Thermal Analysis of Solar Flat Plate Collector using Phase Change Material

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Abstract

Objective: The objective of the paper is to study the performance of solar flat plate collector using phase change material.

Methods/analysis: A phase change material (PCM) was combined with the thermal energy storage system to study the performance of Integrated Collector Cum Storage Solar Water Heater (ICSSWH). The Latent Heat Storage (LHS) was preferred as it stores the excess thermal energy beyond the sunshine and releasing it when there is energy demand. There are many phase change materials that melt and solidify over a range of temperature, among that paraffin wax was selected as it is cost effective and provides better thermal efficiency for longer duration.

Findings: Regardless of the daily operations, the Integrated Collector Cum Storage Solar Water Heater (ICSSWH) gives good thermal efficiency for longer duration by using paraffin wax. In contrast to the conventional solar water heater the integrated PCM storage tank with solar water heater is more efficient because of its large storage capacity, isothermal nature during the charging and discharging and smaller size. During the discharging process, the heat transfer fluid gained large amount of heat from the PCM and it withstood heat for nearly more than five hours. During the night, it was found that the Latent Heat Storage (LHS) was effective as it allows minimum energy losses and conservation of energy. The maximum water outlet temperature was achieved by using paraffin wax and so this PCM can be considered as the most beneficial for the solar application from techno-economical aspects.

Application/Improvements: The mentioned thermal system is used for water heating and space heating as it is cost effective. The system can be further be modified by combining with Sensible Heat Storage (SHS) for better utilization of energy.

Keywords: Flat Plate Collector (FPC), Integrated Collector Cum Storage Solar Water Heater (ICSSWH), Latent Heat Storage (LHS), Phase Change Material (PCM)

1. Introduction

The method of using a Latent Heat Storage (LHS) in a Solar Water Heater (SWH) is one way of storing the excess energy and releasing it when the energy is needed and to extend the utilization. There are many phase change materials that melt and solidifies over a range of temperature, among that paraffin wax is selected in this work as it is cost effective.

The paraffin wax provides higher thermal efficiency for longer duration. When compared with the conventional Solar Water Heater (SWH) the integrated PCM storage with SWH is more efficient. The Thermal Energy Storage (TES) with Phase Change Material (PCM) is used widely because of its large storage capacity and isothermal nature during the charging and discharging process. In the study, a shell and tube arrangement with paraffin wax was used in solar water heating system.

Gbaha et al. studied two solar water heaters; one using glass wool and the other using vegetable fiber. Hematian et al. determined experimentally the efficiency of solar air plate collector. Saitoh et al. experimentally investigated the thermal characteristics of a phase change thermal energy storage unit. Watanabe et al. developed a model for predicting the transient behavior of the latent heat storage system. Velraj et al. numerically studied the solidification of PCM in a vertical internally finned tubes.

Cho et al. investigated the thermal characteristics of paraffin in a spherical capsule during freezing and melting processes. Nallusamy et al. presented the
utilization of solar energy for water heating applications using combined sensible heat and latent heat storage system. Fouda et al. studied the Glauber’s salt as the PCM in the solar storage system. Bellacci et al. used the enthalpy method, numerically analyzed the cyclic behavior of a phase change shell and tube thermal energy storage system. Mehling et al. simulated the energy storage density of solar hot water system using cylindrical PCM modules. Ghoneim et al. studied the thermal performance of latent heat system. Hoogendoorn et al. modeled the latent heat system. Bansal et al. studied the performance equation of collector cum storage system using phase change materials.

PCMs with high latent heat, high thermal conductivity and specific heat are suitable for solar water heating applications. Paraffin wax is suitable for solar water heater due to its availability, non-corrosiveness, low melting point and low cost. In the experimental study melting point of Paraffin wax was found to be 60°C and it is insoluble in water. Paraffin wax is not affected by reagents. Its energy content is more.

2. Materials and Methods

2.1 Experimental Setup

The thermal performance of the water heating system was studied experimentally.

