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Research Article

"Thermal Analysis of Phase Change Materials used in solar Evacuated Glass Tube Collector"

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ABSTRACT

Phase Change Materials (PCMs) are widely used in thermal energy storage systems due to their high latent heat capacity. This research paper focuses on the thermal analysis of paraffin wax, a commonly used PCM, when encapsulated in two different containers—plastic and copper bottles. The study aims to compare the thermal conductivity, heat absorption, and dissipation characteristics of both setups under controlled conditions. By monitoring temperature variation over time, the efficiency of each container in enhancing the PCM& performance is evaluated. Results indicate that the material of the container significantly impacts the rate of heat transfer, with copper demonstrating superior thermal responsiveness. This analysis contributes to the optimization of PCM-based systems in real-world thermal applications.

Keywords: Phase Change Material (PCM), Paraffin Wax, Thermal Analysis, Copper Bottle, Plastic Bottle, Heat Transfer, Thermal Conductivity, Energy Storage.

INTRODUCTION

Thermal energy storage systems play a pivotal role in enhancing energy efficiency and sustainability in various engineering applications. Among the available techniques, latent heat thermal energy storage (LHTES) using Phase Change Materials (PCMs) has garnered significant attention due to its ability to absorb and release large amounts of heat during the phase transition process. Paraffin wax is one of the most commonly used PCMs because of its favorable thermal properties, chemical stability, non-corrosiveness, and cost-effectiveness.

The performance of a PCM is not solely determined by the material itself but also by the characteristics of its container. The container material can significantly influence the rate of heat transfer to and from the PCM, which in turn affects the efficiency and speed of the energy storage and release processes. This study is aimed at investigating and comparing the thermal behavior of paraffin wax encapsulated in two different types of containers: a plastic bottle and a copper bottle. Copper, being a metal with high thermal conductivity, is expected to facilitate faster heat transfer, whereas plastic, a poor conductor of heat, may exhibit slower thermal response. By placing equal quantities of paraffin wax in each bottle and subjecting them to the same thermal conditions, the experiment seeks to observe and analyze differences in melting and solidification behavior, temperature distribution, and heat transfer rates.

The methodology involves heating both bottles simultaneously and recording temperature changes at specific time intervals using thermo-couples. The cooling phase is also monitored to evaluate the overall thermal performance of the containers during the charging and discharging cycles of the PCM. This comparative analysis is crucial for practical applications where container selection influences the effectiveness of thermal management systems—such as in solar energy storage,

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building insulation, electronics cooling, and temperature regulation in food and medical transport. By understanding the impact of container material on PCM performance, this research aims to guide material selection and design improvements in PCM-based thermal systems.

LITERATURE SURVEY

Ahmet Sarı (2003): Investigated a eutectic mixture of myristic and palmitic acid for solar thermal storage in Turkey; results showed effective melting/solidification but called for further integration studies. Vikram D (2006): Demonstrated the feasibility of using paraffin-based LHTES for providing nighttime hot water using solar energy, with successful performance in small-scale systems. Luisa F. Cabeza (2006): Explored PCM modules in hot-water tanks, showing improved energy density and prolonged heat retention, suitable for domestic solar systems. Atul Sharma (2009): Reviewed PCM applications in various solar and thermal systems, emphasizing their high energy density and isothermal characteristics for diverse energy uses.

Anant Shukla (2009): Highlighted improved thermal performance in solar water heaters with PCMs, noting the need for commercially viable, integrated thermal storage designs. Muhsin Mazman (2009): Showed that PCM modules in SDHW tanks enhance thermal performance and recovery efficiency, particularly with PS-based PCMs. Al-Hinti (2010): Found that integrating paraffin PCM in solar water heaters improves heat retention and operational efficiency over extended periods, even under varying usage. B.K. Gond (2012): Demonstrated that modified flat-plate solar heaters with PCM maintain usable temperatures until late evening, enhancing system reliability. Abdul Jabbar N. Khalifa (2013): Validated that PCM-enhanced collectors prolong water heating post-sunset and maintain steady efficiency across seasons.
Abhay B. Lingayat (2013): Reviewed the energy-saving potential of PCMs in buildings and thermal systems, emphasizing the need for optimization and future expansion. Dan Nchelatebe Nkwetta (2013): Reviewed PCM integration in TES systems, identifying performance benefits and practical challenges like cost and design complexity. Mohammad Ali Fazilati (2013): Achieved increased energy storage and hot water duration using PCM in spherical capsules, improving system performance. Camila Barreneche (2014): Developed a PCM database to standardize material selection for TES applications, addressing data inconsistencies and enhancing selection tools. M.H. Mahfuz (2014): Analyzed a shell-and-tube TES system, finding a trade-off between energy and exergy efficiencies with varying flow rates and reduced life-cycle costs.Monia Chaabane (2014): Used numerical modeling to show PCMs reduce night-time losses and improve efficiency in integrated collector storage solar water heaters.

