Performance study of solar water heater integrated with reflectors to enhance the water temperature

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Abstract

Natural convection-based solar water heater is a widely used system to generate hot water for household as well as industrial applications. With the flat plate collector design, the system can generate a water temperature of around 333 K. Forced circulation or evacuated tube-based solar water heaters are available to generate higher temperatures of about 363-368 K, however, they have higher operating and capital costs. With the objective of generating a higher temperature of water above 363 K, for mainly industrial applications at lower cost, this paper presents an experimental performance study of a basic flat plate collector design integrated with side reflectors. It also includes a performance comparison of solar water heaters with and without reflectors and an evaluation of overall thermal efficiency.

Keywords: Solar water heater, Reflector, Solar energy, Thermal efficiency

1. Introduction

One of the reports states that about 54% of the world's total energy delivered is consumed by the industrial sector mainly in steam generation, air conditioning, and heating application (International Energy Outlook, 2016). Further the global industrial energy consumption is expected to grow by 39% from 2012 to 2040, with an average growth of 1.2% per year; simultaneously, the consumption of renewable energy is also expected to grow at the rate of 1.7% per year from 2012 to 2040 (International Energy Outlook, 2016) with a key role to be played by solar thermal energy based systems due to its favorable conditions in comparison to other renewable resources. Solar Water Heaters (SWH) are one of the widely used solar thermal energy systems to generate hot water for domestic and industrial applications. Fernández (2023) reported that the global solar water heating capacity increased to 522 GWTh (Giga Watts Thermal) in 2021 from 171 GWTh in 2019.

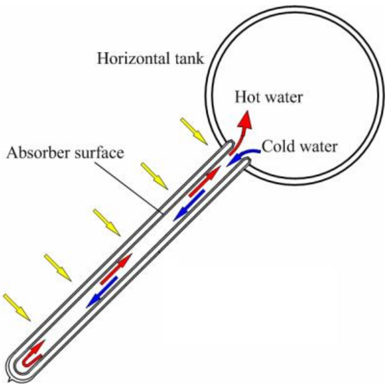

Fig 1: Natural convection process (Budihardjo et al., 2004)

The type of SWH system used for the purpose of this experiment uses natural convection as its working principle. Natural convection is referred to the moment of the fluid caused by the variation in the density due to temperature differences along the fluid body as shown in Figure 1. In the SWH working on this principle, the temperature of water in the solar insolation collecting and absorbing pipes increases relative to the temperature of water in storage tank, this temperature difference is responsible for the natural convection process in the system. The experimental setup has a simple flat plate solar collector design which provides 333-338 K temperature of the water. However, it takes almost complete sunshine hours in a day to achieve such temperatures and this range may not be sufficient for industrial applications. It needs a slightly higher range of hot water temperatures. Other designs such as forced circulation or evacuated tube solar collector-based systems are available to generate a higher temperature of around 363 K at a higher operating and capital cost. In view of this, the efficiency enhancement of natural convection based solar water heater has been selected for the current study.

10.18086/swc.2023.06.01 Available at http://proceedings.ises.org

Enhanced efficiency means a particular solar water heater will be capable of generating more hot water in the terms of temperature, for the same collector design and area for solar insolation collection or a design with some changes, this interprets into lower operating costs over the system's lifetime. Also, as the dependence on conventional fossil fuels decreases, we can avoid the rising costs of energy generation from these fuels by the implementation of such systems.

