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Design, Characterization and Performance Evaluation of PVT Solar Collector in Tropical Area

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Abstract: Solar energy is the most recognized diversified renewable energy from which the production can be extracted into electrical and thermal energy. The aim of the present work is to evaluate the energy efficiency of a thermal-photovoltaic collector with cooling system. It is a question of estimating the difference between the energy necessary for the cooling and the gain in power of the PV/T system. For this, a PV/T collector is designed and builds at the Laboratory of Energetic and Applied Thermals (LEAT) of ENSAI of the Ngaoundere University. A measurement campaign was carried out during the months of March to April 2015. During tests, the collector was orientated south and inclined at an angle of 30° compared to the horizontal. The analysis allowed us to design and size the hybrid PV/T collector. The energy balance method (electrical and thermal balance) was used to determine the electrical and thermal performance of the PV module. A comparison between the hybrid PV/T system and conventional PV panel has been done. The results show that in natural convection, the surface temperature of the cells was 65°C and 61°C respectively for the PV/T and conventional PV panel. The electrical efficiency of conventional PV panel was 9.17% while that of hybrid PV/T system was 7.35%. For 1012 W/m^2 insulation and a PV module temperature of 65°C, the hybrid PV/T system electrical power was 31 W with a thermal power of 457 W. A return of thermal efficiency of 75% which gives a global efficiency of the hybrid PV/T system of 82%.

Keywords: Solar Energy, Photovoltaic/Thermal Collector, Convection, Efficiency

1. Introduction

Over the past 30 years, the global energy consumption has been growing strongly in all regions of the world. It seems like ten dentally; energy consumption will continue to increase, under the effect of energy economic growth on the one hand, the increase in electricity consumption per inhabitant on the other hand [1]. Currently, the production of domestic and industry energy is based largely, on a limited energy resource: oil, gas... The world's energy demands are continually rising and it is estimated that world reserves will be depleted by 2050 if consumption is not radically changed [2, 3].

Looking for alternative energy resources has become a crucial issue nowadays. Much scientific research has been conducted in the area of renewable energy sources, such as wind and solar energy. In the latter case, the design and optimization of photovoltaic systems are current because they lead to a better use of solar energy. The research is very active in the field of solar photovoltaic with the consequence of the constant decrease of prices and increase of the yield of photovoltaic cells. In 20 years, the efficiency has increased from 15% to 36% in the laboratories, and those of the commercially available systems are as to passes of 5% to 20% [4, 5, 6].

Many studies on the influence of the various parameters of the solar photo cell allowed highlighting these parameters on the current/voltage (I-V) and power/voltage (P-V) of the cell [7]. Indeed the sunlight and the temperature are two parameters extremely important in the behavior of solar cell. They have a significant influence on the current/voltage (I-V) and power/voltage (P-V) characteristics curves of the solar cells. The performances of a photovoltaic module are defined for standard test conditions (the temperature of the panel PV set at 25°C, the irradiance of 1000 W/m^2, the number of 1.5). However, in real world these conditions are not respected leading to during prolonged exposure to the sun the heating of the solar module.

The electrical efficiency of photovoltaic cell decreases by about 0.45%/°C [8, 9, 10]. For large increase of temperature, overall reduction of this efficiency can reach 10% half the efficiency of the cell under normal conditions of measurement. In order to optimize the operation of these panels, several methods have been presented in the literature: the Tracker of the Peak Power Point (TPPP), algorithmic methods (O&P, IC) and most recently the recovery of the thermal energy of the panels. This last form of optimization has given birth to photovoltaic/thermal systems (PV/T).

Several works in the literature are emetics in the optics of performance improvement [11-15]. The thermal and electrical performance of four hybrids solar air collector PV/T differentiated by the cooling mode of the PV panels was compared [16]. This work shaw that cooling of both sides of panels improves panels efficiency, but require high ventilation power for cooling. According to Dupeyrat [2], Tiwari *et al*. [17] the reccovery of the thermal energy produced byPV/T systemimproves its overall efficiency of approximatly 18%. A comparative study shows the thermal performance of air compared to water when used as cooling fluid in a PV/T system [9]. A double air circulation coolingsystem in a PV/T systemhas been tested and validated [18]. The cooling system results in a gain in energy of the system, but the energy necessary for the movement of the cooling fluid is not taken into account in the evaluation of this gain. The objectives of our work is to compare the energy gain obtained after cooling to energy necessary for to put in motion of coolant fluid. For the purpose of this article, the aim is to design and characterize a PV/T collector in a humid tropical environment.

