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Potential Application of Nano Materials for Performance Enhancement of Thermal Energy Storage Systems

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ABSTRACT:

The global energy crisis has become a pressing issue, impacting economies, societies, and the environment. As fossil fuel reserves dwindle and climate change accelerates, the requirement for sustainable and innovative energy solutions has never been more critical. Thermal Energy Storage (TES) systems are vital components in the quest for efficient energy management and sustainability. By storing excess thermal energy for later use, these systems help balance energy supply and demand, reduce peak load, and enhance the amalgamation of renewable energy sources. Recently, a variety of new applications for phase change materials (PCMs) have emerged. Their integration in intricate geometries is one of their primary limitations. Shapeable polymer composites with PCM capsules have been created in the current work for TES systems, which require particular integration specifications. To overcome the integration challenges, various PCM preparation techniques are required. This article explores the various types of TES systems, their applications, benefits, and challenges, providing a comprehensive overview of their role in modern energy systems.

Keywords: Energy; Energy storage; Nano material; Phase change material; Thermal energy storage

1. Introduction

The global energy crisis has become a pressing issue, impacting economies, societies, and the environment. As fossil fuel reserves dwindle and climate change accelerates, the requirement for sustainable and innovative energy solutions has never been more critical [1]. The energy crisis is characterized by rising energy prices, supply shortages, and increased demand for energy resources. Factors contributing to this crisis include geopolitical tensions, natural disasters, and the ongoing effects of the COVID-19 pandemic, which have disrupted supply chains and energy production [2]. As countries strive to recover economically, the demand for energy continues to surge, leading to heightened competition for limited resources [3]. This is happening due to excessive usage of fossil fuels, the adverse effect of combustion of fossil fuel on human being and environment etc.

With respect to the energy crisis, many nations are pivoting towards renewable energy sources such as solar, wind, hydroelectric, and geothermal power. These alternatives bid a sustainable solution to the energy demands of the future while reducing the adverse effects of climate change [4]. Technological advancements have made renewable energy more accessible and cost-effective, with solar and wind energy becoming increasingly competitive with traditional fossil fuels. In addition to this, the revolutions in energy storage, such as batteries and pumped hydro storage, are talking the intermittence trials associated with renewable energy generation [5]. Figure 1 shows the reason for energy crisis.

Fig.1 Reason of energy crisis

The evolution to a maintainable energy future also involves enhancing energy efficiency and promoting conservation practices. Governments and organizations are executing policies and incentives to encourage energy-saving technologies and practices among consumers and businesses. Smart grids, energy-efficient appliances, and electric vehicles are just a few examples of how technology can play a pivotal role in reducing energy consumption and emissions. Moreover, the future of energy is likely to be characterized by decentralization [6]. Distributed energy resources, such as rooftop solar panels and community wind farms, empower individuals and local communities to generate their own energy[7]. This shift not only enhances energy security but also fosters resilience against supply disruptions and price volatility [8].

The energy crisis presents significant challenges, but it also offers an opportunity for transformative change. By embracing renewable energy, enhancing efficiency, and fostering decentralized energy systems, we can pave the way for a sustainable energy future. The path forward requires collaboration among governments, businesses, and individuals to innovate and invest in the technologies and practices that will define the energy landscape of tomorrow. The objective of the present work is to explores the current energy crisis, its implications, and the potential pathways toward a more sustainable energy future using thermal energy storage systems.

2. Thermal energy storage

Thermal Energy Storage (TES) systems are designed to store thermal energy for later use, allowing for the efficient management of energy resources [9]. This system can capture excess heat generated during periods of low demand and release it throughout crowning demand times. This capability is particularly valuable in applications such as district heating, industrial processes, and renewable energy integration, where fluctuations in energy supply and demand can pose significant challenges. By serving as a link between renewable energy sources and end users, thermal energy storage, or TES, is crucial to supplying the world's growing energy needs in a sustainable manner. Thermochemical, sensible, and latent heat are the three primary methods in TES [10]. In latent heat storage systems, the materials that store energy are called phase change materials (PCMs). For effective latent heat storage applications, a PCM's storage performance is essential. Latent heat can be stored for a variety of uses.