A case study on the various demonstrated methods that have been studied and employed in the past to enhance the thermal efficiency of flat plate solar collector (FPSC) (Darbari and Rashidi, 2021) includes the use of porous materials, such as conjugated porous blocks placed near the bottom insulator plate to increase collector efficiency by improving heat transfer by effective thermal mixing; similarly, using metal foam for improved thermal mixing; using convective barriers in order to reduce thermal energy loss; using fins to enhance the storage capacity in phase change material with larger values of melting temperature and phase change materials to significantly enhance thermal efficiency. Additionally, the incorporation of nanoparticles, i.e., using enhanced working fluid along with geometrical changes like using converging passages, has been studied, with findings suggesting efficiency improvements as a result of increased convection heat transfer coefficient; the injection of air bubbles into the system has also been explored, resulting in increased outlet temperatures of the working fluid by forming the insulating layer of air on the internal surface of the collector and increasing heat transfer resistance. Also, another method studied was the utilization of rotary pipes to distribute the accumulated heat more efficiently in order to increase convective heat transfer and reduce pressure drop in FPSC. These various techniques collectively contribute to improving the overall performance of FPSCs

The system developed for this experimental study uses reflectors that can be set at different angles to increase the radiation incident on the absorber plate, this constructional improvement helps increase the temperature of the working fluid more effectively, compared to a more conventional SWH without reflectors, for the same ambient temperatures and similar construction. The different constructional requirements include the type of material used for absorbing pipes, the material used for reflectors, the angles at which the reflectors are set, the slope angle, and amount of the water used.

2. Methodology

2.1 Experimental Setup and Components

The complete experiment was carried out in Ahmedabad city (23°01′17.83″ North, 72°34′46.96″ East), Gujarat, India. The experimental setup replicates the conventional parallel tube SWH as shown in Figure 2, consisting of a collector, which is a wooden box with a glass cover and aluminum tubes within it.

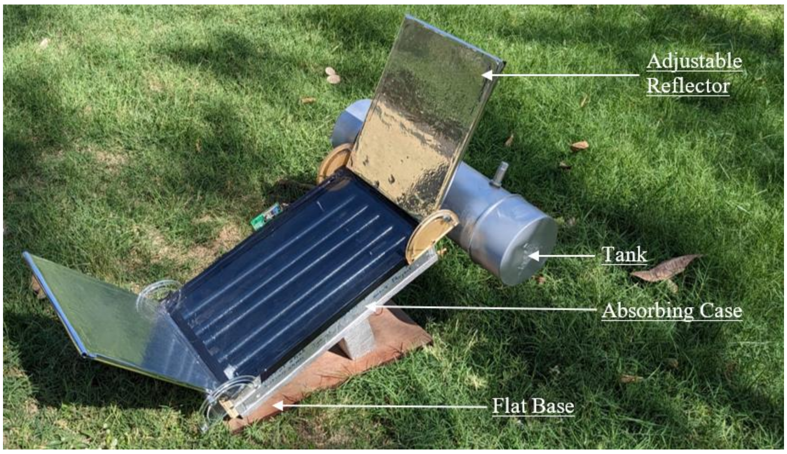

Fig 2: Experiment setup with reflectors and component labels

The collector box is inclined at an angle β, which depends on the latitude of the location (Ali, 2017). The dimensions of the collector box are 560 x 330 x 150 mm, and the interior walls of the collector box are covered with aluminum sheets. The inner base of the collector acts as the absorber, is also covered with an aluminum sheet, and the aluminum tubes are used as thermosyphons (Zohuri, 2020) also painted black. The selection of black paint in the set-up is based on the performed experiments of Tripanagnostopoulos et al. (2000), which evaluated the efficiency and performance of similar collectors with absorbers of different colors, the one with black-colored absorbers yielded maximum efficiency.

The single glass cover is used as a glazing material, of the dimensions 520 x 290 mm with a thickness of 5 mm for optimum SWH efficiency (Bakari et al., 2014). The aluminum tubes are connected to a storage tank externally, which stores as well as supplies the water to be heated. The diameter of the aluminum tubes used is 25 mm with a length of approximately 450 mm within the collector box, such 5 tubes have been used in this setup. The box and the tank are fixed with the supports and are mounted on a base for stability. The exteriors of the collector box and the tank are painted gray, using a light-colored exterior such as gray or white, which helps to keep the tank's exterior temperature lower, reducing the need for adding insulation. The parameters of the setup are given in the Table 1.