2.1.1 Thermal Energy Storage Tank

Figure 1 shows the thermal energy storage tank made of cylindrical mild steel. Inside there is a spiral copper tube. When the hot water flows from flat plate collector to the copper tube inside the thermal storage tank heat transfer takes place between the PCM and copper tube, the tank is filled with PCM between the outer shell and copper tube. PCM was selected as paraffin wax. This tank was well insulated with glass wool to avoid energy losses.

Figure 1. Thermal energy storage tank.

The storage tank dimensions of 600 mm height, 300 mm diameter and 50 mm thickness with glass wool as the insulating material are shown in Table 1. This allows storage of excess energy for use. Figure 2 shows the schematic of the storage tank.

Table 1. Specifications of the storage tank

| Material                  | Mild steel          |
|---------------------------|---------------------|
| Height of the cylinder    | 600 mm              |
| Diameter of the cylinder  | 300 mm              |
| Thickness of the cylinder | 50 mm               |
| Insulating material       | Glass wool          |

Figure 2. Schematic of the storage tank.
2.1.2 Flat Plate Collector

Figure 3 shows the Flat Plate Collector (FPC) which is designed for the low temperature. It absorbs the solar energy and transfers the heat to liquid or gas. It is located on the top of the buildings. It does not require sun tracking and requires less maintenance. The dimensions of the collector are shown in Table 2. The absorber tubes are made of copper of diameter 6.25 mm. They absorb the solar radiation and transfer the energy to the working fluid. Four copper tubes inside the Flat Plate Collector (FPC) are used in the set up.

Table 2. Dimensions of solar Flat Plate Collector (FPC)

| Dimensions of FPC          | 0.5 m x 0.6 m x 0.10 m |
|---------------------------|------------------------|
| Number of copper tubes    | 4                      |
| Diameter of copper tubes  | 6.25 mm                |
| Number of flow pass used  | 2                      |
| Insulation thickness      | Bottom:10 mm, Side:5 mm|
| Glass thickness           | 5 mm                   |

Figure 3. Flat Plate Collector.

2.1.3 Water Collecting Tank

Figure 4 shows the water collecting tank and the specifications of the collecting tank are shown in Table 3, which has the dimensions of length 600 mm, diameter 300 mm and capacity of 40 litres. A flow control valve is shown in Figure 5. A pump was connected to a DC motor, 240 V, 50 HZ supply was used.

Table 3. Specifications of the collecting tank

| Material       | Mild Steel |
|----------------|------------|
| Length         | 600 mm     |
| Diameter       | 300 mm     |
| Volume of tank | 40 litres  |

Figure 4. Water collecting tank.

Figure 5. Flow control valve.

2.1.4 Flow Separation Valve

Figure 6 shows a flow separation valve which is used to separate the water flow coming from the flat plate collector into two pipes one connected to the thermal energy storage tank and other to the water collecting tank.

Figure 6. Flow separation valve.

2.1.5 Solar Water Heating System

The solar water heating has two main components. 1) a
solar collector and an insulated thermal storage tank. In the study, the solar collector and the thermal energy storage were experimentally analyzed. Figure 7 shows the pump connected to a DC motor whereas Figures 8 and 9 show the set up and schematic arrangement.

Figure 7. Pump connected to a DC motor.

The charging of the thermal energy storage was done during the day. During the day, cold water passes through the solar collector. Water absorbs heat and part of the hot water flows through the heat storage unit for charging the PCM tank. The rest of the water directly goes to the water storage tank.

During the night, the flow control valve is closed. In order to maintain uniform outlet temperature, the phase change material is chosen as paraffin wax.

The properties of the paraffin wax are shown in Table 4. The space between the copper tube and outer shell of the tank was filled using Paraffin wax and the tank was well insulated. The input temperature was taken as 65°C, i.e. the output from the solar collector system. The discharge cycle started with the flow of water at a temperature around 30°C. The discharge cycle ended when the outlet temperature came to ambient temperature.

