International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 48 No. 1 Mar. 2026, pp. 150-158

http://www.ijias.issr-journals.org/

Experimental study of the thermal performance of a hybrid photovoltaic-thermal collector

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ABSTRACT: Photovoltaic solar modules are in high demand in Sahel countries. Unfortunately, the intense heat reduces the performance of these modules. Cooling them is therefore recommended. One technique for cooling a photovoltaic solar module involves coupling it with a solar thermal collector to recover some of the heat produced and transfer it to a heat transfer fluid. This work is a comparative experimental study of the thermal performance of a solar thermal collector and a hybrid photovoltaic-thermal (PV-T) solar collector. A water-based solar thermal collector and a hybrid photovoltaic-thermal (PV-T) collector were designed. This experimental study consisted of monitoring the evolution of the water temperature at the inlet and outlet of each collector, the temperature at the surface of the PV-T module, the temperature of the air confined within the solar thermal collector, and the site's solar irradiance. The results showed a maximum hot water temperature of 87°C for the solar thermal collector and 74°C for the PV-T solar collector under a maximum solar irradiance of approximately 985 W/m^2. The thermal efficiency of the PV-T collector is about 0.36 times greater than that of the solar thermal collector. These results clearly demonstrate that sufficient heat can be recovered with a PV-T collector.

KEYWORDS: solar thermal collector, PV-T collector, water, temperature, efficiency.

1 INTRODUCTION

Solar energy represents an inexhaustible primary energy source on a human scale. Its use poses no danger to the environment or living beings. Solar energy is used either for thermal energy production through solar water heaters, solar dryers, etc., or for electrical energy production through PV solar modules and thermodynamic solar power plants. While temperature increase is a major advantage for solar thermal and thermodynamic collectors, the same is not true for PV solar modules. In fact, the efficiency of a photovoltaic solar module decreases as its temperature rises, leading to a drop in production. Cooling a photovoltaic solar module is a major problem, especially in hot countries [1]. The hybrid photovoltaic/thermal solar collector is therefore a solution to overcome this problem. A hybrid photovoltaic-thermal (PV-T) collector is a device that allows the simultaneous production of electricity and heat. It enables true energy cogeneration by allowing the exploitation of the electricity and heat produced. It consists of a flat-plate solar collector and a photovoltaic solar module (crystalline or amorphous). There are several types of PV-T collectors: water-based, air-based, and nanoparticle-based PV-T collectors. The literature reveals enough studies conducted to determine the performance of these PV-T collectors and the parameters influencing this performance. Tiwari et al. (2007) [2], following a parametric study on glazed and unglazed air-based PV-T collectors, found that adding the extra glass almost doubles the useful thermal efficiency, while the electrical efficiency drops by about 10%. Sarhaddi et al. [3] performed an energy and exegetical analysis of a hybrid PV-T air solar collector. The exergetic efficiency of this PV-T collector was approximately 10.75%. Tiwari et al. (2006) [4] also presented a steady-state theoretical and experimental study of a naturally or mechanically ventilated air PV-T solar collector. Their study showed that additional recovery of the thermal energy produced improves the overall efficiency of the air PV-T system by approximately 18%. Tripanagnostopoulos et al., [5] conducted a study on PV-T solar collectors using either air or water as the heat transfer fluid. The objective of their work was to cool the PV solar modules and increase hot air production. While air PV-T solar collectors offer advantages (no freezing, no damage in case of leaks), they are less efficient compared to water-based hybrid PV-T collectors. A glazed water-based PV-T solar collector was studied by Sandnes and Rekstad [7]. The objective of their work was to evaluate the thermal and electrical performance, as well as the interactions between the hot water production and the electrical production of the collector. Ben Cheikh et al. [8] presented a study on the performance of a hybrid water-based solar collector through the development of a heat balance that incorporates the heat exchanges between the different components of the hybrid collector. They concluded that the fluid outlet temperature increases with radiation and that the temperature of the photovoltaic solar cells in the hybrid collector is lower than that of conventional PV solar cells. A. Khelifa et al., [9] performed a numerical study of a water-based PV-T collector. They showed that the device's efficiency is a function of radiation. H. Ben Cheikh et al. carried out a numerical modeling of a water-based PV-T solar collector. They concluded that this technology is an alternative to photovoltaic solar generators and conventional thermal solar collectors installed separately. Faizal et al., [10] studied the thermal performance of nanofluid solar collectors. The results confirmed that the higher density and lower specific heat of nanofluids offer a higher thermal efficiency than water. Luo et al., [11] simulated the performance of a solar collector with nanofluids using a 2D model and by solving the radiative transport equations of the particulate media and the combination of the heat transfer equations by conduction and convection. Their results show that the use of the nanofluid solar collector can improve efficiency and output temperature. Rahman et al., [12] performed a numerical study for a triangular solar collector with nanofluids using the Galerkin weighted residual finite element method for a wide range of Grashof numbers (Gr). Ladjevardi et al., [13] numerically studied the effects of using nanofluids on the performance of a solar collector. They showed that the thermal efficiency of the nanofluid-based collector increases by approximately 88% compared to that of a pure water collector at an inlet temperature of 313 K.

