Dalhousie University – Mechanical Engineering
MECH 4340 – Energy Management – Winter 2015

Thermal Energy Storage Using Phase Change Materials

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Table of Contents

List of Figures

Abstract

This report examines phase change materials (PCMs) and their capacity for thermal energy storage (TES). PCMs store energy in the form of latent heat, which is the energy required for a material to change phase. Latent heat is a good means of energy storage because it has a significantly higher storage density than sensible heat. PCMs come in many forms and can be contained in either micro- or macroencapsulation making them very versatile as heat storage applications.

As institutions seek for economic and effective methods of reducing their energy consumption, PCMs serve as a perfect solution to maintaining high levels of comfort and profitability but by expending significantly less energy. Their ability to be incorporated into building materials and reduce peak loads during the day has increased their market as they start to replace old methods of heating and cooling. As a result of their small structure and high density, they can be placed in locations where other materials cannot and this is what makes them optimal for applications in transportation of goods and being sold in merchandise to the public.

1. Thermal Energy Storage

Thermal energy storage (TES) is the process of generating more energy than is required at a given time and storing it so that it can be retrieved later on. Due to economic and environmental reasons, technology is moving towards higher efficiency systems, making TES more popular in new developments.

1.1. Purpose of Thermal Energy Storage

There are many practical advantages to using a TES system, the most attractive of which being its economic benefits. In cases where energy suppliers have time-of-use ratings, which govern the price of energy base on the time of day it is being used, energy is more expensive during peak hours than at other times of the day. With a good TES system, energy could be purchased and stored during off-peak hours and then extracted during peak hours. This will result in an overall drop in energy cost [1].

Another significant benefit of TES is to solve availability problems when there is a discrepancy between the supply and demand of energy. This is a significant issue with renewable energy generation such as solar and wind power where the capacity of energy being produced is dictated by weather and the time of day. TES can be used to store excess energy while these systems are in operation and distribute it over time when they are not producing. This can greatly increase the practicality of these non-dispatchable energy resources [2].

1.2. Methods of Thermal Energy Storage

The various methods for thermal energy storage are shown in Figure 1.

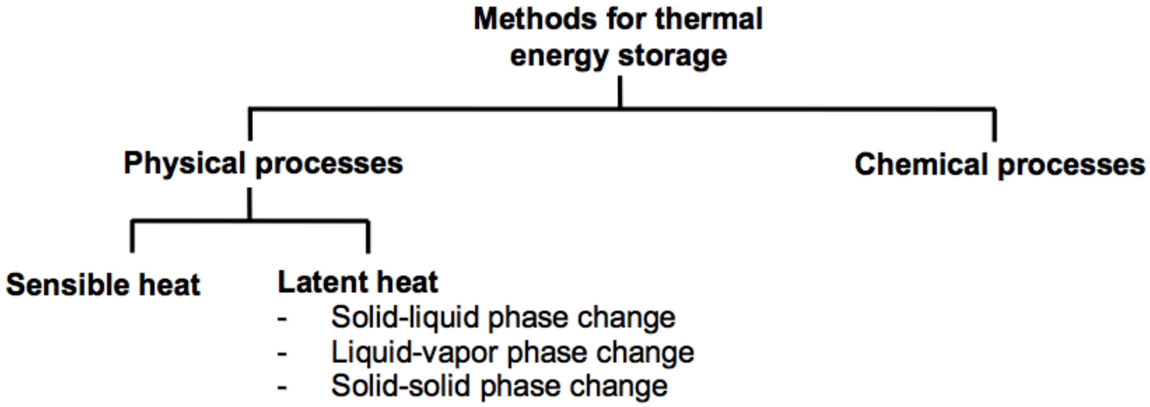

Figure 1: Methods for thermal energy storage [1]

1.2.1. Thermochemical Heat

Thermochemical heat storage refers to heat that is stored in chemical bonds and is released through a chemical reaction. If the reaction is exothermic heat will be released, if it is endothermic heat will be absorbed. This form of energy storage can be good due to its high energy density but it is not often used because it is fairly complex, expensive, and at times can be hazardous [3].

1.2.2. Sensible Heat

Thermal energy storage is most commonly seen in the form of sensible heat storage. Sensible heat is the heat we are most familiar with; it is experienced as the change in temperature that we can feel. Figure 2 shows the relationship between sensible heat storage and changes in temperature.

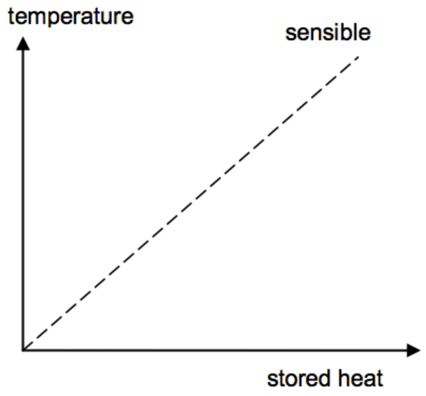

Figure 2: Sensible heat relationship [1]

Sensible heat storage is used in hot water heaters where the heating element raises the temperature of the water (typically to around 60°C) and stores it until it is needed. Sensible heat storage is also seen in ceramics, bricks, and insulation, where the solid retains heat reducing heat loss. Sensible heat ΔQ is governed by equation (1) below:

$$\Delta Q = m \cdot c \cdot \Delta T \tag{1}$$

where ΔT is the change in temperature, m is the mass, and c is the specific heat of the storage medium. This equation can be used to determine how much heat is needed to raise the temperature of the medium by a known amount or how much energy will be released by the medium over a known temperature drop. Specific heats vary greatly between mediums; for good, high energy density heat storage, a high specific heat is desirable [1].

