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Article

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Energy Reports

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Elsevier

Suggested Citation: Charfi, Wael; Chaabane, Monia; Mhiri, Hatem; Bournot, Philippe (2018) : Performance evaluation of a solar photovoltaic system, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 4, pp. 400-406, <https://doi.org/10.1016/j.egy.2018.06.004>

This Version is available at:

<https://hdl.handle.net/10419/243526>

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Research paper

Performance evaluation of a solar photovoltaic system

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ARTICLE INFO

Article history:

Received 20 December 2017

Received in revised form 23 April 2018

Accepted 27 June 2018

Available online 7 July 2018

Keywords:

Solar photovoltaic system

Soil nature and inclination angle effect

Experimental characterization

CFD validation

Comparison of the CIGS PV and flat panel

ABSTRACT

The solar energy conversion into electricity is a very promising technique, knowing that the source is free, clean and abundant in several countries. However, the effect of the solar cells temperature on the photovoltaic panel performance and lifespan remains one of the major disadvantages of this technology. In this work, we present an experimental study of a particular photovoltaic panel. It is self-cooled due to its open design which facilitates natural ventilation helping to improve its performance mainly in hot hours of the day and to avoid dust accumulation on its surface. This solar system is tested for two soil natures, white and gray, and for two inclination angles, 0° and 30°. Results show that the photovoltaic panel performs better when it is inclined and placed on a white soil. A 3D CFD model describing the performance of this solar system is then developed and a good agreement between the numerical results and experimental data is found. Similarly, this CFD model was used to compare the thermal performance of this solar system to that of the flat PV system and to show that its lower temperature allows better electrical production.

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1. Introduction

The increasing political and environmental problems related to the fossil fuel are the main drawbacks of this energy source exploitation. A way to overcome these difficulties and to satisfy the growing electricity demand around the world is the use of photovoltaic systems which allow converting solar energy into electricity from sunlight. This clean technology inspired many researchers who studied the performance of different systems aiming to maximize the PV production with the least cost modifications. Ramadhan and Nasseb (2011) presented an economic study of the viability of the PV solar energy implementation in the state of Kuwait. Other technical and economical analyses of concentrating solar thermal systems, non tracked and tracked photovoltaic systems were performed by Quasching (2004) for different sites in Africa and Europe while Grasso et al. (2012) evaluated the economical competitiveness of a stationary low concentration PV system and discussed the different parameters influencing its optical power ratio. Other research and experimental studies have focused on the comparison of concentrating and non-concentrating photovoltaic systems (Mallick et al., 2006, 2007; Matsushima et al., 2003), fixed and different tracking systems (Koussa et al., 2011;

Gomez-Gila et al., 2012; Kelly and Gibson, 2009) and concentrator based in stationary linear Fresnel lenses and secondary CPC systems (Chemisana et al., 2009). Similarly, the effect of some parameters affecting the PV systems performance like the angle of inclination (Wilson and Paul, 2011; Gajbert et al., 2007), the heat transfer mode (Kumar et al., 2012) and the Thomson effect (Ari and Kribus, 2011) was numerically discussed using different simulation tools in order to find the optimum values of these parameters and to evaluate the optimum configuration of these solar systems. Skoplaki and Palyvos (2009) were interested to another parameter which is the operating temperature of solar cells and modules, they presented different correlations concerning its effect on the electrical performance of photovoltaic installations. Other papers (Razykov et al., 2011; Parida et al., 2011; El Chaar et al., 2011; Si et al., 2017) were focused on the progress made in the different photovoltaic technologies, and particularly on the effect of the solar cells materials. In other experimental investigations (Wu et al., 2012; Ryu et al., 2006), different configurations of solar photovoltaic concentrating systems using Fresnel lenses were proposed and tested under different operating parameters such as the solar radiation intensity, the ambient air temperature and the natural and forced convection. Another new technology, in which PV cells of high flux levels were used for different designs of solar cell concentrators, was proposed by Feuermann and Gordon (2001). These authors proposed a new approach for concentrating