In a previous work, Dianda et al (2018) [14] conducted a numerical study on the electrical and thermal performance of a PV-T sensor. This work follows on from this previous work with a comparative experimental study of the thermal performance of a thermal sensor and a hybrid PV-T sensor.

2 MATERIALS AND METHODS

2.1 MATERIALS

Two systems have been put in place: a solar thermal collector and a hybrid solar PV-T collector.

2.1.1 THE SOLAR THERMAL COLLECTOR

The solar thermal collector studied is a flat-plate glazed collector using water as the heat transfer fluid.

It essentially consists of a glass pane, an absorber, a coil, and insulation.

THE GLASS OR TRANSPARENT COVER

The glass serves to protect the absorber, limit heat loss upwards and create a greenhouse effect in the solar thermal collector. The glass used is clear glass. Table 1 shows some of the characteristics of the glass used.

Table 1. Characteristics of the type of glass used [15]

Type of glass	Reflection (%)	Absorption (%)	Transmission (%)
Clear glass	8	9	83

This choice is motivated by the availability of the material and its more attractive purchase cost. Clear glass also has some interesting characteristics.

THE ABSORBER

The absorber is the component of the solar thermal collector that captures solar radiation, converts it into heat and transfers it to the heat transfer fluid. It must have good thermal conductivity, a high absorption coefficient and, above all, low emissivity.

We used a black-painted aluminium sheet absorber measuring 0.5 m long and 0.4 m wide.

Table 2 shows some of the characteristics of this absorber.

Table 2. Absorber characteristics [16]

Material	Thermal conductivity (w/m °C)	Coefficient of expansion	Absorption (%)	Emission (%)
Aluminium	230	2,38	0.92-0.97	0.95

THE INSULATION

It is used in a solar thermal collector to prevent heat loss downwards. Generally speaking, the choice of insulation is made by considering certain parameters such as thermal conductivity, maximum operating temperature under steady-state conditions, sensitivity to humidity, and cost.

We chose fiberglass as our insulation.

Table 3 presents some characteristics of glass wool

Table 3. Characteristics of glass wool [16]

Materials	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Maximum operating temperature (°C)
Glass wool	0,030-0,040	150

We chose it because of its rather interesting physical characteristics.

THE COIL

The coil, or water circulation pipe, recovers the heat produced at the absorber and transfers it to the water. The coil is made of copper and is ladder-shaped to facilitate the circulation of hot water by thermosiphon.

Figure 1 shows the different elements of the thermal sensor.

