# Performance of Thermal Energy Storage System using Water-Based Nanofluids for Solar Heating Applications

K.Krishna Reddy[1 *], R.Meenakshi Reddy[2], K. Madhava Reddy[3], Y.V. Mohan Reddy[3], K.Poli Reddy[2], G.S. Guru Dattatreya[1]
[1] Assistant Professor, Department of Mechanical Engg, G. Pulla Reddy Engineering College, Kurnool, A.P, India
[2] Associate Professor, Department of Mechanical Engg, G. Pulla Reddy Engineering College, Kurnool, A.P, India
[3] Professor, Department of Mechanical Engineering, G. Pulla Reddy Engineering College, Kurnool, A.P, India
kkreddy642014@gmail.com

**Abstract:** The study evaluates the thermal performance of a packed bed TES system that integrates both sensible and latent heat storage using solar energy as the heat source. A cylindrical, insulated storage tank containing spherical capsules containing phase change materials (PCMs), particularly stearic acid and paraffin wax, makes up the TES unit. These PCMs enhance thermal management, reduce system size and cost, and offer high isothermal and thermal storage capacities. The heat transfer fluid (HTF) is optimized by mixing nanoparticles into water, forming nanofluids, which demonstrated superior heat transfer efficiency compared to conventional water in the TES system. In this study, heat was transferred between a solar collector and the TES unit using nanofluids, accompanied by water serving as the base fluid. The HTF in the experiments was first water alone, and then water combined with $Al_2O_3$ and MgO nanoparticles at three volume fractions: 0.2%, 0.5%, and 0.8%. Flow rates of 2, 4, and 6 L/min were evaluated using a variable heat source provided by the solar flat plate collector. Analyzing the improvement in heat transport and monitoring the impact on the PCMs' melting time under various circumstances was the main goal. For the various HTFs and PCMs, performance criteria such charging time, instantaneous and cumulative stored heat, and system efficiency were assessed. In order to recover the stored heat, batch-wise discharging experiments were also carried out; the findings were provided to shed light on the efficacy of the TES system. The thorough examination of nanofluid-enhanced heat transfer and its effects on PCM melting dynamics makes this work noteworthy.

**Keywords:** Solar Flat Plate Collector, Phase Change Material (PCM), Heat Transfer Fluid (HTF), Paraffin Wax, Stearic Acid, Nanoparticles, Nanofluids, Charging, Discharging, Thermal Energy Storage System (TESS), $Al_2O_3$ Nanoparticles, MgO Nanoparticles, System Efficiency, Latent Heat Storage(LHS), Sensible Heat Storage(SHS), Instantaneous Heat Storage(IHS), Cumulative Heat Storage(CHS).

## 1. Introduction

Thermal Energy Storage (TES) systems, particularly those utilizing Phase Change Materials (PCMs), are at the forefront of energy storage research due to their ability to store and release large amounts of thermal energy during phase transitions. For instance, stearic acid has been thoroughly investigated for its stability and thermal performance as a latent heat storage substance, indicating promise as an effective


