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Study of the Performance of a Thermosiphon Solar Water Heater in the Rainy Season

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Abstract

In this work, we conducted a study of the performance of a solar thermosiphon solar water heater (SWH) during the rainy season. This system is installed in a private home in Ouagadougou, Burkina Faso (12˚19'12.4"N, 001˚27'00.1"W) and has been operating for 10 years. It consists of a flat collector with a surface area of 2 m^2, a storage tank with a capacity of 200 liters and two hydraulic circuits (primary and secondary). The collector and the tank are each insulated with 15 cm thick glass wool. The overall objective of this work is to study the influence of the rainy season on the performance of the device. The methodology used is based on the acquisition and analysis of system operating data (temperatures and solar radiation) for 10 consecutive days. Finally, with the data obtained, the SWH efficiency was calculated. The results showed that the performance of the SWH is poor in the rainy season due not only to the variability of solar radiation but also to water infiltration into the collector. Furthermore, the duration of hot water production as well as the final temperatures reached in the tank depend on the intensity and the degree of variability of solar radiation. Finally, the results also showed that the storage tank is well insulated and that nighttime losses are relatively low.

Keywords

Solar Water Heater, Thermosiphon, Solar Radiation, Rainy Season, Efficiency

1. Literature Review

SWHs have been extensively studied in the literature. Their applications include the supply of domestic hot water in various sectors such as households [1], hospitals [2], beauty salons [3] [4], etc. With the challenges of global warming, their development is booming. A direct correlation has been demonstrated between the degree of SWH use and their payback period, as well as the reduction of carbon dioxide emissions. Thus, greater reliance on SWHs not only allows for a faster return on investment, but also significantly contributes to the reduction of carbon dioxide emissions [5]. The classification divides SWHs into two categories: active systems that use circulation pumps (between the collector and the storage tank) and passive systems that operate naturally without moving parts, making them less expensive to maintain. Passive systems include thermosiphon water heaters and solar water heaters with integrated storage [6]. Thermosiphon solar water heaters (the most dominant among passive systems) generally consist of a solar collector and a storage tank connected by a hydraulic circuit. The fluid flow in the loop in the system is due to the buoyancy forces generated by the difference in density between the hot fluid in the collector and the cold fluid in the storage tank [7]. There are two types of solar collectors: flat-plate solar collectors [8] and evacuated tube collectors [9]. A flat-plate collector contains an absorber made up of collector tubes through which the heat transfer fluid circulates. Transparent glazing allowing solar radiation to pass through covers the entire collector. In evacuated collectors, the absorber consists of vacuum-sealed tubes each containing a heat pipe. The storage tank, like the collector, must be well insulated to avoid heat loss, especially during the night (especially for the tank). It may or may not contain a heat exchanger depending on the desired applications. Improving the performance of solar heaters has been the subject of numerous scientific studies. These studies have primarily focused on solar collectors and are mostly related to improving solar radiation absorption and reducing heat loss. The influence of collector type on SWH performance has been studied in the literature. Several studies suggest that evacuated tube collectors are superior to flat-plate collectors [10]-[12]. However, it should be noted that flat-plate collectors are simpler and less expensive to manufacture, and their maintenance is also easier. However, the choice of absorber material is very important. Indeed, to be effective, this material must meet certain criteria in terms of conductivity and thermal capacity. Various materials, including iron sheets, aluminum, corrugated zinc sheets, copper plates, and steel, have been cited in several studies [13]-[17]. However, some studies indicate that aluminum-based absorbers are the most efficient [18] [19]. Generally, the absorber is painted black to optimize solar energy capture. However, since black is both a good absorber and a good emitter, a selective paint (good absorption coefficient and low emissivity) is significantly better than black paint. Such coatings are described and discussed in the literature [20]-[22]. The spatial arrangement of collectors also influences SWH performance. Thus, work conducted by numerous authors indicates that their orientation (due south or due north) and their inclination relative to the horizontal significantly influence the system's efficiency [23]-[27]. However, optimal inclination angles differ in the literature.

