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A Review of Thermal Performance of Nano-Enhanced PCM for Improving Melting Rate in Heat Exchanger

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Abstract: Energy plays a crucial role in our daily lives and industrial operations. It powers our homes, fuels transportation, and supports technological advancements; however, current energy production and consumption methods are leading to environmental pollution and climate change. Therefore, there is a vital need to shift towards cleaner and sustainable energy sources. Renewable energy sources such as solar and wind power provide clean alternatives, but their intermittent nature requires efficient energy storage systems. Thermal Energy Storage (TES) units act as a bridge by storing excess energy for later use and ensuring a continuous energy supply. The present study addresses the research gap by investigating the effect of nanoparticle dispersion on melting rate enhancement in a semi-circular shell and tube heat exchanger configuration.

Keywords: Phase Change Material, Nano-Enhanced PCM, Latent Heat Thermal Energy Storage, Nanoparticles, Melting Rate, Heat Exchanger.

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I. INTRODUCTION

Renewable energy sources, such as solar and wind energy, provide an environmentally friendly method of electricity generation. These sources are naturally abundant and can be utilized for long-term energy production. The adoption of renewable energy can significantly reduce dependence on fossil fuels and minimize greenhouse gas emissions. However, the intermittent nature of renewable energy sources creates challenges in meeting continuous electricity demand, as wind energy is not always available and solar energy is limited during nighttime. Therefore, efficient energy storage systems are required to store excess energy during availability and utilize it during demand periods. This helps in maintaining a balance between energy supply and demand and ensures a reliable and continuous energy supply.

To overcome these challenges, energy storage systems are implemented between energy generation and utilization. These systems store excess energy when available and release it when required. Thermal Energy Storage (TES) systems perform this function effectively. TES systems are widely used in solar power plants, food processing industries, and heating, ventilation, and air conditioning (HVAC) systems. Thermal energy can be stored in different forms, including sensible heat storage, latent heat storage and thermochemical energy storage. The size and design of the storage system depend on its application, such as buffer storage for short-term variations, diurnal storage for day-to-night energy storage, and seasonal storage for long-term energy requirements.

Among the different TES methods, Latent Heat Thermal Energy Storage (LHTES) systems are preferred due to their high energy storage density and nearly constant temperature operation. LHTES systems utilize Phase Change Materials (PCM) to store and release thermal energy during phase transition

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processes. The development of advanced thermal energy storage devices is essential for reducing energy losses and improving energy supply reliability.

Phase Change Materials (PCM) are substances capable of storing and releasing large amounts of thermal energy during phase transition processes, typically between solid and liquid states. Various types of PCMs are available, including paraffin wax, salt hydrates, bio-based PCMs and eutectic mixtures, which can be selected based on specific application requirements. Paraffin wax is widely preferred due to its high latent heat storage capacity, commercial availability, cost-effectiveness and chemical stability. Additionally, it is non-toxic, chemically inert and environmentally safe.

II. THERMAL ENERGY STORAGE

Thermal Energy Storage (TES) is a technology used to store thermal energy for later use. It can be considered as a thermal battery that stores excess heat when available and releases it when required. TES systems help in maintaining a stable and reliable heat supply by storing surplus thermal energy and utilizing it during peak demand periods.

Various renewable energy sources such as solar, geothermal and wind energy can be integrated with TES systems for efficient energy storage and utilization. Among these sources, solar energy is one of the most widely used renewable energy sources for thermal energy storage applications. Solar energy is obtained from solar radiation and can be converted into thermal energy using solar collectors or concentrated solar power systems.

PCM can be integrated into TES systems such as heat exchangers, storage tanks and modular storage units. During periods of excess heat availability, PCM absorbs and stores thermal energy within its structure. During periods of high demand or low heat availability, PCM releases the stored thermal energy, ensuring continuous and reliable heat supply.

III. CLASSIFICATION OF THERMAL ENERGY STORAGE

Thermal Energy Storage systems are broadly classified into two major categories: thermal energy storage and chemical energy storage, as shown in Figure 1. Thermal energy storage is further classified into sensible heat storage and latent heat storage, whereas chemical energy storage is categorized under thermo-chemical energy storage.