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thermal energy storage medium. Experimental studies have examined the stability of phase change in stearic acid, as well as its ability to store and release heat effectively, underscoring its potential role in enhancing TES systems for renewable energy applications. [1]. This approach provides valuable insights into optimizing TES systems for various applications, helping to identify the most effective combinations of PCM, flow rate, and capsule size for efficient thermal energy storage and release. [2]. Materials like solid particles, sand, and alumina are commonly used in sensible heat storage owing to their capacity to store heat based on temperature changes. Conversely, latent heat storage, in which energy is stored during a solid–liquid phase transition, is a good fit for phase change materials (PCMs), such as paraffin and stearic acid. [3]. To investigate the thermal behavior of TESS that include both sensible and latent heat storage, a number of experimental and numerical studies have been performed. In order to maximize energy transmission and storage efficiency within the system, these research investigate various heat transfer fluids (HTFs). Given their broad applicability and enhanced thermal properties, nanofluids—created by suspending nanoparticles in conventional fluids—have become a major focus of research [4]. Researchers have focused on the synthesis, characterization, and modeling of nanofluid systems. These properties are critical in determining how effectively nanofluids can transfer and store heat in applications like thermal energy storage systems (TESS) [5]. Several studies have explored the applications of heat transfer fluids (HTFs) in solar energy systems, including both experimental and numerical investigations of solar collectors. In this research, a number of critical parameters have been identified to optimize system performance. These include solar collector's efficiency enhancement, determining the optimal volume fraction of nanoparticles in nanofluids, and assessing how particle size affects heat transfer efficiency [6]. Key characteristics of $Al_2O_3$-$H_2O$ nanofluids include increased thermal conductivity and heat capacity, which contribute to more efficient thermal energy exchange [7]. Godson et al. [8] performed both numerical and experimental study on extensive investigation of heat transfer characteristics of nanofluids. Their research examined a range of critical parameters that affect nanofluid performance, including heat transfer efficiency, thermo physical properties, and potential applications. Key factors studied included specific heat capacity, thermal conductivity, viscosity, and density, all of which significantly influence how well nanofluids transfer and dissipate heat. Qinbo He et al. [9] conducted studies on alumina ($Al_2O_3$) particles, focusing on thermo physical properties, which are crucial to findout, their effectiveness as components in heat transfer fluids. Ryan Anderson et al. [10] demonstrated that $Al_2O_3$ (alumina) aqueous nanofluids exhibit significantly enhanced thermal conductivity, making them highly effective for a variety of thermal applications. The enhanced thermal conductivity of $Al_2O_3$-based nanofluids allows for quick and more efficient heat transfer, which are advantageous in applications such as cooling systems, solar thermal energy storage, and industrial heat exchangers. Wu Shuying et al. [11] investigated $TiO_2$ (titanium dioxide) nanoparticles and highlighted their critical thermal properties, particularly chemical compatibility and strong physical interactions with base fluids. These properties make $TiO_2$-based nanofluids highly suitable as heat transfer fluids for applications of solar energy, particularly in domestic solar heating systems. S. Harikrishnan et al.[12] performed experimental validation studies on CuO–oleic acid-based nanofluids, presenting them as a novel type of phase change material (PCM) for TES, particularly in cooling systems. The study explored these nanofluids as solid–liquid composite materials, showcasing their potential for efficient thermal management. S.M.S. Murshed et al. [13] performed an investigation into the enhanced thermal conductivity of $TiO_2$ (titanium dioxide) nanofluids, emphasizing the role of nanofluids in significantly improving heat transfer capabilities. Their experimental findings underscore the importance of nanofluids as efficient thermal conductors in various applications, especially where heat dissipation and transfer are critical. Mahbubul et al. [14] conducted a study exploring the effects of sonication time on the properties of nanofluids, specifically using an ultrasonic homogenizer to vary the sonication duration from 0 to 180 minutes. Their findings revealed that longer sonication times led to improved particle dispersion within the fluid, which is crucial for enhancing the overall stability and performance of nanofluids. Senthilraja et al. [15] an experimental study was conducted to focus on thermal conductivity and heat transfer characteristics of copper oxide (CuO) nanofluids, comparing their performance with water and alumina ($Al_2O_3$) nanofluids, as well as hybrid nanofluids composed of $Al_2O_3$ and CuO suspended in water. Hemanth Kumar Gupta et al. [16] An experimental investigation was conducted on the performance of $Al_2O_3$ (alumina) water nanofluids, specifically examining how varying flow rates affect the conventional solar collector's efficiency. Their study demonstrated that $Al_2O_3$ nanofluids can significantly enhance thermal efficiency, showing improvements of over 8% compared to pure water. Michael Joseph Stalin Prakasam et al. [17] conducted a detailed investigation into the performance of a solar flat plate collector using working fluid $Al_2O_3$/water nanofluid. Their study focused on a low volume concentration of 0.01% $Al_2O_3$ nanoparticles, while also varying the flow rates from 1 to 3 liters per minute. Chandra Prakash et al. [18] highlighted the capabilities of $Al_2O_3$ (alumina) nanofluid in improving the performance of conventional solar TES systems. Their research demonstrated that these nanofluids could effectively generate hot water for domestic applications, showcasing their practical utility in everyday settings. The present work emphasizes the use of nano mixed base fluids at mass flow rates of 2.0, 4.0 & 6.0 liters per minute to investigate the improvement of heat transfer and assess their impact on performance of phase change material based TES system. By utilizing these nano mixed fluids, the study aims to explore how the incorporation of nanoparticles can optimize thermal performance of PCMs, which are critical for effective energy storage and management.

## 2. Experimental Investigation

### 2.1 Experimental test rig

The experimental test rig is shown in Figure 1 and includes a cylindrical TES-insulated tank with spherical capsules encapsulated with Phase change material, solar flat plate collector, control valve, flow meter, and circulating pump. Figure 2 shows a snapshot of the experimental construction. With a 57-liter capacity and dimensions of 535 mm in height and 370 mm in diameter, the TES stainless steel tank is ideal for providing hot water to a household consisting of five or six people. The top and bottom chambers of tank are separated, which may help with thermal stratification and effective heat transfer layers. Additionally, 30 mm thick glass wool reduces heat loss by providing thermal insulation. The spherical capsule has an interior diameter of 70 mm and mild steel walls that are 2 mm thick. The tank uses 90 spherical capsules. The use of wire mesh to support each layer of spherical capsules within the TES tank is an effective way to achieve stability and uniform packing.. Using paraffin wax as the PCM is an excellent choice for thermal energy storage applications, especially given its melting point of 61°C. This temperature aligns well with the range needed for domestic hot water, along a high latent heat of fusion (213 kJ/kg) that ensures substantial energy storage during phase changes. Including an active solar flat plate collector of 2 $m^2$, TES system should be capable of efficiently capturing solar energy to heat the water surrounding the PCM capsules. Using both water and nanofluids as heat transfer fluids (HTF) and sensible heat storage (SHS) materials is an effective strategy. While water provides reliable thermal mass, the addition of nanofluids can enhance thermal conductivity and improve heat transfer rates. This dual approach allows for more rapid heating of the PCM capsules and potentially quicker heat release, leading to better responsiveness and efficiency in the system. The layout of connected PCM capsules in the tank is depicted in Figure 3. The thermal and physical characteristics of PCM are shown in Table 1.