1.2.3. Latent Heat of Solid-Liquid Phase Change

Latent heat is the heat released or absorbed when a medium experiences a phase change. Once a medium reaches a critical temperature (e.g. boiling point or melting point) additional energy is required in order to change the phase of the medium. This energy is known as the latent heat. The volume change between solid and liquid phases is relatively small, typically being less than 10% [1]. This is a very desirable quality because it keeps the pressure fairly constant when changing into the liquid phase. Having a constant pressure is important because it keeps the melting temperature of the material constant during solidification and melting.

The main benefit of latent heat over sensible heat for heat storage is its significantly higher energy density per degree change. Figure 3 shows a visual representation of how latent heat of a solid-liquid phase change has a much higher energy density than sensible heat.

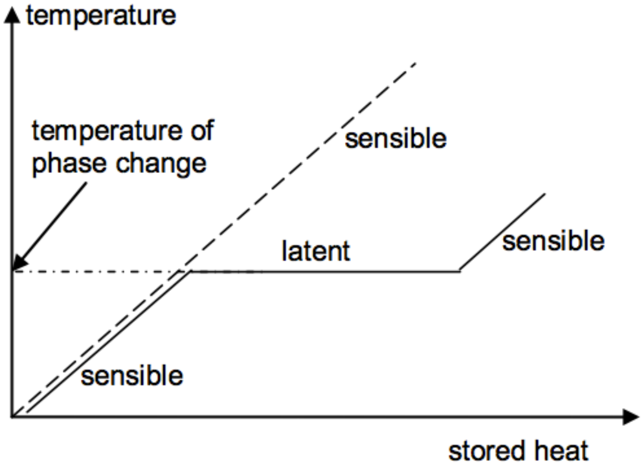

Figure 3: Latent heat of a solid-liquid phase change [1]

The equation for latent heat storage ΔQ is governed by the following equation (2) below:

$$\Delta Q = m \cdot \Delta h \tag{2}$$

where m is the mass of the medium and Δh is the specific phase change enthalpy [1].

The increase in energy density in latent heat versus sensible heat can be demonstrated easily using water as an example. The specific heat of liquid water is 4.186 kJ/kg-K. This means that it will take 4.186 kilojoules to raise the temperature of one kilogram of water by one degree Kelvin. This also means that one kilogram of water will release 4.186 kilojoules for every degree Kelvin the temperature drops by. In contrast, the melting latent heat of water is 333 kJ/kg [1]. This means that one kilogram of water will release 333 kilojoules of energy when it solidifies. Since solidification occurs at a relatively constant temperature, this can be compared to the one-degree temperature change of liquid water. When these two quantities are compared it is shown that latent heat stores approximately 80 times more energy per degree change than sensible heat. Because of this higher energy density, latent heat is much more valuable for storing thermal energy than sensible heat.

1.2.4. Latent Heat of Liquid-Vapour Phase Change

The latent heat of liquid-vapour phase changes is less useful than with solid-liquid phase changes due to its significant volume change. Solid-liquid phase changes typically result in less than a 10% volume change whereas liquid-gas phase changes can result in volume increases of hundreds of times the original volume [1].

When a liquid is in a constant volume container, vaporization results in a pressure increase. When the pressure of the material increases, so does the evaporation temperature of the material. In order for the evaporation temperature to stay constant a constant pressure container is necessary, however, this is impractical as it requires massive changes in volume as the liquid vaporizes. Or these reasons liquid-vapour latent heat is not often used for heat storage [1].

2. Phase Change Material Requirements

As explained in the previous section, phase change materials (PCM) are materials that are used to store heat energy in the form of latent heat, which is absorbed or released during changes in the material's phase. Due to the smaller volume change, solid-liquid phase change is preferable to liquid-vapour phase change for latent heat storage [1]. Because of this, from this point on PCMs will be considered materials that are used to store latent heat of solid-liquid phase changes only.

The two main requirements of PCMs are that they have suitable phase change temperature and a large melting enthalpy [1]. There are many other requirements for a good PCM; however it should be noted that these are not necessarily required for all applications. PCM requirements can be broken down into three categories: physical requirements, technical requirements, and economic requirements.

2.1. Physical Requirements

As previously stated, the two main requirements for PCMs are that they have a suitable melting temperature for their desired application and that they have a large melting enthalpy [4]. The melting temperature assures that the PCM changes phase when necessary and the melting enthalpy determines how much energy can be stored and released. Clearly the larger the melting enthalpy, the better the material is for heat storage.

Cycling stability is the measure of how many phase changes the PCM can experience before the material properties of the PCM change significantly. Cycling stability can vary from one (used for heat protection in case of fire) to thousands of cycles [1]. It is often desirable for the PCM to maintain the same heat storage properties after many cycles. Long-term stability issues with PCMs are due to two main factors: corrosion between the PCM and the container and poor stability of the materials properties [4].