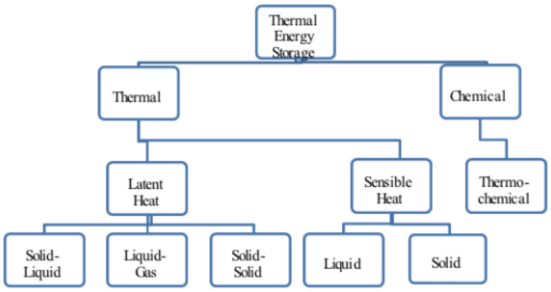


Figure 1: Classification of thermal energy storage

Latent Heat Thermal Energy Storage (LHTES) System

Energy is stored by heating a material that undergoes a phase change without any significant change in temperature. Latent heat storage utilizes Phase Change Materials (PCM), which can store and release thermal energy by changing their phase, such as melting and solidification. PCM has the ability to store a large amount of energy during the phase change process, making it suitable for applications such as solar energy storage and temperature regulation in buildings.

The phase change cycle of PCM is depicted in Figure 2, which illustrates the processes of melting and solidification. PCM undergoes cyclic transitions between solid and liquid phases, allowing efficient storage and release of thermal energy.

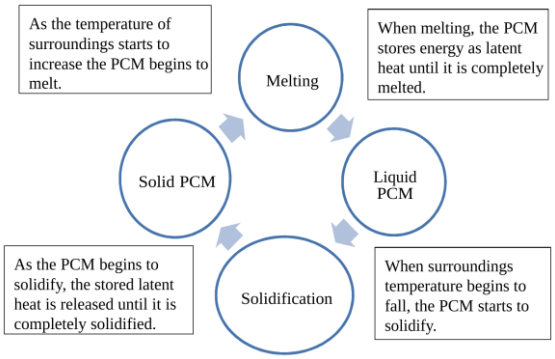


Figure 2: Phase change cycle of PCM

The amount of energy stored depends on the mass of the material and the latent heat of fusion of the material. The expression for latent heat storage is given by:

$$Q = m\Delta H$$

where m is the mass of the material and ΔH is the latent heat of fusion of the material.

Sensible Heat Thermal Energy Storage System

Thermal energy is stored by increasing the temperature of a solid or liquid material without any phase change. Sensible heat storage systems utilize the heat capacity of the material and the temperature variation during the charging and discharging processes. Sensible heat storage is widely used in industrial processes and

heating, ventilation and air conditioning (HVAC) systems. The amount of heat stored depends on the specific heat capacity of the storage medium, the temperature difference and the quantity of storage material.

$$Q = \int_{T_i}^{T_f} mC_p dT$$

$$Q = mC_p(T_f - T_i)$$

where m is the mass of the material, Cp is the specific heat capacity, Q is the heat stored, Ti is the initial temperature and Tf is the final temperature.

Thermochemical Energy Storage System

Thermochemical energy storage is a method of storing and releasing energy using reversible chemical reactions. In this system, energy is stored in the form of chemical bonds and released when these bonds are broken during the reverse reaction. Thermochemical energy storage systems can store a large amount of energy in a small volume and release the stored energy over an extended period.

Thermochemical energy storage can be applied in various fields such as vehicle energy systems, electricity generation and building heating applications. In thermochemical storage systems, the forward reaction occurs by absorbing heat, generally from solar energy, and the energy is stored in the form of reaction products. When heat is required, the products are remixed to allow the reverse reaction to occur, which releases the stored thermal energy.

IV. PHASE CHANGE MATERIALS (PCM)

Phase Change Materials (PCM) are widely used in latent heat thermal energy storage systems. These systems operate by storing and releasing thermal energy during phase change processes, where the material transitions between solid and liquid phases. During the charging process, PCM absorbs thermal energy from a heat source and undergoes a phase change from solid to liquid. During the discharging process, when energy is required, the PCM solidifies and releases the stored latent heat energy.

While selecting PCM for latent heat energy storage systems, several important factors must be considered. PCM should have high latent heat capacity to store a large amount of thermal energy during phase change. High thermal conductivity is desirable to enhance melting and solidification rates. PCM should be chemically stable to withstand repeated phase change cycles without degradation. Additionally, PCM should be readily available, cost-effective and capable of maintaining performance during long-term thermal cycling.

V. CLASSIFICATION OF PHASE CHANGE MATERIALS

Phase Change Materials can be broadly classified into three main categories: organic, inorganic and eutectic PCMs, as shown in Figure 3. Organic PCMs include paraffin-based and non-paraffin-based materials derived from carbon-based compounds. Inorganic PCMs mainly consist of salt hydrates and metallic materials. Eutectic PCMs are mixtures of two or more materials that exhibit lower melting points compared to their individual components. Understanding these classifications is important for selecting suitable PCM for specific thermal energy storage applications.