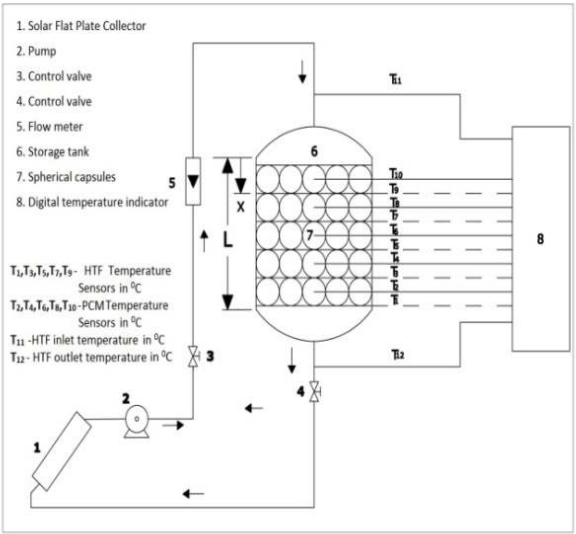


**Fig. 1.** Experimental setup-schematic

**Fig. 2.** Photograph view of experiment

**Fig. 3.** PCM capsules arrangement in the TES tank

**Table 1.** PCM properties - Thermo-physical

| Phase change material | Temperature of Melting [$^{o}$C] | Latent heat of fusion [kJ/kg] | Specific heat [J/kg$^{o}$C] | | Density [kg/m$^3$] | | Thermal conductivity [W/m$^{o}$C] | |
|---|---|---|---|---|---|---|---|---|
| | | | Liquid | Solid | Liquid | Solid | Liquid | Solid |
| *(TGV-MP) Stearic acid | 57 | 198.91 | 2300 | 1600 | 840 | 960 | 0.172 | 0.3 |
| ** Type-II Paraffin wax | 61 | 213 | 2384 | 1850 | 778 | 861 | 0.15 | 0.4 |

Suppliers: * TGV SRAAC Limited, Kurnool, AP. **CPCL, Chennai.

## 2.2 Preparation of nanofluids

Using different concentrations of nanoparticles (0.2%, 0.5%, and 0.8%) in water enhances the thermal conductivity of HTF, which can increase heat transfer efficiency in the TES system. The selected sonication time of 180 minutes helps break up any nanoparticle agglomerates, ensuring a stable and uniform dispersion in the fluid. This approach maximizes the effective surface area of the nanoparticles, improving thermal conductivity and stability within the HTF. [14].This two-step approach using an ultrasonic probe sonicator (figure 4) followed by magnetic stirring (figure 5) ensures optimal nanoparticle dispersion. Sonication helps break up any initial agglomerations of nanoparticles, especially as they approach the target 180-minute period. The subsequent magnetic stirring maintains even distribution and prevents re-agglomeration, allowing the nanofluid to retain enhanced thermal conductivity properties for more effective heat transfer. Table 2 shows the thermo physical properties often characterized for nanoparticles and nanofluids. Specific details about the SEM (Scanning Electron Microscope) images in Figures 6 and 7.

**Table 2.** Thermo-physical properties - Nanoparticles and Nanofluids

| **Property** | **Nanoparticles** | | **$Al_2O_3$ Nanofluid** | | | **MgO Nanofluid** | | |
|---|---|---|---|---|---|---|---|---|
| | **$Al_2O_3$** | **MgO** | **Vol % of 0.2** | **Vol% of 0.5** | **Vol % of 0.8** | **Vol % of 0.2** | **Vol% of 0.5** | **Vol % of 0.8** |
| Density | 3970 $kg/m^3$ | 3580 $kg/m^3$ | 1594 | 2485 | 3376 | 1516 | 2290 | 3064 |
| Thermal conductivity | 30 $W/m^oC$ | 60 $W/m^oC$ | 1.013 | 2.1934 | 6.0885 | 1.028 | 2.286 | 6.8224 |
| Specific heat | 0.955 $kJ/kg^oC$ | 1.03 $kJ/kg^oC$ | 2.5735 | 1.6038 | 1.146 | 2.692 | 1.7177 | 1.2356 |
| Avg nano particle size | 30 - 50 nm | 30-50 nm | --- | --- | --- | --- | --- | --- |

Suppliers: PNPL, Mahagama, Kachwach, Jharkhand.