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Nomenclature

A_c	Collector area (m^2)
G	Solar irradiance ($W m^{-2}$)
I	Current (A)
P	Power (W)
T	Temperature (K)
U	Voltage (V)
V	Velocity ($m s^{-1}$)
η	Efficiency

Subscripts

a	Ambient
el	Electrical
max	Maximum
mp	Optimum operating
oc	Open-circuit
sc	Short-circuit
w	Wind

PV systems that can easily attain the maximum flux level commensurate with solar cell technology. Chaabane et al. (2013) are among the authors who are interested in the exploitation of solar energy in Tunisia using photovoltaic systems. They proposed an experimental study in which they discussed the effect of the cooling system that they designed on the global performance of their photovoltaic device.

In this paper, we present an experimental study of a particular photovoltaic panel. The open design of this solar system, which allows solar cells cooling by natural ventilation, is its main characteristic. Measurements are taken for two different soil natures and inclination angles. Computational fluid dynamics (CFD) are also used to model the performance of this photovoltaic system and to compare it to that of a Flat one.

2. Experimental study**2.1. Experimental setup**

In this study, the tested PV panel consists of 40 cylindrical solar cells made of CIGS (Fig. 1). Due to cylindrical shape of the tube and its concentrating effect, the PV panel is collecting light over 360° and thus operating with direct, diffuse and reflected solar radiation. This experimental investigation has been conducted under a Tunisian Saharan climate, in the city of Tozeur. The experiments were undertaken during three consecutive spring days, 19, 20 and 21 April. These tests correspond respectively to an horizontal panel for a white soil, an horizontal panel for a gray soil and a sloped

Table 1

Photovoltaic panel characteristics.

Parameter	Value
Maximum power at STC (P_{max})	200 W
Optimum operating voltage (U_{mp})	78.3 V
Optimum operating current (I_{mp})	2.55 A
Short-circuit current (I_{sc})	2.78 A
Open circuit voltage (U_{oc})	99.7 V
Electrical efficiency	10.18%
Dimensions of PV panel	1820*1080*50 mm
Temperature coefficient of power	-0.38%/K
Temperature coefficient of voltage	-0.289 V/K

panel for a gray soil. All the measurements were continuously monitored each $\frac{1}{2}$ hour, from 7 am to 6 pm.

The characteristics and dimensions of the photovoltaic panel used in this experimental study are specified in Table 1:

2.2. Analyzed parameters and measuring instruments

For this PV system electrical performance evaluation, the current I and voltage U were continuously measured. The meteorological parameters defined by the ambient temperature T_a , the wind speed V_w and the incoming solar irradiance G were also experimentally determined using specific data acquisition devices. The characteristics of the measuring equipments used in this experimental study are listed in Table 2.

2.3. Experimental results

The ambient temperature, incident solar irradiance and wind velocity were experimentally measured and respectively presented in Figs. 2 and 3. During these three days, the climatic conditions were characterized by clear sky conditions. The solar radiation intensity and therefore the ambient air temperature were slightly higher for the gray soil test days, they achieved respectively $861 W m^{-2}$ and $30.5^\circ C$. Concerning the wind velocity, its maximal value has not exceed 5 m/s, so the climate corresponding to our experiments was stable and without sand storms which can cause disturbances during measurements.

The current I and the voltage U delivered by the PV panel were measured, the electrical power generated by these PV systems, which is defined as their product, was calculated and its temporal evolution is presented in Fig. 4. The analysis of this figure shows that the electrical power increases during the day up to noon, then decreases with the solar radiation intensity decrease. It is also noted that the produced electrical power is higher for the inclined PV panel due to the difference in the incoming solar radiation relatively to the horizontal panel. Concerning the effect of the soil nature, it can be seen that the highest production corresponds to the white soil (181 W), and this is due to its reflected part of the solar radiation which is negligible in the case of the gray soil.