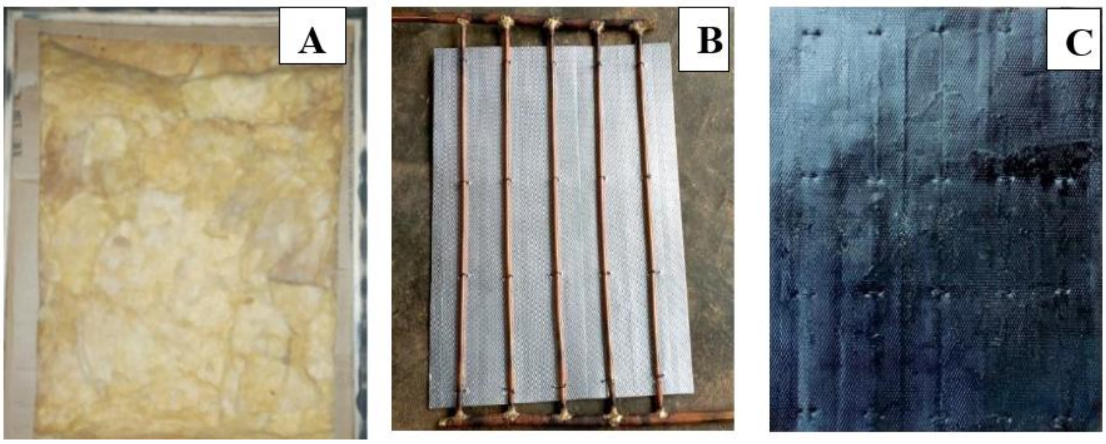

Fig. 1. Elements of the thermal sensor: A- the insulator B- the coil C- the absorber

2.1.2 THE PV-T HYBRID SOLAR COLLECTOR

The hybrid PV-T solar collector, as its name suggests, consists of a PV solar collector and a thermal collector designed to recover the heat produced by the PV module.

The thermal solar collector is similar to the one described in the previous section but without a transparent cover (glass). This collector is placed below the PV module.

The PV solar module occupies the space previously occupied by the transparent cover of the thermal collector. The characteristics of the PV module are listed in Table 4.

Table 4. Characteristics of the PV solar module used

Brand	ETDF German technology
Model	50P
Maximum power (P_{max})	**50 W**
Power Tolerance	**± 3%**
Maximum power voltage (V_{mp})	**17,70 V**
Maximum power current (I_{mp})	**2,83 A**
Open circuit voltage (V_{oc})	**21,60 V**
Short circuit current (I_{SC})	**3,13 A**
Maximum system voltage	**DC 1000 V**
Maximum series fuse	**15 A**
Weight	**4,0 Kg**
Dimensions	**660*550*25mm**
Am	**1,5**
E	**1000 W/m^2**
Température	**25°C**
NOCT (Air 20 °C, Sun 1kW/m^2, Wind 1 m/s)	**50°C**
Application class	**Class A**

Figure 2 shows the rear face of the PV-T hybrid module.