When evaluating cycling stability, phase separation is a primary concern. Phase separation occurs when the components of a composite material melt at different temperatures. This can be a problem if the component with the higher density sinks within the material during this intermittent melting stage and then solidifies with a different composition. This can greatly affect the functionality of the material. Because of this, it is desirable for materials to be eutectic, meaning all of the components melt at the same temperature [1].

Subcooling must also be considered when choosing PCMs. Subcooling refers to when a material must be cooled below its melting temperature before it begins solidifying. This could be only a few degrees or a significant amount. A good PCM should have minimal subcooling to so that heat transfer is fast and reliable.

A final physical consideration for PCMs is the thermal conductivity of the material. In many applications, a high thermal conductivity may be required in order to quickly store and release energy. The application in which the PCM is being used will dictate the importance of this parameter.

2.2. Technical Requirements

An important technical requirement with PCMs is the volume change experienced during melting. With the exception of water, materials expand when they melt. This volume change must be considered when designing the container of a PCM. The container must allow the volume increase of the material in order to assure the material does not damage the container [3]. Encapsulation of PCMs is described in more detail in Section 4.3.

It is also necessary for the PCM to be chemically stable for the conditions it will experience. If the PCM will experience conditions such as high temperatures or radiation, it is important that it will not react negatively to these conditions. Care must also be taken to ensure the PCM is compatible with the materials it will come into contact with. Incompatibility can lead to damage or failure of the system. Care must also be taken to ensure that the material is safe; toxic, flammable, and other hazardous materials should be avoided if possible [1].

2.3. Economic Requirements

Economics are always a major factor in determining the feasibility of a design. Low cost and recyclability are desirable when choosing a PCM. Recyclability can refer to its ability to be reused for some other function or that no disposal plan is necessary (e.g. toxic or hazardous waste). It should be noted again that it is very unlikely that a material will meet all of these requirements.

3. Classes of Materials

With the requirements of PCMs are understood, the different classes of materials can be explored in order to determine how they fulfill these requirements. Because the thermal qualities of materials are primarily based on molecular classification, materials within the same material class behave similarly [1].

As a general rule, melting enthalpy is roughly proportional to the melting temperature of the material [1]. Materials with melting temperatures below 15 °C are often used in air conditioning and storing coolness. Materials that melt above 90°C are often used for absorption refrigeration. Materials that melt between these temperatures are useful for heat load levelling. This temperature range describes the materials that have been studied the most so far [4].

3.1. Inorganic Materials

Inorganic materials have a wide range of melting temperatures. They typically have similar melting enthalpies as organic materials with respect to mass but due to their higher density, have higher melting enthalpies with respect to volume. Inorganic materials can also be corrosive to metals, which can be a significant disadvantage. The main inorganic materials used as PCMs are eutectic water-salt solutions, salt hydrates, and salts [1].

3.1.1. Eutectic Water-Salt Solutions

For melting temperatures below 0°C, eutectic water-salt solutions are typically used. Eutectic solutions are mixtures in which both components solidify simultaneously. Eutectic water-salt solutions as the name implies are solutions that comprise of water and salt [1]. The properties of eutectic water-salt solutions are as follows:

- Melting temperatures below 0°C
- Similar thermal conductivity to water (~ 0.58 W/m °C)
- Subcooling of several degrees or more

- Considerable volume change (5 to 10%)
- Small vapour pressure
- Can be corrosive (salt is corrosive to many metals)

3.1.2. Salt Hydrates

Salt hydrates are mixtures of salt and water in a discrete mixing ratio. The properties of salt hydrates are as follows:

- Melting temperatures between 5 and 130 °C
- High volumetric storage density (~350 MJ/m^3)
- Poor cycling stability, phase separation is an issue
- Relatively high thermal conductivity (~0.5 W/m °C)
- Large subcooling (up to 80 K)
- Volume change up to 10%
- Relatively cheap
- Safety varies between materials

Because of their high volumetric storage densities, salt hydrates are very attractive PCMs, however their cycling and subcooling issues reduce their value considerably [4].

3.1.3. Salts

Salts are often used as PCMs when higher melting temperatures are required. The main properties of salts as PCMs are as follows:

- Melting temperatures above 150°C
- Good thermal conductivity
- Low subcooling
- Low vapour pressure
- Volume change up to 10%
- Corrosive to most metals

- Safety and prices vary greatly

Mixtures of inorganic materials such as salts and salt hydrates have also been tested in order to achieve different melting temperatures or to change the properties of the PCM [1].

3.2. Organic Materials

The main organic materials used as PCMs include paraffins and fatty acids. Organic materials are materials that contain carbon in their molecular structure. Organic PCMs are typically not stable at high temperatures and have lower densities than inorganic PCMs. The melting temperature of organic PCMs typically range between 0 and 200 °C [1].

