Continuous Hot Water Supply from Solar Energy: Phase Change Material-Enhanced System Design

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***Abstract—* The objective of this paper is to study the design and performance of a solar water heating system equipped with Phase Change Materials (PCMs). This solar water heater comprises of evacuated tubes, through which water is heated. Heat is transferred from the water to the PCM by means of an immersion coil heat exchanger. When solar energy is available, thermal energy is stored in the PCM due to a phase change process, whereas when there is no sun, heat is extracted from the PCM to maintain water temperature. From experimental observations, it is found that about 11 kg of PCM melts within 28 minutes when the inlet water temperature is kept at 75 °C, and the flow rate of water is maintained at 1 L/min. Additionally, when there is no solar irradiance, water temperature is raised from 32 °C to 50 °C.**

***Index Terms*—Phase change material (PCM), Solar water heater, Paraffin wax, stearic acid, Evacuated tube**

I. INTRODUCTION

The growing energy demand and the shortage of traditional sources of energy led to an increase in the importance of renewable energy sources. Solar energy is considered to be one of the most widespread and environmentally safe sources of energy and is used widely for water heating because of its simplicity and cheapness [1]. Solar water heaters are usually employed in households and industries. However, solar heaters' productivity depends greatly on the availability of sunshine [2]. One of the significant disadvantages of traditional solar water heaters is the absence of hot water production in periods of no sunshine as during the night and on cloudy days.

However, to make sure that there will be enough hot water during no sunshine hours, it is possible to use various methods of storing thermal energy during sunny hours and using the stored energy when there is no direct sunlight. The most popular method of storing thermal energy consists in using Phase Change Materials (PCMs).

This material is characterized by high latent heat capacity and constant temperature during the process of changing the phase [3]. The integration of PCMs into a solar water heater allows absorbing the heat from sunshine and producing the heat by solidifying it. Many studies prove that the integration of PCMs into a thermal solar system increases the efficiency of the system and provides hot water regardless of the level of solar radiation [5]. Thus, the purpose of the research is to study the thermal performance of PCM-integrated solar water heaters.

II.LITERATURE SURVEY

The integration of Phase Change Material (PCM) with solar thermal collectors for the purpose of domestic hot water heating was studied by Pathak S. K. et al. (2023). The researchers were able to prove that the integration of the PCM with the U-tube solar collector enhances the storage of thermal energy and ensures the availability of hot water during low solar radiation. The study proves that the integration of the PCM with the solar collector significantly enhances the reliability and efficiency of the solar water heating system. The efficiency of the finned and un-finned U-tube solar water heaters with the integration of paraffin wax PCM was analyzed by Sayed S. M. S. E. et al. (2017). The experimental analysis proved that the integration of the PCM with the solar water heating system maintains the water temperature above 30°C during the night hours. The study proved that the integration of the finned tube with the solar collector enhances the heat transfer rate in comparison with the un-finned tube. The significance of the heat transfer enhancement techniques was proved in the study. A comparative study of various designs of evacuated tube solar collectors was carried out by

Said S. et al. (2023). The study aimed to analyze the effect of various designs on heat absorption. The results showed that the optimization of collector design enhances efficiency. This shows that proper collector design selection is important for the efficient utilization of solar energy for water heating. The characteristics of paraffin wax in a cylindrical storage device for thermal energy storage were studied by Huang X. et al. (2019). The study aimed to analyze the melting and solidification of PCM for various temperature conditions. The results showed that a greater temperature difference enhances the heat transfer rate, resulting in improved efficiency. This shows that the temperature gradient also affects the performance of a thermal storage device. The effect of heat exchanger configuration on the melting and solidification of PCM was studied by Radomska E. et al. (2020). The results showed that the geometry of the heat exchanger affects the performance of the heat transfer system. The results showed that proper heat exchanger configuration enhances the efficiency of the thermal storage device.

III. SYSTEM DESCRIPTION

The developed system is a solar water heating system with the integration of Phase Change Material for storing thermal energy. The system uses an evacuated tube collector to collect solar irradiance and heat the water. The water is then circulated through an immersion coil heat exchanger that is placed in the PCM storage tank. This helps in the effective heat transfer between the circulated water and the PCM.

A. Components of the System

The evacuated tube collector is used as the primary heat absorption unit. The solar energy is converted into heat energy. The storage tank is used to hold the water for some time before it is passed into the heat exchanger. The immersion coil heat exchanger is used. Copper is used because it has high thermal conductivity. The heat is transferred efficiently. The PCM used in the system is a mixture of paraffin wax and stearic acid. The mixture is chosen because it has the appropriate melting point and high latent heat. The container holds the PCM. The piping system is used to connect all the devices and ensure that the water flows continuously.

