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Design and Experimentation of a Thermal Energy Storage System using PCM

Dr. Atul Londhekar[1], Ankush Yadav[2], Akshay Wadel[3],Sohail Salmani[4], Vikas Sardar[5]
[1]Assistant Professor, Mechanical Engineering, Rajiv Gandhi Institute of Technology Maharashtra, India
[2] B.E. Mechanical Engineering, MCT Rajiv Gandhi Institute of Technology, Maharashtra, India
[3] B.E. Mechanical Engineering, MCT Rajiv Gandhi Institute of Technology, Maharashtra, India
[4] B.E. Mechanical Engineering, MCT Rajiv Gandhi Institute of Technology, Maharashtra, India
[5] B.E. Mechanical Engineering, MCT Rajiv Gandhi Institute of Technology, Maharashtra, India

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ABSTRACT

The increasing adoption of renewable energy sources, particularly solar energy, for applications such as water heating is driven by their environmental benefits and the goal of minimizing reliance on traditional energy systems. Despite these advantages, solar water heating systems often face the challenge of inconsistent energy availability, especially during night time or cloudy conditions. To mitigate this issue, the present study introduces a novel thermal energy storage unit that integrates seamlessly with a solar water heating setup. This system employs a phase change material (PCM) to effectively capture and store heat energy for later use. The PCM is enclosed within a heat exchanger that works in conjunction with the solar collector, absorbing thermal energy during times of strong sunlight. The selected PCM features a high latent heat of fusion and a melting point well-suited to the temperature range of standard solar water heaters. This setup is designed to improve system performance and ensure a more reliable hot water supply by releasing stored heat when sunlight is insufficient. Critical design considerations include selecting a PCM with appropriate thermal properties, ensuring compatibility with the heat transfer medium, and maintaining durability and cost efficiency. Both simulations and real-world experiments were conducted to evaluate the system's functionality across various environmental and usage conditions. Findings show that incorporating PCM significantly boosts the efficiency and consistency of the solar heating system, extending hot water availability beyond sunlit hours. Additionally, the study explores the financial feasibility and environmental benefits of this integration, emphasizing its potential to support sustainable energy practices and decrease greenhouse gas emissions. In summary, this research proposes an effective method to improve solar water heating systems by incorporating PCM-based thermal storage, offering a practical and eco-conscious solution for residential and commercial water heating needs.

Keywords : - Phase Change Material, Latent Heat, Thermal Storage, Heat Transfer, Paraffin Wax, Copper, Feasibility

1. INTRODUCTION

Solar water heating systems have gained popularity as an eco-friendly and cost-efficient method for fulfilling hot water requirements across residential, commercial, and industrial sectors. By harnessing the plentiful and renewable energy from the sun, these systems operate using solar collectors that capture solar radiation to heat a working fluid—typically water or a water-based mixture. This heated fluid is then directed to a storage tank for later use. Despite the clear advantages of solar water heaters, such as lowered energy bills and reduced carbon footprint, their efficiency is often hindered by the inconsistency of solar energy availability. Specifically, during overcast conditions or nighttime, these systems may fail to provide a steady supply of hot water, impacting their reliability and user satisfaction.

To overcome this limitation, advancements have focused on enhancing the reliability and overall performance of solar water heating technologies. A major area of innovation involves thermal energy storage (TES) systems, which offer a solution to the problem of energy intermittency. TES units can store surplus thermal energy generated during sunny periods and release it when solar input is minimal, ensuring uninterrupted access to heated water.

Among various TES solutions, the use of phase change materials (PCMs) shows significant promise. These materials are capable of absorbing and releasing large quantities of heat during their phase transitions—such as melting and solidifying—while maintaining a stable temperature. This makes them highly suitable for efficient and stable thermal storage applications. The current research focuses on designing, modelling, and experimentally testing a new TES system that incorporates PCMs into solar water heaters. The objective is to improve the dependability and effectiveness of these systems, making them more viable and attractive for broader use in energy-conscious communities.

1.1 Objectives

- To investigate and develop innovative strategies to design and fabricate PCM based warmth exchanger. This heat exchanger can be used as thermal energy storage device and thus can be included in solar water heater.
- This integration is expected to enhance the device's stability and flexibility whilst simultaneously addressing the difficulty of carbon emissions .

1.2 Scope

- PCMs absorb heat during the day and can release it when needed, minimizing temperature fluctuations and ensuring more consistent performance.
- Ongoing research is continuously improving the properties of PCMs, such as enhancing their thermal conductivity and reducing the costs associated with manufacturing.
- By improving energy storage, PCM-based systems reduce the need for backup energy sources (like gas or electric heaters), further contributing to cost reduction and cutting carbon emissions.
- Integrated with smart energy management systems to optimize energy usage based on real-time demand and storage levels.

2. LITERATURE REVIEW

Sharma et al. (2009) : "Thermal Energy Storage with Phase Change Materials and Applications" - Emphasized the advantages of latent heat-based thermal energy storage systems using phase change materials (PCMs). These materials enable high-density energy storage and operate under near-constant temperature conditions, making them suitable for various thermal applications. PCMs have found widespread use in technologies such as solar systems, heat pumps, and thermal control mechanisms in space missions. Their broad range of melting and solidification points allows for customization based on specific requirements, improving overall thermal storage efficiency and system adaptability. This makes PCMs integral to the progression of sustainable and efficient energy storage technologies across multiple industries.

