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REVIEW OF APPLICATIONS OF PHASE CHANGE MATERIAL FOR THERMAL ENERGY STORAGE

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Abstract - Thermal energy storage (TES) systems are crucial for enhancing energy efficiency and enabling the integration of renewable energy sources. Phase Change Materials (PCM) is one of the most suitable materials for storing renewable energy. Phase change materials (PCMs) have emerged as an effective medium for TES due to their high energy density and ability to maintain nearly constant temperatures during phase transitions. Latent heat storage using phase change materials has applications in many areas, including building energy thermal management, waste heat recovery, temperature control, smart data, battery thermal control, microelectronic temperature control, photovoltaic thermal applications, space and vehicles, thermal energy storage applications, and greenhouse temperature control. In this review, topics include an overview of phase change materials (PCMs), use of PCMs in energy storage, use of PCMs in heating and cooling of buildings, use of PCMs in vehicles, and battery thermal management.

Key Words: PCM, Latent heat storage, Thermal storage, Thermal management, solar energy storage

1. INTRODUCTION

In the recent years, the demand for sustainable energy from consumers and industry is increases. How to sustainably maintain a constant desired temperature is a persistent and unresolved issue brought on by the maximum demand for energy consumption in a single day. Heating or cooling is needed in extreme cold or hot weather Peak demand crises are caused by a variety of factors, including working hours, industry procedures, building construction and infrastructure, operational rules, and the kind and quantity of energy production facilities. If some of the peak load can be shifted to the off-peak period, better power management and significant economic benefits can be achieved. This can be achieved with thermal storage for space heating and cooling. Although phase change materials (PCMs) that efficiently store and release latent heat energy have been studied for more than 30 years, the sensible heat method is still the most widely used technique for thermal energy storage. Latent heat storage is more efficient than sensible heat storage because it requires a small temperature difference between storage and the release of energy. The development of new sources of thermal energy requires knowledge of phase transition materials, which is crucial for the development of new electrical devices. Because phase change material (PCM) can efficiently and sustainably harness heat and cooling energies, its usage is essential to the development and construction of sustainable energy systems.

2. LITERATURE REVIEW

Phase change materials (PCMs) have been investigated by Ahmed et al. [1] for their potential for reducing heat transmission through the insulated walls of refrigerated truck trailers. The incorporation of PCMs significantly reduced thermal bridging and improved the overall insulation performance of the refrigerated walls. This led to enhanced energy efficiency and reduced operational costs. The research highlights the application of PCMs as an effective solution for thermal management in refrigerated transportation, which can be extended to other thermal insulation applications. A solar cooker with latent heat storage that uses PCMs was designed and experimentally evaluated by Buddhi & Sahoo [2]. They demonstrated that improved heat retention, enabling cooking during periods of low solar radiation. The PCM system provided a steady heat supply, extending usability beyond peak sunlight hours. This work underscores the viability of PCMs in enhancing solar thermal systems, paving the way for sustainable cooking solutions in off-grid areas. A comprehensive review of recent advancements in phase change materials for energy storage applications has been carried out by Nazir et al. [3]. The study provides insights into the development of novel PCMs, their thermal properties, and integration into various energy storage systems. It also addresses challenges such as cost, thermal stability, and material compatibility. This review serves as a valuable resource for researchers and engineers working on energy-efficient technologies, emphasizing the role of PCMs in addressing global energy challenges.

A parametric analysis of a solar water heater with PCMs integrated for load shifting was conducted by Mellouli et al. [4]. The integration of PCMs enhanced the thermal performance and storage capacity of the solar water heater, facilitating effective load shifting and energy efficiency. The study demonstrates the feasibility of PCM-based thermal storage systems for renewable energy integration and demand-side management. A review of experimental studies on PCM uses in building technologies was conducted by Faraj et al.

[5]. The research focuses on modular PCM prototypes, addressing design optimization and thermal performance. It highlights advancements in PCM integration for heating, cooling, and energy savings in buildings. This review reinforces the importance of PCMs in achieving energy-efficient and sustainable building designs. A numerical simulation and modeling of a solar cooker that uses PCM for thermal energy storage was carried out by Tarwidi [6].