Table 1: Experimental setup parameters

Parameters	Values	Definitions
L_1	560 mm	Length of collector box
B_1	330 mm	Breadth of collector box
H_1	150 mm	Height of collector box
L_2	520 mm	Length of glass cover
B_2	290 mm	Breadth of glass cover
H_2	5 mm	Thickness of glass cover
D	25 mm	Diameter of aluminium tube
L_3	450 mm	Length of aluminium tube
L_4	390 mm	Length of reflectors
B_4	270 mm	Breadth of reflectors
Ψ_1	105°	Angle of top reflector, measured from the collector surface
Ψ_2	120°	Angle of bottom reflector, measured form the collector surface
β	23°	Angle of inclination of collector box
γ	180°	Surface azimuth angle, facing due south

There are two equal flat rectangular reflectors integrated into this conventional SWH setup, one at the top and another at the bottom with angles ψ_1 and ψ_2 respectively having the dimensions of 390 x 270 mm. The optimum angles for those reflectors depend on the collector angle β and further on the angle of incidence θ. An experiment conducted by Rachedi et al. (2022) shows the variation in reflector angles as a function of day, for two systems, one with dual-axis tracking, while the other is static, like this experimental setup. For such a system, during summer the optimum angle for the top reflector is more than 70° and for the bottom reflector, the optimum angle is less than 60°. Chrome silver vinyl sheet is used as a reflecting material for the reflectors having reflectivity above 90% which higher than that of polished aluminum foil (Kedar et al., 2021). Another benefit of using chrome silver vinyl sheet is its simplicity in attaching with reflectors and lightweight in compared to mirrors, therefore, unlike mirror, chrome silver vinyl sheet is easier to use as reflectors.

The entire system is integrated with three K type thermocouples with MAX6675 module, controlled by Arduino UNO R3 microcontroller, to obtain real time data of the temperature measurements in different sections of the setup, a micro-SD card module for data collection and a display is also included in order to monitor these temperatures.

2.2 Experimental Procedure

The volume of water used for all the experiments was 15 liters. Total solar insolation is a combination of direct radiation, diffused radiation, and reflected radiation. It depends on the time of the year as well as the time of the day, therefore selection of the time significantly influences the efficiency of the collector. The maximum temperature output in such a system is achieved at noon when the Sun is at its zenith (Proszak-Miąsik and Rabczak, 2017). Therefore, the experiments were performed between 11 a.m. and 3 p.m., in the month of May, when the solar insolation is maximum throughout India, with 90% of the country receiving solar insolation 5 $kWh/m^2/day$ (Ramachandra et al., 2011).

The orientation of the setup is based on the location of the setup. As mentioned earlier, the optimum angle of inclination will depend upon the latitude of the location, and due to which the β has been taken as 23°, which is equal to latitude. The setup is oriented facing due south i.e., γ = 180°, because for the β value less than 40°, optimum solar irradiance is received when γ = 180°, for a static SWH, (Bari. 2001). Any other orientation of the setup or combination of β and γ will result in a decreased incident solar radiation and ultimately, efficiency.

Two configurations were used for the current experimentation, namely, SWH with reflectors and without reflectors. The experiments were conducted for four hours each day of experimentation, from 11:00 a.m. to 3:00 p.m. in the month of May 2023. The temperature data was collected from the different areas of apparatus at a regular interval of one minute. Further, this data was averaged for every 20-minutes to represent it conveniently.

3. Data Analysis and Discussion

3.1 SWH without Reflectors

Figure 3 and Figure 4 show the variation of ambient, storage water and collector box temperature with time for the SWH without reflectors on May 10 and 11, respectively.

