Packing Heat: Energy Storage Using Phase Change Materials

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Abstract: Many technological applications that involve intermittent energy demand and supply, such as solar or building energy systems, function more effectively if there is a storage mechanism to act as a buffer. Phase Change Materials (PCMs) can greatly increase the energy storage capacity of conventional (sensible energy) storage systems because of the high-energy transfer during their phase transition. With the help of PCMs, larger amounts of energy can be stored in smaller volume and at lower temperatures (resulting in lower insulation costs). This research paper discusses the problem-solving process of selecting a novel PCM (myristic acid) and designing a model apparatus to measure its thermal properties and behaviour. Experiments were conducted on water to calibrate the apparatus and estimate the errors in the experiment.

Key Terms: Phase Change Materials (PCMs); energy storage; latent heat; solar energy; heat storage; myristic acid

Introduction

Many applications in our daily lives require efficient storage and transport of energy in the form of heat. For example, for a solar system to be reliable, the energy available during sunny days should be stored for use during sun-deprived periods. Most heat storage systems use sensible heating of a fluid like water to store heat. To store a substantial amount of heat using sensible heating, either the amount or final temperature of the fluid should be increased, both of which increase the insulation cost for storage. Phase Change Materials (PCMs) have great potential to enhance the efficiency of heat storage by increasing the amount of heat absorbed and released within a narrow temperature range. Despite efforts in using PCMs for energy storage, some practical difficulties complicate the widespread use of PCMs, such as density change, low thermal conductivity, instability of properties (under repeated use), and subcooling of the PCM below melting temperatures (Farid, Khudhair, Razack & Al-Hallaj, 2004). This research paper compares different types of PCMs to propose a novel PCM, with properties favorable for use in energy storage applications. This paper also presents an experimental apparatus designed to measure the thermal properties of the novel PCM, and presents results for preliminary experiments performed in the apparatus.

Phase Change Materials

Phase Change Materials (PCMs) are substances that are capable of absorbing and releasing large amounts of energy (latent heat) within a particular temperature range due to phase change. For solid-liquid PCMs, latent heat of fusion is the energy absorbed during melting and released during solidification.

Applications

Energy storage is a topic of pressing importance in various aspects of technology. For example, solar energy is a renewable energy resource with great potential to solve growing ecological problems, like global warming, by reducing the dependence on fossil fuels for energy. However, most solar energy systems are greatly limited by the availability of the sun, and are rendered inadequate at nights and on cloudy days. Thus, the storage of solar energy becomes vital for a reliable solar energy system. Most solar systems use sensible energy for solar storage (Farid et al., 2004), which is not efficient for storing large amounts of energy and requires an extensive insulation system.

Energy in buildings can be stored and transported effectively using PCMs. Heat energy rejected from one part of the building (as in refrigeration systems) can be utilized in heating systems elsewhere in the building. Some researchers (Khudhair & Farid, 2004) suggest the use of encapsulated PCMs in the walls, ceilings and floors of buildings to store heat energy more effectively. The heat storage system thus serves as a buffer to reduce temperature fluctuations of the air inside the building.

The use of latent energy systems with the help of Phase Change Materials (PCMs) can greatly increase the energy holding capacity (effective thermal capacity) of water or other sensible energy systems at reasonably low temperatures. A considerably high amount of energy is absorbed during the phase change (solid to liquid) of the PCM at the melting point. The stored energy can be reused whenever required by the reverse phase change process, yielding a more efficient energy storage system.

Classification of PCMs

PCMs absorb or release a considerable amount of energy during their transition from one ph

, Cabezab, &
Mehling, 2003):

1. Gas-liquid PCMs
2. Solid-liquid PCMs
3. Solid-gas PCMs
4. Solid-solid PCMs

For the purpose of storage using water or any other carrier-liquid, solid-liquid PCMs (that are insoluble in the given liquid) are convenient to use. The solid-liquid PCMs can be further categorized into the following types.