1.1 **PCM's –latent heat storage materials:**

PCM absorbs and deliver heat at a nearly constant temperature.[4],[10],[11] They store 5–13 times more heat per unit volume than sensible storage materials [4], [13]such as water, masonry, or rock.

$$Q = M \times LH \quad (1)$$

Q is the amount of thermal energy stored or released in form of latent heat (KJ), M is the mass of material used to store the thermal energy (kg), and LH is the latent heat of fusion or vaporization (KJ/Kg).
It's clear from equation that the amount of thermal energy store as latent heat depend on the mass & the value of latent heat of used material. Material used to store the thermal energy in the form of latent heat are called phase change material.[4], [31]

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EXPERIMENTAL SETUP:

Experimental setup consist of Evacuated glass tube collector containing eleven number of tubes, completely insulated hot water tank, Insulated thermal energy storage tank, cold water tank, reflector, Insulating box etc. Here TES tank utilize to increase the performance of the system with the help of paraffin wax used as a phase change material[5], [6], [26] for storing large amount of latent heat during its fusion. Here TES tank & Hot water tank are connected in such way that, they are utilizing in both way separately or together.

A schematic diagram of the experimental setup is shown in Fig. 1. The setup is essentially similar to conventional, commercially available, solar water heating systems with a few differences. It consists of eleven evacuated tubes with an area of 860 mm X 1560 mm, with a tilt angle of 30 ^{o}. The collectors which have black painted reflector plates placed at back of the evacuated tubes. The galvanized steel storage tank is cylindrical in shape having a length of 750 mm, an inner diameter of 500 mm and a volume of 140 lit. It is insulated with 25-mm thick layer of glass wool insulation.

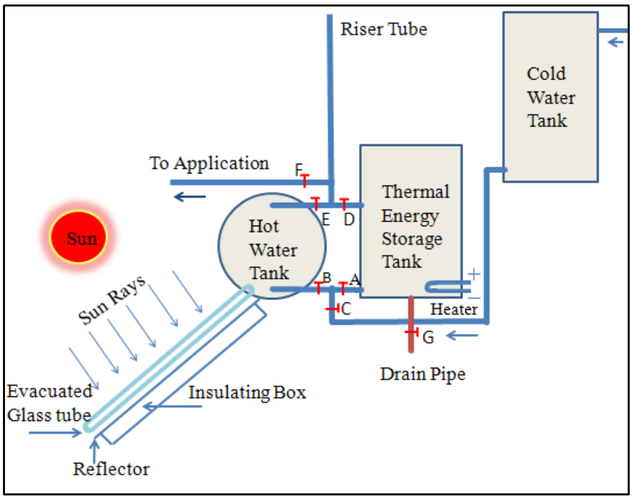

Fig. 1 Experimental setup

When the valve A & D closed normal circuit run without thermal energy storage tank, similarly when the valve E & B closed the circuit run without solar water heating system, when valve A B C D open then heat transfer from hot water tank to TES tank through natural convection, near about same temperature obtain in both the tank.

Fig. 2 Actual Experimental Setup

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Figure 2 shows the actual experimental setup consist of TES tank coupled with hot water tank , through natural convection heat transfer from HWT to TES tank.

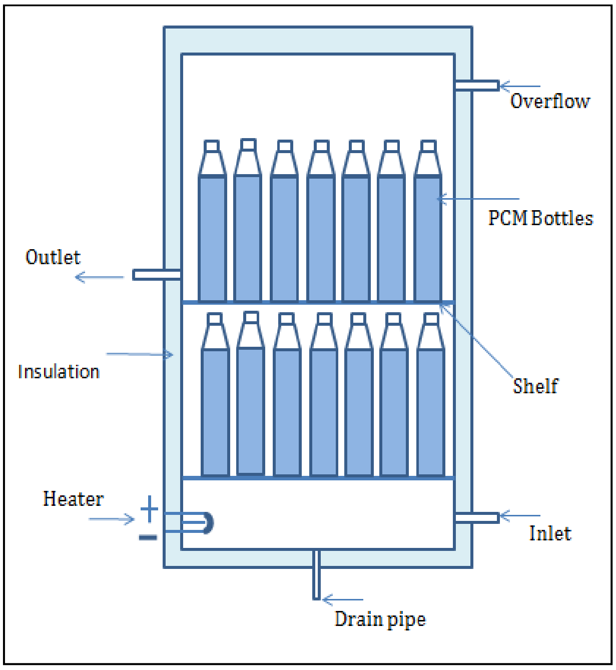

Fig. 3 Geometry of TES Tank

Fig. 3 shows a detailed cross-sectional view of the storage tank. The tank contains a total of 40 thin walled, cylindrical, polypropylene (plastic) containers. Each container has a volume of 1.0 lit, and contains 0.95 kg of paraffin wax which was used in this investigation as the PCM. The thermos-physical properties of the paraffin wax are given in Table 1.

