Introduction to Phase Change Materials: Building Applications

Theo Pacson

79116067

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Introduction

Building insulation has been used for many years to prevent heat from escaping the building during cold days to reduce the cost of heating throughout a house or a building. However, since it's a passive material, it still works during the hot summer days. Radiated heat from that enters through the windows and body heat from people inside the building is kept from escaping the building making it an unbearable work or living space. Typically one would turn on the air conditioning to cool the building and taking the cost of power usage for air conditioning as a fixed cost.

Phase Change Materials (PCM) is an alternative way to reduce long term cost and reduce power consumption. It is a passive material like a regular building insulation but it also has the ability to keep the interior of the building at a constant temperature. The main concept is that the PCM stores excess heat during the day and expelling the stored heat during night time. By using PCM, the power consumption and the cost of temperature management is reduced during the day *and* during the night.

History

The concept of storing heat within the building walls has been around since 1881. A Trombe wall is a massive wall that collects solar energy within the masonry and releases it selectively during the night (Trombe wall) effectively increasing the wall's thermal mass. It was invented by Edward Morse and popularized by Felix Trombe in 1964 (Trombe wall). Modern variation uses insulating glass instead to store the solar energy while convective heat is transferred indoors (Trombe wall).

The concept of using PCM instead to increase the wall's thermal mass was introduced even before 1980. Initial attempts use macro-encapsulation which reduced the surface area contact to the PCM. When it was time to regain the heat from the liquid phase, the PCM solidified on the edges and prevented from effective heat transfer (Castellon, Medrano, Roca, Nogues, Cabeza, & Castell, 2007). The PCM available at the time were also either toxic or flammable which is not ideal for building materials.

PCM is once again gaining popularity due to the micro-encapsulation technology which eliminated the heat transfer problem. Non-toxic and ignition-resistant PCM are now also available. There are plenty of studies that analyze PCM as another energy saving measure due to its flexibility and applicability.

How does it work?

Its functionality is identical to the Trombe Wall; the heat is stored within the wall's thermal mass during the day and released to the interior of the building during the night. However, instead of storing the heat within the masonry, the heat is stored in the form of latent heat of the PCM. In order to fully get the idea of how PCM works the concept of latent heat must be discussed. Typical applications show examples on how PCM can be used effectively.

Trombe Wall

The modern variation of the Trombe wall is depicted on Figure 1 - A Trombe Wall. During the summer time, when the sun sits high in the sky during the day, the roof overhang provides shade on the wall preventing the solar radiation to meet the wall. During the winter time, when the sun sits low on the horizon during the day, the sun will shine on the wall heating the air in between the glazing material and the concrete wall. The heated air then rises and exits towards the interior of the building through the vent near the top of the wall while the cool air gets sucked inside the cavity. The insulation and the glazing material separates the interior temperature and the ambient temperature; the heat absorbed by the wall is mostly due to solar radiation.

Trombe walls suffer the same drawbacks as mentioned above. It is difficult for heat to be removed from the interior when cooling is desired.