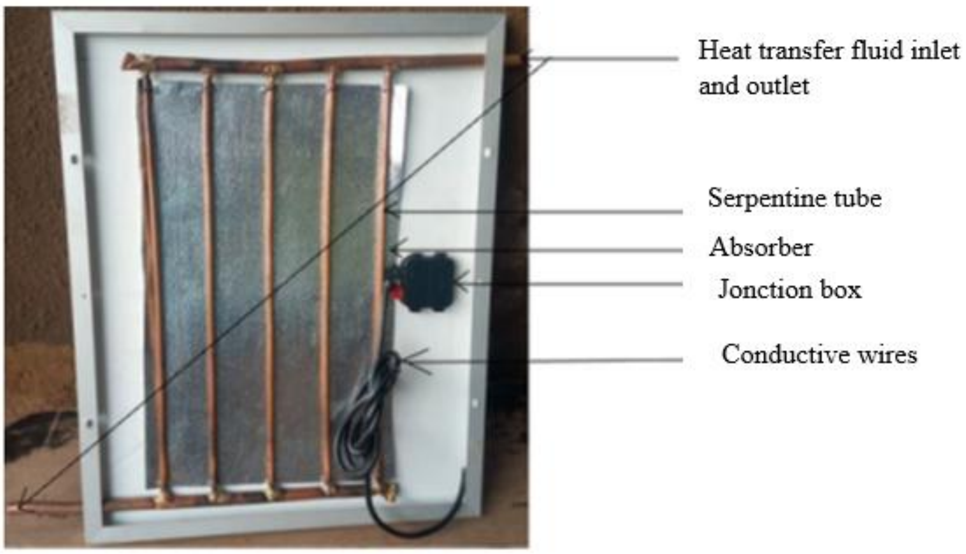

Fig. 2. PV-T solar module without its insulation

2.1.3 MEASURING DEVICES

The temperature evolution of certain parts of the two sensors was monitored using a datalogger equipped with ten thermocouples. Sunlight was also measured using a solarimeter.

Figures 3 and 4 show the measuring devices.

Fig. 3. Datalogger

Fig. 4. Solarimeter

2.2 METHODS

2.2.1 EXPERIMENTAL PROTOCOL

The experimental study consisted of monitoring the temperatures of certain elements of the two sensors and the amount of sunlight throughout the day. This was done to determine the thermal performance of these sensors. The temperatures recorded were that of the water at the inlet and outlet of the sensors, that of the rear surface of the hybrid PV-T solar module, and that of the air confined under the glass of the thermal sensor.

2.2.2 ELEMENTS FOR CALCULATING PERFORMANCE

The thermal efficiencies of the solar thermal collector and the hybrid PV-T solar collector were evaluated and compared.

The efficiency of the solar thermal collector is given by equation 1 :

$$\eta_{th} = \frac{\dot{m}_{th} c \Delta T_{th}}{I_{th} A_{th}} \quad (1)$$

where $\dot{m}_{th}$ is the mass flow rate of water at the thermal sensor (kg/s)

ΔT_{th} is the temperature variation of the water at the thermal sensor (K)

c is the specific heat capacity of water (J/kg.K)

I_{th} represents the solar flux arriving at the thermal collector (W/m^2)

A_{th} denotes the area of the thermal sensor (m^2)

The efficiency of the hybrid PV-T sensor is given by relation 2 :

$$\eta_{PVT} = \frac{\dot{m}_{PVT} c \Delta T_{PVT}}{I_{PVT} A_{PVT}} \quad (2)$$

where $\dot{m}_{PVT}$ is the mass flow rate of water at the level of the PV-T hybrid sensor (kg/s)

ΔT_{PVT} is the variation in water temperature at the level of the PV-T hybrid sensor (K)

I_{PVT} denotes the solar flux arriving at the hybrid PV-T sensor (W/m^2)

A_{th} denotes the area of the hybrid PV-T sensor (m^2)

The quotient of equations 1 and 2 allows a comparison of the thermal efficiencies of the two sensors on the energy supplied by the thermal solar sensor and the hybrid PV-T solar sensor.

$$r = \frac{\eta_{th}}{\eta_{PVT}} \quad (3)$$

3 Results And Discussion

3.1 Temporal Changes In Temperature And Sunshine

The temperature variations of the different elements and the solar irradiance over time are recorded as graphs.

The various tests on the two sensors were carried out simultaneously.

Temperature changes in the different elements of the thermal sensor

Figure 5 shows the temporal evolutions of sunshine, water temperatures at the inlet and outlet of the thermal sensor during the day.