Demirbas (2006) : "Thermal Energy Storage and Phase Change Materials: An Overview" - Underlined the critical function of thermal energy storage in contemporary energy systems. He discussed the contributions of both sensible and latent heat storage in conserving energy sources like solar radiation and waste heat. Among these, latent heat storage—enabled by PCMs—offers superior energy density and operational efficiency, reinforcing its value in energy management solutions.

Akgun et al. (2008) : "Thermal energy storage performance of paraffin in a novel tube-in-shell system"- Explored the efficiency of thermal energy storage using paraffin in a custom-designed tube-in-shell system. Their approach was tailored to enhance performance by aligning the system's physical geometry with the thermal behavior of the PCM. Three types of paraffin with distinct melting points were analyzed, and water served as the heat transfer medium. Using Differential Scanning Calorimetry (DSC), they evaluated the thermophysical properties of the PCMs. The study examined how variables such as the Reynolds and Stefan numbers affected the phase change process, ultimately demonstrating improved energy storage performance through optimized design.

Trp (2005) : "An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell and tube latent thermal energy storage unit" - Carried out a detailed examination of thermal storage systems incorporating shell-and-tube heat exchangers. The research employed both laboratory experiments and simulations to study transient convective heat transfer, thermal conduction, and phase transition behavior of PCMs. A custom FORTRAN-based computational model was used to simulate non-isothermal phase changes, and the results closely matched the experimental data, validating the model's accuracy. The study significantly contributes to better understanding and optimizing thermal energy storage using PCMs.

Jesumathy et al. (2012) : "Heat transfer characteristics in latent heat storage system using paraffin wax"- Conducted experimental research on the performance of paraffin wax within a vertically-oriented annular storage unit. The study focused on temperature distribution during melting and solidification, examining the impact of Reynolds number on heat transfer dynamics. Measurements included the heat transfer coefficient and system efficiency during the freezing phase. The researchers observed that melting occurred from the top downward, while solidification progressed upward, and time-dependent temperature profiles supported their findings. This study provided essential insights for designing effective PCM-based storage systems.

James and Delaney (2012) : "Phase Change Materials for Building Cooling Applications"- Performed a market-oriented study assessing the potential for PCMs in commercial building applications. Engaging with manufacturers, they evaluated the technical readiness and availability of PCM products. The research compared the thermal performance of PCMs with traditional materials, including mass equivalence assessments to guide integration into construction designs. Simulations were also conducted to evaluate temperature control and peak energy demand reduction in different climate zones. The findings supported the potential of PCMs to enhance energy efficiency and reduce cooling loads in commercial environments.

2.1 Overall Conclusion from Literature Review

- Phase change materials (PCMs) provide an effective solution for thermal energy storage, offering high energy density and maintaining a nearly constant temperature during the storage process.
- Integrating PCMs into energy management systems allows for the capture and use of surplus energy, thereby improving overall energy utilization and efficiency.
- A vertical tube-in-shell configuration offers a practical and efficient design for storing large scale thermal energy using PCMs. Customizing the structure of a tube-in-shell storage unit to match the thermal behavior of PCMs can significantly improve the efficiency of heat absorption and release.
- Paraffin wax is widely considered an ideal PCM for solar water heating systems, thanks to its appropriate melting range, ease of use, and ready availability.
- PCMs are expected to play a crucial role in advancing energy-efficient technologies and supporting sustainable energy solutions in the future

2.2 Problem Statements

- Increasing need for efficient and sustainable energy storage solutions, especially in solar thermal systems.
- Systems must effectively manage heat transfer during both charging (melting) and discharging (solidification) phases to prevent thermal losses and uneven heat distribution. Phase Change Materials (PCMs), like paraffin, can store and release large amounts of latent heat, making them promising for thermal energy storage.
- A critical need exists to develop innovative storage unit geometries that match the unique thermal behavior of PCMs, improving energy efficiency and reliability.

3. METHODOLOGY

1. Requirement Analysis

- **Goal**: Understand the thermal energy needs (application, capacity, temperature range).
- **Key Questions**:
  - Is it for solar thermal, HVAC, electronics cooling, etc.?
  - What is the required storage time and temperature?

  - Is the application stationary or mobile?
- **Output**: Defined functional requirements (e.g., store 5 MJ of energy between 25–50°C).

