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Experimental Investigation on the Effect of Water Based Nanofluids (Al_2O_3 And Mgo) Used as Htf in a Pcm Based Thermal Energy Storage System Integrated with Constant Heat Source

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Abstract: This research focuses on evaluating the thermal performance of a combined sensible and latent heat storage unit using a packed bed design integrated with a constant heat source. The Thermal Energy Storage (TES) system features a cylindrical, insulated storage tank filled with spherical capsules containing phase change materials (PCMs) — specifically, paraffin wax and stearic acid. PCMs offer significant benefits in thermal management by enabling isothermal operation and higher thermal storage capacity, contributing to a reduction in system size and cost. To enhance the thermal conductivity of the heat transfer fluid (HTF), nanoparticles are introduced into water, creating nanofluids that improve the efficiency of heat transfer. These water-based nanofluids facilitate heat transfer between the constant heat source and the storage tank, serving as a sensible heat storage medium. The study examines different HTF configurations, starting with water alone and extending to nanofluids with Al_2O_3 and MgO nanoparticles at three volume concentrations (0.2%, 0.5%, and 0.8%). Experiments were conducted at varied flow rates of 2, 4, and 6 liters per minute to analyze the effect of these parameters on heat transfer and PCM melting time. Performance parameters, including charging time, instantaneous stored heat, cumulative stored heat, and system efficiency, were evaluated for each HTF-PCM combination. Additionally, batch-wise discharging experiments were conducted to assess the system's heat recovery capability. The results offer insight into the comparative advantages of different HTF materials and configurations, highlighting the thermal performance enhancements achieved by using nanoparticle-enhanced HTFs.

Keywords: Paraffin wax, Stearic acid, Nanoparticles, Nanofluids, Charging, Discharging, Thermal Energy Storage System (TESS), Phase Change Material (PCM), Heat Transfer Fluid (HTF), Al2O3 Nanoparticles, MgO Nanoparticles, Sensible heat storage, Latent heat storage, System efficiency, Instantaneous stored heat, Cumulative stored heat.

1. Introduction

Karabulut et al. [1] conducted a numerical study on heat transfer and flow dynamics for cube and circular hollow models in channels under cross flow-impinging jet conditions, using water and a 2% CuO-water nanofluid as the working fluids. 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 due to their capacity to store heat based on temperature changes. On the other hand, phase change materials (PCMs) like paraffin and stearic acid are suited for latent heat storage, where energy is stored during a solid–liquid phase transformation. [3]. In this context, various experimental and numerical investigations have been conducted to examine the thermal behavior of thermal energy storage systems (TESS) that incorporate both latent and sensible heat storage. These studies explore different heat transfer fluids (HTFs) to optimize energy transfer and storage performance within the system. 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, examining a range of thermo physical properties such as density, specific heat capacity, viscosity, and thermal conductivity. 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 enhancing the efficiency of solar collectors, 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] conducted an extensive investigation into the heat transfer characteristics of nanofluids through both numerical and experimental studies. 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 thermal conductivity, specific heat capacity, 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 their thermo physical properties, which are crucial in determining their effectiveness as components in heat transfer fluids. The research highlighted key properties such as density, specific heat capacity, viscosity, and thermal conductivity, all of which significantly impact the temperature control and thermal efficiency of systems using alumina-based nanofluids. 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 improved thermal conductivity of Al_2O_3-based nanofluids allows for faster and more efficient heat transfer, which is 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 solar energy applications, particularly in domestic solar heating systems. S. Harikrishnan et al.[12] conducted experimental validation studies on CuO–oleic acid-based nanofluids, presenting them as a novel type of phase change material (PCM) for thermal energy storage, 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] conducted 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 examining 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] conducted an experimental study focused on the thermal conductivity and heat transfer characteristics of copper oxide (CuO) nanofluids, comparing their performance with both 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] conducted an experimental investigation into the performance of Al_2O_3 (alumina) water nanofluids, specifically examining how varying flow rates affect the efficiency of conventional solar collectors. 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 Al_2O_3/water nanofluid as the working fluid. 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) nanofluids in enhancing the performance of conventional solar thermal energy storage (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 liters per minute, 4 liters per minute, and 6 liters per minute to investigate the enhancement of heat transfer and assess their impact on the performance of phase change material (PCM) based thermal energy storage systems (TESS). By utilizing these nano mixed fluids, the study aims to explore how the incorporation of nanoparticles can optimize the thermal performance of PCMs, which are critical for effective energy storage and management.

