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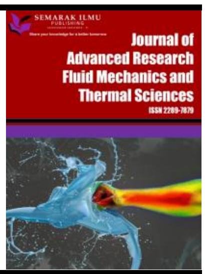

Experimental Study of Hybrid Photovoltaic (PV/T) Thermal Solar Collector with Air Cooling for Domestic Use: A Thermal and Electrical Performances Evaluation

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ABSTRACT

Photovoltaic-thermal (PV/T) collectors convert solar energy into both electrical and thermal energy. This conversion enables the cooling of solar cells while also allowing the produced thermal energy to be used to heat water or space. A hybrid solar panel converts the heat emitted by photovoltaic cells into a transfer fluid (liquid or air), enhancing PV cell efficiency while also producing useful solar heat for household hot water or heating. The heated air extracted from the PV/T collector can be used as a heat source for the building. The paper presents a baffle-based collector for a photovoltaic/thermal system (PVT) to increase output from the system using solar power by comparison with a PVT system without baffles, and its electrical and thermal performance are analysed with the experimental results. Baffles are a solution for optimizing the performance of flat plate solar collectors, which often have low performance. Three typical days from the March 2022 season were chosen and presented as part of this study. For the experiments, two fans were used for air extraction in the PV/T collector, with three speeds chosen: 0.02804 m^3/s, 0.0082 m^3/s, and 0.016 m^3/s, respectively. The variation in thermal and electrical efficiencies of PV/T solar collectors has been calculated for the three tests of March 3, 4, and 5, 2022. The results indicated that the thermal and electrical efficiencies of the PV/T collector were on average 86% and about 9%, respectively, and the thermal efficiency improved by 22% compared with a PV/T collector without baffles in the absorber.

1. Introduction

The combination of photovoltaic and solar thermal systems is designed to produce both electricity and heat. PV/T systems allow for higher yields and, thus, more efficient use. This combination aims to preserve the environment by reducing the use of fossil fuels and simplifying energy production system maintenance costs [1,2].

Previous research showed that more than half of the radiation impacting on the photovoltaic cell is transformed into heat, which motivated the construction of the hybrid PV/T solar collector. This

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heat has the potential to destroy the solar cell's structural integrity. However, by using cooling technology, a longer lifetime module can be maintained, and the recovered heat can be used in a variety of applications such as vegetable drying, heating, and so on. Several changes have been made to the design and air movement in collectors, including the use of absorber fins and a multi-pass airflow to reduce module heat and increase heat efficiency (Figure 1) [3]. The heat extracted from PV/T systems can be used for a variety of purposes, including building ventilation, agricultural use, and industrial material drying [4-6]. PV/T system performances have been improved by modifying their structure.

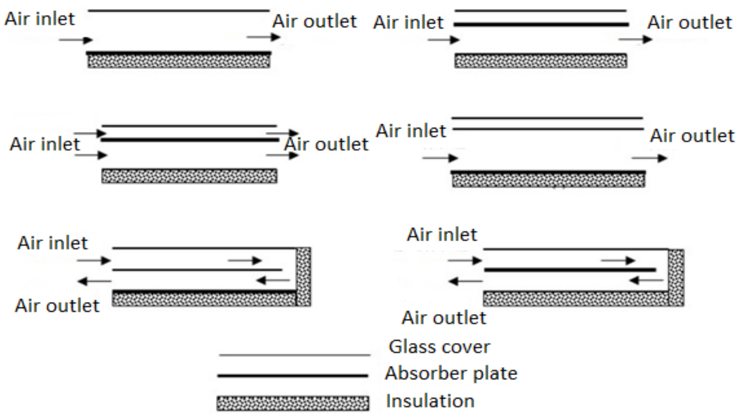


Fig. 1. Different airflow designs in solar air collectors [7]

Agrawal and Tiwari [8] investigated the performance of a hybrid thermal micro-channel solar cell module (Figure 2). The results show that the performance of this system is good compared to a conventional PV module. A comparative study of different configurations of flat PV/T air hybrid solar collectors was presented by Amori and Abd-AlRaheem [9]. For a constant air velocity equal to 0.0991 kg/s, an average reduction of 15.52 °C in cell temperature was observed with a single-pass air channel compared to the PV system without cooling. The efficiencies η_{Th} (Thermal), η_{elec}(electric), and η_T (Total) of the system were improved by 46%, 9.4%, and 55%, respectively. Hassan *et al.,* [10] investigated the feasibility of using PV solar waste heat to regenerate liquid desiccant in the solar air conditioning system, The experiment demonstrates that solar PV waste heat can be used for desiccant solution regeneration at a temperature of 55˚C, enhancing efficiency. Riffat and Cuce [11] investigated the factors that influence the electrical and thermal performance of various PV/T systems. The parameters chosen were the optimum flow rate circulating inside the PV/T collector, the thermal absorber plate, and the air layer thickness. The absorber plate was the parameter that had the greatest impact on the thermal efficiency of PV/T systems.

Amori and Al-Najjar [12] investigated the theoretical thermal and electrical performances of an Iraqi hybrid solar PV/T air collector. They discovered that the PV, thermal, and PV/T efficiencies were 9–12.3%, 19.4–22.8%, and 47.8–53.6%, respectively. Agrawal and Tiwari [13] presented an energetic and exegetical analysis of a hybrid PV/T solar air collector in a cold climate in 2010. They reported that the PV/T energy efficiency was 53.7%. An energetic and exegetic analysis was carried out by Sarhaddi *et al.,* [14] for a PV/T air hybrid solar collector. They reported that the PV, thermal, and PV/T efficiencies were 10%, 17.18%, and 45%, respectively. The exegetical yield of PV/T is 10.75%. Agrawal and Tiwari [13] experimentally and theoretically investigated a PV/T solar air collector. They found that the efficiencies of PV and thermal were 7.13% and 33.54%, respectively.