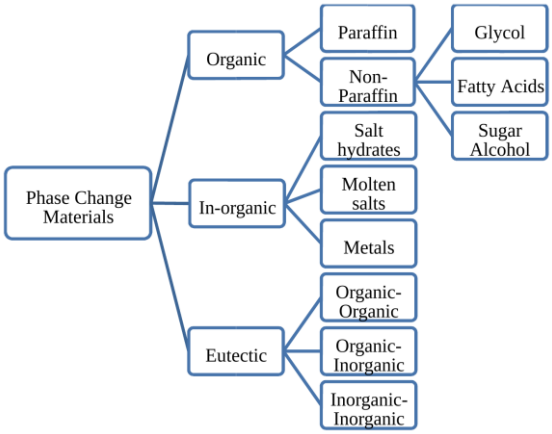


Figure 3: Classification of phase change materials

Organic Phase Change Materials

Organic phase change materials are a type of PCM derived from carbon-based compounds. They are known for their relatively lower melting points compared to other types of PCMs. Organic PCMs are commonly obtained from materials such as paraffin waxes, fatty acids and sugar alcohols. These materials have the advantage of high latent heat storage capacity, allowing them to store a significant amount of thermal energy during the phase change process.

Inorganic Phase Change Materials

Inorganic phase change materials mainly consist of salts and metals. These PCMs generally have higher melting points compared to organic PCMs. Inorganic PCMs include materials such as salt hydrates (for example, sodium sulphate decahydrate) and low melting point metals such as gallium and indium. Due to their higher melting temperatures, inorganic PCMs are suitable for applications operating at higher temperature ranges.

Eutectic Phase Change Materials

Eutectic phase change materials are a type of PCM that consists of a mixture of two or more components. The combination of these materials produces a specific melting point, which can be adjusted according to application requirements. By modifying the composition of the mixture, eutectic PCMs can achieve desirable thermal properties such as a sharp melting temperature and high latent heat storage capacity.

Since the selection of appropriate PCM depends on the specific application, it has been observed that most PCMs generally have low thermal conductivity, which results in slower melting rates. To overcome this limitation, nanoparticles are added in specific volume concentrations to enhance thermal conductivity. This improves the melting rate and ensures faster charging and discharging of Latent Heat Thermal Energy Storage (LHTES) systems.

VI. REVIEW OF LITERATURE

Vajjha and Das (2025) conducted an experimental investigation to evaluate the thermal conductivity of three different nanofluids containing aluminum oxide (Al_2O_3), copper oxide (CuO) and zinc oxide (ZnO) nanoparticles dispersed in an ethylene glycol–water mixture. The study examined thermal conductivity and viscosity behavior at nanoparticle volume concentrations up to 10%. The results showed that both thermal conductivity and viscosity increased with increasing nanoparticle concentration. The nanoparticle sizes used were 53 nm for Al_2O_3, 29 nm for CuO and 77 nm for ZnO.

Arasu et al. (2023) Various theoretical models including Maxwell, Bruggeman, Koo and Kleinstreuer and Hamilton–Crosser models were compared with experimental data. However, deviations were observed, which led to the development of a new correlation for improved prediction accuracy. The study also found that thermal conductivity enhancement increased with temperature. For example, ZnO nanofluid showed a 48.5% increase in thermal conductivity ratio at 7% concentration and 363 K, while CuO nanofluid showed about 60% enhancement. The results also indicated that smaller nanoparticle sizes resulted in higher effective thermal conductivity. The developed correlation showed good agreement with experimental data, with maximum deviation ranging between +2.8% and −2.6% for Al_2O_3 nanofluid.

Godson et al. (2025) presented a comprehensive review of heat transfer enhancement in nanofluids due to nanoparticle dispersion. The study analyzed both experimental and theoretical investigations related to forced and natural convection heat transfer enhancement. The study reported that nanoparticles enhance heat transfer by improving thermal conductivity and by inducing micro-level disturbances in the fluid flow. The study also reported that nanofluid thermal conductivity is highly temperature dependent and improves with increasing nanoparticle concentration and Reynolds number. However, the study highlighted the lack of sufficient experimental data under different flow regimes such as laminar, transition and turbulent flow conditions, indicating the need for further research.