2. Experimental Setup and Procedures

2.1 Experimental Setup

The experimental TES setup, as represented in Figure 1, combines efficient design and strategic material choices for optimal thermal storage. The photograph of the experimental construction is presented in Figure 2.This cylindrical, stainless steel tank with a 57-liter capacity and specifications of 535 mm in height and a 370 mm diameter is well-suited to household use for 5-6 people. The division into two chambers encourages thermal stratification, which improves heat layering, while the 30 mm thick glass wool insulation minimizes heat loss. Containing 90 mild steel spherical capsules of 70 mm inner diameter and 2 mm wall thickness, the tank uses paraffin wax as the PCM. This PCM choice is particularly advantageous, given paraffin's high latent heat of fusion (213 kJ/kg) and a melting point of 61°C, a suitable range for domestic hot water needs. The use of wire mesh helps secure the capsules in a uniform arrangement, aiding stability and efficient packing. The dual approach of using both water and nanofluids as HTFs and SHS materials further enhances the system's performance. While water offers reliable thermal mass, nanofluids improve thermal conductivity, accelerating PCM heating and expediting heat release. This setup is designed for responsive and efficient energy storage, ensuring faster performance and more effective thermal management for domestic applications. Figure 3 shows the arrangement of linked PCM capsules filled in the tank. Table 1 represents the thermo physical properties of PCM.

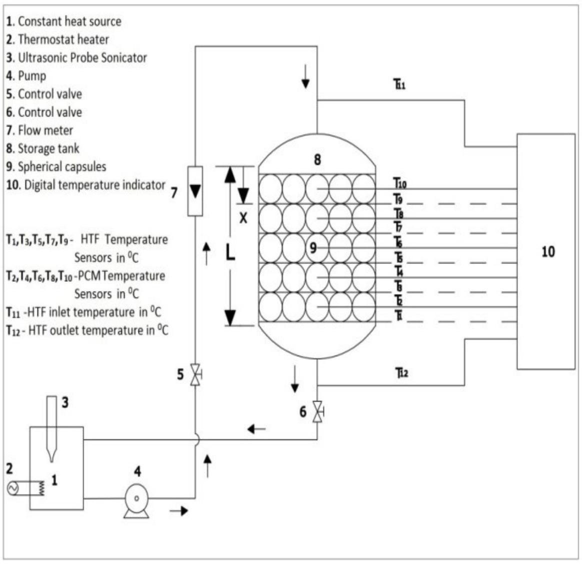

Figure 1 Experimental setup's Schematic

Figure 2 Photograph of experiment

Figure 3 Arrangement of PCM capsules in the TES tank

Table1. PCM properties - Thermo-physical

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

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

2.2 Preparation of nanofluids

Using different concentrations of nanoparticles (0.2%, 0.5%, and 0.8%) in water enhances the thermal conductivity of the HTF, which can improve 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.

Table2. Nanoparticles and Nanofluids - Thermo-physical properties

Property	Nanoparticles		Al_2O_3 Nanofluid			MgO Nanofluid		
	Al_2O_3	MgO	0.2 vol%	0.5 vol%	0.8 vol%	0.2 vol%	0.5 vol%	0.8 vol%
Density	3970 kg/m^3	3580 kg/m^3	1594	2485	3376	1516	2290	3064
Thermal conductivity	30 W/m^{o}C	60 W/m^{o}C	1.013	2.1934	6.0885	1.0284	2.286	6.8224
Specific heat	0.955kJ/kg^{o}C	1.03kJ/kg^{o}C	2.5735	1.6038	1.146	2.6922	1.7177	1.2356
Avg particle size	30-50 nm	30-50 nm	---	---	---	---	---	---

Suppliers: PNPL, Kachwach, Mahagama, Jharkhand.