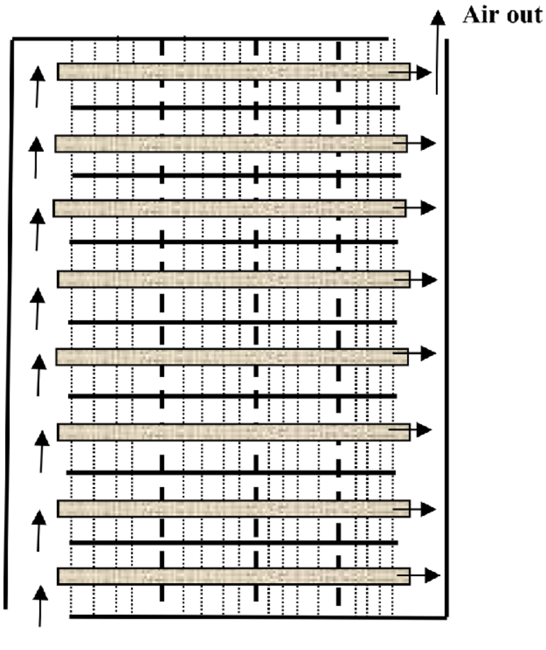


Fig. 2. Micro-channel PV/T hybrid module [8]

Pottler *et al.,* [15] optimized the absorber geometry for a hybrid solar air collector (PV/T). They discovered that the best distance between the fins is between 5 and 10 mm. The collector's thermal efficiency can be increased to 77% with optimized geometry. Because the pressure drops increase dramatically with the distance between the fins, this factor should be taken into account in the design. The purpose of this work is to contribute mainly to improving the hybrid solar collector (PV/T) performance by introducing thin wooden obstacles called baffles into the absorber air space. The results obtained from the experimental study will be analyzed and interpreted.

The baffles are a thin obstacle compared to their heights; they are inserted at the level of the heat transfer devices to increase the heat transfer, extending the path of the heat transfer fluid to exploit a heat exchange surface, as shown in Figure 2 [16]. According to the literature, the introduction of these obstacles in the path offered to the heat transfer fluid allows for an increase in heat exchange with the absorber. It has been established that the passage geometry in the cross-section perpendicular to the flow plays an important role, and thus the thermal performance is significantly improved [16].

Hu *et al.,* [17] conducted a numerical study validated by another experimental study; their objective was to show the effect of rectangular baffles on the thermal performance of a solar flat plate air collector, as shown in Figure 3. They found that introducing the baffles into the moving airstream prolongs the path of the air and modifies its trajectory to increase the residence time of the air in the collector, reduce dead zones, and strengthen internal disturbance, which improves the heat transfer between the air and the absorber plate. For a laminar regime of airflow in the useful duct of an air solar collector, having an aspect ratio of 6, Akpinar and Koçyiğit [18,19] experimentally examined the effect of adding three types of baffles, the configuration and layout geometry of which are shown in Figure 4. A comparative study between four types has been made, and the results obtained for a Reynolds number of 700 and 1000, show that the use of the standard configuration (sheet: 5x5 cm) gives better thermal performance.

Ahmadinejad *et al.,* [20] present a novel baffle-based collector for a photovoltaic/thermal system (PV/T) to increase system output. The baffles installed in the collector increase the heat transfer area and convectional heat transfer coefficient, resulting in better heat transfer between the solar cells and the collector fluid. In comparison to the simple collector, using baffles reduces solar cell temperature by 3.83%, and increases outlet temperature, and increases electrical and thermal efficiencies by 1.63%, 0.83%, and 4.39%, respectively. The overall efficiency of the baffle-water-based system is 66.45%, while the simple-water-based system is 63.85%. Kim *et al.,* [21] developed an air-type PV/T collector with baffles and performed outdoor experiments according to ISO 9806. The experimental results showed that the thermal efficiency was 26–45% when the average solar radiation of 950 W/m^2, an ambient temperature of 0° C, and an inlet flow rate of 60 to 200 m^3/h. When the inlet flow rate was 100 m^3/h, the collector had a thermal and electrical efficiency of 37.99% and 16.21%, respectively. Kim *et al.,* [22] tested an air-type PV/T collector with perforated baffles in outdoor experiments using the ISO 9806 standard. The total energy (thermal and electrical characteristics) and exergy of the PV module of the air-type PV/T collector were studied relating to flow rate (100, 150, and 200 m3/h), solar radiation, and rear temperature. As a result, the total exergy efficiency of the air-type PV/T collector with perforated baffles was 24.8-30.5%, while the total energy efficiency was 44.1-63.3%.

Introduction of baffles into the air channel. Improve heat transfer in solar heat collectors by increasing the heating time between the fluid and absorber (residence time), creating turbulence for intense mixing, and avoiding 'hot spot', which therefore minimizes heat loss [23]. As a result, this study presents an innovative collector design combined with a photovoltaic system. The solar collector has baffles that connect to the top of the absorber and extend to the bottom. This allows for better heat transmission from the PV cells to the working fluid, leading to increased electrical and thermal efficiency. In this case, the role of these baffles favors heat transfer to the working fluid in two ways: they allow for turbulent flow on the absorber and extend the working fluid path.

