Part I

Phase change materials

3

Introduction to phase change materials

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3.1 Introduction

Generally speaking, phase change materials (PCM) are thermal storage materials that are used to regulate temperature fluctuations. As thermal barriers they use chemical bonds to store and release heat and thus control the heat transfer, e.g., through buildings, appliances and textile products. This chapter focuses on phase change materials used in texiles.

In a cold environment the primary purpose of clothing is to protect the wearer from cold and thus prevent the skin temperature from falling too low. Conventional thermal insulation depends on the air trapped in the clothing layers. When this layer of air gets thinner, e.g., due to windy weather, thermal insulation will be reduced significantly. The situation is the same when the garment becomes wet or perspiration condenses in it. It is possible to increase the thermal comfort by interactive insulation which means use of phase change materials, because compression and water has no effect on the insulation properties of PCM.

Phase change technology in textiles means incorporating microcapsules of PCM into textile structures. Thermal performance of the textile is improved in consequence of the PCM treatment. Phase change materials store energy when they change from solid to liquid and dissipate it when they change back from liquid to solid. It would be most ideal, if the excess heat a person produces could be stored intermediately somewhere in the clothing system and then, according to the requirement, activated again when it starts to get chilly.

The basis of the phase change technology was developed as a consequence of the NASA space research program of the early 1980s. The aim was to protect astronauts and instruments from extreme fluctuations of temperature in space. In 1987 the Triangle Research and Development Corporation (Raleigh, USA) demonstrated the feasibility of incorporating phase change materials within textile fibres and that the fabric's thermal capacity was independent of the amount of still air in the fabric loft. Triangle Research transferred the patent rights of this technology to a company called Gateway Technologies, which is now known as Outlast Technologies (Boulder, Colorado).

3.2 Heat balance and thermo-physiological comfort

It is very important to maintain a relatively even temperature to guarantee human vital functions. The normal human body temperature, 37 °C, fluctuates a little according to the time of the day, being at its lowest early in the morning and its highest in the evening. Also temperatures in different parts of the body fluctuate a little. For example, the temperature of the internal organs in the core of the body is higher than the temperature in other areas. In physical exercise the temperature of the muscles can rise to 39–40 °C. The surface parts of the body and the extremities are from time to time almost hemocryal according to the changes in the ambient air temperature.

Trying to reach thermal equilibrium, man produces and dissipates different amounts of heat depending on the ambient air temperature. Depending of the physical workload, the human being produces a heat quantity of 100 W in the state of rest and up to 600 W by physical effort. Heat production can temporarily be even more, e.g., in skiing up to 1250 W. This resultant quantity of heat has to be dissipated to prevent any marked increase in the rectal temperature and to maintain thermal equilibrium. The human being is in heat balance, when heat production is equal to heat loss. Factors influencing heat balance are the produced heat quantity (physical activity, work), ambient conditions (temperature, wind, humidity), the clothing worn and the individual properties of humans.[1,2]

Clothing is comfortable when humans feel physical, physiological, and mental satisfaction as heat and moisture transfer efficiently from the body to the environment through the clothing.[3] Therefore, development of intelligent fabrics, including thermal storage/release ones, which can adjust and maintain comfort as circumstances change, is very important and necessary.[4]

3.3 Phase change technology

Phase change materials are latent thermal storage materials. They use chemical bonds to store and release heat. The thermal energy transfer occurs when a material changes from a solid to a liquid or from a liquid to a solid. This is called a change in state, or phase.[5] Every material absorbs heat during a heating process while its temperature is rising constantly. The temperature of a PCM rises until it reaches its melting point. During the physical phase change the temperature remains constant until the PCM has totally changed from solid to liquid. Energy is absorbed by the material and is used to break down the bonding responsible for the solid structure. A large amount of heat is absorbed during the phase change (latent heat). If the material is warmed up further its temperature will begin to rise again. The latent heat will be released to the surroundings when the material cools down. The temperature remains constant again until the phase change from a liquid to a solid is complete, when the crystallization temperature of the PCM is reached. PCMs absorb and emit heat while maintaining a nearly constant temperature.

In order to compare the amount of heat absorbed by a PCM during the actual phase change with the amount of heat absorbed in an ordinary heating process, water is used for comparison. If ice melts into water it absorbs approximately a latent heat of 335 J/g. If water is further heated, a sensible heat of only 4 J/g is absorbed while the temperature rises by one degree. Therefore the latent heat absorption during the phase change from ice to water is nearly 100 times higher than the sensible heat absorption during the heating process of water outside the phase range.[6] In addition to water, more than 500 natural and synthetic PCMs are known. These materials differ from one another in their phase change temperature ranges and their heat-storage capacities.[7]

Solid-solid PCMs absorb and release heat in the same manner as solid-liquid PCMs. These materials do not change into a liquid state under normal conditions; they merely soften or harden. Relatively few of the solid-solid PCMs that have been identified are suitable for thermal storage applications. Liquid-gas PCMs are not yet practical for use as thermal storage. Although they have a high heat of transformation, the increase in volume during the phase change from liquid to gas makes their use impractical.[5]

3.4 PCMs in textiles

The most widespread PCMs in textiles are paraffin-waxes with various phase change temperatures (melting and crystallization) depending on their carbon numbers. The characteristics of some of these PCMs are summarized in Table 3.1. These phase change materials are enclosed in microcapsules, which are 1–30 µm in diameter. Compared to our hair the size of the capsule is usually about half the diameter of human hair or it can be 1/20th of it. Phase change materials can be incorporated in textiles only enclosed in these

Table 3.1 Phase change materials[1]

Phase change material	Melting temperature in °C	Crystallization temperature in °C	Heat storage capacity in J/g
Eicosane	36.1	30.6	247
Nonadecane	32.1	26.4	222
Octadecane	28.2	25.4	244
Heptadecane	22.5	21.5	213
Hexadecane	18.5	16.2	237

capsules in order to prevent the paraffin's dissolution while in the liquid state. The shell material of the capsule has to be abrasion and pressure resistant, heatproof and resistant to most types of chemicals.[8,9] Outlast®, Comfortemp® and Thermasorb® are commercially available PCM products based on paraffin-waxes and microcapsule technology.

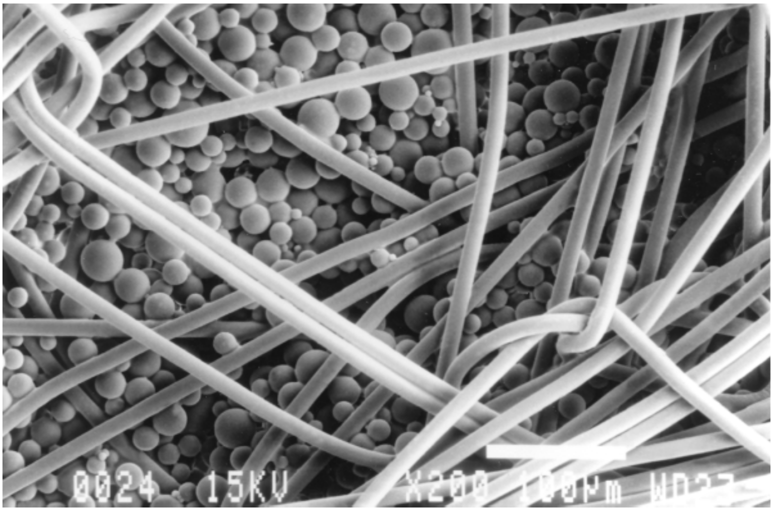
Hydrated inorganic salts have also been used in clothes for cooling applications. PCM elements containing Glauber's salt (sodium sulphate) have been packed in the pockets of cooling vests.[10]

3.4.1 Textile treatment with PCM microcapsules

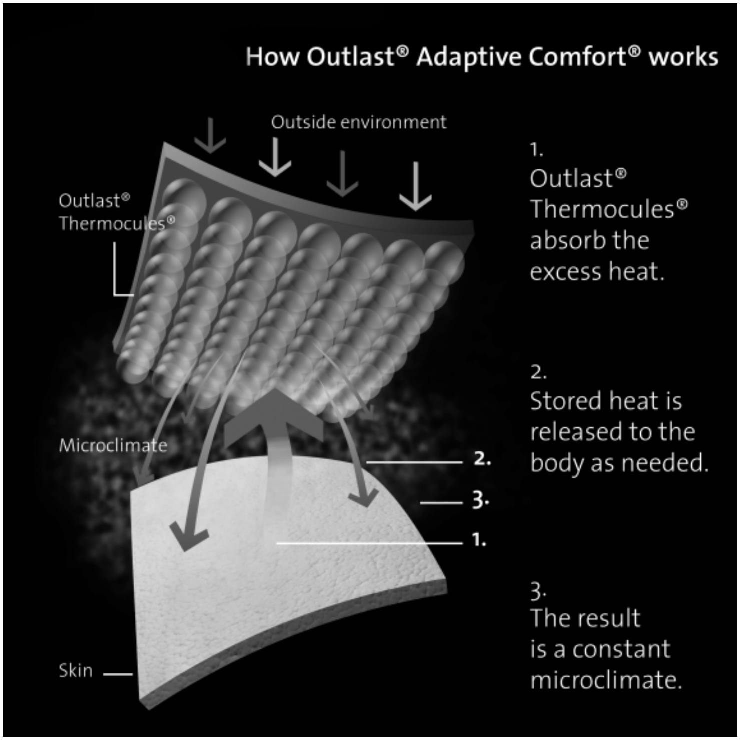
Usually PCM microcapsules are coated on the textile surface. Microcapsules are embedded in a coating compound such as acrylic, polyurethane and rubber latex, and applied to a fabric or foam. Capsules can also be mixed into a polyurethane foam matrix, from which moisture is removed, and then the foam is laminated on a fabric.[7] In Fig. 3.1 you can see PCM microcapsules (Outlast) in fabric and in Fig. 3.2 how it works. PCMs-containing microcapsules can be incorporated also into acrylic fibre in a wet spinning process. In this case the PCM is locked permanently within the fibre. The fibre can then normally be processed into yarns and fabrics.[6,7]

3.4.2 Thermal performance

In treating textile structures with PCM microcapsules for garment applications, the following thermal benefits are realized:



3.1 PCM microcapsules in a fabric (Outlast Europe).



3.2 Functioning principle of PCM in a fabric (Outlast Europe).

- a ‘cooling’ effect, by absorbing surplus body heat
- an insulation effect, caused by heat emission of the PCM into the textile structure; the PCM heat emission creates a thermal barrier which reduces the heat flux from the body to the environment and avoids undesired body heat loss
- a thermo regulating effect, resulting from either heat absorption or heat emission of the PCM in response to any temperature change in the microclimate; the thermo-regulating effect keeps the microclimate temperature nearly constant.[11]

Body temperature varies considerably: 34–36.5 ºC at the head and trunk, 27–30 ºC at the thigh and only 25.5–27.5 ºC at the hands and feet.[5] The primary purpose of clothing designed to protect the wearer from the effects of a cold environment is to prevent the skin temperature from falling too far. Such clothing normally consists of layers, possibly an outer layer, a lining and a lofted fabric.[6] In this traditional insulation system the lofted fabric provides the vast majority of the insulation (passive insulation). Without phase change materials the thermal insulation capacity of clothing depends on the thickness and the density of the fabric. The thicker the material and the lower the density, the better is the thermal insulation influence of the product. The air within the clothing directly influences the thermal insulation capacity. Normally the thermal insulation capacity of the fabric decreases when the fabric is compressed. It happens in the same way if the material becomes wet, because the thermal conductivity of water is greater than air. Pressure and moisture is not affected by the functionality of PCM. It is possible to improve the passive insulation with an active system of the phase change technology, which reacts immediately to changes in environmental temperature and adapts to the prevailing hot or cold conditions (active insulation).[8]

In a garment system the thermal resistance of textile layers, and the air layers between, limit heat flux from the body to the environment. This passive thermal insulation effect can only be adjusted to the often-changing thermal wearing conditions by adding or removing garment layers but in reality this is not always possible. Thus, strenuous exercise often leads to a thermal stress situation and increased sweat production. In contrast, light exercise combined with low ambient temperatures often results in a decrease in body temperature.[11]

The application of PCM to a garment provides an active thermal insulation effect acting in addition to the passive thermal insulation effect of the garment system. The active thermal insulation of the PCM controls the heat flux through the garment layers and adjusts the heat flux to the thermal circumstances, i.e., the prevailing activity level and the existing ambient temperature. If the heat generation of the body exceeds the possible heat release through the garment layers into the environment, the PCM will absorb and store this excess heat. On the other hand, if the heat release through the garment layers exceeds the body's heat generation during lighter activities, the heat flux through the garment layers is reduced by heat emission of the PCM. The active thermal insulation effect of the PCM results in a substantial improvement of the garment's thermo-physiological wearing comfort.[11]

The steadily-changing intensity of the body's activities leads to a constant charging and recharging of the PCM microcapsules. Furthermore, the change from a cold outdoor environment to a warm indoor environment results in a recharging of the PCM microcapsules. Thus, a necessary PCM quantity can be relatively small.[11]

Thermal performance of active wear

In order to improve the thermal performance of active wear, clothing textiles with thermo-regulating properties are widely used. The thermo-regulating effect provided by these textiles is based on the application of PCM. However, a suitable thermo-regulating effect according to the prevailing wearing conditions can only be realized when specific design principles are applied in the development process of such active wear garments. It is necessary, for instance, to match the PCM quantity applied to the active wear garment with the level of activity and the duration of the garment use. Furthermore, the garment construction needs to be designed in a way which assists the desired thermo-regulating effect.[11]

Intensity and duration of the PCM's active thermal insulation effect depend mainly on the heat-storage capacity of the PCM microcapsules and their applied quantity. In addition, performance tests carried out on textiles with incorporated PCM microcapsules have shown that the textile substrate construction also influences the efficiency of the active thermal insulation effect of the PCM. For instance, thinner textiles with higher densities readily support the cooling process. In contrast, the use of thicker and less dense textile structures leads to a delayed and therefore more efficient heat release of the PCM. Furthermore, the phase change temperature range and the application temperature range need to correspond in order to realize the desired thermal benefits.[11]

In order to ensure a suitable and durable active thermal insulation effect of the PCM in active wear garments, it is necessary to apply proper PCM in sufficient quantity. Selecting a suitable substrate requires considering whether the textile structure is able to carry a sufficient PCM quantity and provide an appropriate heat transfer to and from the PCM microcapsules. Further requirements on the textile substrate in a garment application include sufficient breathability, high flexibility, and mechanical stability. The substrate with incorporated PCM microcapsules needs to be integrated into a suitable location of the garment design.[11]

In the first step of the design process, temperature profiles are developed considering possible application temperatures. The temperature profiles are used to determine the temperature ranges in which the PCM is supposed to function because the temperatures in different garment layers vary widely. This must be considered when selecting the PCM for a certain application. For instance, if PCM should be applied to textiles used for underwear, the phase change of selected PCM would have to take place in a temperature range which corresponds with the skin temperature. On the other hand, a PCM applied to the liner material of outer wear needs to exhibit a phase change which takes place within a much lower temperature range.[11]

In order to determine a sufficient PCM quantity the heat generated by the human body has to be taken into account carrying out strenuous activities under which the active wear garments are worn. The heat generated by the body needs to be entirely released through the garment layers into the environment. On one side, this heat release takes place in the form of dry heat flux which is defined by the total thermal resistance of the garment system. Furthermore, heat is also released from the body by means of evaporative heat flux. The amount of heat released by means of evaporative heat flux is determined by the water vapour resistance provided by the garment system. In addition, the garment textiles also absorb surplus body heat with a steady rise in their temperatures. Measurements of the heat and moisture transfer as well as the heat and moisture absorption of the textile layers are used in preliminary tests to determine the total heat flux through the garment system and its thermal buffering. The necessary PCM quantity is determined according to the amount of heat which should be absorbed by the PCM to keep the heat balance equalized.[11]

