Guidelines for the Design of Products Equipped with Phase Change Material

Guidelines for the Design of Products Equipped with Phase Change Material

By

Barbara Pause

Cambridge
Scholars
Publishing

Guidelines for the Design of Products Equipped with Phase Change Material

By Barbara Pause

This book first published 2024

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-0364-0457-9
ISBN (13): 978-1-0364-0457-4

TABLE OF CONTENTS

Application of Phase Change Material for Thermal Protection and Thermo-Physiological Comfort Improvement

Applications of Phase Change Material for Improving Energy Efficiency

Summary of the Design Guidelines

CHAPTER ONE

INTRODUCTION

1.1 Market development and current applications

Phase change materials have been utilized as thermal storage means for quite some time. Currently, the demand for energy-efficient products, rising environmental consciousness, and laws addressing climate change drive growth in the market related to phase change materials. The global phase change material market was estimated to have a value of USD 1.78 billion in 2021 by the market research organization “Straits Research”, based in India, and was forecasted by this organization to be about USD 7.60 billion by 2030 [1]. This means that the market would quadruple in size within about a decade. Other market research groups are more conservative in their predictions. The US-based market research and consulting company “Reports and Data” determined that the phase change material market had a value of USD 1.65 billion in 2022 and forecasted a market size of USD 3.62 billion by 2032 [2]. Under these considerations, the market would double in this decade. But even with this deviation in mind, there will be substantial growth in utilizing phase change materials in the coming years.

Currently, phase change materials are mainly used in:

- Building components, such as floor heating systems, space cooling installations, hot water storage, and thermal buffers for heat pumps.
- Cold chain and shipping components, i.e., transport containers and cold storage units.
- Electronics components comprising heat dissipation systems.

In these applications, phase change materials are utilized for thermal storage purposes where heat and cold storage are provided. Another objective for the current application of phase change material is heat dissipation. Heat is drawn away from a source, such as an electronic device/component, and stored in a heat sink.

Related to textiles, the major applications of phase change materials are currently in bedding products and cooling vests [3, 4].

1.2 Objectives of the Design Guidelines

Besides the applications in building components, cold chain and shipping components, and electronics cooling solutions, there are many more areas where products could benefit from phase change material technology. There is also a wide range of possible applications in which textiles could be used as the carrier for phase change material.

The efficiency of thermal storage and heat dissipation is always limited by the amount of phase change material utilized in the system. Furthermore, there is a challenge regarding recharging the phase material used in such a system. If there is only a partial recharge, the phase change material will perform at a limited capacity in the next cycle of operation.

In contrast, applications in which the phase change material's heat absorption and heat emission features are used alternately and in equal proportion have a greater potential for providing long-lasting thermal effects. These systems act, for instance, as thermostats keeping enclosed systems at a nearly constant temperature. Examples of such applications will be discussed in the book.

Another feature that is obtained when applying phase change material to a sheet-like substrate is the potential of a temperature-controlled heat flux through it. For instance, many applications in heat protection would benefit from this feature. Because these changes in the heat flux are triggered by an outside stimulus, in this case, the temperature, substrates with the phase change material treatment are called "smart materials". The heat flux control feature is not utilized in current applications of phase change materials. However, examples of possible applications are included in the book and will be discussed.

Many years of experience developing products utilizing phase change material technology have demonstrated that some requirements must be considered in the design process. If these requirements were not met in the past, the products mostly failed consumer expectations regarding thermal performance and were often taken off the market in a short period. To avoid such pitfalls, the book will give designers guidelines and a toolbox to support successful product development. Furthermore, the book provides information about testing procedures applied to validate the thermal performance of the developed products.

References

1. Straits Research. 2023. “Phase Change Materials Market: Information by Type (Organic PCM, Inorganic PCM), Form (Encapsulated, Non-encapsulated) Application (Packaging, HVAC), and Region-Forecast till 2030”. https://straitsresearch.com.
2. Reports and Data. 2022. “Phase Change Material Market By Type (Organic, Inorganic, Bio-based) By Application (Building & Construction, HVAC, Energy Storage, Cold Chain & Packaging, Textile, Electronics, and Others), and By Region Forecast to 2032”. https://www.reportsanddata.com.
3. MarketWatch. 2023.” 2030 Phase Change Material (PCM) Market Research”. Press Release on June 19, 2023, https://www.marketwatch.com
4. Brütting, Michael, Haussmann, Thomas, Mehling, Harald. 2022. “PCM products and their fields of application – An overview of the state in 2020/2021”. Journal of Energy Storage, 51. https://doi.org/10.1016/j.est.2022.104354

CHAPTER TWO

PHASE CHANGE TECHNOLOGY

2.1 Phase change effect

The most well-known thermal energy storage occurs when a material, such as water, is heated in an ordinary heating process. The amount of sensible heat absorbed in such a heating process depends on the weight of the heated material, the temperature difference covered in the process, and the material-related specific heat capacity. However, because of the low energy density of such systems, sensible heat storage requires large volumes to be effective.