There are other possibilities for improving collectors' solar radiation capture. The use of a system for concentrating direct and diffuse solar radiation towards the collector through reflectors improves collector efficiency [28]-[30]. Sun tracking devices can also significantly improve collector efficiency [31]-[33]. Finally, bifacial absorbers have shown better performance compared to monofacial absorbers thanks to double capture of solar radiation by both faces [34] [35]. The nature of the heat transfer fluid also influences the performance of SWHs. Generally, water or a water-glycerol mixture is used as the heat transfer fluid, but some recent studies indicate that nanofluids may be more efficient than water [36]-[38]. The flow rate of this fluid also influences the system's efficiency. Indeed, experiments conducted at the Baghdad University of Technology in Iraq showed that water at a flow rate of 5.3 L/min heated more than at a flow rate of 6.51 L/min. Indeed, the maximum temperature reached was 51.4˚C and 49˚C at flow rates of 5.3 L/min and 6.51 L/min, respectively [39].

Recently, researchers have focused on integrating thermal storage materials (particularly phase change materials) into SWHs to limit heat losses [40]-[44]. Regarding studies on the thermal performance of SWHs, several works have been conducted in the literature. They are all based on calculating efficiency by establishing an energy balance of the system [45]-[49]. Unfortunately, these works do not take into account the specificities linked to the rainy season (high relative humidity of the air, low sunshine, high variability of solar radiation, etc.), hence the interest of the present work.

2. Materials and Methods

2.1. Materials

In this study, we used:

- **A prototype of SWH**

Figure 1. Prototype of SWH studied.

This is a thermosiphon solar water heater installed in a private home in Ouagadougou (12˚19'12.4"N, 001˚27'00.1"W) and has been in operation for 10 years. It consists of a flat aluminum solar collector with a surface area of 2 m^2 and a 200-liter storage tank insulated with 15 cm thick glass wool. The collector is south-facing and inclined 15˚ to the horizontal. The absorber is made of aluminum and painted matte black. The transparent casing of the collector is made of 4 mm thick clear glass. The bottom and side faces of the collector are insulated with 15 cm thick glass wool. A corrugated sheet protects the insulation from the weather, and a purge regulates the pressure inside the tank. The water contained in the collector forms a loop with the tank by thermosiphon effect through tubes (primary circuit). The hot water circuit intended for use passes through a heat exchanger (secondary circuit) for the use. The prototype of SWH studied is illustrated in **Figure 1**.

Measuring instruments, including: A data acquisition chain consisting of a midi LOGGER GL220 type datalogger with an accuracy of 0.05% (read value) ±1˚C uncertainty, type K thermocouples with an uncertainty of ±1.5˚C, and a solarimeter. The solarimeter (solar radiation sensor EN-02) was calibrated by the manufacturer. The manufacturer does not indicate the uncertainty of the equipment but we consider an uncertainty of (±8% of the read value) recommended for measurements carried out in West Africa [50]. The datalogger was set to record data with a time step of 10 minutes.

2.2. Methods

The chosen period of the experiment is a period of high variability of solar radiation in Burkina Faso, in this case, the month of July. The secondary circuit of the SWH is closed to prevent the drawing of hot water and to avoid disturbing the experiment. The probes are placed in the device in such a way as to continuously and simultaneously measure the water temperatures at the inlet and outlet of the collector, the temperatures of the upper and lower part of the storage tank, the ambient temperature as well as the solar radiation. The measurement campaign lasts ten days. The experimental diagram is shown in **Figure 2**.

