

Enhancing Thermal Energy Storage Using Phase-Change Materials in a Horizontal Cylinder

Shahid Ali^{a,b*}, S. P. Deshmukh^b

^a Department of Mechanical Engineering AISSMS COE, PUNE- 411001, Maharashtra, India

^b Department of General Engineering., ICT Mumbai- 400019, Maharashtra, India

(shahid.ansari1507@gmail.com, sp.deshmukh@ictmumbai.edu.in)

[‡] AISSMS COE, PUNE- 411001, Maharashtra, India ICT Mumbai- 400019, Maharashtra, India, Tel: +918983153332,

Fax: +91-20 2605 8943, shahid.ansari1507@gmail.com

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Abstract-

The world's energy landscape heavily relies on fossil energy sources including natural gas, coal, and oil which power various sectors of society. However, the utilization of these energy resources is accompanied by the release contribute to climate change and global warming through the release of greenhouse gases and carbon dioxide. To address the environmental limitations associated with fossil fuels, there is a pressing need to explore alternative methods for energy production.

The present study introduces a distinctive approach to energy production and storage by employing phase-change materials (PCMs) for latent heat thermal energy storage. The primary objective is to assess the thermal performance of this energy storage technique utilizing materials with phase change. To achieve this, an experiment is conducted to measure temperature variations along the axial direction of copper tubes. These tubes, measuring 650 mm in length, 25 mm in diameter, and 2 mm in thickness, are employed as the core components of our system. To minimize heat transfer losses to the surrounding environment, we implemented a design strategy consisting of encasing the copper tubes within a 600 mm long acrylic tube 45 mm in diameter and 5 mm in thickness. Furthermore the tube is rapped with insulated with thermal insulating materials. The experiments were conducted within a double-pipe, horizontal acrylic-based unit for latent heat storage.

Keywords: Paraffin wax, copper tube, acrylic pipe, thermal energy storage unit.

1. Introduction

Decomposed plants and various organisms buried beneath the Earth's crust have undergone a transformation over many years, resulting in the formation of carbon-rich substances commonly known as fossil fuels. These invaluable resources, which encompass natural gas, coal, and oil, have been the principal resources of energy production, supplying approximately 80% of the world's energy demands. However, their utilization has brought about detrimental consequences, primarily in the form of emissions of greenhouse gases and carbon dioxide (CO₂). These emissions have significantly contributed to the global issues of global warming and climate change, underscoring the urgent need for alternative energy production methods.

In today's modern world, energy storage solutions based on thermal principles, particularly those utilizing phase change materials (PCMs), have gained momentous attention. PCMs possess the unique ability to store substantial quantities of energy through their phase alterations, involving the melting, solidification, or evaporation processes, which are accompanied by the process of absorbing or releasing heat. Depending on the specific phase change, heat can either be absorbed or emitted, whether transitioning from a solid to a liquid state or vice versa [1, 2, 3]. PCMs have found practical application in both sensible and latent heat storage systems, with the latter proving to be notably more efficient due to the precise control of phase changes occurring at constant temperatures. In latent heat storage systems, the energy is stored and released through a sudden phase transition of the PCM, offering a highly

effective means of energy storage. Various latent heat energy storage materials exist, with organic materials such as paraffin and non-paraffin compounds being widely utilized in diverse applications ranging from building construction to heating and cooling systems [4]. Figure 1 [5] showcases the diverse and extensive range of applications for thermal energy storage using PCMs, highlighting their potential to transform various industries and parts of our everyday existence.

