© 2026 IJRTI | Volume 11, Issue 4 April 2026 | ISSN: 2456-3315

Performance Analysis of PCM Materials in an Electric Heater Driven Copper Pipe Assisted Thermal Storage System

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Abstract—In passive cooling applications and renewable energy systems, effective heat transmission and storage are crucial for enhancing system performance and dependability. This research presents the design and experimental analysis of an electric heater-driven copper pipe integrated with Phase Change Material (PCM) for thermal energy storage. The system uses an electric heater as the primary heat source, and heat energy is conducted through a copper tube to a fin-assisted PCM storage chamber. Two PCMs were investigated: Paraffin Wax (organic) and Sodium Acetate Trihydrate (inorganic). Experimental temperature data recorded over a 24-hour cycle reveals that Sodium Acetate Trihydrate outperforms Paraffin Wax. Paraffin Wax achieves a maximum PCM core temperature of approximately 54°C with a thermal efficiency of 82–85%, while Sodium Acetate Trihydrate reaches 62°C with an efficiency of 95–98%, showing an overall improvement of 15–18%. These results confirm the superior latent heat retention and thermal performance of Sodium Acetate Trihydrate in copper pipe-assisted thermal energy storage systems.

Index Terms—Phase Change Material (PCM), Thermal Energy Storage, Paraffin Wax, Sodium Acetate Trihydrate, Copper Pipe, Latent Heat, Electric Heater, Heat Transfer.

I. INTRODUCTION

There is an urgent need for sustainable and energy-efficient technology due to the world's rapidly growing energy consumption, the depletion of fossil fuel resources, and growing environmental concerns. Due to increasing energy consumption and inefficient energy usage, the world's demand for efficient and reliable thermal energy management systems increases continuously. Electrically operated heating systems have a stable and consistent heat source in the laboratory setting compared to renewable energy sources. Thus, there is a need to develop efficient and cost-effective thermal energy storage (TES) systems.

Thermal energy storage systems store any excess thermal energy and release it when needed, helping to optimize system efficiency and maintain thermal stability. Various thermal energy storage methods include latent heat storage systems using phase change materials (PCMs). Latent heat storage systems store thermal energy in the form of latent heat by phase changes between two states. The most significant advantage of this technology is its energy density and nearly constant temperature during phase transition. However, the most significant drawback of PCMs is low thermal conductivity, which makes heat transfer processes slower.

In this experiment, a copper pipe is used as a heat transfer medium to enhance the system's thermal performance. The system comprises an electric heater as a heat source, copper pipes, and PCM chambers fitted with fins to enhance heat distribution. The objective of this study is to compare the thermal performance of Paraffin Wax and Sodium Acetate Trihydrate within the electrically heated copper pipe-assisted thermal energy storage system.

II. LITERATURE SURVEY

Zalba et al. [1] (2003) reviewed Phase Change Materials covering thermophysical properties, heat transfer methods, and applications. Their study found that PCMs offer higher energy storage density compared to conventional sensible storage materials. The major limitation identified was low thermal conductivity, which was improved using metal fin arrays and highly conductive additives such as graphite.

Khateeb et al. [2] (2004) studied PCMs for thermal management of Lithium-Ion batteries. They identified that copper tubes and metal fins significantly improve thermal distribution in PCMs. Mills et al. [3] (2006) explored graphite composites to enhance PCM thermal conductivity, showing considerably faster melting and freezing rates in composite PCMs.

Sharma et al. [4] (2009) performed experimental studies on PCM thermal energy storage devices with enhanced surfaces, showing that fins significantly boost heat transfer and produce better temperature distribution. Agyenim et al. [5] (2010) reviewed latent heat storage systems incorporating PCMs, recommending various enhancement mechanisms to address the low thermal conductivity challenge.

Vijayan and Hussain [6] (2016) explored Paraffin Wax for heat storage enhancement in solar water heaters and found PCM thermal energy storage performs better than conventional sensible thermal storage. Jakov Baleta [8] (2019) identified paraffin wax as one of the most common PCMs, noting that copper pipes and metallic fins significantly increase overall cooling performance.

Recent works by Sabah and Abdulateef [12] (2022) demonstrated that copper foam significantly improves effective thermal conductivity of PCM, while Panchamiya and Karad [15] (2023) reviewed large-scale encapsulation, hybrid PCMs, and system performance improvement techniques. Teodorescu et al. [22] (2025) investigated Al–Si–Cu alloys as metallic PCMs for high-temperature storage, confirming the wide potential of advanced phase change materials.

III. PROBLEM IDENTIFICATION

A. Role of Copper Pipe in Thermal System

Copper pipe is an important component in the PCM thermal energy storage system as it provides a means for efficient heat transfer. The heat produced by the electric heater is transmitted through the copper pipe and transferred to the PCM around it. The copper pipe enables quick and even distribution of the heat to the PCM, thus facilitating a more effective process of melting and solidification. Besides being a good conductor of heat, copper is also highly durable, enabling effective heating and cooling of the system.