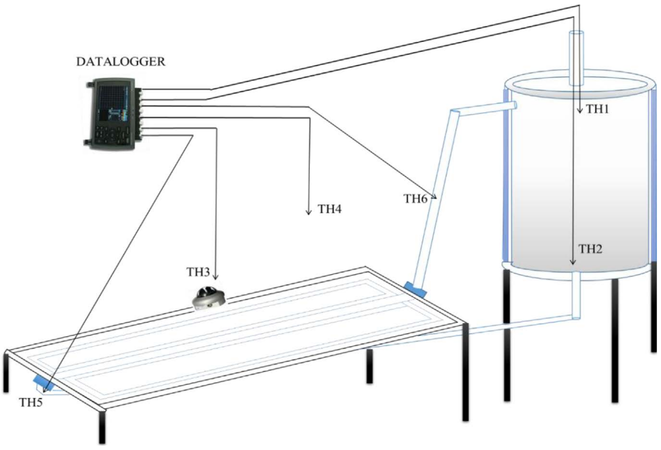

Figure 2. Experimental design.

TH1: Temperature measuring probe for the upper part of the tank.

TH2: Temperature measuring probe for the lower part of the tank.

TH3: Solar radiation measuring probe.

TH4: Ambient temperature measuring probe.

TH5: Water temperature measuring probe at the inlet of the collector.

TH6: Water temperature measuring probe at the outlet of the collector.

To calculate the instantaneous efficiency of the system, we use the following formula:

$$\eta_{inst} = \frac{Q_{useful}}{GS} \tag{1}$$

Where Q_{useful} (W) is the useful power, G ($W\cdot m^2$) the intensity of solar radiation and S (m^2) the surface area of the solar collector.

$$Q_{useful} = \dot{m}C_p\left(T_{out} - T_{in}\right) \tag{2}$$

With $\dot{m}$ ($Kg\cdot s^{-1}$) the mass flow rate of the heat transfer fluid (water), Cp the specific heat of the water (taken equal to 4185 $J\cdot Kg^{-1}\cdot{}^\circ C^{-1}$), Tin (˚C) and Tout (˚C) the water temperatures at the inlet and outlet of the collector, respectively. To calculate the mass flow rate, we use a correlation from the literature [51] :

$$\dot{m}\ (l/h) = 0.095SG/C \tag{3}$$

Where S (m^2) is the surface area of the collector, G ($W\cdot m^2$) the intensity of solar radiation and C ($J\cdot g^{-1}\cdot{}^\circ C^{-1}$) the specific heat of the water.

3. Results and Discussions

The experiment took place from July 16, 2022, to July 25, 2022.

Figures 3-12 show the daily temperature variations in the upper and lower parts of the balloon, the ambient temperature as well as solar radiation, during the ten days of the experiment.

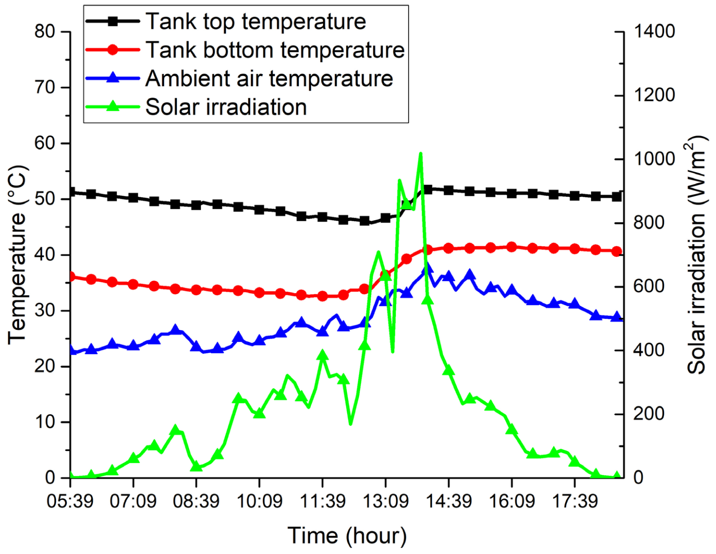

Figure 3. Day 1.