2. Material and Methods

2.1. Presentation of the Study Site

The tests took place within the ENSAI of Ngaoundere (Latitude: 7.32 North; Longitude: 13.58 East; Altitude: 1205 m). This collector was exposed to the natural solar radiation in the side without shading. The manipulations were carried out during the month of March and April 2015 each day from 9 amto 16 pm with recording measurments any thirty minutes (30 mn).

2.2. Design Method

For the design phase of the hybrid PV/T collector, functional analysis was applied as design method. Figure 1 shows the different phases of the engineering design method.

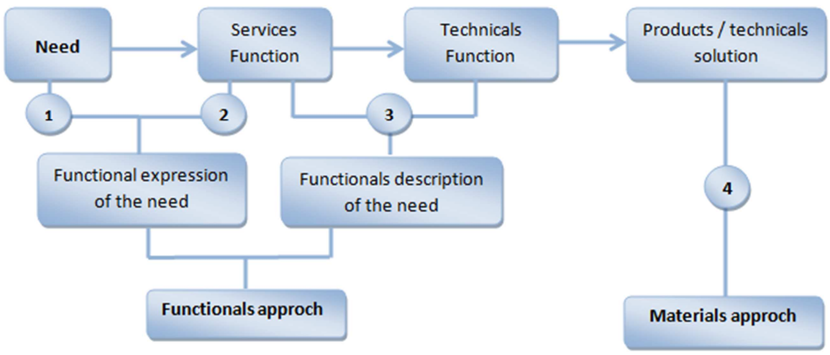


Figure 1. *Phase of functional analysis.*

2.3. Photovoltaic/Thermal Hybrid Collector Models

The hybrid PV/T system studied is a flat plate solar collector consisting of a convectional photovoltaic solar module (monocristalline silicon technology) with a simple glazing all placed in a wooden support so that the air circulated between the PV module and the glass cover. Sunlight, which in the form of photon energy is absorbed by the system. It is able to generate simultaneously electricity and heat energy. The PV module is used as a heat absorber. Within this framework, two configurations were used to characterize the experimental device: conventional PV module system (figure 2a), PV/T system (figure 2b).

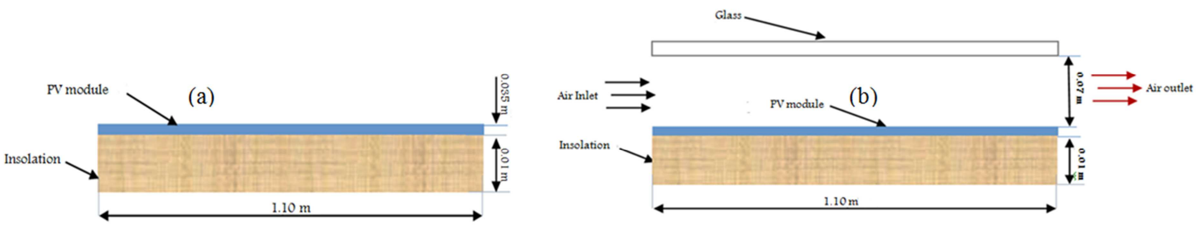
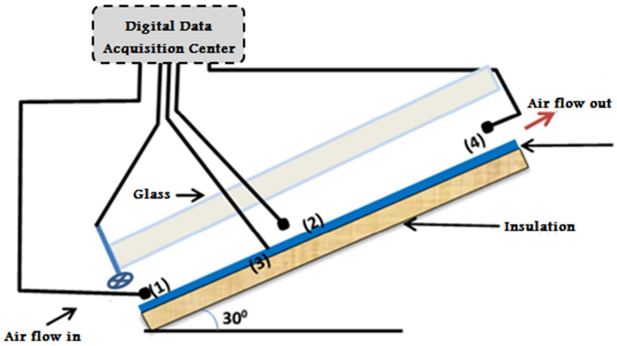


Figure 2. *Studied configuration.*

2.4. Equipments and Measuring Instruments

For the experimental part, the measuring instruments were constitute by: a ALMEMO 2590 data acquisition unit for automatic setting of all the parameters; thermocouples for measuring the temperature; a pyrometer (type FLA- 613-GS) for measuring the irradiance of the study site; a anemometer (Almemo FVAD 15S120 R1E4) for measure air velocity; a "Almemo" ZAD936 RAK brand moisture meter to measure the relative humidity of the air and the ambient air temperature. The position of the sensor is presented by figure 3.