During strenuous activity heat is mainly generated in the muscles and needs to be released. Because every sport makes use of different muscles, heat generation in distinct parts of the body varies between the strenuous activities. This has to be taken into account in designing active wear garments with PCM. It is mostly not necessary to put PCM in all parts of the garment. Applying PCM microcapsules to the areas that provide problems from a thermal standpoint and thermo-regulating the heat flux through these areas is often enough. It is also advisable to use different PCM microcapsules in different quantities in distinct garment locations. In order to identify the thermal problem areas, heat flux measurements as well as infra-red photographs are taken during strenuous activities.[11]

3.4.3 Test methods

Traditional thermal insulation materials rely upon trapped air for their performance. The non-physiological testing procedures for quantifying the performance of such materials have therefore been designed accordingly. Trapped air insulation is a static system, which relies upon the convection/conduction of heat through air voids and fibre. The TOG and CLO tests therefore are designed to measure this effect. Fabrics containing PCM form a dynamic system that responds to changes in skin temperature and external conditions. It is therefore quite logical that the traditional non-physiological testing procedures for the old trapped air technology do not quantify the benefits of PCM.[12]

The best type of testing for all of these materials is of course human physiological testing, but as always these are very time consuming and costly and could never be used for routine quality control testing. The American Society for Testing and Materials (ASTM) approved a new standard test procedure to measure the amount of latent energy in textile materials in June 2004. Based on years of research and testing textiles containing ‘phase change materials’ (PCMs) by Outlast Technologies, Inc., and Prof. Dr Douglas Hittle, Director Solar Energy Applications at Colorado State University (http://welcome.colostate.edu), the first ‘Test Method for Steady State and Dynamic Thermal Performance in Textile Materials’ (ASTM D7024) was established by the ASTM.[13]

Phase-change technology in temperature-regulating textiles with increased latent energy represents an entirely new approach to providing increased comfort and performance. Standard testing procedures used for determining the insulating value of traditional fabrics do not measure the stored energy in these new, innovative 'smart' fabrics. Therefore a new test method and apparatus was required as ASTM D1518 'Standard Test Method for Thermal Transmittance of Textile Materials' determined only the R-value (or CLO value as used in the garment industry) in a steady state. This new test method measures dynamic temperature changes and differentiates and quantifies the temperature-buffering properties of a material in a dynamic environment. It measures the effects of changing temperature and a fabric's ability to absorb, store and release energy. This test provides the measurement to separate PCM technology from unsubstantiated claims of temperature regulation through moisture management, wicking or straight thermal insulation properties of a fabric.

A differential-scanning calorimeter (DSC) is used to measure the heat capacity or enthalpy of the microcapsules and the fibre containing the microcapsules. This is a well established procedure that has been used for many years to quantify the melting and crystallization points, or ranges, of materials as well as the heat absorption and release potential of the same material. The same technique is used to measure the heat capacity of the finished article.[12] Another technique known as thermo-gravimetric analysis (TGA) is used to assess the thermal strength of the micro PCMs. This is important because the process used to manufacture the fibre and the processes through which the fibres containing the microcapsules are subjected to in conversion to yarns and fabrics use heat.[12]

3.4.4 Applications

In textiles phase change materials are used both in winter and summer clothing. On the market can be found clothes and footwear incorporating PCMs mainly for active sports, extreme sports and casual wear. PCM is used not only in high-quality outerwear and footwear, but also in the underwear, socks, gloves, helmets and bedding of world-wide brand leaders. Seat covers in cars and chairs in offices can consist of phase change materials. In the medical textiles field can be found PCMs in acrylic blankets and in bed covers to regulate the micro climate of the patient. Possible applications also include work and protective clothes for both cold and hot environments.

Suitable technical equipment is becoming more and more important for authorities and the military. Not only are electronics, hard- and software playing a large role, there are also increasing demands for apparel. The call for intelligent fabrics is becoming more and more insistent. A new generation of these fabrics feature phase change materials (PCMs) which are able to absorb, store and release excess body heat when the body needs it resulting in less sweating and freezing, while the microclimate of the skin is influenced in a positive way and efficiency and performance are enhanced.[14]

Two companies, Outlast Europe GmbH, Heidenheim, and UCO Sportswear NV, Ghent/Belgium, succeeded in developing denim fabrics with temperature-regulating properties. Around two years of development were necessary for the innovation. One of the greatest challenges was to guarantee the durability of the coating for the usual industrial washes that denim undergoes. Thanks to further development of the coating compound the performance is now guaranteed against the effects of stone, enzyme and other washes. By modifying the coating process of the compound it can be incorporated directly into the fabric structures. This results in the textile touch of the denim fabric being conserved, the coating film being invisible and there is no unpleasant feel on the skin. Comprehensive tests were conducted on coated pure cotton fabrics, cotton/polyester blends and elastic fabrics (weights between 240 g and 360 g) as the summer product has a cooling fresh effect that is very comfortable.[15] Motorcyclists also swear by this intelligent fabric in many situations – on tours through shady woods, sunny roads or when they are exposed to changing influences caused by the wind chill effect while riding or stationary at traffic lights. It was police motorcyclists in the UK who first tested their garments to the limit in all weather conditions providing input from their experiences for the development of innovative motorcycling jackets and trousers.[14]

Cooling vest (TST Sweden Ab) is a comfort garment developed to prevent elevated body temperatures in people who work in hot environments or use extreme physical exertion. The cooling effect is obtained from the vest's 21 PCM elements containing Glauber's salt which start absorbing heat at a particular temperature (28 °C). Heat absorption from the body or from an external source continues until the elements have melted. After use the cooling vest has to be charged at room temperature (24 °C) or lower. When all the PCMs are solidified the cooling vest is ready for further use.[16]

3.5 Future prospects of PCM in textiles and clothing

Retailers and consumers are asking more and more for function, for added values like appearance and improved comfort. The component 'temperature regulation' is continuing to receive increased attention. Outlast Europe, market leader of PCMs has reacted and designed an attractive offer for the season Spring/Summer 2006: the maximum 'lightness' is top priority.[17]

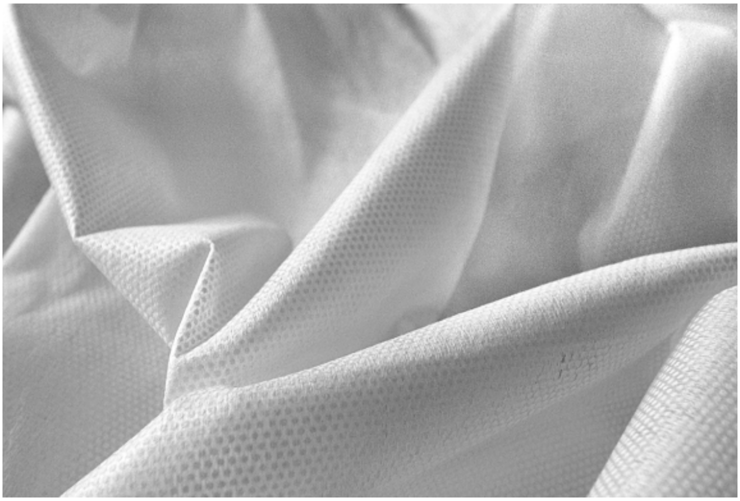
New to the range of thermo-regulating fabrics are two items. For the first time Outlast has created a lightweight coated net lining with a high performance. The hole structure of the fabric is retained due to a special coating process.

The coating on the reverse does not show through and the hand is pleasant and soft. Apparel can be equipped with a net lining, which can absorb excess body heat, store and release it when needed, creating increased freshness in hot summer weather (Fig. 3.3).[17]

3.3 Optimised climate due to Outlast® Adaptive Comfort®: also linings with net optic are now available. In spite of the coating on the back the hole structure is visible. (Outlast Europe)

Another lining has been specially developed for summer-weight clothing. The basis is a polyester nonwoven with significantly reduced weight. In that way the Outlast® fabric can be inserted between the outer layer and the lining to balance temperature swings. The advantage for the manufacturer is freedom to choose the top fabric and lining, without losing added value, the function of Outlast® Adaptive Comfort® (Fig. 3.4).[17]

Textile testing & Innovations, LCC, has developed a cooling undergarment especially for fire fighters, steel mill workers, and workers in nuclear and chemical facilities in order to avoid heat stress and related illnesses while performing their duties. The suit can also been worn by police and army personnel in order to improve the thermo-physiological wearing comfort of ballistic vests and combat suits. A non-combustible salt hydrate was selected for the cooling suit application in order to meet the fire-resistant requirement. Due to the very high latent heat storage capacity of the selected PCM, a durable cooling effect is already obtained with a relatively small amount of PCM which enhances the cooling suit's weight only slightly. After taking off the cooling suit, the PCM is regenerated under room temperature and is seen available to cool again after a short period of time. The PCM is embedded in a polymer matrix from which a film-like structure is made. The polymer film



3.4 Light and soft: the new Outlast® Adaptive Comfort® liner is suited very well for summer jackets regulating the temperature actively (Outlast Europe).

with PCM is applied to fabrics made of fire-resistant fibres. The application of the cooling suit leads to extended wearing times of the protective garment systems resulting in enhanced productivity. The heat stress-related health risks the wearers of protective garments are exposed to is minimized by the application of this cooling suit.[18]

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4

Intelligent textiles with PCMs

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4.1 Introduction

In the last decade one of emerging technologies is microencapsulated phase change materials (PCMs), which are being developed to provide significantly enhanced thermal management for fibres, foams and textiles with applications to apparel and technical textiles. Phase change technology originates from the NASA (National Aeronautics and Space Administration) research programme of the 1970s. The aim of this programme was to provide astronauts and instruments with better protection against extreme fluctuations of temperature in space. At present, microencapsulated PCMs have been applied in many fields, including heat management of electronics, telecommunications and microprocessor equipment, solar heat storage systems for buildings, microclimate environmental control for vegetation in agriculture, biomedical and biological carrying systems, and so on.

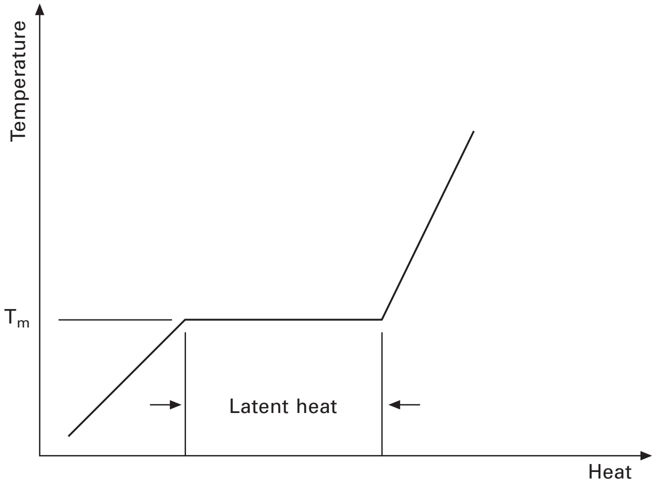
In this chapter a basic overview of the phase change materials, with particular reference to the linear alkyl hydrocarbons, is presented. The principal functions of the microPCM in textiles are discussed. Special attention is paid to the mode of PCM performance in clothing. The most common methods of incorporating microPCMs into fibrous substrates and the various applications of textiles containing microPCMs are discussed. Additionally, the apparatus for testing thermal properties of the fabrics containing PCMs is presented.

4.2 Basic information on phase change materials

Phase change is a process of going from one physical state to another. The three fundamental phases of matter, solid, liquid and gas, are known but others are considered to exist, including crystalline, colloid, glassy, amorphous and plasma phases. Substances that undergo the process of phase change are known as phase change materials (PCMs). By definition PCMs are materials that can absorb, store and release large amounts of energy, in the form of latent heat, over a narrowly defined temperature range, also known as the phase change range, while that material changes phase or state (from solid to liquid or liquid to solid).

The phase change from the solid to the liquid state occurs when the melting temperature in a heating process is reached. During this melting process the PCM absorbs and stores large amounts of a latent heat. The temperature of the PCM remains nearly constant during the entire process (Fig. 4.1). During the cooling process of the PCM the stored heat is released into the environment within a certain temperature range and a reverse phase change from the liquid to the solid state takes place. During this solidifying process the temperature of the PCM also remains constant. Thus the PCM can be used as an absorber to protect an object from additional heat, as a quantity of thermal energy will be absorbed by the PCM before its temperature can rise. The PCM may also be preheated and used as a barrier to cold, as a larger quantity of heat must be removed from the PCM before its temperature begins to drop. The phase change process results in a density and volume change of the PCM that has to be taken in consideration into its application.

The best-known PCM is water, which at 0 °C becomes ice or evaporates at 100 °C. In addition to water, the number of natural and synthetic phase change materials known today exceeds 500. These materials differ from one another in their phase change temperature range and their heat storage capacities. In order to obtain textiles and clothing with thermal storage and release properties the most frequently used PCMs are solid–liquid change materials. Research on solid–liquid phase change materials has concentrated on the following materials:



4.1 Heat transfer characteristic of phase change material as it changes from solid to liquid or from liquid to solid.

- linear crystalline alkyl hydrocarbons
- fatty acids and esters
- polyethylene glycols (PEG)
- quaternary ammonium clathrates and semi-clathrates
- hydrated inorganic salts (e.g.lithium nitrite trihydrate, calcium chloride hexahydrate, sodium sulphate decahydrate, zinc nitrate hexahydrate)
- eutectic alloys, containing bismuth, cadmium, indium, lead.

An ideal PCM should meet numerous criteria such as a high heat of fusion, high heat capacity, high thermal conductivity, small volume change at phase transition, be non-corrosive, non-toxic, non-flammable and exhibit little or no decomposition or supercooling. Organic PCMs, such as linear alkyl hydrocarbons, are chemically stable, non-corrosive, and exhibit no supercooling properties. They have a high latent heat per unit weight. Their disadvantages are low thermal conductivity, high changes in volume during phase change and flammability. Inorganic compounds, such as hydrated inorganic salts, have a high latent heat per unit weight and a high thermal conductivity, are inflammable and low-cost. Their utilisation is, however, limited because they suffer decomposition and supercooling which can influence their phase change properties.

In addition to solid–liquid change materials there is another class of substances that are characterised by their high enthalpies or thermal storage and release properties. These substances, commonly called plastic crystals, have extremely high thermal storage or release values that occur prior to or without melting. This thermal effect is believed to be a transition between two solid states (e.g. crystalline or mesocrystalline phase transformation) characterised by large enthalpy changes and hence typically does not become a liquid during a use. Hence these substances are called solid–solid change materials.

Polyhydric alcohols are the solid-solid change materials, which have been recommended for use in textiles.[1–4] Polyhydric alcohols may be selected from the group consisting of pentaerithritol, 2,2-dimethyl-1,3-propanediol, 2-hydroxymethyl-2-methyl-1,3-propanediol and amino alcohols such as 2-amino-2-methyll-1,3-propanediol.

4.3 Phase change properties of linear alkyl hydrocarbons

In the present applications of PCM technology in the textile industry the crystalline alkyl hydrocarbons are used exclusively. The phase change properties of the alkyl hydrocarbons suitable for incorporation into textiles are shown in Table 4.1. These data reveal quite clearly that their melting temperature increases with the number of carbon atoms. Each of the alkyl hydrocarbons

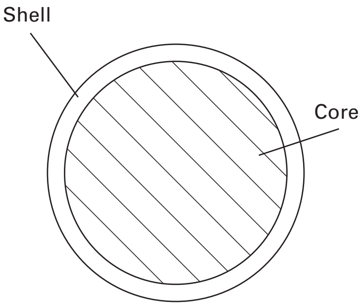
Table 4.1 Thermal characteristics of selected alkyl hydrocarbons

Name	Formula	Temperature of melting, T_m °C	Temperature of crystallisation, T_c °C	Enthalpy, J/g
n-hexadecane	$C_{16}H_{34}$	18.2	16.2	237.05
n-heptadecane	$C_{17}H_{36}$	22.5	21.5	213.81
n-octadecane	$C_{18}H_{38}$	28.2	25.4	244.02
n-nonadecane	$C_{19}H_{40}$	32.1	29.0	222.0
n-eicosane	$C_{20}H_{42}$	36.1	30.6	246.34
n-heneicosane	$C_{21}H_{44}$	40.5		199.86

Data from refs 4 and 5.

is most effective near the melting temperature indicated in Table 4.1. The alkyl hydrocarbons are non-toxic, non-corrosive and non-hygroscopic. In order to realise desired temperature range in which the phase change will take place, the hydrocarbons can be mixed. As a by-product of petroleum refining they are inexpensive. A disadvantage of hydrocarbons is their low resistance to ignition but the addition of fire retardants can solve this problem.