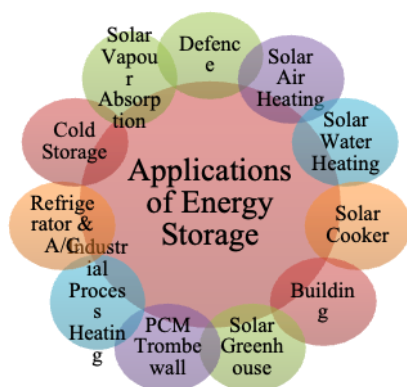


Fig.1.Classification based on Application of Energy Storage [5]

2. Literature Survey

Applications for building heating and cooling also make use of eutectic mixtures, comprising compositions that can exist in nature as organic-inorganic, organic-organic, or inorganic-inorganic. M. Fadl et al [6] conducted experimental investigations into the thermal performance of portable thermal energy storage systems. Their findings indicate that the HTF inlet temperature exerts a more significant influence on charging time during the charging process, as well as on the flow rate. They also provide insights into how the average power factor affects the charging method and the heat exchange fluid inlet temperature. Ismael S. Al-Hinti et al [7] are actively engaged in the experimental exploration of water-phase change substance storage systems, which can be incorporated with traditional solar water heating systems. Their research results reveal that forced circulation of water over short durations has the least impact on system performance. Additionally, they have analyzed the retrieval effect and the PCM storage performance under open-loop operating conditions, which are designed to replicate daily usage patterns.

Jesumathy S. P. et al. conducted experimental research focused on the heat transmission attributes of a double pipe filled with paraffin for horizontal latent heat storage. Their findings suggest that lowering the heat transfer medium's input temperature can lead to a decrease in discharging time due to an improved rate of heat transfer, while raising it may result in a decrease in charging time [8]. In a horizontal thermal energy storage system using a shell tube configuration, N. Das et al. examined the improved melting behavior of phase change nano-composite materials. According to their predictions, the performance of the thermal energy storage system would benefit from the addition of nano-composite materials to the phase change

materials [9]. Rohit Kothari et al. conducted an experimental examination of the heat transfer rate in a cylinder-shaped latent heat storage system with phase transition materials. Their results highlight the system's efficiency when dealing with charging and discharging progressions at different rate of flow and HTF temperatures inlet [9]. Dinkar et al. studied beeswax-expanded graphite amalgams as potential thermal energy storage ingredients. They analyzed various properties of paraffin wax using techniques such as differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA), scanning electron microscopy (SEM), and X-ray diffraction (XRD) of phase change materials (PCM) to evaluate system performance [10–13].

Jayakumar, T. et al. experimentally examined the latent heat energy of a helical coil thermal system for renewable energy utilization. They examined various charging and discharging enactment parameters for this LHESS [14]. Akgün et al. investigated the thermal energy storage capabilities of paraffin in a novel tube-in-shell system. They used three different types of paraffin wax to anticipate results and assessed the thermal and physical characteristics of the materials, as well as the effects of melting and solidification variables on system performance using DSC testing [15]. Mehta, Digant S. et al. conducted a thermal performance analysis of a shell and tube latent heat storage scheme, focusing on the orientation of the latent heat storage unit. They demonstrated the performance of solidification and melting processes and provided descriptions of solid-liquid interfaces, liquid fraction profiles, and solidification and melting performance parameters [16]. Manish K. Rathod et al. investigated the augmentation of thermal efficiency in latent heat storage schemes through the use of longitudinal fins. They presented the outcomes of increasing the material's thermal conductivity, which led to improved system performance [17]. Abduljalil A. Al-Abidi et al. conducted an experimental investigation on phase-change materials in a heat exchanger, focusing on their behaviour during charging and discharging progressions in triplex tubes. They examined the paraffin wax discharging process under various temperature gradients and rates of mass flow in both angular and radial directions within the storage thermal unit [18]. Ammar M. Abdulateef et al. experimentally and computationally considered the melting of phase-change material in a triplex tube heat exchanger. They included longitudinal and triangular fins and assessed a range of melting temperatures and flow rates to understand their effects on system performance [19]. Avci, Mete et al. accompanied a study on the experimental characteristics of paraffin for thermal energy storage in a horizontal tube-in-shell storage component [20]. They aimed to investigate latent heat storage for low-temperature solar heating base applications.