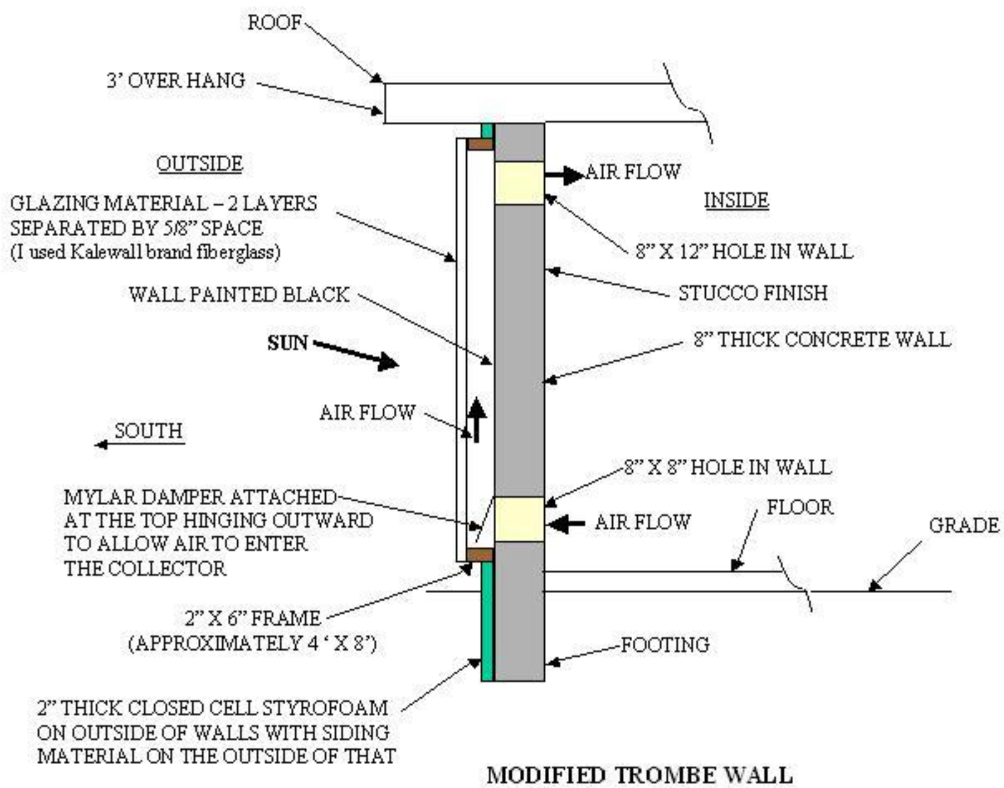

Figure 1 - A Trombe Wall. Image from Wikipedia

Latent Heat

When heat is added to a material at constant pressure, the material's temperature increases proportionally to the amount of heat added. However, at certain critical temperatures, when the material transitions from solid to liquid or liquid to gas or vice versa, the temperature remains constant until a large amount of heat is added before the temperature rises once again. The amount of heat added or removed during phase transitions is called *latent heat*. This phenomenon can be observed from a simplified graph of temperature versus heat added for water shown on Figure 2.