2. Material Selection

- **PCM Selection Criteria**:
  - Suitable melting point range
  - High latent heat
  - Thermal stability
  - Chemical compatibility
  - Cost and availability
- **Examples**:
  - **Organic PCMs**: paraffin, fatty acids
  - **Inorganic PCMs**: salt hydrates
  - **Eutectics**: combinations for custom melting points

3. Design Consideration

- **Storage Type**: Sensible vs latent (latent dominates with PCM)
- **Containment Material**: Should be compatible with PCM, corrosion-resistant
- **Geometry**:
  - Cylindrical, rectangular, or packed bed
  - Surface area to volume ratio to enhance heat transfer
- **Heat Transfer Enhancement**:
  - Fins, encapsulation, graphite additives
- **Safety**: Expansion, flammability, leakage issues

4. CAD Design

- Use CAD tools (e.g., SolidWorks, AutoCAD) to:
  - Create a 3D model of the PCM container
  - Visualize fin arrangements or encapsulation techniques
  - Plan integration with heat exchangers or solar panels
- Include sensors, insulation, and ports in the model

5. Prototyping

- **Fabrication**:
  - Build a small-scale or full-size prototype
  - Use selected materials and encapsulate the PCM
- **Assembly**:
  - Integrate with heaters/cooling systems for testing
  - Include instrumentation (thermocouples, flow meters)

6. Test and Evaluation

- **Performance Testing**:
  - Measure charging/discharging time
  - Temperature distribution
  - Energy storage/release rate
- **Tools**: Thermography, data loggers, calorimetry
- **Validation**: Compare experimental data with theoretical calculations

7. Experiment Procedure

- Define test cycles (e.g., heat to 60°C, hold, cool to 25°C)
- Record:
    - PCM temperature change
    - Heat transfer fluid (HTF) behavior
    - System efficiency
- Perform multiple cycles for durability assessment

8. Environment and Economic Analysis

- **Environmental Impact**:
    - Is the PCM biodegradable?
    - Energy savings vs environmental cost
    - Emissions reduction potential
- **Economic Feasibility**:
    - Payback period
    - Cost of PCM per kWh stored
    - Life cycle cost

9. Documentation and Reporting

- Create a detailed report including:
    - Objectives, design rationale, materials, CAD drawings
    - Experimental procedures and results
    - Analysis (thermal, economic, environmental)
    - Improvements and future work suggestions
- Useful for publications, project presentations, or industry implementation

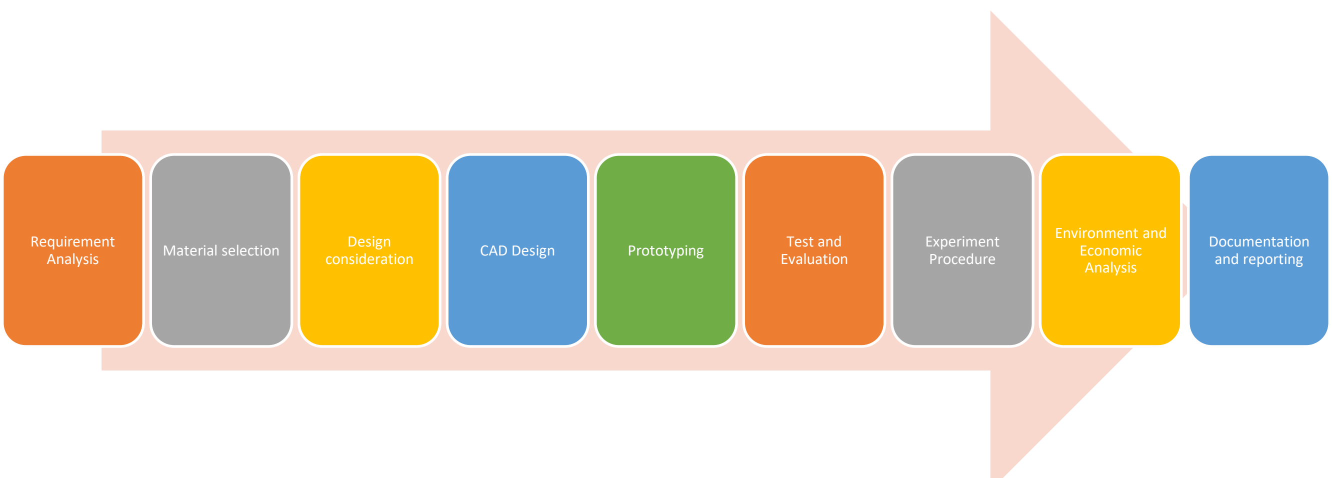

Chart -1 : Methodology

4. DESIGN AND DEVELOPMENT

4.1 Material Selection

Paraffin wax was selected as the optimal PCM for the thermal storage system due to its superior thermal properties, widespread availability, and proven performance through analysis and experimentation reviews.

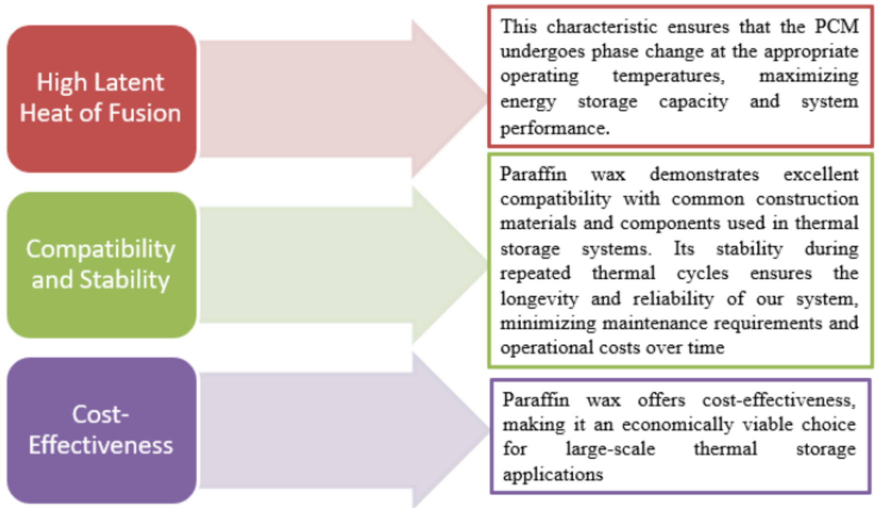

Chart -2: Criteria for selection of PCM .

