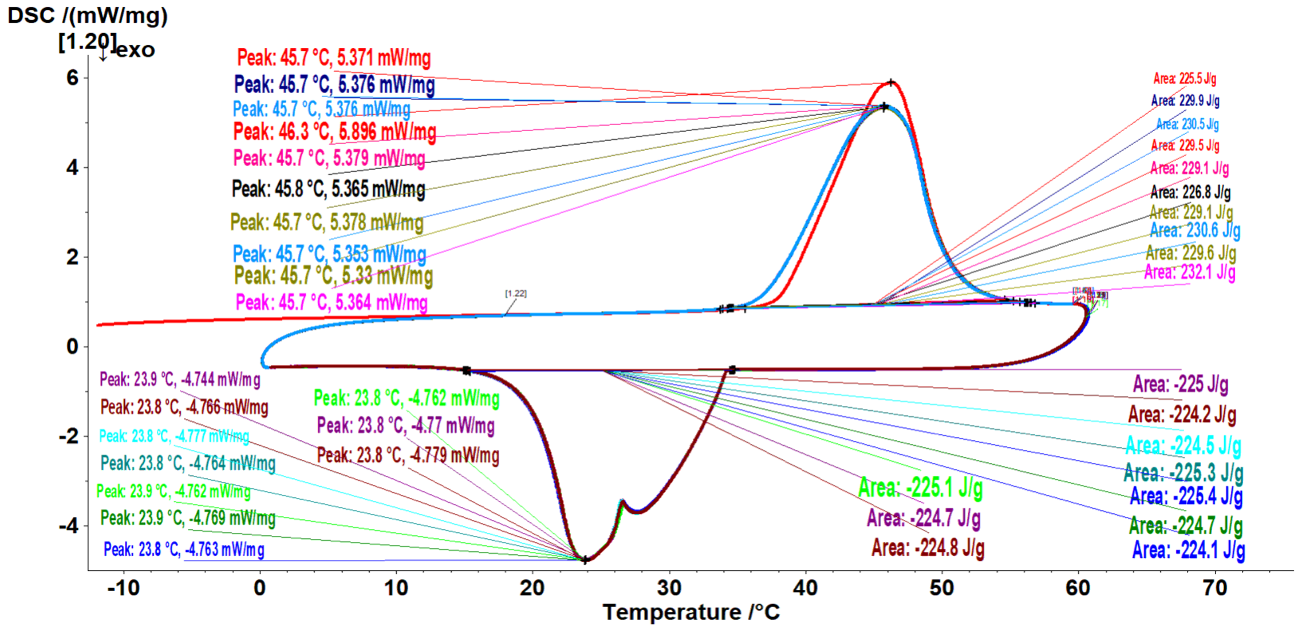

Fig. 5. DSC spectra for 10 heating and cooling cycles of 1-teradecanol macro-encapsulated in aluminized polypropylene (colour online)

Table 2. Evolution of the melting and solidification peak of 1-tetradecanol macro-encapsulated in aluminized polypropylene with the number of heating and cooling cycles

Heating			***Cooling***		
No. of cycle	***T, °C***	***ΔH, Jg^{-1}***	***No. of cycle***	***T, °C***	***ΔH, Jg^{-1}***
1	*46,3*	*229,5*	*1*	*23,8*	*-224,1*
2	*45,7*	*229,6*	*2*	*23,9*	*-225,0*
3	*45,7*	*230,6*	*3*	*23,8*	*-224,2*
4	*45,8*	*226,8*	*4*	*23,8*	*-225,1*
5	*45,7*	*232,1*	*5*	*23,8*	*-225,3*
6	*45,7*	*229,9*	*6*	*23,8*	*-224,5*
7	*45,7*	*229,1*	*7*	*23,9*	*-224,7*
8	*45,7*	*225,5*	*8*	*23,9*	*-225,4*
9	*45,7*	*229,1*	*9*	*23,8*	*-224,7*
10	*45,7*	*230,5*	*10*	*23,8*	*-224,8*
Mean value	***45,77***	***229,27***		***23,83***	***-224,78***

Using the transient plane source hot disk method the following thermal properties were measured on macro-encapsulated 1-tetradecanol disks:

- Thermal conductivity $\lambda = \frac{Q*d}{A*\Delta T}$ (1)

where Q is the thermal flux proportional with the electric power source, d is the sample thickness, A is the area of the hot plate surface and ΔT is the temperature difference between sample faces.

- Specific heat, c=Q/mT, where m is the sample mass
- Thermal diffusivity, $a = \lambda / (\rho \cdot c)$ (2)

where ρ is the sample density

- Thermal effusively, $e = \sqrt{\lambda \rho c}$ (3)

The experimental values obtained are presented in Table 3.

Table 3. Thermal properties of the 1-tetradecanol macro-encapsulated in aluminized polypropylene

No. exp.	***T***	***λ***	***a***	***c***	***e***
	°C	$Wm^{-1}K^{-1}$	mm^2s^{-1}	$MJm^{-3}K^{-1}$	$Ws^{1'2}m\text{-}^2K^{-1}$
1	*29.0*	*0.3109*	*0.1704*	*1.825*	*753.2*
2	*29.0*	*0.2990*	*0.1830*	*1.634*	*699.1*
3	*29.0*	*0.3022*	*0.1651*	*1.830*	*743.7*
4	*29.0*	*0.3020*	*0.1643*	*1.838*	*745.1*
5	*29.0*	*0.3016*	*0.1700*	*1.774*	*731.6*
6	*29.0*	*0.3022*	*0.1593*	*1.897*	*757.1*
7	*29.0*	*0.2989*	*0.1614*	*1.852*	*743.9*
8	*29.0*	*0.3013*	*0.1568*	*1.922*	*761.0*
9	*29.0*	*0.3006*	*0.1546*	*1.944*	*764.5*
10	*29.0*	*0.2978*	*0.1573*	*1.894*	*751.0*
Mean	***29.0***	***0.30165***	***0.16422***	***1.841***	***745.02***

Compared to the measured value λ = 0.358 $Wm^{-1}K^{-1}$ of the 1-tetradecanol, the lower value of the macro-encapsulated PCM is attributed to the porosity of the aluminized polyethylene envelope.

4. Conclusions

The 4 types of commercial PCM materials proposed for cooling the EOD suit were analysed by the differential scanning calorimetry method, namely 1-tetradecanol, 1-dodecanol, n-Eicosane and n-octadecane. Based on the analysis of the thermal behaviour using DSC method 1-Tetradecanol or myristicol alcohol, saturated fatty alcohol with linear chain, with the molecular formula $CH_3(CH_2)_{12}CH_2OH$, with molecular weight M = 214.393 $gmol^{-1}$, melting temperature of 38°C close to the temperature of the human body, boiling temperature of 295.8 °C, high latent heat of melting value about 200 $kJkg^{-1}$ and good thermal conductivity (0.358 Wm^{-1} K^{-1} at 25°C).

The experimental works performed demonstrate the efficiency of a subvestimentar cooling system based on 1-teradecanol as phase change material macro-encapsulated in aluminized polypropylene. DSC studies prove the thermal stability of the system during 10 heating/cooling cycles, maintaining the temperature in the range 23.83 °C – 45.77 °C with a mean enthalpy of transformation 224.78 - 229.27 Jg^{-1} and mean thermal conductivity measured with the planar hot disk method 0.30165 $Wm^{-1}K^{-1}$.

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