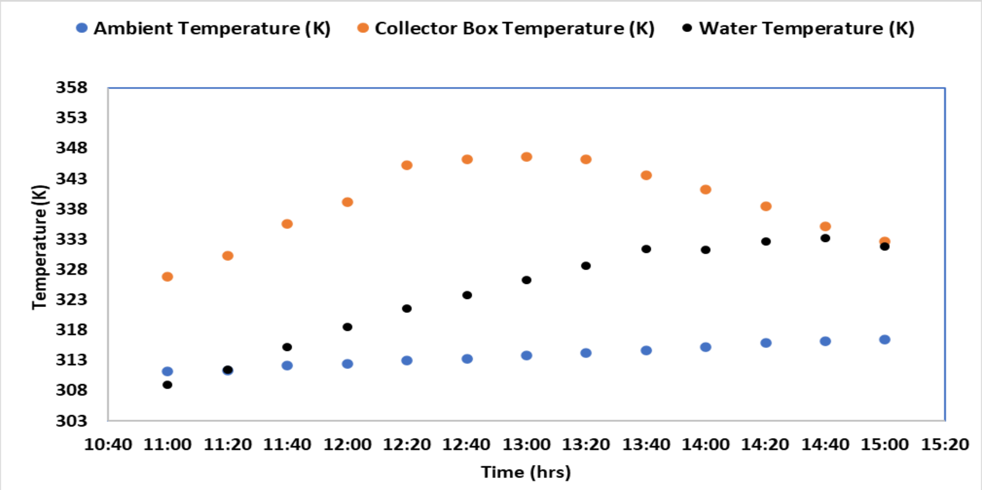

Fig 3: Variation of ambient, water and collector box temperatures with time for SWH without reflectors for May 10

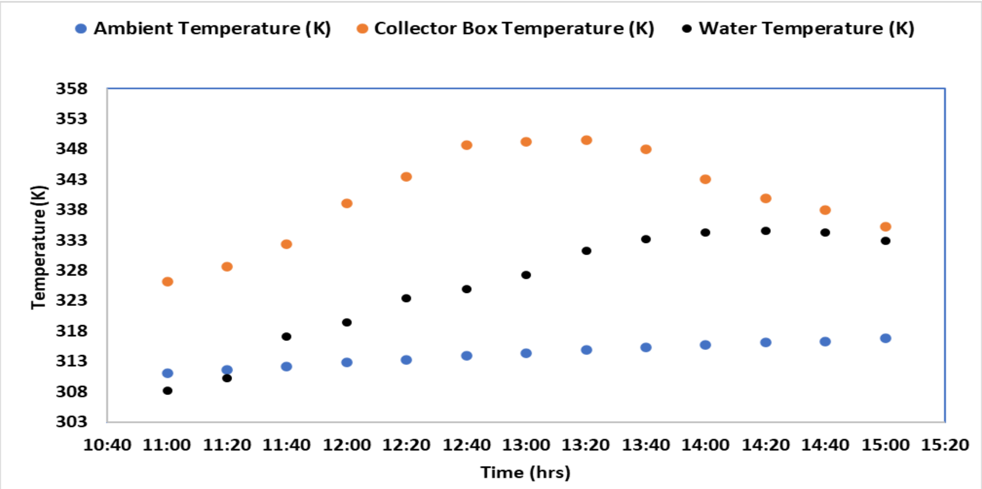

Fig 4: Variation of ambient, water and collector box temperatures with time for SWH without reflectors for May 11

From the figures it is observed that the average rise in the water temperature was about 24 K, the recorded initial temperature of the water on both days was nearly the same that is 308 K which eventually rose to nearly 332 K. Here, the ambient temperature was seen to steadily rising throughout the experiment. However, the temperature inside the collector box sees a high rate of increase till the solar noon and attends almost constant maximum value from 12:30 p.m. to 1:30 p.m. The collector box temperature can be observed to fall after 1:30 p.m. on both days due to a decrease in the solar insolation as mentioned by Mahadi et al. (2014). Also, a similar trend can be observed in the water temperature on both days. Initial recorded water temperature stays below the ambient temperature on both the days which finally attends approximately the same temperature of collector box. A steady rise in the temperature of the water was recorded till the fall in the temperature of the collector box that is approximately 1:30 p.m. and after that it achieves steady value of around 332 K. Interestingly, a subtle drop in the temperature of the water is observed from around 2:30 p.m. on both days. A possible explanation for this observation can be the high rate of decrease in collector box temperature which finally settles below the maximum temperature of the water. In both the scenarios the maximum value of water temperature is achieved couple of readings before the last temperature reading of water (Mahadi et al., 2014).