**Fig. 4.** Ultrasonic probe sonicator

**Fig. 5.** Magnetic stirrer

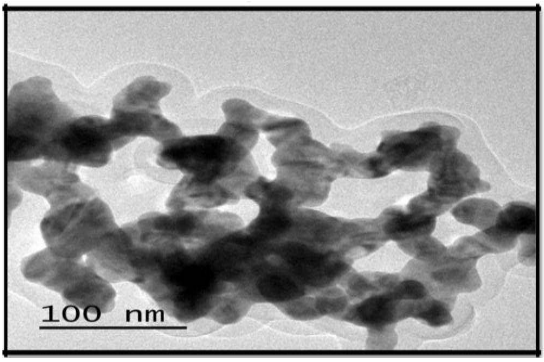


**Fig. 6.** Crystal orientations of $Al_2O_3$ nanoparticles for SEM analysis

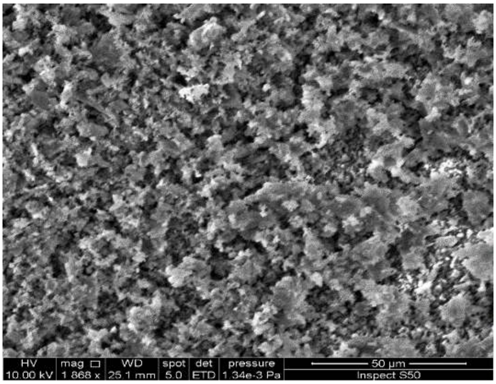


**Fig. 7.** MgO -Magnified view nanoparticles for SEM analysis

## 2.3 Experimental method

### 2.3.1 Process of Charging

One important aspect affecting the effectiveness and performance of TES system is the fluctuating HTF inlet temperature during the charging tests. The operation of TES system depends on the thermal energy transfer process from the heat transfer fluid (HTF) to the phase change material (PCM). A crucial stage in the entire thermal management process is the first energy storage phase in TES system, where the energy is held as sensible heat. To maximize the efficiency and capacity of a TES system, the phase change material (PCM) must melt and transition to superheat at the following stages of the energy storage process. The experimental design offers important information about the thermal performance of the TES system by tracking the PCM temperatures and HTF at dissimilar points in the tank.

### 2.3.2 Process of Discharging

The batch-wise method allows for full extraction of thermal energy from TES tank. By removing hot water in specific quantities (20 liters per batch), efficiently manage the discharge process while monitoring temperature changes. Collected hot water is stored in an insulated drum to minimize heat loss during the monitoring period. This is crucial for obtaining accurate temperature readings and ensures that the hot water remains effective for its intended use. Continuous monitoring of the withdrawn hot water's temperature allows for the assessment of the heat extraction efficiency and helps in calculating the average temperature across multiple batches. This average can indicate the effectiveness of the TES system in delivering hot water. Keeping the inlet flow to the tank constant at 2.0 lit/min ensures a consistent supply of cold water, which is important for maintaining thermal dynamics within the TES system. This consistency allows for more reliable data collection during discharge. Allowing a retention period of 20 min between batches helps stabilize the thermal conditions within the tank. This period allows for thermal stratification to develop, ensuring that the hottest water is extracted first while maintaining a steady temperature gradient. Continuing the discharge process until the outlet temperature reaches

45°C provides a clear endpoint for the experimental phase. This threshold can help in assessing the performance of the TES system in meeting the desired hot water supply temperature.

# 3. Results And Discussion

## 3.1 Charging-experiments

### i. Temperatures -History

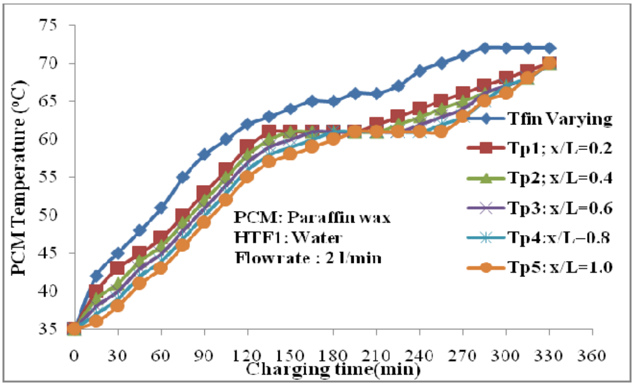


**Fig. 8.** Temperatures Variations in PCM during process of charging and 2 lit/min flow-rate of water as HTF

By measuring temperatures of PCM at five different axial segments (x/L = 0.2, 0.4, 0.6, 0.8, and 1.0), clearly understand that heat is distributed throughout the tank during charging. This segmentation is crucial for identifying thermal gradients and efficiency in heat transfer. The gradual increase in PCM temperature along the axial direction indicates effective heat transfer from hot HTF (water) to PCM. This progression suggests that the design facilitates proper thermal conduction and convection. The observation that the uppermost layers of PCM have higher temperatures at any given time aligns with expected thermal stratification effects. This is likely due to the proximity of these layers to the HTF inlet and the natural tendency of warmer fluids to rise. The slow increase in PCM temperature during the initial charging stages reflects the sensible heat absorption before reaching the melting point.The PCM's temperature remaining unchanged during the melting process confirms that latent heat is being absorbed without a temperature increase, a hallmark of effective thermal energy storage systems. After phase change, the sudden rise in temperature during the liquid PCM heating phase indicates that the system is now storing additional energy as sensible heat. This rapid temperature change highlights the TES system's efficiency in utilizing the latent heat stored during phase change. The total time for charging of 330 minutes at a 2 lit/min, flow-rate for the PCM to reach 70°C indicates a well-defined operational period for the system. This information is critical for evaluating system performance and optimizing charging protocols.

**ii. HTF flow rate effect**

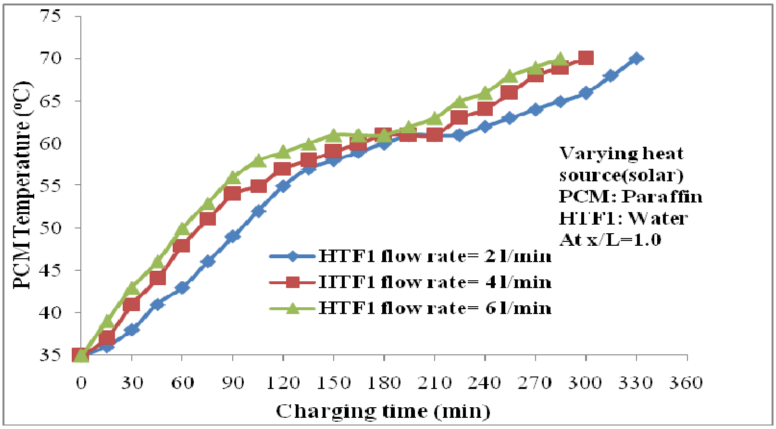


**Fig. 9.** HTF flow-rate effect on time required for charging process (at x/L=1.0)

Figure 9 illustrates the total charging times of 330 min for 2.0 lit/min, 300 min for 4.0 lit/min, & 285 min for 6.0 lit/min highlight the impact of flow rates on system performance. As flow rates increase, the required time decreases for charging . The observed reductions in charging time of 9.09% from 2.0 lit/min to 4.0 lit/min and 13.63% from 2.0 lit/min to 6.0 lit/min indicate a clear advantage of higher flow rates.