Figure 4 Ultrasonic probe sonicator

Figure 5 Magnetic stirrer

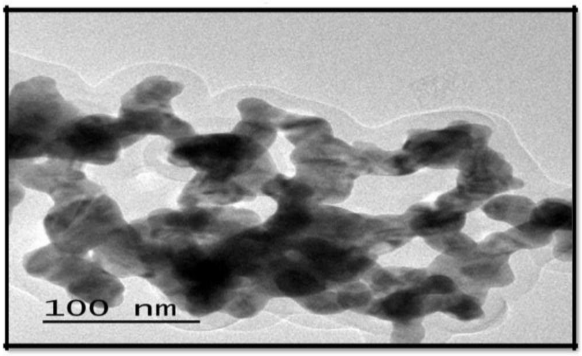

Figure 6 Crystal orientations of Al_2O_3 nanoparticles for SEM analysis

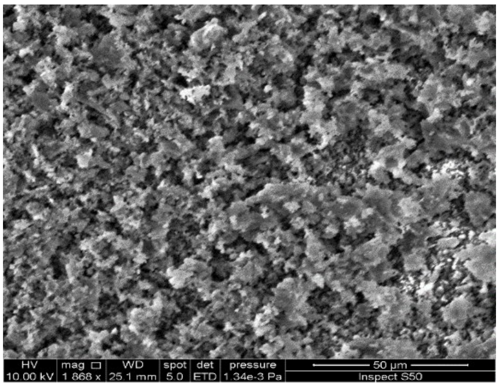

Figure 7 Magnified view of MgO nanoparticles for SEM analysis

2.3 Procedure of the Experiment

2.3.1 Charging Process

This charging process, repeated with different nanofluids, allows for detailed performance analysis of the TES system. The initial sensible heating of the PCM to its melting point, followed by latent heat storage during melting, and finally, the sensible heat storage in the liquid phase, all contribute to a comprehensive understanding of how each HTF enhances heat transfer. The use of nanofluids like Al_2O_3, and MgO can significantly influence the charging time and efficiency due to their higher thermal conductivity compared to water. Recording temperatures every 5 minutes provides a precise profile of the thermal dynamics within the TES tank, crucial for assessing the performance impact of each nanofluid on both heat storage rate and efficiency.

2.3.2 Discharging Process

The batch-wise method allows for full extraction of thermal energy from the 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 l/min ensures a consistent supply of cold water, which is important for maintaining the thermal dynamics within the TES system. This consistency allows for more reliable data collection during discharge. Allowing a retention period of 20 minutes 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 Experiments for Charging

3.1.1 History of Temperatures

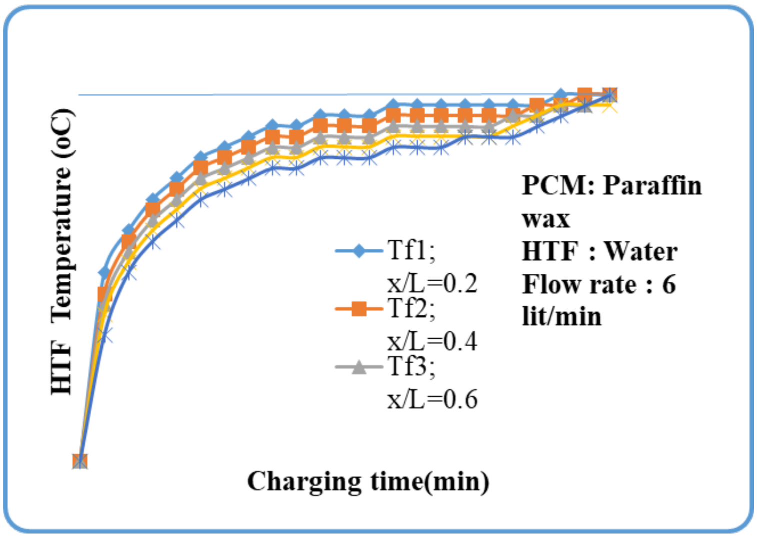

Figure 8 Variations in PCM temperatures during charging process and rate of flow of 6.0 l/min for water as HTF

Figure 8 illustrates, measuring PCM temperatures 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 the hot HTF (water) to the 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. This is essential for preparing the PCM for the phase change. 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 efficiency of the TES system in utilizing the latent heat stored during phase change. The total charging time of 110 minutes at a flow rate of 6 l/min 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.