A more efficient way to store thermal energy is provided by the application of phase change material. Phase change materials possess the ability to change their physical state from solid to liquid and vice versa within certain temperature ranges. During the phase change from a solid into a liquid, a change from a defined oriented solid crystalline structure into a randomly oriented liquid state occurs. This is due to an increase in vibrational energy generated by heat which breaks the bonds between the molecules. The energy necessary to cause the phase change material to change from a solid into a liquid, i.e., to break down the bonding responsible for the solid structure, is absorbed from the surrounding area during a heating process. The result is that the temperature increase, which usually occurs in a material while heated, is interrupted when the melting temperature of the phase change material is reached. During the entire melting process, the temperature of the phase change material remains constant. When the phase change process is complete and the material is further heated, its temperature will continue to rise (Fig. 2-1).

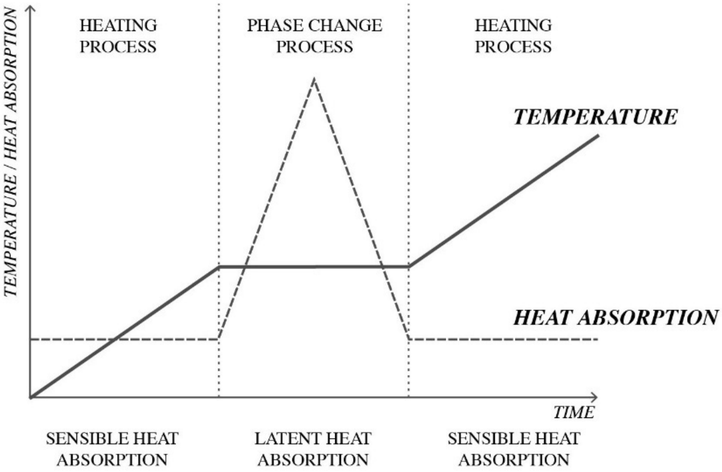


Fig. 2-1: Phase change effect.

The latent heat is stored in the phase change material and released in a reverse cooling process when the crystallization temperature of the phase change material is reached. A nucleation process then rearranges the molecules into the crystalline lattice. The material temperature also remains constant during the reverse phase change from a liquid into a solid. However, when the phase change is complete, a continued cooling process results in a further temperature decrease.

Water shall be used to compare the amount of latent heat absorbed by a phase change material during the actual phase change with the amount of sensible heat absorbed in an ordinary heating process. If ice melts into water, it absorbs a latent heat of about 335 Joules per gram. If water is further heated, only 4 Joules per gram of sensible heat is taken up while the temperature rises by one degree. Therefore, the latent heat absorption during the phase change from ice into water is nearly 100 times higher than the sensible heat absorption during the heating process of water outside the phase change temperature range. In other words, water needs to be heated from about 1 °C up to 85 °C to absorb the same amount of heat that is absorbed during the melting process of ice.

In addition to the variances in the amount of heat that can be absorbed or released, there are several other differences between the sensible heat exchange and the latent heat exchange, which are summarized in Table 2-1.

Characteristics	Sensible heat absorption/release	Latent heat absorption/release
Heat exchange process	continuously	discontinuously
Material temperature	increases/decreases	remains constant
Material density	remains constant	increases/decreases

Table 2-1: Comparison between sensible heat exchange and latent heat exchange.

The major advantage of the latent heat exchange compared to the sensible heat exchange is the much higher amount of heat that can be absorbed or released without a significant change in the material's temperature. On the other hand, a disadvantage in using a latent heat storage material or phase change material is its density change resulting from the phase transition, leading to a change in the material's volume. But altogether, the materials that store latent heat are thermally more effective than those that store sensible heat on both the weight and volume bases.

Besides the solid-liquid phase changes, solid-solid phase changes have also been experienced where the crystalline structure is only changed into a semi-crystalline or amorphous structure when a phase transition at a given temperature in a heating process occurs. During this solid-solid phase transition, the material absorbs latent heat. The latent heat is released in a reverse cooling process at the phase transition temperature. At this point, the semi-crystalline or amorphous structure transforms back into the defined crystalline structure. Unlike phase change materials with solid-liquid transitions, solid-solid phase change materials mainly retain their physical properties. Their density changes only slightly, and their volume remains nearly constant. These properties create advantages for a variety of applications.