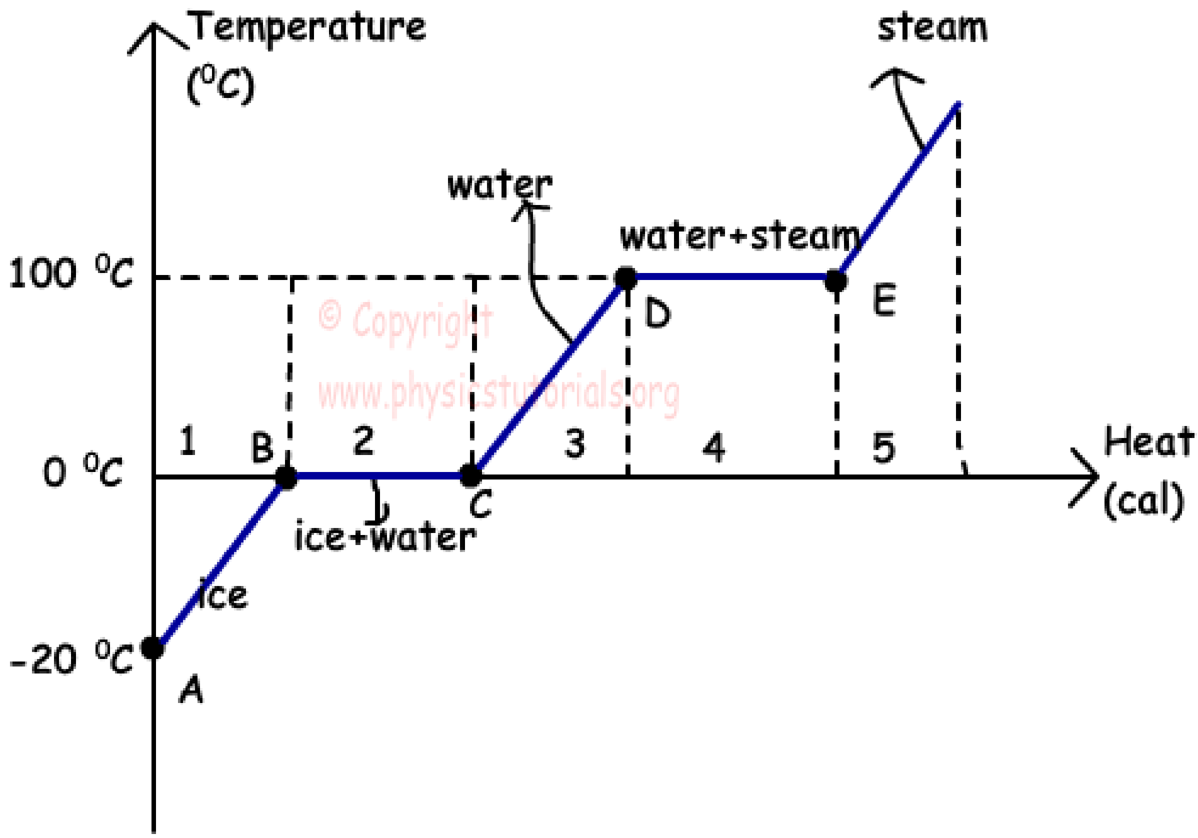

Figure 2 – As heat is added to or removed from water, the temperature remains constant as it changes phase. Image from www.physicsturtorials.org

In other words, latent heat is the amount of heat that is 'stored' within the material per kilogram during the time when it changes from solid to liquid or liquid to gas. This stored energy can be reclaimed by having the material to change back from gas to liquid or liquid to solid.

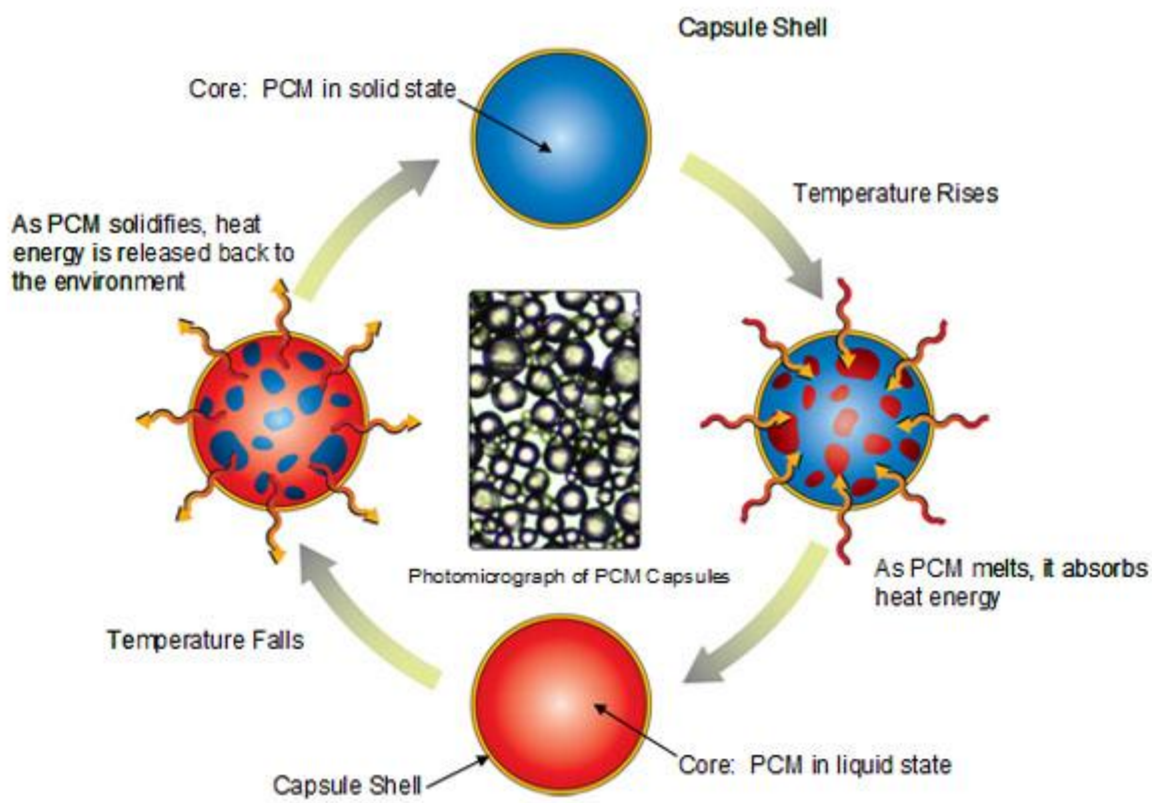

Figure 3 - Image of microencapsulation and how it works. Image from www.microteklabs.com

PCM takes advantage of its phase transition temperature. While different materials will have different critical temperatures as well as different latent heat during phase transitions, a particular material with the desired characteristics will be chosen as PCM to meet the application and the temperature requirements.