3.1.2 HTF's flow rate effect

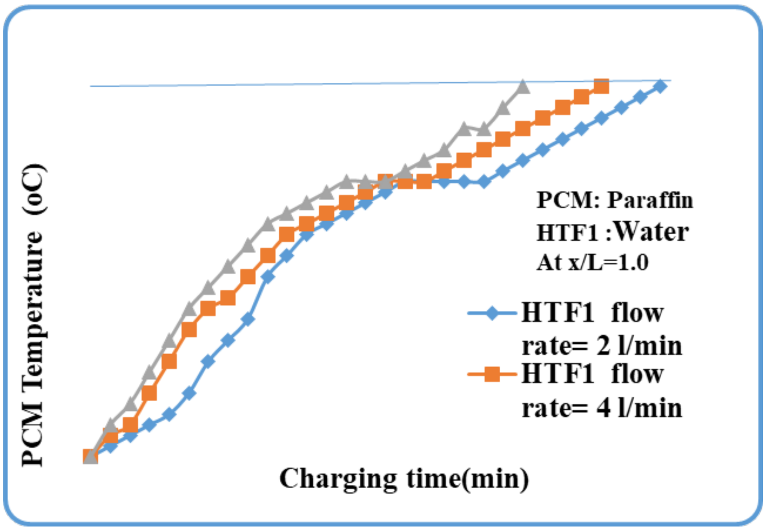

Figure 9 HTF's flow rate effect on the time required for the process of charging (at x/L=1.0)

Figure 9 indicates the total charging times of 145 min for 2.0 l/min, 130 min for 4.0 l/min, and 110 min for 6.0 l/min highlight the impact of flow rates on system performance. As flow rates increase, the time required for charging decreases. The observed reductions in charging time of 10.34% from 2.0 l/min to 4.0 l/min and 24.13% from 2.0 l/min to 6.0 l/min indicate a clear advantage of higher flow rates.

3.1.3 Effect of Nanoparticles volume concentration

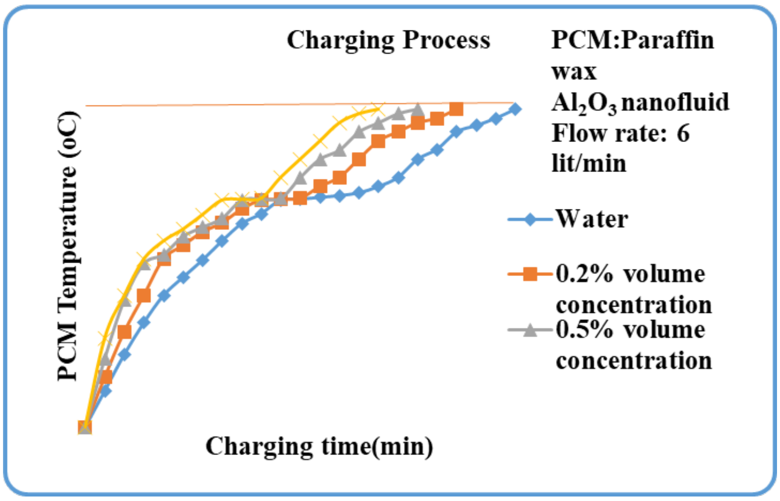

Figure 10 Variations in PCM temperatures during charging period for 0.2% volume concentration of Al_2O_3 nanofluid as HTF and rate of flow of 6.0 l/min

Figure 10 indicates, the initial increase in PCM temperature indicates effective heat transfer from the 0.2% volume concentration Al_2O_3 nanofluid at a flow rate of 6 l/min. This aligns with expectations, as higher thermal conductivity of nanofluids enhances the heat transfer capabilities 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 attain 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 times of 110 min for water, 95 min for 0.2 vol. %, 85 min for 0.5 vol. %, and 75 min for 0.8 vol. % 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 10.52% from 0.2% to 0.5% and 21.05% from 0.2% to 0.8% indicate that increased nanoparticles concentration can significantly improve thermal energy transfer rates.