2.1 Types of thermal energy storage systems

There are several types of thermal energy storage systems, each with its own characteristics and applications. The different types of TES systems are shown in figure 2 [11].

(a) Sensible Heat Storage

Sensible heat storage systems store thermal energy by raising the temperature of a solid or liquid medium [12]. Common materials used include water, sand, and concrete. The amount of energy stored is proportional to the temperature change and the mass of the storage medium. Sensible heat storage is widely used in applications such as hot water tanks and thermal mass in buildings.

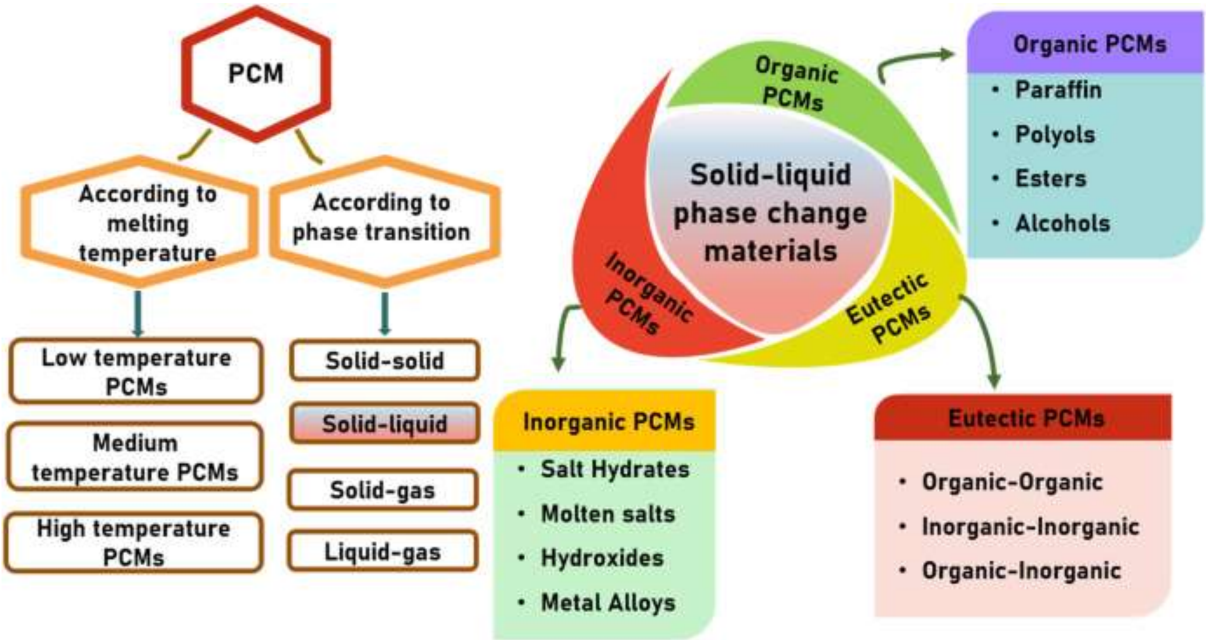

Fig.2 Classification of TES systems

(b) Latent heat storage

Latent heat storage systems utilize phase change materials (PCMs) to store and release energy. These materials absorb or release heat during phase transitions, such as melting or solidifying, without a significant change in temperature[13]. Latent heat storage is particularly effective for applications requiring precise temperature control, such as in HVAC systems and thermal comfort in buildings [14].

(c) Thermochemical storage

Thermochemical storage systems store energy through reversible chemical reactions. These systems can achieve higher energy densities compared to sensible and latent heat storage. They involve the absorption of heat during a reaction and the release of heat when the reaction is reversed [15]. Thermochemical storage is still in the research and development phase but holds promise for long-term energy storage solutions. The important characteristics of PCM materials are shown in figure 3 [16].