The simulation results revealed enhanced heat storage and utilization, allowing for a steady and prolonged cooking process. The study showcases the potential of PCMs in thermal energy storage applications for solar cookers, contributing to sustainable energy solutions. The use of PCMs in the IIT Plug-in Conversion Project for electric vehicles has been studied by Sveum [7]. The application of PCMs in the project improved thermal management of vehicle batteries, extending their lifespan and efficiency. This work highlights the critical role of PCMs in advancing thermal management solutions for electric vehicle technologies. A review of PCM applications in battery thermal management systems (BTMS) was conducted by Liu et al. [8]. The study emphasizes how well PCMs work to reduce heat problems in batteries, improving longevity, performance, and safety. Challenges such as weight, cost, and thermal conductivity were also discussed. The study emphasizes the importance of integrating PCMs in BTMS to address heat-related challenges, ensuring reliable operation of modern energy storage systems.

3. PHASE CHANGE MATERIALS FOR ENERGY STORAGE DEVICES

The principle of heat storage according to the required heat is to reach the desired temperature by absorbing energy or heat. Figure 1 shows the temperature profile of the solid-liquid phases of the PCM temperature curve. The temperature remains constant or within a small range in that region where latent heat is effective. The phases of the material turn from one to another, and both phases appear in the medium. When storage heat is released, the temperature drops, and two different temperature points are provided to define the storage and release functions. However, phase shift data is different. They work by storing energy at a constant temperature during a transition, such as from a solid to a liquid, as shown in the middle of the PCM temperature curve. The material's temperature does not rise when heat is supplied; rather, the heat is transformed into a higher energy level. For example, a liquid has the kinetic energy of atomic motion that is not present in a solid, so its energy is higher. The fact is that liquids have higher latent heat energy than solids. When the solid completely turns into a liquid and, if heat energy is added, causes the temperature of the liquid to rise.

Liquids can store and release a large amount of heat energy at high temperatures. PCM stores heat in the form of latent heat of fusion, which is approximately 100 times the sensible heat. For instance, at 25°C, the perceptible heat is around 4.18 kJ/kg, whereas the latent heat of fusion of water is approximately 334 kJ/kg. Following solidification, PCM will begin to release thermal energy near the freezing point (Figure: Phase Transformation of PCM). The water and wax are the two most commonly used heat transfer materials. Consider how much energy water must have to change from a solid to a liquid at 0°C, or how to use wax to delay the burning of a candle. Additionally, the melting and solidification cycles can be repeated many times.

Materials studied in the last 40 years include salt hydrates, paraffins, fatty acids, and eutectics of organic and inorganic compounds. Figure 2 shows the classification of phase change materials (PCM) for latent heat storage applications. As part of the design process for thermal storage, phase change materials with phase change temperatures should be chosen. It should have good heat transfer properties and high latent heat of transition. The melting temperature of the PCM must be within the operating range, and it should be chemically stable, low cost, non-corrosive and non-toxic. Paraffin wax and hydrated salt are the best phase change materials. Generally speaking, the fusion energy of paraffin wax is lower than that of salt hydrates, but the reversible issue does not exist, that is, paraffin wax changes its phase and maintains its composition whereas salt hydrates undergo an exothermic or endothermic reaction to change its phase.