This work was carried out by the Research Unit in Renewable Energies in Saharan Medium (URER.MS), Adrar-Algeria. Presents an experimental study of the modified hybrid PV/T solar air collector. This PV/T collector represents another design to improve a PV/T solar collector with a simple absorber. The main parameters characterizing the PV/T solar collector (temperature and thermal efficiency, electrical efficiency, and power) are evaluated.

2. Description of Modified Solar Hybrid PV/T Air Collector

Figure 3 shows an experimental setup descriptive diagram of the proposed to evaluate the thermal modified solar hybrid PV/T air collector performance by the integration of baffles in a simple absorber. An absorbing with baffled is shown in Figure 5. It consists of 08 baffles (15 cm * 1.5 cm*1cm) of rectangular shape placed in a space of 10 cm between each one; glued to a rectangular galvanized sheet with a surface area of 0.424 m² (1.06 cm*0.4 cm) and a thickness of 0.5 mm, painted matt black to increase the absorption of solar rays.

To evaluate the thermal and electrical performances of hybrid Photovoltaic/Thermal (PV/T) solar air collector, an experimental study is carried out. These experimental tests were carried out for three days in March 2022, at URER.MS, Adrar-Algeria, (Latitude: 27°8’N, Longitude: -0°17 ’E and Altitude: 279 m). Three experimental tests presented in this study concern three typical days March 03, 04, and 05, 2022.

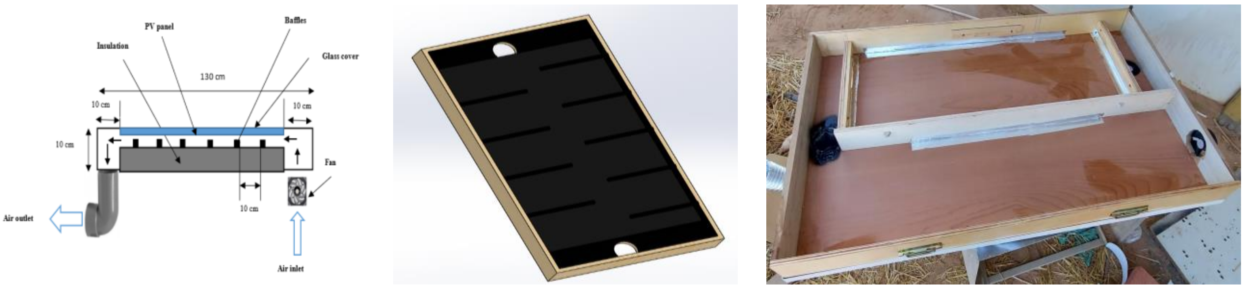


Fig. 3. Descriptive diagram of a hybrid solar PV/T air collector with the modified absorber

The meteorological parameters describing weather conditions throughout the test days, namely: solar radiation, ambient temperature, and wind speed, are provided by the research unit meteorological station and recorded at an interval time of 1 min. This weather station is linked to the Concentrating Solar Power services (CSP).

The experimental setup is instrumented to measure the total solar radiation, the air mass flow rate, and the main temperatures during test days. These measurements have been recorded from 06:00 a.m. to 09:00 p.m. Solar radiations are measured by using a Kipp & Zonen CMP21 Pyranometer. The fan speed is measured by using Testo 425 type Thermo-anemometer. Ambient temperature is measured by Campbell Scientific CS215 probe. Calibrated K-type (Ni-Cr) thermocouples are used to measure the inlet air temperature, center air temperature, absorber temperature, inner glass surface temperature, outlet air temperature, and Tedlar PV panel temperature. These thermocouples are connected to an automatic data acquisition system (Fluke 2638A Hydra Series III Data Acquisition system). All measurements are saved through a data acquisition system for an interval time of 10 min. The accuracy and error percentages of the measuring devices used in this study are given in Table 1 where the maximum calculated error in the measuring instruments is about ± 3.1%.

Table 1
Accuracies and uncertainty errors for the measuring instruments

Measure Instrument	Model/type	Accuracy	Range
Thermocouples	Type-K (Ni-Cr)	±1°C	-100 à 500°C
Pyranometer	Kipp & Zonen CM11	±1 W/m2	0 à 4000 W/m2
Anemometer	Testo 425	±(0,03 m/s + 5 % v.m.)	0 à +20 m/s

Figure 4 shows a photograph of the experimental setup proposed for the experimental study of a modified solar PV/T hybrid collector. The system consists of two essential parts: the thermal solar collector with baffles, and the second is essential part it is the electrical part represented by the photovoltaic panel PV type UDTS-50 monocrystalline to power two fans (DC); one to evacuate the air above the solar thermal collector between the absorber and the glass and the second to evacuate the air below the photovoltaic panel and cool it by extracting the heat from the cells to improve its electrical efficiency. This PV panel allows the PV/T system to operate in stand-alone mode. To measure the air temperature in the solar thermal collector and PV module, thermocouples type-k (Ni-CR) is placed at the inlet and exit and in the medium of the solar collector, and another to measure the PV panel rear face temperature. According to the Figure 4, the formation of a meandering flow of air in the collector with baffles from the inlet to the outlet. In this case, it is clear that the length of air trajectory is more than double that of the length of the collector, thus increasing the heat transfer and effectively reducing dead zones.

