International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 02 Issue: 02 February 2024
Page No: 142 - 145
https://irjaeh.com

Enhancing Solar Thermal Efficiency: PCM Integration for Compact Energy Storage Systems

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Abstract

The optimal utilization of solar energy presents a challenge in meeting round-the-clock hot water demands while accommodating limited space in modern architectural designs. Solar collectors, operating solely during daylight hours and weather-dependent, necessitate efficient energy storage to meet evening and morning peak hot water consumption in households. Current architectural trends, marked by smaller boiler rooms, further compound the challenge of integrating conventional solar tanks, emphasizing the critical need for compact energy storage solutions. Addressing this challenge, this paper proposes a ground-breaking solution: a solar tank infused with phase change material (PCM). This innovative tank design not only boasts smaller dimensions but also significantly higher heat capacity compared to conventional counterparts. Crucially, the PCM solar tank enables solar collectors to operate at lower temperatures, potentially elevating the overall efficiency of the solar collector system. The proposed storage system comprises two synergistic heat-absorbing units: a solar water heater and a PCM-based heat storage unit. While the solar water heater fulfills the daytime hot water supply, the PCM storage unit accumulates and retains heat throughout the day, ensuring continuous hot water availability during night hours and overcast periods. Leveraging small cylinders filled with paraffin, serving as the PCM, integrated with solar collectors maximizes solar energy absorption and storage. This paper meticulously compares the performance of the PCM-based thermal energy storage system with conventional sensible heat storage systems, presenting insightful conclusions derived from the comparative analysis. The findings underscore the remarkable efficiency and efficacy of the PCM-based solution in meeting the challenges posed by solar energy intermittency and limited space constraints, offering a promising avenue for sustainable and efficient solar energy utilization in residential settings.

Keywords: *Thermal Energy, Solar water heater, Phase change material (PCM), Weather dependency.*

1. Introduction

In an era where global energy demands escalate alongside the exponential growth of population, the vitality of accessible and sustainable energy sources cannot be overstated. India, in particular, has experienced a remarkable surge in energy demand, growing steadily over the past three decades due to its rapid economic expansion. This burgeoning need for energy has instigated a critical necessity to explore alternative and renewable sources. Among the array of renewable options, solar energy emerges as a prominent candidate. Recognized for its simplicity, cleanliness, and inexhaustible nature, solar power has garnered substantial attention. However, its intermittent nature necessitates effective storage solutions for optimal utilization.

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Addressing this need, Phase Change Materials (PCMs) stand out as a viable technique for storing thermal energy through latent heat. PCM, predominantly inorganic compounds like hydrated salts, possesses the unique ability to absorb or release significant heat energy during state changes, sustaining its latent heat across numerous cycles without altering its properties. In the context of solar water heating, PCM plays a pivotal role in storing energy by melting at consistent temperatures, ensuring efficient utilization during usage cycles. The selection of appropriate PCM hinges on several critical factors, notably its melting point, latent heat capacity, and safety considerations. Balancing these aspects with application-specific temperature requirements is paramount, especially in residential, commercial, and industrial domains, each with distinct thermal demands. While inorganic compounds boast high latent heat capacities, they are susceptible to undercooling, potentially hindering effective phase changes. Conversely, organic compounds, excluding paraffin, tend to be expensive or pose toxicity concerns. Paraffin, despite its flammability, emerges as a pragmatic choice due to its favorable physical and chemical properties, affordability, and compatibility within water-based systems. Furthermore, commercially available specific temperature PCMs, particularly various paraffin types, provide versatile options for diverse applications. In essence, this paper explores the multifaceted landscape of PCM utilization, highlighting their pivotal role in enhancing the efficacy of solar energy utilization, particularly in the context of water heating applications.

Table 1 Physical Properties of Paraffin 5838

Melting point	58-62 degrees Celsius.
Latent heat of Fusion	Typically around 200 J/g.
Viscosity	1.9 mm^2/s
Density	0.9 to 0.94 g/cm^3.
Specific heat capacity-solid	Approximately 2.0-2.5 J/g°C.
Specific heat capacity- liquid	
Thermal Conductivity	Ranges from 0.2 to 0.3 W/m°C.