1. Inorganic PCMs, which can be further divided into the following (Sharma, Tyagi, Chen & Buddhi, 2009):
   a) Salt Hydrates: salt hydrates are inorganic compounds combined with water in a definite ratio to form a characteristic crystalline solid. Salt hydrates actually undergo dehydration (or hydration) to some degree during the phase change process.
   b) Metallics: metallics have high heat of fusion per unit volume and high thermal conductivity. However, they are unfavorable for use as a PCM because of high density (and low heat of fusion per unit mass).
2. Organic PCMs, which undergo phase change without degradation of their latent heat of fusion. They also crystallize with no supercooling (i.e. the process of lowering the temperature of a liquid or a gas below its freezing point without it becoming a solid) and are usually non-corrosive. Organic PCMs are divided into the following two types:

   a) Paraffins: paraffins consist of straight chain alkanes (alkanes are organic compounds consisting of only carbon and hydrogen in single bonds). The values of melting point and latent heat of fusion increase with increase in carbon number of the alkane (Sharma et al., 2009).

   b) Non-Paraffins: non-paraffins include a wide range of organic compounds including fatty acids, alcohols, glycols, and esters. The novel PCM chosen for this research (myristic acid) is a fatty acid.
3. Eutectic PCMs: a eutectic is a minimum-melting composition (mixture) of two or more components that usually melts and freezes without any segregation (Sharma et al., 2009).

Novel PCM Selection

PCMs can be classified into various categories based on their operation phases or chemical composition. Based on the criteria for selection of PCMs (Farid et al., 2004) and comparison of the different types of PCMs, myristic acid was chosen as a novel PCM for this research due to the following favorable thermal, physical, kinetic, chemical, and economic properties:

Thermal Properties

1. Phase-transition temperature range: the temperature range of interest was 50-60°C because it is well above atmospheric temperature in most areas (to ensure that the phase transition does not occur due to atmospheric heat), and low enough to reduce the cost of insulation. The melting point of myristic acid is 49-51°C (Sarı & Kaygusuz, 2001).
2. High latent heat of fusion: the latent heat of fusion of myristic acid is 199 kJ/kg (Sharma et al., 2009), which is high compared to the other PCMs in the temperature range considered.

Physical Properties

1. Density: the density of myristic acid is 990kg/m^3(Sharma, Won, Buddhi & Park, 2005) which is comparable to that of water at 1atm. and 4°C (1000kg/m^3). The density of water decreases on increasing temperature and attains a value of 990kg/m^3 near the temperature range of interest. This property will be interesting to observe in the experiments to determine if density plays a role in clumping of myristic acid during solidification.
2. Insolubility in water: myristic acid is insoluble in water. Thus, the physical properties of myristic acid will remain unchanged when added in water.

Kinetic Properties

No supercooling: myristic acid does not undergo supercooling because of self-nucleation.

Chemical Properties

Non-toxic: myristic acid does not have any serious health hazards.

Economics

Availability: myristic acid occurs in nature in cow's milk, some fish oil, some seeds (e.g. coconut and palm kernel). Furthermore, It can also be manufactured using nutmeg. Myristic acid is also used as a food additive. Due to its availability and low health hazards, the cost associated with chemical safety precautions for myristic acid is low.

Experimental Apparatus

An experimental apparatus was designed and built for the purpose of determining the thermal properties and observing the behavior of PCMs used for thermal storage.

Experimental Objectives

The main purpose of the experiment was to measure the thermal properties (thermal conductivity, and effective thermal capacity) of the PCM (when mixed in water in different concentrations), in order to estimate the increase in energy-holding capacity of a simple water-based solar-energy-storage system. To obtain the desired results from experiments using simple and achievable data and calculations, the following features were required:

1. A one-dimensional heat flow system (i.e., heat flow only in the vertical direction with negligible losses through the side walls)
2. No convection effects to simplify the calculations
3. Insulated heating system, where the amount of heat input in the system and the temperature of the liquid-PCM mixture were measured constantly.

Design Requirements

The design of the experimental apparatus required fulfilling all the experiment objectives. Thus, the design requirements were as follows.

1. Small size: the size of the whole experimental set-up required to be small (in the order of mm) to reduce boundary effects (higher boundary effects would lead to more errors in the result)
2. High aspect ratio: the aspect ratio of the PCM-liquid container needed to be high (more width than height) to ensure one-dimensional heat flow.
3. High conductivity of heating plate: To reduce heat loss from the heating plates, the thermal conductivity of the plates required to be high (i.e., low thermal resistivity).

4. Minimal convection: Convection effects increase the complexity of the experiment by increasing the amount of data and calculations needed to obtain results. Thus convection effects needed to be minimized.
5. Insulation: The heat loss from the system was required to be negligible.
6. Watertight: The entire system needed to be watertight, to prevent water from leaking out and hampering the results.
7. Controlled heat flow: A source of heat energy (that can be controlled and measured) was required.
8. Temperature measurement: The temperature of the liquid-PCM mixture needed to be measured and recorded at frequent intervals (approx. 0.5 seconds).

