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Sustainable Futures with Paraffin Wax Balls: Advancements in Thermal Energy Storage

P. Shanmugavalli[1], R. Rajaraman[2]

Department of Mechanical Engineering, College of Engineering and Technology, SRM Institute of Science and Technology, Vadapalani Campus, No.1 Jawaharlal Nehru Road, Vadapalani, Chennai, Tamil Nadu, India

Abstract

The significance of Thermal Energy Storage (TES) systems in attaining environmentally friendly energy solutions, specifically for heating purposes, is becoming more widely acknowledged. This research paper introduces innovative developments in TES with Paraffin wax as a Phase Change Material (PCM) in a compact tank design. The study centers on the analysis of thermal stratification in a 280mmx280mm tank, with an assessment of the efficacy of PCM-enhanced TES in the charge and discharge procedures. Comparative studies were made between conventional TES systems and incorporating PCM via experimental analysis. The findings of these analyses unveil noteworthy enhancements in thermal performance and efficiency. Significantly, the TES system incorporating PCM demonstrates a noteworthy efficiency rating of 90.25%, emphasizing its feasibility for tangible implementations. In addition, a comprehensive analysis of the mechanisms that govern thermal stratification and heat transmission dynamics within the system is conducted, yielding significant findings that can be utilized to enhance the design of TES. The results emphasize the capacity of PCM-based TES systems to promote environmentally friendly heating methods, which has far-reaching consequences for various sectors including industrial operations and residential heating.

Keywords: Thermal Energy Storage, Paraffin wax, thermal stratification, Phase Change Material, Charging and discharging

1. Introduction

Thermal Energy Storage (TES) is crucial in modern societies for efficient energy management and promoting sustainability. Efficient storage solutions are essential for balancing energy supply and demand. TES devices play a crucial role in storing excess energy when demand is low[1,2]. This function not only improves the reliability of the energy system but also encourages the adoption of renewable resources. As a result, it leads to fewer greenhouse gas emissions and a smaller ecological impact [3,4]. Advanced methods were used to improve the performance of the TES system. These included implementing cutting-edge insulation materials to reduce heat loss during storage, optimizing ball distribution for maximum heat transfer, and integrating intelligent control algorithms for accurate temperature regulation and efficient energy management. These changes improved the system's energy storage capacity, efficiency, dependability, and cost-effectiveness [5]. Reverse identification methods were employed in mathematical models, with seven different cases, to determine the density, specific heat capacity, and thermal conductivity of the PCM (Phase Change Material). DE and LSHADE were identified as the two best-performing methods for determining the effective heat capacity of the PCM [6]. Paraffin wax, chosen for its low cost, stability, and absence of supercooling, was used as the PCM in this study. This suggests that future TES innovations could incorporate Paraffin wax balls.

Despite advancements in TES technology, there remains a lack of complete knowledge and optimization of TES systems that utilize Paraffin wax as a PCM. This is especially true for TES tanks with an Aspect Ratio(AR) of 1:1. The AR is a critical factor in determining the thermal efficiency of storage tanks as it establishes the correlation between their height and width. Yang (2021) found that different ARs can influence the rate of melting and propose appropriate tilted angles for achieving optimal performance. In a study conducted by Impact of aspect ratio on thermal layering in storage tanks can result in the formation of stratified cores. Park (2014) highlighted the significance of achieving a harmonious equilibrium between thermal efficiency and structural soundness in the process of choosing the aspect ratio(height to diameter ratio) of rock caverns employed for thermal storage. Studies by Kumar et al. and Izgi et al. showed the usage of certain PCMs increased the mixed number and Richardson number. Meanwhile, Afshan et al. experimented with HS89 as a PCM for TES tanks with aspect ratios of 1:1, 2:1, and 3:1, and found that a 1:1 TES tank with 24 balls achieved a maximum temperature difference of 16.68˚C. However, there is a lack of comprehensive research on the thermal conductivity, phase change behavior, and long-term stability of Paraffin wax in spherical balls in TES devices. Our goal is to enhance Paraffin wax ball

TES systems' functionality, efficacy, and ecological sustainability by addressing these gaps. Therefore, we conducted experiments using 24 balls in a 1:1 AR TES tank to optimize hot water output. The following section details about methodology, results discussion, and conclusion.