Transition temperature	40°C to 50°C
Latent heat capacity	206 kJ/kg
Density	789 kg/m^3

Chart -3:Thermal Properties of Paraffin wax .

4.2 Calculations

- **Amount of heat energy to be stored**

During the winter season, when the ambient temperature often hovers between 15-20°C, the water stored in tanks tends to remain relatively cool. However, for comfortable bathing, the water temperature needs to be raised to around 40°C, providing a soothing and invigorating experience. This implies a temperature difference of approximately 20-25°C needs to be achieved to meet the desired bathing temperature.

Considering an initial water temperature (Ti) of 15°C and

A desired final temperature (Tf) of 40°C,

We aim to raise the water temperature by 25°C to achieve optimal comfort.

To calculate the amount of heat required for this transition, we utilize the heat capacity of water (Cv), which is approximately 4.187 kJ/kg.

Using the formula $Q = m_{water} \times (Tf - Ti) \times Cv$,

Where Q represents the amount of heat energy required,

m_{water} denotes the mass of water, and

(Tf – Ti) signifies the temperature difference,

We can determine the heat energy needed to raise the water temperature.

Assuming a mass of water (m_{water}) to be heated as 10 kg, the calculation yields:

Ti=15°C

Tf=40°C,

We aim to raise the water temperature by 25°C to achieve optimal comfort.

Cv=4.187 kJ/kg.

$Q = m_{water}$ x (Tf – Ti) x Cv,.

Assuming, m_w=10 kg

Q = 10 x 25 x 4.187 ≈ 1046.75 kJ

Therefore, the amount of energy required to achieve the desired temperature increase for comfortable bathing is approximately 1046.75 kJ.

This calculation serves as a crucial benchmark for determining the energy storage capacity needed within the system to ensure an adequate supply of hot water during the winter season.

- **Estimation of amount of PCM and Dimensions of Heat Exchanger(H.E.)**

The amount of PCM to be incorporated in estimated as follows:

Q = 1046.75 kJ

$Mass_{pcm}$ = Q/ (Latent heat) = 1046.45/206 = 5.0816kg.

Hence approximately 5.1 kg of PCM needs to be incorporated in the heat exchanger.

Volume of H.E. = Mass of PCM / ρ

$\rho = 789\ kg/m^3$

Volume of H.E. required = $6.46 \times 10^{-3}\ m^3$

Volume of H.E required= 6460 cm^2

Selecting dimensions L=30cm , B=15cm , H= 15cm

Volume of H.E. = L x B x H = 6750 cm^2

- **Amount of heat energy to be stored**

Referring from the literature review number of energy storage units to be used =n= 4 Length of each energy storage unit = 0.25 m and Diameter = 0.05 m for effective contact.

- **Cross-sectional area of the outer tube** = $Ao = \pi r^2$

r = 0.05/2 = 0.025 m

$Ao = 1.96 \times 10^{-3}\ m^2$

- **Volume of the outer tube =** Vo = Ao x L

$Vo = 4.91 \times 10^{-4}\ m^3$

- **Volume of all tubes =** Vt = 4 x Vo

$Vt = 1.96 \times 10^{-3}\ m^3$

- **Mass of PCM in all tubes =** $Mass_{pcm}$ = Vt x ρ (PCM)

Mt = 1.55 kg

- **Mass of PCM per unit tube** = $Mass_{pcm}$ / n

$Mass_{pcm}$ =1.55 kg

n =4

Mass of PCM per Unit = 0.3875 kg

- **Volume of PCM =** Mass of PCM per Unit / ρ

ρ = 789 kg/m^3

Mass of PCM per Unit = 0.3875 kg

Volume of PCM = 0.00049112 m^3.

- **Selection of suitable diameter for the internal pipe = Di =** A standard diameter of the copper pipe is chosen.