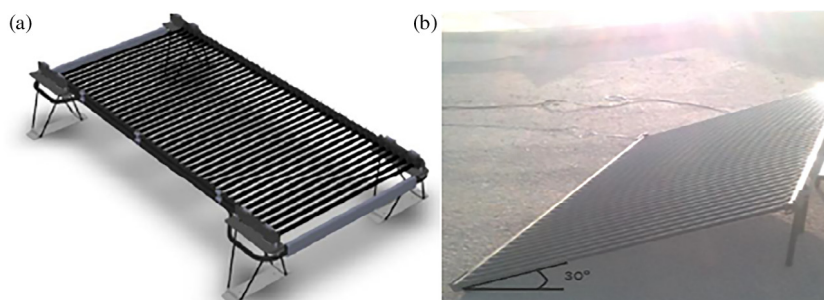
**Fig. 1.** Photographic picture of the horizontal (a) and titled (b) PV panel.

Table 2
Equipments used for the experimental measurements.

Parameter	Unit	Measuring instrument	Model
temperature T	°C	Infrared thermometer with K thermocouple	Fluke 63
Wind speed V_w	m/s	Handheld Rotating Vane Anemometer	HHF141
Solar irradiance G	W/m ²	Solarimeter	CR 100
Current I	A	Compact digital multimeter	Amprobe AM-240
Voltage V	V	Compact digital multimeter	Amprobe AM-240

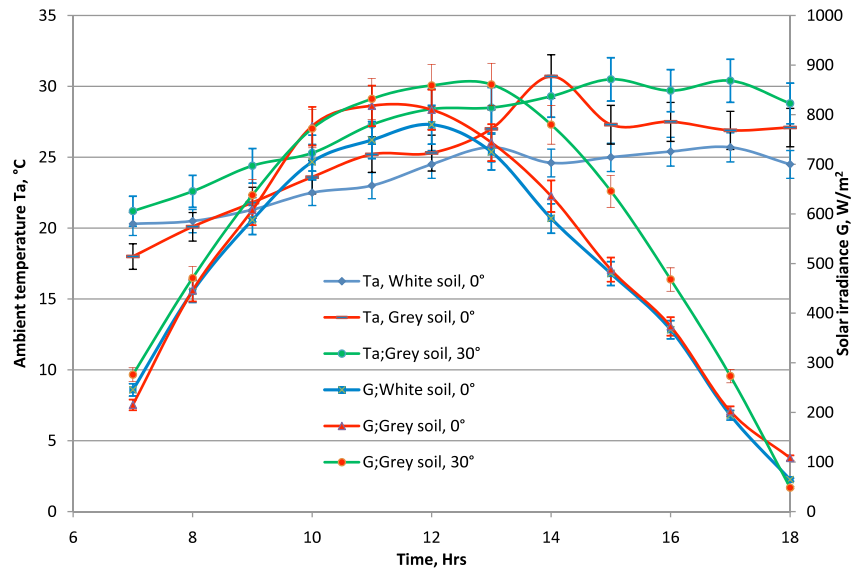


Fig. 2. Variation of the solar irradiance and ambient temperature with time.