Kumar et al. investigated various phase transition materials for latent heat storage in low-temperature solar heating base applications. They used differential scanning calorimetry to assess the thermo-physical characteristics of different phase change materials and their impact on solidification and melting processes [21]. Alkilani and colleagues conducted experimental investigations utilizing PCMs in the form of capsules for solar air heating

applications. Their findings revealed that adding aluminum to paraffin wax could reduce the charging duration, and the system's effectiveness improved when wax was mixed with aluminum powder [22]. In a study related to solar collectors, Koca et al. examined a latent heat storage system based on phase-change materials, following the principles of the second law of thermodynamics. They determined that the average energy and exergy effectiveness are 45% in addition to 2.2%, respectively [23]. This analysis, conducted using the first law of thermodynamics, could be valuable for evaluating system efficiency throughout the charging cycle.

Fadl et al. conceived, constructed, and experimentally examined a shell and multi-tube latent heat storage system which is oriented horizontally. According to their experimental results, the time required for both charging and discharging significantly decreased as the shell and multi-tube latent heat storage system mass flow rate of the HTF increased [24]. They also investigated how the Stefan number and Reynold number influenced melting properties.

Considering the current global population growth rate of approximately 2%, with some countries exceeding this rate, the demand for energy is expected to increase significantly. This is driven not only by population growth but also by rising living standards. It is projected that energy demand may increase by 2 to 3 times before 2050, as suggested by Padmaraju et al [25]. Phase change materials (PCMs) find significant applications in Heating, Ventilation, and Air Conditioning systems. One of the most important applications of PCMs is in space heating and cooling [26]. PCMs play a crucial role in changing phases due to energy interactions and are widely used in modern technologies for thermal energy storage. Broadly, there are two main types of thermal energy storage systems, as discussed by Bayomy et al: Sensible Heat Storage Systems and Latent Heat Storage Systems. SHSS uses single-phase materials and stores heat simply by raising the material's temperature. It can utilize either solid materials like packed beds or liquid materials to store energy. On the other hand, LHSS employs materials that undergo phase transitions from solid to gas, either solid to gas or liquid to gas. The materials with solid-to-liquid phase change have an advantage over others because they require less volume for energy storage. In solid-phase materials, heat transfer occurs primarily through conduction, while in liquid-phase materials, convection plays a more significant role, as explained by Sivasamy [27].

Dincer and colleagues conducted an investigation of Sensible Heat Storage Systems performance in relation to thermal applications [28]. Their deductions cover various aspects, including the economics of SHS systems, selection criteria, availability for solar thermal applications, key considerations in assessing SHS systems, feasibility, environmental effects, and standards for feasibility studies. They also discuss energy-saving options in detail. The utilization of stratification to increase the efficiency of hot water heat stores through PCM modules was explored by Mehling et al [29]. This approach is frequently used in conjunction with renewable energy sources and surplus heat recycling in hot water heat tanks. By placing a PCM module located at the highest point of the water tank, the system can

store more energy and address top-layer heat loss. The study includes numerical modeling using a direct finite-difference technique and presents experimental results. Various cylindrical PCM modules were used in investigations and simulations, resulting in an average energy density increase of 20% to 45%. Additionally, It was noted that the uppermost water of the storage tank remained heated for an additional 50% to 200% of the time, even with only 1/16 of the store's volume being PCM. The properties of myristic acid as a phase-change material for energy storage were examined by Sari et al. [30-31]. They also measured the rates of heat transfer when myristic acid, a latent heat-storing substance, was melted and solidified in a sole vertical pipe with a cylindrical heat storage container mounted vertically as the heat exchanger. The study of energy storage via phase change material, specifically palmitic acid, included parameters such as heat flow rate characteristics, transition timings, temperature range, and solid-liquid interface separation. Experimental findings showed that the melting front advanced axially from the PCM tube's apex toward the base and radially inward. Convection in the liquid phase had a big impact on the melting process. In the investigated range, the flow rate and entrance temperature of the HTF had negligible effects on phase change processes. Sari et al. also conducted a study that examined the thermal and heat transport properties of a system using lauric acid to store latent heat [32]. Investigational results demonstrated since the PCM solidified and melted uniformly. The process of solidification and melting front traveled radially from the heat transfer fluid (HTF) container's outer wall to the PCM container's inner wall. Within the PCM container, the melting obverse migrated axially from the uppermost to the lowest. While it was challenging to prove solidification at axial distances, the process of melting was primarily partial by natural convection in the liquid phase due to the effects of buoyancy. In contrast, the process of solidification was managed through heat conduction and was held up by thermal resistance within the solidification layer.