In addition to the solid-liquid and the solid-solid phase change, there are other possible transitions in the physical state of a material, such as

- Solid-vapor transitions.
- Liquid-vapor transitions.

Solid-vapor and liquid-vapor transitions are related to a much higher amount of heat to be exchanged compared to solid-liquid transitions as well as solid-solid transitions. For instance, the amount of heat absorbed during the vaporization of water is about 10 times higher than the amount of heat absorbed during the melting process from ice into water. However, solid-vapor or liquid-vapor transitions cannot be practically used in many applications because of their tremendous volume, density, and pressure changes resulting from the vaporization process. Furthermore, the reverse transition process from vapor into solids or liquids is technically impossible for many applications.

2.2 Phase change materials

2.2.1 Overview and selection requirements

Besides water, more than 500 natural or synthetic phase change materials are known which differ from one another by the temperatures at which their phase changes take place and their latent heat storage capacities [1]. Phase change materials should be selected for a specific application, considering the appropriate phase change temperature range and the necessary latent heat storage capacity.

Furthermore, the phase change material selection shall also be predicated on physical and chemical properties desirable or undesirable for the prevailing application. For many applications, the selected phase change material must be nontoxic, noncorrosive, non-hygroscopic, and non-flammable.

Further requirements are, for instance, low volume changes during the phase transition, low vapor pressures near the melting points to prevent excessive stress on surrounding storage containers, and high thermal conductivity to avoid the appearance of thermal gradients.

In addition, the selected phase change material should be stable to repeated thermocycles. Furthermore, it must melt and crystallize in a congruent manner. The phase change material should not show a supercooling behavior where a liquid phase change material is cooled below the phase change temperature range without forming a solid phase. Finally, price and availability also play an important role in selecting a phase change material for a specific application.

Phase change materials are divided into the categories summarized in Fig. 2-2. Phase change materials transferring from a solid into a liquid and vice versa are categorized as organic phase change materials and inorganic phase change materials. Organic phase change materials comprise paraffin and non-paraffinic organics such as fatty acids and polyethylene glycols. Salt hydrates, salt eutectics, and metallics are summarized under the term 'inorganic phase change material'. Solid-solid phase change materials include organics, organometallics, inorganics, and polymerics.

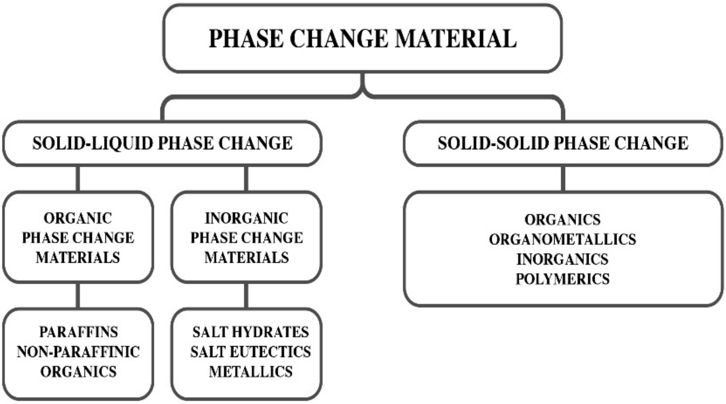


Fig. 2-2: Phase change material categories.

2.2.2 Organic phase change materials

Paraffin

The paraffins of type C_nH_{2n+2} are parts of the family of saturated hydrocarbons and possess similar properties. The materials with carbon atom numbers below pentane (C_5H_{12}) are gases at room temperature.

From pentane (C_5H_{12}) to pentadecane ($C_{15}H_{32}$), paraffins are liquids at room temperature. Paraffins with higher carbon atom numbers are waxy solids when stored at room temperature.

The melting temperature of the paraffins increases with the number of carbon atoms in the hydrocarbon chain, as shown in Fig. 2-3.

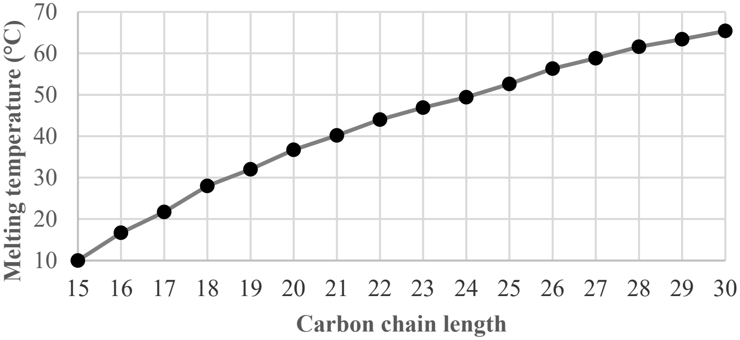


Fig. 2-3: Melting temperatures of different paraffins depending on their carbon chain length.