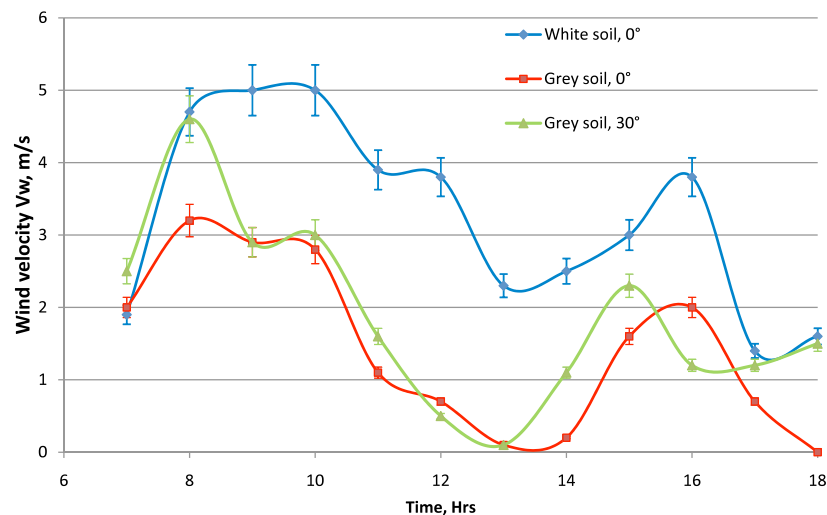


Fig. 3. Daily temporal evolution of the wind velocity.

Regarding the energy conversion efficiency, it was evaluated according to the following relation: $\eta_{el} = \frac{P}{GA_c}$; where A_c is the panel surface, P is its electrical production and G is the incoming solar irradiation. The temporal evolution of this solar system electrical efficiency is described in Fig. 5. It can be seen that the electrical efficiency is decreasing up to noon due to the negative effect of the solar cells temperature during this period of the day and it is increasing for the rest of the day. It is also noticed that the PV panel electrical efficiency is higher for a white soil due to its higher electrical production.

In addition to these electrical parameters, a thermal characterization of this solar system is presented. Indeed, the solar tubes

temperature was measured and its average variation is shown in Fig. 6. From this figure, it can be seen that the PV tubes temperature increases at the midday, achieves its maximum value which is of 54 °C for the case of a sloped panel on a gray soil, and decreases next with the decrease of the solar radiation. Similarly, by analyzing the measured values of the temperature, we can notice the advantage of this open design of the PV panel which allows the solar cells cooling by natural ventilation.

In this study, the experimental performance analysis of a photovoltaic system was presented. It has been observed that the electrical production and efficiency of the solar panel are much higher when it is tilted and above a white soil.

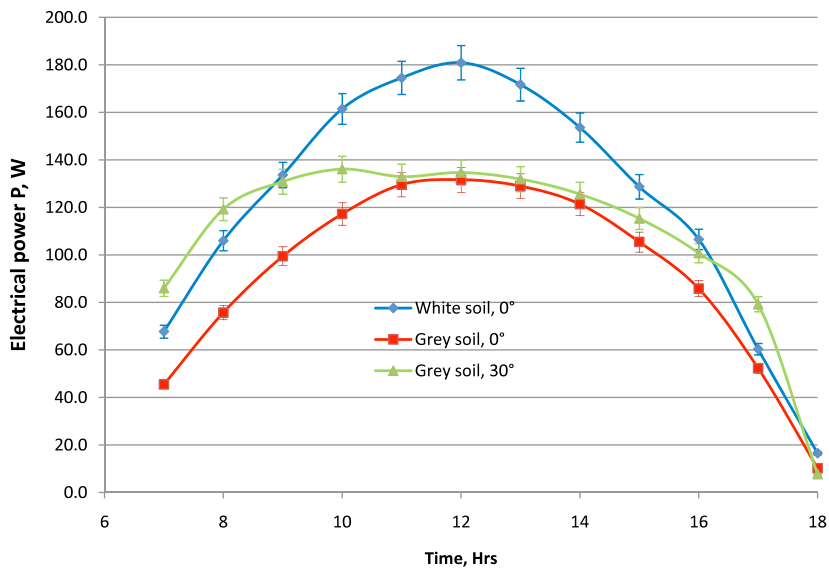


Fig. 4. Electrical power of the PV system.