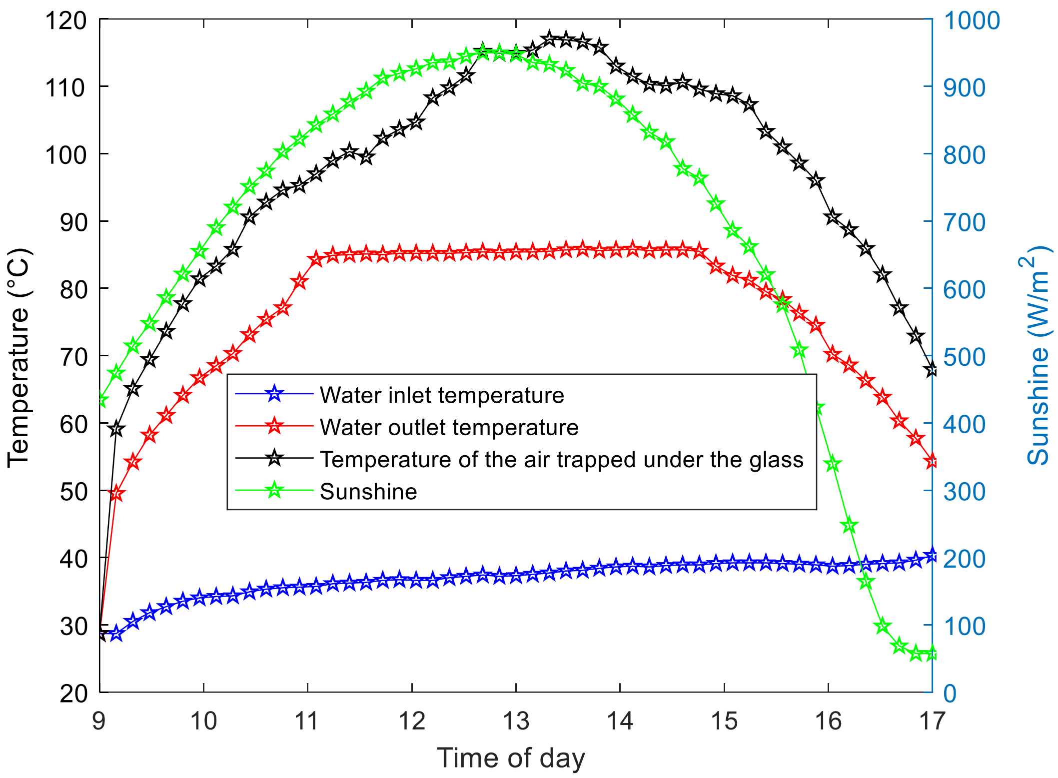

Fig. 5. Evolution of sunlight and temperatures of the different elements of the solar thermal collector during the test day

The solar irradiance increases from 9: 00 AM to 12: 30 PM, reaching its maximum value of approximately 985 W/m^2. It then decreases rapidly, reaching a value of 50 W/m^2 around 5: 00 PM. The average daily solar irradiance is approximately 500 W/m^2. The air trapped between the glass and the absorber follows a similar pattern to the solar irradiance. This behavior is explained by the fact that the heat obtained originates from the ground. It reaches a temperature of approximately 118°C. This explains the good performance of the thermal collector. The water supplying the collector comes from the national water distribution network. Its temperature varies slightly from 30°C to approximately 40°C. The water temperature at the collector outlet evolves according to a rising (rapid) phase from 9am to 11am, a falling phase from 2: 45pm to 5pm and a phase at a stable temperature of 87°C between 11am and 2: 45pm. This significant rise in water temperature of approximately 40°C demonstrates good thermal conversion of the solar thermal collector.

TEMPERATURE EVOLUTION OF THE DIFFERENT ELEMENTS OF THE HYBRID PV-T SOLAR COLLECTOR

Figure 6 shows the temporal evolution of sunlight and temperatures of certain elements of the hybrid PV-T sensor.