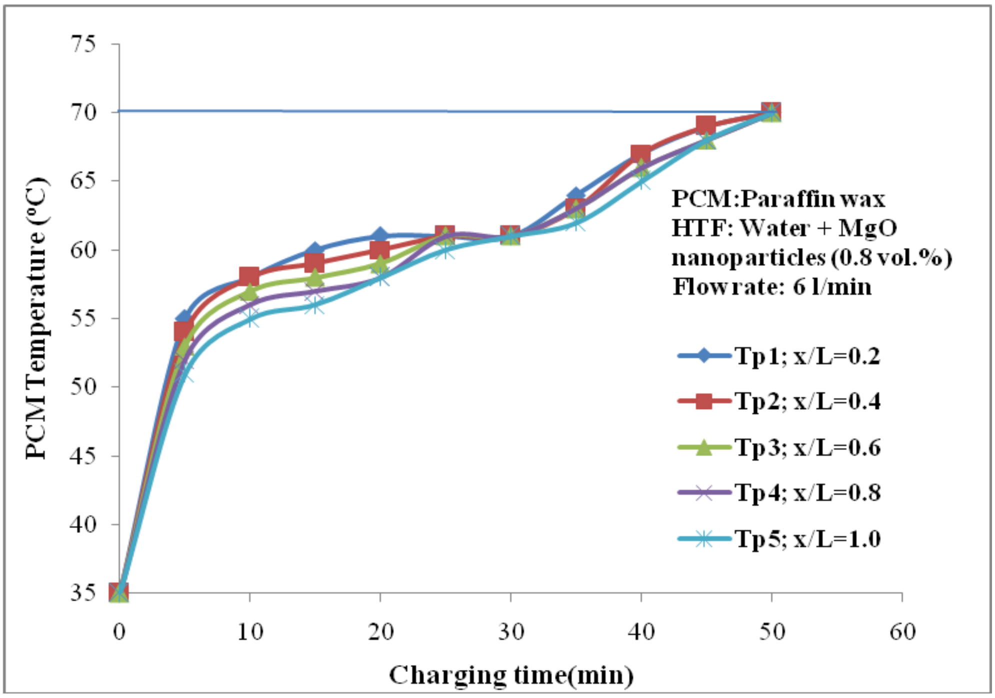

Figure 11 Variation of PCM temperatures during process of charging for 0.8 vol. % MgO nanofluid as HTF and flow rate of 6 l/min

Figure 11 represents the gradual increase in PCM temperature at the initial charging period suggests effective heat transfer from the MgO nanofluid to the PCM. This is indicative of the improved thermal properties of the nanofluid, which can enhance heat transfer rates compared to conventional HTFs. The total charging time of 50 minutes for the PCM when using 0.8% MgO nanofluid at a flow rate of 6 l/min suggests a very efficient charging process. This relatively short time indicates that the MgO nanofluid significantly enhances the heat transfer characteristics, leading to quicker charging.