The experimental findings, as presented by Sari et al., indicate that the addition of stearic acid as a PCM in a system for thermal energy storage results in superior radial melting stability compared to axial melting stability [33-34]. Furthermore, the study investigates the relationship between changes in inlet water temperature and the melting and solidification processes properties of the phase change materials. The author hypothesized that when the heat exchanger tube is oriented horizontally rather than vertically, the phase change materials exhibits improved phase change properties that are continuous and more effective. In this study, the typical heat storing efficiency, or heat exchanger efficacy, is measured at 50.3%, which is lower than anticipated for the container (PCM tube). An experiment was carried out by Punniakodi et al. investigation using a concentric short helical heat transmission tube to enhance vertical PCM melting in systems with cylindrical latent heat storage [35]. Despite numerous research efforts to alleviate the impact of low PCM thermal conductivity, ensuring long-term benefits through such improvement techniques remains challenging. The current study recommends the use of a helical tube design (HTT) to enhance melting. This proposed

approach offers a straightforward design but proves advantageous for long-term usage. There is potential for applying TES setups in solar-water heaters (SWH) and air heaters to meet both residential and commercial thermal needs. Further investigation is required to explore HTT modifications and thermal storage container layouts under various charging and discharging scenarios, with a focus on targeted thermal conductivity improvements. The study by Shamsundar N presents an analysis of freezing outside a circular tube with angular coolant temperature variation. The study utilizes closed-form equations to approximate the behavior of a material freezing outside a tube used for carrying coolant [36]. While the convective coefficient and coolant flow are thought to remain constant over time., the study acknowledges that the temperature of the coolant inlet may fluctuate both temporally and axially. In the plane of radials, a logarithmic temperature circulation is observed. The distribution of the F factor, solid percentage along the axis, centrifugal plane, and axial temperature distribution are all found to be identical. In cases with large Biot numbers, the interface takes the form of the axial temperature distribution takes on the shape of a truncated cone and becomes parabolic.

In this paper, a test facility for the proposed work has been constructed to explore the solidification and melting behaviors of PCM. The primary impartial of this investigation is to understand the functioning of phase transition materials under varying operational conditions. This paper provides a detailed account of an experimental study on phase-change-related heat transfer within a horizontal system for thermal energy storage housed in an acrylic cylinder. The material chosen for energy storage in these experiments is wax paraffin. The primary focus of this research is to investigate the selected material's phase change behaviour in a latent heat energy storage device during charging and discharging.

3. Experimental Set Up

Phase Change Materials have a unique ability for energy storage by melting at a constant temperature, making them a novel choice with characteristics unlike any other material. However, selecting the right Phase Change Materials for a specific application necessitates carefully evaluating its characteristics in conjunction with other substances used in the system. There is a wide range of PCM mixtures available, categorized as single-component systems, congruent mixtures, eutectic mixtures, and peritectic mixtures. The selection must align with the specific requirements of the application.

The heat-storing container comprises two cylinder-shaped pipes arranged concentrically. These tubes have the size of 740 lengths in millimetres, 1.5 mm in thickness, and an inner diameter of 20 mm. Copper tubes are chosen due to their high thermal conductivity. The outer shell has a 40 mm internal diameter, a 3 mm in thickness and 510 mm in length. Polycarbonate, known for its low thermal conductivity, is used for observing the charging and discharging process of paraffin wax is depicted in figure 2.