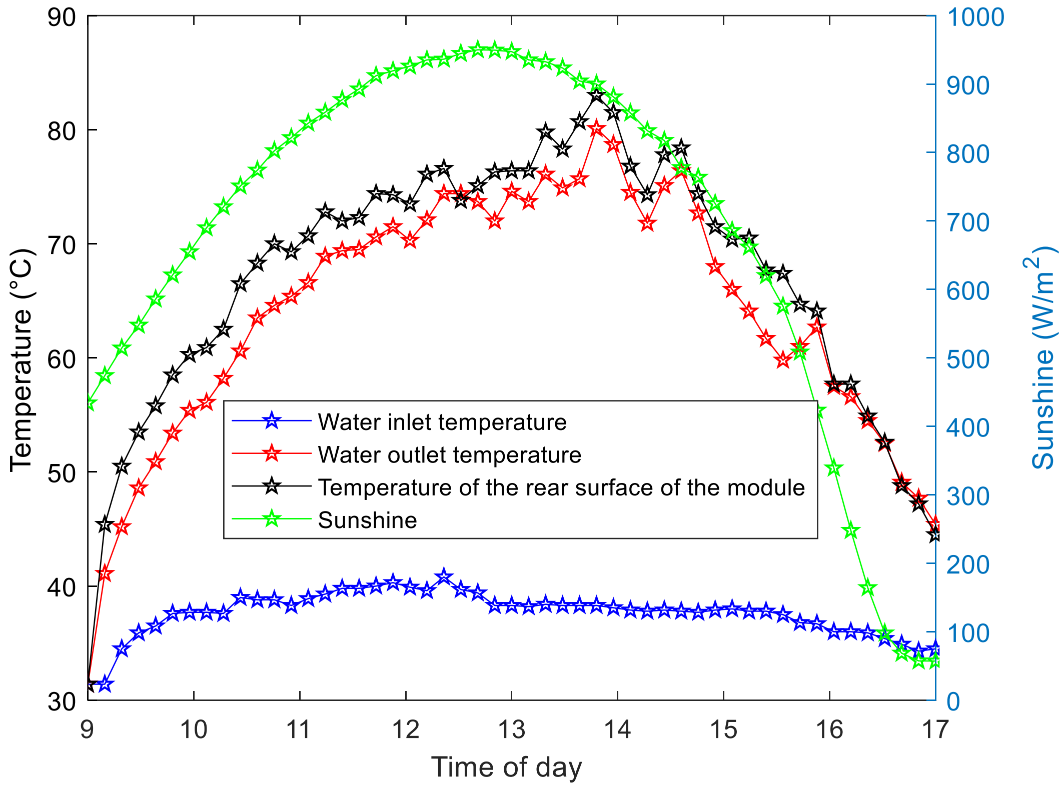

Fig. 6. Temporal evolution of the temperatures of the different elements of the hybrid PV-T solar collector during the day

A solar thermal collector is placed on the back of the PV module to recover heat. Figure 6 shows that the temperatures of the water and the back of the PV module evolve similarly, with the temperature at the back of the module being slightly higher than that of the water (at the outlet). This demonstrates good "direct" heat transfer from the absorber to the water. The maximum temperature reached by the water is approximately 80°C. The temperature of the mains water supplying the collector fluctuates slightly between 30°C and 40°C. Between 11: 00 AM and 2: 45 PM, the average temperature of the hot water is approximately 74°C. The significant rise in water temperature indicates the amount of heat recovered by the PV module.

COMPARATIVE EVOLUTION OF WATER OUTLET TEMPERATURES IN THE THERMAL COLLECTOR AND IN THE PV-T COLLECTOR

Figure 7 shows the comparative evolution of the water outlet temperatures in the thermal collector and in the PV-T collector.