Di = 1.4cm

- **Cross-sectional area of the internal pipe** = Ai = πr^2

r = Di /2 = 0.7 cm

Ai = 1.5393 cm^2

4.3 CAD Design

Based on the above calculations CAD model was designed

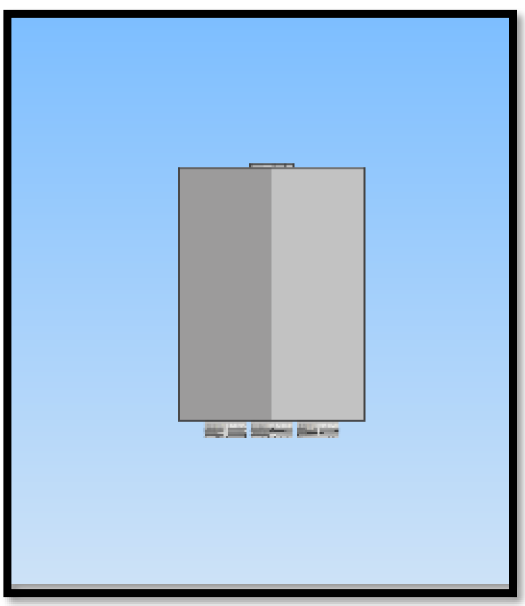

Chart -4: Side View

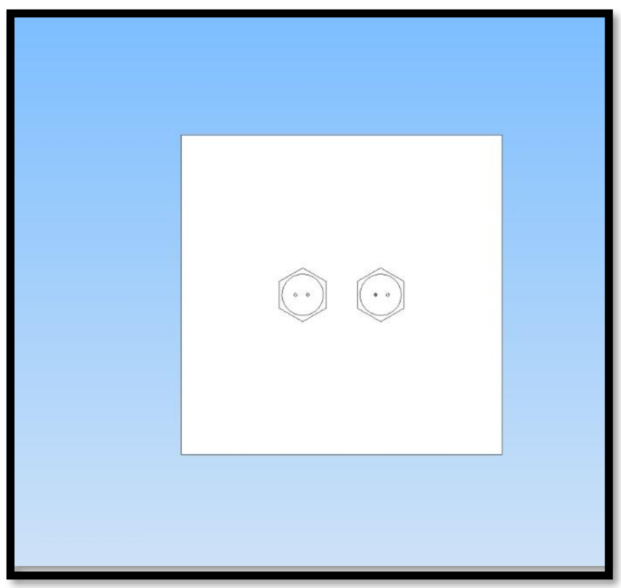

Chart -5: Bottom View

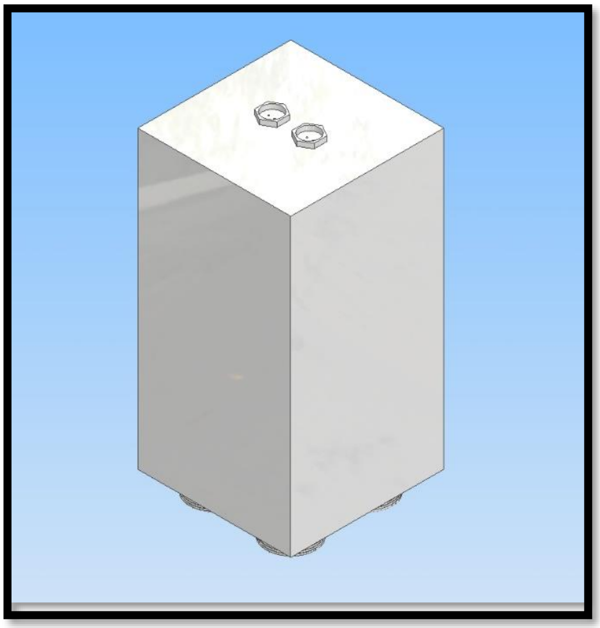

Chart -6 : Isometric View

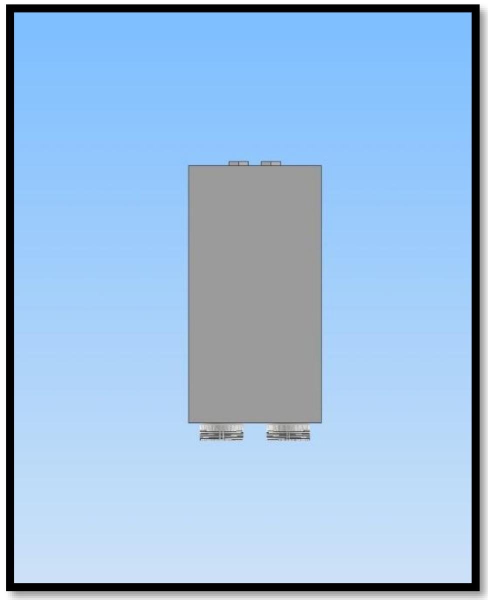

Chart -7: Front View

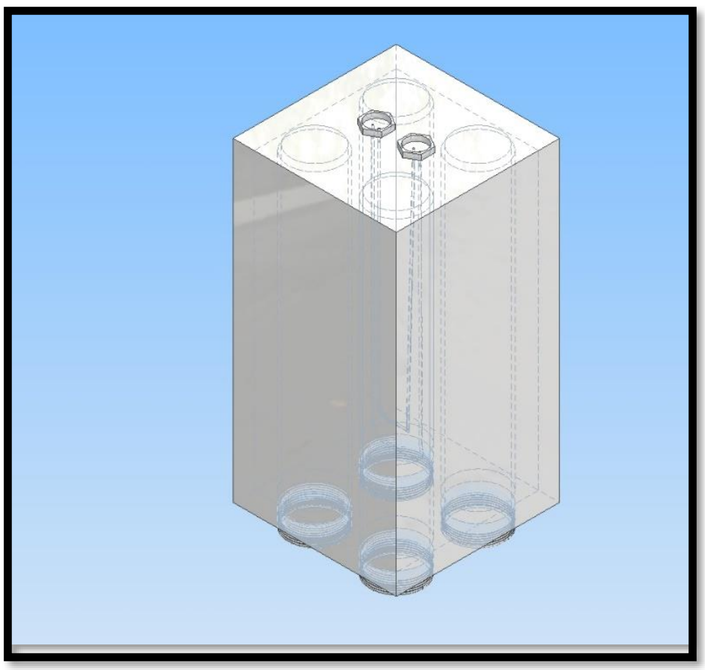

Chart -8: Isometric View with Hidden Lines

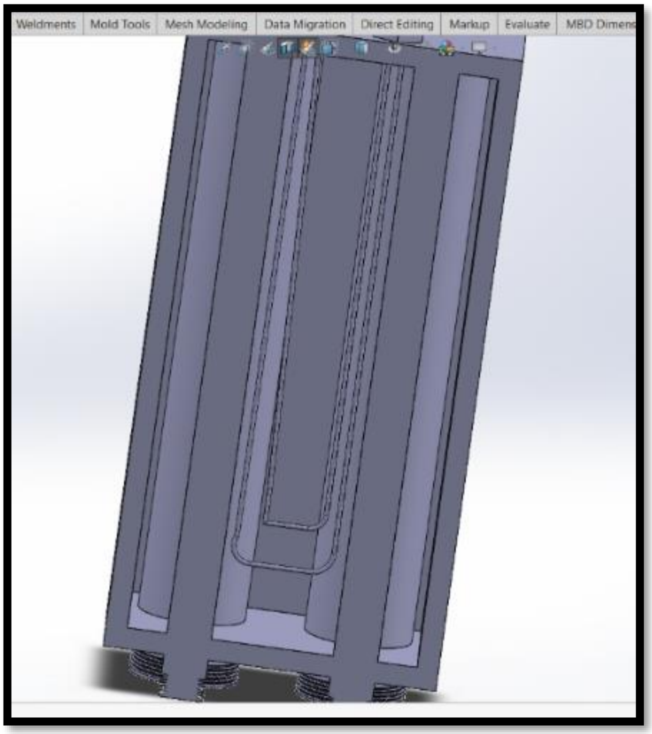

Chart -9: Sectional Front View

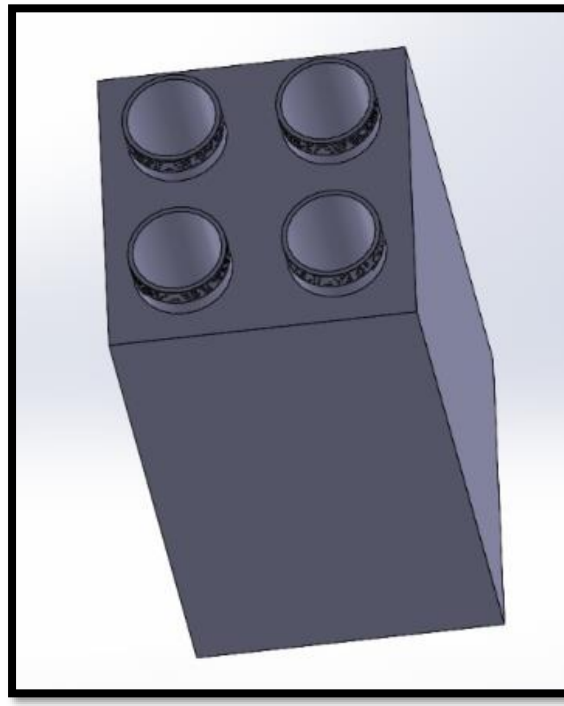

Chart -10: Top Isometric View

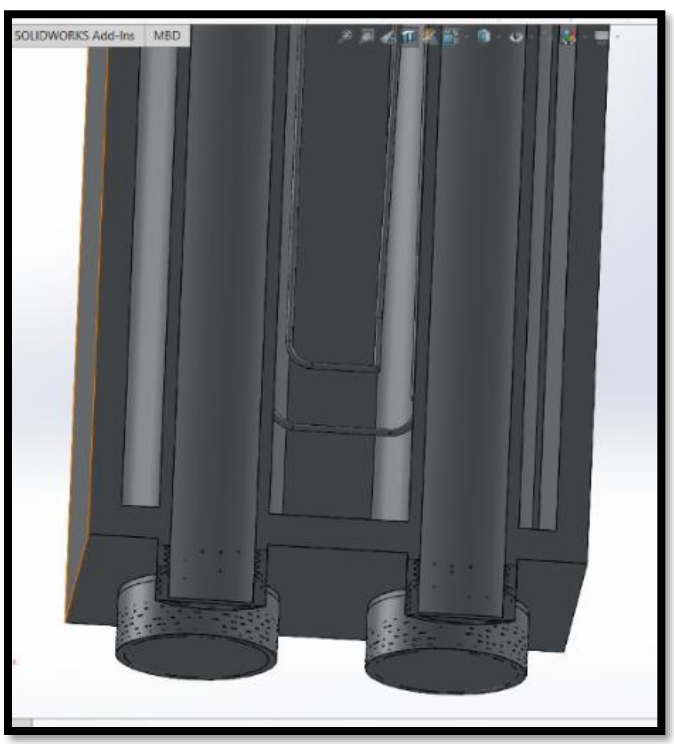

Chart -11: Cap Threading

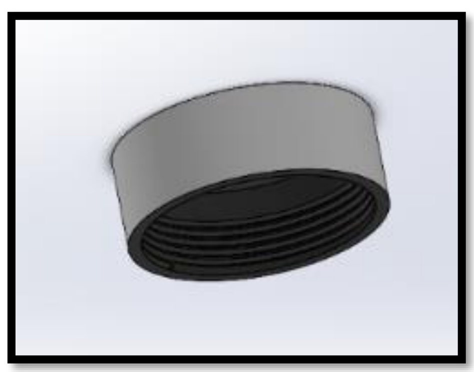

Chart -12: Cap

5. COMPONENTS OF TEST RIG

- ➢ Energy storage unit

- Central component for assessing thermal performance and efficiency in the test rig.
- Design:
  Inner copper pipe for heat transfer fluid.
  Outer Box for insulation and containment of paraffin wax (PCM).
- Function of PVC Pipe: Prevents melted paraffin wax from solidifying post-charging phase

- ➢ Storage tank

- Stores the heat transfer fluid (water) used in the charging and discharging phases.
- Acts as a reservoir for circulating water, essential for thermal energy storage.
- Insulation:
  Key design consideration to minimize heat exchange with the environment.
  Maintains water temperature and prevents unnecessary heat loss or gain.