(1): hygrometer; (2)-(4): Thermocouples

Figure 3. *Schematic of experimental device and position of sensor.*

2.5. Performance Evaluation of the PV/T System

2.5.1. Evaluation of the Electrical Energy

The PV module produced an electrical power evaluated by the following relation [11].

$$P_{élec} = \mathrm{U.I} \quad (1)$$

2.5.2. Evaluation of the Thermal Energy

The thermal energy is the product of the mass flow of the air in the collector, of the specific heat mass and the temperature variation between the outlet and the collector inlet. It is given by the expression 2 [11]:

$$P_{ther} = \dot{m}\mathrm{C_{Pair}}\Delta\mathrm{T} \quad (2)$$

$$\text{Or } \dot{m} = \rho\dot{V} = \rho\mathrm{v}S \quad (3)$$

$$P_{ther} = \rho\mathrm{v}S\mathrm{C_{Pair}}(T_S - T_e) \quad (4)$$

For temperatures ranging from 0°C to 100°C the thermal properties of air are determined by correlations (5) and (6):

$$\mathrm{C_{pair}} = 1007\ \mathrm{J.Kg^{-1}{}^{\circ}C^{-1}} \quad (5)$$

$$\rho = \frac{353}{(\mathrm{T_f}+273)} \quad (6)$$

2.5.3. Expressing Electrical and Thermal Efficiency of the Hybrid PVT Collector

Depending on the temperature of the panel, the electrical efficiency $\eta_{élec}$ will be calculated using the expression described by [18].

$$\eta_{élec} = \eta_o[1 - \beta\,(T_{pv} - T_{ref})] \quad (7)$$

With η_o nominal efficiency under the standard conditions given by the equation (8)

$$\eta_o = \frac{P_{max}}{A.G} \quad (8)$$

Similarly, the general expression of the thermal efficiency is a function of the air flow, specific heat mass, the input and output temperatures of the exchanger, respectively T_e and T_s, this is a function of total area S and the surface of collector Ac.

$$\eta_{ther} = \frac{P_{ther}}{A_c \int Sdt} = \frac{\dot{m}C_p \int(T_S - T_e)dt}{A_c \int Sdt} \quad (9)$$

2.5.4. Expressing of the PVT Energy Balance

This total energy is the sum of the electrical and thermal power produced; it is given by the relation.

$$P_{total} = P_{élec} + P_{ther}(\mathrm{W}) \quad (10)$$

Similarly, this total efficiency is the sum of the electrical and thermal efficiency.

$$\eta_{total} = \frac{P_{élec}}{P_a} + \frac{P_{ther}}{P_a}(\%) \quad (11)$$

3. Results and Discussion

3.1. Characterization of the Site of Study

Figures 4, 5 and 6 present the evolution of the site's parameters. These are respectively the evolution of the irradiance and the temperature of the ambient air as a function of the time of the day (figure 4), the evolution of irradiation and the relative humidity depending on the time of day (figure 5) and the evolution of irradiation air speed in relation to the time of day (figure 6). On figure 4, a proportional evolution between solar irradiation and ambient air temperature was observed. This ambient temperature reaches a value of 36.5°C when the solar irradiation is at maximum (1013 W/m^2) at 12.30 pm. These results are consistent with the literature and the work of Ben-Cheikh *et al.* [19] showing that the temperature of outdoor air is proportional to solar irradiance.

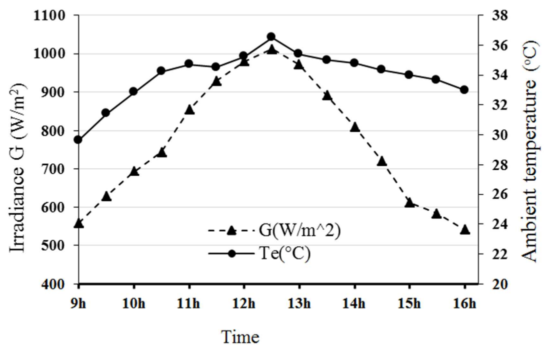


Figure 4. *Variation in irradiation and ambient temperature versus hours of the day.*

The analysis of the figure 5 shows that the relative humidity of the air decreases whatever the irradiance. Indeed for an irradiance of 560 W/m^2, the relative humidity is 36.5%, at 12.30 pm for an irradiance of 1013 W/m^2, the relative humidity of 22.87% between 12 am and 16 pm and a decrease in the relative humidity of the ambient air was noted.