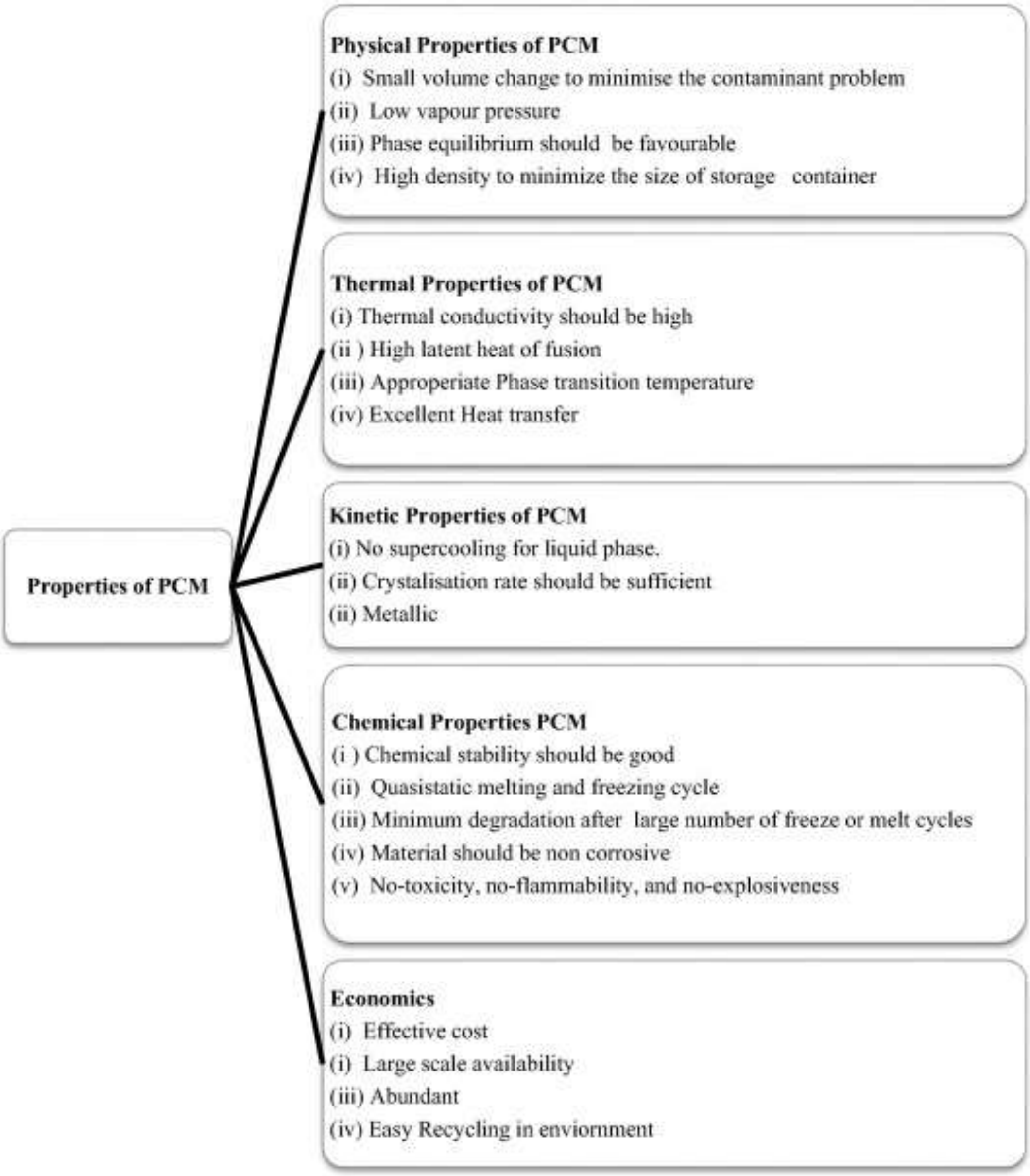

Fig.3 Characteristics of PCM materials

2.2 Applications of thermal energy storage

The TES system is an innovative technology that allows for the storage of thermal energy for later use. Many studies have been done on various applications of TES, highlighting its significance in enhancing energy efficiency, reducing peak demand, and integrating renewable energy sources [17–19]. By capturing excess thermal energy during periods of low demand and releasing it during peak times, TES plays a crucial role in modern energy systems.