  Insulation enhances system performance by preserving stored thermal energy.
- Practical Role: Ensures a stable and reliable heat transfer fluid supply for the system, optimizing energy storage and release.

- ➢ Pump

- Pump Function: Circulates the heat transfer fluid (water) through the system, ensuring effective thermal energy absorption or release.
- Type: Non-submersible water pump with a 6-foot head (maximum vertical lift).
- Head: The pump can lift water up to 6 feet against gravity.
- Mass Flow Rate: 15 liters per minute (lpm), ensuring adequate water circulation for efficient heat transfer

- ➢ Heating Coil

- Heating Coil Function: Heats the water in the storage tank, eliminating the need for additional heating components.
- Power Rating: 1500 watts (W), indicating the electrical power it consumes to generate heat.
- Heating Capacity: The 1500 W coil can effectively raise the water temperature to the desired level.

- ➢ Flow Control Valve

- Flow Control Valve Function: Regulates the mass flow rate of the heat transfer fluid for efficient heat exchange.
- Type: Simple gate valve with a sliding mechanism to adjust fluid flow by raising or lowering the gate.
- Purpose: Modulates flow rate to ensure optimal velocity for heat transfer efficiency.
- Advantages: The gate valve's simplicity, reliability, and ease of operation make it ideal for the system

- ➢ Thermocouple Wires with Indicator

- Temperature Sensing: Measures temperature by generating voltage based on temperature difference between two junctions.