Table 4. Properties of Paraffin wax

| Property               | Value          |
|------------------------|----------------|
| Density                | 900 Kg/m³      |
| Temperature Range      | 46°C to 68°C   |
| Melting Point          | 60°C           |
| Heat Of Combustion     | 42 KJ/gm       |
| Specific Heat Capacity | 2.14-2.9 J/gm K|
| Heat Of Fusion         | 200-220 J/gm   |

Water inlet temperature to the collector was 26°C and was passed to the copper tube which was attached to the absorber plate; the maximum hot water temperature obtained by the collector was 65°C. The hot water at 65°C flows outside the flat plate collector and passed to PCM tank where its temperature was measured by the temperature gauge connected at the end of the collector.

Figure 8. Arrangement of the set up.

Figure 9. Schematic set up.
Average temperature maintained at storage tank was 62°C. At 60°C paraffin wax phase changes from solid stage to liquid stage and charging happened even at cloudy condition and the average temperature was maintained.

3. Results and Discussions

Direction of FPC: South direction
Inclination angle (θ): \( θ = \text{latitude} + 15° \)
Latitude of Chennai = 13°08’
\( θ = 13.08 + 15 = 28.08° \)
Thermal energy storage:
Length of the collecting tank = \( L = 0.6 \) m
Diameter of the collecting tank = \( D = 0.3 \) m
Cross sectional area of collecting tank \( A_c = \frac{π}{4} (30)^2 \)

\[ = 707.14 \text{ cm}^2, \text{Therefore } A_c = 0.070714 \text{ m}^2 \]  

(1)
Surface area of the collecting tank = \( A_s = 3.14 \times 30 \times 60 = 5657.14 \text{ cm}^2 = 0.565714 \text{ m}^2 \).

(2)
Volume of the collecting tank = \( V = \frac{π}{4} (30)^2 \times 60 = 42411.6 \text{ cm}^3 = 0.0424116 \text{ m}^3 \)

(3)
Required mass of paraffin wax = \( m = 900 \times 0.0424116 = 38.1699 \) kg. Required wax for filling thirty percentage of the tank = \( 30/100 \times 38.1699 = 11.45 \) kg.

(4)
The Flat Plate Collector (FPC) was oriented south. The inclination angle was taken as 28°. The above calculations were performed for the experimental set up. The mass of Paraffin wax was found as 11.45 kg.

Figure 10. Time vs temperature plot without PCM.

Figure 10 shows the time vs temperature plot without PCM. The inlet temperature was 28°C. The readings were taken for three days and the average readings were obtained. The temperature rose and along with the decrease in temperature the decrease in water temperatures were noted. The temperatures obtained here are very low because the solar flat plate collector used here was a model. The inlet water temperature was raised by boiling.

Figure 11 shows the time vs temperature plot with PCM. Here the temperature obtained was observed from the outlet of the thermal storage tank. The temperature is measured by using temperature gauges. The obtained temperature is not enough to melt the phase change material as it is having melting point around 60°C. So instead of using the normal tap water directly, it is heated by external heater to higher temperature and now the water is used.

Figure 11. Time vs temperature plot with PCM.

Figure 11 shows the time vs temperature plot with PCM. Here the temperature obtained was observed from the outlet of the thermal storage tank. The temperature is measured by using temperature gauges. The obtained temperature is not enough to melt the phase change material as it is having melting point around 60°C. So instead of using the normal tap water directly, it is heated by external heater to higher temperature and now the water is used.

Figure 12. Time vs temperature plot without PCM using heated water.

Figure 12 shows the time vs temperature plot without PCM using heated water. Here the temperatures rose to more than 60°C. The highest temperature obtained here was 66°C. Temperature gauges are used to measure the temperature. The temperatures obtained here are relatively higher than the previous readings. The efficiency can be increased by increasing the temperature of the water. The variations and observations are shown in Figure 13.

Figure 12. Time vs temperature plot without PCM using heated water.
Figure 13. Time vs temperature plot with PCM using heated water.