To prevent the liquid hydrocarbons from migrating within a fibrous substrate they need to be microencapsulated. The microencapsulation of the PCMs involves enclosing them in thin and resilient polymer shells so that the PCMs can be changed from solid to liquid and back again within the shells. Figure 4.2 shows a structure of a single-shell microcapsule. A variety of chemical and physical techniques for manufacturing different types of microcapsules exists[6] and can be employed for forming microencapsulated PCMs. Two of the most important chemical methods are coacervation and interfacial polymerisation. In microencapsulation using coacervation, the core particles are uniformly dispersed in an appropriate medium and the coacervate layer is deposited uniformly around the particles. The coating is then hardened by adding a reagent such as formaldehyde resulting in the cross-linking of the



4.2 Structure of microcapsule.

coacervate. In interfacial polymerisation, the capsule wall is formed directly around the core material by polymerisation reactions.

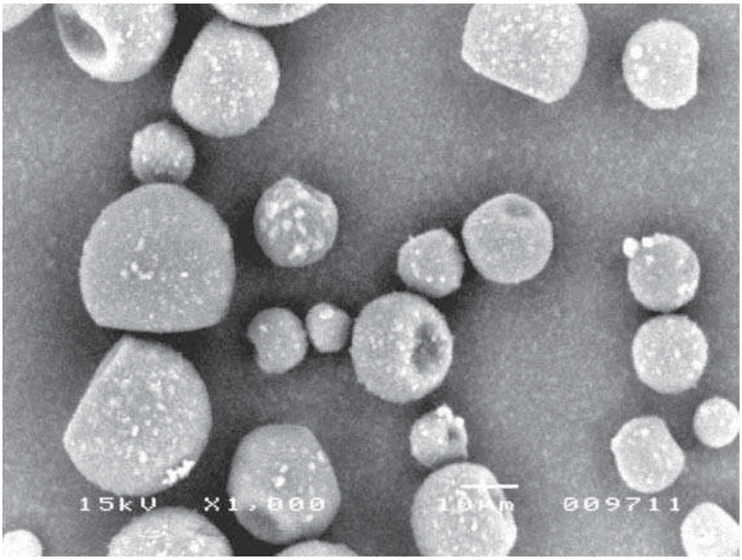
The key parameters of microencapsulated PCM are:

- particle size and its uniformity
- core-to-shell ratio, with PCM content as high as possible
- thermal and chemical stability
- stability to mechanical action.

Diameters of microPCMs can range from 0.5 to 1000 μm. Very small microcapsules ranging from 1 to 10 μm in diameter are used for incorporation within textile fibres.[8] Larger microPCM particle of 10–100 μm can be incorporated into foams or coatings applied on fabrics.[3,8,9] The core of a microcapsule constitutes 60–85% of the particle volume, while the polymer shell is approximately 1 μm thick. Still larger macroencapsulated PCMs ranging from 1 to 3 mm are being developed[11,12] to produce textiles that permit high thermal storage as well as high moisture transport between the capsules.

The microencapsulation process and the size of the microcapsules affect the phase change temperatures. The larger particles, the closer the phase change temperature is to that of the core material. The smaller particles, the greater is the difference between the melting and solidifying temperatures for the PCM. The effective specific heat of encapsulated material undergoing phase change depends on the physical properties of the microcapsule enclosing it. The shell material should conduct heat well and it should be durable enough to withstand frequent changes in the core's volume as the phase change occurs. Experimental results[13] show that microPCMs expand and contract during the phase change process of the core with an order of magnitude of 10%. After solidification of the core on the surface of the microcapsules there are dimples (Fig. 4.3), which are attributed to the lower contract coefficient of the shell than that of the core. Selecting an appropriate shell material to improve the thermal stability of microencapsulated PCMs has been studied intensively. MicroPCMs have been synthesised with urea-formaldehyde,[14] cross-linked nylon,[14] melamine-formaldehyde,[15,17–20] polyurethane,[16,18] urea-melamine-formaldehyde copolymer[17] as shell materials. Thermal stability of microPCMs can be improved by adding the stabilising agent selected from the group consisting of antioxidants and thermal stabilisers.[21]

Microcapsules for textile materials should be stable against mechanical action (e.g. abrasion, shear and pressure) and chemicals. Shin *et al.*[18] tested the stability of the melamine-formaldehyde microcapsules containing n-eicosane. The results confirmed that microcapsule shells were durable enough to secure capsule stability under stirring in hot water and alkaline solutions. The microcapsules did not show any significant changes in their



4.3 Microcapsules containing octadecane (magnification: 1000×).

morphology and size, and more than 90% of the heat storage capacity of the microcapsules was retained after testing.

4.4 Textiles containing PCM

Intelligent textiles are able to sense stimuli from the environment, to react to them and adapt to them by integration of functionalities in textile structure. According to this definition textiles containing the PCM are considered as intelligent, because they react immediately to changes in environmental temperature and adapt to the prevailing hot or cold conditions.

4.4.1 Historical background

In the 1980s work on temperature-adaptable fabrics was undertaken at the US Department of Agriculture's Southern Regional Research Centre in New Orleans. The extensive researches were conducted by Vigo and his co-workers. Vigo and Frost[22] filled hollow fibres with inorganic salt hydrates (e.g. lithium nitrite trihydrate, calcium chloride hexahydrate in admixture with strontium chloride hexahydrate). The treated fibres exhibited poor thermal behaviour on repeated thermal cycles, i.e., heating and cooling. Vigo and Frost described also experiments with polyethylene glycols (PEGs).[23,24] They incorporated PEGs having 7 to 56 monomer units with an average molecular weight ranging from 400 to 3350 into the hollow polypropylene and rayon fibres or topically applied PEGs to fabrics consisting of most representative fibre types. The fabrics treated with PEGs were temperature adaptable in both hot and cold environments for 150 heating and cooling cycles, by releasing heat when the temperature drops, and storing heat when the temperature rises. Such treatments however were not durable to laundering or leaching since the PEGs are water-soluble and can thus be removed from the substrate.

Vigo and Bruno[25] reported that low molecular weigth PEGs may be insolubilised on fabrics by their reaction with DMDHEU (dimethylol-dihydroxyethyleneurea) under conventional pad-dry-cure treatment conditions to produce textiles thermally adaptable even after launderings. The resultant knitted fabrics, designated Neutratherm, were used for manufacturing underwear.[26] Vigo and Frost have also incorporated into textile fibres some of solid-solid change materials, e.g., 2,2-dimethyl-1,3-propanediol (DMP).[23] However, the application of textiles modified with polyhydric alcohols is limited due to their phase change transition temperature being higher than 40 °C.

Since 1983 considerable research work on including PCMs into textiles has been done at Triangle Research and Development Corporation. Several research programs at TRDC have demonstrated that microcapsules containing selected PCMs (alkyl hydrocarbons and plastic crystals) can be either spun into textile fibres or coated onto them.[2,4] They can also be embedded in a variety of foams.[3] The incorporation of microPCMs within textiles imparted thermal storage and thermoregulating properties. These inventions were awarded several patents that TRDC licensed to Outlast Technologies. TRDC is currently developing other products with microPCMs for enhanced apparel cooling.[11,12]

Since the mid-1990s scientists from Outlast Technologies have developed several processes for incorporating microPCMs into textile products, especially sportswear, protective clothing, home and technical textiles. Recently microPCM technology has drawn the attention of research workers from universities. This has been reflected in an increasing amount of published work on incorporation processes of microPCMs into fabrics[8–20] and properties of textiles containing microPCMs.[33–35]

4.4.2 Function of textile structure with PCM

From comprehensive analysis given by Pause[27,28] it follows that there are several thermal effects that can be obtained by incorporation of PCM into a textile substrate:

- a cooling effect, caused by heat absorption of the PCM
- a heating effect, caused by heat emission from the PCM
- a thermo-regulating effect, resulting from either heat absorption or heat

emission of the PCM which keeps the temperature of the surrounding substrate approximately constant

- an active thermal barrier effect, resulting from either heat absorption or heat emission of the PCM and creating a thermal barrier in surrounding substrate, which regulates the heat flux through the substrate and adapts the heat flux to thermal needs.

The function of the textile substrate with PCM as a barrier or buffer evolves from the characteristic of a phase change process. As the PCM undergoes a phase change, depending upon its initial state, it can either absorb or release a quantity of heat equal to its latent heat of fusion while still maintaining a constant temperature. In such a manner, heat can be lost or gained from either side of this barrier, yet the temperature at this barrier will remain constant. This remains true until all of the PCM has either solidified or melted. After this point, all the latent capacity of the PCM has been consumed and a sensible change in temperature results. The textile substrate with PCM then acts as a conventional textile product. The desired thermal effects have to be identified before selecting the PCM. The efficiency and duration of each of these effects are determined by the total thermal capacity of the PCM incorporated into the textile substrate, the phase change temperature range, the structure of the textile substrate, and the structure of the final product.

The total thermal capacity of the PCM depends on its specific thermal capacity (latent heat of the phase change) and the quantity applied on the textile substrate. The necessary quantity of the PCM can be estimated by considering the application conditions, the desired thermal effect and its duration and the thermal capacity of the specific PCM. In order to obtain the desired thermal performance of the textile product it is necessary:

- to select the appropriate PCM
- to determine the sufficient quantity of the PCM
- to choose the appropriate fibrous substrate
- to design the product.

The choice of which PCM to use in the fibrous structure depends principally on two factors: the latent heat of the phase change and the phase change temperature. In general, the higher latent heat of phase change is, the better PCM because more thermal energy can be stored in it. The choice of the phase change temperature depends largely on the intended application of the textile. The phase change temperature range should correspond with the application temperature range.

To select the appropriate fibrous structure it is necessary to consider whether the textile structure is able to carry a sufficient quantity of the PCM and whether it can provide an appropriate heat transfer to micro PCM.

4.4.3 Mode of PCM performance in clothing

The principal function of clothing assembly is to provide the wearer with protection against undesirable environments. Due to the fact that a human being is homeothermal, the human body regulates temperature in narrow limits around 37 °C. The human body regulates the core temperature by vasomotoric actions, muscle work, general behaviour, sweat production and metabolic heat production.[29] Physical activity and a high temperature of the environment cause an increase in core temperature. Temperature around 38 °C is typical for moderate work. For heavy exercise values up to 39 °C are observed. The amount of heat generated by the human body is determined by metabolic activity. At rest the human body releases the amount of heat needed for the body's basic functions that is equal to about 100 W, and produces little sweat. During strenuous exercise the heat produced by physical muscular activity adds quickly to the basic metabolic heat production and at strenuous work the values over 1000 W are observed.[30] The increased heat must be released into the ambient environment. It can be done either by higher blood flow through extremities or through evaporation of liquid sweat on the skin. Due to the body's ability to sweat, large amounts of heat can be dissipated from the body: 1 dm^3 of sweat that evaporates on the skin corresponds to approximately 670 W heat which is withdrawn from the body.[29]

Physiological regulation of the body temperature is partially or completely inhibited by clothing. Clothing, an intermediate medium between the skin and the ambient environment, provides resistance to heat and to evaporation of perspiration escaping from the human body. The presence of sweat on the skin is a significant discomfort factor. Typically, a skin temperature between 33 and 35 °C and no deposition of liquid sweat on the skin surface are associated with thermal comfort.[31,32]

Fabrics containing PCMs appear to be effective in contributing to apparel comfort by buffering and reducing overheating, the cause of perspiration. The fabric with PCM reacts immediately to changes in environmental temperature and adapts to the prevailing hot or cold conditions. When temperature rise occurs as a result of body activity or a higher environmental temperature, PCM reacts by absorbing the heat. Storing this surplus energy the PCM liquefies. This phase change produces a temporary cooling effect in the clothing layers. Once the PCM has completely melted, the storage of heat stops. The PCM releases the stored heat with a drop of environmental temperature or when a body is at rest, and a temporary warming effect occurs in the clothing layers. This heat exchange produces a buffering effect in clothing layers, minimising changes in skin temperature. The PCM incorporated into clothing layers should be able to operate at or near the temperature of human skin. This temperature is different for different parts of the body.[29] The average head temperature is 35 °C, the average abdominal skin temperature is 34–35 °C, whilst the average temperature for hands and feet is 31–32 °C. It is therefore important to choose the PCM with the relevant melting point.

The garments made up from fabrics with incorporated microPCM are intended to moderate skin temperature when wearers experience varying levels of activity. The clothing layer containing microPCM has to go through the transition temperature range before the PCM will change phase and either generate or absorb heat. The PCMs have no effect under steady state conditions. In the last decade the fabrics containing microPCM have appeared in garments sold by well-known companies. However, there is little published work on thermal performance of the garments made up from PCM fabrics.

Shim and McCullough[33] investigated the effects of PCM on heat and moisture transfer in clothing during sensible temperature transients. In their study they used an open-cell, hydrophilic, expanded PU foam containing an optimum level of 60% microPCM. They 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 minutes, and that the heat release by microPCM 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. They concluded that microPCM can produce small, temporary heating and cooling effects in clothing layers when the temperature of layers reaches the PCM transition temperature. They supposed that the effect of phase change materials will probably be maximised when the wearer is repeatedly going through temperature transients (i.e. going back and forth between a warm and cold environment) or intermittently touching or handling cold objects.

Ghali *et al.*[34] analysed the effect of microPCM on the thermal performance of fabric during periodic ventilation. The results obtained indicated that the presence of microPCMs in fabric causes a temporary heating effect when subjected to a sudden change from a warm environment to a cold environment. This effect is revealed in a decrease in the sensible heat loss during the phase change process compared to a fabric without microPCM. The duration interval of the phase change process decreases with increased frequency of ventilation, while duration increases with an increased percentage of PCM in fabric and with an increased environmental temperature.

Li and Zhu[35] presented the mathematical model of heat and moisture transfer in porous textiles containing microPCM. On the basis of a finite difference scheme, the thermal buffering effect of PCM is simulated. With specification of initial and boundary conditions, the distributions of temperature, moisture concentration and water content in the fibres can be numerically computed for different amounts of PCM in textiles. They compared the predictions of temperature changes during combined moisture and temperature transients with experimental measurements and they found reasonable agreement. In their opinion this model can be used in the design of new fabrics containing microPCM and intelligent clothing products.

4.4.4 Manufacture of textiles containing microPCMs

In applications of PCM technology to textile industry, microcapsules containing selected PCM can be applied to fibres in a wet-spinning process, incorporated into foam or embedded into a binder and applied to fabric topically, or contained in a cell structure made of a textile reinforced synthetic material.