3.2.1. Paraffins

Paraffins are the most commonly used organic PCM on the market to date. Paraffin usually refers to linear alkanes. The properties of paraffins as PCMs are as follows:

- Melting temperatures between 0 and 140 °C
- Little to no subcooling
- Moderate thermal storage density (~200 kJ/kg)
- Volumetric storage density ~150 MJ/m^3
- Relatively low thermal conductivity (~0.2 W/m °C)
- Insignificant vapour pressure
- Volume increase around 10%

Paraffins show similar volume increases as inorganic materials however it is less critical with paraffins because they are softer than inorganic materials resulting in less force upon expansion. Paraffins are also water repellent and do not react with most reagents. Paraffins are compatible with most metals but can cause softening in some plastics [1][3][4].

3.2.2. Fatty Acids

Fatty acids are a similar composition to paraffins except that their molecule structure ends with –COOH instead of $-CH_3$ [1]. Their properties are as follows:

- Melting temperatures between 30 and 65 °C
- Latent heat between 153 to 182 kJ/kg
- Stable upon cycling; no phase separation
- Little to no subcooling
- Low thermal conductivity

Because of their unique properties, fatty acids have been found to be useful in space heating applications [4].

4. Material Problems and Solutions

No one PCM will satisfy all the requirements listed in Section 2. Trade-offs must be made when choosing an appropriate PCM for a specific application. Although PCMs have certain limitations, some of the issues that arise can be prevented or at mitigated using special techniques.

4.1. Phase Separation

Phase separation occurs when the components of a composite material melt at different temperatures. This phenomenon is also known as incongruent melting. When the first component melts the component with the higher density can sink to the bottom. If this occurs it can change the composition of the material, changing its properties. This can significantly reduce the energy storage density of the material [1][4].

One technique to prevent phase separation is artificial mixing. This simply involves mixing the solution when it is in the liquid phase to homogenize the PCM. The main disadvantage of this technique is the additional equipment required in order to mix the PCM [4].

Another technique to reduce phase separation in salt-water solutions is to add more water to the solution. The disadvantage of this technique is that it reduces the storage density of the PCM. Other methods used to mitigate phase separation include gelling, thickening, or the addition of other materials to the PCM [4].

4.2. Subcooling

In order for a material to freeze, nucleation must occur. Nucleation is the beginning of the freezing process when a small part of the material solidifies. The solidification will spread from the point of nucleation until the entire material has solidified. Subcooling occurs when nucleation does not begin until the temperature of the material is well below its melting temperature [1]. Figure 4 shows a graphical representation of the temperature profile of a material experiencing subcooling.

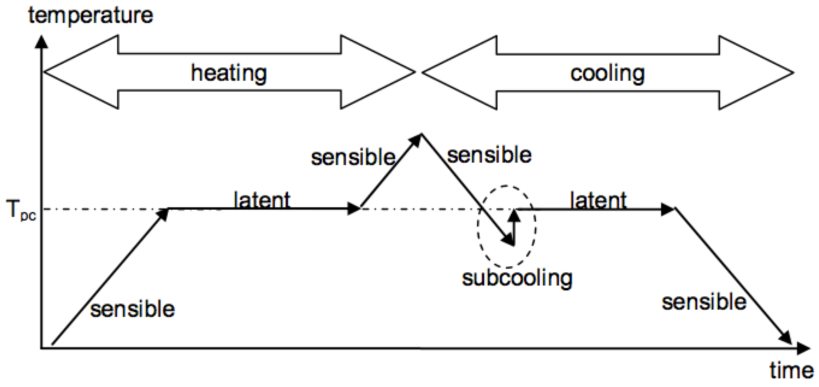

Figure 4: Subcooling schematic [1]

There are two forms of nucleation: homogeneous and heterogeneous. Homogeneous nucleation is when nucleation is started solely by the PCM itself, either from low temperature or through the addition of solid PCM. Adding solid PCM to the liquid to promote nucleation is also known as secondary nucleation. Heterogeneous nucleation is when the nucleation is not started by the PCM itself but rather has been initiated by other means [1].

The most common solution to subcooling is the addition of special additives called nucleators to the PCM. These additives are solids that typically have a similar crystal structure to the PCM. The PCM begins solidifying on the surface of the additives, reducing the subcooling significantly. Although additives have been proven to work there are currently no reliable theoretical approaches to determine how specific additives will affect subcooling [4].

Another approach to reduce subcooling is the "cold finger" technique. This involves keeping a section of the PCM vessel at a lower temperature than the rest of the material. This could be done using selective cooling, having a section of the material remain solid, or by intentionally using less insulation at a certain area. This cooler section will cause nucleation to occur more quickly as the cooler section of the PCM will freeze before the rest of the material, providing nucleation sites for the rest of the material [1].

4.3. Encapsulation

Encapsulation of PCMs is important for containing the liquid phase of the PCM and to avoid contact with the environment. While encapsulation is not necessarily a problem for PCMs, it must be considered when deciding how to most effectively use the PCM. Besides being a necessary requirement, encapsulation can also serve as a construction element, giving mechanical stability to the system. Encapsulation also serves as a heat transfer surface for the PCM. There are two general encapsulation options: macroencapsulation and microencapsulation [1][5].

Macroencapsulation refers to encapsulations from several milliliters to several liters. This option is very common due to the simplicity and accessibility of macroencapsulation and typically refers to containers or bags, which are generally metal or plastic [1].