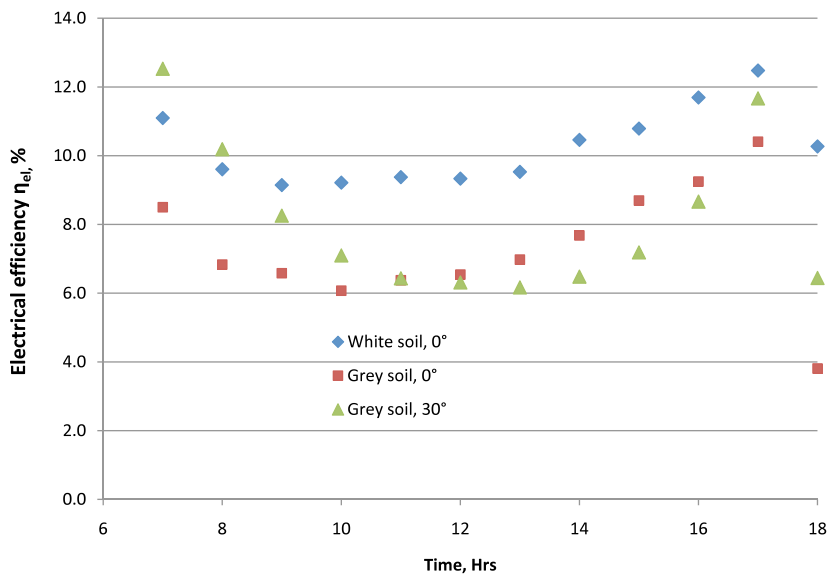


Fig. 5. Electrical efficiency of the PV system.

3. Numerical results

3.1. Geometry description and meshing

A 3D CFD models interpreting the photovoltaic system is developed. The same dimensions, physical characteristics and specifications as the experimentally tested system are considered. A grid dependency test was carried out and we chosen a mesh size of 1067040 cells. The generated mesh, which consists of hexahedral cells clamped at the tubes and looser in the rest of the field, is shown in Fig. 7.

3.2. Numerical procedure

Numerical simulations are carried out under the same climatic and operating conditions of the experimental study. The simplifying assumptions concern mainly the fluid properties and particularly its density which changes with temperature according to

the Boussinesq approximation expressed as follows: $(\rho - \rho_0) = -\rho_0\beta(T - T_0)$.

The turbulence model used to simulate the flow in this solar system is the standard K-ε turbulence model which presents the advantage of its accuracy in addition to its fast calculation time. Concerning the radiative term, we considered a non-gray model, the Discrete Ordinates DO which is based on the radiative transfer equation resolution. High resolution schemes are selected for the pressure, velocity and temperature terms discretization and a convergence criteria of 10^{-4} is used for all the equations resolutions, except for the energy residual where a value of 10^{-6} is given.

3.3. Simulation results

In order to prove the credibility of the developed CFD model, the thermal behavior of the PV tubes in this solar system is characterized and the PV panel electrical performance is then evaluated. We chosen to present results corresponding to an horizontal panel placed on a white soil. Numerical results of the solar tubes

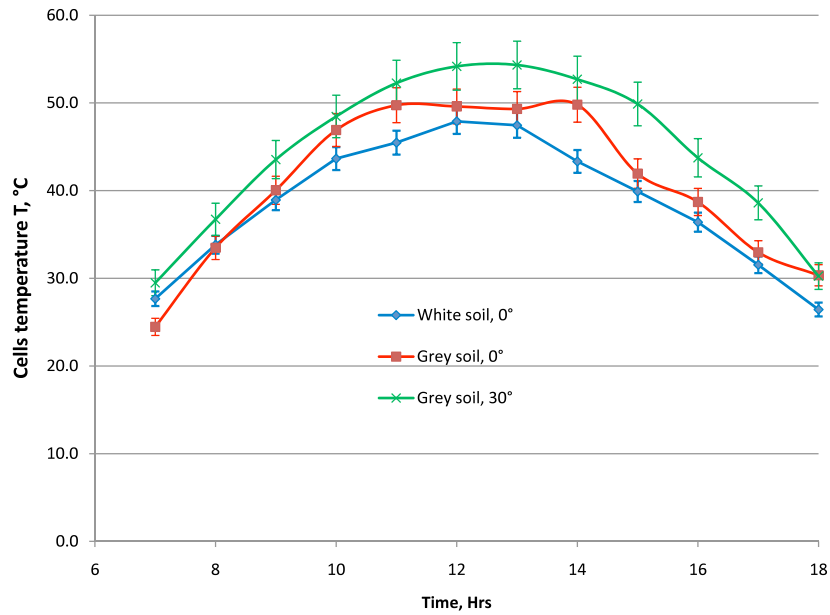


Fig. 6. Measured solar cells temperature in the PV system.