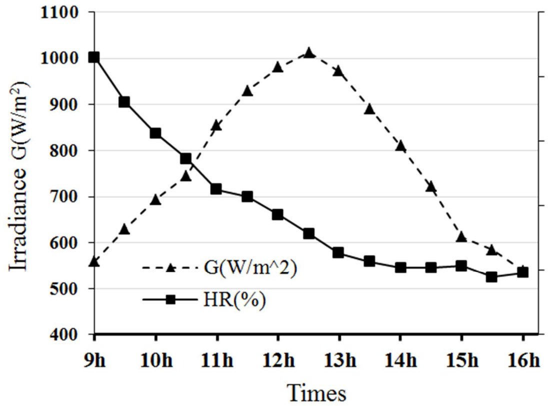


Figure 5. *Hourly variation in irradiation and air humidity.*

With regard to the figure 6 with presents the evolution of the air velocity during the day, we observe that, the air velocity of the study sites varies during the day. It increase from 0.34 m/s to 0.59 m/s from 9 am to 11.30 pm and decrease for 0.6 to 0.4 m/s between 12 am and 16pm. Although this evolution is quasi random, it follows that of irradiation. This velocity which is relatively small compared to the air velocity under standard test conditions of 4-5 m/s will have a negative influence on the performance of the photovoltaic collector [10, 20].

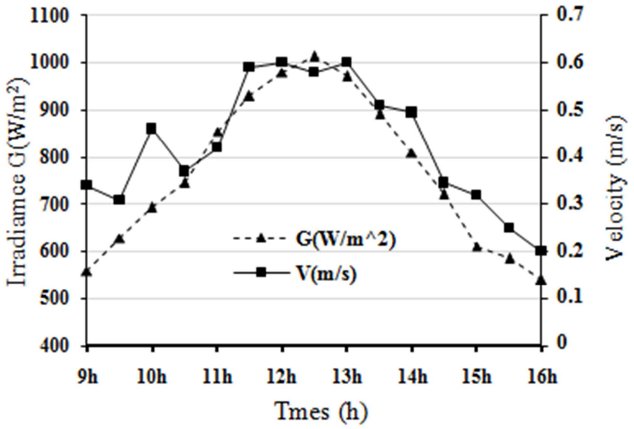


Figure 6. *Hourly variation in irradiation and air velocity.*

3.2. Characterization of the Photovoltaic Collector

3.2.1. Temperature Distribution at the Surface of the PV Module

Figure 7 shows the evolution of the temperature of the PV module with the irradiance during the day. It is noted that the temperature of the PV module increases with the increase of irradiance and decreases when it decreases. Indeed between 9 am and 12.30 pm when the irradiance increase from 560 to 1013 W/m^2, the temperature of the panel PV increases from 45°C to 62°C, and by 12.30 am to 16 pm when the irradiance decreases from 1013 to 540 W/m^2, the temperature of the PV module decreases for 62°C to 49°C. It is explained by the fact that PV module during this operation behaves as a transforming absorbent to a part of the solar radiation in the form of heat. This result is similar to those found in the literature [16, 8, 2, 10].

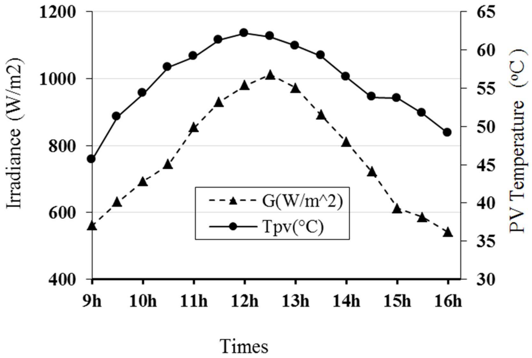


Figure 7. *Hourly variation of the temperature of PV module according to their radiance.*

The Evolution of the temperature of PV module according to the irradiance during the day is represented in figure 8. In general, there is proportionality between different temperatures and irradiance throughout the day. In addition, the temperature under the PV module (70°C) is greater than all other size on the PV module. In fact, for irradiance condition of 1067 W/m^2, an ambient air temperature of 35.5°C, a relative humidity of 14.6%, an air velocity 0.46 m/s, we measure the temperature of the air under the PV module which a value of 70°C, 64.33°C PV module temperature, 58°C for the outlet air temperature, 52.23°C for the air temperature in the vessel and 43.7°C for the temperature of the external cover glass. This result can be explained firstly by the fact that the photovoltaic module are look as a thermal generator, converting a part of the solar radiation received into heat and secondly by the low velocity of air circulation around the PV collector (less than 0.5 m/s).