Figure 13 shows the time vs temperature plot with PCM using heated water. Here the temperatures obtained were sufficient to melt the phase change material that was present in the thermal energy storage tank. The maximum temperature obtained here was 69°C. So with the usage of heated water the efficiency was increased when compared to the previous observations. The observations and variations between time and temperature are shown in the graph.

Figure 14 shows the variation of temperatures for discharging process. It shows the variation of temperatures by using PCM along with the normal water and without using PCM. From the above graph we can say that slope of the curve with PCM is almost constant when compared to curve without PCM.

Figure 14. Variation of temperatures for discharging process.

4. Conclusion

Regardless of the daily operations the Integrated Collector Cum Storage Solar Water Heater (ICSSWH) gives better thermal efficiency for longer period of time by using paraffin wax as PCM. When compared with the solar water heater the integrated PCM storage tank with solar water heater was found to be more efficient and cost effective. During the discharging period, the heat transfer fluid gained enormous amount of heat from the PCM. Hence paraffin wax can be used for solar application from techno economical aspects.

5. References

1. Gbaha P, Ori TR, Andoh HY, Koffi PME, Konan V, Saraka JK. Thermal and economical study of two solar water heaters: the one using glass wool and the other vegetable fiber as thermal insulator Indian Journal of Science and Technology. 2011 Jul; 4(7):1–6.
2. Hematian A, Ajabshirchi Y, Bakhtiari A. A. Experimental analysis of flat plate solar air collector efficiency. Indian Journal of Science and Technology. 2012 August 5(7); 1–5.
3. Saitoh T, Hirose K. High performance phase-change thermal energy storage using spherical capsules. Journal of Chemical Engineering.1986; 41:39–58.
4. Watanabe T, Kikuchi H, Kanazawa A. Enhancement of charging and discharging rates in a latent heat storage system by use of PCM with different melting temperatures. Heat Recovery Systems and CHP. 1993; 13:57–66.
5. Velraj R, Seeniraj RV. Heat transfer studies during solidification of PCM inside an internally finned tube. Journal of Heat Transfer. 1999; 121:493–7.
6. Cho K, Choi SH. Thermal characteristics of paraffin in a spherical capsule during freezing and melting processes. International Journal of Heat and Mass Transfer. 2000; 43:3183–96.
7. Nallusamy N. Effective utilization of solar energy for water heating applications using combined Sensible and Latent heat storage system. Proceedings of the International Conference on New Millennium Alternate Energy Solutions for Sustainable Development, PSG Tech; 2003. p. 103–8.
8. Fouda AE, Despault, GJG, Taylor JB, Capes CE. Solar storage systems using salt hydrate Latent heat and direct contact heat exchanger characteristics of pilot system operating with sodium sulphate Solution. Solar Energy. 1984; 32(1):57–65.
9. Bellacci C, Conti M. Phase change thermal storage: transient behavior analysis of a solar receiver storage module using the enthalpy method. International Journal of. Heat and Mass Transfer. 1993; 36:2157–63.
10. Mehling H, Cabezal, F, Hippel S, Hiebler S.PCM-module to improve hot water heat stores with stratification. Renewable Energy. 2003; 28(5):699–711.
11. Ghoneim AA, Klein SA. The effect of phase-change material properties on the performance of solar air-based heating systems. Solar Energy. 1989; 42(6):441–7.
12. Hoogendoorn CJ, Bart GCJ. Performance and modelling of latent heat storage. Solar Energy; 1992; 48(1):53–8.
13. Bansal NK, Buddhi D. Performance equation of a collector cum storage using phase change materials. Solar Energy. 1992; 48(3):185–94.
**Nomenclature**

| Symbol | Description                               |
|--------|-------------------------------------------|
| $A_c$  | Area of cross section of the collecting tank |
| $A_s$  | Area of surface of the collecting tank     |
| $D$    | Diameter of the collecting tank            |
| $L$    | Length of the collecting tank              |
| $m$    | Mass of Paraffin wax                       |
| $V$    | Volume of the collecting tank              |
| $\theta$ | Inclination angle                         |