**iii. Effect of volume concentration of Nanoparticles**

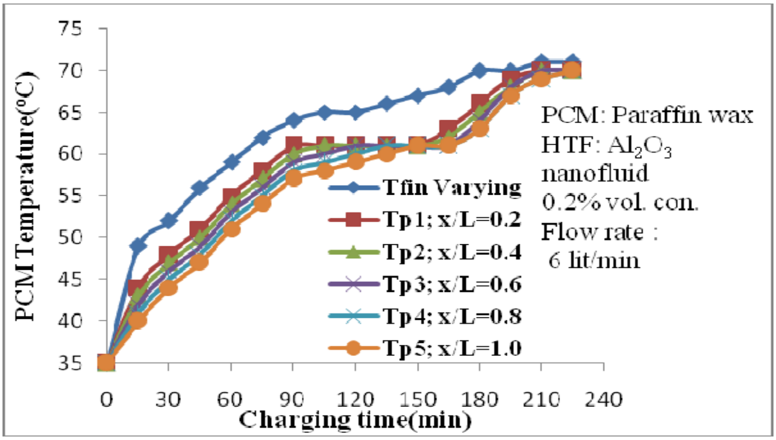


**Fig. 10.** Temperatures-variations in PCM during period of charging for volume concentration of 0.2% -$Al_2O_3$ nanofluid as HTF and flow rate of 6.0 l/min

The initial increase in PCM temperature indicates effective heat transfer from the 0.2% volume concentration $Al_2O_3$ nanofluid at flow rate of 6.0 lit/min. This aligns with expectations, as the heat transfer capabilities are enhances by higher thermal conductivity of nanofluids compared to water. The PCM maintaining a constant temperature during the melting phase further confirms efficient energy storage, as latent heat is absorbed without increasing temperature. This characteristic is essential for the effectiveness of a TES system. After the melting phase, the PCM's temperature rising rapidly in the liquid state indicates that energy is now being stored as sensible heat. This behaviour illustrates the transition from latent heat storage to sensible heat storage once the PCM has melted. The observation that the topmost segments of the PCM achieve the phase change temperature faster and complete the phase change earlier is consistent with thermal stratification principles. These segments are likely receiving direct exposure to the HTF and thus heat up more quickly. The total charging time of 225 minutes for the PCM to reach 70°C at flow rate of 6.0 lit/min suggests a significant improvement in charging efficiency with the use of nanofluid compared to earlier trials.

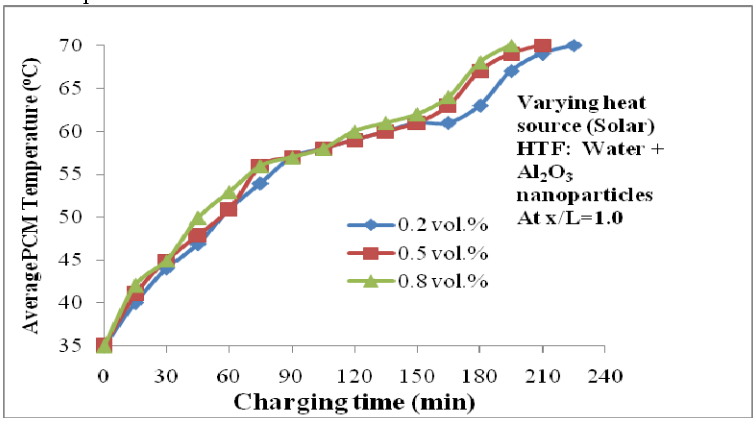


**Fig. 11.** Variation of PCM temperatures during charging period at varied % of volume of $Al_2O_3$ nanofluid as HTF and flow rate of 6.0 lit/min

Figure 11 represents the significant rise in PCM temperature at all volume concentrations (0.2%, 0.5%, and 0.8%) indicates effective heat transfer, primarily due to the substantial temperature differences between the hot HTF and the cooler PCM. This is a crucial factor in enhancing the thermal performance of the TES system. The total charging times of 225 min for vol. % of 0.2, 210 min for vol. % of 0.5 and 195 min for vol. % of 0.8 highlight the improved efficiency as the concentration of $Al_2O_3$ nanofluid increases. The results suggest that higher concentrations of nanoparticles enhance heat transfer capabilities. The reductions in charging time of 6.66% from 0.2% to 0.5% and 13.33% from 0.2% to 0.8% indicate that increased nanoparticles concentration can significantly improve thermal energy transfer rates.