Incorporation of microPCMs into fibres

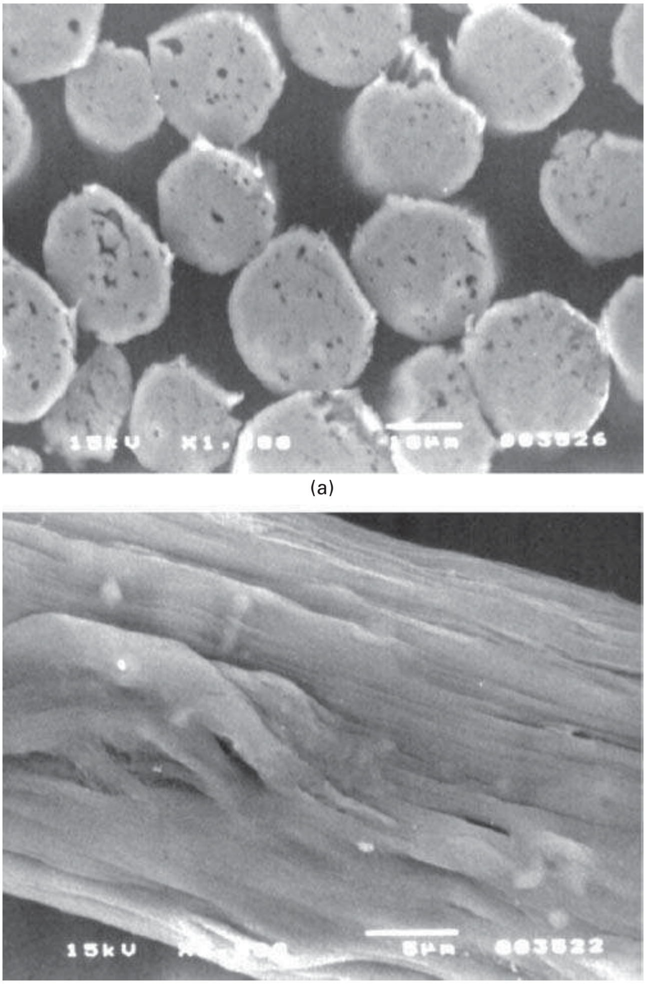
In 1988 Bryant and Colvin[2] presented the conceptual feasibility of fibres with microencapsulated PCMs such as alkyl hydrocarbons (e.g. eicosane or octadecane) integrally incorporated into the matrix of fibres during manufacturing. Plastic crystalline materials such as DMP (2,2-dimethyl-1,3-propanediol) and HMP (2-hydroxymethyl-2-methyl-1,3-propanediol and the like may also be used. In manufacturing the fibre, the selected PCM microcapsules are added to the liquid polymer or polymer solution, and the fibre is then expanded according to the conventional methods such as dry or wet spinning of polymer solutions and extrusion of polymer melts.

Fabrics can be formed from the fibres containing PCM by conventional weaving, knitting or nonwoven methods, and these fabrics can be applied to numerous clothing applications. The advantages of incorporating microPCM into fibres are as follows:

- the micro PCMs are permanently locked within the fibres
- the fibre is processed with no need for variations in yarn spinning, fabric knitting or dyeing
- properties of fabrics (drape, softness, tenacity, etc.) are not altered in comparison with fabrics made from conventional acrylic fibres.

At present, microencapsulated PCMs have been incorporated only into acrylic fibres (trade name Outlast).[8,36] Figure 4.4 shows microphotographs of Outlast fibre. The microcapsules incorporated into the spinning dope of acrylic fibres have an upper loading limit of 5–10% because the physical properties of the fibres begin to suffer above that limit, and the finest fibre available is about 2.2 dtex. Due to the small content of microcapsules within the fibres their thermal capacity is rather modest, about 8–12 J/g.

The incorporation of microPCMs into acrylic fibres is readily accomplished due to the wet solution process of forming acrylic fibres. However, it is more difficult to incorporate PCMs into melt-spun fibres, because during a melt-



4.4 Microphotographs of Outlast fibre. (a) cross-section, (b) longitudinal view.

spinning process temperatures involved are typically in the range 200–380 °C and pressures may be as high as $2 \cdot 10^4$ kN/m^2. Such processing conditions may damage the microcapsules shell and induce degradation of PCM. Degradation of PCM may lead to inadequate thermal properties. Nevertheless, scientists continue trying to develop melt-spun fibres with microPCMs. The process of forming the polypropylene fibres containing alkyl hydrocarbons on a laboratory spin draw device was studied by Leskovsek *et al.*[37] Microcapsules 2 μm in diameter were chosen as the most appropriate for spinning. The shell of the microcapsules was melamine-formaldehyde resin, while the alkyl hydrocarbon with a melting point of 50 °C (tetracosane) constituted the core. The key problem was achieving the homogeneous distribution of microcapsules into fibres. Microcapsules showed the potential to form clusters that became bigger at the fibre spinning and consequently caused discontinuity of the process, filament breaks and enlarged the thickness of fibres.

Lamination of PU foam containing microPCMs onto a fabric

Colvin and Bryant[3] described a method of fabrication of the foam insulation materials containing microPCMs. The selected microPCMs are added to the liquid polymer or elastomer and mixed therein to ensure wetting and equal dispersion throughout the mixture. After mixing the microcapsules will be wetted and substantially spaced apart from each other. Typical concentrations of microPCMs range from 20% to 60% by weight. Next, the base polymeric material is foamed. Common methods of foaming include adding a hardening agent which causes a chemical reaction, thermally setting the base material with heat, or bubbling a gas through the liquid polymer (or elastomer) while hardening. Microcapsules should be added to the liquid polymer or elastomer prior to hardening.

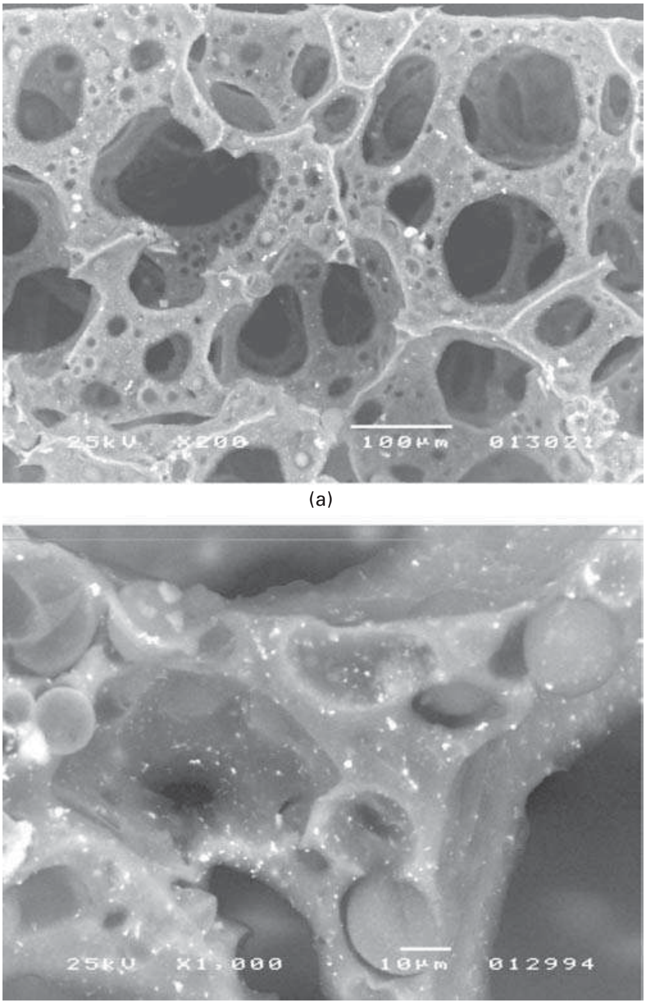
After foaming microcapsules will be embedded within the base material matrix so that they are individually encapsulated and embedded within the base material and the space between neighbouring adjacent microcapsules will be base material, not the foaming gas. The foam pad containing PCMs may be fabricated from neoprene or polyurethane. The application of the foam pad is particularly recommended because:

- a greater amount of microcapsules can be introduced
- different PCMs can be used, giving a broader range of regulation temperatures
- microcapsules may be anisotropically distributed in the layer of foam. The possibility of anisotropic insertion of the microcapsules in the foam can reinforce the thermoregulation effect by concentrating PCMs towards the interior of the clothing.

The foam pad with microPCMs may be used as a lining in a variety of clothing: gloves, shoes, hats, outerwear. Before incorporation into clothing or footwear the foam pad is usually attached to the fabric, knitted or woven, by any conventional means such as glue, fusion or lamination. Figure 4.5 shows the cross-section of the knitted fabric laminated with polyurethane foam containing PCM microcapsules.

Incorporation of microPCMs to fibrous structure by different processes

In the last decade several methods of incorporating microPCMs into fibrous structures were developed to produce fabrics having enhanced thermal



4.5 Cross-section of a PU foam containing microPCM. (a) magnification 200×, (b) magnification 1000×.

properties. A number of experimental conditions should be optimised before these methods are developed to produce fabrics with the desirable structure and properties to meet practical applications. Most work in this field can be found in patent literature and only a few papers in published literature report the formulation of PCM microcapsules, finishing of fabrics and the evaluation of their characteristics, including their thermal properties and durability.

The PCM microcapsules are applied to a fibrous substrate using a binder (e.g. acrylic resin). All common coating processes such as knife over roll, knife over air, screen-printing, gravure printing, dip coating may be adapted to apply the PCM microcapsules dispersed throughout a polymer binder to fabric. The conventional pad–mangle systems are also suitable for applying PCM microcapsules to fabrics. The formulation containing microPCMs can be applied to the fabric by the direct nozzle spray technique.

The method for manufacturing a coating composition was described by Zuckerman *et al.*[10] A coating composition for fabrics includes wetted microcapsules containing PCMs dispersed throughout a polymer binder, a surfactant, a dispersant, an antifoam agent and a thickener. As a result of experiments Zuckerman has found that wetting PCM microcapsules with water and maintaining a uniform dispersion of the microcapsules in a wet coating minimises the tendency of such microcapsules to destabilise the binder polymer. A coating composition is prepared by mixing dry microcapsules with water to induce the microcapsules to swell. A surfactant and a dispersant are added to the water prior to mixing with the microcapsules. The surfactant decreases surface tension of the layers of microcapsules and thereby promotes their wetting. An antifoam agent is added and mixed slowly with the mixture to remove air trapped as dispersed bubbles in the mixture. A thickener is added to adjust the viscosity of the mixture and to prevent the microcapsules from floating or sinking in the mixture. Adjusting the pH of the mixture to 8.5 or greater promotes swelling of microcapsules. Swelling is typically completed within 6 to 24 hours. Thereafter, the microcapsules dispersion is added to a mixture of a polymer dispersion, surfactant and dispersant having a pH approximately the same as the pH of the microcapsules dispersion. The polymeric binder may be in the form of a solution, dispersion or emulsion. The most frequently used are acrylic resins or acrylic/butadiene copolymer.

The most preferred ratios of components of the coating composition are:

- 70 to 300 parts by dry weight of microcapsules for each 100 parts by dry weight of acrylic resin
- 0.1 to 1% dry weight of each surfactant and dispersant to dry weight of microcapsules
- water totalling 40% to 60% of the final wet coating composition
- antifoam agent 0.1% to 0.5% of the final wet coating composition.

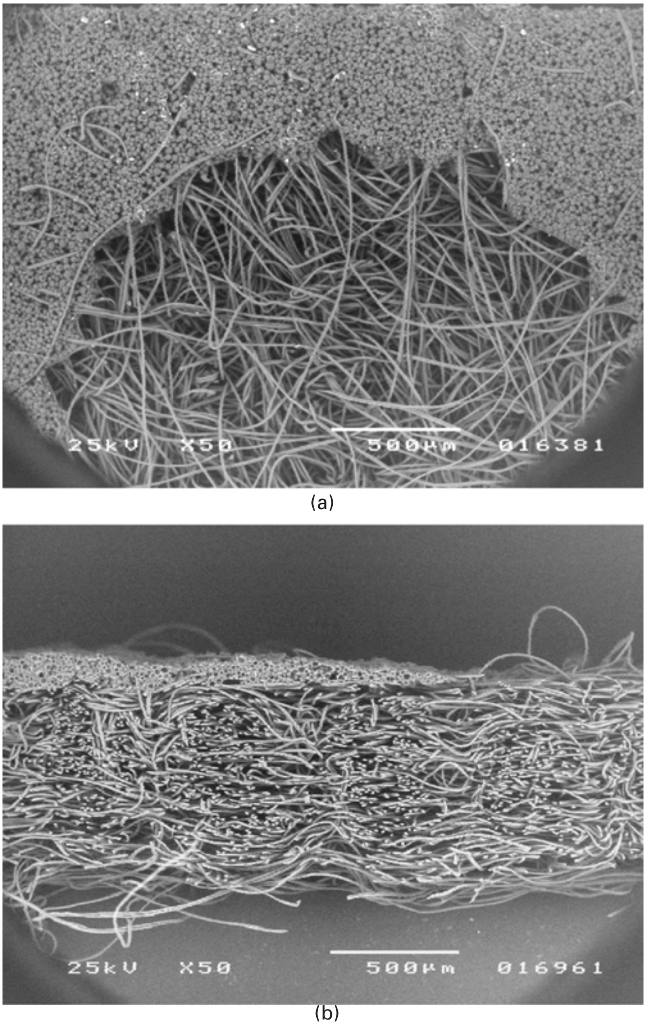
The use of polymeric binders has some drawbacks. The amount used should be enough for good fixation of the microcapsules, but the properties of fabrics such as drape, air permeability, breathability, thermal resistance, softness and tensile strength can be affected adversely as the percentage of binder add-on increases. Pushaw[9] reported that it was difficult to maintain durability, moisture vapour permeability, elasticity and softness of coated fabrics when the coating was loaded with a sufficiently high content of microPCM.

Choi *et al.*[19] synthesised, by the interfacial polymerisation method, the melamine-formaldehyde shell on microspheres of octadecane. The mean diameter of the microcapsules ranged from 1 to 1.5 μm and their shapes were almost spherical. The microcapsules were mixed with acrylic binder and urethane binder and the coating mixture was applied on polyester fabrics by the knife-over-roll and screen printing methods. They found that thermal properties of treated fabrics increased as microcapsules concentration increased, but there was no great difference between these two adhesive methods. The thermal properties of coated fabrics, analysed by DSC, were rather poor, because latent heat of fabric samples hardly reached 7.5 J/g. It is obvious that shear stiffness and bending rigidity of coated fabrics were greater compared with printed fabrics.

Chung and Cho[20] investigated the possibilities of producing thermally adaptable, vapour-permeable and water-repellent fabrics. Microcapsules containing octadecane were added to polyurethane and the coating mixture was dissolved in DMF (dimethyl formamide). This was coated onto the 100% nylon fabrics. The average diameter of microcapsules ranged from 3 to 5 μm. Due to the greater volume of microcapsules their latent heat was higher and the latent heat of the coated fabric was about 14 J/g. This amount of latent heat was maintained after 30 launderings. The water repellence of a fabric coated with microPCMs was the same as for a coated fabric without PCM, but the water resistance decreased dramatically.

Shin *et al.*[18] prepared melamine–formaldehyde microcapsules containing eicosane by interfacial polymerisation. The mean diameter of the microcapsules was 1.89 μm and most of the microcapsules had a particle size of 0.1–10 μm. The core to shell ratio was about 53% and the heat storage capacity of the microcapsules was 143 J/g. The prepared microcapsules were added to polyester knitted fabrics by the conventional pad–dry–cure process. The treated fabrics had heat storage capacities of 0.91–4.41 J/g, depending on the addition of the microcapsules. After five launderings the treated fabrics retained 40% of their heat storage capacities. The results suggest that microcapsules with a higher core-to-shell ratio should be used to improve the thermoregulating properties of fabrics.