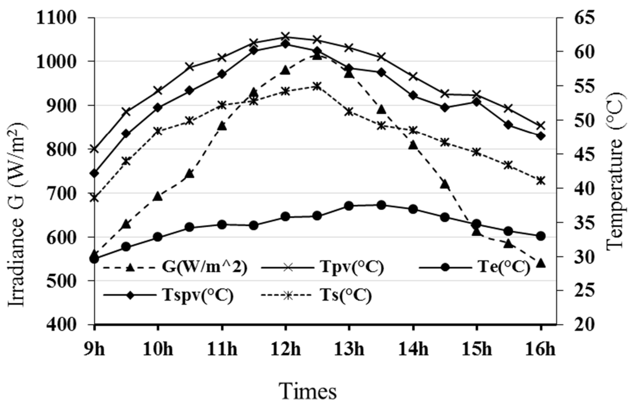


Figure 8. *Hourly evolution of temperature at different sizes of PV module.*

3.2.2. Electrical Characteristics

The figure 9 shows simultaneously the evolution of I-V and P-V of PV module. With regard to the first characteristic, the short-circuit current produced has a value of 3.43 A (I_{cc} = 4.95 A under standard test conditions) and the open circuit voltage is 18.8 V (U_{oc} = 21.6 V under standard test conditions) a decrease in the values was observed like prescribed by the manufacturer, like wise at the point of maximum power the values of I_{ppm} equal to 3.3 A and V_{ppm} equal to 15.8 V which are less than given values in the standard test conditions (I_{ppm} = 4.5 A and V_{ppm} = 17.6 V): this is cause to the influence of the external conditions and specially to the increase in the temperature of the surface of the PV module. In terms of power, the maximum value produced by the PV module in operation is 52.4 W which is lower than those standard conditions of 80 Wc value.

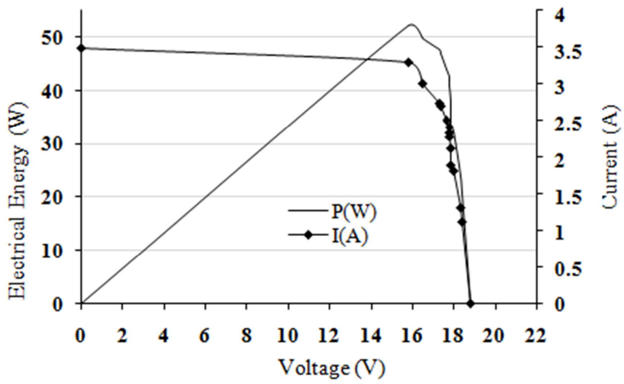


Figure 9. *I-V and P-V characteristics.*

The evolution of the electrical power as a function of the irradiance is presented in figure 10. From the observation of this figure, it is noted that the power increases by 30 W to 34 W during the period 9 to 11 pm when the irradiance varies to560 at 930 W/m^2. When the irradiance decreases from 1013 to 540 W/m^2, the electric power of panel also decreases from 33.5 to 27 W. The maximum production value 34 W is obtained in condition of irradiance of 1013 W/m^2, an ambient temperature of 35.9°C, a relative humidity of 22.8%, an air velocity of 0.34 m/s and the temperature of panel equal to 57°C.

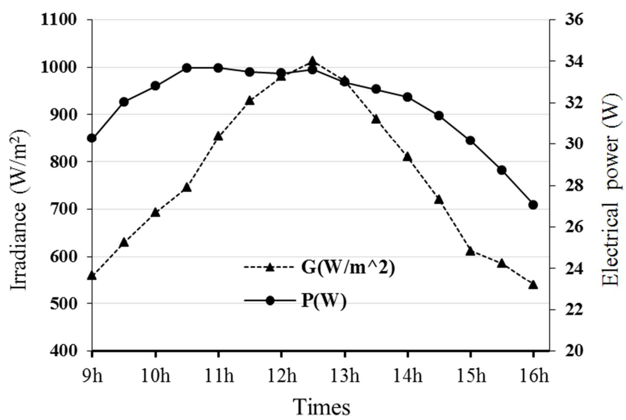


Figure 10. *Hourly evolution of electrical power as a function of the irradiance.*

3.2.3. Electrical Efficiency According of the PV Module Temperature

In the figure 11 which present the variation of electric efficiency according of the temperature of PV module shows that the electrical efficiency varies with the temperature of PV module. These values increase for 6.18 to 10.1% between 9 am and 11 am. After this time the efficiency decreases for 10.1 to 6.32% with the increase of the PV module temperature. For a solar irradiance of 1013 W/m² and a PV module temperature of 61°C, the electric efficiency is 9.17%.