Paraffins possess relatively high latent heat storage capacities [2]. Some of them are summarized in Table 2-2. Table 2-2 also contains the melting and crystallization temperatures of the selected paraffins.

Paraffin	Formula	Melting temperature, °C	Crystallization temperature, °C	Latent heat storage capacity, J/g
Hexadecane	$C_{16}H_{34}$	16.7	12.2	237
Heptadecane	$C_{17}H_{36}$	21.7	16.5	213
Octadecane	$C_{18}H_{38}$	28.0	25.4	244
Nonadecane	$C_{19}H_{40}$	32.0	26.4	222
Eicosane	$C_{20}H_{42}$	36.7	30.6	247
Hen-eicosane	$C_{21}H_{44}$	40.2	35.9	213

Table 2-2: Phase change temperatures and latent heat storage capacities of selected paraffins.

A comparison of the latent heat storage capacities summarized in Table 2-2 shows that the paraffins with even numbers of carbon atoms possess slightly higher latent heat storage capacities than the paraffins with odd numbers of carbon atoms. The distance between melting and crystallization temperature is less than 10 degrees Celsius for all paraffins. Thus, the paraffins appear to be self-nucleating.

The “pure” paraffins are nontoxic and noncorrosive. They are non-hygroscopic and absorb little or no moisture at high humidities or when exposed to liquid water.

Paraffins show congruent melting and freezing behavior, so they are stable regarding repeated thermocycles. However, prolonged exposure to temperatures above 150°C can chemically degrade them.

A sample of an eicosane paraffin at room temperature is shown in Fig. 2-4.

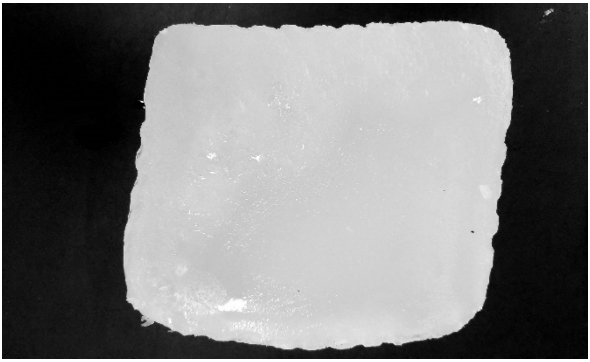


Fig. 2-4: Eicosane paraffin piece at room temperature.

Besides all these advantages, there are also some disadvantages related to the use of paraffin. Paraffins are known for extremely low thermal conductivities. They have insulating properties comparable to the best insulators. However, the thermal conductivity can be enhanced, for instance, by mixing them with metallic fillers [2].

The density of the paraffins decreases when they melt and become liquid. These density changes lead to an average volume expansion of about 8 percent. Densities and thermal conductivities in the solid states and liquid states of the paraffins included in Table 2-2 are summarized in Table 2-3.

Furthermore, like other organic compounds, paraffins will burn if ignited. Paraffin can be incorporated or encapsulated in non-flammable materials to avoid such an ignition. In addition to that, paraffin could be made self-extinguished by formulating them with small quantities of specific fire-retardant additives such as organic halides or antimony oxides. Tests have shown that there is no significant change in the melting and crystallization behavior of the paraffins after combining them with fire-retardant additives.

Paraffin	Density (liquid), kg/m^3	Density (solid), kg/m^3	Thermal conductivity (liquid), W/m K	Thermal conductivity (solid), W/m K
Hexadecane	770	835	0.150	0.183
Heptadecane	774	839	0.152	0.200
Octadecane	777	844	0.155	0.218
Nonadecane	783	848	0.161	0.224
Eicosane	789	854	0.172	0.236
Hen-eicosane	792	859	0.175	0.243

Table 2-3: Densities and thermal conductivities of selected paraffins in liquid states and solid states.

There are two ways of manufacturing paraffins:

- Ethylene polymerization.
- Fractionation of petroleum refining residues.