- Signal Transmission: Carries the voltage signal from the sensing point to the indicator.
- Real-time Monitoring: The indicator displays the temperature instantly.
- Control Feedback: Provides data for automatic temperature control systems.

Chart -13: Pump

Chart -14: Temperature indicator

Chart -15: Energy storage unit

Chart -16: J-type Thermocouple

6. RESULTS AND DISCUSSIONS

Passing water through a thermal energy storage (TES) device using paraffin wax as the phase change material (PCM) in a solar water heater at flow rates of 10 kg/min yield varying results in terms of thermal performance, energy storage efficiency, and overall system operation. Also the readings were taken after each charging and discharging phase of 20 minutes. Here's a description of the expected outcomes:

Charging Phase:

- After passing water through the heat exchanger for 20 min the reading of the discharge tank was taken at a interval of 5 min .
- Data showed that the temperature was absorbed by the PCM for around 20 min which resulted in PCM charging.

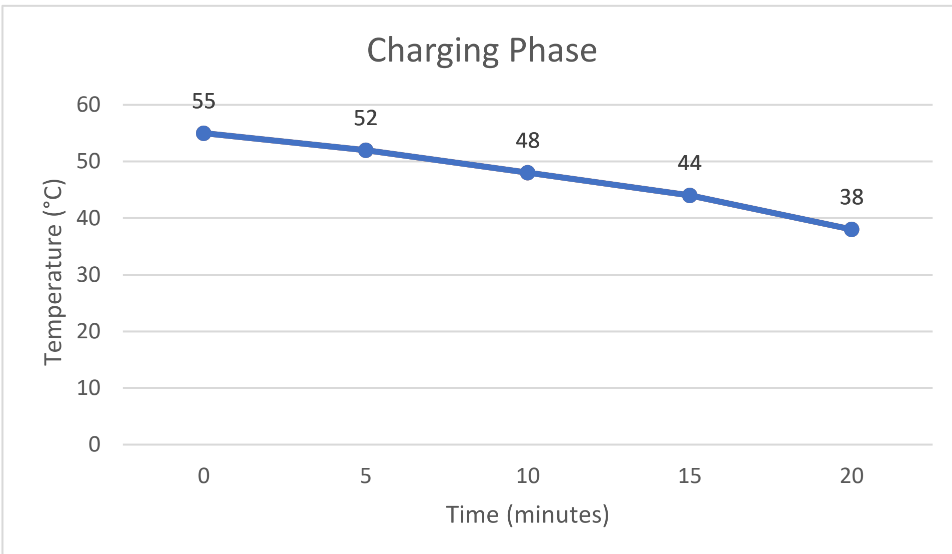

Chart -17: Charging of PCM

Discharging Phase:

- After passing water through the heat exchanger for 20 min the Heat exchanger was kept still in insulated environment and normal water was passed through it.
- Data showed that the temperature that was absorbed by the PCM for around 20 min resulted in the normal water to raise its temperature by 15ºCwhich resulted in PCM discharging.