Sr. No.	Property name	Values
1	Melting point	58-60 ^oC
2	Latent heat of fusion	190 KJ/Kg K
3	Density (Solid Phase)	820 Kg/m^3
4	Density (Liquid Phase)	780 Kg/m^3
5	Specific Heat	2.4 KJ/Kg K
6	Thermal Conductivity	0.24 w/mk

Table 1. Thermo-physical properties of the paraffin wax.

The PCM containers are arranged in the tank on two levels, each containing 20 containers, with the aid of two perforated sheet metal separators. The choice of these containers was meant to reach a relatively large heat transfer surface area in comparison with the volume of the PCM [3], [14], and to minimize the thermal resistance between water and the PCM. The total volume of the PCM containers is 40 lit, with water occupying the remaining 100 lit, in the storage tank. The bottom

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section of the storage tank also contains an auxiliary 1.5 kW electrical heater, in order to enable controlled conditions investigations.[14], [27]

THERMAL ANALYSIS OF SYSTEM

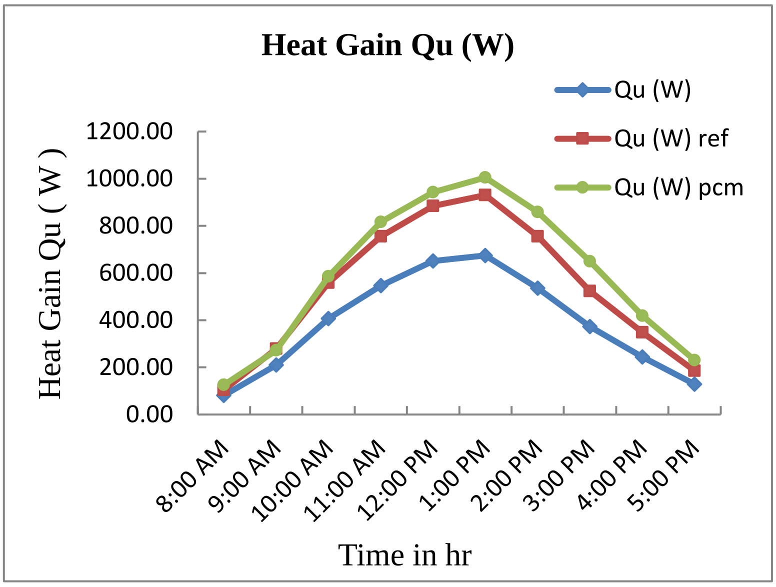

Fig. 4 Heat gain comparasion (Plastic Bottels)

Hourly Efficiency (Plastic Bottles) – Comparison of Cases 1, 2, and 3: The fourth graph compares the hourly efficiencies of all three cases—Case 1, Case 2, and Case 3—on a single plot. Case 3 consistently outperforms the other two, especially during peak solar hours. Case 2 remains in the middle range, while Case 1 has the lowest performance throughout the day. This comparison clearly shows the incremental benefits gained by each design improvement, with Case 3 offering the highest efficiency.

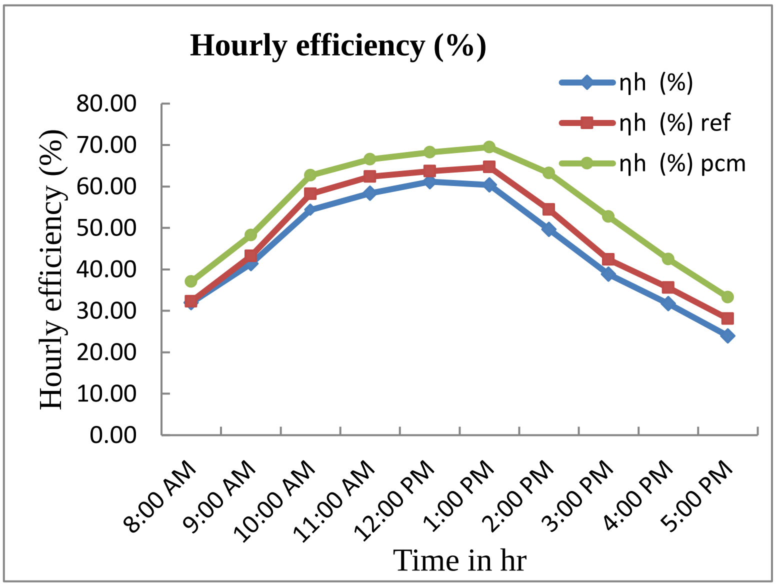

Fig. 5 Hourly Efficiency Comparasion (Plastic Bottels)