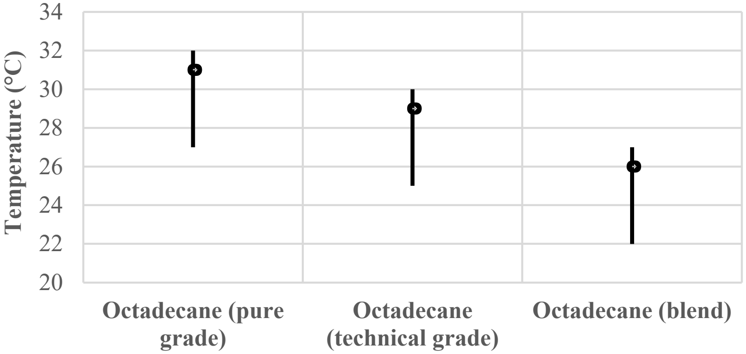
Paraffin products resulting from the polymerization of ethylene monomers possess high purities. They are marketed for a comparatively high price.

Paraffins made as byproducts of petroleum refining are sold at much lower prices in tank car quantities. These paraffins are technical grades with a purity of about 95 percent or blends of paraffins with different chain lengths.

In textile applications, technical grade paraffin or paraffin blends are often used. Compared to pure-grade paraffin, they usually possess lower heat storage capacities and melt as well as freeze over a wider temperature range. Fig. 2-5 shows a comparison of melting temperature ranges of pure octadecane, technical grade octadecane, and a blend of 40 percent octadecane (C_{18}) with 38 percent heptadecane (C_{17}) and smaller portions of nonadecane (C_{19}), and eicosane (C_{20}) paraffin.

Technical grade octadecane possesses a slightly lower melting temperature range than pure octadecane, which needs to be taken into consideration for practical use of technical grade octadecane.

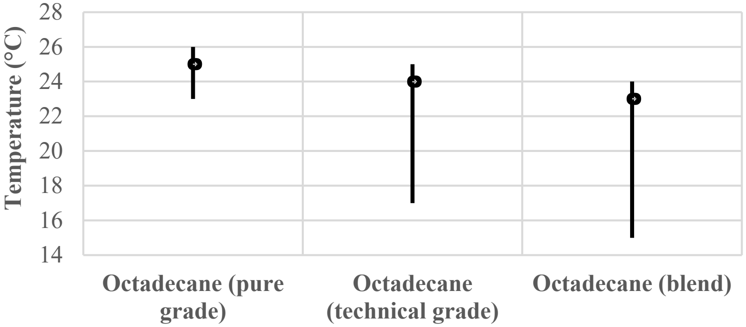
Blending octadecane mainly with heptadecane leads to a further decrease in the melting temperature range. A comparison of the melting temperature ranges of the different octadecane variants is shown in Fig. 2-5.



● marks the peak melting temperature.

Fig. 2-5: Comparison of the melting temperature ranges of different variants of octadecane paraffin.

Reducing the purity of octadecane lowers the temperature range in which the melting process takes place. In addition, the reduction in the purity of octadecane leads to an extension of the crystallization temperature range, as shown in Fig. 2-6.



● marks the peak crystallization temperature.

Fig. 2-6: Comparison of the crystallization temperature ranges of different variants of octadecane paraffin.

Finally, Fig. 2-7 summarizes the latent heat storage capacities of the different variants of the octadecane paraffine. The results shown in Fig. 2-7 indicate that the latent heat storage capacity of technical grade octadecane is about 13 percent lower than the latent heat storage capacity of pure octadecane. The investigated blend possesses a latent heat storage capacity which is about 35 percent lower than that of the pure octadecane. Similar results have been received for other paraffin configurations.

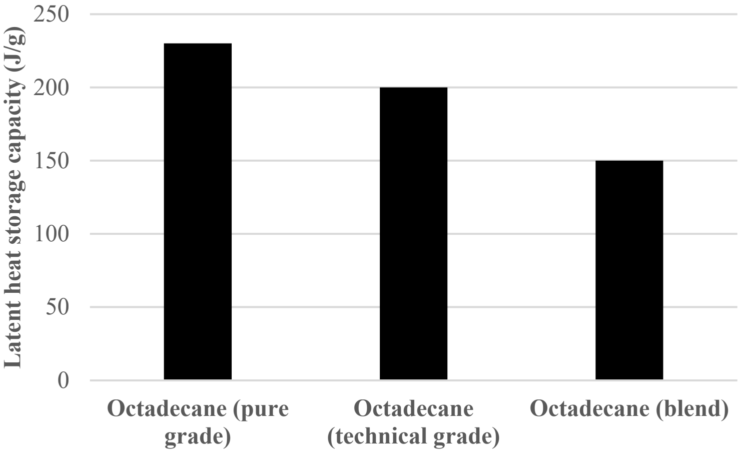


Fig. 2-7: Comparison of the latent heat storage capacities of different variants of octadecane paraffin.

Non-paraffinic organics

Non-paraffinic organics include a wide variety of organic materials such as fatty acids, esters, alcohols, and glycols. Each of these materials has its own characteristics, unlike paraffins which possess very similar properties.