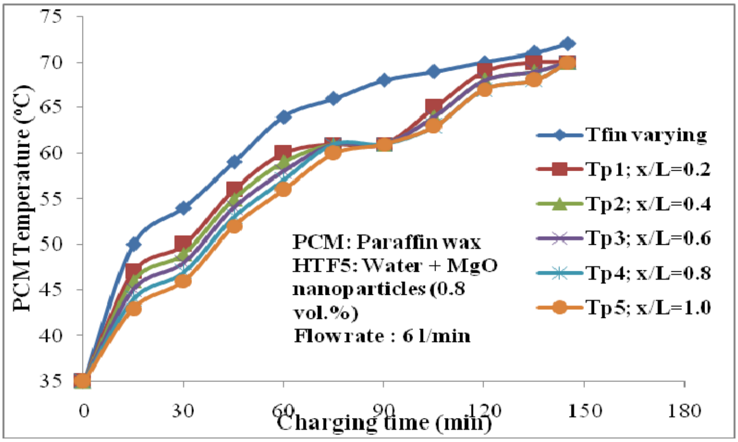


**Fig. 12.** Variation of PCM temperatures during process of charging for vol. % of 0.8- MgO nanofluid as HTF and flow rate of 6.0 lit/min

Figure 12 indicates the gradual increase in PCM temperature at the initial charging period suggests effective heat transfer from the MgO nanofluid to PCM. This is indicative of improved thermal properties of the nanofluid, which increases the heat transfer rates compared to conventional HTFs. The total charging time of 145 minutes for the PCM when using 0.8% MgO nanofluid at flow rate of 6.0 lit/min suggests a very efficient charging process. This relatively short time indicates, the MgO nanofluid significantly increases the heat transfer characteristics, leading to quicker charging.

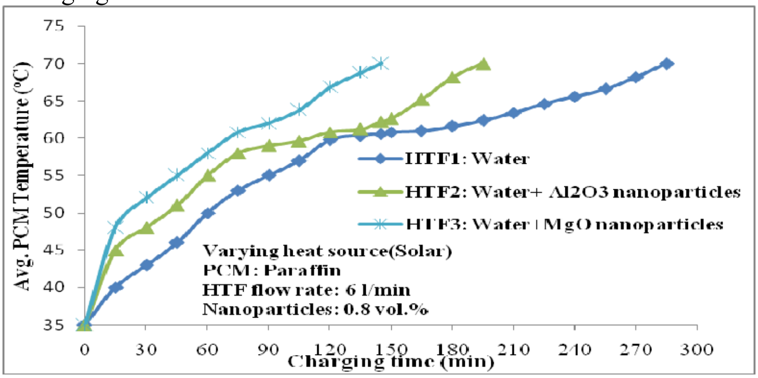


**Fig. 13.** Variation of PCM temperatures during charging period for vol. % of 0.8 - paraffin and nanoparticles as PCM, at flow rate of 6.0 lit/min

Figure indicates the initial slow rise in PCM temperatures indicates that the system is efficiently absorbing heat from the HTF, whether it's water, $Al_2O_3$ nanofluid, and MgO nanofluid. The observed charging times are 285 min, 195 min and 145 min for water, $Al_2O_3$ nanofluid and for MgO nanofluid respectively. Showcase a remarkable decrease in time with the use of nanofluids. The charging time reductions of 31.57% for $Al_2O_3$ nanofluid and 49.12% for MgO nanofluid compared to water demonstrate the substantial benefits of using nanofluids in thermal energy storage systems. The greater reduction in charging time indicates an even more significant enhancement in heat transfer properties, suggesting that MgO nanofluid is particularly advantageous for applications requiring rapid heat accumulation.

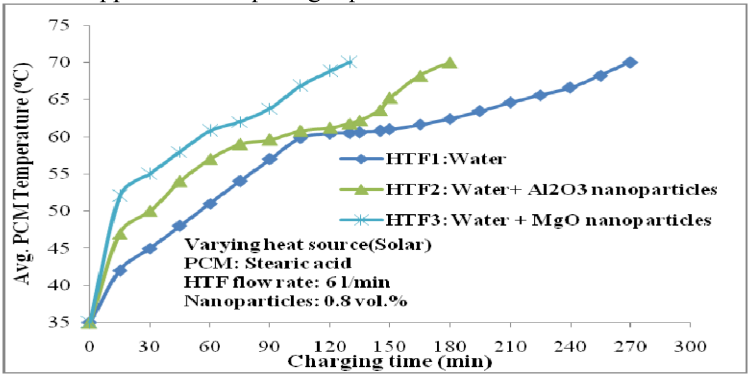


**Fig. 14.** Variation of PCM temperatures during charging period for vol. % of 0.8 - nanoparticles & stearic acid as PCM, and flow rate of 6.0 lit/min

Figure 14 illustrate charging process of PCM, showing how the temperature increases gradually at begining stage, remains same throughout the period of phase transition, and then rises sharply during the heating of the liquid PCM. The observed charging times of 270 min, 180 min and 130 min for water, $Al_2O_3$ nanofluid and MgO nanofluid respectively. It indicates a remarkable decrease in time with the use of nanofluids. The charging time reductions of 33.33% for $Al_2O_3$ nanofluid and 51.85% for MgO nanofluid compared to water demonstrate the substantial benefits of using nanofluids in TES systems.