Typical Application

PCM can be considered as an extra layer of insulation applied to the walls, floor, and ceiling to separate the inside temperature of the building to the ambient temperature. Once the walls are lined with the PCM, the temperature of a certain space can be kept relatively constant at the phase change temperature.

Insulation

It works well in tandem with regular insulation. The insulation in placed in between the exterior wall and the PCM material. By placing it this way, the insulation can repel outside heat during the day while the PCM absorbs the heat that radiates from the windows. During night time, the PCM expels its stored heat while the insulation then keeps the heat inside the building.

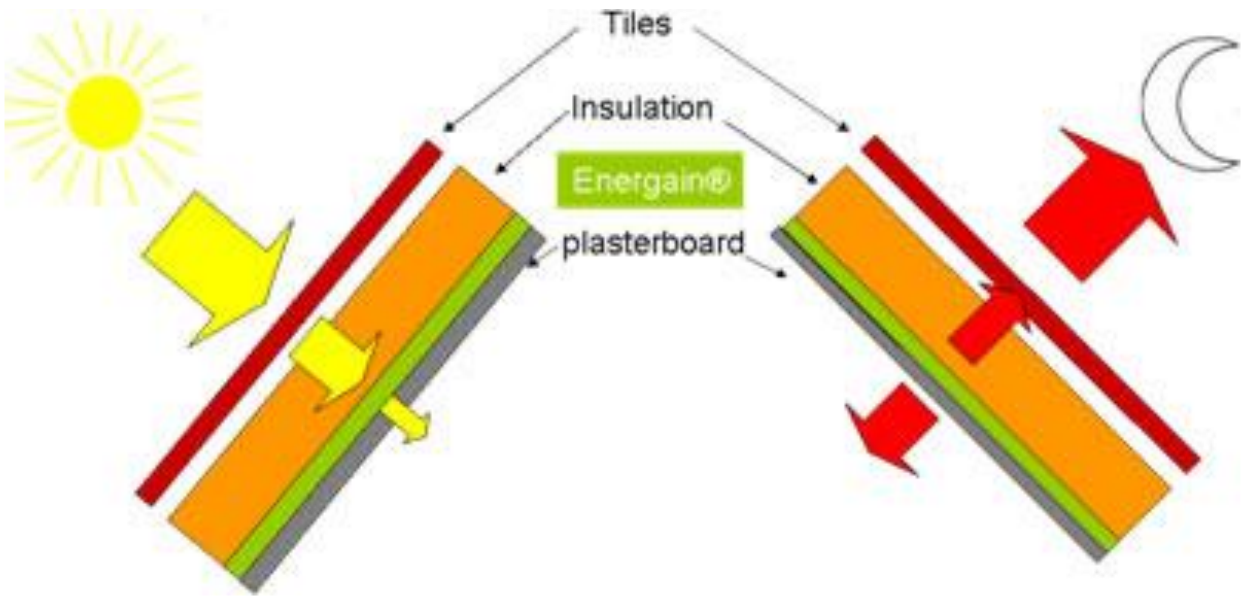

Figure 4 – The Ideal Configuration of Insulation with PCM, a variation of Trombe walls. Image from energain.co.uk

Material

They come in the form of salts, organics (such as wax), and materials whose crystalline structure changes from one to another at a precise temperature (Solid-State PCM). They can be also categorized as either positive temperature or negative temperature PCM, whose critical temperatures are below or above 0˚C respectively. The PCM can be chosen depending on the application to meet the temperature requirements. Typically, for PCM applications, a material that changes between solid and liquid at the desired temperature is chosen since there is only a small volume change between the two phases for a certain mass.

For building insulation purposes, the PCM chosen is a wax that liquefies at a certain critical temperature. Wax is considered to be the best choice since it's not harmful on contact. The critical temperature can be adjusted by adding impurities to the wax during manufacturing. Wax is preferred over salt hydrates since it is usually cheaper in comparison. Also, salt hydrates cannot be encapsulated with metal containers since it will corrode the container (Hittle, 2002). The capsules may also crack and tear when salt hydrates crystallize and solidify (Hittle, 2002).

Packaging

In order for the PCM to be used, it should be manageable in both solid form and liquid form. Furthermore, the most effective way to use PCM is to spread it out so that the temperature gradient within the room is minimal. The best way to keep the PCM from flowing down when it changes from solid to liquid and to spread it around is to put it into a package. The packaging can be chosen depending on the application.