2. Methodology

This section explains the experimental setup, procedure, data collection and analysis, and applications. Fig 1 shows the setup made for the experiment.

2.1 Experimental Setup:

Employed components include a Data Acquisition System (NI9213) for temperature indication, an insulated TES tank (40mm glass wool), a circulating hot water bath, a solar heat-replicating heater – 2nos (1.5kW immersion), and an HTF (Heat Transfer Fluid) loop (refer to Fig.1).

The TES tank has an aspect ratio (AR) of 330mm in diameter and 320mm in height, containing Paraffin wax loaded in stainless steel balls (75mm diameter, 2mm thick) designed for precise measurement and energy transfer. J - Thermocouples in the tank monitor temperature, pressure, and energy flow during charging and discharging. A 0.80 kW centrifugal pump circulates water, and PCM balls

are arranged in three layers with eight balls in each layer in stacked positions.

2.2 Experimental Procedures:

Two sets of experiments were conducted: charging and discharging processes with and without PCM balls. Fig 2(s) shows without PCM balls in the TES tank and Fig 2(b) shows with PCM balls in the TES tank.

In the charging process without PCM balls, water is pumped from the main storage tank through a centrifugal pump to the hot water bath, heated by immersion heaters (1.5 kW each) mimicking solar heat. The water flow rate is maintained at 2.5 liters/minute, with temperatures monitored using thermocouples.

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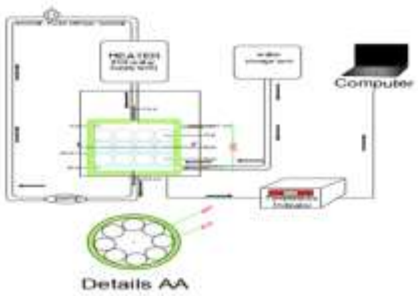


(i) In the charging process without PCM balls, water is pumped from the main storage tank through a centrifugal pump to the hot water bath, heated by immersion heaters (1.5 kW each) mimicking solar heat. The water flow rate is maintained at 2.5 liters/minute, with temperatures monitored using thermocouples.

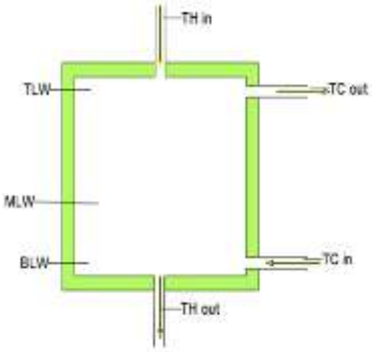


Fig 1 Experimental set-up

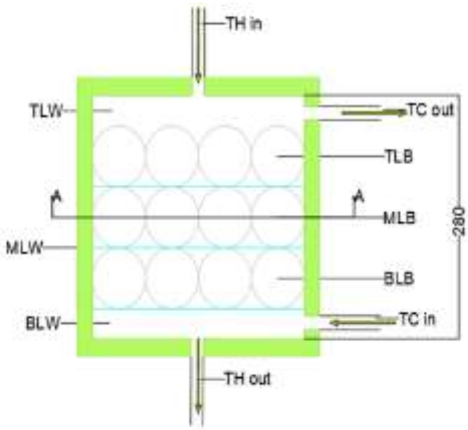


Fig 2(a) TES tank without PCM

Fig 2(b) TES tank with PCM

In the discharging process without PCM balls, hot water inlet and outlet valves are closed, and cold water is circulated from the bottom of the tank, with temperature and time measured at the cold water outlet.

(ii) In the charging process with PCM balls, the water flow rate is maintained at 2.5liter/50 sec having a minimum temperature of 24˚C stored, and the heater in the hot water bath raises the TES tank temperature until the PCM melts above 69˚C, absorbing heat. Heating is stopped at 97˚C, with temperatures monitored at various points.