In terms of potential applications, it needs to be considered that some of the non-paraffinic organics are flammable. Many of them have low flash points, and they will decompose at elevated temperatures. They possess low thermal conductivities like those of the paraffins. To improve the heat transfer to and from them, the use of metallic fillers is recommended.

Some of the non-paraffinic organics, i.e., many of the fatty acids are plant-based or bio-based products. Therefore, they are considered as “green” materials. A selection of fatty acids is summarized in Table 2-4.

Fatty acid	Formula	Melting temperature, °C	Latent heat storage capacity, J/g
Acetic acid	CH_3COOH	17	184
Elaidic acid	$C_8H_{17}C_9H_{16}COOH$	47	218
Myristic acid	$CH_3(CH_2)_{12}COOH$	58	199
Stearic acid	$CH_3(CH_2)_{16}COOH$	69	199

Table 2-4: Melting temperatures and latent heat storage capacities of selected fatty acids.

Fatty acids exhibit excellent melting and crystallization characteristics [3]. Their latent heat storage capacities are comparable to those of paraffins. A myristic acid sample at room temperature is shown in Fig. 2-8.

Fig. 2-8: Myristic acid sample at room temperature.

Both paraffins and fatty acids possess a white, waxy, and soft appearance in their solid states. While paraffins are often sold in chunks such as seen in Fig. 2-4, fatty acids are submitted in the form of flakes.

Polyethylene glycol is a polyether compound that is derived from petroleum. Polyethylene glycols with molar masses between 400 g/mol and 20,000 g/mol possess melting points between 0 °C and 70 °C. Their latent heat storage capacities increase with a rise in the molar mass and range from about 90 J/g to 190 J/g. In comparison of the latent heat storage capacities of the paraffin nonadecane and polyethylene glycol 1000 operating in the same temperature range, the latent heat storage capacity of polyethylene glycol 1000 is only about 65 percent of the latent heat storage capacity of nonadecane.

Polyethylene glycols are chemically and thermally stable, nontoxic, noncorrosive, and biodegradable. However, a substantial disadvantage is the large difference between their melting and freezing temperatures which leads to incongruent melting behavior, resulting in a significant loss in latent heat storage capacity even when used only over a short period [4].

Applications of organic phase change material

Because of the temperature range in which some organic phase change materials, such as paraffin and fatty acids, operate and their relatively high latent heat storage capacities, they are especially suitable for applications in garments, sporting goods, and medical equipment. Furthermore, their performance does not change over time even under repeated thermocycles. By mixing different paraffins, specific temperature ranges can be covered, and the desired application temperature range can be met.

2.2.3 Inorganic phase change materials

Salt hydrates

Salt hydrates are alloys of inorganic salts and water. The water molecules are absorbed into the crystalline structure of the salts. Salt hydrates are non-combustible and, therefore, meet the fire-resistance requirements of a variety of products and applications.

The most attractive properties of salt hydrates are their comparatively high latent heat storage capacities, high thermal conductivities, and small volume changes at melting. However, most salt hydrates are corrosive which can be problematic when storing them in metal containers. Salt hydrates possess higher densities than organic phase change materials leading to higher masses per volume, i.e., higher weights.

Salt hydrates show three kinds of melting behavior: congruent, semi-congruent, and incongruent melting. Incongruent and semi-congruent melting salt hydrates are inexpensive, but they are difficult to handle [5]. Their components get separated during the melting process. In a reverse cooling process, the components are unable to recombine appropriately to form the original crystalline structure. The lack of reversible melting and freezing makes the salt hydrates with incongruent and semi-congruent melting and freezing behavior unsuitable for many applications. On the other hand, salt hydrates melting congruently are expensive [6]. The thermal properties of three salt hydrates are given in Table 2-5.

Salt hydrate	Formula	Melting temperature, °C	Latent heat storage capacity, J/g
Lithium nitrate trihydrate	$LiNO_3$ x 3 H_2O	30	296
Sodium hydrogen phosphate dodecahydrate	Na_2HPO_4 x 12 H_2O	36	280
Sodium acetate trihydrate	$NaC_2H_3O_2$ x 3 H_2O	58	265

Table 2-5: Melting temperatures and latent heat storage capacities of selected salt hydrates.

A sample of the salt hydrate sodium acetate trihydrate is shown in Fig. 2-9. The crystalline structure of the salt hydrate particles can be clearly identified in the picture.

Fig. 2-9: Sodium acetate trihydrate sample at room temperature.