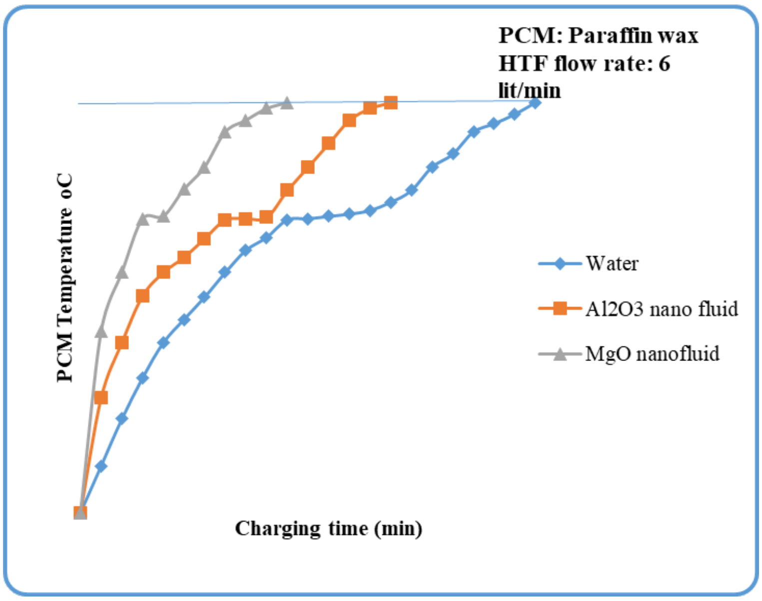

Figure 12 Variation of PCM temperatures during charging period for 0.8 vol. % of nanoparticles and paraffin as PCM, flow rate of 6 l/min

Figure 12 indicates that 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 of 110 min for water, 75 min for Al_2O_3 nanofluid and 50 min for MgO nanofluid showcase a remarkable decrease in time with the use of nanofluids. The charging time reductions of 31.81% for Al_2O_3 nanofluid and 54.54% 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.

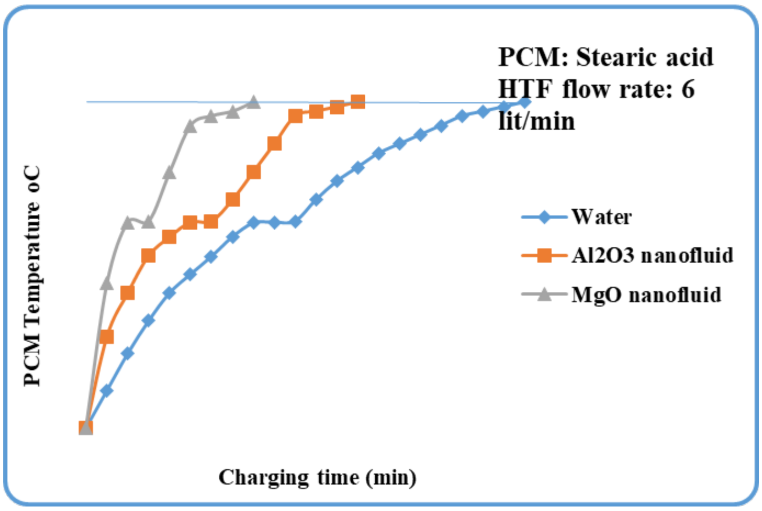

Figure 13 Variations of PCM temperatures during charging process for 0.8 vol. % of nanoparticles and stearic acid as PCM, flow rate of 6 l/min

Figure 13 illustrates the charging process of PCM, showing how the temperature increases gradually at the initial stage, remains constant during the phase transition, and then rises sharply during the heating of the liquid PCM. The observed charging times of 110 min for water, 65 min for Al_2O_3 nanofluid and 40 min for MgO nanofluid showcase a remarkable decrease in time with the use of nanofluids. The charging time reductions of 40.90% for Al_2O_3 nanofluid and 63.63% for MgO nanofluid compared to water demonstrate the substantial benefits of using nanofluids in thermal energy storage systems.

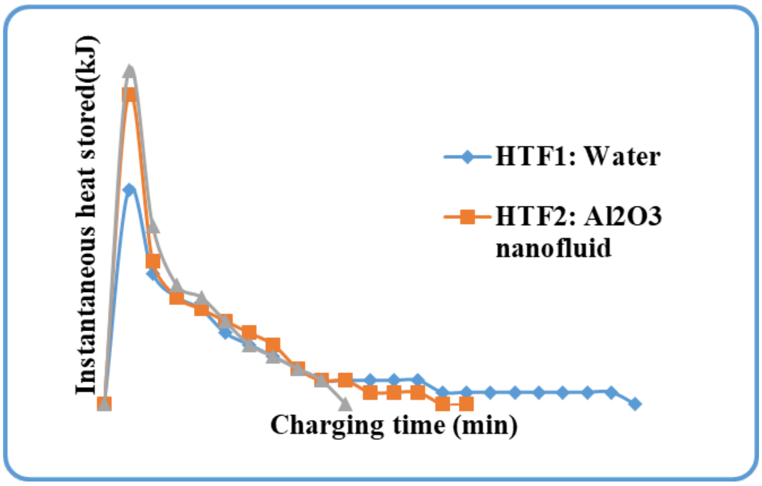

Figure 14 Variation of Instantaneous heat stored in the charging process for various HTFs -Varying heat source