3.2 SWH with Reflectors

Figures 5 and 6 show the variation of ambient, storage water and collector box temperature with time for the SWH with reflectors on May 12 and 13, respectively.

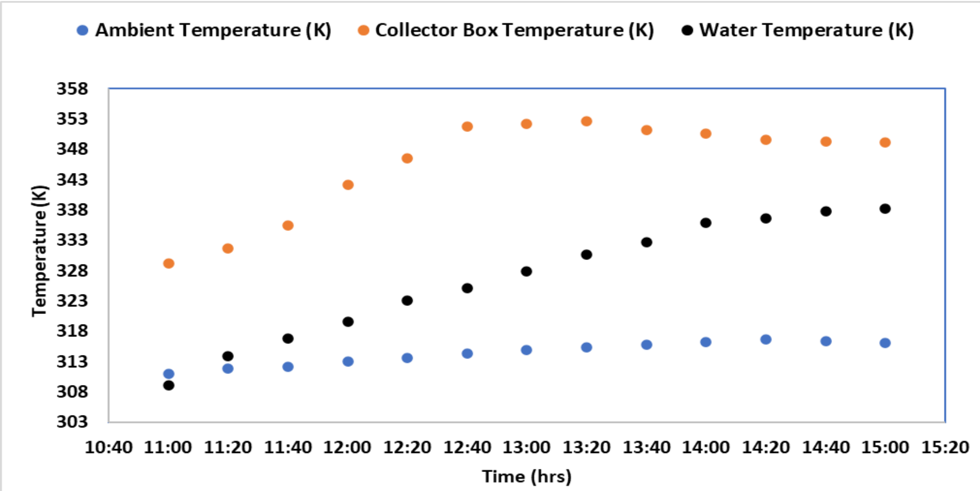

Fig 5: Variation of ambient, water and collector box temperatures with time for SWH with reflectors for May 12, 2023

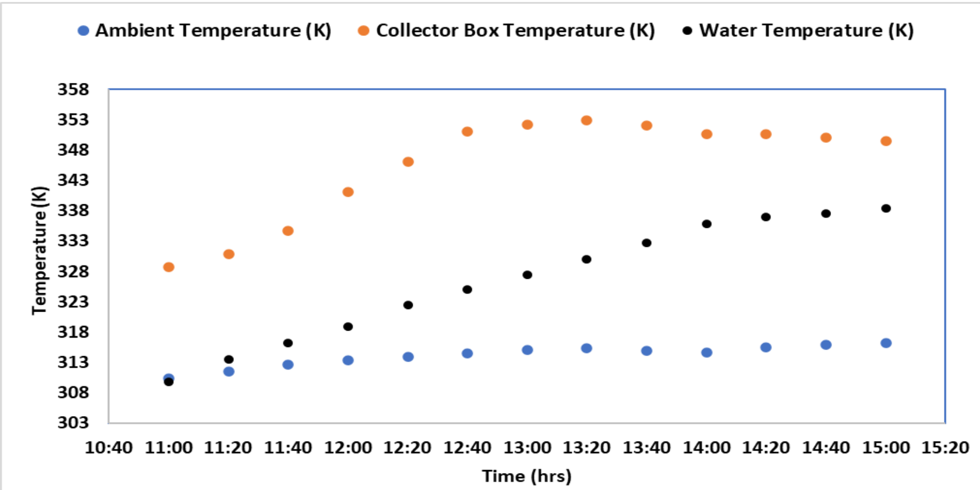

Fig 6: Variation of ambient, water and collector box temperatures with time for SWH with reflectors for May 13, 2023

From the figures it is seen that the rise in water temperature showed nearly the same results for both days, which is about a 30 K rise from 308 K to nearly 338 K. Furthermore, by analyzing Figure 5 and 6 one can deduce a general trend in the rate of temperature increase for all three areas of setup, that is ambient temperature, collector box temperature and water temperature.