Plates

Plates are moulded high-density polyethylene (HDPE) into flat containers with indentations. These containers are then filled with the chosen PCM. They are made to be stackable so to form a large bulk volume tank of PCM for building temperature control applications. Once stacked, there are gaps formed between the plates that allow air or water to flow easily as well as provide large surface area contact.

Figure 5 – Stacked Plates that form a PCM Tank. Image from pcmproducts.net

Figure 6 – Ball capsules

Balls

The same HDPE can be moulded into balls from as small as the size of a marble up to the size of a ping pong ball and then filled with the appropriate PCM. Larger sized balls are used by embedding them within the concrete flooring. The shape of the ball allows the maximum amount of PCM that can be used as well as provide some structural strength due to its shape.

Pouches

Putting PCM into pouches gives rise to flexibility in terms of cost. These are manufactured using the same type of techniques in manufacturing bubble wrap, sealing slabs of PCM into evenly spaced pouches. Depending on the application, PCM pouches can be cut or folded to quickly line irregular shaped walls with PCM. Examples of the pouches are shown on Figure 7 and Figure 8.

Figure 7 - Image from pcmproducts.net

Figure 8 - Image from pcmproducts.net

Tubing

Similar to the plate packaging, it is a moulded tube container that is filled with PCM. The tubular shape allows it to be stacked side by side. Its shape allows better air flow and larger area of thermal contact. Ideal to be placed on the ceiling with PCM intended for passive cooling application. With this type of application, rather than absorbing the heat during the day, it 'stores' cold energy from the cool air during the night so that cooled air will fall to the ground during the day.

Figure 9 - Passive Cooling using Tubing Packaging. Image from pcmproducts.net

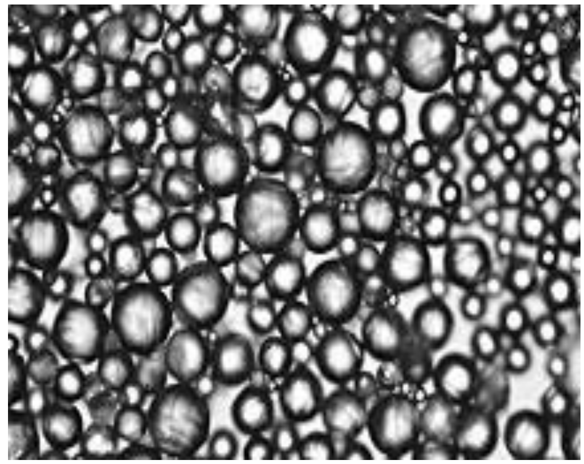

Figure 10 – Close-up of Fire-Resistive Microencapsulated PCM. Image from www.ornl.gov/info/reporter/no113/august09_dw.htm

Microencapsulation

The PCM, which is typically chosen to be a type of paraffin wax, is enclosed plastic micro granules such that the PCM can be treated as a powder. An advantage with microencapsulation it is easier to mix with other materials, such as plaster, during processing distributing the material evenly. Another advantage of microencapsulation is due to its size and form, it is virtually indestructible from normal work such as hammering and drilling as the granules will simply flake off from the plaster when the plaster is deformed. A photomicrograph of microencapsulated PCM is shown on Figure 10 – Close-up of Fire-Resistive Microencapsulated PCM. Image from www.ornl.gov/info/reporter/no113/august09_dw.htm. Another advantage of its size is that it has a large surface area for heat exchange. Compared to macro-encapsulation, the PCM does not run into the problem of partially solidifying or liquefying during phase changes due to the temperature gradient within the core. The shells for granules can also be made from ignition resistant material.