To ensure accurate temperature measurements, all K-type thermocouples were calibrated to within $\pm 0.25^{\circ}\text{C}$ before use. A pair of thermocouples is strategically positioned to measure temperature changes at the heat transfer tube's entrance and exit. Additionally, three thermocouples are attached to the copper tube's edge to measure the temperature of the heat transfer fluid and three others monitor the temperature of the paraffin wax is presented in figure 3. To maintain a constant isothermal temperature, a 2 kW electrical heater with a thermostat is provided. Water circulation is facilitated by a hot water pump with a $\frac{1}{4}$ hp power rating. The rate flow is measured using a rotameter, equipped with a measurement uncertainty of ± 0.03 kg/sec. The test setup is horizontally oriented, and contains solid paraffin wax, which serves as a medium for storing heat.

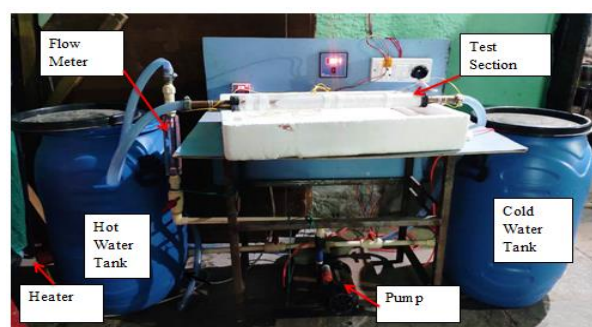


Fig.2. Experimental setup

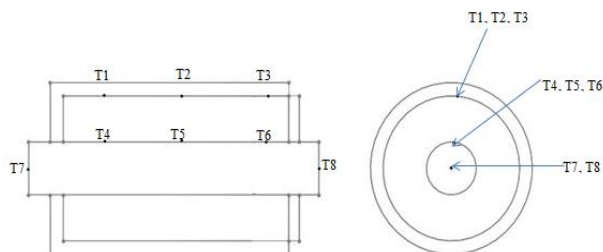


Fig. 3: Position of Various Thermocouples intimates the Thermal Energy Storage Unit

The charging process commenced with adjustable flow rates of two, four, and six lit/min, where hot water was pumped through the heat transfer tube. Temperature deviations in the axial direction were recorded every five minutes during the charging procedure. After the melting phase was completed, cold water was circulated through the heat transfer tube at varying flow rates of two, four, and six lit/min, to initiate the solidification process. The procedures for charging and discharging the phase-change material were directed at different intake HTF temperatures and rate of mass flow within the laminar range.

Types of Thermal Energy Storage:

The subsequent section discusses various methods of categorizing thermal energy storage techniques.

1. Sensible Heat of Storage (SHS):

Sensible storage of heat involves altering the temperature of a storage medium to store energy. The extent of heat stored is determined by the quantity of storage media, the temperature fluctuation, and the specific heat of the medium, as depicted in Equation 1:

$$Q_{ch} = mC_p(T_{in} - T_{out}) \quad 1$$

Where T_{in} and T_{out} are the HTF inlet and exit temperatures, respectively, and m is the mass flow rate, C_p is the heat transfer fluid's (HTF) specific heat.

2. Latent Heat of Storage (LHS):

Latent heat of storage focuses on the heat absorbed or released during a transition of the material, such as from gas to liquid or from solid to liquid. For Phase Change Material (PCM) media, the capacity for storing of a Latent heat of storage is represented by Equation 2:

$$Q_w = m[C_{sp} \cdot (T_m - T_i) + L + C_{lp} \cdot (T_f - T_m)] \quad 2$$

Where the temperatures are T_m , T_i , and T_f at which PCM melts, starts to melt, and fully melts, respectively. the mass of PCM is m , The specific heat of solid PCM is L , and C_{sp} is the specific heat of solid PCM, and C_{lp} is the liquid PCM's specific heat.

4. Results and Discussion

This section explores the transient changes in HTF and PCMs during the melting process of phase change materials at three various HTF flow rates. A comprehensive analysis of the temperature profile of wax paraffin inside an enclosed tube during melting is presented.