The ambient temperature logged on both days displays a steady rise throughout the day. Strikingly similar observation is shown by the collector box temperature in both graphs. Initially, the temperature climbs up the values rapidly, which settles near the maximum value at the solar noon, around 12:30 p.m. Further, the temperature fluctuates at this value till 1:30 p.m. after which it shows a slight deep till the end of the experiment. The third variable, that is water temperature, also followed a similar general trend in both graphs. Initial water temperature was slightly lower than the ambient temperature, it followed a steep increase in the temperature till nearly 2:00 p.m. After which the rate of increase of temperature reduced noticeably till the end of the experiment. This repeating observation can be understood by understanding the collector box temperature which dropped slightly after 1:30 p.m. For both the cases the last recorded value of the water temperature represents the maximum temperature achieved.

In both scenarios, i.e., whether with or without the use of reflectors, we consistently recorded an ambient temperature of approximately 314 K, with individual measurements falling within the range of roughly 311 K to 316 K.

Furthermore, there was a gradual increase in ambient temperature observed throughout each experiment. As for the collector box temperature, a common trend was observed across all data sets. There was a sharp rise in temperature leading up to solar noon, typically around 12:30 p.m., followed by a slight fluctuation around the peak values until approximately 1:30 p.m. Subsequently, there was a subtle decline in temperature for the water heater with reflectors, while the experiment without reflectors exhibited a more significant temperature drop. The best possible explanation for this trend line can be understood from the solar insolation at different times of the day.

However, the most striking and noteworthy distinction between the two cases lies in the maximum water temperature achieved. Without the use of reflectors, the water reached a maximum temperature of approximately 333 K. In contrast, when reflectors were employed, the same setup achieved an astonishing 338 K, representing an increase of 5 K, the results are identical to the results of experiments conducted by Alwan et al.,(2000).

3.3 Water temperature rise

Based on the data analysis, it can be depicted that the approximate average temperature rises for the SWH without and with reflector are 26 K and 29 K respectively. It means the overall enhancement in temperature rise is 14% after incorporating reflectors on the SWH.

This rise in the temperature can be confirmed by understanding the trend line of collector box temperature in both cases. The collector box temperature reached 346 K in the case of without reflectors, while with reflectors it reached approximately 351 K. However, this explains only half the reason for hotter water, the prominent reason for hotter water is the temperature retention quality of the setup when the reflectors are installed. For both the scenarios we observed a drop in collector box temperature at around 1:30 p.m. due to reduced solar insolation, but with the setup without reflector, the collector box temperature recorded a drastic drop, while the setup with reflectors this drop was almost negligible. What the reflectors essentially did was that they prevented the collector box temperature from dropping below the maximum temperature of the water and water continued to heat even at the end of the experiment. This trend is observed due to the increased surface area and ultimately, increased solar insolation by installing the reflectors, which helps the collector box to retain the temperature achieved, at the time of retarding solar insolation.

4. Conclusions

This paper presents an experimental study of SWH with and without reflectors. The experiments clearly showed the maximum temperatures attained by the water in the case of the setup with the integration of reflectors was noticeably on the higher side compared to the setup without reflectors, for the similar conditions of time of the day and duration of the experiment, this was true for the maximum temperatures attained by the collector box as well. The rise in the temperature of the water for the setup with reflectors was 14% higher with respect to the rise in water temperature for the setup with no reflectors.

The observations made and the data recorded suggests that integrating reflectors in a system like the one used for the experiment, i.e., flat plate collector, can enhance the temperature of the water, without any major constructional changes.

5. Acknowledgment

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector.

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