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The graph titled Hourly Efficiency presents a comparative analysis of the hourly performance of three different cases: ηh , ηh ref, and ηh pcm, over the course of a typical day from 8:00 AM to 5:00 PM. The results indicate that the case with phase change material consistently exhibits the highest efficiency throughout the day, particularly during peak solar hours between 10:00 AM and 2:00 PM. The reference case ηh ref shows moderate performance, while the base case (ηh) records the lowest efficiency at all observed times. All three cases follow a similar trend, with efficiency gradually increasing during the morning, reaching a peak around midday, and then declining in the late afternoon. This comparison clearly demonstrates the positive impact of incorporating phase change materials [6], [19], [21], [30], which enhance thermal storage capacity and improve the system's overall efficiency.

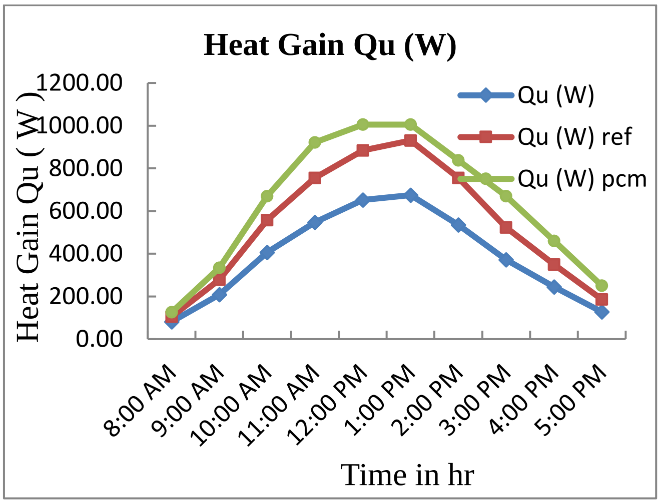

Fig. 6 Heat gain comparasion (Copper Bottels)

This graph displays the hourly heat gain (Q_a) for the same three systems. The PCM system again exhibits the highest heat gain values, peaking around 1:00 PM at nearly 1100 W. The heat gain increases steadily from morning to early afternoon and then drops off, matching the sun's intensity cycle. The PCM system's higher heat absorption highlights its effectiveness in storing and managing thermal energy compared to the base and reference systems.

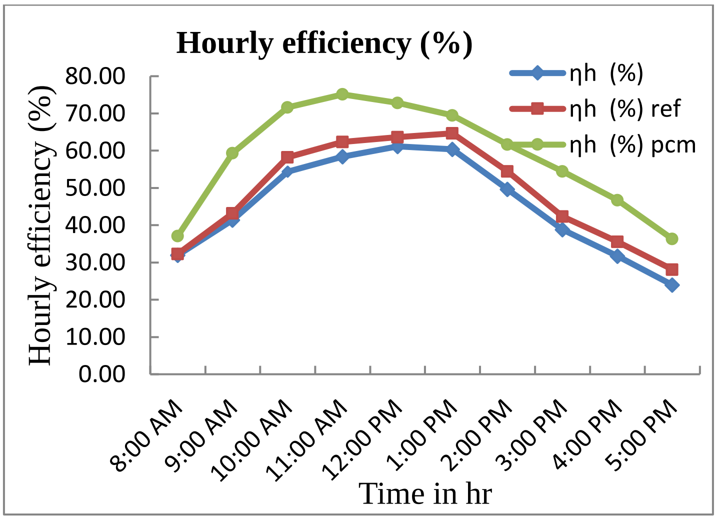

Fig. 7 Hourly Efficiency Comparasion (Copper Bottels)

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This graph illustrates the hourly thermal efficiency of three systems: a base system (ηh), a reference system (ηh ref), and a PCM-enhanced system (ηh pcm). The PCM (Phase Change Material) system consistently shows higher efficiency throughout the day, peaking around noon (12:00 PM) at approximately 75%, indicating its superior thermal performance. All systems show a similar trend of increasing efficiency in the morning, reaching a peak at midday, and then gradually decreasing in the afternoon.