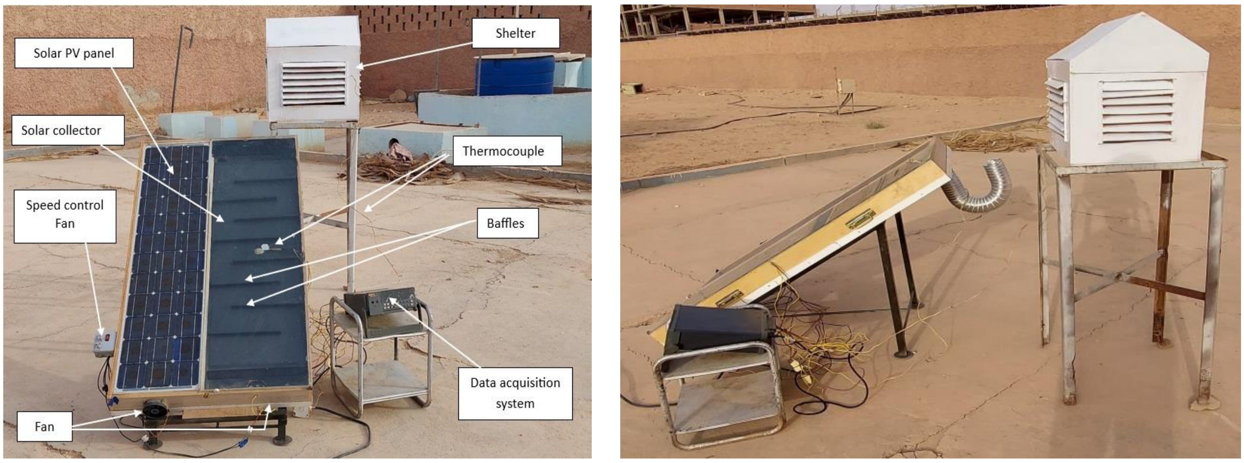


Fig. 4. Photography of the experimental setup

The solar hybrid PV/T collector used in this dimension study is a length of 130 cm, a width of 73 cm, and a thickness of 10 cm. The hybrid solar collector is placed on a metal support tilted to 27° and facing north-south to receive the maximum amount of solar irradiation during the test days. The photovoltaic module used in this study is a monocrystalline panel (UDTS-50 type) under STC conditions (AM=1.5, G=1000W/m², and Tc=25°C). The UDTS-50 solar panel is made up of 36 square monocrystalline silicon solar cells, 10 cm square, connected in series.

The technical specifications of the modules provided by the manufacturer are recorded in Table 2.

Table 2
The PV module Data sheet UDTS-50 for STC (Standard Test Conditions) [24]

Parameter		Monocrystalline UDTS-50
Open-circuit voltage Voc	V	21.60
Short-circuit current Isc	A	3.18
Voltage at MPP Vmp	V	17.50
Current ar MPP Imp	A	2.90
Maximum power Pm	W	50
Cell series resistance Rs	Ω	0.25
Cell shunt resistance Rsh	Ω	98.11
Fill factor FF		72.00
Efficiency η	%	2.33
Panel area	m^2	0.385
Temperature coefficient of Isc	mA/°C	+8.70
Temperature coefficient of Voc	mV/°C	-72

3. Results and Discussion

Three typical days, covering a season in March 2022 were selected and presented as part of this study. The main meteorological parameters characterizing the test days, namely: solar irradiation and ambient temperature, are shown in Figure 5 and Figure 6, respectively. The meteorological parameter variation between test days is not significant as long as the days are successively according to the solar irradiation and ambient temperature profiles.

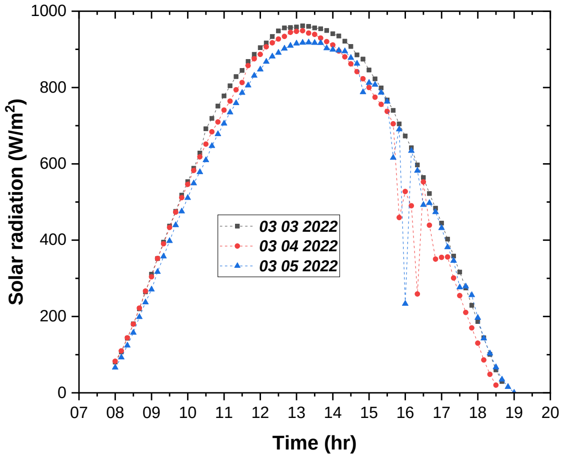


Fig. 5. Global solar radiation variance during test days

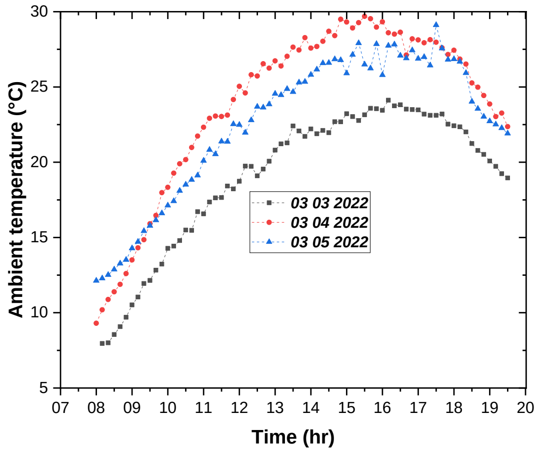


Fig. 6. Ambient temperature variance during test days

The first test is represented by the day 03/03/2022 which is marked by ambient temperatures between 7.95°C and 24.11°C and by an intensity of solar irradiation (from 0 to 961.53 W/m²), relative to the other test days. For the test (04/03/2022), the maximum solar irradiation reached 948.84 W/m² and the ambient temperature was moderate and between 9.3 and 29.68°C. Same for the test day (05/03/2022), the weather was a bit cold, marked by ambient temperatures reaching 29.11°C with a very high solar irradiation that exceeds 918.34 W/m².

4. PV/T Hybrid Solar Collector Performance Analysis

PV/T solar hybrid air collector and the PV panel are inclined at an angle equal to Adrar's attitude and oriented south (27°). The experimental results reported in this section describe the solar collector's thermal behavior.