Microencapsulation refers to small, spherical or rod-shaped particles that contain PCM enclosed in a thin polymeric film [6]. Their sizes range between 1 to 1000 micrometers in diameter making them ideal for being incorporated into other materials. These containers typically have high heat transfer due to their large surface area to volume ratio [1]. Microencapsulation is also good for cycling stability as it gives little room for phase separation [4]. Some disadvantages with microencapsulation are that it results in a higher chance of subcooling and that the process is more complicated and difficult to achieve than macroencapsulation [1].

4.4. Composite Materials

Composite materials can be very useful for PCM systems; they can add mechanical stability or increase the thermal conductivity if necessary. Composite PCMs can be either embedding another material into the PCM or embedding the PCM into another material. The method used depends on the desired application of the material [1].

Composite materials are often used to provide mechanical stability to PCMs. This may involve embedding PCMs into the pores of a structurally sound material. This allows the shape of the PCM to be maintained for both phases and is referred to as a shape stabilized PCM (ss-PCM) [1]. Microencapsulation allows PCMs to be easily integrated into conventional construction materials easily giving them additional thermal storage properties. Since the capsules are so small there is no risk of leakage and no care must be taken to prevent destruction. For this reason, microencapsulated paraffin waxes are often integrated into building materials [5][6].

Composite materials can also be used to improve the thermal conductivity of a PCM. Non-metallic liquids typically have low thermal conductivities. The addition of materials with higher thermal conductivities may remedy this. Materials with high thermal conductivities can be added on either a micro- or macroscopic scale in order to increase conductivity. This may however reduce the convection of the PCM in the liquid phase. It must be examined on a case-by-case basis whether the addition of the material will help or hamper its thermal conductivity [1].

5. Latent Heat Storage Design

5.1. Methods of Heat Exchange

The heat transfer process involves a heat source that transfers its energy to a heat storage and then releases to a heat sink. The energy flow is always from the hotter temperature at the source to a heat storage of less or equal temperature and then to a lower temperature at the sink. Three basic methods of latent heat storage include exchanging heat at the surface of the storage, heat transfer on large surfaces within the storage and exchanging heat by exchanging the storage medium [1][9].

5.1.1. Exchanging Heat at the Surface of the Storage

In order for an object to remain at a constant temperature, a heat storage with a phase change temperature equivalent to the object's temperature is placed adjacent to the object. This ensures that as the object is losing or absorbing latent heat from its environment it is being compensated by the energy released or absorbed by the PCM within the storage. This method of temperature control is used in transportation applications when products need to be delivered at a desirable temperature [7]. To ensure a good thermal contact, the PCM is placed directly on the object and the system can also be insulated to delay heat loss to its surroundings. If greater heat transfer is required to control the temperature, then the surface area in contact with the object can be increased or the heat transfer coefficient can also be increased by forced convection [1][7][9].

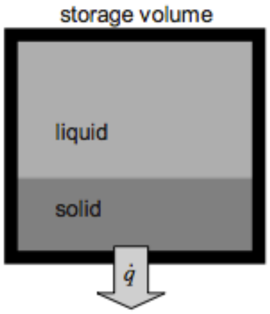

Figure 5: Heat Exchange at Surface of Storage [1]

Figure 5 presents the process of the phase change occurring within the PCM as it loses heat to the ambient through the surface of the storage.

5.1.2. Exchanging Heat on Large Surfaces Within The Storage

When more surface area is required to increase the heat transfer rate but are limited by the volume of the space, then additional surfaces can be created within the heat storage. Methods of increasing the exposed surface area include designing channels that run through the heat storage with the option of adding fins. In these channels a heat transfer fluid must be used to deliver the energy absorbed or released from passing through the PCM to the supply side of the system. As a result of the added surfaces, a pump is usually necessary to induce flow through the channels and therefore increases the heat transfer coefficient within the heat transfer fluid [4][9].

The most widely used method of exchanging heat within the storage is with the use of a heat exchanger that has PCM replacing the fluid on one side of the exchanger. The high storage density of the PCM used for the storage vessel effectively increases the amount of thermal energy that can be stored for a longer period of time [3]. The heat exchanger within the PCM has multiple channels that assist in transferring the thermal energy and once all of the sensible heat is extracted from the PCM that was above the phase change temperature, the outlet of the exchanger will have heat transfer fluid that exits below the phase change temperature. Therefore as the heat is exchanged between both mediums, the heat transfer fluid temperature will change in proportion to how much energy the PCM in the storage vessel will gain or release as it never remains constant [4][9].

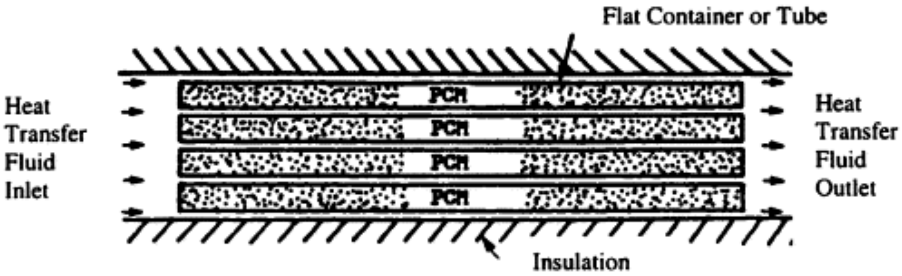

Figure 6: Heat Exchanger within PCM Storage Vessel [4]

Figure 6 presents the process of heat exchange within the storage vessel as the heat transfer fluid passing along the PCM contained in a flat container or tube. In this case insulation is added to the exterior to minimize heat loss from the system.