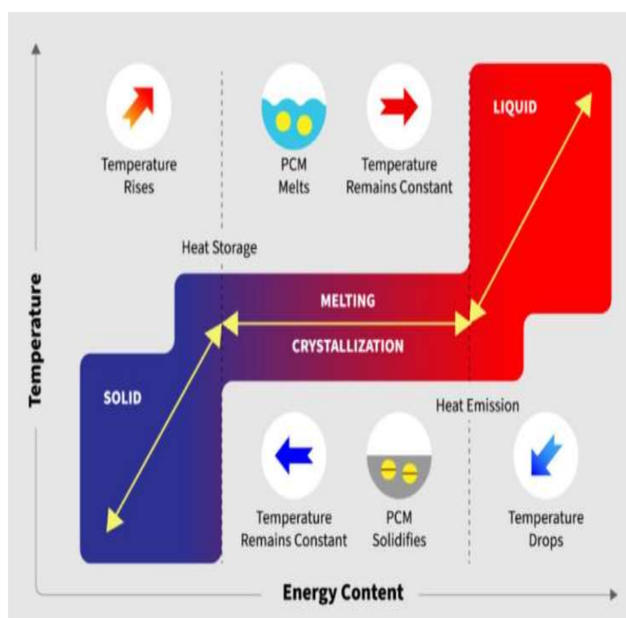

Figure 1: Temperature Profile of a PCM

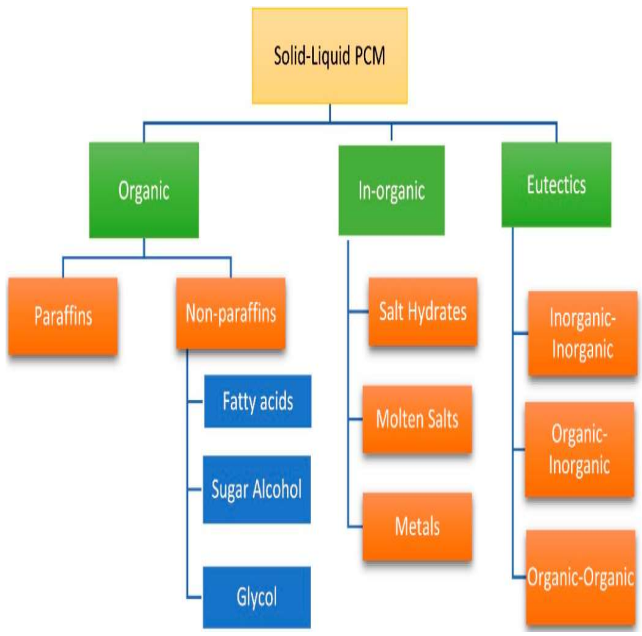

Figure 2: Classification of phase change materials (PCM) for latent heat storage applications

Therefore, a major problem with salt hydrates is inconsistent melting, which reduces the reversibility of the phase change process. This also causes the storage temperature of the salt hydrate to decrease. On the other hand, paraffin wax also has significant disadvantages compared to salt hydrates. Low thermal conductivity creates a disadvantage that reduces the amount of heat stored and released during melting and solidification processes, thus reducing its efficiency. The thermal conductivity of paraffin wax used as PCM is slightly higher than 0.20 W/ mK (compared to ice; k_{ice} = ~ 2 W/ mK). Figure 3 represents the phase change of a PCM when heat is applied or removed.

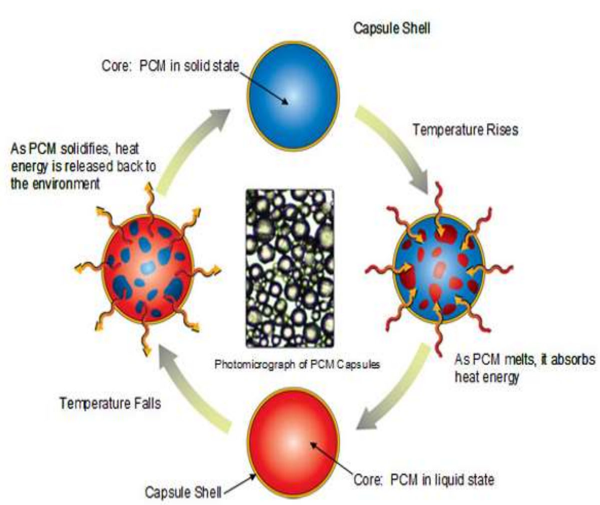

Figure 3: Phase Change of a PCM

Various methods are being studied to improve the heat transfer of phase change materials, such as finned tubes with different structures and metal matrixes containing heat transfer materials. New PCM composites with excellent properties are also proposed for various applications. For example, when PCM is embedded in a graphite matrix, thermal conductivity can be increased without reduction in energy storage.

4. APPLICATIONS OF PCMS

The three applications of PCM materials listed below (solar energy, building construction materials, and automotive vehicles) are just a few of the many areas in which they can be used (food preservation, telecom shelters, electronics, etc.). The use of PCMs in these areas is increasingly being explored to reduce the greenhouse effect and the need for fossil fuels. Growing concerns about the environmental impacts and rising costs of fossil fuels have led to research into thermal energy storage for space heating and cooling of buildings. Extremely cold or hot weather increases the need for heating or cooling. If thermal energy for heating or cooling purposes is stored and provided during the day or night, some of the peak consumption can be transferred to off-peak times. Therefore, effective energy management and economic benefits can be achieved. But in nature, the situation is exactly the opposite: there is no sunlight at night. The reliability of solar energy can be increased by storing it during peak loading times and using the stored energy when needed. For many years, PCM applications were thought to reduce losses and gains, thus reducing the cost of electricity and fossil fuel consumption of buildings. Studies on the feasibility of phase shift data in vehicle use is also under development. Denaturation of food during transportation is a major problem, and refrigerated trucks are a partial solution to this problem. However, this not only leads to increased food prices, but also has a negative environmental impact on living organisms.

