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The Use of PCM in Thermal Energy Storage Applications: Recent Advances

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ABSTRACT

There is a need for technological advancements using renewable energy sources to bridge the gap between the rising demand and supply of energies caused by rapid urbanization, consumerism, and dwindling fossil fuel resources. The best material for the storage and efficient use of thermal energies from renewable energy sources is a phase change material (PCM). The application of various phase change materials based on thermophysical properties is the main topic of this paper. Particularly, melting points, thermal energy storage densities and conductivities of PCM, as well as material that changes into eutectic phases, are the most effective bases for various thermal energy storing applications that operate over a wide temperature range. It is effective to store energy in a variety of storage systems utilizing PCM, and it has the benefit of allowing cooling and heating systems to be installed to maintain temperature within comfort zones. Thermal energies are stored by raising the temperature of liquids or solids in sensible heat storages. The characteristics and properties of various PCM are analyzed thoroughly in this paper. During the charging and discharging processes, the sensible heat storages system makes use of heat capacities and variations in material temperatures. When storage material changes its phase from liquid to gas or from solid to liquid, latent heat storage is dependent on heat absorptions or releases. Properties like as thermal, physical, and chemical are essential for constructing thermal energy storages with PCM. Over the years, PCM have been extensively employed in various storage systems for heat pumps, solar engineering, and thermal controls. There are more PCMs, which melt and solidify over a greater temperature range, making them more appealing for applications. This paper analyses the application of phase change materials in many domains and sketches out investigations.

Keywords: Encapsulation, Latent heat, Nanoparticles, Phase change material (PCM), Thermal energy storage (TES).

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I. INTRODUCTION

Applications requiring thermal storage can use phase change material (PCM) heat sinks for a wide range of reasons. Because latent heat from melting and freezing can store far more heat than sensible thermal storage alone, PCMs are perfect for this purpose. The PCM will keep the heat-generating component at a specific temperature while passively storing the heat when it is turned on. The PCM will start to solidify after the heat-generating component is turned off by releasing the stored energy as shown in *figure 1*. Those applications with predictable duty cycles are the most frequent ones that benefit from PCM.

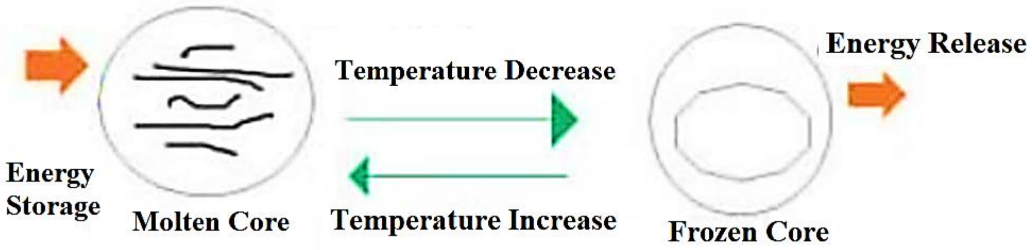

Figure 1: Principle of Energy Storage in PCM

Phase Change Materials (PCMs) are the substances utilized for latent heat thermal energy storage [1]. PCMs are a class of materials with an inherent capacity for absorption and releasing heat during phase transition cycles, which results in charging and discharging [2]. PCM could be organic, inorganic or eutectic mixtures as depicted in figure 2. The exothermic and endothermic phase transition of the PCMs can be utilized effectively by incorporating them in thermal energy storage (TES) systems and thermal loads could be met by controlling the operating parameters of systems. However, a number of problems exist, including poor thermal stability, high flammability, supercooling, corrosiveness, and changes in volume and pressure occurs during phase transformation also contamination of molten PCMs in surrounding of TES system decreasing the commercial feasibility of PCMs [3-5]. In order to make PCMs more commercially viable, researchers are putting a lot of effort into enhancing their thermophysical characteristics as illustrated in *figure 2,* various heating / cooling strategies and performance enhancement techniques are used to effectively use the vast spectrum of PCMs in the TES system. The inclusion of various additives to enhance thermal conductivity and prevent supercooling is one way to address these issues [6, 7]. Compared to other nations, the USA has higher commercialization operations with roughly 12 businesses. Additionally, Germany, the UK, and China are all quite involved in the development and marketing of PCMs for various TES applications. Since the composition, working range, durability, and other features of PCMs vary, the pricing is still under the hands of the specific manufacturers [8]. A revolution in the energy storage industry is envisaged as a result of the maturation of such approaches and the decline in PCM cost [9]. The material costs might be reduced to as little as $ 15 per kWh and an exergy efficiency of about 95 % could be achieved using combination of sensible / latent heat TES systems [10].