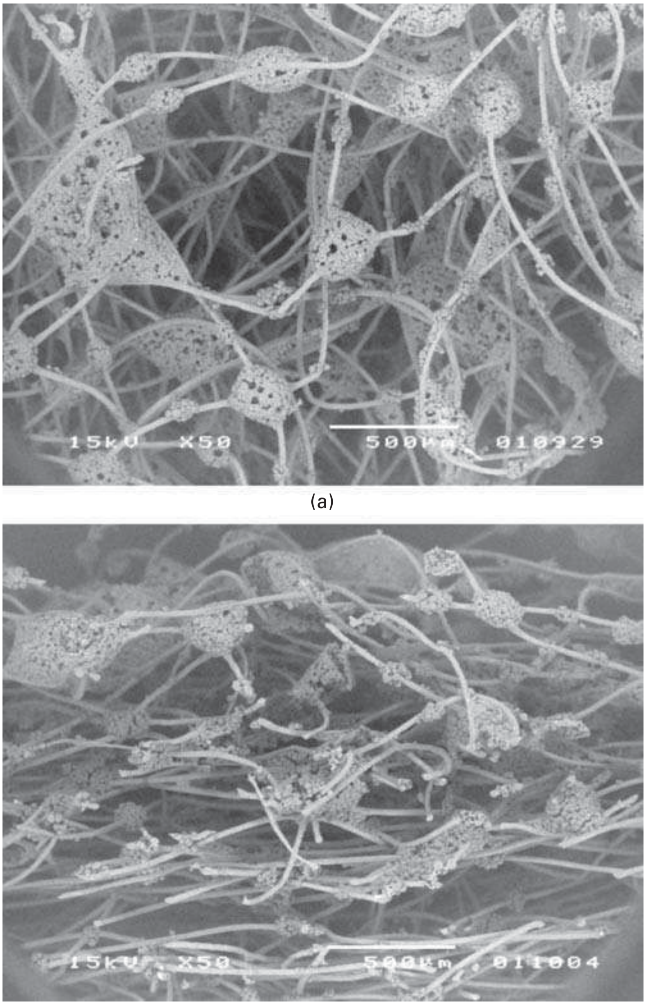
Lotenbach and Sutter[38] described a novel method of screen-printing on textile surfaces during which the print is provided in the form of naps containing a high concentration of microPCM. In their opinion, the accumulation of the PCM in the form of a number of naps largely preserves the elasticity as well as the substrate's ability to exchange vapour and moisture. Figure 4.6 shows the SEM picture of a nonwoven sample containing microPCM applied by the screen-printing technique. The PCM microcapsules occur on one side only, forming a very thin layer of 0.10–0.14 mm. In the sample of nonwovens prepared by the spraying method (Fig. 4.7) microPCMs occur on both sides in thin layers ca. 1.4 mm thick. In the samples of nonwoven prepared by pad-mangle method (Fig. 4.8) microPCMs occur in the entire cross-section of tested nonwovens.



4.6 Microphotographs of nonwoven sample with microPCM incorporated by screen printing. (a) surface of the nonwovens; (b) cross-section of the nonwovens.

4.4.5 Applications of textiles containing PCMs

Fabrics containing microPCMs have been used in a variety of applications including apparel, home textiles and technical textiles. Some exemplary applications are presented below.



(a)

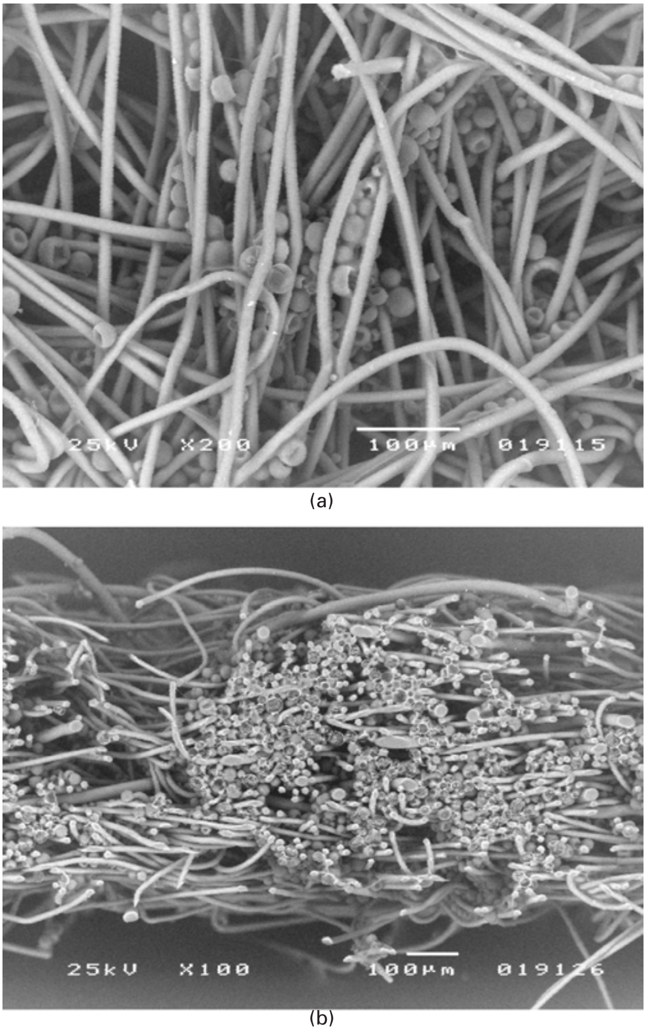
(b)

4.7 Microphotographs of nonwoven with microPCM incorporated by spraying. (a) surface of the nonwoven, (b) cross-section of the nonwoven.

Apparel

Major end-use areas include:

- life style apparel – smart jackets, vests, men's and women's hats, gloves and rainwear
- outdoor activewear apparel – jackets and jacket lining, boots, golf shoes, trekking shoes, socks, ski and snowboard gloves
- protective garments.



(a)

(b)

4.8 Microphotographs of nonwoven with microPCM incorporated by padding (a) surface of the nonwoven, (b) cross-section of the nonwoven.

In protective garments PCMs functions are as specified:

- absorption of body heat surplus
- insulation effect caused by heat emission of the PCM into the fibrous structure
- thermo-regulating effect, which maintains the microclimate temperature nearly constant.

Pause[39] described the application of PCMs in nonwoven protective garments used in pest control or the treatment of hazardous waste. In order to improve the wearing comfort of these protective garments, PCM was incorporated into a thin polymer film and applied to the inner side of the fabric system via lamination. The test results indicated that the cooling effect of the PCM can delay the temperature rise and hence limit the moisture rise in the microclimate. As a result, the wearing time of the garment can be extended without the occurrence of heat stress as a serious health risk.

Safety helmets have a thermal resistance of approximately 1.0 m^2 k/W and due to their structure the heat generated by the wearer can be dissipated only by means of convection. The results of tests carried out by Weder and Herring[40] indicated that an incorporation of microPCM in the helmet liner leads to substantial reduction of the microclimate temperature in the head area.

In the case of chemical or biological protective clothing a conflict between the protective function of clothing and the physiological regulation of body temperature may occur. The conflict led to discomfort and physical strain and in extreme cases can put the person at risk from heat stress. Colvin and Bryant[12] developed and patented microclimate cooling apparel for the military and civilians that can be used beneath protective garments to provide significant microclimate cooling for 1–3 hours under unusually high heat conditions. This cooling apparel uses macroenapsulated PCMs uniformly distributed within lightweight vests, helmet liners, cowls and neck collars. The diameter of macrocapsules ranges from 2 to 4 mm. The macrocapsules containing octadecan change phase at 26–28 °C. Other temperatures can also be selected by changing macroPCMs or by using mixtures of them to optimise their performance with different environmental conditions. The macrocapsules can be recharged without refrigeration.

Recently, the US Navy has investigated microPCMs inside divers' dry suits to thermal protection in extremely cold water applications. Nuckols[41] developed an analytical model of a dry suit system to predict its thermal performance in simulated ocean environments. The results of this study indicated that the foam with embedded microPCMs can reduce diver heat loss during the initial phase of dive by releasing the latent heat in microcapsules during the cold exposure. The result of this release of latent energy is lower temperature gradients on the inside of the suit. The reduction of diver heat loss will continue until the PCM in microcapsules solidifies, at this point the foam will behave as conventional suit insulation.

Domestic textiles

Employment of domestic textiles containing microPCM leads to an improvement of the thermal comfort of dwellings. Blinds and curtains with microPCMs can be used for reduction of the heat flux through windows. In the summer months large amounts of heat penetrate the buildings through windows during the day. At night in the winter months the windows are the main source of thermal loss. Results of the test carried out by Pause[42] on curtains containing microPCM have indicated a 30% reduction of the heat flux in comparison to curtains without PCM.

In rooms there is usually a temperature difference between floor and ceiling. During the heating period, this temperature difference can exceed 5 °C. The comfort sensation of human beings is especially dependent on the temperature gradient between floor and ceiling. The higher the temperature gradient the greater the feeling of discomfort. PCM can be used to reduce the temperature gradient between floor and ceiling and keep it constant over a specific period. By using floor coverings laminated with PU foam containing microPCM it is possible to improve the room climate.[42]

PCM is also used to improve the thermal comfort of upholstery products. This idea has been used in the development of the new office chair. While sitting in a chair, the heat flux from the body through the seat into the environment is essentially reduced leading to a rapid temperature increase in microclimate. The moisture transfer from the body through the seat into the environment is also reduced resulting in a substantial moisture increase in the microclimate. The cooling effect provided by the heat absorption of the PCM incorporated in the chair cushion leads to the lower temperature increase in the microclimate above the chair cushion and the reduction of the microclimate moisture content.[42]

The microencapsulated PCM can also be used to improve the thermal comfort of bedding, e.g., mattresses, mattress pads, pillows, blankets. Rock and Sharma[43] developed heating/warming textile articles with phase change components. A fibrous electric blanket with electrical resistance heating elements also contains a phase change component which releases and absorbs latent heat in cycles corresponding to on/off operation of a power source thus saving energy. The heating element is formed of a conductive yarn. Upon application of electrical power to the heating elements, heat is generated to increase the temperature within the blanket. During this ‘on’ period of heat generation the PCM incorporated into the blanket is also caused to change phase from solid to liquid. When a desired temperature is achieved, application of electrical power is discontinued. During this ‘off’ period heat is released from the blanket. The rate of heat loss – cooling action – is delayed by the release of latent heat by the PCM as it changes phase with cooling, from liquid back to solid.

Medical products

Buckley described[5] a therapeutic blanket made of a flexible PCM composite. If such a blanket contains a microPCM having a transition temperature below normal skin temperature, it can be used for cooling febrile patients in a careful and controlled manner. A careful selection of the phase change temperature makes it possible to avoid the danger of overcooling the patient that is inherent with ice packs. Alternatively, a blanket with PCM can be useful for gently and controllably reheating hypothermia patients. Another therapeutic medical use of the PCM is to incorporate it into elastic wraps or orthopaedic joint supports. Thus hot or cold therapy can be combined with supporting bandage for joints or muscles.

Automotive textiles

Barbara Pause demonstrated that there are substantial benefits in exploiting PCMs to moderate the temperature and comfort of the interior of an automobile.[44] Studies were carried out in order to select the appropriate PCMs, the necessary amounts, and a suitable location in the passenger compartment.[45] Results of these studies show that by using microPCMs containing hydrocarbons integrated into textiles, particularly in headliner and seating materials, interior temperature reductions of 2–4 °C can be obtained, along with less moisture build-up, reducing the load on the air-conditioning unit and thereby saving energy.

Air-conditioning buildings with PCM

Recently PCMs have been studied for application to solar thermal storage and air conditioning in domestic buildings. By PCM applications in coatings for textiles used in roof covering, the thermal insulation value may be greatly enhanced. After the PCM has absorbed the surplus heat during the day it can be recharged by the overnight cooling effect. Pause described[42] a special panel system with PCM, which can be used for increasing the thermal resistance of lightweight construction walls. The main element of this panel is the cell structure, which is made of a textile reinforced material and filled with PCM. The quantity of the PCM contained in the panel is equivalent to a thermal storage of 700 kJ. Computer simulations have indicated that application of this panel can provide energy savings of about 20%.

4.5 Measurement of thermoregulating properties of fabrics with microPCMs

Fabrics containing PCM microcapsules present a unique challenge to the standard test procedures used for determining the thermal properties of fabrics. In the case of traditional fabrics, the thermal properties are investigated by standard steady state procedures involving the use of guarded hot plate apparatus. Steady state procedure is inadequate in assessing the dynamic performance of the fabrics containing PCMs, because PCM is a highly productive thermal storage medium. Hittle and Andre[46] formulated a model of heat transfer through a textile containing PCM, and based on this model the new test instrument and testing procedure has been developed. In 2004 ASTM standardised this test method.[47]

4.5.1 Heat transfer through textiles containing PCM

Heat conduction through a one-dimensional homogeneous material is governed by the following second-order partial differential equation:

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} \qquad 4.1$$

where:

T = temperature at position x

t = time

α = thermal diffusivity $\alpha = \frac{k}{\rho C_p}$

k = thermal conductivity (W/m K)

ρ = density (kg/m^3)

C_p = specific heat (J/kg K).

The heat flux at position x and time t is given by eqn 4.2:

$$q(x,t) = -k\frac{\partial T(x,t)}{\partial x} \qquad 4.2$$

Hittle and Andre assumed that in both equations k, ρ i C_p are constant. Additionally, they assumed that a constant and comparably large C_p in the temperature region of the phase change is a reasonable approximation for the energy storage of the PCM in the fabric. This assumption leads to a convenient metric called temperature regulating factor (TRF).

Hittle and Andre gave a solution to the above equations for sinusoidal boundary conditions. In order to characterise the thermoregulation effect they have proposed the use of the quotient of the amplitude of the temperature variation and the amplitude of the heat flux variation present in this solution. The smaller the quotient the better the regulation effect.

Dividing this quotient by the value of the steady state thermal resistance of the fabric (R) they obtained TRF value:

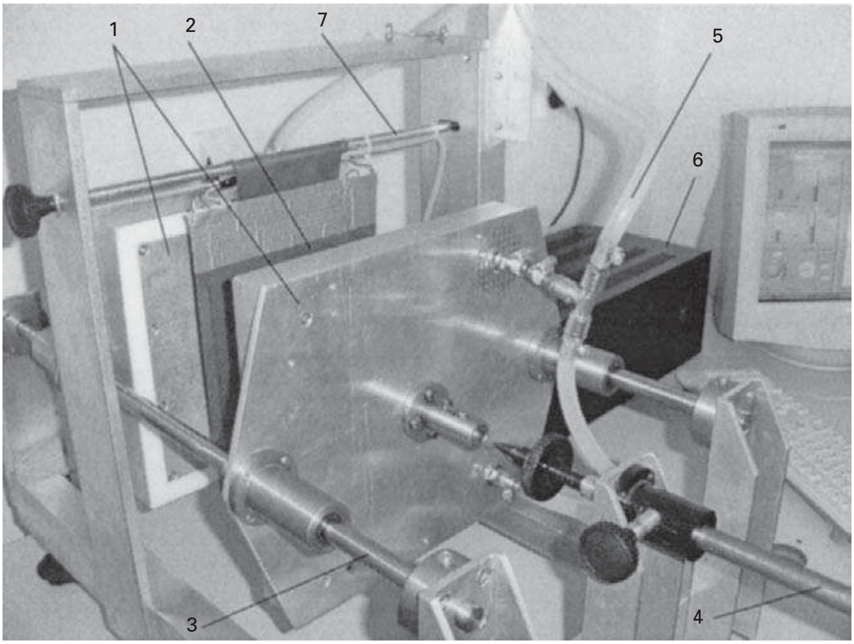
$$\mathrm{TRF} = \frac{(T_{max} - T_{min})}{(q_{max} - q_{min})}\frac{1}{R} \qquad 4.3$$

TRF is a dimensionless number varying in range (0,1). TRF shows how well a fabric containing microPCM moderates the hot plate temperature. A TRF value of 1, means the fabric has no capacitance and poor temperature regulation.

If TRF equals zero, it means that the fabric has infinite capacitance and that a body being in contact with it will remain at a constant temperature. It is obvious that all fabrics fall somewhere between these extreme values. TRF is a function of the frequency of the sinusoidal variation of the heat flux into the hot plate. The temperature regulation increases with increasing frequency. Hence TRF increases with increasing cycle time of sinusoidal variation, going exponentially from 0 to 1.