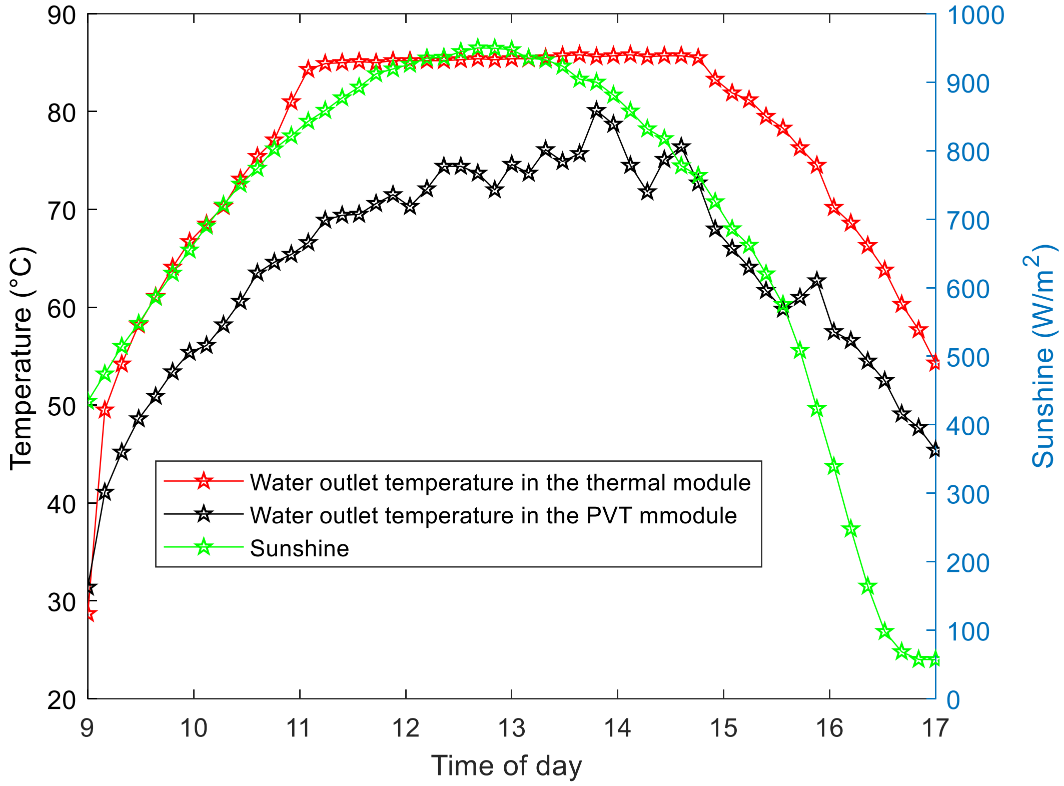

Fig. 7. Temporal evolution of water outlet temperatures in the thermal collector and in the PV-T hybrid solar collector

Comparing the water outlet temperatures of the solar thermal collector and the PV-T hybrid solar collector, the thermal solar collector's water outlet temperature is higher than that of the PV-T hybrid solar collector. This is explained by the fact that the thermal solar collector receives direct solar radiation. However, the fact that the temperature differences are not large demonstrates the efficiency of the PV-T hybrid collector.

3.2 Efficiency Ratio

The efficiency ratio given by equation (3) was calculated assuming that the mass flow rates of water in the solar thermal collector and in the hybrid PVT solar collector are identical.

A value has been found. This shows that the solar thermal collector has an efficiency approximately 2.75 times that of the hybrid PV-T solar collector, and that the hybrid PV-T collector has an efficiency approximately 0.36 times that of the hybrid collector. This result clearly demonstrates that hybridization offers a dual advantage: the production of hot water and the cooling of the PV module.

4 Conclusion

In this experimental study, the thermal performance of a hybrid PV-T solar collector and a conventional solar thermal collector was evaluated. The results show that the water temperature at the outlet of the solar thermal collector is higher than that of the hybrid collector. However, the latter can reach 74°C. The hybrid PV-T solar collector has an efficiency exceeding one-third that of the conventional solar thermal collector. Hybridization therefore offers advantages. Indeed, it allows for the production of hot water at a relatively high temperature while simultaneously cooling the PV module, thus improving its electricity production. In this experimental study, the thermal performance of a hybrid PV-T solar collector and a conventional solar thermal collector was evaluated. The results show that the water temperature at the outlet of the solar thermal collector is higher than that of the hybrid collector. However, the latter can reach 74°C. The hybrid PV-T solar collector has an efficiency exceeding one-third that of the conventional solar thermal collector. Hybridization therefore offers advantages. Indeed, it allows for the production of hot water at a relatively high temperature while simultaneously cooling the PV module, thus improving its electricity production.

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