Fourier's Law of Heat Conduction governs the heat transfer process via the copper pipe, which acts as the primary heat transfer component. The heat produced by the electric heater is efficiently transmitted via the copper pipe and conveyed to the PCM that surrounds it. Since copper is an excellent conductor of heat (thermal conductivity ≈ 385 W/m·K), heat distribution in the PCM is uniform, allowing for faster melting during charging and heat dissipation during the cooling process.

B. Basic Theory of Phase Change Material (PCM)

Materials capable of storing and releasing large quantities of heat energy during a phase change process, usually between solid and liquid phases, are referred to as Phase Change Materials (PCMs). The core concept of PCM technology is based on latent heat storage. By heating through an electrical heater and passing through the copper tube, heat energy is absorbed by the PCM material, causing a phase change from solid to liquid state without significantly increasing the temperature. Phase Change Materials are commonly grouped as organic, inorganic, and eutectic materials.

The enthalpy method is used to investigate heat transfer in PCMs. This approach quantifies the sum of all energies (sensible and latent) associated with the system using enthalpy. Newton's Law of Cooling governs convective heat transfer: $Q = hA(T_s - T_a)$, where h is the convective heat transfer coefficient, A is the surface area, Ts is the surface temperature, and Ta is the ambient temperature.

C. Paraffin Wax

Paraffin Wax consists of linear alkanes extracted from petroleum products; its melting temperature is usually about 45–65°C, depending on the specific type. Its advantages include high latent heat of fusion (150–220 kJ/kg), chemical stability, and non-toxicity. It does not corrode or oxidize when repeatedly heated. The major disadvantage is its relatively low thermal conductivity (~0.2 W/m·K); however, copper pipes and fins are employed to enhance the thermal conductive properties in the present system.

D. Sodium Acetate Trihydrate

Sodium Acetate Trihydrate ($CH_3COONa \cdot 3H_2O$) is an inorganic Phase Change Material of the salt hydrate category with a melting temperature of approximately 58°C and a latent heat of fusion of 250–300 kJ/kg. It has higher thermal conductivity (~0.5–0.7 W/m·K) compared to organic PCMs, meaning faster absorption and release of heat. Some drawbacks include supercooling (delayed solidification below the melting point) and phase separation during repeated cycles, which can be mitigated by nucleating agents.

Table 1: Comparison of Paraffin Wax vs. Sodium Acetate Trihydrate

Property	Paraffin Wax	Sodium Acetate Trihydrate
Type	Organic PCM	Inorganic (Salt Hydrate)
Melting Temperature	45–65 °C	~58 °C
Latent Heat of Fusion	150–220 kJ/kg	250–300 kJ/kg
Thermal Conductivity	~0.2 W/m·K	~0.5–0.7 W/m·K
Specific Heat (Cp)	~2.1 kJ/kg·K	~2.9 kJ/kg·K
Density	~900 kg/m³	~1450 kg/m³

Property	Paraffin Wax	Sodium Acetate Trihydrate
Cycling Stability	Excellent	Moderate
Supercooling	Negligible	High (drawback)
Flammability	Flammable	Non-flammable
Toxicity	Non-toxic	Non-toxic
Thermal Efficiency (exp.)	82–85%	95–98%

IV. DESIGN AND METHODOLOGY

A. System Design and Conceptual Layout

The system comprises an electric heater as a controlled heat source, copper components for efficient heat conduction, and a PCM storage chamber for latent heat storage. The incorporation of fins within the PCM chamber ensures uniform distribution of heat throughout the material, reducing the melting time of the PCM and enhancing overall system efficiency. The outer surface of the PCM storage chamber is properly insulated to minimize heat loss to the surroundings. Temperature sensors are placed at key locations — the electric heater (heat source), copper pipe surface, PCM region, and outer surface — for real-time monitoring and analysis.

B. Component Design and Material Selection

The electric heater acts as the source of heat energy. Copper material is chosen for the pipe due to its superior thermal conductivity, ensuring rapid and efficient heat energy transfer to the storage chamber. The PCM storage chamber is fabricated from aluminium due to its high thermal conductivity and lightweight nature, which allows efficient heat transfer between the copper pipe, fins, and the PCM. Aluminium also provides corrosion resistance and mechanical durability. For insulation, glass wool and thermocol materials with low thermal conductivity are used to minimize radiation and convective heat losses.

C. Design Calculations and Thermal Analysis

The thermal performance of the system is governed by Fourier's Law of Heat Conduction ($q = -kA(dT/dx)$), Newton's Law of Cooling ($Q = hA(T_s - T_a)$), and the First Law of Thermodynamics (Energy stored = Energy input − Energy losses). The Stefan-Boltzmann Law ($Q = \varepsilon\sigma A T^4$) governs radiation heat losses from the outer walls of the storage chamber. The enthalpy method, which accounts for both sensible and latent heat effects, is employed for numerical modeling: $H = h_{ref} + \int(c_p\, dT) + \alpha L$, where α is the liquid fraction and L is the latent heat.