4.5.2 Principle of measuring

Determination of the temperature regulating factor (TRF) of apparel fabrics is done by means of the instrument which uses a dynamic heat source (Fig. 4.9). This instrument simulates an arrangement: skin–apparel–environment. The fabric sample is sandwiched between a hot plate and two cold plates, one on either side of the hot plate. These cold plates at constant temperature simulate the environment outside the apparel. Sinusoidally varying heat input to the hot plate simulates human activity. To measure the steady state thermal resistance of the fabric (R), the controlled heat flux is constant and the test



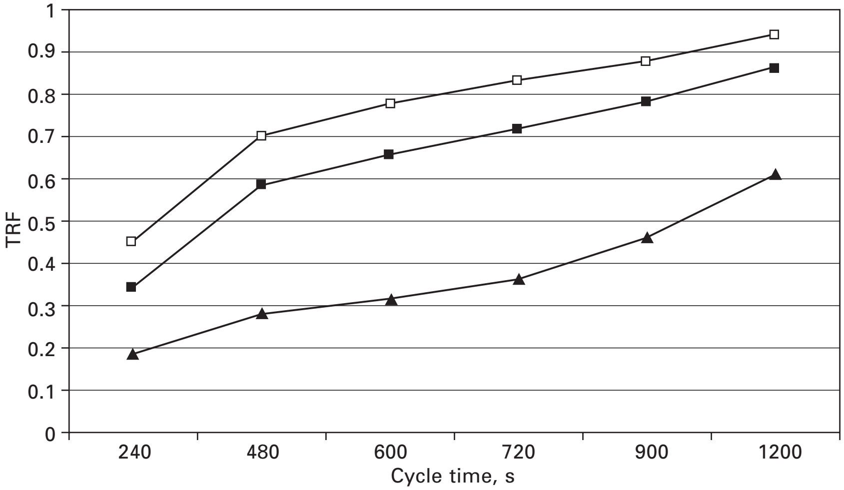
4.9 General view of the apparatus to determine temperature regulating factor (TRF). 1, cold plates; 2, hot plate; 3, guide bars; 4, cold plates pressure adjustment; 5, cooling water supply to cold plates; 6, thermostat with Peltier cells; 7, sample holder.

proceeds until steady state is reached. To assess temperature regulating ability, the heat flux is varied sinusoidally with time and the temperature regulating factor (TRF) is determined. This is a function of the frequency of the sinusoidal variation of the heat flux into the hot plate. The temperature regulation increases with increasing frequency. Hence TRF increases with increasing cycle time of sinusoidal variation, going exponentially from 0 to 1.

Examples

Since 2002 a systematic study involving nonwoven fabrics containing PCMs has been conducted at Instytut Włókiennictwa (Textile Research Institute, Poland). In this study microencapsulated octadecane and eicosane was used. MicroPCMs dispersed in acrylic-butadiene copolymer were applied on polyester hydroentangled nonwovens by the screen-printing method or the pad-mangle method.

Figure 4.10 shows TRFs as a function of cycle time for nonwoven samples treated by the pad-mangle method. Tested nonwoven samples differ in microPCM mass contained in one square metre of the nonwoven; this means they differ in thermal capacitance. The diagram also shows, for comparison needs, the curve of reference nonwoven, i.e., not containing microPCM. We can see that nonwovens with microPCM exhibit lower TRF values in the whole range of cycle times of heat flux changes when compared to the reference nonwoven. This is due to the increase of nonwoven thermal



4.10 TRF as a function of cycle time (padded nonwoven samples). ☐ NP41/0 nonwoven sample without microPCM; ▲ NP41/95 padded nonwoven sample with microPCM (24.3% microPCM); ■ NP15/95 padded nonwoven sample with microPCM (36.1% microPCM).

Table 4.2 Characteristics of tested nonwovens

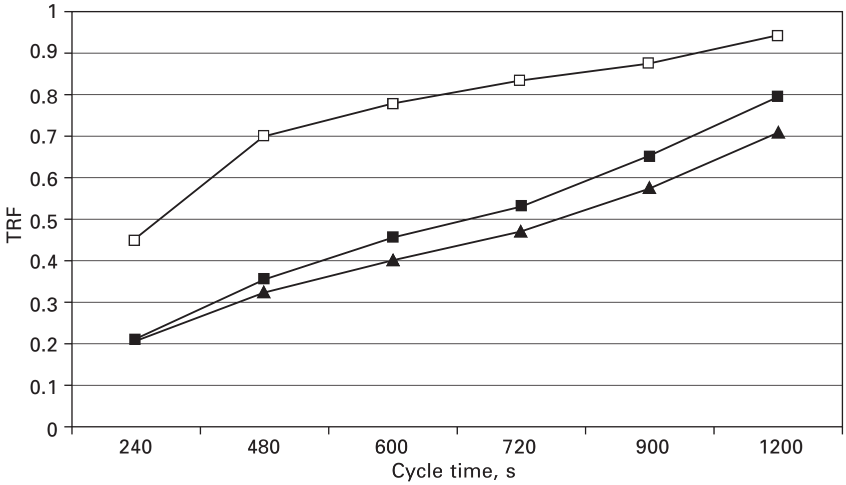
Sample	Area weight g/m^2	Thickness mm	Percentage of microPCM (on weight) %	Latent heat/m^2 of nonwovens kJ/m^2
NP41/0	97	0.78	0	–
NP41/95	133	0.78	24.3	6.0
NP15/95	182	0.83	36.1	12.0

capacitance resulting from the incorporation of microPCM. It can be observed that with the increase in microPCM mass contained in one square metre of nonwoven there occurs an improvement of thermoregulating properties defined by the lower TRF value.

Figure 4.11 shows the results of determination of the temperature regulating factor for the assemblies of nonwovens. The whole assembly was composed of two nonwovens:

1. hydroentangled nonwoven with microPCM incorporated by screen-printing, denoted DR1/95
2. needled nonwoven without microPCM, denoted NAdg.

Measurements of TRF performed on the assembly: needled nonwoven without microPCM + printed nonwoven indicated that the location of the surface



4.11 TRF as a function of cycle time for nonwoven assemblies. ☐ nonwoven assembly without PCM (DR1/0 + Nadg); ■ nonwoven assembly DR1/95 + Nadg , printed side in contact with hot plate; ▲ nonwoven assembly DR1/95 + Nadg, nonprinted side in contact with hot plate (Nadg – needled nonwoven without PCM).

covered with a microPCM layer towards the hot plate has a substantial influence on the TRF value. When a printed surface contacts the hot plate TRF values are higher than in the case where a non-printed surface contacts the hot plate. The examples above show that the new testing method can provide information for fabric and garment designers and can be useful in quality control during manufacture of fabrics with microPCMs.

4.6 Summary

It is evident from the literature reviewed that studies on the application of microPCM technology in the textile industry and properties of textiles containing microPCMs are at the beginning. Fabrics containing PCMs are particularly attractive to the apparel industry because of their ability to improve clothing comfort. Preliminary studies clearly demonstrate the suitability of fabrics with PCMs for protective clothing and home textiles. To assess the impact of PCMs for specific applications a basic study on heat and moisture transfer in textiles with PCMs has to be continued. Probably over the next decade many new products based on microPCMs technology will be produced and commercialised.

4.7 Acknowledgements

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5

The use of phase change materials in outdoor clothing

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5.1 Introduction

Phase change materials (PCMs) store and release thermal energy as they go through solid-liquid transitions. PCMs used in textiles are combinations of different types of paraffins – each with different melting and crystallization (i.e., freezing) points. By changing the proportionate amounts of each type of paraffin in the phase change material (e.g., hexadecane, octadecane), desired melting and freezing points can be obtained. The PCMs are enclosed in a protective wrapping, or microcapsule, a few microns in diameter. The microcapsule prevents leakage of the material during its liquid phase (Bryant and Colvin, 1992). Microcapsules of phase change materials can be incorporated into the spinning dope of manufactured fibers (e.g., acrylic), incorporated into the structure of foams, and coated onto fabrics.

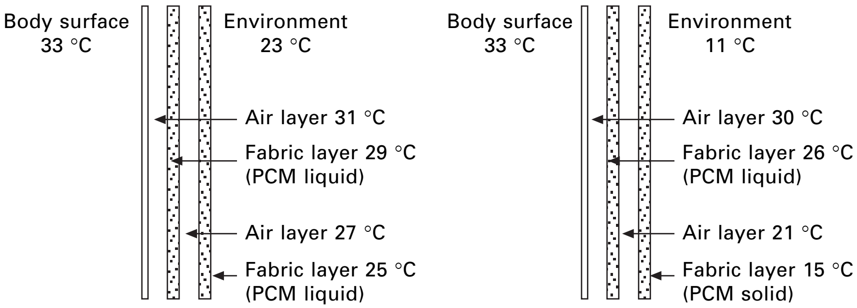
When the encapsulated PCM is heated to the melting point, it absorbs heat energy as it goes from a solid state to a liquid state. This phase change produces a temporary cooling effect in the clothing layers. The heat energy may come from the body (e.g., when the wearer first dons the garment) or from a warm environment. Once the PCM has completely melted, the storage of heat stops. If the PCM garment is worn in a cold environment where the temperature is below the PCM's freezing point, and the fabric temperature drops below this transition temperature, the micro-encapsulated liquid PCM will change back to a solid state, generating heat energy and a temporary warming effect. The developers claim that this heat exchange produces a buffering effect in clothing, minimizing changes in skin temperature and prolonging the thermal comfort of the wearer.

The clothing layer(s) containing PCMs must go through the transition temperature range before the PCMs will change phase and either generate or absorb heat. Consequently, the wearer has to do something to cause the temperature of the PCM fabric to change. PCMs are a transient phenomenon; they have no effect under steady-state thermal conditions.

5.1.1 Change in environmental temperature

Some people have jobs where they go to and from a cold storage facility or transport vehicle and a warm building or outside environment on an intermittent basis. PCM protective garments should improve the comfort of workers as they go through these environmental step changes (e.g., warm to cold to warm, etc.). For these applications, the PCM transition temperature should be set so that the PCMs are in the liquid phase when worn in the warm environment and in the solid phase in the cold environment.

The developers and producers of phase change materials in textiles claim that garments made with PCMs or 'dynamic insulation' will keep a person warm longer than conventional insulations when worn in cold environments. They also claim that the use of PCMs in outdoor clothing will decrease the thickness and weight of the clothing required (Pause, 1998). There is no question that a phase change material will liberate heat when it changes from a liquid to a solid. However, in order for PCMs to improve the thermal comfort characteristics of a clothing ensemble in a cold environment, they must produce enough heat in the garment layers to reduce heat loss from the body to the environment. Even if all of the garments in a clothing ensemble were treated with PCMs, not all of the PCM microcapsules would go through phase changes when the wearer went from an indoor environment to a cold environment. (See Fig. 5.1.) Heat flows from the warm body to the cooler environment, and there is a temperature gradient from the skin surface through the clothing layers to the environment. The PCMs closest to the body (e.g., in long underwear or socks) will probably remain close to skin temperature and stay in the liquid state even when the wearer moves to the colder environment. PCMs in the outermost layers of clothing will probably get



5.1 In a warm indoor environment (left), the two PCM fabric layers are above the 20°C transition temperature, and the PCMs are in the liquid state. When the wearer enters a cold environment, the temperature gradient from the warm body to the cold air changes and the temperature of the outermost fabric layer drops below 20 °C; the PCMs solidify, producing heat.

cold and solidify, thus producing some heat. However, in the outer layers of clothing, a portion of the heat would be lost to the cold environment. Once the PCMs have changed from a liquid to a solid, the liberation of heat energy is over. Consequently, a good insulation system with adequate thickness is still necessary for thermal comfort and safety during extended exposure to cold environments.

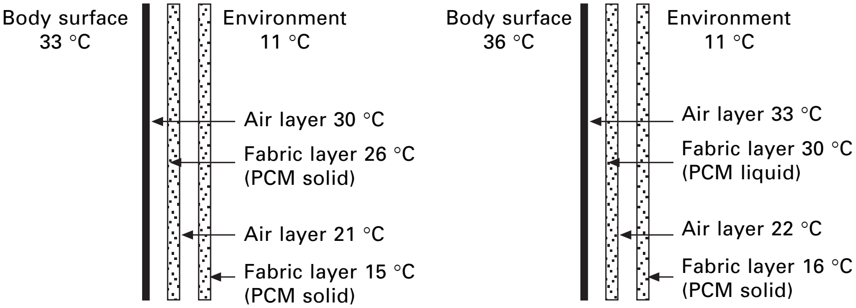
When workers wear flame resistant clothing and are exposed to high environmental temperatures for short periods of time (e.g., race car drivers), PCMs may improve their comfort and/or safety by providing a short-term cooling effect. In these circumstances, changing the PCM back to a solid and liberating heat would not be necessary or desirable. However, the addition of paraffin-based PCMs to fabrics may increase their flammability. If this becomes a problem, the PCMs could be used in garment layers under a flame resistant outer shell.

Some jobs require workers to handle hot or cold objects. In these instances, the PCM transition temperature should be set between the ambient environment and the temperature of either hot or cold objects. If the workers touch the objects repeatedly for short periods of time, (so that the PCMs have time to change back to their initial state in the ambient environment), the resulting buffering effect would continue, and thinner materials could probably be used in the gloves.

5.1.2 Change in skin temperature

In some jobs and sports (e.g., skiing), people are very active and inactive on an intermittent basis. As the activity level of a person increases, so does the amount of heat produced by the body. The companies that produce PCM garments claim that PCMs will improve the comfort of people as they go through changes in activity and metabolic heat production. They are assuming that PCM garments will absorb some of the extra body heat produced during exercise, change to the liquid state, and produce a temporary cooling effect (Cox, 1998). When the person becomes inactive, the PCMs will solidify again and liberate heat (assuming the air temperature stays below skin temperature). This has been called the 'thermal regulating effect' of PCMs.

For PCMs to work in this scenario, the transition temperature would have to be set between the highest and lowest skin temperatures resulting from changes in metabolic heat production. A person's skin temperature changes only a few degrees during exercise, even when a large amount of heat is being generated by the body. For example, when a person is downhill skiing, he/she may produce about five times more body heat than he/she would produce while sitting. However, the skin temperature does not increase by a proportionate amount. First, the blood vessels near the skin surface vasodilate, raising the skin temperature slightly, and increasing the temperature gradient



5.2 When a person is sitting in a cold environment, his skin temperature is 33 °C and the two PCM layers are below the 30 °C transition temperature. When he/she becomes active, the skin temperature rises to 36 °C and the temperature of the inner layer increases to 30 °C; the PCMs liquefy, producing a cooling effect.

for heat loss to the environment. (See Fig. 5.2.) However, this physiological response is not adequate for getting rid of the excess body heat produced during vigorous exercise. Consequently, the body begins producing sweat at the skin surface. The process of changing liquid sweat to vapor is a phase change in itself which takes heat from the body surface, providing a natural cooling effect. The sweat is the same temperature as the skin and has a minimal effect on the temperature of the clothing layers as it diffuses through them. Even if the PCMs in the innermost clothing layer liquefy and produce a cooling effect, the PCMs in the outermost layer may not.

Skin temperatures vary on different parts of the body. For example, the average temperature of the head is higher than that of the feet. In addition, the variability of skin temperatures from person to person is often greater than the change in skin temperature of one person due to exercise. Therefore, producing PCM thermal regulating effects that result from small changes in skin temperature is a difficult challenge for designers and manufacturers of protective clothing.

5.1.3 The need for research

Most of the published research that is available in the scientific literature was conducted on small pieces of fabric – not on garments – where it is relatively easy to demonstrate and quantify the heating and cooling effect (Pause, 1994, 1995, 1998; Cox, 1998). The magnitude and duration of the phase change heating and cooling effects on a clothed body have not been documented in the scientific literature**.** Factors such as the amount of PCM in a garment layer, the melting/freezing points of the PCMs incorporated in each garment layer, the number of PCM garment layers in a clothing ensemble, the amount of body surface area covered by garments with PCMs, the looseness or tightness of fit, and the effect of mixing garment layers with and without PCMs will influence the amount of heat in the clothing that actually affects body heat loss and the thermal comfort of the wearer.

