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Thermal Manikin Evaluation of PCM Cooling Vests

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Abstract

To diminish a worker's thermal discomfort in a moderately hot environment, a new microclimate cooling vest was designed and tested. The cooling vest was intended to be worn under a chemical protective garment. As coolants, encapsulated phase change materials in the form of macrocapsules of 3 mm diameter were used. The cooling effect is based on the latent heat absorption of phase change material; a highly-productive means of thermal storage. Two kinds of macrocapsules were selected: containing hexadecane (melting point 18 °C) and containing octadecane (melting point 28 °C). MacroPCMs were inserted into small knitted sacks, which were then adhered to the inner surface of the vest i.e. near the skin. Air gaps between the macroPCM particles facilitate both heat and moisture transport through the vest. The total weight of the cooling vest was 2.64 kg, the vest area comprising about 20% of the total body surface area. A stationary thermal manikin consisting of 16 electrically independent heating segments was used to evaluate the cooling effectiveness performance of the vests. Experiments were carried out in a climatic chamber where the air temperature was 20 °C, the relative humidity 50% RH, and the air velocity 0.4 m/s. The results of the experiments demonstrated that the vest containing a mixture of macrocapsules with hexadecane and macrocapsules with octadecane had the best cooling characteristic.

Key words: cooling vest, cooling effectiveness, thermal manikin, phase change material, thermal comfort.

protective garments leads to reduced productivity and the likelihood of accidents [1, 2]. Therefore microclimate cooling systems have been developed to reduce the risk of heat stress and heat related injuries and illness [3].

The use of cooling vests that reduce the temperature of the torso is recognised as the most practical for persons wearing protective clothing. Reductions in the core temperature by 0.4 – 1.7 °C have been reported, with the torso cooling in a variety of occupations, including fire-fighters [4, 6, 11] and personnel wearing nuclear, biological and chemical (NBC) protective apparel [7, 8] or equivalent clothing ensembles [9, 10].

Cooling vests fall into two categories: liquid- or air-cooled vests and phase change material (PCM) vests. Liquid- or air-cooled vests provide efficient cooling, but the worker is restricted in movement due to auxiliary equipment required to circulate the fluid [11]. PCM vests consist of a torso garment containing pockets surrounding the chest cavity that holds the PCM packs. Body heat carried to the surface of the skin by the circulatory system is absorbed by the PCM packs. A garment loaded with packs is completely unattached to any external devices, making it much more portable than liquid- or air-cooled garments.

Phase change materials (PCMs) can absorb, store and release large amounts of energy in the form of latent heat, over a

narrowly defined temperature range, during phase transitions between two solid states and/or liquid and solid states [12]. They can be classified into two major categories: inorganic compounds and organic compounds. Inorganic PCMs include salt hydrates, salts, metals and their alloys, whereas organic PCMs are linear chain hydrocarbons known as paraffin waxes (or *n*-alkanes), polyethylene glycols (PEGs) and fatty acids. In general, the higher the PCMs' latent heat of phase change is, the more thermal energy a material can store [12, 13]. The phase transition process is completely reversible.

PCM incorporated into garments absorbs excessive heat generated by the body while performing strenuous activities [14]. The most known PCM is water, which at 0 °C becomes ice with a latent heat storage capacity of 335 J/g. Cooling vests containing ice packs have been commercially available for 40 years, and their thermal comfort and effectiveness have been evaluated by several authors [3, 4, 10, 12, and 14]. Konz [3] pointed out the advantage of an ice-cooling vest as follows: It has a high latent heat of melting; it changes phase at a temperature well below skin temperature; it is readily available and inexpensive; it is not harmful and does not irritate the skin, and the incorporation of ice packs into a garment is easy. The drawbacks of ice vests are as follows: The bulkiness of the ice packs reduce the wearer's mobility; extended cold exposure to the skin can cause harm to skin tissue and the devel-

■ Introduction

Nonwoven protective garments are used in a variety of application such as cleaning chemical facilities and contaminated soil areas, transportation of hazardous chemical goods, pest control, and asbestos abatement. The structure of the nonwoven materials used in such garments provides a high barrier function against penetration by dust, liquids or gases. However, it also limits the outward passage of body heat and moisture. As a result, during strenuous activity and in moderate to hot climatic conditions, the core temperature of the wearer's body may rise above the comfort level into the heat stress zone. These heat stress conditions lead to discomfort and fatigue and, in severe cases, risk the health and safety of the garment wearer. In addition, constant discomfort while wearing such

Table 1. Phase transition characteristics of PCMs in macrocapsules (according to [15]); a – liquid; b – solid.