2. Literature Review

The integration of phase change materials (PCMs) within solar water heating systems has been the subject of extensive research over the years [1]. Studies on PCM utilization within thermal energy storage units have explored various methodologies to intensify heat transfer, showcasing promising advancements [2]. Evaluations of solar collector designs featuring integrated latent heat thermal energy storage have underscored the potential for enhancing system efficiency [3]. A comprehensive review of thermal energy storage utilizing phase change materials emphasizes their versatile applications and their role in enhancing energy sustainability [4]. Investigations into the thermal performance of water-phase change material solar collectors have highlighted their efficacy in harnessing solar energy [5]. Review articles have extensively covered the materials, heat transfer analyses, and practical applications related to thermal energy storage with phase change [6]. Research on integrated solar collector/storage units employing phase change materials at a specific temperature of 65°C has elucidated their thermal behavior and operational efficiencies [7]. Additionally, experimental studies on prototypes equipped with latent heat storage have provided valuable insights into system performance [8, 9]. The cumulative body of research in this domain converges on the potential and efficacy of phase change materials in augmenting solar water heating systems, emphasizing their pivotal role in advancing sustainable energy solutions. Physical Properties of Paraffin 5838 are shown in Table 1.

3. Methodology and Experimental Setup

Figure 1 illustrates the configuration of the experimental setup utilized in this study. The Thermal Energy Storage (TES) tank, possessing a capacity of 48 liters, was designed to meet the hot water demands of a standard family comprising four individuals. The tank incorporates two plenum chambers located at its top and bottom, complemented by a flow distributor at the tank's apex to ensure a homogeneous flow distribution. To meet the daily requirement of approximately 60 liters of heated water for household use, the energy is stored within the TES tank as a composite of sensible and latent heat of Phase Change Material (PCM), alongside the sensible heat of water. For the sake of this study, it is assumed that two-thirds of the total energy is stored within the PCM, with the remaining third retained as sensible heat within the water. For comparative purposes, an identical TES tank without PCM shells is employed in the PCM-less

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system variant.

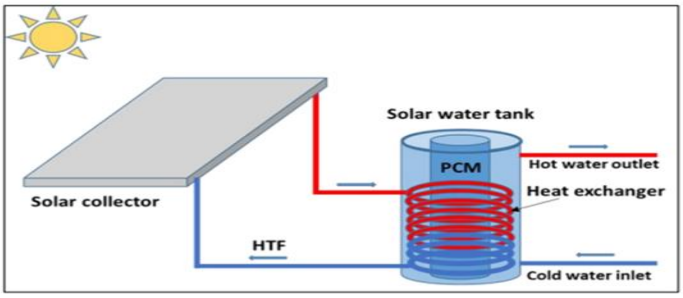

Figure 1 The Diagram of the SWH–PCM System

4. Results and Discussion

The comparison between systems with and without Phase Change Material (PCM) revealed distinct thermal energy storage mechanisms. In the PCM-absent system, the water alone acquires and stores solar energy, while in the PCM-equipped system, both water and PCM absorb and retain energy, resulting in PCM melting above its specified melting point. Figure 2 shows the comparison of cumulative heat in both systems.