4.1 Temperature Profile during Melting Process

This section experimental analysis is conducted based on several parameters: the effect of the rate of flow of HTF during charging and discharging on the heat transfer tube, PCM inlet and outlet temperatures, and the PCM and heat transfer tube. Figure 4 illustrates the rate of HTF flow influences the temperature at which paraffin wax melts at various flow rates. As depicted in the graph, as the HTF flow rate increases at different points across the test section, the temperature at which melting occurs also rises. This change is due to the alteration in temperature between the intake and outflow temperatures.

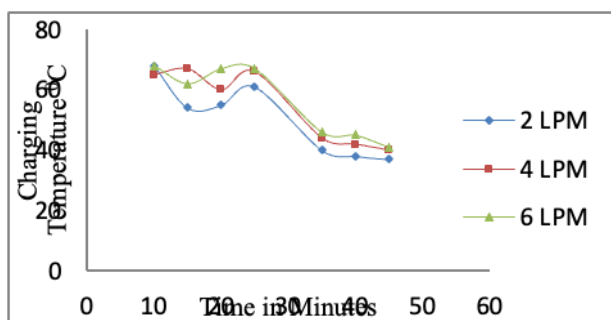


Fig.4. Effects of charging process rate of flow and inlet HTF temperature

From the experimentation, it is evident that the melting periods decreases as the charging temperature rises, as

illustrated in Figure 3 which depicts the influence of melting temperature during charging. Furthermore, Figure 3 shows the correlation between phase change materials temperature and melting time in minutes at various locations along the between phase change materials tube and tank axial pathways for volume of 2, 4, and 6 litres per minute of flow. As the PCM reaches its transition phase temperature of 58°C, there is a uniform increase in the temperature variation of the phase change materials at various locations until it reaches that temperature value. When heating liquid PCM, an isothermal phase change process is observed, and its amplitude increases rapidly. Latent heat, in this context, represents a form of heat storage through the melting of PCM.

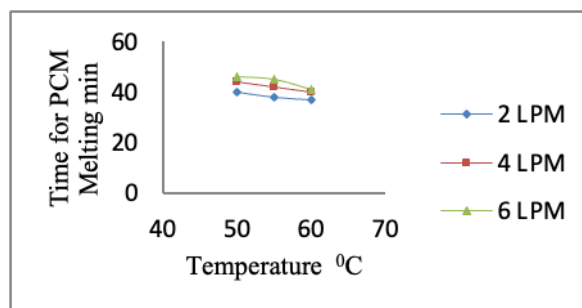


Fig. 5: Implications of HTF Flow Rate on Paraffin Wax Temperature Profile at Various Thermocouple Positions (T4, T5, T6)

Figure 5 demonstrates the temperature variations of wax paraffin at different thermocouple points. In this context, convection plays a more significant role than conduction. Melting of phase change materials is observed at 2, 4, and 6 litres per minute of flow within the test section, monitored by thermocouples T4, T5, and T6. The predominant heat transfer method is convection between wax paraffin and the HTF, intensifying with rising temperatures. In this study, the increase in PCM temperature correlates with the heat transfer fluid temperature in the hot water tank, steadily aligning with the heat transfer fluid's inlet temperature from the bath's consistent temperature. Consequently, an escalation in fluid flow rate leads to increased PCM melting. The rate of flow directly influences the surface heat transfer coefficient between the PCMs, impacting the duration needed for PCM in the tube to melt due to the heat transfer fluid's presence inside the tube.