Symbol	n-alkanes	Formula	Density at 20 °C kg/m ³	Heating from 0 to 50 °C at a speed of 10 °C/min			
				Onset T, °C	Peak T, °C	End T, °C	Enthalpy, ΔH, J/g
C16	n-hexadecane	C ₁₆ H ₃₄	770 ^a	10.0	18.2	22.0	236
C18	n-octadecane	C ₁₈ H ₃₈	779 ^b	24.0	28.1	34.0	244

Table 2. Characteristics of vest clothing materials.

	Description	Area weight, g/m ²	Thickness, mm	Air permeability (20 Pa), mm/s	Thermal resistance R _t , m ² K/W
Outer shell	100% cotton woven fabric	218.0	0.57	14.4	0.013
Liner	100% PA knitted fabric	80.4	0.33	1266.1	0.003

Table 3. Characteristics of coverall material.

Description	Area weight, g/m ²	Thickness, mm	Water vapour resistance R _e , m ² Pa/W	Thermal resistance R _t , m ² K/W
100% polyolefin spunbonded nonwoven	41.0	0.77	14.4	0.008

opment of flu-like symptoms; the regeneration of ice packs requires a freezer.

Recently, considerable research effort has been devoted to the development and evaluation of torso cooling garments utilising alternative PCMs, organic or inorganic, as a coolant. In the case of cooling vests, the most frequently used PCMs are linear chain hydrocarbons, known as paraffin waxes, composed of *n*-alkanes, CH₃-(CH₂)_{*n*}-CH₃. The melting points of *n*-alkanes depend on the length of the carbon atom chains, i.e. on the number of carbon atoms in the molecule. Long chain hydrocarbons with 13 – 28 carbon atoms have phase change temperatures ranging from –5 to 65 °C [15]. By selecting two or more different alkanes and forming a mixture thereof, a temperature stabilising range can be widened for any desired application [15]. Compared to other PCMs, paraffin waxes have high energy storage densities (200 – 220 J/g), high boiling points and stability - up to 250 °C. They are chemically stable, showing no phase segregation with minimum sub-cooling during repetitive phase transitions, non-toxic, not corrosive, odourless, ecologically harmless and easily available.

Because of its higher phase change temperature compared with water (i.e., 18.3 °C vs. 0 °C), less refrigeration power is required to solidify the PCMs, and there is less subject discomfort due to contact with a cold surface close to the skin.

Due to the relative newness of these garments, few published studies exist on

their effectiveness [16 - 20]. A number of the vests studied were designed for specific applications (typically military operations) and therefore are not available to the general public. Cooling vests with PCM packets have some drawbacks: Moisture cannot be transferred away from the skin because it is blocked by the PCM packets; and the stiffness of the PCM packets reduces wearer mobility. To overcome these problems, Colvin and Bryant [20] proposed applying macroencapsulated PCM instead of PCM packets. A cooling vest containing a macroencapsulated PCM provides freedom of movement to the wearer while closely conforming to the body shape of the wearer. The air gaps between macrocapsules facilitate both heat and moisture transport through the vest as well as its thermal recharging.

The aim of this study was to design and prepare a prototype of a PCM cooling vest intended to be worn under chemical protective garments. As coolants, two kinds of macrocapsule with *n*-alkanes were selected: C16 macrocapsules containing *n*-hexadecane and C18 macrocapsules containing *n*-octadecane.

Evaluation of the cooling performance of the vest was performed using a thermal manikin in a climatic chamber. During the experiments performed in the climatic chamber, the cooling vest was inserted under a coverall made of spunbonded polyolefin nonwoven (a Tyvek Classic coverall). A Tyvek Classic coverall is a chemical protective garment which pro-

vides protection against airborne solid particulate chemicals as well as limited protection against liquid aerosol and low concentrations of water-based chemicals. Additionally, a Tyvek Classic coverall gives protection against particulate radioactive contamination and biological contamination. It also prevents human contamination of products and processes in clean-room, pharmaceutical and food industry environments.

Typical applications of Tyvek Classic coveralls can be found in agriculture, food processing, medicine, fiberglass manufacturing, spray painting / finishing operations, lead abatement, asbestos abatement, mould remediation, and other areas involving dry chemicals, dirt and radioactive dust.

This investigation is part of series on PCM cooling vests. In earlier research [21] we described the thermal manikin testing of the cooling effectiveness of PCM vests inserted under firefighter clothing.