The added cost of using fins or metallic structures that can be combined with the PCM to increase the heat transfer is eliminated if the direct method of heat transfer in the storage vessel is used. This process involves having a heat transfer fluid directly contact the PCM fluid however it is important that the two do not mix. If the heat transfer fluid has a lower density than the PCM, like for cases that use salt hydrates as the PCM and oil as the heat transfer fluid, then the heat transfer fluid which is pumped in at the bottom of the vessel as droplets will rise in the PCM. The heat storage contains 90 vol.% of PCM and the material melts or solidifies as the heat transfer fluid exchanges energy as it moves within the vessel and once they reach the top they are pumped out [1] [10].

5.1.3. Exchanging Heat by Exchanging The Storage Medium

The process of exchanging the storage medium is a method that uses PCM modules small enough to be incorporated within the flowing heat transfer fluid. This allows one fluid to be formed that consists of a component that stores heat by a phase change and a component that is always liquid and assures the fluid properties. This process is termed the slurry type method and is advantageous because it enables the fluid to be used in standard practices like being stored in tanks and pumped through pipes. As a result of the induced motion through the pipes, the heat transfer coefficient is increased and will transport more heat or cold at the same volumetric flow rate. Due to the higher storage density that the incorporated PCM provides, it is able to store more energy than heat transfer fluid alone which consequently permits smaller systems to be used for the process [1].

6. Applications

6.1. PCM Used in Transportation

Many products need to be stored at a specific temperature to remain of value and this is challenged when the merchandise has to be shipped to a new location. One of the first commercial uses for PCMs was for transportation of goods as they provide an effective method of keeping the product in a narrow temperature range. When the phase change occurs in the PCM, the temperature remains constant until it has completely transitioned. This process must be prolonged because it will conserve more energy and keep the system at stable temperature for a longer period of time. In order to accomplish this, insolation must be applied to the PCM material as it helps create an isothermal environment between the stored object and the PCM. Assuming that the insolation is infinitely thin and does not store any heat, it can reduce the heat transfer coefficient by a third and therefore take three times longer for the PCM to change temperature. This method works best when the PCM is placed on the interior surface of the insolation as it keeps the objects temperature at the phase change temperature and stops the loss of heat from the object [7].

6.1.1. Methods of Using PCM in Storage Containers

There are other methods that use forced convection to stabilize the temperature and is generally used for larger containers. A ventilator is placed on the top of the stacked PCM material and can condition the air up to 48 hours before they need to be recharged in a main electrical unit. The benefit of not having to plug the PCM in to an electrical grid while it is operating is essential, as certain situations do not have this as an option, such as a cargo bay in airplanes. The PCM material also generates no noise while conditioning the surrounding environment, which makes it favourable to use in areas that are heavily populated [7]. Since there are so many applications for transporting certain goods at a critical temperature, companies tend to manufacture storage containers that are not designed for one specific purpose. The company va-Q-tec AG produces an insolation with an efficient vacuum seal that reduces the thermal conductivity by 7 to 8 magnitudes more than other insulations typically used and does not need an internal or external electrical input. With this unique design, the PCM can sustain a temperature of -20°C inside the insulated container for 4 days with an ambient temperature of +30°C. This company also developed a trolley that can store food below -10 °C for around 35 hours with the outside temperature being 25 °C and is used in locations like hospitals and schools. These design conditions allow products to be delivered at a suitable temperature over relatively long periods of time and is essential when transporting products that are essential for human health like food and medicine [1].

6.1.2. Storage Containers for Transporting Pharmaceuticals

Successful delivery of pharmaceuticals is another important application for PCMs. This product depends heavily on temperature and needs to be maintained in narrow temperature ranges that can be as little as a 4°C difference. Unlike food that can be kept frozen with PCM, certain pharmaceuticals cannot be preserved in too hot or too cold of an environment as it compromises the product. The importance of proper thermal storage is a result of the value of medicine as it can be very expensive merchandise. Despite price however, product such as blood plays a critical role in the healthcare system and if the storage temperature is outside the necessary range then the blood can no longer be used. Wasted blood or other limited products would be detrimental as there are countless of people who depend on the availability of these healthcare products to survive [7]. Even if expensive cooling or heating systems are used for the majority of transportation, what makes PCMs so important for this application is to provide a method of transporting the product from the location it was produced to the transportation vehicles and then from the vehicles to the final location. Although it may not take long for this process to occur, it is not worth the risk of destroying the product and therefore thermal storage methods are used. The company delta T developed an independent system that can keep the temperature of blood between 2 °C and 10 °C for 12 hours which is sufficient time if only short transportation is necessary [1].