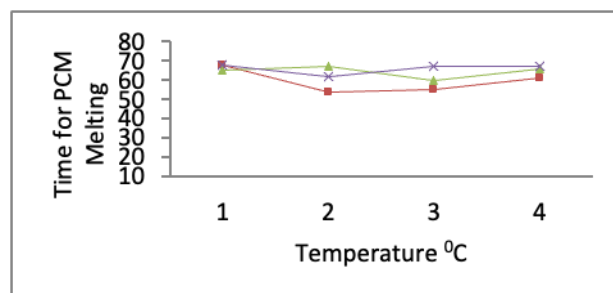


Fig.6 The effect of rate of HTF flow on temperature profile of TESU at various position of thermocouple T1, T2, T3

The information presented in Figure 6 illustrates the flow rate of HTF affects the temperature profile of the TESU at various thermocouple locations. The HTF temperature in the left and right portions of the test section is displayed. The main reason for the rising temperature is the conduction of heat through the copper tube. Due to the conductive nature of heat transfer, the melting phenomenon occurs more rapidly as the temperature increases for the whole length of the test section. At an HTF flow rate of two litres per minute, Figure 6 illustrates the variation in HTF and PCM temperatures at the top layer. It has been noted that the temperature rise in water is higher than that in PCM. This is because water can absorb heat energy more rapidly than phase change materials, contributing heat to the phase change materials.

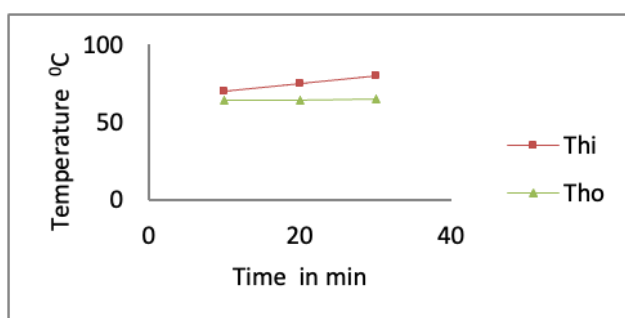


Fig.7. Effect of charging HTF temperature period at the input and exit of PCM

The outcomes of the water's temperature at the HTF fluid entrance and exit are depicted in Figure 7 above. Throughout the experimental investigation, it was found that the HTF exit temperature was lower than the HTF inlet temperature but greater than the paraffin wax PCM temperature.

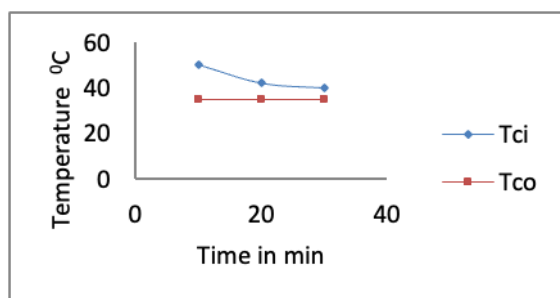


Fig.8. Impact of HTF temperature discharge period at the intake and outflow of PCM

The effect of inlet and HTF outlet temperatures on the water discharging time is illustrated in Figure 8 above. To maintain equilibrium, the water's initial temperature must be higher than its final temperature.

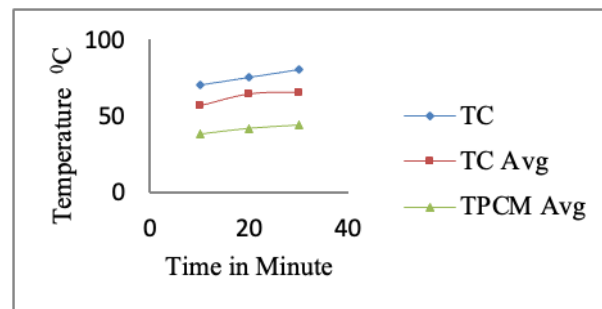


Fig.9. Effect of average temperature of copper and PCM during charging process

In this experiment, the PCM temperature increases in line with the heat transfer fluid's temperature within the tank of hot water, which rises progressively in compliance with the incoming HTF the tank's temperature set at a constant temperature. The coefficient of surface heat transfer between PCM and HTF tubes increases, leading to a rise in fluid flow rate. This impacts the duration required for PCM to melt inside the tubes. Due to the materials and the working fluid's thermal conductivity, Figure 9 illustrates that the typical temperature of a copper tube is significantly higher than the average temperature of the wax paraffin.