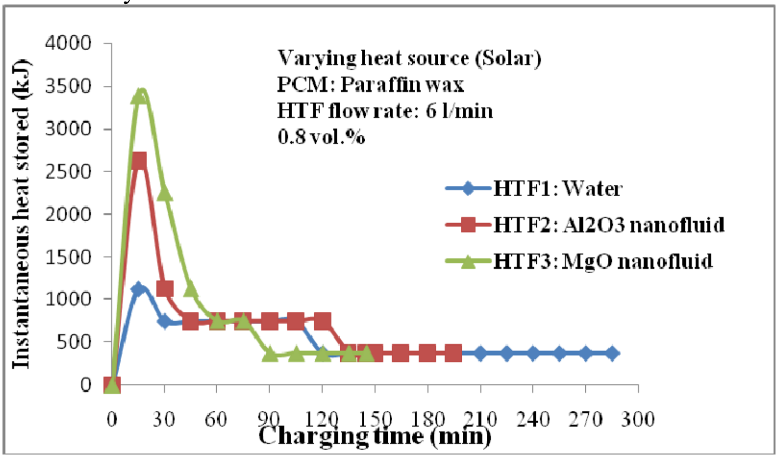


**Fig. 15.** Variation of Instantaneous-heat storage with charging time

Figure 15 shows the instantaneous rate of collected heat in the thermal energy storage (TES) tank throughout the charging process at flow rate of 6.0 l/min. HTF's current temperatures at inlet and outlet serve as the basis for the graph. When the temperature differential between the TES tank and the HTF is large, the PCM exhibits a high rate of heat accumulation, indicating efficient heat transmission. The rate of heat storage falls as the charging process goes on. This decrease is explained by the HTF and PCM's decreasing temperature differential, which lowers heat transfer efficiency. As the PCM begins to melt, the amount of stored heat stabilizes. During this phase, the temperature remains relatively constant, indicating that the heat energy is being utilized for the phase change rather than increasing the temperature of the PCM.

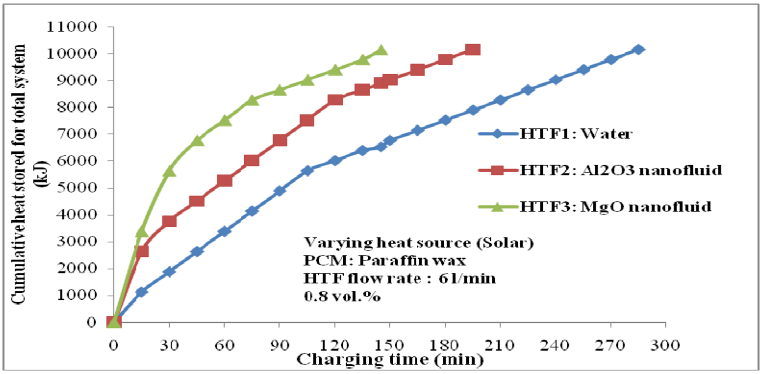


**Fig. 16.** Variation of Cumulative-heat storage with charging time

Figure 16 illustrates cumulative stored heat in the thermal energy storage (TES) tank during the charging process at flow-rate of 6 lit/min, comparing water, $Al_2O_3$ nanofluid & MgO nanofluid as heat transfer fluids (HTFs). The cumulative heat stored is significantly greater when using 0.8 vol. % of either $Al_2O_3$ or MgO nanofluid compared to water. This increase in stored heat can be attributed to the superior heat transfer capabilities of nanofluids that enhance the thermal performance of the system. When the PCM temperature reaches to 70°C, the total amount of cumulative stored heat in the system is recorded at 10,400 kJ. This value reflects the effective energy storage capacity achieved by the use of nanofluids.

The efficiency of a TES system is expressed by

$\eta sys = (m*Cp*(Tin-Tout))/(\lambda* A)$,

Where, A =Area of the solar collector in $m^2$ and

$\lambda$ = The solar insolation in $W/m^2$.

The initial system efficiency tends to be high due to thermal inertia, which refers to the system's capacity to store heat over time, leading to effective energy capture from solar radiation. The solar radiation measured has ±2.5% of accuracy, which is important for calculating the efficiency accurately. This uncertainty can influence the reliability of efficiency calculations, especially in variable weather conditions.

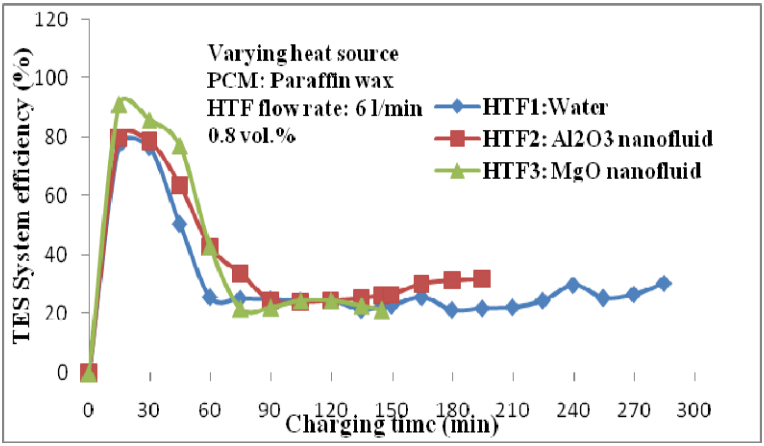


**Fig. 17.** Variation of TES System efficiency with charging time

Comparing various heat transfer fluids (HTFs), Figure 17 shows system efficiency of the storage tank throughout charging process at flow rate of 6 l/min. The ratio of thermal energy captured from solar radiation to the energy stored in the tank used to compute the efficiency. The efficiency of the system declines as charging proceeds. This pattern is especially noticeable during the PCM's phase change and, later, during the liquid PCM's sensible heating. As the PCM gets closer to its melting point, temperature differential between HTF and the PCM decreases, which is the cause of the efficiency decline. The TES system efficiency increases of 3.88% for $Al_2O_3$ nanofluid and 18.28% for MgO nanofluid compared to water demonstrate the substantial benefits of using nanofluids in thermal energy storage systems.