The incongruent melting and freezing behavior of various salt hydrates is especially experienced when the materials do not freeze at their solidification point, requiring substantial subcooling before solidification nucleation begins. This problem can be solved by using nucleation agents [7]. These agents provide a surface from which the formation of a crystalline structure can occur faster, preventing what is called the supercooling effect. The elimination of the supercooling in these salt hydrates ensures that their latent heat storage capacity does not decrease over time, i.e., it remains stable over many thermocycles.

Salt eutectics

Salt eutectics are created by mixing two or more salt hydrates. They melt and crystallize at specific temperatures, often deviating from those of the single components. Their behavior is analogous to congruent melting salt hydrates. For instance, a stable eutectic mixture consists of 49.3 percent Mg Cl x 6 H_2O and 50.7 percent Mg $(NO_3)_2$ x 6 H_2O, melting at 58 °C and absorbing a latent heat of about 132 J/g.

Some of the salt eutectics possess not one but several melting temperatures. These melting temperatures can be changed by altering the ratio of the eutectic components or the water content.

Salt eutectics have advantages in high thermal conductivity and large energy density. A disadvantage is their corrosivity.

Applications of inorganic phase change materials

Salt hydrates and salt eutectics are preferably used for industrial applications where fire-resistant requirements must be met. Salt hydrates can be mixed to create salt eutectics that cover the desired temperature ranges where the phase change occurs. The high thermal conductivity of salt hydrates ensures sufficient heat transfer to and from the phase change material.

Metallics

Metallics are very heavy compared to other phase change materials, and their latent heat storage capacities per unit weight are comparatively low. But compared based on a volume base, their latent heat storage capacities are acceptable. The advantages of metallics are their high thermal conductivity and sufficient thermal stability. An example of a metallic phase change material is gallium which melts at a temperature of 30 °C and possesses a latent heat storage capacity of about 80 J/g. The thermal conductivity of gallium is about 34 W/m K. An interesting feature is the shrinkage of the material during melting [1]. The volume change is about 3 percent. Gallium is nontoxic but very corrosive. Compared to other phase change materials, gallium is also very expensive and, therefore, not suitable even for industrial applications.

2.2.4 Solid-solid phase change materials

Phase change materials that transfer from one solid material into another solid material retain their bulk solid properties within the temperature range of the phase change. By staying solid, leakage problems experienced at solid-liquid phase changes can be avoided. They can be blended into a matrix material without a need for encapsulation. Solid-solid phase change materials show only small volume changes by undergoing a phase transition [8].

Organics

Organic solid-solid phase change materials have phase transitions in a temperature range between about 60 °C and 190 °C. Their latent heat storage capacities range from 180 J/g to 300 J/g. Some examples of organic solid-solid organic phase change materials are summarized in Table 2-6.

Organic solid-solid phase change material	Formula	Melting temperature, °C	Latent heat storage capacity, J/g
Tris hydroxymethyl-ethane	$C_5H_{12}O_3$	82	190
Tris hydroxymethyl-aminomethane	$C_4H_{11}NO_3$	131	285
Pentaerythritol	$C(CH_2OH)_4$	185	300

Table 2-6: Melting temperatures and latent heat storage capacities of selected organic solid-solid phase change materials.

The thermal conductivity of these organic solid-solid phase change materials is only low and comparable to the thermal conductivity of paraffins and fatty acids. For instance, the thermal conductivity of pentaerythritol is about 0.2 W/m K. The appearance of pentaerythritol is a fine white powder shown in Fig. 2-10.

Fig. 2-10: Pentaerythritol sample.

Organometallics

Organometallics consist of alternate inorganic and organic layers. They create a sandwich-like crystalline structure.

The phase transition is only performed in the organic part. Organometallics consist of a paraffinic chain with alkyl-ammonium groups creating the organic part and a metal or a halogen building the inorganic part. Their solid-solid transition temperatures are between 20 °C and 90 °C. The latent heat storage capacities of these phase change materials range from 60 J/g to 150 J/g. Since the inorganic components (metal and halogen) of the organometallics do not participate in the phase transition, they contribute only to the weights of the phase change materials and not their latent heat storage capacities.

This explains the low numbers obtained for the latent heat storage capacities of these solid-solid phase change materials. Organometallics show a very small volume change during the phase transition. Due to the metal components in the materials, their thermal conductivities are very high.

Inorganics

Inorganic solid-solid phase change materials operate between 680 °C and 900 °C. They have very low latent heat storage capacities, around 50 J/g. An example of an inorganic solid-solid phase change material is an iron-cobalt alloy. Inorganic solid-solid phase change materials possess high thermal conductivities between 0.3 W/m K and 5 W/m K [8].