The main temperatures describe the thermal behavior of the different parts of the solar collector inlet air ($T_{in\text{-}air}$), the absorber (T_b), the air between the glass and the absorber ($T_{cent\text{-}air}$), the glass (T_g), the air outlet temperature (Tout-air) and the ambient temperature for the three days of testing for different mass flow rates are shown in Figure 7.

According to the figures, the temperature profiles clearly indicate how climatic variables affect the thermal behavior of the solar collector throughout test days. It is also obvious that the temperature profile of the solar collector is roughly proportional to the solar irradiation profile.

The maximum absorber temperature registered corresponds to the three air velocities for the three tests: 91.03°C (V_{air}=1.3 m/s), 98.93 (V_{air}=2.3 m/s), and 59.78°C (V_{air}=3.6 m/s), respectively. The comparison shows that there is not a significant difference in absorber temperature for the two tests corresponding to 03 and 04 March 2022, for the test of 05 March, we observe a difference of more than 30°C compared to the inlet air temperature. When comparing the temperature of the glass cover. The results show that the glass cover temperatures are 53.01 (V_{air}=1.3 m/s), 63.93 (V_{air}=1.3 m/s), and 40.6°C (V_{air}=1.3 m/s), respectively, this increase is explained by the radiation transfer effect that occurs between the glass and the sky and also between the glass and the absorber because these materials have different temperatures, then this transfer mode that passes through them occurs by the medium of electromagnetic emission and absorption.

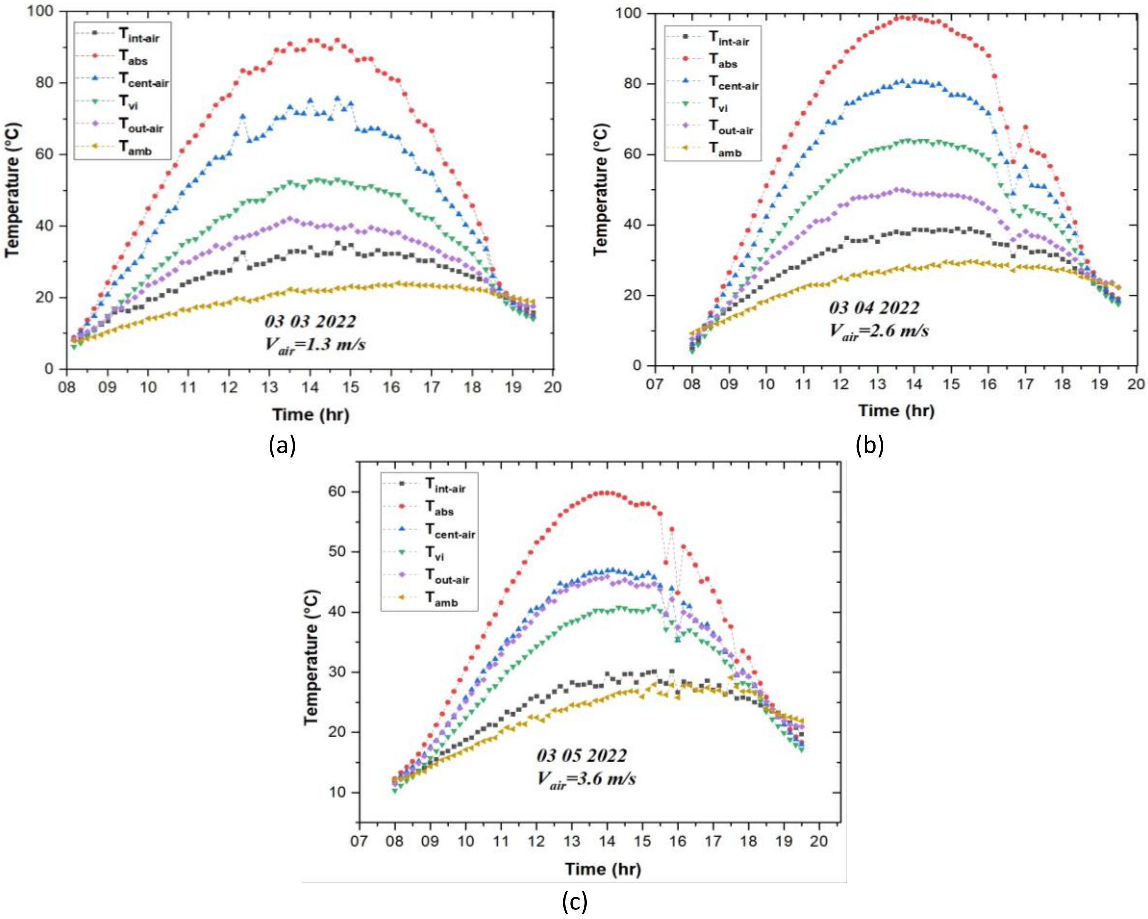
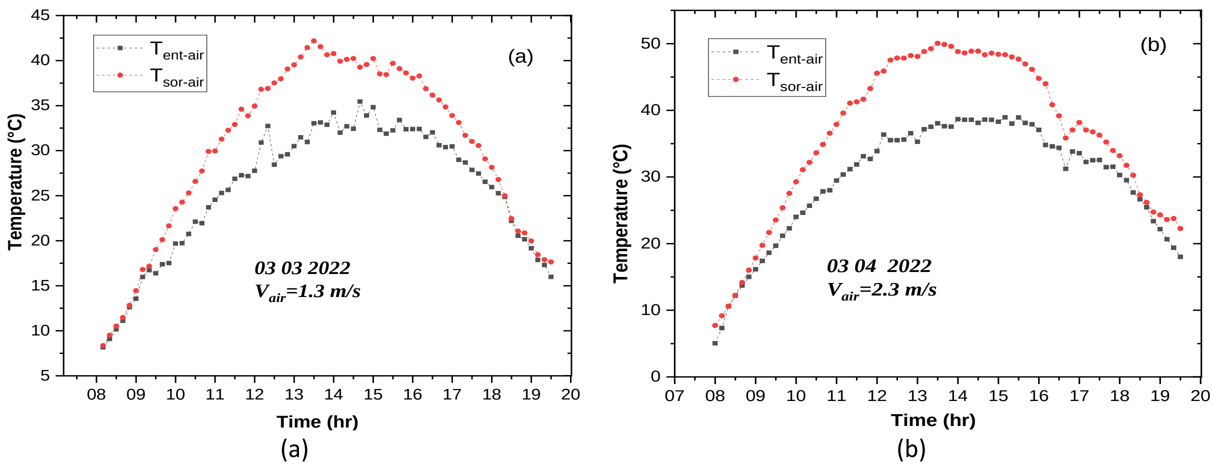
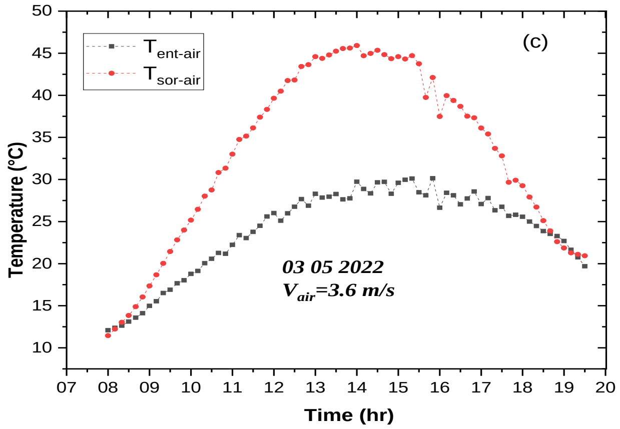