6.1.3. Storage Containers for Transporting Food and Beverages

PCM can also be used as a replacement for containers that once used ice to cool but also dilute a drink. A company called Sofrigam manufactures a double wall bottle where the PCM is placed between two layers of the wall and can keep a 0.5 liter beverage at 13 °C for 3 hours in an ambient temperature of 25 °C when initially precooled. Another useful method for preserving food is the pizza heater designed by the company Rubitherm Technologies GmbH that can maintain a temperature of 65 °C and greater for a period three times longer than with boxes that contain no thermal storage. Although the cost will be greater to provide hot pizzas with PCM impregnated plates, the increased profit that the company will receive by having satisfied costumers return to the establishment exceeds the amount that was originally paid for the pizza heaters [1][7].

6.2. Applications for Electrical Equipment

Other applications that involve electrical equipment require narrow temperature ranges as well. If a battery is too hot or too cold it will significantly reduce its lifetime or even result in breaking down completely. This can occur when electrical equipment is placed in harsh environments and if these locations are remote then maintenance will be minimal therefore thermal storage methods must be used to protect the equipment. The PCM is able to absorb energy from peak load operations and then reject the heat when the ambient temperature is cold enough to allow for heat rejection [1][7].

6.3. Applications for the Human Body

Applications for PCMs used for the human body have started development for public use and has been steadily growing due to their economical benefits. One of the first applications for PCM used in clothing was in spacesuits for astronauts in the US space program and because PCM does not require a power source to operate it was able to make this possible. Many factors influence the temperature of a human body and as a result, maintaining a healthy temperature of 37 °C can be difficult. Due to this narrow temperature range, the potential for PCM to be used in stabilizing an appropriate body temperature is promising as the human body is a natural energy source. In situations where the body can no longer release heat to the environment due to increased metabolic activity, the PCM integrated clothing can absorb this extra heat and keep the body cool. However in cases where the opposite is true and the body loses more heat than it can replace, then the PCM will release the energy stored as latent heat and keep the body warm [1].

6.4. Methods of Integrating PCM

Methods of applying the PCM into clothing include macroencapsulation, microencapsulation and developing a composite material. The first method involves placing the PCM into pockets that are sized based on preference. The benefit to this is that it is the cheapest method of combining PCM into clothing however the disadvantage is that the clothing must be specially designed to hold large amounts of PCM [1]. This design is not appealing to a market that is trying to attract the average consumer as aesthetics play an important role in retail. Microencapsulation methods avoid this disadvantage as it consists of incorporating the PCM into the fibres of the clothing and therefore provide a more diverse market. Although it is a more expensive method, it can be placed in mitts, hats, and any other type of insolating material without affecting its appearance. Lastly the method of using PCM to create composite material can be used in building applications as the material can be cut into desirable sizes after the powder has been placed into molds that can be of any random shape. Applications of these three methods range from being used in sleeping bags to underwear and can even provide heat therapy that reduces body pain [1][9].

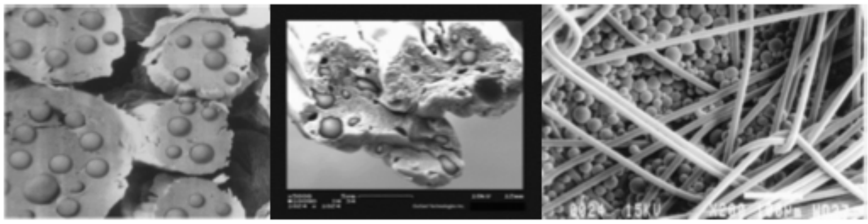

Figure 7: Microencapsulation of PCM into Fibres [1]

Figure 7 presents the method of incorporating microencapsulated PCM into fibres that can later be used in clothing or other accessories.

6.5. Building Applications

The study of using PCM for storing solar heat for use in space heating began in 1930 and has continued to grow since. Due to the increased cost of energy in the last decade and the increasing demand for human comfort, PCM is becoming more economical for industrial and commercial use of thermal energy storage [6]. Factors such as the relative humidity, ambient temperature and speed of the air affect the amount of heat exchanged from the human body to the environment and therefore determine comfort.

Because the demand for electricity varies greatly during the day and night, with peak hours that occur as a result of residential and industrial requirements, PCM can be utilized to time shift the peak load and even reduce the sizing of HVAC equipment. The importance of delaying these peak hours is to avoid the peak electricity prices that apply during this time period. In cases where the decision is made to provide insufficient heating or cooling to a building to save on energy costs is never beneficial as it will decrease the productivity of the workers in the establishment. As a result of low production, the savings expected from the cutbacks will never result and for this reason, PCM is the perfect solution for reducing energy costs but also maintaining high levels of productivity in workers. Typically people enjoy similar environmental conditions and this occurs over a small temperature range. This is what makes PCM so useful for heat and cold storage in building applications because they operate best in small temperature ranges as well [6].

For buildings that have low thermal mass, PCM can be used as thermal storage in the building envelope as it reduces the impact of the varying temperatures. Factors such as internal gains from appliances and people, heat capacity of the building and the rate of infiltration and exfiltration have a major affect on the building's ambient temperature. Based on these parameters HVAC units need to be designed for peak load capacity as the necessary air conditioning for a particular day can change significantly as a result of the climate and activity within in the building. PCM uses latent heat to condition a room where typical building materials use sensible heat. This is because as the ambient temperature rises above the melting temperature of the PCM it absorbs energy, and when it falls below it releases energy. Therefore in hot climates where the daily temperatures are high and have intense solar radiation, the PCM material can be placed in the envelope of the building where it will absorb the natural energy [10].