Polymerics

Polymeric solid-solid phase change materials consist of hard and soft segments, and the phase change takes place only in the soft segments. For instance, polyethylene glycol serves as the soft segment in a polymeric phase change material, while polystyrene creates the hard segment functioning as the "backbone".

Polymeric solid-solid phase change materials operate in a temperature range between 10 °C and 65 °C and possess latent heat storage capacities varying in a wide range between 10 J/g and 200 J/g. The volume change during the phase transition is only small. They are thermally stable. The thermal conductivity of polymeric solid-solid phase change materials is with 0.1W/m K to 0.2 W/m K only low, i.e., in the range of the thermal conductivity of paraffin and fatty acids [8]. They are nontoxic but possess a low fire resistance.

Applications of solid-solid phase change materials

Based on the temperature range in which the inorganic solid-solid phase change materials are operating and their low latent heat storage capacities, they are not suitable candidates for current and probably also future applications. The polymeric and organometallic solid-solid phase change materials possess phase transitions in a more suitable temperature range, but their latent heat storage capacity is not high enough to be considered in current applications. In contrast, organic solid-solid phase change materials possess desirable latent heat storage capacities for a variety of industrial applications. The only disadvantage in utilizing these materials is their low thermal conductivity comparable to the thermal conductivity of paraffin and fatty acids.

References

1. Hale, D. V., Hoover, M. J., O'Neill, M. J. 1971. "Phase change materials handbook". NASA Contractor Report, Contract NAS8-25183, NASA Marshall Space Flight Center, Alabama, USA
2. Fleischer, Amy S. 2015. "Thermal Energy Storage Using Phase Change Materials: Fundamentals and Applications". Springer Briefs in Applied Science and Technology, Thermal Engineering and Applied Science, 2015 Edition, Springer Cham, Heidelberg, New York, Dordrecht, London

3. Chowdhury, Hasnat Noor, Hamja, Abu, Rahman, Mahbubur. 2013. “Phase Change Materials: Characteristics and Encapsulation”. International Conference on Mechanical Engineering and Renewable Energy, Chittagong, Bangladesh, December 24-27, 2013
4. Onder, Emel, Sarier, Nihal. 2015. “Thermal regulation finishes for textiles”. In: Functional finishes for textiles. 17-98. Woodhead Publishing Ltd. https://doi.org/10.1533/9780857098450.1.17
5. Buddhi, D., Chen, C.R., Sharma, Atul, Tyagi, V.V. 2009. “Review on thermal energy storage with phase change materials and applications”. Elsevier, Renewable and Sustainable Energy Reviews. No. 13: 318-345. https://doi.org/10.1016/j.rser.2007.10.005
6. Cabeza, Luisa F., Marin, Jose M., Mehling, Harald, Zalba, Belen. 2003. “Review on thermal energy storage with phase change: materials, heat transfer analysis and applications”. Pergamon, Applied Thermal Engineering. No. 23: 251-283
7. Gluesenkamp, Kyle R., Graham, Samuel, Hirschey, Jason, Kumar, Navin, et al. 2021. Review of Low-Cost Organic and Inorganic Phase Change Materials with Phase Change Temperature between 0°C and 65°C”. 6th International High Performance Buildings Conference at Purdue, USA, May 24-28, 2021
8. Fallahi, Ali, Granados-Focil, Sergio, Guldentops, Gert, Tao, Mingjiang, et al. 2017. “Review on solid-solid phase change materials for thermal energy storage: molecular structure and thermal properties”. Elsevier, Applied Thermal Engineering. No. 127: 1427-1441. https://doi.org/10.1016/j.applthermaleng.2017.08.161

CHAPTER THREE

ENCAPSULATION

3.1. Encapsulation requirements

The solid-liquid phase change materials must be properly contained to prevent dissolution out of an end-use product configuration while in their liquid stage. The encapsulation needs to fulfill several requirements:

- Accommodates a volume change related to the phase change from solid to liquid and vice versa.
- Ensures a sufficient heat transfer to and from the encapsulated phase change material.
- Is thermally stable.
- Possesses sufficient mechanical strength.
- Does not react chemically with the encapsulated phase change material.
- Does not change the phase itself.

There are four forms of encapsulation currently utilized or under investigation:

- Macro-encapsulation.
- Micro-encapsulation.
- Nano-encapsulation.
- Shape-stabilization-encapsulation.

3.2 Macro-encapsulation

Several companies use macroscale container systems to encapsulate phase change materials. Most of these containers are made of plastic, such as HDPD, or metal [1, 2]. Some of the containers possess a rectangular shape. These containers are manufactured in various sizes, as shown in Fig. 3-1.