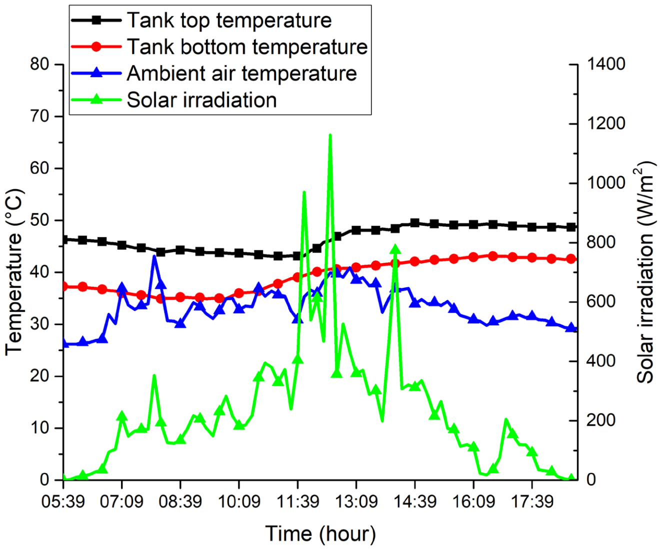

Figure 4. Day 2.

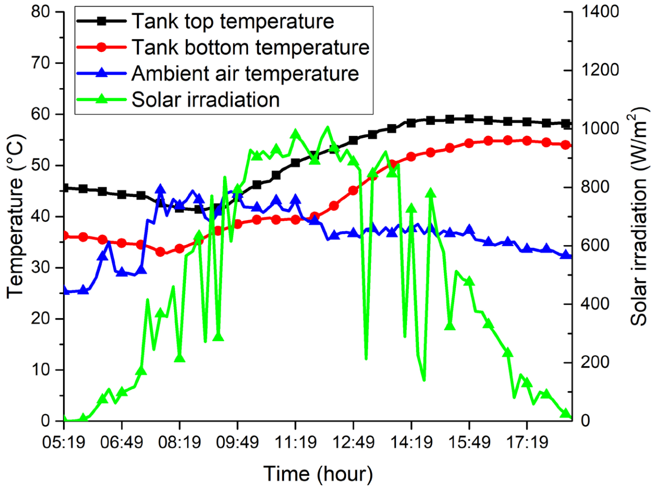

Figure 5. Day 3.

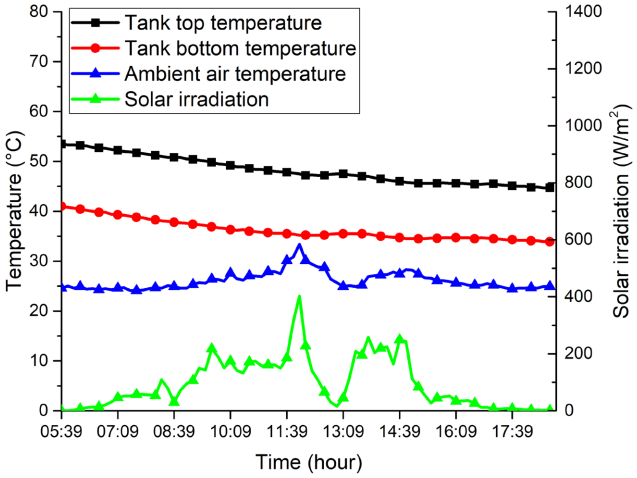

Figure 6. Day 4.

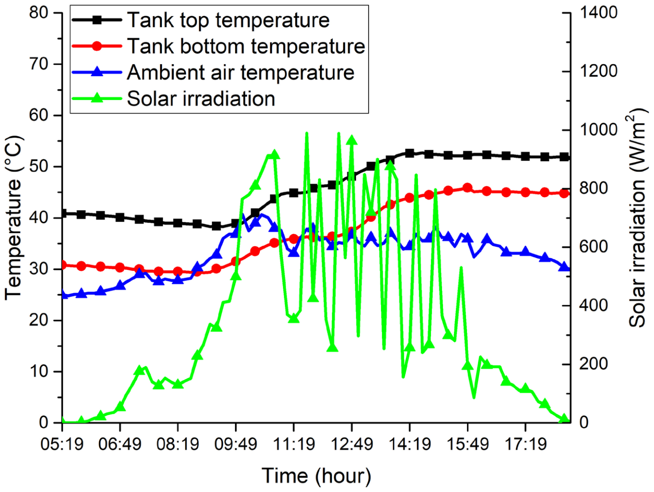

Figure 7. Day 5.