Figure 14 illustrates the instantaneous rate of accumulated heat in the thermal energy storage (TES) tank during the charging process at a flow rate of 6.0 l/min, using water, Al_2O_3 nanofluid, and MgO nanofluid as heat transfer fluids (HTFs). The graph is based on the real-time temperatures of the HTF at both the inlet and outlet. There is a high rate of heat accumulation in the PCM, indicating effective heat transfer when there is a significant temperature difference between the HTF and the TES tank. As the charging process progresses, the rate of heat storage decreases. This decline is attributed to the diminishing temperature difference between the HTF and the PCM, leading to reduced 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.

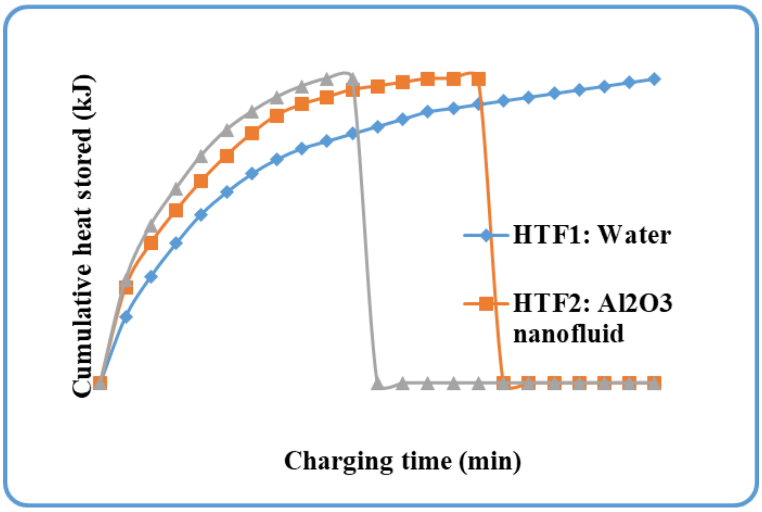

Figure 15 Variation of Cumulative stored heat for total system at charging period for various HTFs -Varying heat source

Figure 15 illustrates the cumulative stored heat in the thermal energy storage (TES) tank during the charging process at a flow rate of 6.0 l/min, comparing water, Al_2O_3 nanofluid, and 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, which enhance the thermal performance of the system. When the PCM temperature reaches 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 through the use of nanofluids.

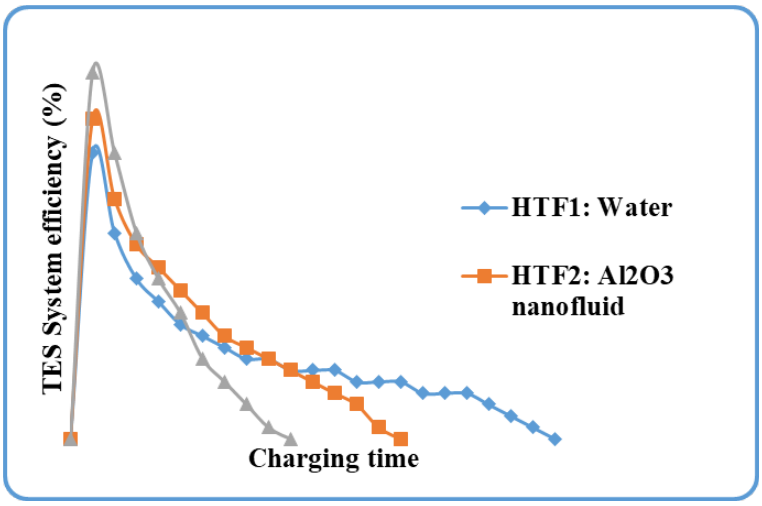

Figure 16 Variation of TES System efficiency during charging process for different HTFs