B. Working Principle

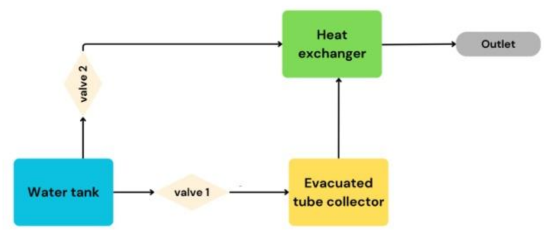

Fig 1. Flow chart of the system.

During the sunshine period, water is heated in the evacuated tube collector up to a higher temperature and flows through the immersion coil heat exchanger. In this condition, Valve 1 is kept open and Valve 2 is closed, allowing hot water to circulate through the heat exchanger. Due to the temperature difference between the hot water and the PCM, heat is transferred to the PCM, causing it to melt and store thermal energy in the form of latent heat.

During the non-sunshine period, the flow path is altered by operating the valves. Valve 1 is closed and Valve 2 is opened, allowing relatively cooler water to pass through the heat exchanger. The PCM, which has stored thermal energy, begins to solidify and releases heat to the water. As a result, the outlet water temperature increases, providing usable hot water even in the absence of solar radiation.

IV. METHODOLGY

The developed system is a solar water heating system with the integration of Phase Change Material for storing thermal energy. The system uses an evacuated tube collector to collect solar irradiance and heat the water. The water is then circulated through an immersion coil heat exchanger that is placed in the PCM storage tank. This helps in the effective heat transfer between the circulated water and the PCM.

A. System Parameters

The performance of the PCM-based solar water heating system is evaluated using the following parameters. The amount of PCM used in the system is 11 kg. The latent heat of the system is 207 kJ/kg. The melting point of the system is around 55°C. Water is used as the heat transfer fluid in the system. The specific heat capacity of water is 4.18 kJ/kg°C. The inlet temperature of water during the sunshine period is around 75°C. During the non-sunshine period, the temperature is around 32°C. The flow rate of water is maintained at 1 litre per minute, which is equivalent to 1 kg/min.

B. Experimental Procedure

The system operates in two distinct conditions. The conditions include sunshine and non-sunshine periods. During the sunshine period, water is heated in the evacuated tube collector. The hot water is then circulated in the immersion coil heat exchanger. During this time, Valve 1 is left open, while Valve 2 is closed. This is done to allow hot water to flow in the direction of the PCM container. The temperature of the water at both the inlet and outlet of the heat exchanger is measured. During the non-sunshine period, the system operates with the opposite conditions. Valve 1 is closed, while Valve 2 is left open. This enables cold water to flow in the direction of the heat exchanger. The thermal energy is released by the PCM as it solidifies. The temperature of the water at the outlet is measured.

Fig 2. Fabricated model of the system

C. Thermal Analysis

For the purpose of simplifying the analysis, the following assumptions are made. The heat loss to the surroundings is neglected. The flow rate of water is taken to be constant during the entire process. The temperature of the PCM is taken to be constant during the phase change process. The thermal properties of water and the PCM are taken to be constant over the range of the temperature. The heat required to melt the PCM is calculated.

The heat required to raise the temperature of water is calculated by:

$$Q = m \times c \times \Delta T \qquad (1)$$

where,

Q = heat required (kJ)
m = mass of water (kg)
c = specific heat capacity of water (kJ/kg·K)
ΔT = temperature rise (°C)
Substituting the given values:

$$Q = 6 \times 4.186 \times 40 = 1004.64 \text{ kJ} \approx 1.0 \text{ MJ}$$

Thus, about 1004.64 kJ of heat energy is required to heat the water.
The PCM storage capacity is calculated as:

$$Q = m \times L \qquad (2)$$

where,
m = mass of PCM (kg)
L = latent heat of fusion (kJ/kg)
Mass of PCM = 11 kg

$$Q = 11 \times 207 = 2277 \text{ kJ}$$

Therefore, the PCM can store about 2277 kJ of thermal energy, which is enough to supply the heat during the non-sunshine periods.
The rate of heat transfer between the circulating water and the Phase Change Material is also affected by the temperature variation between the inlet water and the PCM, and the rate at which the mass of the water contained in the immersion coil heat exchanger flows. The heat transfer rate is estimated by the calculations and the time taken to get the complete one melting of the PCM.

- Mass of PCM = 11 kg

- Latent heat of PCM = 207 kJ/kg
- Inlet water temperature = 75 °C
- PCM melting temperature = 55 °C

Temperature difference:

$$\Delta T = T_{in} - T_{pcm}$$
$$\Delta T = 75°C - 55°C = 20 \circ C$$

Specific heat capacity of water: Cp = 4.18 kJ/kg·°C

Water flow rate = 1 litre/min

Since 1 litre of water 1 kg The mass flow rate becomes: = 1 kg/min .