The addition of the phase change materials to fibers, fabrics, or foams may change certain textile properties, so these effects need to be measured. Studies have shown that PCMs increase the weight of textile structures (Pause, 1994, 1995), and decrease the strength and elongation of fabrics (Bryant and Colvin, 1992). Changes in physical properties will vary depending upon what percentage of PCM by weight is used in the textile, and they should be measured prior to use in garments.

5.1.4 Purpose

Currently, phase change materials are being used in a variety of outdoor apparel items (e.g., gloves, boots, jackets, earmuffs, etc.) under the trade names Outlast™ and ComforTemp^{R}. The addition of PCMs to fibers, foams, and fabrics substantially increases the price of the textile. The price increase varies based on the volume being produced and the percent by weight of PCM that is added. Considering product safety, performance, and cost issues, the effect of PCMs in types of garments worn in cold environments on thermal comfort should be investigated prior to their use. Therefore, the purpose of this project was to quantify the effect of PCMs in fabric-backed foams on selected fabric characteristics (Phase I), on heat loss from a thermal manikin's surface to the environment during environmental temperature transients (Phase II), and on human subjects' physiological responses and comfort perceptions during environmental temperature transients and changes in activity (Phase III). Identical fabrics and garments – with and without the PCMs – were compared.

5.2 Methodology

5.2.1 Materials and garments

An open-cell, hydrophilic polyurethane foam was produced directly on a fabric substrate of polyester knitted fleece. The experimental foam contained 60% PCM microcapsules and 40% foam (by weight), whereas, the control foam contained 100% polyurethane foam. Approximately 40% of the PCM microcapsules contained 75% octadecane and 25% of other chemicals that change phase at 28.3 °C (83 °F), and 60% of them contained 75% hexadecane and 25% of other chemicals that change phase at 18.3 °C (65 °F).

The experimental suits for the manikin tests consisted of a long-sleeved, fitted top that was about one inch longer than waist level and a pair of fitted long pants. Two sets of each garment were produced with the experimental and control materials (i.e., four suits total). The second suit was slightly larger than the first to minimize compression when the two garments were worn together. The PCM treated foam side of the fabric was on the outside of each garment (i.e., away from the body). The garments in the ensemble were designed to minimize overlap so that the layering effects of treated and untreated garments could be controlled. The manikin's head was covered with a knitted wool hat. His hands were covered with knitted polyester fleece gloves. His feet were covered with ankle length knitted acrylic socks and athletic shoes. Manikin tests were conducted on one layer and two layer suits, and the orientation of the PCM layer to the body and the amount of PCM coverage were evaluated using two layer combinations.

Ski jackets and ski pants – with and without the PCMs – were made for the manikin and human tests. The ski garments were made of the same fabric-backed foam as the experimental suits with a woven nylon shell fabric used as the outside layer. The ski garments were worn with a 50% cotton/50% polyester, long-sleeve, turtleneck knitted shirt, men's briefs, and the auxiliary garments listed above.

5.2.2 Phase I: measurement of textile properties

The textile samples were conditioned at the standard temperature of 21 °C (69.8 °F) and relative humidity (65%) at least 24 hours prior to testing, according to ASTM D 1776, Standard Practice for Conditioning Textiles (ASTM, 2000). Fabric stiffness was measured according to ASTM D 1388, Standard Test Method for Stiffness of Fabrics. Four specimens measuring 2.54 cm × 20 cm (1 in. × 8 in.) were cut from each fabric with the long direction parallel to the wales and four with the long direction parallel to the courses. To conduct a test, a specimen was moved parallel to its long dimension on the platform of the cantilever and allowed to bend 41.5° under its own weight. Then the overall flexural rigidity (i.e., stiffness) was calculated. Fabric thickness was measured according to ASTM D 1777, Standard Test Method for Measuring Thickness of Textile Materials, using a pressure foot 7.6 cm (3 in.) in diameter under 0.117 kPa (0.017 psi) of pressure. The average thickness was determined from ten readings on each fabric. Fabric weight was measured according to ASTM D 3776, Standard Test Methods for Mass Per Unit Area (Weight) of Woven Fabric, option C on small swatch of fabric. Two specimens measuring 13 cm × 13 cm (5 in. × 5 in.) were weighed on a Mettler balance. The mean weight per unit area for each fabric was reported. Fabric flammability was measured according to ASTM D 2863, Standard Test Method for Measuring Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index). Oxygen Index is defined as the minimum concentration of oxygen, expressed as volume percent, in a mixture of oxygen and nitrogen that will support flaming combustion of a material initially at room temperature under equilibrium conditions of candle-like burning. Ten specimens measuring 5.1 cm × 12.7 cm (2 in. × 5 in.) were tested, and the average oxygen index values for the fabrics were reported. The lower the OI value, the higher the flammability of a fabric.

The fabric insulation value (i.e., resistance to dry heat transfer) was measured using the constant temperature method specified in Part A of ASTM F 1868, Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate (ASTM, 2000). The hot plate measurement section was a 25.4 cm × 25.4 cm (10 in. × 10 in.) square surrounded by a 5 in. (12.7 cm) guard section. The three specimens measuring 50.8 cm × 50.8 cm (20 in. × 20 in.) were tested at a 20 °C (68 °F) air temperature, 50% relative humidity, and 0.7 m/s (140 ft/m) average air velocity under the hood. The plate temperature was maintained at 35 °C (95 °F). Each fabric was placed on the horizontal, flat plate so that the fleece side was next to the plate. When the system had reached steady-state, data including the plate surface temperature, air temperature, dew point temperature, and current and voltage to the test section were collected by computer for 30 minutes. The insulation value for the fabric alone was determined by subtracting the mean dry resistance value measured for the air layer (i.e., bare plate test) from the mean insulation value for the total fabric system.

The evaporative resistance of the fabrics was measured using the method specified in Part B of ASTM F 1868. A liquid barrier (PTFE film laminated to a tricot knit fabric) was placed on the plate to prevent the water (which is supplied through the porous metal in the plate surface) from wetting the fabric. In this way only water vapor had contact with the fabric sample, not liquid water. The procedures were basically the same as those for the dry tests. However, the air temperature was the same as the plate temperature so that there was no temperature gradient for dry heat loss, and the relative humidity was 40%. This is called an isothermal test.

5.2.3 Phase II: environmental step change tests with a manikin

A life-size, computerized, thermal manikin was used to simulate the heat loss from a human being to a cooler environment and to measure the insulation (clo) value of the clothing systems. Fred is a full-size male manikin with 18 electrically separate segments which provide independent temperature control and measurement. The manikin's skin temperature distribution corresponds to the temperatures on different parts of the body when a person is sedentary and comfortable.

In order to make the phase change materials go from liquid to solid and vice versa, they must go through a temperature change, and a transient test must be conducted. The environmental temperature transient was achieved by using two adjacent environmental chambers. One chamber simulated a warm indoor environment: 25 °C (77 °F) air temperature, 50% relative humidity, and 0.2 m/s (39.4 ft/min) air velocity. For the warm condition, we selected the highest 'indoor' temperature that would still permit heat loss from all of Fred's body segments when he was dressed in the most insulative ensemble (i.e., the ski ensemble). The 25 °C (77 °F) temperature maximized the amount of PCM that actually liquefied when the garments were worn on the manikin while maintaining a temperature gradient between the manikin's skin temperature and the environment that allowed body heat loss to occur. Another chamber simulated a cold outdoor environment: 10 °C (50 °F) air temperature, 75% relative humidity, and 0.2 m/s air velocity (39.4 ft/min). For the cold condition, we selected the lowest 'outdoor' temperature that would allow the manikin's body segments to reach their set points when he was dressed in the least insulative ensemble (i.e., the one layer experimental suit).

An overhead track was mounted between the two chambers, and the manikin hung from this track on a roller hooked to his head. This arrangement allowed the manikin to be moved from one chamber to the other very quickly (i.e., 1–2 minutes) and with minimal disruption. The air temperature and dew point temperature were measured continuously in each chamber. The garments were conditioned in the warm chamber. To conduct a test, the manikin was placed in the warm chamber and dressed in a specific set of garments. For the tests, the manikin was heated to an average skin temperature of 33.2 °C (92 °F).

Equilibrium was maintained for at least one hour prior to testing. First, the insulation (clo) value of the clothing and the average level of body heat loss were measured according to ASTM F 1291, Standard Test Method for Measuring the Thermal Insulation of Clothing using a Heated Manikin (ASTM, 2000). Data were collected by computer every 30 seconds for a 30 minute test. The total thermal insulation value of the clothing plus the surrounding air layer was calculated using eqn 5.1 and multiplying by 6.45 to convert SI units to clo units.

$$R_t = \frac{(T_s - T_a)A_s}{H} \qquad 5.1$$

where

R_t = resistance to dry heat transfer provided by the clothing and air layer, m^2 °C/W

A = surface area of the manikin, m^2

T_s = surface temperature of the manikin, °C

T_a = air temperature, °C

H = heat flow, W

The amount of power that it takes to keep the manikin heated to the proper skin temperature is equal to the amount of heat loss from his body surface.

After the baseline insulation and heat loss data were collected under steady-state conditions in the indoor environment, the manikin was moved quickly to the adjacent cold chamber. The power level to the manikin was recorded every minute during the transient. After the transient was over, the insulation value and the average power level at steady-state in the cold environment were measured again. The process was repeated as the manikin was moved back to the warm chamber. The entire transient test took about six hours. Two replications of each test were conducted.

5.2.4 Phase III: exercise/rest tests with human subjects

A one-way treatment structure in a randomized complete block design (where subjects served as blocks) was used to determine the effect of phase change materials (independent variable) on the skin temperatures, thermal sensations, and clothing comfort sensations perceived by 16 male subjects (dependent variables) during an exercise/rest protocol that simulated skiing. In addition, the amount of unevaporated sweat in the ski ensemble was determined by weighing the garments before and after the experiment. The amount of sweat per unit area was determined by weighing a cotton pad before and after placing it on a subject's back. Each subject wore two ski ensembles – one with the PCM fabric-backed foam and one without the PCM – in a random order.

The experiment began in a warm chamber with an air temperature of 25 °C (77 °F), 50% relative humidity, and an air velocity of 0.2 m/s (39.4 ft/min). Then the subjects moved to an adjacent cold chamber with an air temperature of –4 °C (24.8 °F), 65% relative humidity, and an air velocity of 0.2 m/s (39.4 ft/min). When the subjects arrived for a test session, they went inside the warm environmental chamber and took off their clothes (except briefs). Then the experimenter attached thermocouples on the subjects' skin with transpore tape on the pectoral region of the chest, the radial surface of the forearm, the fibular surface of the calf, and the tip of the middle finger. Cotton cosmetic pads measuring 5.1 cm × 5.7 cm (2 in. × 2.25 in.) were oven-dried at 93 °C (200 °F) for one hour, placed in an air-tight container, and weighed. The cotton pads were taped to the back of each subject at the same time, ten minutes before the experiment began. Plastic vinyl measuring 6.35 cm × 7.0 cm (2.5 in. × 2.75 in.) was used to cover the cotton pad, and plastic tape was used to seal it tightly to the skin. Then the subjects put on the ski ensemble, except for the gloves and hat.

The activities of the subjects were designed to simulate the metabolic heat production of a male who is alternately sitting (as on a ski lift) and skiing. Sitting produces about 1 MET of heat and skiing produces about 5.5 MET (McArdle *et al.*, 1981). The speed and incline of the treadmill that would generate 5.5 MET of heat production was determined using procedures given in *Guidelines for Exercise Testing and Prescription* (American College of Sports Medicine, 1995). The exercise/rest protocol is listed below:

0–15 minutes, 1 MET: subjects sat in the warm, ambient environment.
16–30 minutes, 1 MET: subjects put on their hat and gloves and sat in the cold chamber.
31–45 minutes, 5.5 MET: subjects walked on a treadmill at 4.0 mph and a 3% incline in the cold.
46–60 minutes, 1 MET: subjects sat in the cold.
61–75 minutes, 5.5 MET: subjects walked on the treadmill again in the cold.
76–90 minutes, 1 MET: subjects sat in the cold.

After going through the exercise/rest protocol, the subjects returned to the warm environment and removed their clothes and thermocouples. The experimenter put each subject's turtleneck knitted shirt, jacket, and pants in a plastic garbage bag, sealed it, and weighed it. The experimenter removed the cotton pad from each subject's back and put it in an air-tight container and weighed it. The turtleneck knitted shirts and socks were laundered and conditioned in preparation for the next test. The jackets and pants were dried in a tumble drier on low heat to remove the moisture prior to conditioning for the next test.

The subjects' four skin temperatures were measured every minute during the exercise/rest protocol using a computerized data acquisition system. Thermal sensation and clothing comfort responses were measured at the end of each 15 minute period using ballots. Thermal sensation was rated from #1 very cold to #5 neutral to #9 very hot. The clothing comfort of the ski ensemble was rated from #1 uncomfortable to #5 comfortable and from #1 clammy to #5 dry using a semantic differential scale.

5.3 Results

5.3.1 Phase I: measurement of textile properties

Separate one-way analyses of variance were used to determine the effect of PCMs on various textile properties. (See Table 5.1.) The PCM foam had a significantly higher insulation value and evaporative resistance value than the control foam. The insulation value may have been higher in the PCM foam because it was significantly thicker. The evaporative resistance may have been higher in the PCM foam because it was thicker and because the PCM microcapsules displaced air in the foam structure and inhibited diffusion. This might be a problem when PCMs are coated on fabrics also, but it would not be a problem when PCMs are put inside manufactured fibers. The PCM foam had a significantly higher weight and stiffness than the control foam.

Table 5.1 Physical properties of fabric-backed foam – with and without phase change materials

Physical property	Foam with PCM	Foam without PCM
Fabric thickness	4.13**	3.44**
Fabric weight (g/m^2)	455.2**	267.4**
Fabric stiffness (mg ≅ cm)	2924.9**	2089.4**
Oxygen index (flammability)[a]	18.5**	19.2**
Fabric insulation (m^2 · °C/W)	0.120*	0.111*
(clo units)	(0.774)	(0.714)
Fabric evaporative resistance (m^2 · kPa/W)	0.0120**	0.0096**
Insulation per unit thickness (clo/mm)	0.187	0.208
Insulation per unit weight (clo/g/m^2)	0.002	0.003

[a] The lower the index number, the higher the flammability.

*Means were significantly different at the 0.05 level.

**Means were significantly different at the 0.01 level.

It was also significantly more flammable. The PCM foam had an oxygen index value of 18.5 which was similar to that of a cotton fabric. Therefore, the addition of the PCM microcapsules to the fabric-backed foam significantly altered its properties as compared to those of the fabric-backed foam without PCMs. The increases in stiffness, flammability, evaporative resistance, and weight are not desirable for cold-weather clothing, but a higher insulation value is desirable.

5.3.2 Phase II: environmental step change tests with a manikin

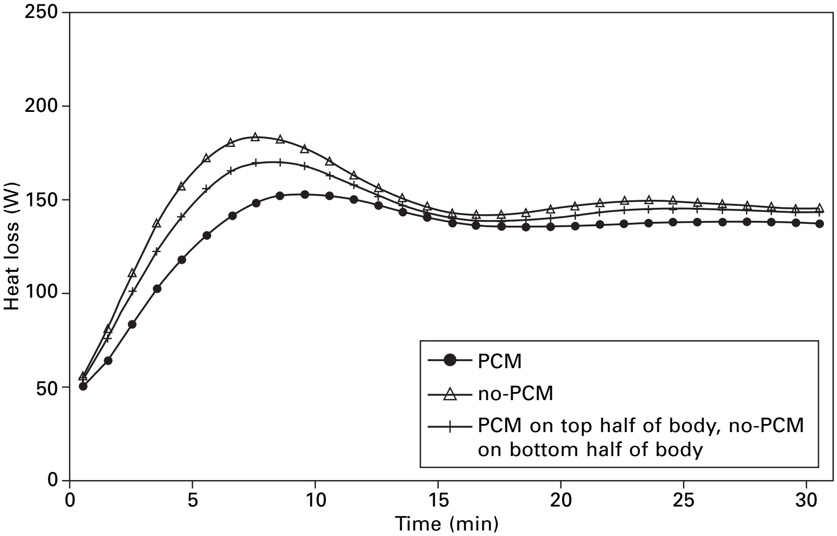
Steady-state manikin tests

Insulation values for the PCM suits were slightly higher than those measured for the suits without PCM, probably because the PCM fabric-backed foam had a higher insulation value, as measured in the hot plate test. The one layer suit with PCM was 1.57 clo and without PCM was 1.48 clo. The two layer suit with PCM was 2.07 clo and without PCM was 1.95 clo. In addition, the heat loss values were lower for the PCM foam. The insulation values for the ski ensembles with and without PCM were the same (2.19 clo). The ski ensemble fit more loosely and had more air layers between the garments compared to the tight-fitting experimental suits. Air layers have a major effect on the thermal insulation of a clothing system, and they were about the same in both ensembles since the same pattern was used to make them. Also the auxiliary garments (e.g., hat, gloves) were the same in both ensembles, so small differences in the fabric insulation did not have much effect on the overall ensemble insulation.