In the discharging process with PCM balls, cold water is circulated to extract thermal energy from PCM balls, with temperatures measured at inlet and outlet points.

2.4 Data Collection and Analysis:

Measurements include hot water inlet and outlet temperatures, PCM ball temperatures in layers, and water temperatures in layers during both the charging and discharging processes.

The study assesses the TES tank's effectiveness with and without PCM, calculating the discharge duration for hot water.

2.5 Application:

The hot water generated is intended for various purposes `to meet peak energy demand and to evaluate the thermal energy storage tank's performance for practical applications.

3. Discussion of results

This section explains the properties of the selected PCM and the charging and discharging process with and without PCM balls. Table 1 shows the properties of PCM (Paraffin wax)

Table 1 Properties of PCM (Paraffin wax)

Characteristics	Value
Heat of melting temperature, T_m(ºC)	69 -74.4
Temperature of Solidification, (ºC)	49 - 40
Thermal Conductivity, k(W/mºC)	0.23
Specific heat capacity, C_p(kJ/kgºC) (Solid)	2.16
Specific heat capacity, C_p(kJ/kgºC) (Liquid)	2.16
Thermal diffusivity, D(mm^2/s)	0.113
Density liquid, ρ (kg/m^3)	743

Fig 3(a) illustrates the charging process in the absence of PCM balls. It is displayed for 200 minutes. At the onset, the water has a minimum temperature of 22ºC. With the heater turned on, the temperature rises to 44ºC during the first 10 minutes. As time progresses, the water in the intermediate layer (MLW) and the hot water outlet (THout) also increases. After 200 minutes, the temperature reaches 96ºC, indicating the completion of the charging process.
The 200-minute discharge process is shown in Fig 3(b). The hot water exit has a maximum temperature of 84°C for the first 10 minutes. As time goes on, the temperature drops. There is 30°C in the air after 70 minutes.

Fig. 4(a) illustrates the PCM ball charge procedure. The initial temperature of the hot water input is 26°C. The temperature and discharge of hot water in the middle layer both increase in tandem with the duration of hot water input. After 230 minutes, the temperature rises to 98 degrees Celsius. The PCM begins to temperature meet at 69°C and accumulates heat throughout the charging process.

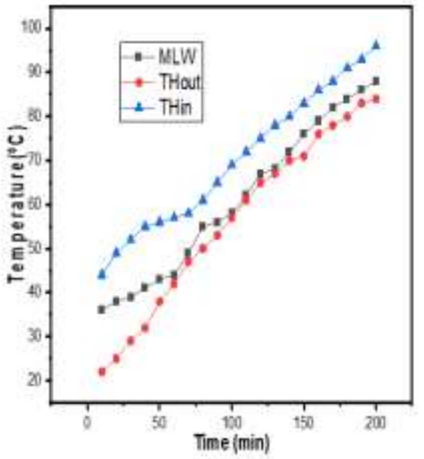


Fig 3(a) Without PCM charging process

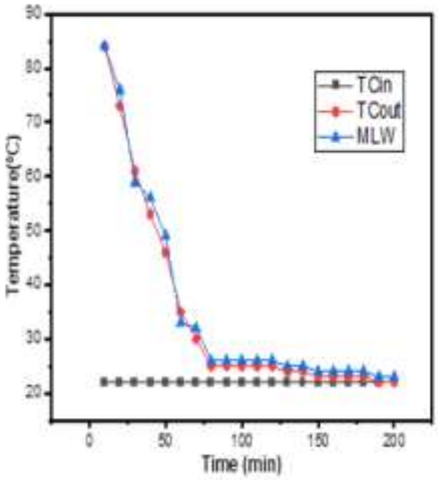
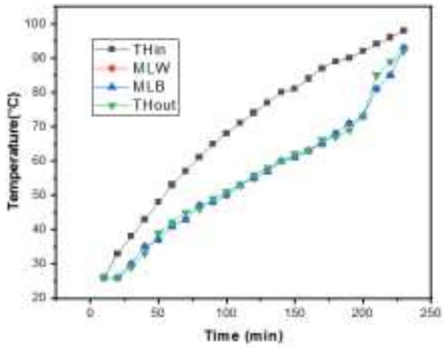
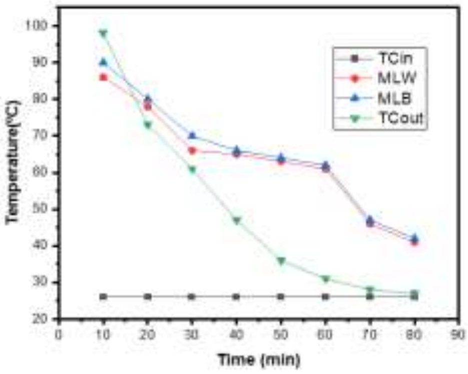