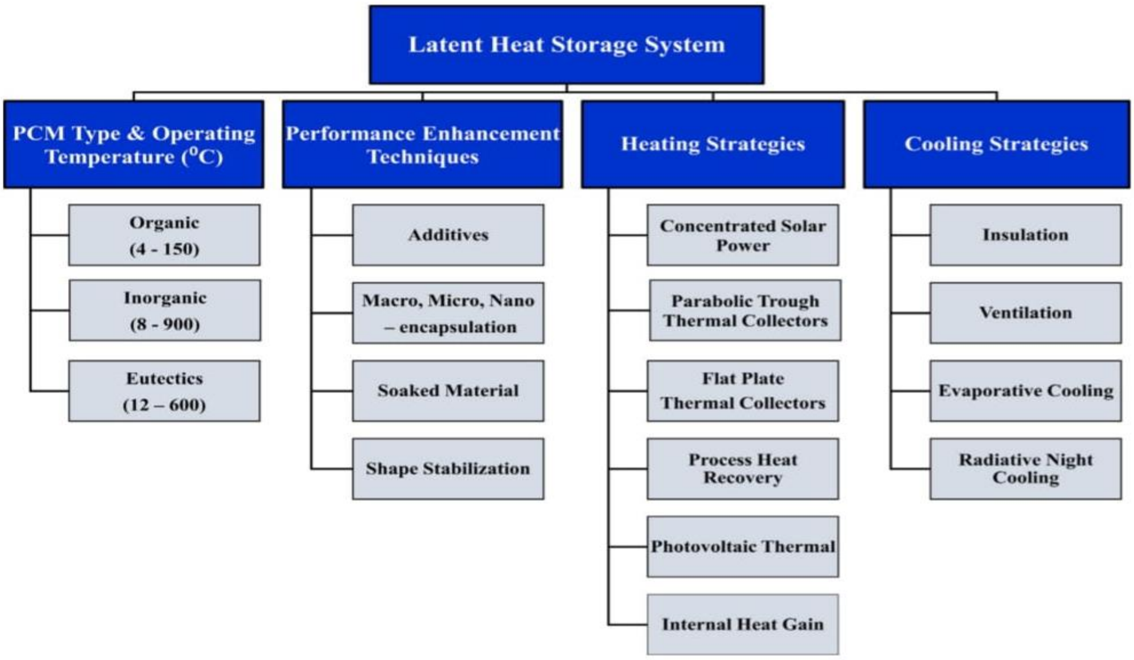

Figure 2: Techniques for Latent Heat Storage System

1.1 Thermal Energy Storage:

There are several alternatives for incorporating TES into energy systems that use non-renewable resources, including waste heat recovery, as well as renewable energy sources, like solar, wind, geothermal, and hydropower [8]. Both chemical and physical techniques, as seen in *figure 3,* can be used to store thermal energy.