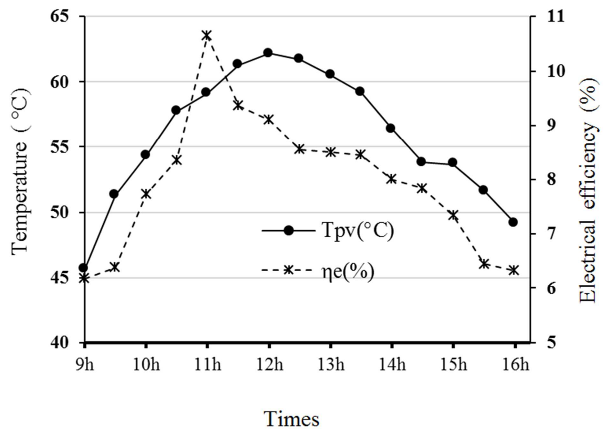


Figure 11. *Evolution of efficiency according the PV temperature versus times.*

3.3. Study and Characterization of the Hybrid PVT System

3.3.1. Presentation and Constitution of PVT System

a) Presentation

The hybrid PVT system produced in this work is composed of photovoltaic solar module (monocristalline technology), to plate glass cover and all placed in a wooden support that created the air flow circulation between the PV module and the glass cover. In this study PV module is used as a heat absorber. The hybrid PVT module designed and tested is presented in figure 12.

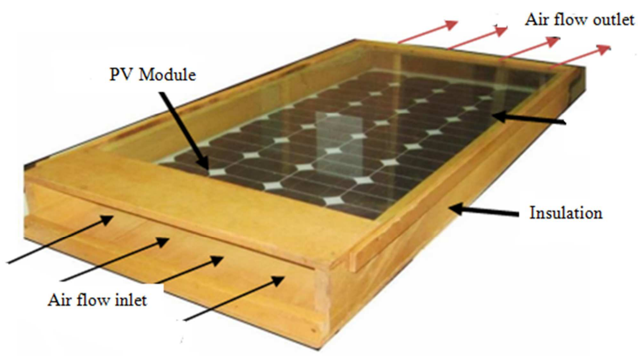


Figure 12. *PVT solar collector.*

b) Characteristics of PVT solar collector components

The characteristics of the hybrid PVT collector components are listed in the following table 1.

Table 1. *Characteristics of the hybrid PVT solar collector.*

Components	Characteristics	Values and Units
Insulation	Length	1130 mm
	Width	59 mm
	Heigth	13 mm
	Distance between PV module and the Glass cover	9 mm
PV Module	Length	1110 m
	Width	54 m
	kitchness	35m
	Absorption coefficient	0.95
Glass cover	Length	1110m
	Width	58m
	kitchness	4mm
	Absorption coefficient	0.065
	Transmission coefficient	0.85

c) PVT system operating principle

Hybrid photovoltaic/thermal technology is based on the production of a photovoltaic combined with a heat recovery system generated by photovoltaic cells**.** The operating principle is as follows: during the day, the circulation of air through a fan placed at the entrance of the device allows to cool the upper surface of the PV module exposed to solar radiation; this is order to maintain a temperature of smooth operation and optimum performance of the PV module. The energy absorbed by the heat transfer fluid (air) generates the heat energy which can be used for the drying operations of the foods products or air heating of buildings.

3.3.2. Thermal Characteristics of the PV/T Hybrid Collector in Natural Convection

a) Profil of the inlet and outlet temperatures of the collector

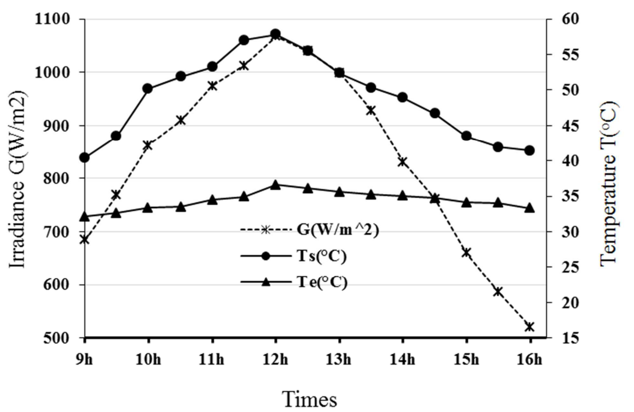


Figure 13. *Profile of inlet and outlet air temperatures of the thermal collector.*