One of the primary applications of TES is in district heating and cooling systems. By storing heat generated from centralized sources, such as biomass, geothermal, or waste heat, TES can provide a reliable supply of thermal energy to residential and commercial buildings. This not only improves energy efficiency but also reduces greenhouse gas emissions by optimizing the use of renewable energy sources. Concentrated solar power (CSP) plants utilize TES to store excess thermal energy generated during sunny periods. This stored energy can then be used to produce electricity during cloudy days or at night, thereby enhancing the reliability and dispatchability of solar power. By integrating TES, CSP systems can provide a continuous power supply, making solar energy a more viable option for large-scale electricity generation [20].

Many industrial processes require significant amounts of heat, which can be supplied through TES systems [21]. Industries such as food processing, chemical manufacturing, and metal production can benefit from TES by storing heat during off-peak hours and utilizing it during peak production times. This leads to cost savings and improved operational efficiency. In the realm of building energy management, TES can be employed to optimize heating and cooling systems. By storing excess thermal energy generated from HVAC systems, buildings can reduce their energy consumption during peak demand periods. This not only lowers energy bills but also contributes to a more sustainable urban environment. TES plays a vital role in the integration of renewable energy sources, such as solar and wind. By storing excess energy generated during peak production times, TES systems can help balance supply and demand, ensuring a stable energy grid [22]. This capability is essential for transitioning to a more sustainable energy future, where renewable sources play a dominant role.

Thermal Energy Storage can also provide valuable support to electric grids by acting as a buffer during peak demand periods. By discharging stored thermal energy, TES systems can help reduce the load on the grid, preventing blackouts and ensuring a stable supply of electricity. This is particularly important as more intermittent renewable energy sources are integrated into the grid. Thermal Energy Storage systems find applications across various sectors:

- **District Heating and Cooling**: TES systems can store heat generated from centralized plants and distribute it during peak demand periods, improving the efficiency of district heating networks.
- **Renewable Energy Integration**: TES systems can store excess energy generated from renewable sources, such as solar thermal or biomass, ensuring a stable energy supply even when generation is low.
- **Industrial Processes**: Industries can utilize TES to manage energy consumption, reduce costs, and improve process efficiency by storing heat generated during off-peak hours.
- **Building Energy Management**: TES systems can enhance the energy efficiency of buildings by storing excess heat or cooling, thereby reducing reliance on conventional heating and cooling systems.

2.3 Benefits of Thermal Energy Storage

The implementation of thermal energy storage systems offers several benefits:

- **Load Shifting**: TES allows for the shifting of energy consumption from peak to off-peak periods, reducing strain on the energy grid and lowering energy costs.
- **Increased Efficiency**: By optimizing energy use, TES systems can improve overall system efficiency and reduce greenhouse gas emissions.
- **Enhanced Renewable Integration**: TES facilitates the integration of intermittent renewable energy sources, contributing to a more resilient and sustainable energy system.
- **Energy Security**: By providing a buffer against fluctuations in energy supply and demand, TES systems enhance energy security and reliability.

3. Performance enhancement of TES systems

The literature currently in publication reports on the experimental study of form-stable PCM based on surface-altered porous materials after employing different surface modification techniques [23]. Nevertheless, few studies have examined the mechanism underlying surface modification and adaptation in PCM. Thus, the techniques and mechanism underlying surface modification of porous media are described in this review. The study focuses on how the overall thermal performance of form-stable phase-change materials is affected by surface modification of the porous matrix[24]. There has been discussion of the intrinsic qualities and benefits of hydrophilic and hydrophobic surfaces. Additionally, transformable wetting surfaces' impact has been emphasized. Finding the best modification technique for a given application requires a thorough understanding of the morphology of the pore structure. The different methods to enhance the performance of TES systems are shown in figure 4 [11].