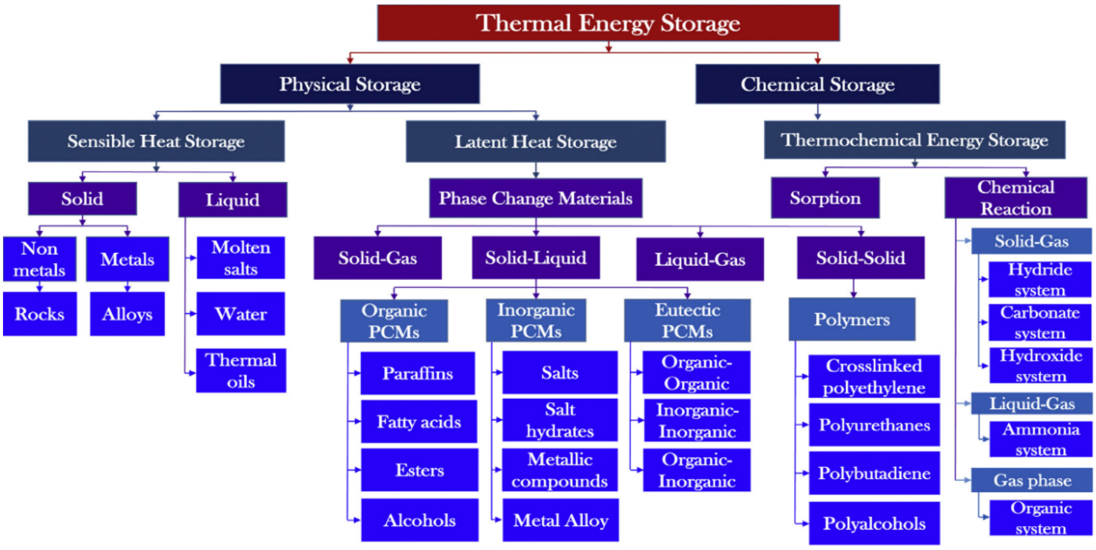

Figure 3: Classification of Thermal Energy Storage System

II. CLASSIFICATION OF PCMs

Table 1: Types of PCMs **[11]**

Sr. No.	PCM Types	Sub Types
1	Organic	a. Paraffin b. Non-Paraffin
2	Inorganic	a. Salt Hydrates b. Metallics
3	Eutectic	a. Organic-organic b. Inorganic - inorganic

2.1 Organic PCMs:

J. L. Zeng and colleagues studied how Ag nanoparticles affect a material's capacity to conduct or transfer PCM heat. 1-Tetradecanol (TD) was utilized as a phase change substance. A variety of nano-Ag-TD composite materials were examined in an aqueous solution using the thermal conductivity evaluation approach, TG-DSC, IR, XRD, and TEM. The composite material's thermal conductivity increased as Ag nanoparticle content did. Their phase change enthalpy was proportional to the amount of TD loaded, despite the fact that their phase change temperature was slightly lower than pure TD. The thermal stability of the composite materials was on par with pure TD [12]. Ag nanoparticles and the TD seemed to have only tenuous interaction.

2.2 Inorganic PCMs:

One of the most popular inorganic PCMs is salt hydrate. For use in thermal energy storage (TES) applications, they are available at a variety of phase transition temperatures. The materials are excellent for TES applications because they have a high energy absorption/release value, strong heat conductivity value, low cost, and are non-flammable. Inorganic PCMs are capable of corroding metals. By microencapsulating them in non-reactive polymers, this can be prevented. F. Frusteri et al. examined the thermal conductivity and charging-discharging kinetics of an inorganic PCM44 with carbon fibers. The hot wire technique states that when the carbon fiber loading increases, the mixture's thermal conductivity increases linearly. It has been demonstrated that carbon fibers increase the PCM system's heat transmission rate, speeding up phase transitions. Experimental results utilizing the "hot wire" method revealed a linear relationship between carbon fiber loading and heat conductivity [13]. In order to collect time-temperature data automatically, Rahayu et al. conducted tests in a small, adiabatic environment using an Arduino microcontroller and an LM35 temperature sensor connected to a computer. As TES methods for use in conditioning systems with a working temperature range of 15 – 28 ºC and water as the environment medium, carbon dioxide and CaCl2.6H2O perform better than water. This is due to the fact that in these temperature range, water only absorbs sensible heat, whereas CO and $CaCl_2.6H_2O$ absorbs sensible and latent heat too [14].