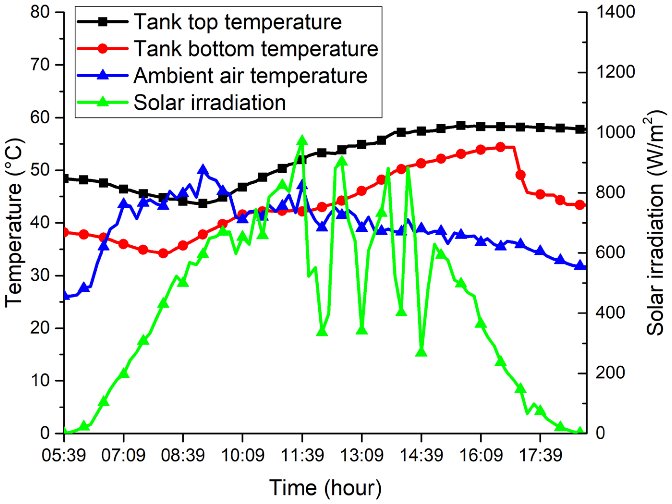

Figure 8. Day 6.

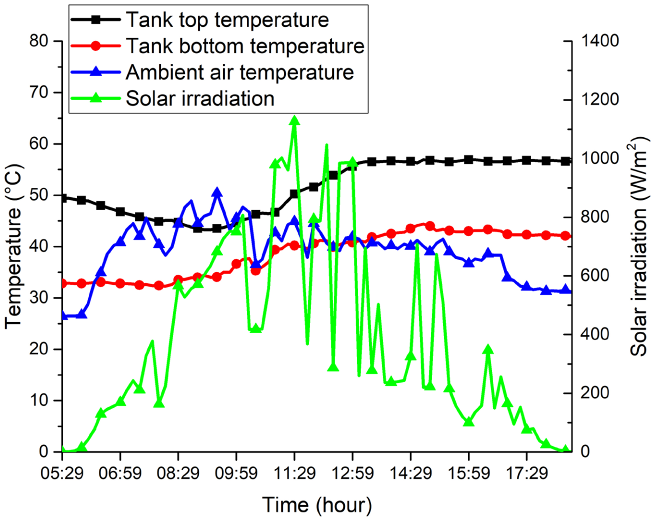

Figure 9. Day 7.

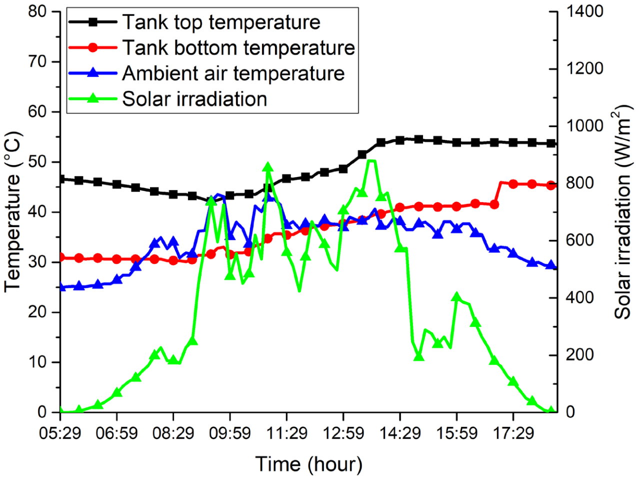

Figure 10. Day 8.