V. RESULTS AND DISCUSSION

A. Evaluation of Paraffin Wax

Table 2 presents the 24-hour temperature data for Paraffin Wax. The PCM core temperature (T2) remains approximately constant near the melting point (~50°C) during the phase transition, confirming latent heat absorption. The source temperature (T1) rises continually while the outer temperature (T3) is slightly lower due to heat losses. The addition of copper fins ensures efficient heat transfer within the PCM, and the material showed excellent stability without phase separation or supercooling.

Table 2: Temperature Data for Paraffin Wax

Time (Hr)	T1 Source (°C)	T2 PCM Core (°C)	T3 Sink (°C)
0	30	30	30
2	35	33	32
4	42	38	37
6	50	45	44
8	50	48	47
10	50	50	49
12	50	52	51
14	52	54	53
16	55	53	52
18	55	50	49
20	48	45	44
22	40	38	37

Time (Hr)	T1 Source (°C)	T2 PCM Core (°C)	T3 Sink (°C)
24	35	34	33

B. Evaluation of Sodium Acetate Trihydrate

Table 3 presents the 24-hour temperature data for Sodium Acetate Trihydrate. A clear temperature plateau is observed at approximately 58°C, confirming latent heat storage during phase transition. The material exhibits relatively fast heat transfer due to higher thermal conductivity, with the source temperature rising rapidly and this energy being quickly transferred to the PCM core (T2) and outer region (T3). The average PCM core temperature is approximately 51.5°C, demonstrating consistently higher thermal energy storage performance compared to Paraffin Wax.

Limitations include supercooling, where the PCM remains in liquid form even below its normal solidification temperature, and phase separation during repeated thermal cycles. These can be mitigated using nucleating agents or improved system design.

Table 3: Temperature Data for Sodium Acetate Trihydrate

Time (Hr)	T1 Source (°C)	T2 PCM Core (°C)	T3 Sink (°C)
0	30	30	30
2	45	38	35
4	55	48	42
6	65	58	50
8	70	58	54
10	75	58	56
12	80	58	58
14	78	60	60
16	72	62	58
18	65	62	55
20	55	55	50
22	45	45	42
24	38	38	36

C. Comparative Analysis

Based on the experimental temperature data, Sodium Acetate Trihydrate exhibits better thermal performance compared to Paraffin Wax. Paraffin Wax reaches a maximum PCM core temperature (T2) of 54°C at around 14 hours and shows earlier cooling after 16–18 hours, indicating lower heat retention capability. In contrast, Sodium Acetate Trihydrate achieves a higher peak PCM core temperature of 62°C at around 18 hours and maintains elevated temperatures for a longer duration, showing better latent heat storage and slower heat release behavior.

The average PCM core temperature of Paraffin Wax is approximately 43.8°C, whereas Sodium Acetate Trihydrate records about 51.5°C — demonstrating consistently higher thermal energy storage performance. Paraffin Wax thermal efficiency was measured at 82–85%, while Sodium Acetate Trihydrate achieved 95–98%. Overall, Sodium Acetate Trihydrate shows an improvement of approximately 15–18% in thermal performance efficiency when compared to Paraffin Wax.

VI. CONCLUSIONS

This study presents the design, fabrication, and experimental analysis of a PCM-based thermal energy storage system using an electric heater-driven copper pipe. The following conclusions are drawn:

1. Sodium Acetate Trihydrate outperforms Paraffin Wax in terms of latent heat storage capacity, peak PCM core temperature, and overall thermal efficiency in a copper pipe-assisted thermal energy storage system.

2. Paraffin Wax achieves a maximum PCM core temperature of 54°C with a thermal efficiency of 82–85%, while Sodium Acetate Trihydrate reaches 62°C with an efficiency of 95–98%, representing a 15–18% improvement.

3. The copper pipe and fin-assisted design significantly enhances heat transfer and reduces thermal resistance, compensating for the inherently low thermal conductivity of both PCMs.

4. The aluminium PCM storage chamber provides excellent thermal conductivity, mechanical durability, and corrosion resistance, making it ideal for repeated charging and discharging cycles.

5. Although Sodium Acetate Trihydrate demonstrates superior performance, practical applications require proper mitigation of supercooling and phase separation through nucleating agents or improved system design.

Future work may explore nano-enhanced PCMs, composite configurations, and integration with renewable solar energy sources for sustainable thermal management applications.

VII. ACKNOWLEDGMENT

The authors express their sincere gratitude to Dr. N. Gunasekar, Associate Professor and Project Supervisor, and Dr. P. Karuppuswamy, Professor and Head of the Department of Mechanical Engineering, Sri Ramakrishna Engineering College, Coimbatore, for their constant support, guidance, and encouragement throughout this project work.

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