2.3 Eutectic PCMs:

An organic eutectic PCM is a mixture of two or more organic PCMs. It acts as a single component, condensing into a close-knit crystal arrangement and melting simultaneously. A wide variety of organic eutectics can be tailored to almost any necessary melting point for TES systems. On Eutectic PCMs, cyclic heating and cooling has no impact. Sharma et al. discuss creating eutectic Phase Change Materials and examining their life spans. Sharma and colleagues discuss how eutectic PCMs have changed over time and how long they might survive. They used the organic compounds polyethylene glycol 2000 and 6000, whose melting points are 50 to 55 °C and 59 to 64 °C, respectively. An accelerated thermal cycle test was run on a 50:50 composition by weight percent in the temperature ranges of 30 to 120 °C to look into the thermal stability of the eutectic mixture. Differential scanning calorimetry (DSC) analysis was applied throughout the process. After 1500 cycles, with a total variance of 8 %, it was found that the latent heat values were continuously decreasing. Overall, the report claimed that, assuming 300 melt / freeze cycles per year, this material may be employed as a phase change material for thermal energy storage for at least 5 years [15].

III. SELECTION STANDARDS

For any given TES application, a variety of factors, including the material's physical, thermal, chemical, and kinetic qualities, cost, availability, product safety, adaptability, and reliability are taken into consideration. *Figure 4*, depicts a general PCM selection criterion [8]. The center and top of the triangle, where the thermophysical characteristics of the PCM are viewed as game-changers and where the operating needs of the system for demand-side management are addressed by taking the most suitable options, exert a strong pull. In order to discover the prospective PCMs, the reliability of the shortlisted candidates is examined, and the ones with exceptionally higher cycle stability are always thought to be the most suitable. In order for a technology to be successfully applied and to compete with conventional technologies for market share, the perception and convenience of the end user are regarded as being of the utmost importance. The associated cost for the less expensive solution satisfying all the limits and product safety, such as health hazard and toxicity, are the essential considerations to be taken into consideration for environmental sustainability and to fulfil regulatory compliance. These are some significant barriers towards the bottom. The environmental and social consequences of PCMs-based TES are also taken into account as part of the evaluation criteria, in addition to its technical features.

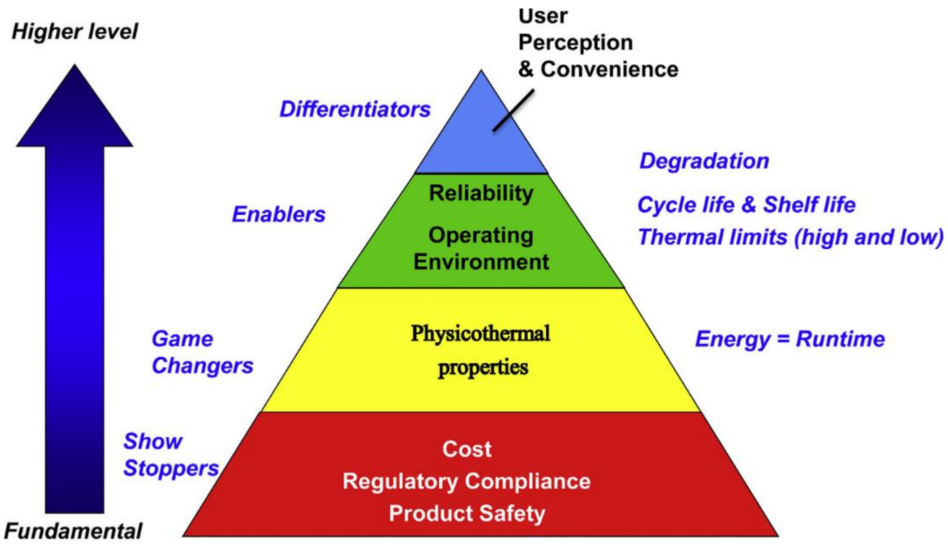

Figure 4: PCM Selection Criteria for Thermal Energy Storage Applications

IV. APPLICATIONS AND VIABILITY IN MARKET

As a component or integral part of cascaded TES systems, PCMs have a variety of applications for passive and active heating/cooling [16,17,18]. PCMs are hired based on the selection criteria's discussion of the system requirements [19]. Smart thermal grid, compact TES systems, and CSP plants are just a few of the numerous uses of PCMs that are now at the research and development stage.