Treatment of transient manikin data

Heat loss data from two replications of the environmental transient tests with the manikin were averaged for each minute of the data collection period. Data were collected for one hour in each chamber, but only the first 30 minutes were graphed because the effect of the PCM was usually over in 15 minutes. The experimental suits – with and without the PCM – were not exactly identical with respect to their heat loss and insulation values under steady-state conditions. Therefore, the heat loss curves for the PCM suits were slightly lower than they would have been if they had been identical to the control suits. (See Fig. 5.3.)

To correct this problem, the average heat loss measured for each suit at steady-state was used to correct the transient data (Shim *et al.*, 2001). Then the difference between the PCM curve and the no-PCM curve (i.e., the buffering effect of the phase change material) was plotted for each suit type. The difference curves indicated that the effect of the phase change materials on body heat loss lasted approximately 15 minutes. Therefore, the magnitude of this buffering effect was calculated and reported as the integrated total difference in heat loss for the 15 minute period (J) and as the average difference in the rate of heat loss during the 15 minute period (W). (See Table 5.2.) The PCM heating effect (during a warm to cold environmental transient) and the PCM cooling effect (during a cold to warm transient) are the resulting differences in body heat loss to the environment. This is not the amount of



5.3 Warm to cold: average heat loss from the manikin wearing the two-layer suits – with PCM, with PCM on top half of body, and no-PCM control.

Table 5.2 Heating/cooling effects of clothing during the first 15 minutes of environmental temperature transients

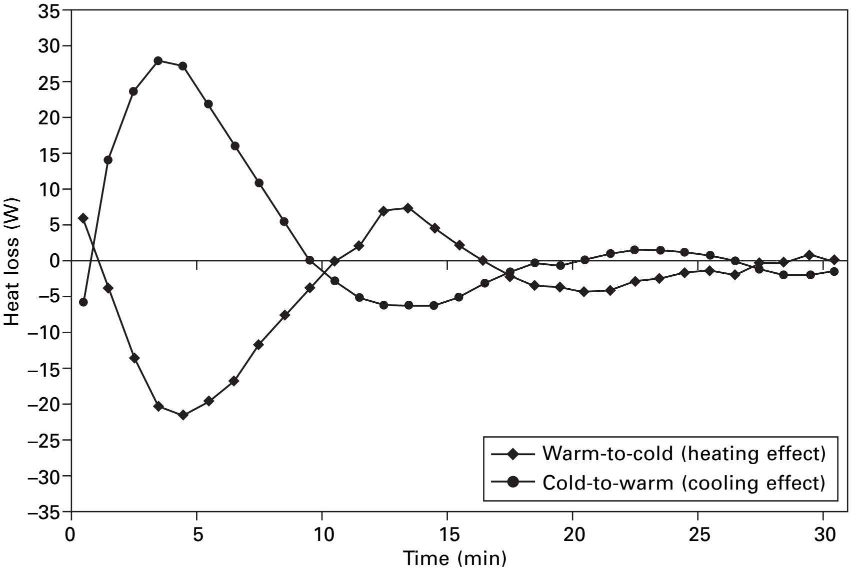
Garments with PCM compared to garments without PCM	Average heating effect during warm to cold transient (W)	Total energy gain for 15 minutes during warm to cold transient (J)	Average cooling effect during cold to warm transient (W)	Total energy loss for 15 minutes during cold to warm transient (J)
One-layer suit with PCM vs. no-PCM control	6.5	5,850	7.6	6,840
Two-layer suit with PCM vs. no-PCM control	13.2	11,880	11.0	9,900
Two-layer suit (inner layer with PCM, outer layer without PCM) vs. two-layer suit without PCM	4.5	4,050	2.0	1,800
Two-layer suit (outer layer with PCM, inner layer without PCM) vs. two-layer suit without PCM	9.9	8,910	7.1	6,390
Two-layer suit with PCM on top 39% of body and without PCM on bottom 42% of body vs. two-layer suit without PCM	6.3	5,670	3.4	3,060
PCM ski ensemble vs. ski ensemble without PCM	5.9	5,310	7.4	6,660

heat actually produced or stored by the PCM in the material. Some of this heat is lost to or gained from the environment. Therefore, the effect on body heat loss measured in this study is the actual heating or cooling 'buffering' effect of the PCM that the wearer would experience.

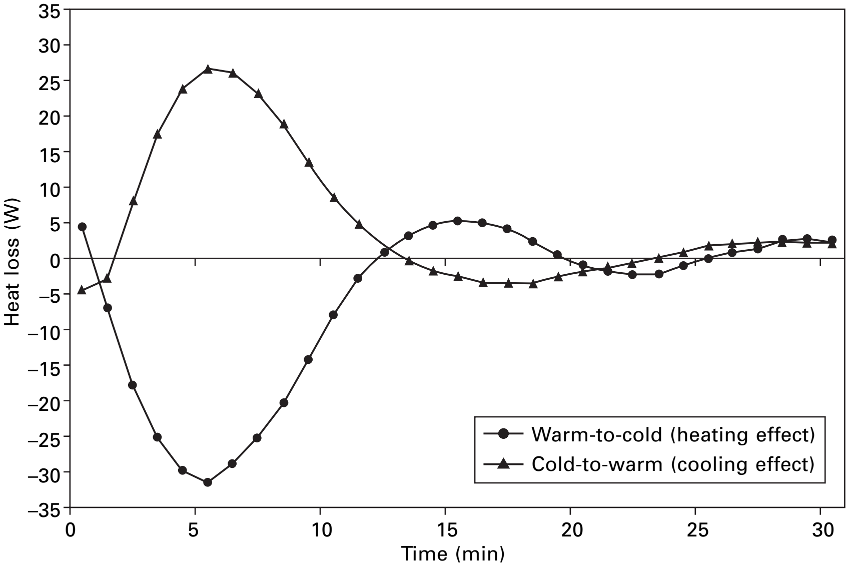
Results of transient manikin tests

The difference in heat loss between the one-layer PCM suit and the control suit without PCM is graphed in Fig. 5.4. The PCM one-layer suit produced an average heating effect of 6.5 W in the first 15 minutes after the manikin was moved from a warm environment to a cold environment. In other words, the manikin lost 6.5 W less heat during the first 15 minutes of wearing the PCM suit as compared to the control suit. When the manikin was moved from the cold chamber to the warm one, the PCM suit produced an average cooling effect of 7.6 W. (See Table 5.2.)

The difference in heat loss between the two-layer PCM suit and control suit is graphed in Fig. 5.5. The PCM two-layer suit produced an average heating effect of 13.2 W in the first 15 minutes after the manikin was moved from a warm environment to a cold environment. When the manikin was moved from the cold chamber to the warm one, the PCM suit produced an average cooling effect of 11.0 W. The effect of the PCMs on body heat loss was greater in the two-layer suits than in the one-layer suits. This result was



5.4 Difference in heat loss from the manikin wearing the one layer-suits – with PCM and no-PCM control.



5.5 Difference in heat loss from the manikin wearing the two-layer suits – with PCM and no-PCM control.

expected because there was more PCM present in the two-layer ensemble. In addition, more of the PCM microcapsules were away from the body in the two-layer suit so that they could respond to changes in the environment. (See Table 5.2.)

As expected, the heating and cooling effects of the two-layer suits containing only one layer of PCM were less than the effects produced by the two-layer PCM suit. There are less PCM microcapsules in one layer of clothing (as compared to two layers) to go through the phase change. In addition, there was a larger heating and cooling effect when the PCM layer was on the outside than when it was on the inside, next to the body. The suit with a PCM inner layer produced an average heating effect of 4.5 W in the first 15 minutes of the warm to cold transient, whereas the suit with the PCM outer layer produced an average heating effect of 9.9 W. These layering differences may not be as great in clothing systems that fit more loosely on the body and contain thicker air layers. In addition, the heating and cooling effects of a two-layer suit containing PCM on the top half of the body only were less than the effects produced by the two-layer PCM suit with full coverage.

The PCM ski ensemble produced an average heating effect of 5.9 W in the first 15 minutes after the manikin was moved from a warm environment to a cold environment. The ski jacket and pants contained one layer of fabric-backed foam and an outer shell fabric. A turtleneck knitted shirt was worn under the jacket. The heating and cooling effects associated with phase change materials in the ski garments were similar to the effects produced by the tight-fitting, one-layer suit.

In conclusion, the magnitude of the heating and cooling effects associated with phase change materials in clothing increases as the number of PCM garment layers increases and as the amount of body coverage with PCM fabrics increases. Consequently, if a person wears only a jacket containing PCM, the effect on body heat loss will be smaller than if he/she wears a sweat shirt, jacket, and long pants containing PCM. In addition, it is apparently more effective to have one layer of PCM on the outside of a tight-fitting, two-layer ensemble than it is to have it as the inside layer. This may be because the PCMs closest to the body do not change phase.

5.3.3 Results of phase III: exercise/rest tests with human subjects

Skin temperature data and subjective data

The average skin temperatures of the subjects were plotted for the 90 minute exercise/rest experiment. Then an analysis of variance was conducted on the skin temperature data collected during the 12th minute of each 15 minute period. The 12th minute was selected because the effect of the PCM on body heat loss was probably complete, and the subjects were changing conditions during the 14th and 15th minute of each period. The skin temperatures varied considerably from subject to subject. In addition, an analysis of variance was conducted on the subjects' thermal sensation responses and clothing comfort responses collected near the end of each 15 minute period in the 90 minute experiment.

Environmental effect

When the subjects moved from a seated position in a warm environment to a seated position in a cold environment, their average leg skin temperature was significantly higher when wearing the PCM ski ensemble than the ensemble without PCMs (F value = 6.53, $p = 0.022$). The average leg temperature was 31.5 °C (88.7 °F) under the PCM ensemble and 30.3 °C (86.5 °F) under the control. The PCMs probably solidified in the cold environment, producing a heating effect. The other skin temperatures were not statistically different, probably because a turtleneck knitted shirt was worn between the jacket and the body and because subject variability was high and the average heating effect of the PCM ski ensemble was low (about 6 W). No statistically significant differences in the subjects' thermal sensations or comfort levels were found when wearing the PCM ensemble as compared to the control ensemble during the environmental step change at low activity.

Exercise/rest effect

The results of this study indicated that there were no statistically significant differences in the skin temperatures of males wearing PCM ski ensembles vs. control ensembles without PCMs during exercise/rest periods in the cold. When the subjects were walking at 5.5 MET in the cold environment, they were producing more than five times the amount of heat than they did while sitting (1 MET). This extra body heat did not raise their skin temperatures to proportionately higher levels and heat the PCMs so that they would change back to liquid. Instead, the body dissipated the extra heat energy by producing sweat at the skin surface. The process of changing liquid sweat to vapor is a phase change in itself which takes heat from the body surface, providing a cooling effect. The sweat vapor is generated at the same temperature as the skin and has a minimal effect on the temperature of the clothing layers as it diffuses through them. The temperature of a PCM garment layer has to increase to its melting temperature in order to turn to liquid and store heat. Consequently, the PCMs probably did not change from solid to liquid when the subjects were exercising, and the phase change activity in the cold environment was over.

There were no statistically significant differences in the thermal sensation and clothing comfort responses of the subjects wearing the PCM ensemble as compared to the control ensemble in the cold. However, the subjects did feel significantly more clammy (as opposed to dry) during the last two test periods in the cold chamber when they were exercising in the PCM ensemble (F value = 12.10, p = 0.003) and sitting in the PCM ensemble (F value = 5.79, p = 0.030). The PCM microcapsules increased the evaporative resistance of the PCM fabric-backed foam which probably contributed to these results.

Sweat accumulation in garments

A cotton pad taped to each subject's back was used to determine sweat rate during the 90 minute experiment. There was no statistically significant difference in the amount of sweat absorbed in the pad under the PCM ensemble (0.428 g, 0.015 oz.) and the amount absorbed under the control ensemble (0.355 g, 0.013 oz.). However, there was significantly more sweat in the PCM jacket and pants (5.14 g, 0.18 oz.) as compared to the control garments (2.75 g, 0.10 oz.) (F value = 16.61, p = 0.002). There also was significantly more sweat in the turtleneck knitted shirt (worn under the jacket) when the subjects wore the PCM ski ensemble (2.38 g, 0.08 oz.) than the control (1.55 g, 0.05 oz.) (F value = 6.74, p = 0.023). More moisture may have been trapped in the PCM garments and the shirt worn under the PCM jacket because the evaporative resistance of the PCM fabric-backed foam was higher than the control. The higher level of sweat in the PCM ensemble probably contributed to the subjects feeling clammier at the end of the exercise/rest protocol.

5.4 Conclusions

The addition of phase change materials (PCMs) to a fabric-backed foam significantly increased the weight, thickness, stiffness, flammability, insulation value, and evaporative resistance value of the material. According to the transient tests with a thermal manikin, PCMs produced a small, temporary heating or cooling effect when garments made of the material went through a step change in temperature. The PCM heating and cooling effects changed body heat loss by an average 2–13 W for the first 15 minutes of the environmental transient, and then the effects were over. The magnitude of the effect increased as the number of garment layers and the amount of body coverage with PCM fabrics increased. In addition, it was more effective to have one layer of PCM on the outside of a tight-fitting, two layer ensemble than to have it as the inside layer. This may be because the PCMs closest to the body did not change phase.

When 16 male subjects moved from a seated position in a warm environment to a seated position in a cold environment, their average leg skin temperature was significantly higher when wearing the PCM ski ensemble as compared to the control ensemble. The PCMs probably solidified in the cold environment, producing a heating effect. However, the subjects' chest, forearm, and finger skin temperatures and their thermal sensations and comfort perceptions were not significantly different during this environmental step change at low activity. There were no statistically significant differences in the skin temperatures and thermal sensations of males wearing the PCM ski ensemble compared to the control during the four remaining exercise/rest periods in the cold. When the 90 minute experiment was over, there was significantly more unevaporated sweat in the PCM ensemble than the control, and the subjects felt significantly clammier when wearing it during the last exercise period and rest period of the test.

The increase in a person's metabolic heat production during exercise in the cold may not increase the skin temperature enough to warm the PCM garment layers to the melting point and keep the cooling and heating cycle going. The effect of phase change materials in clothing on the physiological and subjective thermal responses of people would probably be maximized if the wearer was repeatedly going through temperature transients (i.e., going back and forth between a warm and cold environment) or intermittently touching hot or cold objects with PCM gloves.

5.5 Implications and recommendations

The magnitude and duration of PCM heating and cooling effects in clothing systems are dependent upon several textile and design-related factors. Each of these variables needs to be considered in relation to the type of temperature transient anticipated during use (i.e., environmental temperature and/or skin temperature changes). Product variables include

- 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.

Considering product safety, performance, and cost issues, the effect of PCMs in protective clothing on the thermal comfort of the wearer should be investigated carefully prior to their use. In addition, changes in the performance characteristics of fabrics with PCMs (e.g., weight, stiffness, flammability, evaporative resistance, strength) and their durability during use and maintenance should be determined.

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