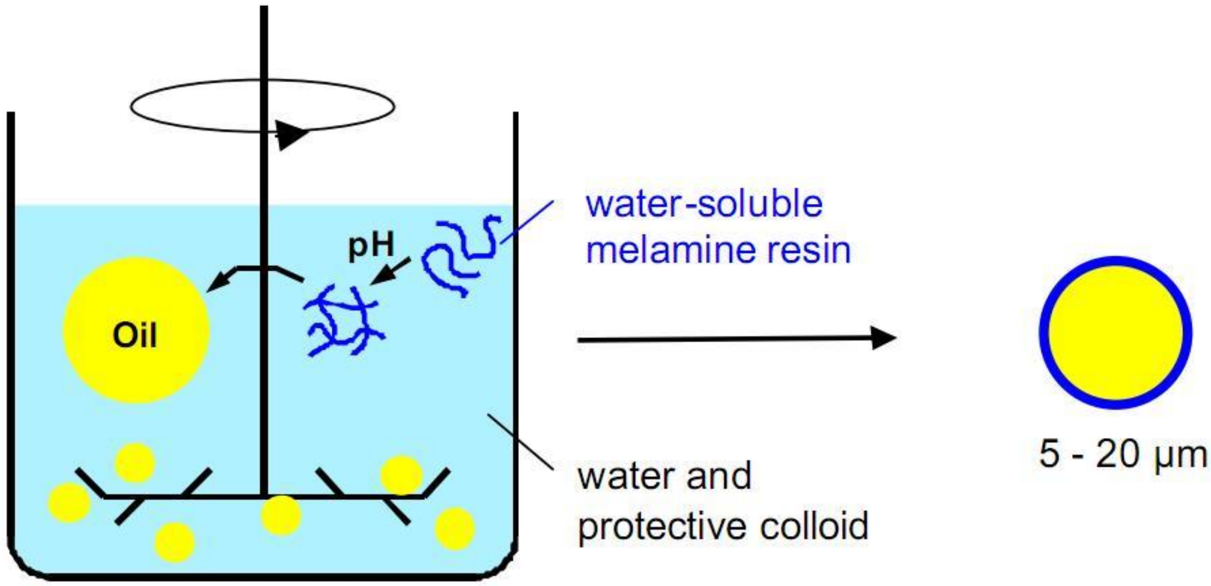

Figure 11 - Microcapsulation Process (Jahns)

The manufacturing process is started by emulsifying the PCM into the water using water-soluble polymers and high-shear mixers (Jahns). This produces droplets of the PCM to form. The average size of the droplets is inversely proportional to the amount of emulsifiers and mixers added. Then the water-soluble resin is added to the mix. A precipitant is added that allows polycondensation of the resin. The condensed resin becomes interlocked and deposit at the surface of the PCM droplets. Once the solidification of the resin is completed, the microcapsules are formed and received. A graphic representation of the manufacturing process is shown on Figure 11 - Microcapsulation Process .

This is ideal for drywalls and tiles. This virtually allows enclosing the room or building with PCM to shield the inside from changes of the ambient temperature outside. The fire resistant rating of the drywall can also be increased by using ignition resistant material to encapsulate the PCM.

Integrating PCM into Building Materials

Castellon *et al. (2006)* studied how integrating PCM in construction materials (concrete in their case) would affect the effective thermal energy storage (TES) of a building. Using the granules of microencapsulated PCM as part of the aggregate for the concrete, the PCM is embedded simply and effectively within the construction material. Their experiment included a building a small concrete cubicle with embedded PCM and another cubicle made from regular concrete. The results indicate that the peak temperature of the cubicle with PCM occurred about 2 hours later; this means that the cubicle was kept cooler longer.

Studies by Hittle *(2002)* were made to determine the energy saving capability of PCM when it is applied to floor tiles. The study also compared the initial cost of manufacturing tiles with PCM and the tile's energy savings. The tile was made from a mixture of quartz, binder, and phase change material (Hittle, 2002).

The cost of the tile production can be as low as \$0.59/lb and it can go as high as \$12/lb (Hittle, 2002). The cost does not represent the effectiveness of the tile's theoretical TES. The cost variation is due to the availability of the materials used. Even though paraffin waxes do not have the largest latent heat, it is the most commonly used and the greatest produced PCM. Meanwhile, some solid-state phase change materials require special capsules and special binders to be used as agglomerate for the tile which drastically increases its cost.

Hittle used encapsulated technical grade octadecane (~95%) as the PCM of choice. Octadecane was chosen since it has the largest potential energy storage amongst the most readily available PCM at the time of the experiment. Octadecane yielded potential energy storage of 2.02-2.14 MJ/m^2 for ½" floor tile and 3.02-3.21 MJ/m^2 for ¾" floor tile. This is a theoretical number. Hittle estimates that the actual energy storage of the tile is about half of the theoretical number. Manufacturing encapsulated octadecane was estimated to be \$11.53/lb. This number may not have proportionally indicated the final cost of the tile since a readily available polyester binder can be used which would have reduced the cost. The final cost of the tile would have been reduced even more if mass production of the tile is considered.