The profil of the inlet and outlet temperatures of the heat transfer fluid as a function of the irradiance during the day is presented in figure 13. In this figure we observe that: when the irradiance increase from 684 to 1067 W/m^2 during the period from 9 am to 12am, the values of temperature increases, indeed, for an air inlet of temperature of 32°C we have at the outlet temperature of 40.5°C at 9pm. At noon, for an inlet temperature 36°C we have an outlet temperature of 57.8°C. From 12 pm to 16 pm when the irradiance decreases, temperatures fall within the collector. The heat temperature is 41.4°C for an inlet temperature of 33°C. We note that from 10.30 am to 1 pm we have significant temperatures differences between entry and exit of nearly 22°C. Similar behaviors were highlighted by the work of Aoues *et al.* [21].

b) Temperature distribution in the hybrid PVT collector

In this configuration, we measured the temperature at each layer of the caper. This distribution of the temperature at each characteristic point of the collector as a function of the time of day is shown in figure 14. There is a strong proportionality between the temperatures and the sunshine. Indeed the temperatures reaches 65°C on the front face of the PV module (Tpv) and 71°C on the back of PV module (Tspv). These results show that the addition of the glass above the PV collector causes a temperature increase at all levels of the sensor compared to the previous configuration. Indeed, the presence of the glass has created a greenhouse effect added to the system and thus the sun's rays are trapped between the glass cover and the front face of the collector, this has led to an increase in temperature. These trends are also observed in the work of [2] and [10].

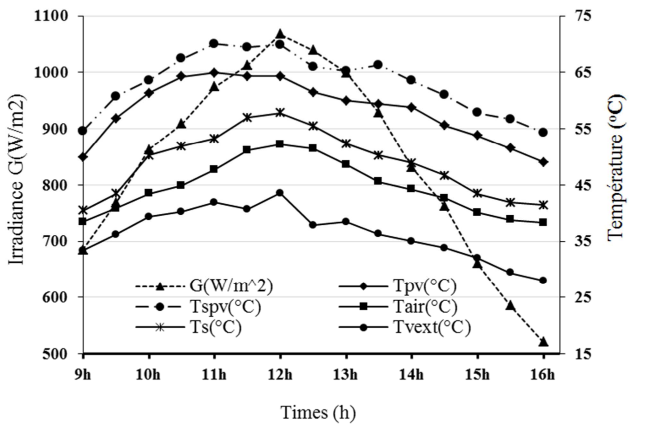


Figure 14. *Timely Evolution of temperature at different size of hybrid PVT module.*

c) Variation of the thermal power according to the irradiance

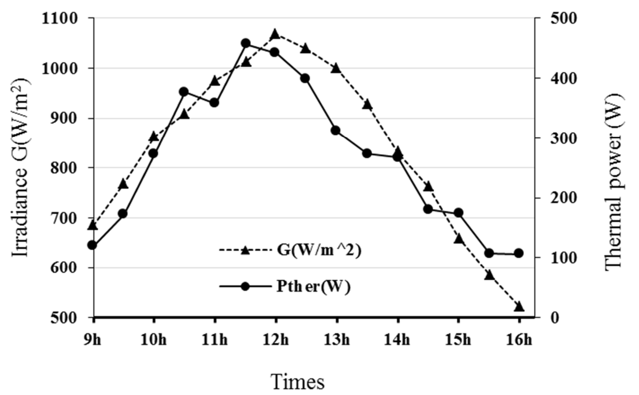


Figure 15. *Timely variation of thermal power.*

The Variation of the thermal power according to the irradiance is represented figure 15; this figure shows that the thermal power is proportional to the irradiance. This thermal power increases from 119.62 to 463 W with irradiance between 9am and 12pm and decreases from 463 W to 113 W between 12 and 16pm. Under an irradiance of 1013 W/m^2 the maximum thermal power is 457 W.

d) Variation of thermal efficiency

The thermal efficiency is showing by figure 16. This efficiency varies between 29 and 75% on the middle of day and decreases from 75 to 28% when irradiance drope from 1067 to 521 W/m^2. Average values are 49.50%. These rater high efficiency values make it possible to say that the PVT collector in forced convection mode can fulfill large thermal functions such as the drying operations of agro-food products and domestic water heating [22, 23].

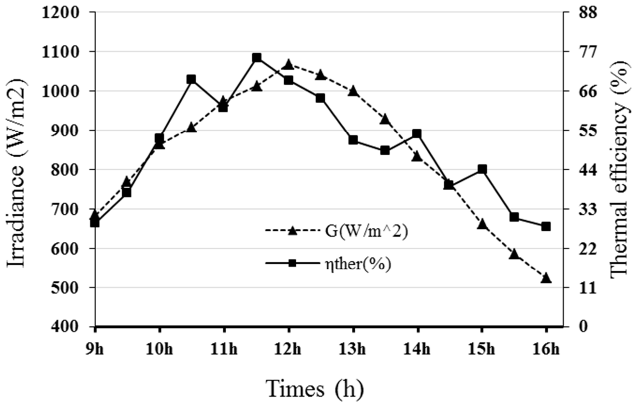


Figure 16. Timely variation of thermal efficiency and solar irradiance.