In the solidification process, the changes in heat transfer fluid and phase change material at different rates of HTF flow are analysed. The temperature profile of the wax paraffin during solidification in an enclosed tube is studied in detail.

4.2 Temperature Profile during Solidification Process

The experimental analysis is conducted considering the influence of HTF flow rate on the processes of charging and discharging heat transfer tube, PCM inlet and outlet temperatures, and the phase change material. Figure 10 illustrates how the HTF flow rate influences the solidification temperature of paraffin wax at various rates of flow. As indicated in the graph, the HTF flow rate has increased, the temperature at which solidification occurs rises at different points along the test section. This variation is due to the alteration in between the intake and outlet's temperatures caused by the different flow rates.

The experimentation shows that the solidification time decreases as the solidification temperature rises. Figure 9 depicted that the influence of the solidification temperature during the charging process. Additionally, the correlation between PCM temperature and solidification time in minutes at various PCM tube locations and axial positions of the tank is presented in Figure 10, considering 2, 4, and 6 litres per minute of flow rate. As the PCM approaches its transition phase temperature of 58°C, the temperature variation of the PCM at various locations increases uniformly till it reaches that temperature value. When cooling the liquid PCM, an isothermal phase change process is observed, and its amplitude increases rapidly. Latent heat is stored through the solidification of PCM.

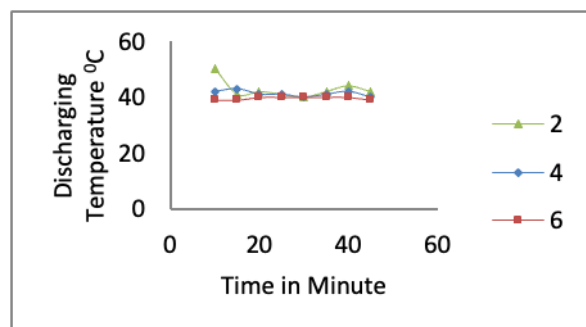


Fig.10: Effects of Solidification Process Flow Rate and Inlet HTF Temperature

4.3 Temperature Profile during HTF Discharge Process

Figure 10 illustrates the impact of the temperature profile during the HTF discharge procedure. This discharge process occurs in the same direction as the charging process. Cold HTF is pumped into the test section to initiate the discharge. The temperature of the cold HTF is maintained at ambient temperature. Initially, there's an obvious temperature difference between the phase change materials and the heat transfer fluid. Consequently, the temperature of the liquid phase change material experiences a rapid reduction at the beginning of the solidification process, marking the initiation of the discharge process. After a specific duration, the temperature nearly equals the HTF temperature on the cylinder surface. Consequently, the discharge process is exceptionally swift, requiring minimal time.

5. Conclusions

This study critically examined the limitations associated with fossil energy, particularly concerning the emission of toxic and greenhouse gases. To address these challenges, the concept of latent heat storage thermal systems has been introduced. Extensive experiments were conducted to evaluate the characteristics of the proposed latent heat storage thermal system. The experiment results provided valuable insights into various performance parameters, including Reynolds number, Stefan number, time required for PCM melting, and PCM temperature at different experiment points. Through a series of experiments, it was observed that raising the source tank's HTF temperature to 70 °C expedited the process of charging, taking about 15-20 minutes. The PCM process of charging, in turn, took about 30-45 minutes. The duration of these experiments determined the system's heat storage capacity. Optimal efficiency was achieved with a storage time of 4-6 hours. Discharging time varied based on flow rate, ranging from 15-30 minutes.

6. Future Scope

The experimental results clearly demonstrated that the proposed energy storage method significantly reduced both melting and solidification times. This innovative approach holds the potential to enhance the overall enactment of thermal energy storage systems. Moving forward, further research and development in this area could revolutionize energy storage technologies, paving the way for a more

sustainable and efficient energy future perspectives of material optimization and system integration for different application

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