For a floor area of 346.5ft^2, the average daily energy storage was shown to be 65.0-68.9 MJ and 97.2-103.3 MJ for ½" floor tile and ¾" floor tile respectively (Hittle, 2002). This reflected that the increased solar savings 17.3% and 23.9% for ½" floor tile and ¾" floor tile respectively. Increased solar savings indicate the reduced amount of heat required to heat the building during the night. The annual heating cost savings was then projected from the increased solar savings. Assuming that the annual heating load to be 50MBtu at a cost of $11.6/MBtu, the annual heating cost saving were determined to be $100.34 and $138.62 for ½" floor tile and ¾" floor tile respectively.

Although, further studies are still being made how the PCM granules change the other properties of the floor tiles, these results are still promising. Hittle predicted that by using PCM within the mix, not only will change the TES of the tile but also change the structural integrity of the tile; Hittle's tests concluded that this was in fact true. However, industrial standards could still be met with the change of percentages with the resin, agglomerate and PCM granules.

Green and economical buildings are already built based on the PCM technology. Even though the application of PCM technology has already been deemed practical, studies are being continued in order to further develop PCM in terms of building application, manufacturing techniques and cost reduction.

Other Building Applications using PCM

Other applications than heat insulation and thermal rejection for using PCM has been explored. Applications that are described below are not an exhaustive list.

Hot Water Heating System

Chen, Cheng, and Hu from the University of Science and Technology of China have developed a hot water heating system involving PCM. Water is heated using electric broilers. Typically, the hot water is then stored in a storage tank. In order to store more energy, a larger storage tank is required; this requires extra space and large amounts of water. By pumping the heated water through a tank of PCM, the heat is transferred to a material whose effective heat capacity is greater. This means a greater amount of energy can be stored within a smaller space and less amount of water.

In order to get heated water, a small amount of water is pumped through the PCM tank which retrieves the heat stored within it. A schematic of their system is shown on Figure 12. The preheated water exiting the tank is then pumped into the broiler once again to be heated to the set temperature. It requires less energy to reheat the water coming from the tank than heating water coming from the city's water system.

Hot water heating system can be implemented in North America. It would make a good fit to the Smart Grid technology. To balance the load of the electrical system, excess electric energy can be dumped into the hot water heating system. While the demand is high, the hot water heating system can still run due to its reduced energy requirement.

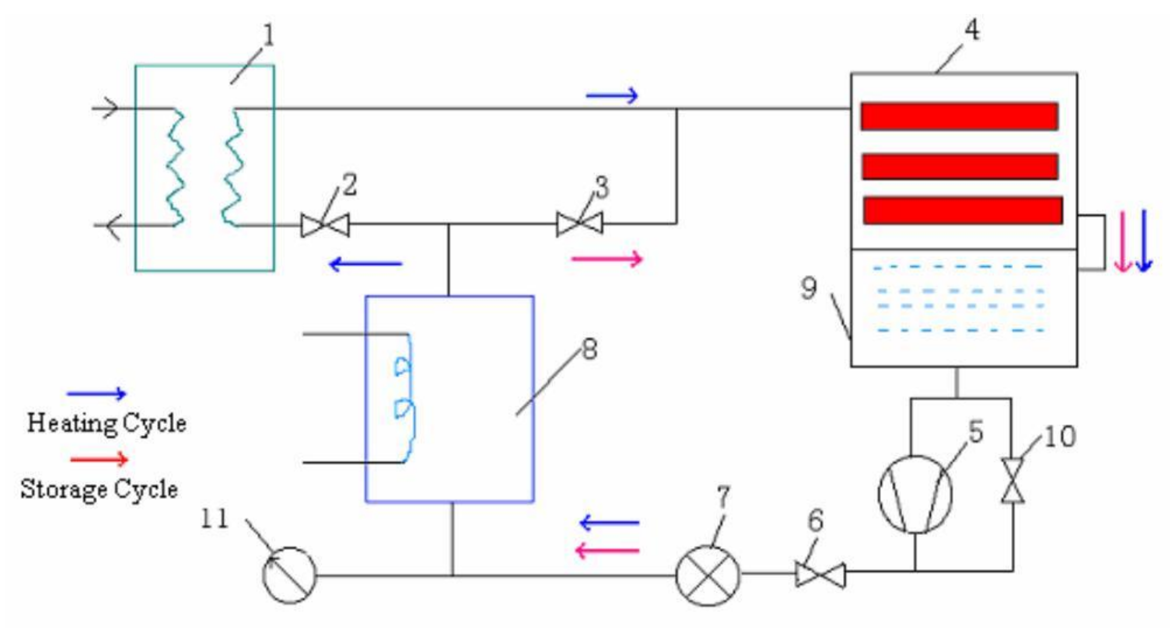

Fig. 3 Sketch of the hot water heating system with phase material.
1: Plate-type heat exchanger 2: Electromagnetic valve for heating cycle 3: Electromagnetic valve for storage cycle 4: Storage tank with PCM 5: Variable frequency pump 6: Valve 7: Flow gauge 8: Electric boiler 9: Storage tank with water 10: By-pass valve 11: Pressure