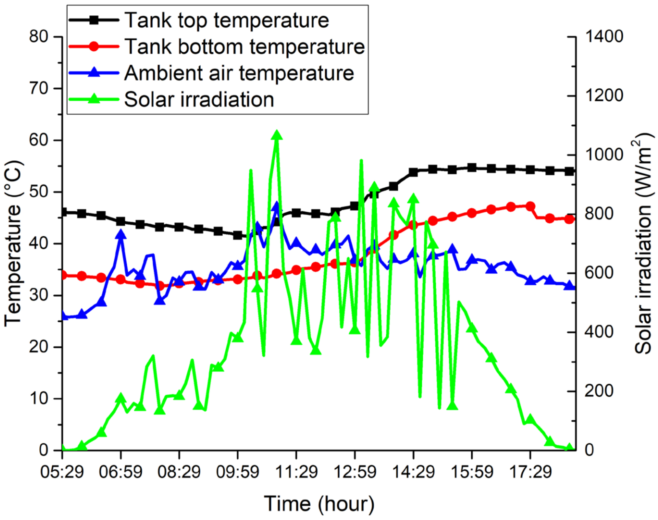

Figure 11. Day 9.

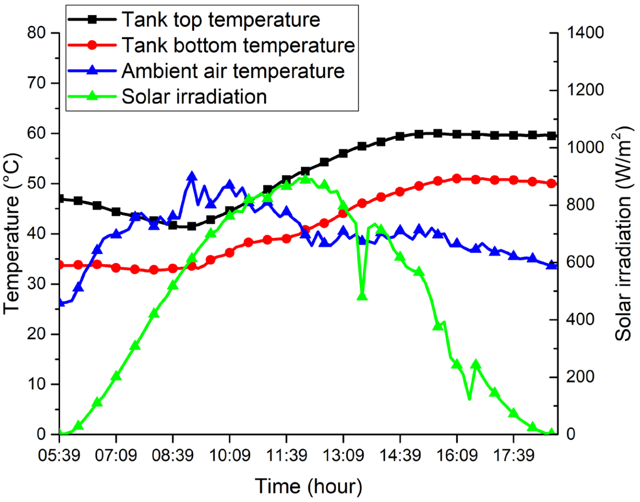

Figure 12. Day 10.

We note that regardless of the day, the temperature profile at the top of the tank is a curve with three parts: a decreasing part, an increasing part, and a nearly constant part, except for day 4 (**Figure 6**), where the curve is strictly decreasing. The decreasing phase of the curves corresponds to a loss of energy from the hot water stored in the tank through heat exchange with the low-temperature zones. The temperature of the stored water is high from sunrise because there is no hot water draw during the experiment (closed secondary circuit). This phase is due to the thermal inertia of the system, which must store enough energy to trigger hot water production. Its duration depends on solar radiation. Indeed, we can observe that during days of low or high variability in solar radiation, this phase is longer (**Figures 1-2**). The increasing phase represents the production of hot water in the tank. We note that regardless of the power and variability of solar radiation, hot water is produced in the tank, except for day 4 (**Figure 6**), when the sunshine is very low (maximum solar radiation intensity around 400 W/m^2). For other days, the duration of hot water production depends not only on the power of the solar radiation but also on its variability. We observe that during periods of low intensity or high variability of solar radiation, the duration of water production is short (**Figure 1**, **Figure 2**, **Figure 9**). On the other hand, during periods of high intensity or low variability of solar radiation, the duration of hot water production is longer (**Figure 3**, **Figure 8**, **Figures 10-12**). The same is true for the final hot water temperatures reached in the tank. The beginning of the constant phase marks the end of hot water production by the collector. The constant temperature profile that extends until the end of the day also indicates that the hot water produced is well preserved, which is an indicator of good tank insulation. The temperature profile at the bottom of the tank is almost identical to that at the top of the tank because the upper and lower zones of the tank exchange heat by convection and conduction. However, some fluctuations can sometimes be observed in the temperature curves at the bottom of the tank because it is directly connected to the collector, which is more sensitive to disturbances in the external environment. As for the ambient temperature, it follows almost the same profile as the sunlight. When we look at the hot water production profile and the final temperatures reached in the tank (less than 60°C except for the last day), we can question the actual performance of the collector despite the limitations due to the variability of sunlight. In fact, during monitoring of the system, the formation of air bubbles was observed on the internal face of the glazing as shown in **Figure 13**.