3.3.3. Electrical Characteristics of Hybrid PVT in Natural Convection

a) Variation of electrical power of hybrid PVT system

Figure 17 present the hourly evolution of electrical power. We note an almost constant electric power between 9 am and 12am (29.68 W à 31 W) nevertheless between 12 am and 4 pm, we notice that the electric power falls of 31 W in 16.2 W. The maximum value of electrical power for solar irradiance of 1013 W/m^2 is 30 W.

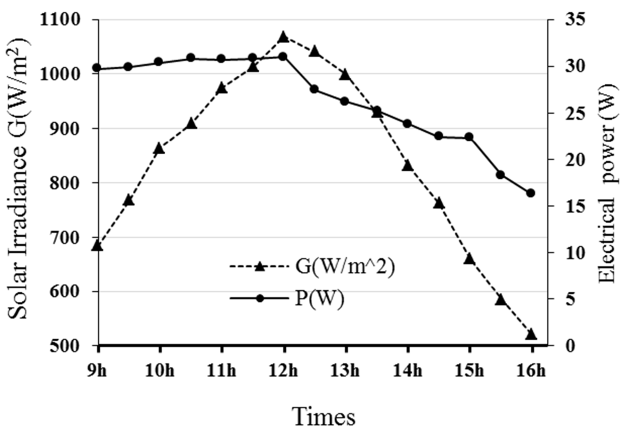


Figure 17. Hourly evolution of electrical power.

b) Variation of electrical efficiency of hybrid PVT system

The evolution of the electrical efficiency is represented in the figure 18, where we observe that the electric efficiency varies from 6 to 8.5% when the solar irradiance believes 684 W/m^2 in 1067 W/m^2 and decreases from 8.5 to 5% when the irradiance decreases of 1067 in 521 W/m^2. The value of this electrical efficiency is equal to 7.35% under a solar irradiance of 1013 W/m^2.

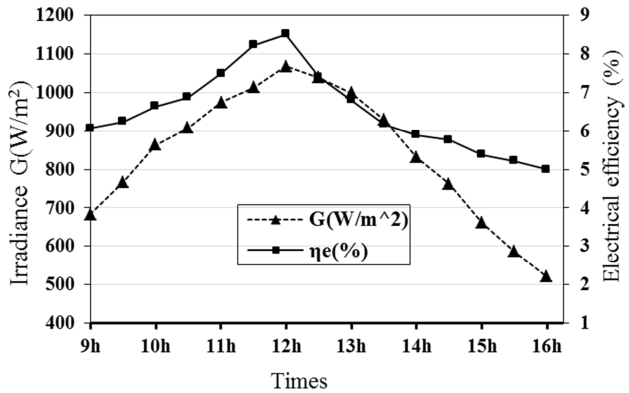


Figure 18. Timely evolution of electrical power.

6. Conclusion

At the term of this work, the objective fixed «to estimate the gain of energy obtained by a Photovoltaic/thermal system (PV/T) in forced convection and to compare it with the energy necessary for the putting in movement of the coolant " is reached. At the end of the experimental tests, in natural convection, for a solar irradiance of 1012 W/m^2, a temperature of surface of the cells of 65°C for the PV/T system and 61°C for the conventional PV module was be noted. In these conditions, the electric efficiency on the conventional PV module is 9.17% while that of the hybrid PV/T system is 7.35%. Also, for a solar irradiance of 1012 W/m^2 and a temperature of the PV module of 65°C, the electrical power, thermal power and the thermal efficiency of the hybrid PV/T system are respectively 31 W, 457 W and 75%. These results show that the use of a hybrid PV/T system allows getting back the heat energy, while increasing the electric production of the conventional PV module.

Abbreviation

G: Solar Irradiance (W/m^2);
I: Current (A);
$P_{élec}$: Electrical power (W);
P_{total}: Total power (W);
P_{ther}: Thermal power (W);
S: Area (m^2);
T_{air}: Air temperature (°C);
Tcellpv: PV temperature (°C);
T_e: Inlet air température (K),
T_{ex}: ambient temperature (°C);
Ts: Outlet air temperature (°C);
Tspv (°C): Air temperature under the PV;

U: Voltage (V);
V: Air velocity (m/s),
$\eta_{élec}$: Electric efficiency (%);
η_{total}: Total efficiency (%);
η_{ther}: Thermal efficiency (%);

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