Figure 12 – Sketch of the Hot Water Heating System with Phase Material (Cheng, Chen, & Hu)

Reflective Shielding

Ideally, glass walls and large windows are preferred since it allows plenty of sunlight in and gives an open space feeling. However, by using glass walls and large windows, the thermal mass of the building is drastically reduced. This means that it quickly gets hot inside the building during day time due to the radiation coming from the sun.

By using a thick layer of PCM within the inside walls in the direct path of the sunlight, the wall then reflects the sunlight while it absorbs the radiation that flows in.

Seasonal Thermal Storage

Compared to the Trombe wall, which goes through the collection-emission cycle within a day, a seasonal thermal storage system goes through one cycle through seasons. During the warm season, it works by pumping water from the solar collector located at the roof through a PCM tank underneath the building; this acts as heat rejection. During the cold season, the heat collected during the warm season is transferred to the interior of the building by running the water from the PCM through the piping underneath the floor. The heat is allowed to rise from the floor to the interior of the building. A large PCM tank is required to store a large amount of energy during the warm seasons. The concept is similar to MIT’s Solar House #1 built in 1939 (schematic depicted on Figure 13 - MIT's Solar House #1. Image from bruteforcecollaborative.com), except a PCM tank is used which is smaller than a water tank.

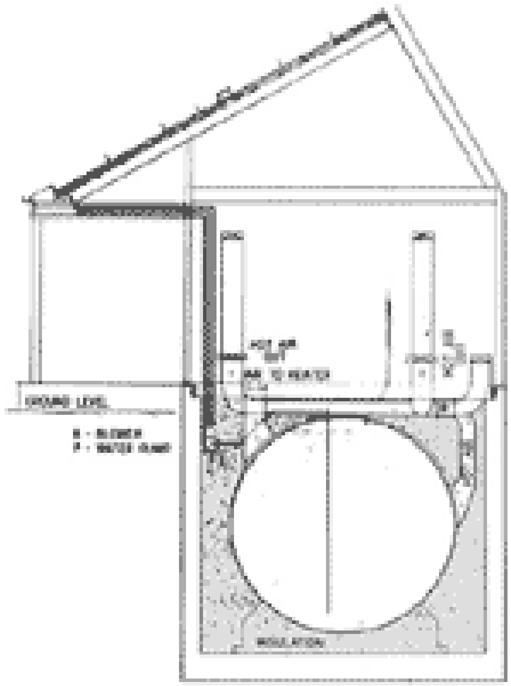

Figure 13 - MIT's Solar House #1. Image from bruteforcecollaborative.com

Non-Building Applications for PCM

Building applications is merely a small fraction of which PCM can be used. It can be applied to anything that requires thermal regulation. The following list is not exhaustive.

Clothing

Outlast Technologies, Inc. integrates microencapsulated PCM with clothing material. They claim that the microencapsulated PCM technology can be applied to clothing without a significant change in overall weight. They have incorporated fire suits with flame retardant PCM. They also incorporated PCM with wetsuits; they claim that this technology will regulate body heat longer even when submerged in water.

Food Transportation

Negative temperature or low temperature PCM can also be applied to food transportation. These types of PCM can be used to insulate trucks that deliver produce or frozen products. This reduces the amount of fuel used to keep the product at a certain temperature during transport.

Chillers

Chillers lined with PCM are used and readily available. The most notable use of these types of chillers is storing blood or organs during transport. It is imperative to keep them chilled in order to avoid damage.

Conclusion

With the development of microencapsulated and fire retardant PCM, PCM technology is once again gaining popularity as a viable long-term cost saving measure. Mixing microencapsulated PCM during the manufacturing of building materials proved to be simple and effective. Although microencapsulated PCM is still expensive, the cost will be reduced in time as the popularity and production of PCM continue to increase. Other applications to increase the efficiency of heating and cooling were also discussed.

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