4.1 Solar Energy Applications

Solar energy is absorbed by the earth and dissipated from the ground surface around the world at different rates, depending on the composition of the soil and the amount of water. The solar energy can be converted into space heating/cooling energy. Solar water heaters played an important role in this aspect and became popular in the 1960s. Figure 4 shows the solar water heater without PCM and Figure 5 shows the solar water heater with PCM. In order for solar energy to be used at any time, it must be stored in the form of latent heat and used when needed. Passive systems using PCM are good candidates for thermal energy storage and have been used since the 1980s. However, the amount of energy available in the storage system is limited due to the low thermal conductivity of the phase change material. Since then, extensive research has been conducted on improvements in thermal storage systems and the integration of phase change materials to harness solar energy. Adding PCM modules up to the top end of the water tank allows the system to achieve a higher volume and compensate for heat from the PCM latent heat in the top layer. PCM storage installation can control the rise and fall of water temperature during the day and night. For this reason, thermal layer water tanks are widely used for short-term thermal energy storage. The application of these water tanks not only increases the energy density of PCM modules but also shortens the cooling time and ensures that the water temperature remains higher than in water tanks without PCM. Additionally, solar water heaters operate over a wide temperature range, from ambient temperature to 80°C. Phase change materials can store more heat than water within a narrow range of temperatures.