**b. Experiments on Discharging**

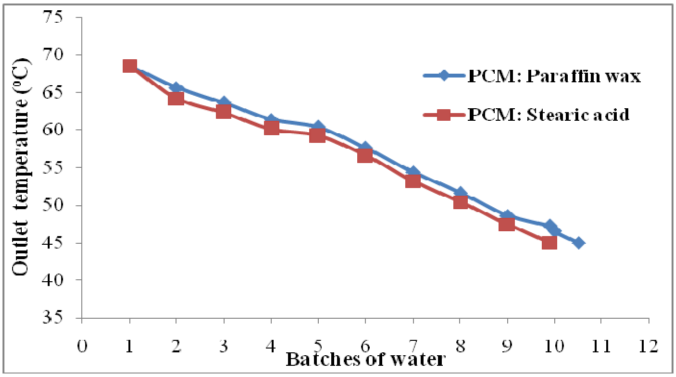


**Fig. 18.** Variation of outlet water temperature with batches of water

Figure 18 result indicates that paraffin wax, as the PCM, enables a slightly higher quantity (210 litres) of hot water extraction compared to stearic acid (198 litres). The higher thermal storage capacity of paraffin wax likely accounts for this difference, allowing it to sustain a higher temperature over a greater volume. This makes it more effective for applications requiring a consistent supply of hot water over time.

# 4 Conclusions

This research provides valuable insights into optimizing PCM melting times by adjusting the HTF flow rates and nanoparticles concentrations. The use of $Al_2O_3$ and MgO nanofluids enhances heat transfer, with MgO showing the most substantial effect in reducing melting time.

- Using water as the HTF with increasing flow rates of 2.0, 4.0, and 6.0 lit/min significantly reduces total charging time from 330 minutes to 300 minutes and finally to 285 minutes. This decrease illustrates the effectiveness of higher flow rates in improving heat transfer, as they allow more rapid temperature increase and energy storage in the PCM. This insight is valuable for optimizing TES systems where water serves as the primary HTF.

- The results indeed highlight that higher HTF flow rates lead to a noticeable reduction in charging time, specifically by 9.09% when increased from 2 to 4 lit/min, and by 13.63% from 2.0 to 6.0 l/min. This efficiency boost makes higher flow rates advantageous, as they facilitate quicker thermal energy transfer to PCM, thereby improving the overall performance of the TES system.

- Using $Al_2O_3$ nanofluid with different volume fractions as HTF effectively decreases the total charging time: 225 minutes for 0.2%, 210 minutes for 0.5%, and 195 minutes for 0.8%. This trend underscores that higher concentrations of $Al_2O_3$ nanoparticles enhance heat transfer properties, reducing the required time to charge the TES system completely. This efficiency gain makes higher nanoparticles concentrations a practical approach to improving TES performance.

- The results clearly illustrate that increasing the volume concentration of $Al_2O_3$ nanofluid leads to significant improvements in charging efficiency. The 6.66% reduction in charging time when increasing from 0.2% to 0.5% and the 13.33% reduction when increasing from 0.2% to 0.8% demonstrate that higher nanoparticles concentrations facilitate better thermal conductivity and heat transfer.

- The charging period is significantly simplified as compared to the current HTF, water, in case of flow rate of 6.0 l/min and nanoparticles vol.% of 0.8, around 31.57 % for $Al_2O_3$ nanofluid and 49.12% for MgO nanofluid.

- A considerable quantity of energy storage was accomplished by the system, as evidenced by the cumulative stored heat of 10,400 kJ at a PCM temperature of 70°C. This figure, which represents the system's effectiveness in thermal energy storage applications, is essential for comprehending its ability to provide heat when required.

- The notable advantages of employing nanofluids are demonstrated by the measured efficiency gains of 3.88% for $Al_2O_3$ nanofluid and an astounding 18.28% for MgO nanofluid at a 0.8% volume concentration in comparison to water as HTF. Due to high thermal conductivity, Brownian motion effect, low density, agglomeration, and micro convection have all contributed to the amazing melting time decrease of MgO nanofluid.

- The faster performance of MgO nanofluid as HTF makes it a suitable choice for various domestic applications, including water heating, clothes drying, and cooking. Its enhanced heat transfer capabilities can lead to quicker heating times and greater energy efficiency, providing significant benefits for household energy management. This insight could encourage broader adoption of nanofluids in domestic heating systems.

- The collection of 210 liters of hot water with paraffin wax as PCM compared to 198 liters with stearic acid highlights paraffin wax's superior thermal storage capacity in this TES system.

## The limitations of present study

- When volume concentration of nanoparticles in nanofluids is increased over 1%, the heat transfer fluid's (HTF) specific heat capacity decreases. Therefore, to optimize heat transfer efficiency while maintaining the desired thermal properties, the selected nanoparticles volume concentrations are 0.2%, 0.5%, and 0.8%. This careful selection allows for effective enhancement of heat transfer without compromising the HTF's performance, making it suitable for various thermal applications.

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