Experimental

PCM macrocapsules

To prepare the cooling vests, PCM macrocapsules denoted as C16 and C18 from Microtek Laboratories were used. PCM macrocapsules are large 3-mm spherical beads containing high concentrations of phase change materials. The PCMs are low melting paraffin waxes (alkanes). The macrocapsules contain 80% effective PCM. The density of the macrocapsules is slightly less than 1 g/cm³.

Table 1 shows the characteristics of PCMs contained in selected macrocapsules.

Before incorporation into the cooling vests the PCM macrocapsules were inserted into small knitted sacks prepared from polyester yarn of 110 dtex on an open top machine.

Cooling vests

Cooling vests of lightweight construction were made from a cotton fabric and a polyamide liner, with adjustable straps to provide a close fit. **Table 2** shows characteristics of fabrics used to prepare cooling vests.

The sacks with macroPCMs were inserted into pockets on the inner side of

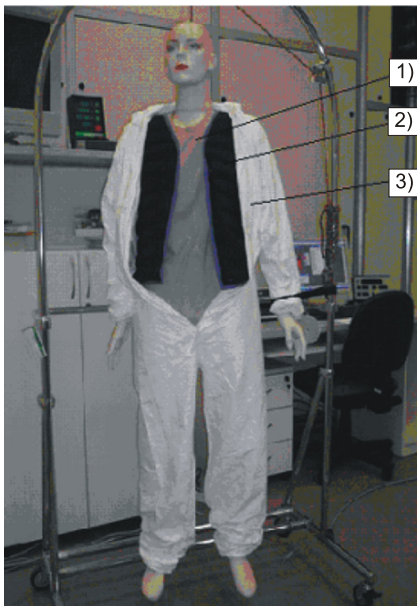


Figure 1. Thermal manikin dressed with all garment layers; 1 - t-shirt, 2 - cooling vest, 3 - protective coverall.

the vest. The pockets were prepared from the liner and arranged horizontally in the vest. The sacks containing macroPCMs were adhered to the inner surface of the vest i.e. near the skin.

The total weight of the cooling vest was 2.64 kg, with a vest area of about 20% of the total body surface area. The total weight of the macrocapsules inserted into the vest equalled 2.3 kg. This amount of macrocapsules provided a latent heat storage capacity of the cooling vest equal to 440 kJ.

Three microclimate cooling vests were tested:

- vest A with 100% C18 macrocapsules ;
- vest B with 100% C16 macrocapsules
- vest C with a 50/50 mixture of C16 and C18 macrocapsules.

Nonwoven protective garment

During the experiments performed in a climatic chamber, a one-piece coverall made of spunbonded polyolefin nonwoven (Tyvek Classic coverall) was used as an outer garment. The thermal insulation of the coverall was equal to 0.126 m²K/W.

Coveral description:

- 3-piece hood.
- Elasticated facial opening,
- External stitched seams,
- Elasticated waist,
- Elasticated cuffs and ankles,
- Zipper with protective flap,
- Additional 3-piece gusset fabric.

The **Table 3** (see page 71) shows characteristics of the coverall material.

Thermal manikin

In this study, experiments were performed using a dry thermal female manikin of the TM 3.2/R110 type named Diana (designed by PT-Teknik, Denmark and manufactured by the Central Institute for Labour Protection, National Research Institute) which simulates dry heat loss from the human body. Diana is made of 16 electrically independent heating seg-

ments which are individually controlled/regulated by a computer. The temperature-sensing elements (nickel wire) are distributed all over the segments. Measurement of the wiring's resistance gives the mean temperature of the actual body segment.

Environmental conditions

Measurements were performed in a Weiss climatic chamber. During the tests, ambient conditions were maintained at a constant level: the air temperature (T_a) remained at 20 ± 0.1 °C, the air velocity at 0.4 m/s and the relative humidity of air at $50 \pm 3\%$. The average manikin surface temperature (T_s) in the above-mentioned conditions was maintained at a level of 34 °C (static mode), hence corresponding to the skin temperature of the human body. Such conditions are in accordance with the requirements of Standard EN ISO 15831 "Clothing: Physiological effects: Measurement of thermal insulation by means of a thermal manikin" [22].

Procedure of cooling vest testing

After dressing the manikin with a cotton t-shirt, shorts and protective coverall, we set the surface temperature of each zone at 34 °C. When a thermal steady state was achieved, the coverall was removed from the manikin. Next, the cooling vest was placed on the t-shirt, and the coverall quickly replaced (**Figure 1**).