Final Design

The final design of the apparatus included a stack of six copper discs (with high thermal conductivity) with grooves for a heater and 8 thermocouples. An acrylic glass ring was sandwiched between the middle copper discs (containing four thermocouples each for recording temperatures across the PCM-water chamber) to store PCM-liquid mixture or water. Heat was supplied from the top to avoid convective currents. A cylindrical acrylic glass insulation minimized heat losses from the copper stack. O-rings were used to ensure that the PCM-liquid chamber was airtight and watertight. A heater wire of known resistance was used to provide steady heating. Using the value of resistance and the current/voltage supplied, the heat input was calculated. T-type thermocouples were connected to SR630 Thermocouple Reader to obtain frequent measurements of temperature. The design was compact, small and had a high aspect ratio (approximately 15:1).

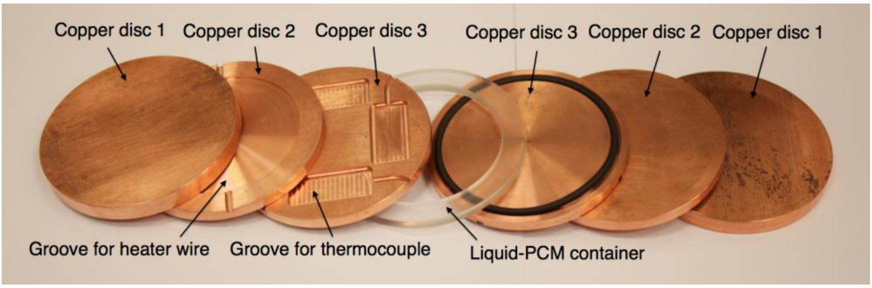

Figure 1: Copper stack (with Liquid-PCM container) in exploded view in the order of assembly (Author's image)

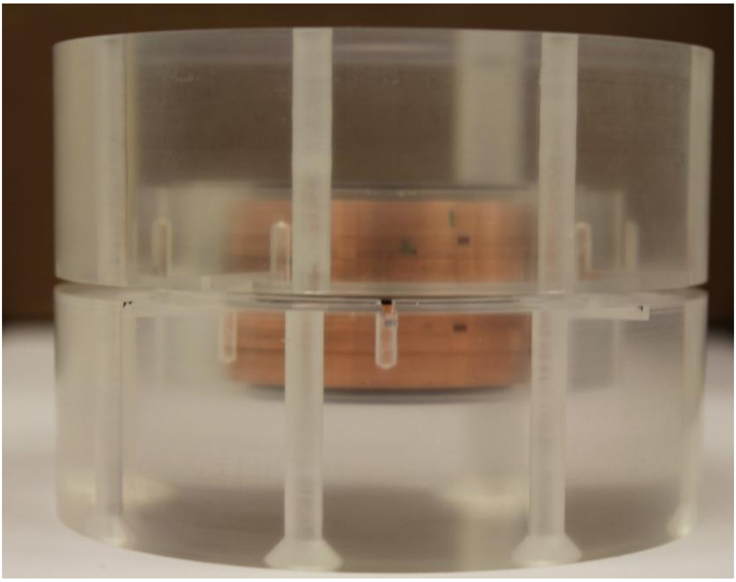

Figure 2: Photograph showing the assembled apparatus (without thermocouples and heater wire) (Author's image)

The apparatus was also modeled in COMSOL (a computer simulation software used for heat transfer calculations) to simulate the experiments performed. This would allow for better comparison of theoretical and experimental results to gauge inconsistencies or errors in the experimental values.

Experimental Results

To check the accuracy of the apparatus, experiments were performed with water alone. The first experiment therefore focused on the determination of the thermal conductivity of water. Steady heat was supplied using the heater wire for a specified period of time. The temperature of copper plates just above and below the water layer was recorded, plotted and analyzed. The experiment approximated steady state heat transfer (as seen in the almost parallel section of the graph in Figure 3). This approximation was used to find the thermal conductivity of water.