Fig 3(b) Without PCM discharging



|Fig 4(a) Charging process with PCM balls



|Fig 4(b) Discharging process with PCM balls

Fig. 4(b) shows how the PCM balls empty out. As the cold water comes in, the PCM lets go of the heat it has been holding on to and the hot water comes out. At the start, the cold water temperature is the highest at 92°C, and at the end of 80 minutes, it drops to its lowest at 27°C. This shows that PCM can be used to get the most hot water out.

Table 2 PCM Performance metrics

Metrics	**Result**
Specific heat of water, Cp, kJ/kg⁰C	4.186
PCM mass for 24 balls,m_p,kg	3.3
PCM specific heat, C_p, kJ/kg⁰C	2.16
Hot water mass,m_w, kg/litre	500
Charging	
PCM lowest temperature,⁰C, $P_{c,low}$	26
PCM highest temperature,⁰C, $P_{c,high}$	98
Discharging	
PCM lowest temperature,⁰C, $P_{d,low}$	27
PCM highest temperature,⁰C, $P_{d,high}$	92
PCM heat absorption,Q_{abs} kJ	513.21
PCM heat released,Q_{rel} kJ	463.22
Efficiency of PCM in TES tank,η %	90.25

3.1 PCM heat absorption during charging(Q_{abs})

The Eq.1 provides the detail for the PCM heat absorption on the charging process

$Q_{abs} = mp* Cp.(P_{c,high} - P_{c,low})$---(1)

Where

mp= PCM mass, kg

cpcm(avg) = PCM specific heat, kJ/kg⁰C

$P_{c,high}$ = PCM highest temperature on the charging,⁰C

$P_{c,low}$ = PCM lowest temperature on the charging,⁰C

3.2 PCM heat release during discharging(Q_{rel})

The Eq.2 provides the detail for the PCM heat release on the discharging

$Q_{rel} = mp* Cp.(P_{d,high} - P_{d,low})$----(2)

Where

mp= PCM mass, kg

Cp = PCM specific heat, kJ/kg⁰C

$P_{d,high}$ = PCM highest temperature on the discharging,⁰C

$P_{d,low}$ = PCM lowest temperature on the discharging,⁰C

3.3 Efficiency of PCM in TES tank,(η)

The efficiency of PCM in TES tank is the ratio between heat released by the PCM to the heat absorbed by the PCM.

$$\text{Efficiency}, \eta = \frac{\textit{Heat released by the PCM},(\text{Qrel})}{\textit{Heat absorbed by the PCM},(\text{Qabs})}$$

---(3)

Conclusion

As demonstrated by the substantial improvement in both the charging and discharging procedures, the implementation of PCM (Phase Change Material) balls within thermal energy storage (TES) containers has been remarkably successful. During the charging phase, the expeditious heat absorption property of PCM facilitated a rapid increase in water temperature to 96°C in just 200 minutes. Conversely, during discharging, the effective dissipation of heat ensured the continued availability of usable hot water levels. The exceptional 90.25% efficiency of PCM in the TES tank demonstrates its capability of accumulating and liberating thermal energy. Anticipating future developments, potential areas of concentration may include the optimization of PCM composition to increase storage capacity, investigation of advanced encapsulation techniques to enhance durability, and integration of predictive modeling to optimize systems. These developments hold the potential to fundamentally transform sustainable heating and cooling solutions in numerous industries, thereby promoting energy conservation and environmental friendliness.