The following variables were recorded at 30 second intervals:

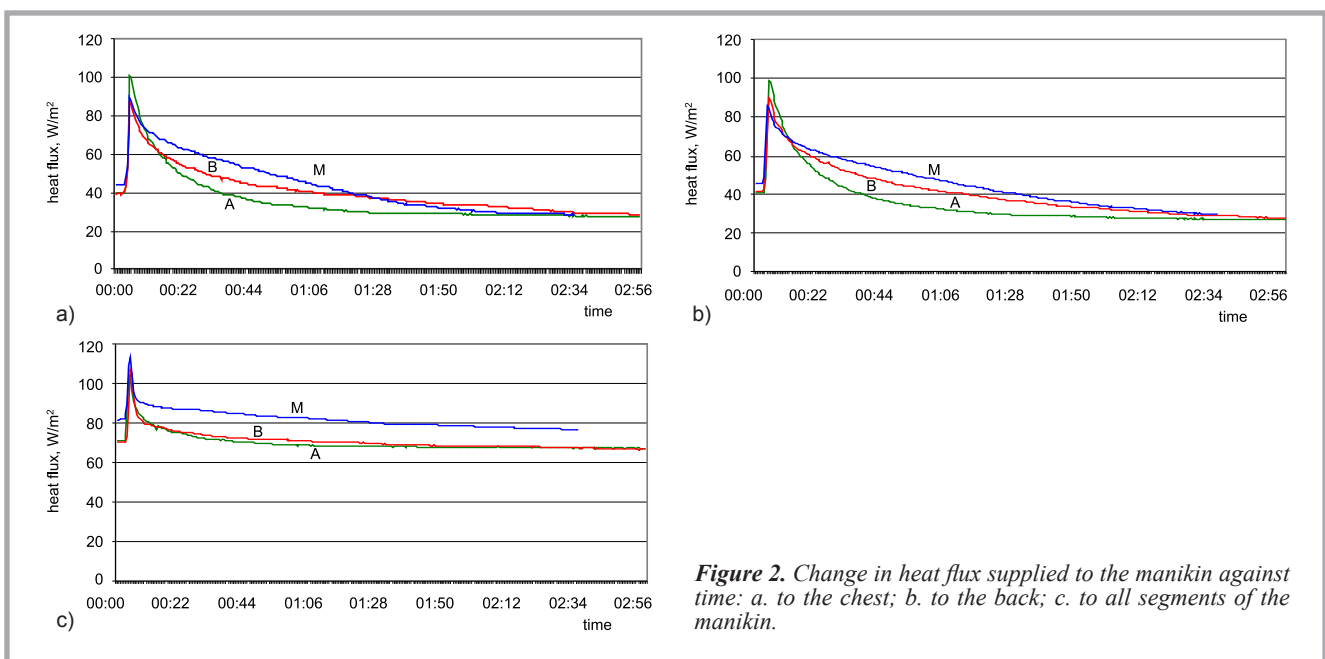


Figure 2. Change in heat flux supplied to the manikin against time: a. to the chest; b. to the back; c. to all segments of the manikin.

Table 4. Average value of heat flux supplied to the manikin over the first hour of testing.

Vest	Average value of heat flux supplied to the manikin, W/m ²		
	to the back	to the chest	to all segments of the manikin
A	47.9	47.8	73.9
B	52.1	53.7	74.9
M	56.7	55.9	85.3

- the heating power flow density supplied to each segment (H_{ci}),
- the total heating power supplied to the manikin (H_c), and
- the air temperature in the climatic chamber (T_a).

These variables were recorded until a thermal steady state was reached once again. Each clothing ensemble was tested three times. Average values of the measurements were used to prepare graphs, as presented in **Figure 2**.

Results and discussion

Figure 2 shows curves illustrating changes in the heat flux supplied to the manikin against the time. **Figure 2.a** shows the heat flux supplied to the chest, **Figure 2.b** – to the back, and **Figure 2.c** – to all segments of manikin.

During the first minutes, heat from the manikin was required to warm the vest from room temperature to the melting temperature of PCM. When the melting temperature was reached, the temperature stayed at this level in this garment layer as long as the melting process continued. When all the PCM was melted, the temperature in the vest rose to 34 °C, and the test was interrupted.

A close look at **Figure 2** shows that before applying the vest, the heat fluxes

supplied to the manikin segments were steady. On attaching the cooling vest, the heat fluxes increased sharply and then decreased gradually until a steady state was achieved once again.