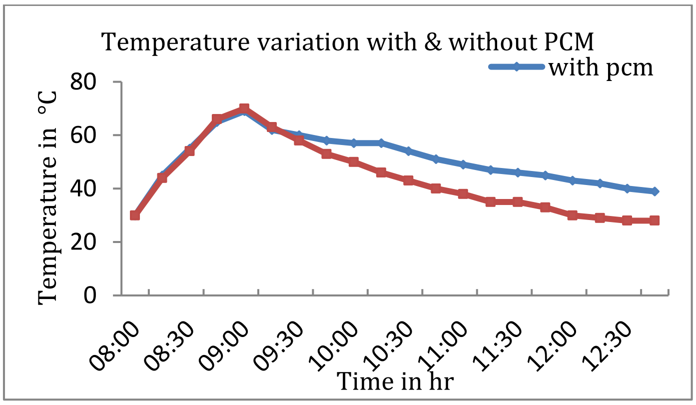

Fig. 8 Variation of Temperature with & without PCM

Fig. 8 shows the time variation of the water temperatures at the tank midpoint section with the existence of the PCM and without it. It can be seen that although the maximum water temperature obtain around 68°C at the end of the heating process in both cases, water gains and loses heat at a slightly slower rate in the presence of PCM [5], [14], [26]during the first 8 h of the experiment. A significant difference between the two cases becomes apparent after that, as the water temperature reaches around 58–60 ^{0}C. This is attributed to the release of the stored latent heat [4], [6], [25] during the gradual solidification of the PCM at this range of temperatures. The temperature advantage of the PCM case reaches 11–12°C after 4 hours of the start of the experiment; the temperature of water in the presence of the PCM was still 39°C higher, in comparison to a difference of only 28°C in the case without PCM.

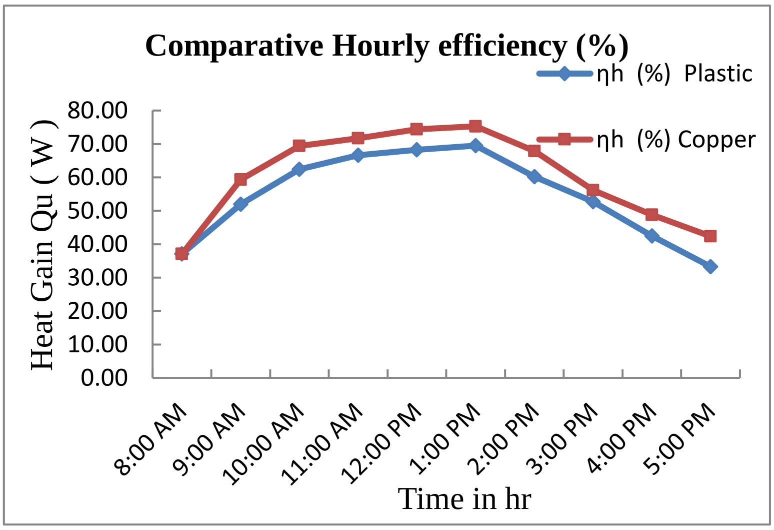

Fig. 9 Comparative Hourly efficiency

This graph compares the thermal efficiency (ηh) of plastic and copper materials in a solar collector over time from 8:00 AM to 5:00 PM. Both materials show a similar trend, with efficiency rising steadily in the morning, peaking around noon to 1:00 PM, and then gradually declining in the afternoon. Copper consistently outperforms plastic in terms of thermal efficiency throughout the day, achieving a maximum of 74.33% at 12:00 PM, compared to plastic's peak of 69.47% at 1:00 PM. This indicates that copper provides better heat retention and transfer capabilities, particularly during peak solar radiation hours.

CONCLUSION

The comparative thermal analysis of paraffin wax encapsulated in plastic and copper bottles clearly demonstrates the significant impact of container material on the performance of Phase Change Materials (PCMs). Copper, due to its high thermal conductivity, enabled faster heat absorption and dissipation, resulting in quicker melting and solidification of the paraffin wax compared to the plastic bottle. In contrast, the plastic container exhibited slower thermal response due to its insulating nature, which limited effective heat transfer. These findings emphasize the importance of container selection [7], [8], [9], [24] in PCM-based thermal energy storage systems, particularly in applications requiring rapid thermal regulation. Overall, copper proves to be a more efficient material for enhancing the thermal behavior of paraffin wax and can be preferred in high-performance energy storage[31], [36] and management solutions.

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