References

1.Eze, V. H. U., Robert, O., Sarah, N. I., Tamball, J. S., Uzoma, O. F., & Wisdom, O. O. (2024). Transformative Potential of Thermal Storage Applications in Advancing Energy Efficiency and Sustainability. IDOSR JOURNAL OF APPLIED SCIENCES, 9(1), 51-64. https://doi.org/10.59298/IDOSRJAS/2024/1.8.9.295

2.Junaid, M. F., ur Rehman, Z., Ijaz, N., Farooq, R., Khalid, U., & Ijaz, Z. (2024). Performance evaluation of cement-based composites containing phase change materials from energy management and construction standpoints. Construction and Building Materials, 416, 135108. https://doi.org/10.1016/j.conbuildmat.2024.135108.

3.Jayathunga, D. S., Karunathilake, H. P., Narayana, M., & Witharana, S. (2024). Phase change material (PCM) candidates for latent heat thermal energy storage (LHTES) in concentrated solar power (CSP) based thermal applications-A review. Renewable and Sustainable Energy Reviews, 189, 113904.https://doi.org/10.1016/j.rser.2023.113904

4.Umate, T. B., & Sawarkar, P. D. (2024). A review on thermal energy storage using phase change materials for refrigerated trucks: Active and passive approaches. Journal of Energy Storage, 75, 109704.https://doi.org/10.1016/j.est.2023.109704

5.Laasri, I. A., Es-Sakali, N., Outzourhit, A., & Mghazli, M. O. (2024). Evaluation of phase change materials for a light-weight building in Morocco: Effect of building's volume, window orientation & infiltration. Energy and Built Environment, 5(6), 863-877. https://doi.org/10.1016/j.enbenv.2023.06.013

6.Kůdela, J., Zálešák, M., Charvát, P., Klimeš, L., & Mauder, T. (2024). Assessment of the performance of metaheuristic methods used for the inverse identification of effective heat capacity of phase change materials. Expert Systems with Applications, 238, 122373.https://doi.org/10.1016/j.eswa.2023.122373

7.Yang, X., Wang, X., Liu, Z., Guo, Z., & Hooman, K. (2021). Thermal performance assessment of a thermal energy storage tank: effect of aspect ratio and tilted angle. International Journal of Energy Research, 45(7), 11157-11178. https://doi.org/10.1002/er.6598

8.Park, D., Park, E. S., & Sunwoo, C. (2014). Heat transfer and mechanical stability analyses to determine the aspect ratio of rock caverns for thermal energy storage. Solar energy, 107, 171-181. https://doi.org/10.1016/j.solener.2014.06.008

9.Probert, D. (1975). Design and performance of hot-oil storage tanks. Applied Energy, 1(4), 247-278. https://doi.org/10.1016/0306-2619(75)90028-8

10.P.M. Kumar and K. Mylsamy. 2019. Experimental investigation of solar water heater integrated with a nanocomposite phase change material: Energetic and exergetic approach, J. Thermal Anal. & Calorimetry, 136, 121-132. https://doi.org/10.1007/s10973-018-7937-9

11.B. Izgi and M. Arslan. 2022. Effect of phase change material on thermal stratification of solar hot water tank with a mantle: A numerical analysis, J. Energy Storage, 52, 105078. https://doi.org/10.1016/j.est.2022.105078.

12.M.E. Afshan, A.S. Selvakumar, R. Velraj and R. Rajaraman. 2020. Effect of aspect ratio and dispersed PCM balls on the charging performance of a latent heat thermal storage unit for solar thermal applications, Renewable Energy, 148, 876-888. https://doi.org/10.1016/j.renene.2019.10.172.