The heat flux curves presented in **Figure 2** show a prominent peak. This initial peak of the heat flux was achieved after ~5 min. of testing, irrespective of the kind of macrocapsule inserted into the cooling vest. **Figure 3** shows the heat flux peak bar graph for clarity. As can be seen from **Figure 3**, the greatest value of the heat flux peak supplied to the torso segments (chest and back) was recorded in the case of vest A (with macrocapsules containing n-octadecane). Nevertheless, the amount of heat absorbed by this vest was the smallest, as can be deduced from the heat flux curves presented in **Figure 2**.

Table 4 presents the average value of heat flux supplied to the manikin in the first hour of testing. It can be observed from **Table 4** that the average heat flux supplied to the manikin in first hour of testing was the greatest for vest M compared to either vest A or vest B, which means that vest M with a mixture of macrocapsules containing hexadecane and macrocapsules containing octadecane is able to absorb the greatest amount of heat.

As can be seen from **Figure 2**, the heat fluxes achieved a steady state:

- in the case of vest A (with C18 macrocapsules) after ~90 min,
- in the case of vest B (with C16 macrocapsules) after ~110 min,
- in the case of vest M (with a mixture of C16 and C18 macrocapsules) after ~150 min.

This means that in the case of vest M, the cooling time was significantly longer than in the case of the two other vests. The explanation for the longer cooling period with vest M is probably the greater transition temperature interval of the macrocapsule mixture.

When the results obtained from DSC analyses (**Table 1**) of the alkanes used in this study are considered, we can state that the transition temperature interval for n-hexadecane is 10 – 22 °C and for n-octadecane: 24 – 34 °C. In vest M, a mixture of C16 macrocapsules containing n-hexadecane and a mixture of C18 macrocapsules containing n-octadecane, with a weight ratio of 50:50, were used as coolants. In consequence, the transition interval of the mixture was 10 – 34 °C. Further research is needed in order to find an optimal weight ratio of macrocapsules.

Summary

A microclimate cooling vest intended to be worn under chemical protective clothing was designed and tested. The cooling effect is based on the latent heat absorption of phase change material (PCM). As PCM, encapsulated n-alkanes in the form of macrocapsules of 3 mm diameter were used. Two kinds of macrocapsules were selected: containing n-hexadecane (melting point 18 °C) and containing n-octadecane (melting point 28 °C).

The cooling effectiveness of the PCM vest was assessed using a thermal manikin in a climatic chamber. Three types of cooling vest were tested:

- vest A with 100% C18 macrocapsules ;
- vest B with 100% C16 macrocapsules
- vest C with a 50/50 mixture of C16 and C18 macrocapsules.

A one-piece coverall made of spunbonded polyolefin nonwoven was worn outside the vest.

The results of the experiments indicate that vest M has the best cooling charac-

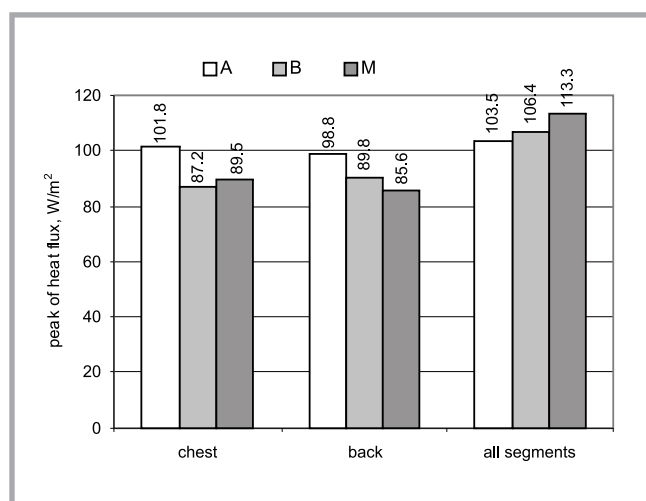


Figure 3. Peak of heat flux supplied to the manikin segments.

teristic, with a mixture of macrocapsules containing hexadecane and macrocapsules containing octadecane.

Compared with the other two, the vest with a mixture of alkanes was able to absorb the greatest amount of heat for a longer period. The findings of the current study support previous studies concerning PCM cooling vests worn under firefighter clothing [21].

To confirm these results, prototypes of PCM cooling vests need to be tested on human volunteers under artificially created conditions in a climatic chamber. Next, further research needs to be carried out in actual use.

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For more information see also
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