Fig. 7. Temperature variation at different locations in the solar collector for test days: (a) 03/03/2022, (b) 03/04/2022, (c) 03/05/2022

The air inlet temperatures at the center and outlet of the solar collector are shown in the same figures. Figure 8 shows the difference in the air inlet and outlet temperature. For the test of 03 March 2022, the maximum temperature difference registered at 13:20 is 10.48°C, which is 12.26°C registered on 04 March 2022, for the third day the temperature difference was equal to 17.91°C. This increase is due to the increase of the metal plate temperature (absorber) when the air circulates through the absorber, a convective exchange creates between the absorber and the air, The air takes the heat generated by the plate which increases its temperature.

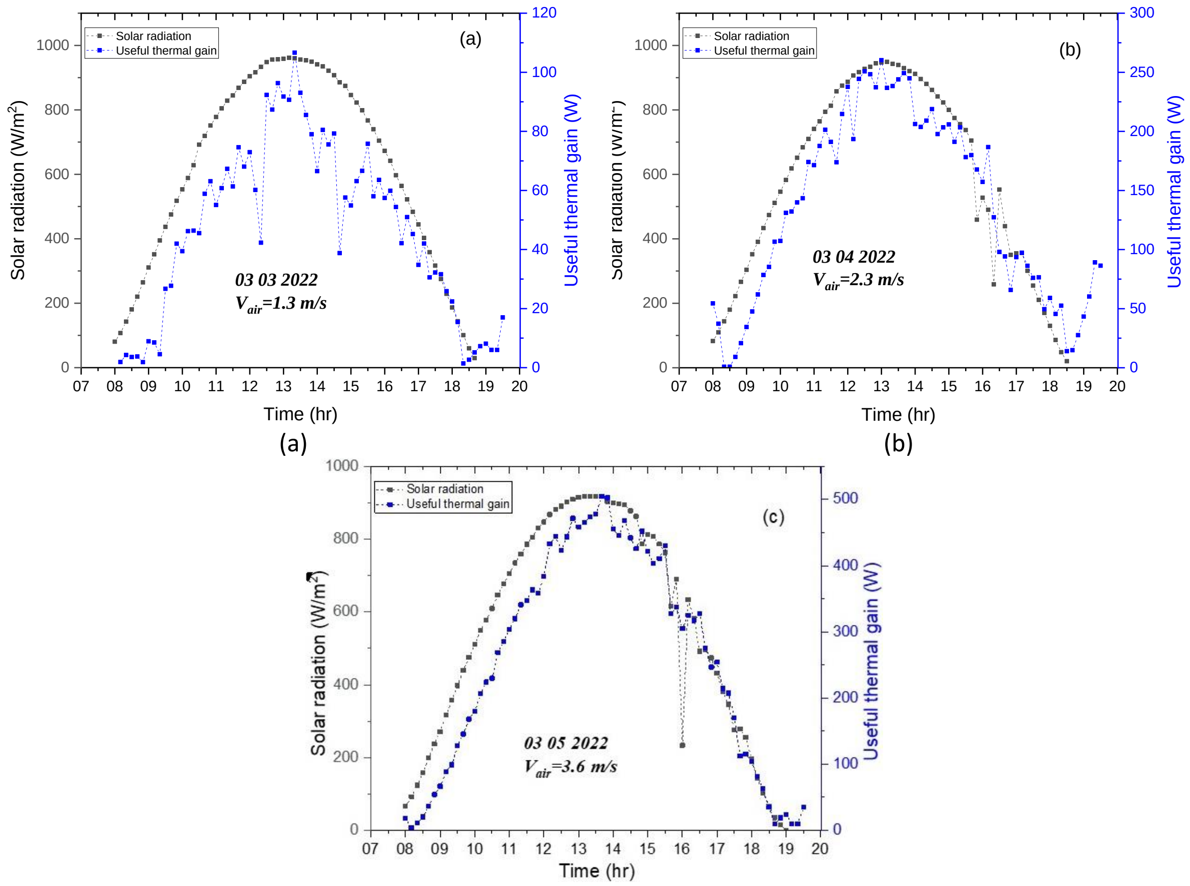




(c)