The selected flow rate ensures continuous circulation of water through the copper coil heat exchanger and allows effective heat transfer between water and PCM.

The total heat required to melt the PCM is calculated using:

$$Q = m \times L$$
$$Q = 11 \times 207 = 2277 \text{ kJ}$$

Therefore, 2277 kJ of thermal energy is required to completely melt the PCM.

The heat supplied by the circulating water per minute is calculated as:

$$Q = \dot{m} \times Cp \times \Delta T$$
$$Q = 1 \times 4.18 \times 20 = 83.6 \text{ kJ/min}$$

Thus the circulating water supplies approximately 83.6 kJ of heat per minute to the PCM.

The time required to melt the PCM is calculated by dividing the required heat by the heat supplied per minute.

$$t = \frac{Qrequired}{Qper\ minute} \tag{3}$$
$$t = \frac{2277}{83.6} = 27.23 \text{ minutes}$$

Therefore, the time required to melt the PCM completely is approximately: t = 28 minutes

V. RESULTS AND DISCUSSION

The performance of the PCM integrated solar water heating system was tested under sunshine and non-sunshine conditions. The results of the experiment highlight the melting characteristics of PCM, heat storage capacity, and heat recovery characteristics.

A. Experimental Observations

Table below presents the key experimental observations of the system, focusing on temperature variation, PCM behavior, and heat transfer performance during different time intervals.

Table 1: Operating Temperature Conditions

Condition	Inlet Temperature	Outlet temperature
Sunshine Period	75·°C	55·°C
Non sunshine Period	32·°C	50·°C

During the sunshine period, the excess heat of the solar water is transferred to the PCM through the coil. The heat transfer melts the PCM and stores the heat in the form of latent heat, reducing the temperature of the outlet water to 55°C. During the non-sunshine period, the heat is released from the PCM and transferred to the water, increasing its temperature to 50°C. This system ensures the continuous supply of hot water even in the absence of sunshine. During the sunshine period, the PCM is charged with heat Water, cooler water at 32°C, enters the system. The melted PCM will give off its latent heat through the coil and cause the water temperature to rise to 50°C. This will provide hot water without the need for sunlight. From the experimental results, it is evident that the PCM stores excess heat during the sunshine period and maintains water at 55°C. This indicates that it can absorb heat well. During non-sunshine periods, the stored heat is used to warm the water from 32°C to 50°C. Therefore, it increases the efficiency of the solar heater by providing hot water day and night.

VI. APPLICATIONS

The developed PCM-integrated solar water heating system has many significant applications in different fields. The ability of the system to store thermal energy and provide hot water continuously is significant for different applications. The major application areas of the developed system are as follows:

A . Domestic Continuous Hot Water Supply

Provides uninterrupted hot water for residential areas even at night or in cloudy weather. Ensures energy savings as it reduces the need for electric geysers.

B . Suitable for hotels, hostels, and resorts

Hot water is often in demand in hotels, hostels, and resorts. The PCM storage system will ensure hot water is available 24/7. This will increase customer satisfaction.

C . Hospitals and Healthcare Facilities
Used for sterilization, cleaning, and other healthcare activities that require hot water continuously. The system will provide reliable service in case of power failure due to stored thermal energy.

D . Industrial Water Heating Applications
Suitable for industries like textile, food processing, dairy industries, etc. The system will reduce fuel consumption and save cost.

VII. CONCLUSIONS

The findings of this study verify that the combination of Phase Change Material (PCM) with solar water heating systems is capable of overcoming the problems faced by traditional systems that do not have the ability to provide hot water at times when there is no sunlight. A mix of stearic acid and paraffin wax has been shown to provide latent heat storage and control over the release of energy through stable temperature maintenance, thus enabling the storage of excess heat during the day and providing hot water at night (even in the absence of solar radiation) making this system reliable and consistently functional. The experimental results provide further evidence of the consistent temperature difference between the inlet and outlet of the system, along with proof of efficient heat transfer occurring through the use of a copper coil heat exchanger. The results of both sunshine and non-sunshine testing on the PCM-based thermal energy storage system confirm that PCM-based thermal energy storage systems provide significantly increased levels of reliability and continuity for the heating system as compared to conventional heating systems. The proposed system also has an amazing ability to function as a renewable heating solution for domestic hot water. Because of this ability to use a relatively low-priced and sustainable building material combined with its small size and use of the sun's energy, the system can be considered to be a very environmentally sound and inexpensive way to supply heat for appliances in homes and businesses. It contributes greatly to the reduction of the amount of electricity taken from the grid and, therefore, to saving energy and lowering costs associated with electricity use. Additionally, due to its potential to be made in a variety of sizes, the system could be used to fill a wide variety of needs in homes, schools, and small manufacturers. Overall, PCM technology can significantly improve the performance of solar heating systems and potentially provide a solution for energy-efficient thermal storage systems in the future.

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