The idea of adding PCMs into a smart thermal grid system is primarily driven by applications with significant thermal inertia that integrate erratic supplies of renewable resources and necessitate the storage and delivery of heat as needed [20]. Additionally, the concept of compact TES systems is largely credited to PCMs' ability to store more heat per cubic meter than any other traditional technologies, which promotes the system's compactness. The same idea underlies the integration of PCMs into CSP applications, with a focus on performance, cost, and reliability. The volume of the storage tank required by CSP technology can be greatly reduced by the use of EPCMs, which can result in lower construction and material costs for the system [21].

In addition to being used in greenhouse temperature control systems, PCMs can also be used in building energy storage systems [22], waste heat recovery systems [23,24], thermo-regulating fibers, smart textile materials [25], thermal management of batteries [26], temperature management of microelectronics [27], photovoltaic thermal (PV/T) applications [28], and space and terrestrial thermal energy storage applications [29].

V. RECENT ADVANCES IN PCM

To enhance the thermal conductivity of PCM following techniques are suggested by few researchers.

5.1 Blending of PCM with Nanoparticles:

Nanoparticles are added to the PCM to improve its heat transmission and stability during charging and discharging operations. The PCM is used as a material of heat storage that is widely employed in thermal applications, such as solar applications. Incorporated nanoparticles are solid materials with nanoscale dimensions that should be a conductor to improve heat transmission and be used as storage. The research in this area shows that using nanotechnology to improve heat transmission is an effective strategy. According to [30], the PCM can be used as a storage material and the time needed for charging and discharging operations can be shortened by blending the nanoparticles into PCM. The Rayleigh and Darcy numbers, two of the most crucial operational factors, should be taken into consideration while selecting the appropriate nanoparticle. [31] suggested use of high-temperature nano-enhanced PCM (NePCM) materials. In addition to paraffin PCM, they advised employing $A1_2O_3$, copper, and carbon as effective nanoparticles.

5.2 Encapsulation of PCM:

It is one of the past, present, and future technologies to improve the performance of PCM to save energy, particularly for solar energy before using the PCM and to mitigate the major drawbacks like limited thermal conductivity and leakage that prevent the PCMs from wide application in desired areas [32]. In order to protect the PCM from external factors like the impact of the environment and to improve heat transfer by enlarging the PCM, particularly the surface area, encapsulation for PCM material utilized in 100 ºC to 200 ºC is used [33]. Recently, the encapsulation has two methods that can be applied, namely:

i. Multifunctional materials are employed to improve the PCM's thermal capabilities. It resembles a shell encapsulation.
ii. The creation of capsules makes efficient use of the wasted heat energy. This will lead to having a passive system for thermal organization and control. On-demand energy storage was subsequently employed as a result.

A Layer-by-Layer (LbL) encapsulation technique is proposed [34] to stabilize the PCM size during the change of heat and the change of operation cycles. Currently, nano-encapsulation for nano-particles is used where capsules with sizes <1 µm are used [35]. The two primary substances that are effectively used in encapsulation are polyelectrolytes poly and poly sodium salt (PSS). Bovine serum albumin (BSA) and / or sodium dodecyl sulphate (SDS) are employed with these two materials to build the encapsulating shell, which allows for stability in thermal energy along with any cycles of operation.

VI. CONCLUSION

This paper has concentrated on recent advancements in TES employing PCMs, which utilize latent heat. Higher thermal storage density PCMs result in smaller/less volumetric storage tanks, together with a variety of adjustable operating temperatures. However, the use of latent heat PCMs for large-scale commercial applications is still restricted and the durability is less than that of materials resistant to sensible heat. The choice of organic, inorganic, and EPCMs is made based on their melting point, latent heat, energy density, thermal conductivity, and cost, as well as on their kinetic and thermodynamic properties and availability. This paper also highlighted a number of businesses uses for PCMs.

Encapsulation and nanomaterial additions are the two most common methods for expanding surface area, shielding from the environment, improving compatibility with storage materials, and minimizing corrosion when trying to improve the attributes of PCMs.

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