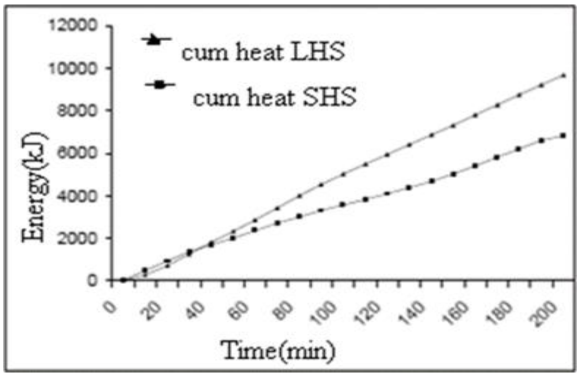

Figure 2 Comparison of Cumulative Heat in Both the System

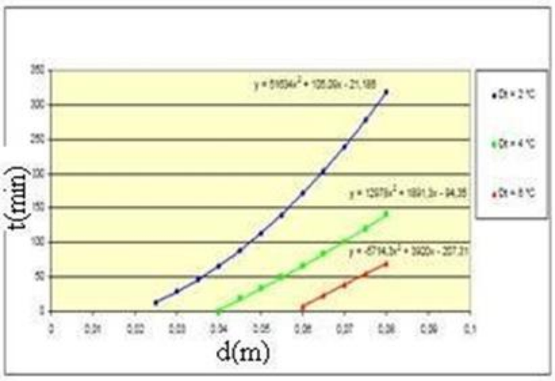

Figure 3 Solidifying Time in Function of Time and Temperature Difference

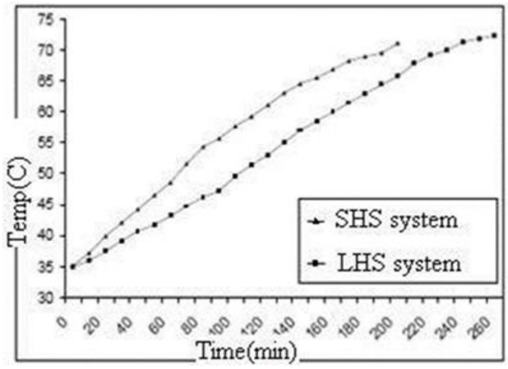

Figure 4 Temperature Histories of Both Systems during Charging

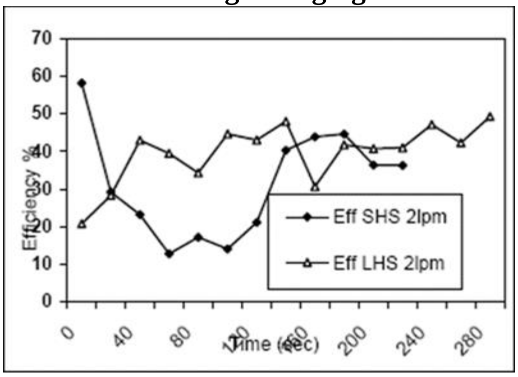

Figure 5 Comparison of System Efficiency

4.1 Comparison of Heat Energy Storage

The comparison between systems utilizing and not utilizing Phase Change Material (PCM) demonstrates significant variations in heat storage efficiency. The system incorporating PCM surpasses the PCM-lacking system of identical size and tank volume. Calculations reveal a heat storage of 0.234 kJ/cc for the PCM system and 0.144 kJ/cc for the PCM-less system, indicating a substantial decrease in necessary storage volumes for equivalent heat storage in the PCM-equipped system. Solidifying Time in Function of Time and Temperature Difference are shown in Figure 3.

4.2 Solidification Time of PCM

Understanding the solidification time of PCM is crucial for ensuring sustained hot water availability in the absence of solar energy. Experimental findings report a solidification time of 172 minutes with a 2°C temperature difference between the phase change temperature and the outer wall of a tube with a diameter of 60mm and 1mm wall thickness. A reduced solidification time of 66 minutes was noted with a similar temperature difference in a tube with a 40mm diameter and 1mm wall thickness. Temperature Histories of Both Systems during Charging shown in Figure 4.

4.3 Tube Diameter and PCM Solidification

The impact of tube diameter on PCM solidification time is evident; smaller diameters necessitate more tubes for the same PCM quantity. While smaller diameters facilitate quicker specific heat exchange and solidification, they decrease the tank's overall heat capacity due to increased tube material volume.

4.4 Charging Dynamics and System Efficiency

During charging, the PCM-equipped system redistributes solar energy to both water and PCM, contrasting the PCM-less system, which solely relies on water for energy absorption. Notably, the PCM-less system reaches a maximum temperature of 70°C 40 minutes earlier than the PCM system, with an average charging time of 30-60 minutes faster. Figure 5 shows a Comparison of System Efficiency.

4.5 System Efficiency Comparison

System efficiency analysis indicates that the PCM-less system exhibits fluctuating efficiency levels over time, whereas the PCM-equipped system maintains consistent efficiency across phase transition temperatures, displaying higher and more consistent efficiency levels. Consequently, the system employing PCM demonstrates enhanced efficiency in solar thermal storage applications.

5. Conclusion

This study delved into the thermal behavior of systems incorporating Phase Change Material (PCM) under varied operating conditions. The investigation encompassed charging times, energy storage capacities, PCM solidification duration, and system efficiencies, facilitating a comprehensive comparison between both systems. The findings underscore the economic and spatial advantages of PCM-based tanks over conventional counterparts of equal heat capacity. Notably, PCM tanks exhibit lower manufacturing costs and reduced spatial demands, offering a more cost-effective and space-efficient solution for thermal energy storage. Furthermore, PCM tanks demonstrate the remarkable advantage of maintaining a consistent temperature profile during heat accumulation. This attribute, governed by the specific PCM type, enables flexible temperature settings conducive to higher solar collector efficiency, particularly in colder external environments. Conclusively, systems integrating PCM emerge as a highly viable option for solar heat energy storage. Their distinct advantages, including cost-effectiveness, space efficiency, and temperature control benefits, position them as promising alternatives to prevailing domestic solar water heating technologies reliant solely on sensible heat storage. Embracing PCM-based systems signifies a tangible stride toward more efficient and sustainable solar thermal energy utilization in domestic settings.

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