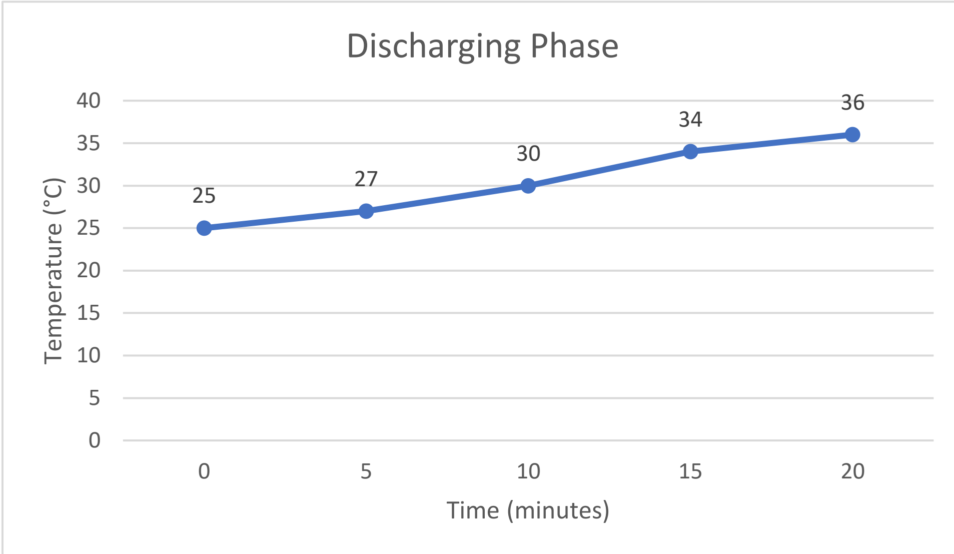

Chart -18: Discharging of PCM

Water Flow Rate: 10 kg/min

- This intermediate flow rate offers a good compromise between thermal exchange efficiency and water movement speed.
- Although the residence time of water in the thermal energy storage (TES) system is shorter than at lower flow rates, it remains adequate for effective heat transfer.
- The outlet water temperature may be somewhat lower than that achieved at slower flow rates, but it will still be considerably above the incoming temperature.
- This rate is well-suited for scenarios requiring a balance between flow speed and heat retention, such as in institutional or commercial facilities with moderate hot water needs

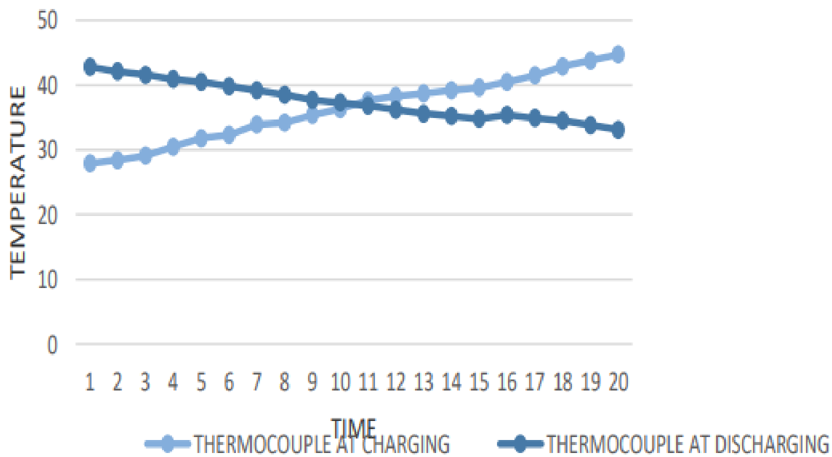

Chart -14: Charging and discharging of pcm at water flow rate 10 kg/min

7. CONCLUSION

The development of a rectangular thermal energy storage (TES) unit incorporating copper tubing and an aluminum casing, with paraffin wax as the phase change material (PCM), presents a promising approach to improving the effectiveness and dependability of solar water heating systems. The use of copper for tubing and aluminum for the outer structure addresses critical design needs such as efficient heat conduction, resistance to corrosion, and structural integrity, ensuring both performance and longevity.

By capitalizing on the excellent thermal conductivity of copper and the lightweight, durable properties of aluminum, the TES system efficiently absorbs and releases heat, extending the availability of heated water even during non-sunny periods. The structured experimental methodology helps verify the system's heat storage capability and thermal efficiency, delivering valuable insights for real-world use and optimization.

In addition, paraffin wax is chosen for its cost-effectiveness, safety, and wide thermal operating range, making it ideal for diverse applications across residential, commercial, and industrial sectors. Altogether, the integration of a rectangular TES system using copper and aluminum materials represents a highly effective and sustainable upgrade for solar water heating technologies, supporting the broader shift toward cleaner and more energy-efficient solutions.

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