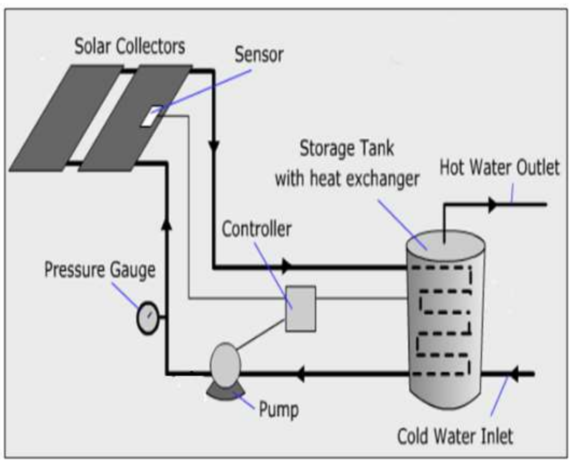

Figure 4: Solar Water heater without PCM

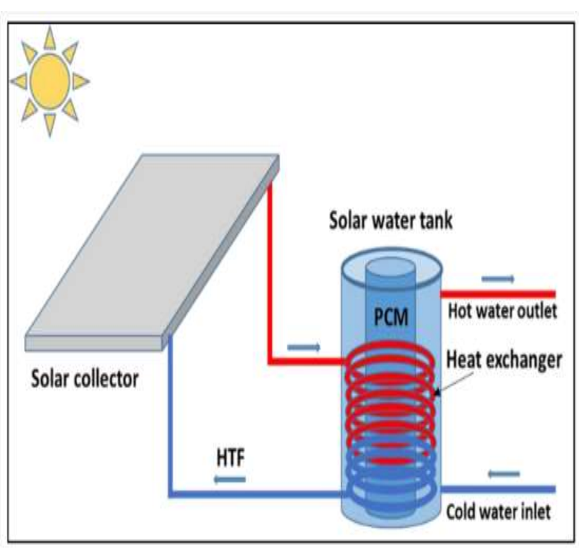

Figure 5: Solar Water heater with PCM

Solar energy is used for home cooking, especially in our world. A solar cooker is a device that uses solar energy to heat food or beverages for cooking purposes. Figure 6 shows the schematic of the solar cooker with PCM in the inner walls of the cooking vessel and Figure 7, a separate PCM thermal energy storage tank. It requires no fuel, has no operating costs, and reduces pollution. The reflective surface of a solar cooker concentrates the light into a small cooking area and turns the light into heat. It is important to keep heat inside the cookware because heat is easily lost by convection and radiation. Since 1995, people have begun to investigate the possibility of using PCMs as heat storage for solar cookers. Cooking at night takes longer because of the extremely sluggish heat transfer rate from PCM to the cooking vessel during the release mode. Fins welded to the inner wall of the PCM box are used to heat the PCM and the inner wall of the PCM box. Since the PCM surrounds the cookware, the heat transfer between the PCM and the food is higher, resulting in a shorter cooking time. It is worth noting that food can also be cooked and eaten during the winter months if it is loaded into the solar cooker before 3.30 p.m. However, the melting temperature of PCM must be chosen carefully.

A solar cooker with a separate PCM thermal energy storage tank can be used for cooking even at nighttimes by using stored thermal energy in the thermal storage tank. The more solar radiation there is, the more heat is observed in the PCM. Examples of phase change materials used in solar cooker applications are acetamide (melting point 82°C), acetanilide (melting point 118°C), erythritol (melting point 118°C), and magnesium nitrate hexahydrate (melting point 89°C).

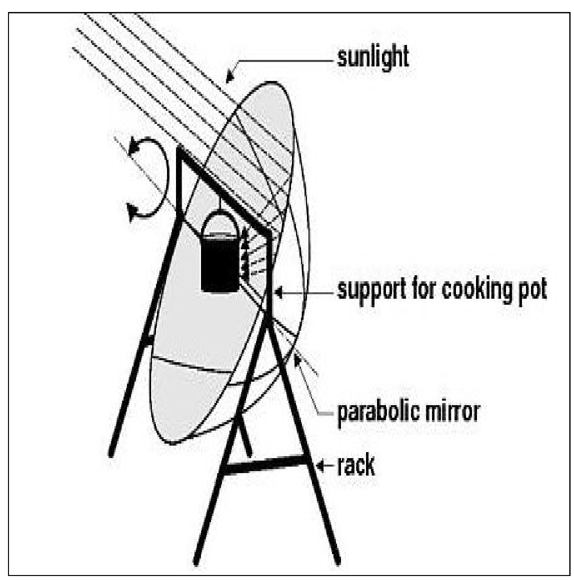

Figure 6: Solar Cooker with PCM in the inner walls of the coking vessel

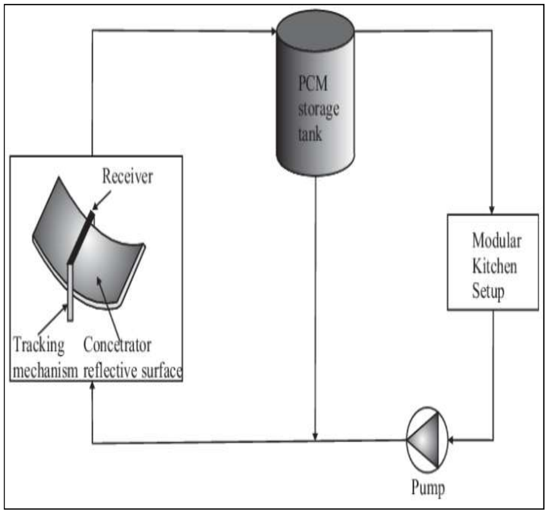

Figure 7: Solar Cooker with separate PCM thermal energy storage tank

4.2 Building Applications

The PCMs can be used for heat or cool storage for space heating or cooling in buildings, providing thermal comfort and regulating the temperature. Figure 8 illustrates passive and active PCM thermal energy storage systems in building applications. The temperature range over which heat is delivered and stored is rather small. Wallboards containing PCM have a large heat transfer area that supports large heat transfers between the wall and the space. Therefore, if solar energy is stored in PCM containers, it can be used for heating purposes at night. The use of stored energy in the PCM containers brings an opportunity to meet the demand for heating. The PCM stores energy during the daytime and and releases the heat energy, and keeps the building temperature at a comfortable level throughout the day. The latent heat capacity of PCM is used to absorb sunlight, heat, or cool energy directly and reduce the temperature in the building. It also keeps the temperature close to the desired daily temperature. Researchers have proposed macro or micro level encapsulated PCM in concrete, gypsum wallboard, ceilings, and floors in order to achieve a reasonably constant temperature range and reduce energy consumption in buildings without a substantial increase in the weight of the construction materials. The maximum and minimum peak temperatures can be reduced by using a small amount of PCM and mixing it with building materials. or sticking it as a thin layer on the walls and roof.