Since the origin of these bubbles can only be explained by the fact that the boiling point of the water has been reached, it is very likely that water is infiltrating into the collector. Thus, part of the captured solar energy is lost in the process of heating the infiltrated water, which is energy-intensive, increasing the thermal inertia of the collector. Consequently, when we add the phenomena linked to the variability of solar radiation, the efficiency of the system (calculated during periods of hot water production) is relatively low and variable, as shown by the results below concerning the first 2 days (least sunny days) and the last 2 days of the experiment (sunniest days).

Figure 13. Formation of bubbles on the internal surface of the glazing.

The daily evolution of the instantaneous thermal efficiency of four days is illustrated by **Figures 14-17**.

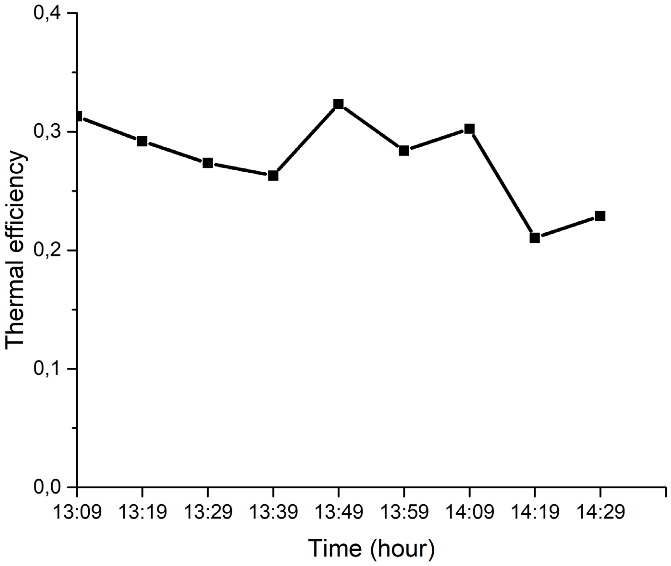

Figure 14. Performance evolution during the 1st day of experience.

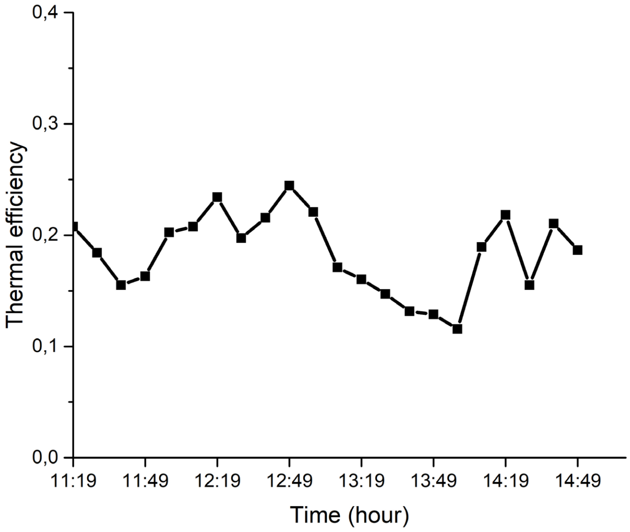

Figure 15. Evolution of performance during the 2nd day of experience.

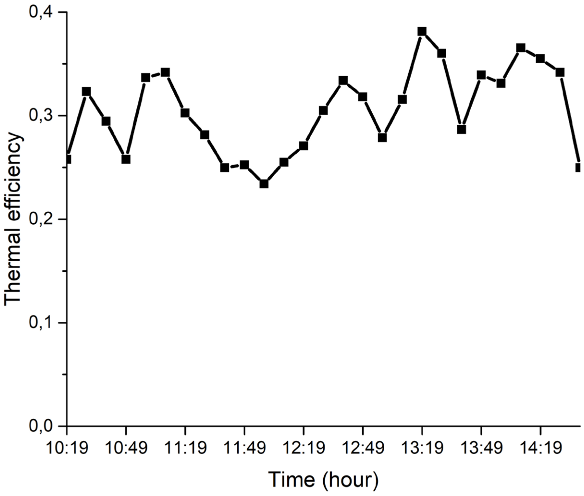

Figure 16. Evolution of performance during the 9th day of experimence.