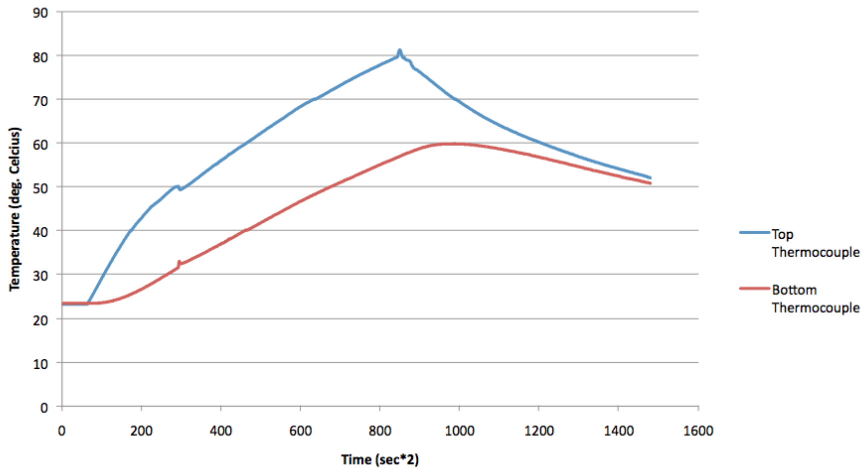

Figure 3: Graph of temperature vs. time for thermal conductivity experiment

Another experiment was conducted by controlling the heat supply, so that the water temperature cycled between two extremes. The data of this experiment was used to find the thermal capacity of water. The temperatures recorded above and below the PCM-chamber are shown in blue and red, respectively, in the graph in Figure 4.

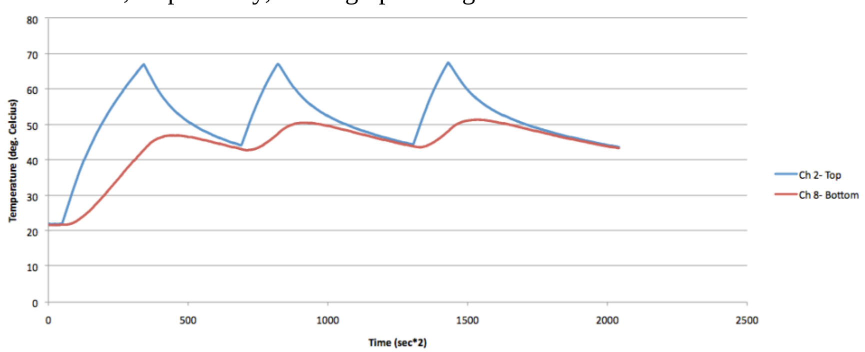

Figure 4: Temperature vs. time graph for specific heat experiment

The results obtained from the experiments were consistent. However, the experimental errors due to heat loss through the acrylic glass insulation were larger than expected, and affected the accuracy of the results. To resolve the issue, the error term needed to be calculated by comparing the obtained results with expected theoretical values or virtual simulations (using COMSOL). With the help of the error term, the experimental apparatus can be calibrated to yield more accurate results.

Recommendations

Based on the research and design discussed in this paper, some recommendations for further research or experimentation on PCMs (or myristic acid) are as suggested. The experiment should be conducted in the apparatus discussed in the paper by varying the concentration of myristic acid (or other PCMs) in water, as a slurry, in order to determine the concentration of the mixture that performs most suitably as a PCM (in terms of energy storage capacity and repeatability). During the experiment, any sign of agglomeration (or clumping) of the PCM (in solid or liquid phase) should be observed, and its effect on the thermal properties should be measured. In case of agglomeration, the possibility of encapsulating PCMs should be considered (Alvarado et al, 2008). Furthermore, the PCM should be tested for long-term stability by repeating the experiment many times. The PCM will be preferable if its performance does not decrease considerably in successive cycles. The possibility of enhancing heat flow in the PCM-liquid mixture should also be considered (e.g., use of finned tubes (Zalbaa et al., 2003)). Additionally, the experiment should be simulated in COMSOL to estimate errors due to heat losses. Finally, the cost benefits of using PCMs in thermal energy storage systems should be analyzed with an effort to maximize the cost efficiency of the system.

Conclusion

After comparing the different types of PCMs in the desired temperature range (50-60°C), the novel PCM selected was myristic acid. Myristic acid was shown to have many favorable properties for use as a PCM, such as appropriate phase-transition temperature range of 49-51°C (Sari & Kayjusuz, 2001), high latent heat of fusion of 199 kJ/kg (Sharma et al., 2009), no supercooling, non-toxicity, and availability in nature.

The final apparatus design satisfied the design requirements to measure the properties of PCMs. However, the heat loss error term needs to be calculated using computer simulations (using COMSOL) and/or theoretical calculations to calibrate the apparatus, following which the thermal properties of myristic acid (and other such PCMs) can be measured. Using the calculated error term, experiments (as described in the paper) can be used to calculate thermal properties of myristic acid and other PCMs. Thus, the relative increase in energy-holding capacity of the conventional storage systems using different PCMs can be calculated and compared, to develop a safe, compact, and efficient energy storage system for numerous technological applications in the future.

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