PCMs encapsulated and sandwiched between two metal sheets called PCM board have been used in some building materials. The PCM wall board absorbs heat energy from solar radiation, and the PCM changes its phase from solid to liquid. This will reduce the inner wall temperature during charging, and the PCM wall temperature will be higher than other walls during discharging heat into the room. The heat flux density in the melting zone of the PCM wall is almost twice that of the ordinary wall. In addition, the thermal insulation of the PCM wall during the charging process is better than that of the ordinary wall, and during the heat dissipation process, the PCM wall releases more heat energy.

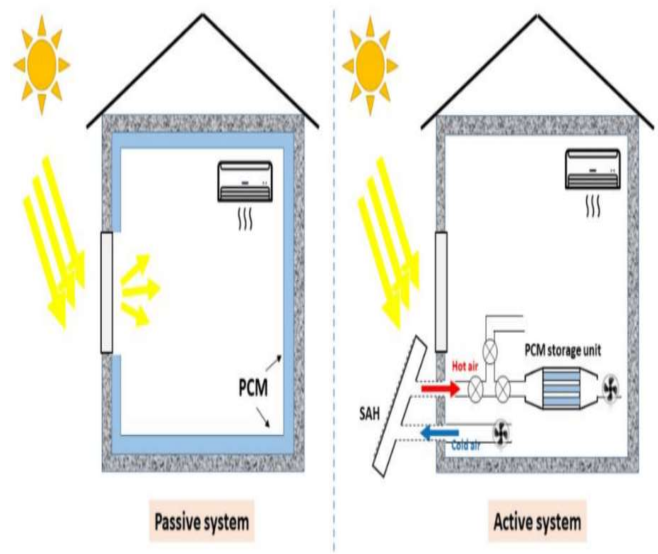

Figure 8: Typical Applications of PCM in Buildings

Unlike structured insulated panels, PCM panels always work preventing overheating and resisting thermal flow from higher temperature to lower temperature and the heat flux is proportional to the temperature difference between insulated panels. The effect of PCM can be seen when the temperature at the wall is sufficient to change the state of PCM. The greater the variation in temperature between day and night, the more effective PCM is at reducing heat, according to calculations. PCM incorporated structural insulated wall panels are ideal for places where the temperature difference between day and night is high (days are very hot and nights are very cold). In an active PCM thermal storage system, the heated air from the solar air heater is stored in the PCM-based storage type heat exchanger, and which keeps the temperature of the air during the day time at comfortable level. During the nighttime the blower is used to extract the heat energy from the thermal storage heat exchanger, circulate it into the room, and maintain the room temperature at a comfortable level.

4.3 Vehicle Applications

Studies on the feasibility of PCM in vehicle applications are growing widely. For example, refrigerated trucks are designed to transport perishable goods at low temperatures.

Refrigerated vehicles are cooled by small refrigerators placed outside the vehicle to maintain the specific temperature and relative humidity inside the vehicle. They operate by burning fuel, so shipping costs are greatly affected by temperature changes in the trailer. The use of PCM helps reduce heat transfer and overall heat flow into the refrigerated trucks. Ahmed, Meade, and Medina (2010) improved the insulation process of refrigerated trucks by using paraffin-based PCM in the trailer wall. Figure 9 shows the PCM Filled Thermo-tab Active Plates in a Reefer Truck.

Figure 9: PCM Filled Thermo-tab Active Plates in a Reefer Truck

When all walls (south, east, north, west, and top) were taken into account, the peak heat transfer rate decreased by an average of 29.1%, while for individual walls, the drop ranged from 11.3 to 43.8 percent. It was found that the total average daily heat flux entering the refrigerated compartment decreased by 16.3%. These benefits can be translated into energy savings, less pollution of diesel burning refrigeration units, reduced unit size, and longer equipment life.