Fig. 8. Difference in air temperature between inlet and outlet solar collector: (a) 03/03/2022, (b) 03/04/2022, (c) 03/05/2022

Figure 9 shows the solar radiation variance and the useful thermal rate energy. It should be noted that the useful thermal energy rate supplied by the solar collector gradually increases when the solar radiation increases to a maximum value of 260.17 Watt at 13.00 for the test of 04/03/2022, and for the test of 05 March 2022 the useful thermal energy rate reached equal to 504.44 Watt.



(c)

Fig. 9. Global solar radiation variance of the and the rate useful thermal energy: (a) 03/03/2022, (b) 03/04/2022, (c) 03/05/2022

The thermal efficiency (η_{th}) can be also expressed as the heat gain of the working fluid between the outlet and inlet divided by incident solar radiation. The instantaneous thermal efficiency of solar thermal collector is [25]

$$\eta_{th} = \frac{Q_u}{A.G} = F_r.A.[G.\tau\alpha - U_L.(T_e - T_{amb})]/A.G \quad (1)$$

The thermal efficiency variation of hybrid solar collector PV/T, for three tests of 03, 04, and 05 March 2022, is illustrated in Figure 10. The system's thermal efficiency is more important when the intensity of the solar radiation is high. The calculation shows that the maximum thermal efficiency of the hybrid solar PV/T collector (03/03/2022) is 26.19% for a mass flow rate of 0.01013 kg/s.

For the day of 04 March 2022, the solar collector achieves the maximum thermal efficiency of 62.73% for a mass flow rate equal to 0.02025 kg/s, while for the test of 05 March 2022 the efficiency is 87.27 % for a mass flow equal to 0.02804 Kg/s. While a hybrid PV solar collector without baffles (Figure 4) tested on the same day (05 March 2022) had an efficiency of 0.69% with a mass flow rate of 0.02804 Kg/s.

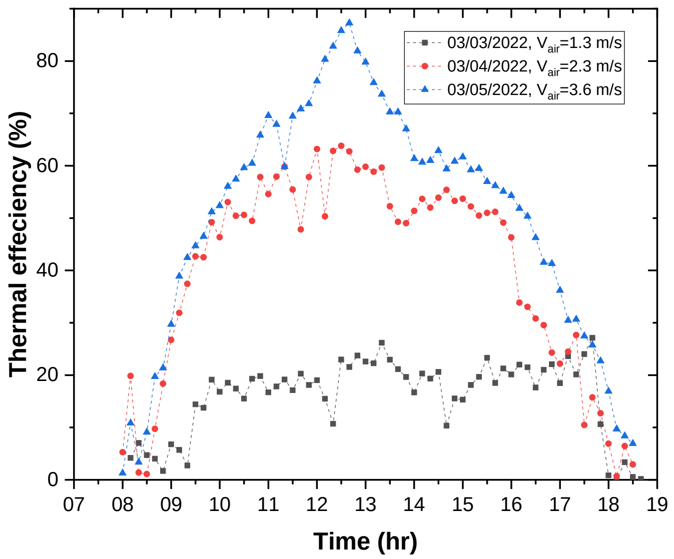


Fig. 10. Thermal efficiency variance

5. Electrical Performance

In a photovoltaic system, when solar radiation increases, the photovoltaic panels' power increases. On the other hand, photovoltaic panels lose their efficiency when the ambient temperature increases.

In this case, the photovoltaic panels heat removal is essential. The air passing under the PV panels reduces the PV panels operating temperature and increases their electrical power.

When air passes under the photovoltaic panel, its temperature increases due to the panel's heat absorption, which leads to an increase in the solar hybrid PV/T collector thermal efficiency.

During the tests, the PV panel electrical outputs (I_m current and V_m voltage) were connected to the fan for the purpose of measurement. Electrical efficiency depends mainly on the incoming solar radiation and the PV panel temperature. It is calculated with the following equation [26]

$$\eta_{ele} = I_m \,.\, V_m \,/ S_{pv}.G \quad (2)$$

Figure 11 shows the electrical efficiency variation over three test days. According to the graphs, the efficiency increases slightly during the day beginning and decreases solar radiation increase for an air velocity equal to 3.6 m/s.

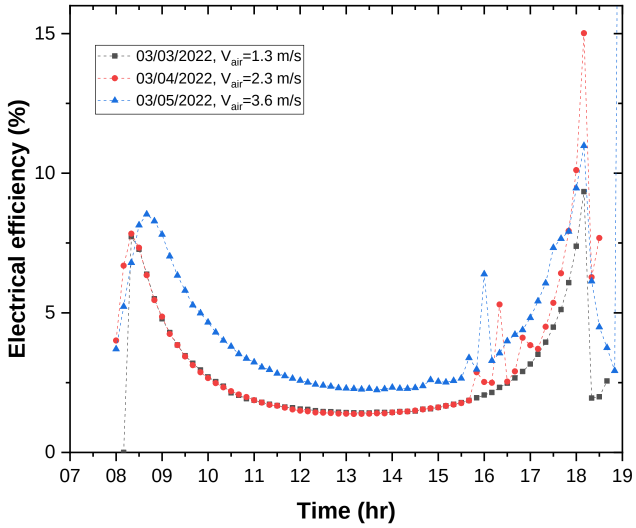


Fig. 11. Electrical performance variation

Figure 12 depicts the evolution of electrical power throughout three experiments (March 3, 4, and 5, 2022). Electrical power grows in the morning until it reaches its maximum value, and then falls with solar radiation until it stabilizes at constant values, at which point electrical efficiency decreases.