Al-Abidi et al. (2023) conducted experimental and numerical investigations to study the melting behavior of PCM in a triplex tube heat exchanger using different internal and external fin configurations. The study investigated seven different configurations. The results showed that increasing fin length significantly reduced melting time. For fin lengths of 10 mm, 20 mm, 30 mm and 42 mm, melting time reductions of 73.9%, 60.8%, 47.8% and 43.4% were observed respectively. Thinner fins also improved melting performance. The study also showed that steel material provided acceptable melting performance compared to copper and aluminum while offering lower cost and easier manufacturability.

Arasu et al. (2022) performed numerical simulations to study the melting and solidification behavior of paraffin wax with alumina nanoparticles in a concentric double pipe heat exchanger. The study considered nanoparticle concentrations of 0%, 2%, 5% and 10%. The results indicated that nanoparticles significantly influenced the solidification process more than the melting process. Energy storage during solidification increased by 25.6%, 31.8% and 41.5% for 2%, 5% and 10% nanoparticle concentrations respectively. However, maximum energy storage capacity slightly decreased at higher nanoparticle concentrations.

Al-Abidi et al. (2014) conducted experimental investigations on PCM melting and solidification in a triplex tube heat exchanger with fins. The results showed that increasing heat transfer fluid temperatures significantly reduced melting time. Increasing HTF temperature from 85°C to 100°C reduced melting time by approximately 86%.

Darzi et al. (2016) performed numerical simulations to analyze melting and solidification behavior of PCM in different annulus geometries. The results showed that

vertically oriented elliptical tubes improved melting rate compared to circular tubes. Addition of nanoparticles at 2% and 4% concentrations reduced melting time by 25% and 46% respectively. Installation of fins significantly reduced both melting and solidification times.

Mahdi and Nsofor (2016) studied solidification behavior of alumina nanoparticle enhanced PCM in a triplex tube heat exchanger. The results showed that increasing nanoparticle concentration reduced solidification time. Solidification time reductions of 8%, 12.6% and 19.7% were observed for 3%, 5% and 8% nanoparticle concentrations respectively.

Chiam et al. (2017) numerically analyzed nanofluid heat transfer performance in different tube geometries. The results showed that heat transfer coefficient increased with increasing number of Reynolds and nanoparticle concentration. Flat tubes showed higher heat transfer performance but also higher friction factor. Circular tubes showed lower pressure drop but lower heat transfer enhancement. Twisted tape inserts improved heat transfer performance but increased friction losses.

Mahdi and Nsofor (2017) investigated the effects of fins and nanoparticles on the melting characteristics of paraffin wax in a triplex tube heat exchanger. Three enhancement techniques were considered, namely the use of fins alone, nanoparticles alone and a combined application of fins and nanoparticles. The nanoparticle volume fraction was restricted to 2% to maintain the thermal energy storage capacity. The study reported that the addition of nanoparticles improved the melting rate; however, fins alone provided comparatively higher enhancement. It was also observed that increasing fin length reduced the total melting time, while thin and elongated fins showed better heat transfer performance. Furthermore, an increase in heat transfer fluid temperature resulted in faster melting. The combined use of fins and nanoparticles demonstrated better performance compared to nanoparticles alone. Additionally, due to dual-sided heating in the triplex tube heat exchanger, the melting rate was higher compared to the double pipe heat exchanger

Godson et al. (2015) presented a comprehensive review of heat transfer enhancement in nanofluids due to nanoparticle dispersion. The study analysed both experimental and theoretical investigations related to forced and natural convection heat transfer enhancement.

Ebadi et al. (2013) The study reported that nanoparticles enhance heat transfer by improving thermal conductivity and by inducing micro-level disturbances in the fluid flow. The study also reported that nanofluid thermal conductivity is highly temperature dependent and improves with increasing nanoparticle concentration and Reynolds number. However, the study highlighted the lack of sufficient experimental data under different flow regimes such as laminar, transition and turbulent flow conditions, indicating the need for further research.

VII. RESEARCH GAP

From the literature review, it is observed that many researchers have studied phase change materials (PCM) for latent heat thermal energy storage applications due to their high energy storage capability. Several studies have also reported that the addition of nanoparticles improves thermal conductivity and enhances the melting rate of PCM.

However, most of the available research is limited to conventional geometries such as circular shell and tube heat exchangers and triplex tube heat exchangers. Very few studies have focused on semi-circular shell and tube heat exchanger configurations. The heat transfer characteristics and melting behavior of nano-enhanced PCM in such non-conventional geometry are still not clearly understood.

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