Petrol and diesel are generally used liquid fuels in automobiles. Recently, hybrid vehicles have become popular among consumers because they can very well reduce carbon emissions if the vehicle operates in electric mode. Lithium-ion batteries have long been used in electronic devices (cell phones, laptops, and portable devices). Many researchers, especially in the United States, are investigating the possibility of using lithium-ion batteries in transportation application to double the fuel efficiency of hybrid vehicles and reduce emissions. The lithium-ion battery module is connected according to the vehicle's nominal voltage, allowing the vehicle to operate in electric mode. However, this leads to a major problem that prevents the use of lithium-ion batteries in many applications.

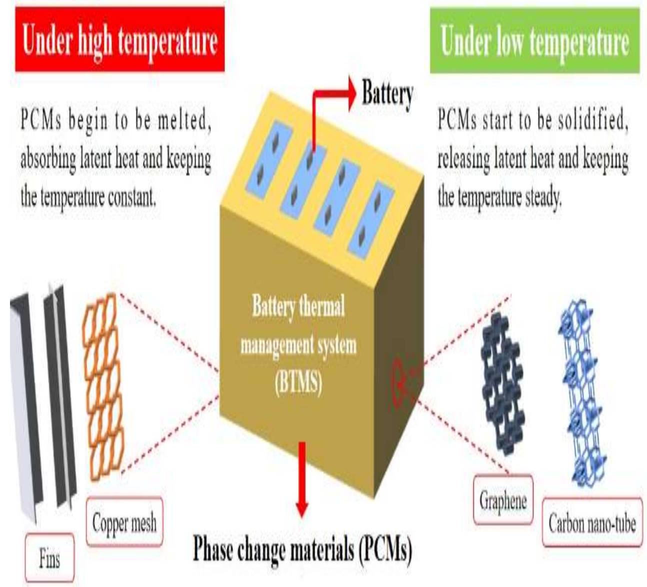

Figure 10: Phase Change Materials based Battery Thermal Management System

Li-ion batteries release energy during discharge due to exothermic electrochemical reactions. The energy produced must be transferred from the battery body to the environment. If the rate of transfer is not sufficient, some of the material in the gel phase passes into the gas phase, increasing the internal energy of the cell. Therefore, the energy must be discharged from the battery as soon as possible; otherwise, the temperature of the battery should not be increased. Sveum, Kizilel, Khader, and Al-Hallaj (2007) showed that thermal management of lithium-ion batteries using PCM eliminates the need for additional cooling systems and increases available power. Figure 8 shows the phase change materials based battery thermal management system. The PCM keeps the battery pack at the right temperature through proper thermal management, and it can release a lot of heat due to its high latent heat of fusion. Figure 10 shows the Phase Change Materials based Battery Thermal Management System.

5. CONCLUSION

PCM has the right choice to create new thermal energy storage devices in order to reduce the greenhouse effect. PCM stores heat in the form of latent heat, which is approximately 100 times higher than sensible heat. The temperature stays the same when heat is added to the phase change material, but the heat is transformed into a greater energy level. Hydrated salts, paraffin's, fatty acids, and eutectics of organic and inorganic compounds are the main phase change materials that melt at a wide temperature range. The specific melting point of the phase change material determines the design of the thermal storage process and system.

Solar water heaters have been popular since the 1960s, and phase change materials (PCMs) have been used to store thermal energy from the sun since the 1980s. PCMs are widely used in solar cookers, especially in third world countries, to reduce thermal related costs. These cookers do not use solid, liquid, or gaseous fuels, thus reducing pollution. Phase change materials are used for storing solar heat energy in the form of latent heat and reducing the temperature fluctuations of buildings. In addition, since the thin layer of PCM is sufficient to collect solar energy; thermal comfort can be achieved without a substantial increase in the weight of building materials.

The application of PCMs in transportation is growing widely. Recently, the specific temperature in refrigerated vehicles has been regulated by refrigeration units, but the use of phase change products (PCMs) is a better option to prevent food from denatured during transportation. PCM can greatly reduce the rate of heat transfer. Additionally, PCM is used for high energy density lithium-ion batteries for thermal management suitable for high power applications. The power produced in discharge or driving mode can be transferred from the battery body to the environment with the help of PCM. With proper thermal management, the battery pack can be maintained at a constant temperature, and PCM has been shown to be able to remove a large amount of heat due to its high latent heat of fusion.

Even though there is a lot of research going on in the field of effective and efficient applications of PCMs in a variety of areas (e.g. solar cookers, buildings, and vehicles), PCMs have yet to become a widely used technology for sustainable energy.

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