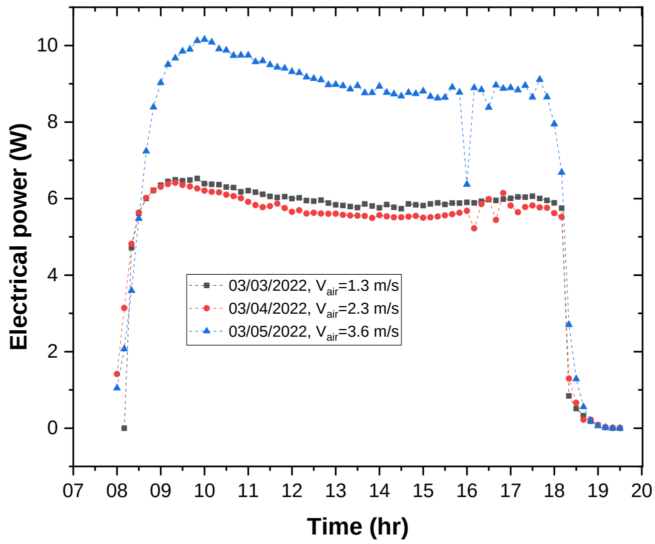


Fig. 12. Electrical power variance

Two other tests were carried out to measure the PV panel temperature, with and without ventilation. The meteorological conditions are almost the same in these two days with (the) maximum solar radiation equal to 1042 W/m^2 for the day of 25 March 2022 and a maximum ambient temperature equal 31.14°C; 1048.79 W/m^2 and 33.57°C for the day of 26 March 2022. The first day of the test, the PV panel cooling fan is off, according to the Figure 13 the panel temperature reaches the maximum value 70.28°C whereas for the test of 26 March 2022 the fan is in operation the maximum PV panel temperature was 61.16°C, this shows the advantage of integrating a fan under a photovoltaic panel.

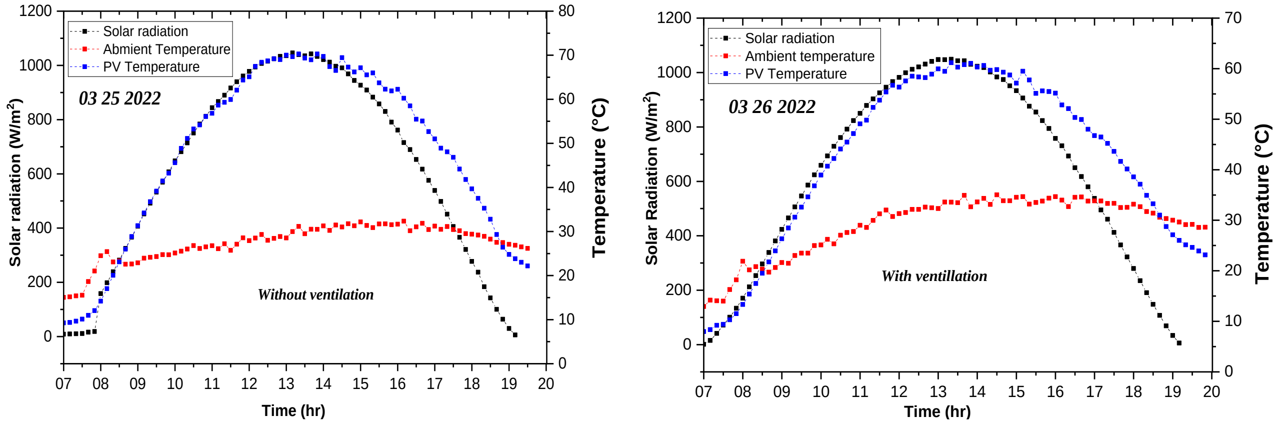


Fig. 13. PV panel temperature variance

6. Conclusion

In this work, a solar hybrid thermal, photovoltaic collector detailed experimental study is presented with baffles, this solar collector was carried out in the Research Unit in Renewable Energies in Saharan Medium, Adrar-Algeria. Research findings can be summarized as follows

i. Solar radiation intensity and ambient temperature significantly impact temperature rise, but have little impact on heat collection efficiency. This type of PVT has potential applications in various fields such as: solar drying; heating of agricultural greenhouses…
ii. The addition of internal baffles increases the air dwell time in the collector, strengthens the internal disturbance, and adds to improved efficiency. At the same time, the existence of baffles causes significant flow separation and reattachment which results in flow loss to some extent, A 64 to 86% increase in PV/T hybrid collector efficiency compared to the single solar hybrid PV/T collector.
iii. Adding a fan below the PV panel decreases its temperature by 11°C.
iv. An air temperature difference at the inlet and outlet of the solar hybrid PV/T collector reaches 17.91°C in the time interval between 11:00 and 15:00.
v. When designing, it's important to consider the optimal number of baffles to prevent excessive pressure loss and raise operational costs. In the future, a CFD simulation will be conducted to evaluate the performance of the PVT system with various baffle configurations.

Acknowledgment

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