6.5.1. Temperature Control

The best conditions for using PCM is with a phase change temperature that is the same as the average temperature during a full 24-hour period. Because of seasonal changes however, this average may rise higher or lower than the phase change temperature of the PCM. Despite these deviations, using PCM in building applications in varying climates is still very useful as it significantly buffers temperature fluctuation and maintains the ambient temperature closer to the phase change temperature. Small amounts of PCM adds a significant amount of thermal mass to a structure compared to other building materials and therefore reduces the affect of fluctuating indoor temperatures. An example of this is presented in the following figure [1][10].

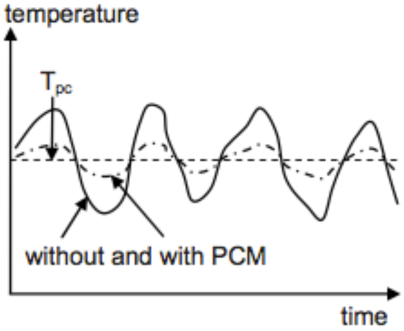

Figure 8: Temperature Fluctuations With and Without PCM [1]

Figure 8 presents temperature fluctuations recorded for various 24-hour cycles and how the peak temperatures are buffered by incorporating PCM into the building envelope.

Another possibility besides placing PCM sheets on interior walls is to integrate them into building materials that would make them PCM-composite materials. This decision is only useful however for the PCM placed closely to the outer surface because if it is placed too deeply within the composite wall then the phase change temperature will not be reached from daily temperatures and will not give effective results. For processes that involve heat and cold storage such as space cooling, space heating, or domestic hot water heating, PCM can be used as its high storage density for narrow temperature ranges reduces the amount of space needed for other storage devices [3][8].

6.5.2. Integrating PCM into Building Materials

Concerns about having PCM leak or evaporate into the air as materials containing PCM are cut for building applications is eliminated by using the microencapsulating method. This method allows for the material to be treated as normal building material and does not require extra expertise when handling. Microencapsulated PCM can be integrating into materials such as gypsum plasterboard, which is highly used in construction [3][8][10].

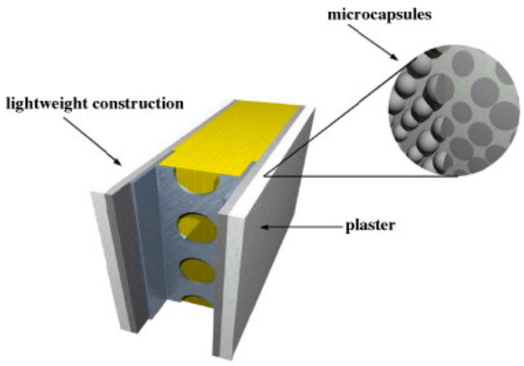

Figure 9: Microencapsulation of PCM into the interior plaster [3]

Figure 9 demonstrates a method of integrating microencapsulated PCM into plaster for construction. Due to the PCMs small size it can be drilled or cut into without leakage, which makes it ideal for easy installation.

Although materials that are altered during construction are limited to microencapsulating techniques, building components can be fabricated beforehand and are not altered can use microencapsulation. Several of these methods include placing PCM on top of suspended ceilings, so when the temperature rises and reaches the ceiling it will absorb the energy and release it when room temperatures cool at night. Another method is installing PCM incorporated blinds that absorb the solar radiation and releases it at a later time instead of releasing it soon after it was absorb which standard blinds may do depending on their emissivity. In cases where PCM is used in ceilings, walls and floors, forced convection is used to create larger temperature gradients and increase the systems efficiency [3][10].

6.5.3. Methods of Thermal Storage

The use of a separate storage unit is also an option rather than incorporating PCM directly into or around building materials. This system collects thermal energy into the PCM plates from cold night air and then releases it during the day when the temperatures are high. The company Imtech has developed this system and has around 1 kWh or storage capacity and can reduce the inlet temperature by 5 K. This reduces electricity consumption by 5 – 7 % and can provide around 82 % of the required cold for the building [1][10].

All of the heating and cooling methods previously discussed are decentralized as they condition the air for a specific room. This is beneficial when comfort conditions vary for each space as they are exposed to different amounts of thermal energy. A different method that has been developed by the company Rubitherm Technologies involves feeding air through the central air-conditioning system that has macroencapsulated metal sheets of PCM placed directly within it. Due to its simplistic and versatile design, building modifications are not necessary for proper installation and therefore make it an attractive investment for customers [1].

7. Conclusion

It is evident that thermal storage will become more dominant in society as environmental and economic policies become more rigid. The demand for this product has been quickly escalating as industrial and commercial uses for PCM are starting to replace old methods of heating and cooling. Utilizing PCM as a solution to the rising energy prices in the past decade is a major factor contributing to its growing success as it is more economically feasible to be implemented. The ability for PCM to be used to reduce energy costs during peak demand hours along with the successful transportation of goods is what continues to increase its market and will continue to do so as the demand for storing natural thermal energy rises. Its ability to be incorporated into merchandise that can be sold to the public is a promising market as the demand for human comfort increases with social and economic development.

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