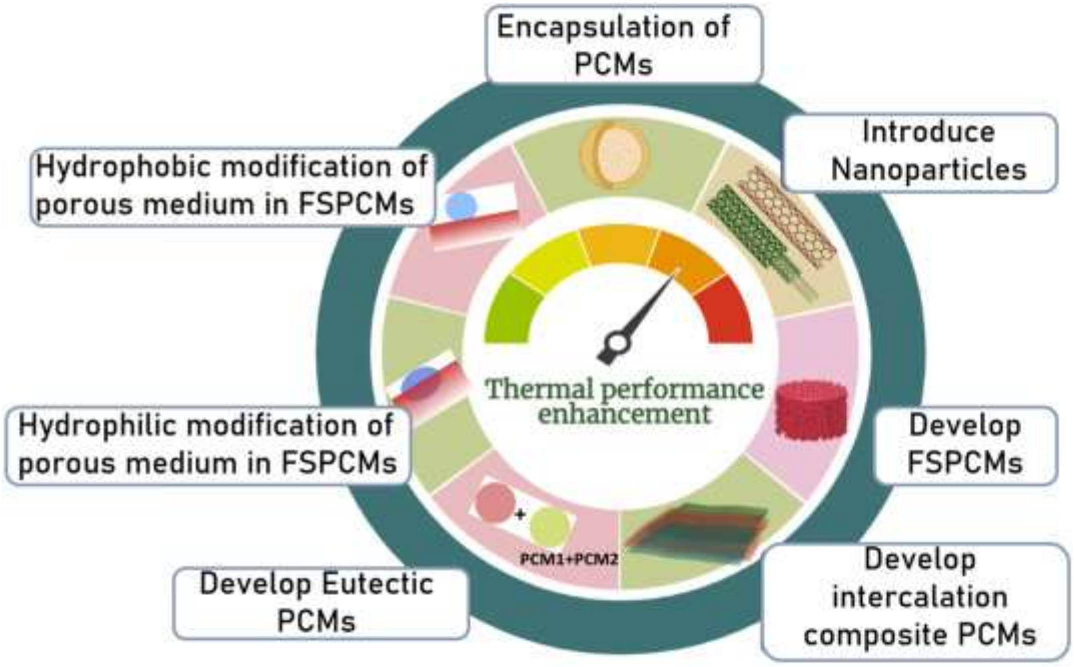

Fig. 4 Performance enhancement of TES systems

4. Challenges and considerations

Numerous hydrophilic/hydrophobic modification techniques have been considered in the literature[25][26]. However, the techniques of hydrophilic/hydrophobic modification can be varied to create modern materials that can be used for thermal energy storage. Acid functionalization, sol-gel, solution immersion, and electrospinning all rely on the affinity between PCM and the porous matrix [27]. Achieving high porosity in addition to permeability is crucial for creating leak-proof FSPCMs when hydrophilic alteration is used. Therefore, in the case of both hydrophilic and hydrophobic modification, a comprehensive investigation into the proportion of porous matrix [28]. With the exception of their insulating capacity, aerogels are becoming more and more popular in the field of thermal energy storage (as a porous matrix in FSPCMs) because of their great strength, low weight, and large specific surface area. In addition to achieving a higher encapsulation ratio, graphene and silica-derived aerogels can be further studied with the goal of achieving higher thermal conductivity because the surface properties can be changed based on the application[29]. Adaptable wetting surfaces have remarkable properties like charge-polarization in the liquid phase and micelle formation in the solid phase. This encourages surface self-cleaning and allows the porous matrix to hold the PCM firmly in its molten state [30]. Therefore, it is crucial to conduct experiments in order to create flexible wetting surfaces. Despite their advantages, thermal energy storage systems face several challenges:

- **Cost**: The initial investment for TES systems can be high, which may deter adoption, especially in smaller applications.
- **Space Requirements**: Some TES systems, particularly those using sensible heat storage, require significant space for installation.
- **Material Limitations**: The performance of latent heat and thermochemical storage systems depends on the availability and effectiveness of suitable phase change materials and chemical reactions.

5. Conclusion

TES systems play a crucial role in modern energy management, offering solutions to enhance efficiency, integrate renewable energy, and improve energy security. As technology advances and the demand for supportable energy solutions grows, the expansion and deployment of TES systems will be crucial in shaping the future of energy systems worldwide. Continued research and investment in this field will help overcome existing challenges and unlock the full potential of thermal energy storage. Thermal Energy Storage is a versatile technology with numerous applications across various sectors. From enhancing the efficiency of district heating systems to supporting renewable energy integration, TES is a key component in the evolution to a more sustainable energy landscape. As the demand for energy continues to grow, the importance of TES in optimizing energy use and reducing environmental impacts will only increase.

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