Figure 16 illustrates the system efficiency of the storage tank during the charging process at a flow rate of 6.0 l/min, comparing different heat transfer fluids (HTFs). The efficiency is calculated based on the ratio of the energy stored in the tank to the thermal energy harvested from solar radiation. As charging progresses, system efficiency decreases. This trend is particularly evident during the phase transition of the PCM and subsequently during the sensible heating of the liquid PCM. The drop in efficiency can be attributed to the diminishing temperature difference between the HTF and the PCM as the PCM approaches its melting temperature. The TES system efficiency increases of 10.81% for Al_2O_3 nanofluid and 27.02% for MgO nanofluid compared to water demonstrate the substantial benefits of using nanofluids in thermal energy storage systems.

3.2 Discharging experiments

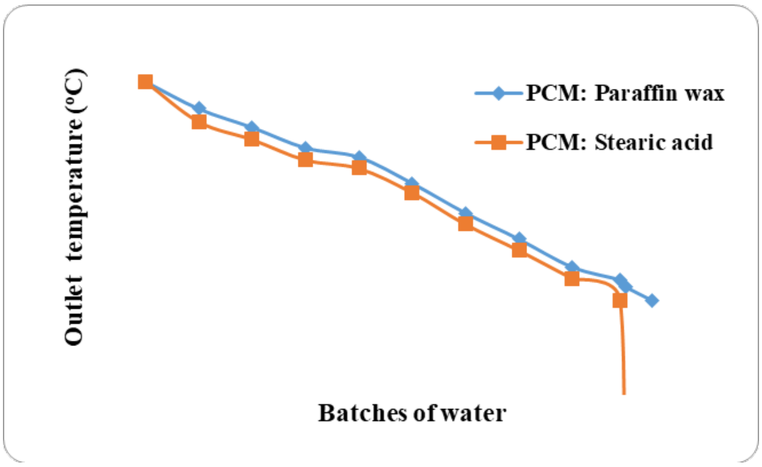

Figure 17 Batches of withdrawn water vs. Outlet temperature of water

Figure 17 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 l/min significantly reduces the total charging time from 145 minutes to 130 minutes and finally to 110 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 10.34% when increased from 2.0 to 4.0 l/min, and by 24.13% from 2.0 to 6.0 l/min. This efficiency boost makes higher flow rates advantageous, as they facilitate quicker thermal energy transfer to the 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, 95 minutes for 0.2%, 85 minutes for 0.5%, and 75 minutes for 0.8%. This trend underscores that higher concentrations of Al_2O_3 nanoparticles enhance heat transfer properties, reducing the time required to fully charge the TES system. 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 10.52% reduction in charging time when increasing from 0.2% to 0.5% and the 21.05% reduction when increasing from 0.2% to 0.8% demonstrate that higher nanoparticles concentrations facilitate better thermal conductivity and heat transfer.

When compared in relation with the existing HTF, water, there is significant rate of simplification in the charging period, in case of flow rate of 6 l/min and 0.8% volumetric based percentages of nanoparticles, around 31.81 % for Al_2O_3 nanofluid and 54.54% for MgO nanofluid.

The cumulative stored heat of 10,400 kJ at a PCM temperature of 70°C indicates a significant amount of energy storage achieved by the system. This value is critical for understanding the system's capacity to supply heat when needed; reflecting its efficiency in thermal energy storage applications.

The observed efficiency improvements of 10.81% for Al_2O_3 nanofluid and a remarkable 27.02% for MgO nanofluid at a 0.8% volume concentration compared to water as HTF highlight the significant benefits of using nanofluids. Nanofluid of MgO has given a remarkable state in melting time reduction due to higher thermal conductivity, Brownian motion, low density, agglomeration and micro convection.

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, indicates that paraffin wax has a higher thermal storage capacity in this application.

4.1 The present study limitation

In nanofluids, increasing the volume concentration of nanoparticles beyond 1% results in a decrease in the specific heat capacity of the heat transfer fluid (HTF). 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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