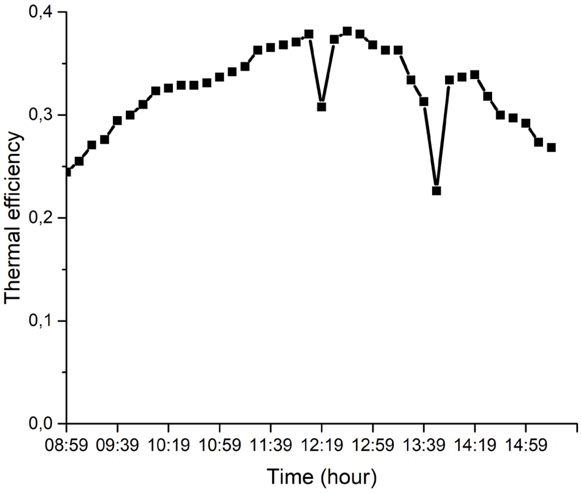

Figure 17. Evolution of performance during the 10th day of experience.

The average yields are respectively 27% for the 1st day, 18% for the 2nd day, 30% for the 9th day and 32% for the 10th day.

Finally, **Figure 18** shows the nocturnal evolution of the balloon temperatures for the 3rd day of the experiment.

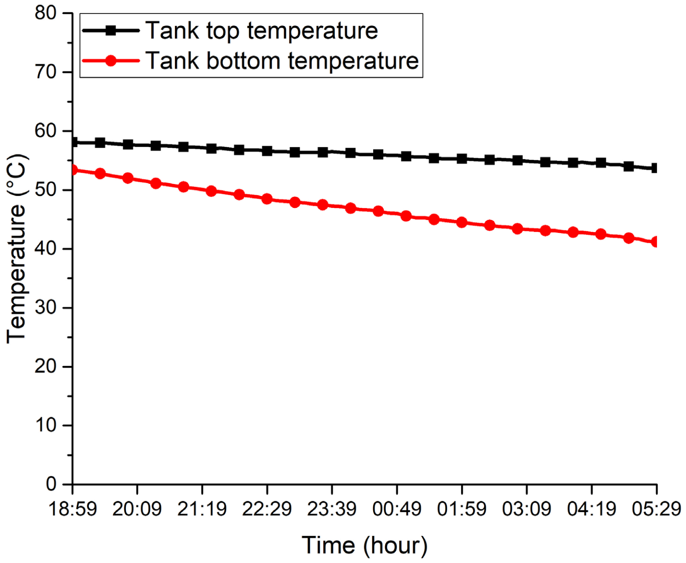

Figure 18. Nighttime evolution of balloon temperatures.

There is a continuous drop in the temperatures at the top and bottom of the tank during the night. This drop in temperature is due to nighttime losses. It is more pronounced for the temperature at the bottom of the tank because it is directly connected to the sensor. For the top of the tank, these losses remain relatively low (around 0.45˚C/h).

4. Conclusions

This work involved the study of the rainy season performance of a thermosiphon solar water heater (SWH) installed in a private home in Ouagadougou (12˚19'12.4"N, 001˚27'00.1"W). The system consists of a flat solar collector with a surface area of 2 m^2, a 200-liter storage tank, and two hydraulic circuits (primary and secondary). The collector and the tank are each insulated with 15 cm thick glass wool. The methodology used is based on the acquisition and analysis of system operating data (temperatures and solar radiation) for 10 consecutive days without drawing hot water, along with the calculation of the system's efficiency. The main results can be summarized as follows:

- The SWH efficiency is very low and variable due not only to the variability of solar radiation but also to water infiltration into the collector;
- During the rainy season, the variability of solar radiation does not prevent the SWH from producing hot water, except in cases where sunshine is very low;
- The duration of hot water production and the final temperatures reached in the tank depend on the intensity and degree of variability of solar radiation;

- The tank is well insulated;
- Nighttime losses in the tank are relatively low.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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