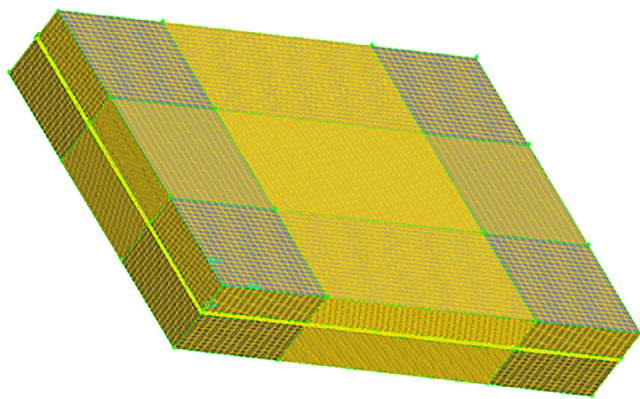


Fig. 7. Geometry meshing.

9. According to these figures, the maximum difference between the two results does not exceed 10%, which shows a satisfactory agreement proving the validity of the CFD model and justifying its used for further improvements in this PV panel conception.

To confirm the previous findings, and based on our validated CFD model, a flat PV panel having the same peak power than the studied CIGS panel was numerically modeled and results of these two systems solar cells temperature and electrical power are respectively compared in Figs. 10 and 11. The analysis of these figures show the advantage of the naturally ventilated system which is the CIGS one relatively to the flat PV panel, and that its lower temperature results in higher electrical power.

In Fig. 12, we present the temperature distribution for a cross section of these two photovoltaic panels, for a solar irradiation of 800 W m^{-2} . These temperature contours show that the tubes spacing in the CIGS panel allows the air circulation in these zones and thus their cooling by natural ventilation, which results in the PV panel performance improvement relatively to the flat one. Similarly, it is noted that this arrangement of the tubes gives an uniform temperature profile, without any overheating zone.

average temperature and electrical power are so compared to the experimental data and respectively presented in Figs. 8 and

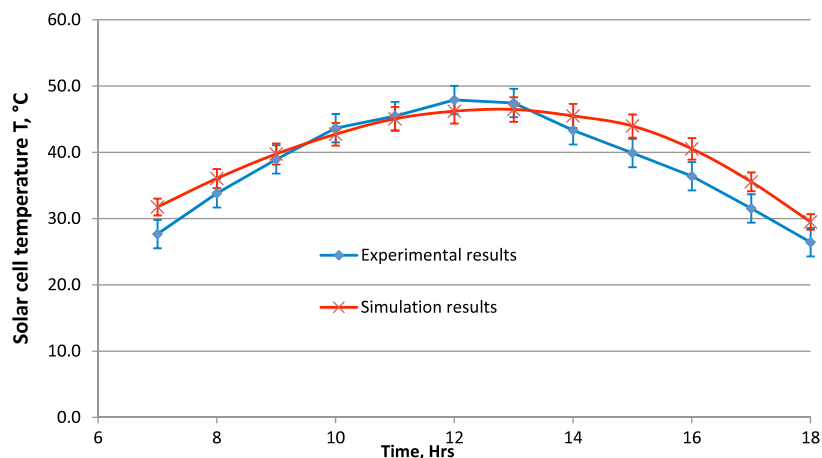


Fig. 8. Comparison of the solar cells temperature numerical and experimental results.

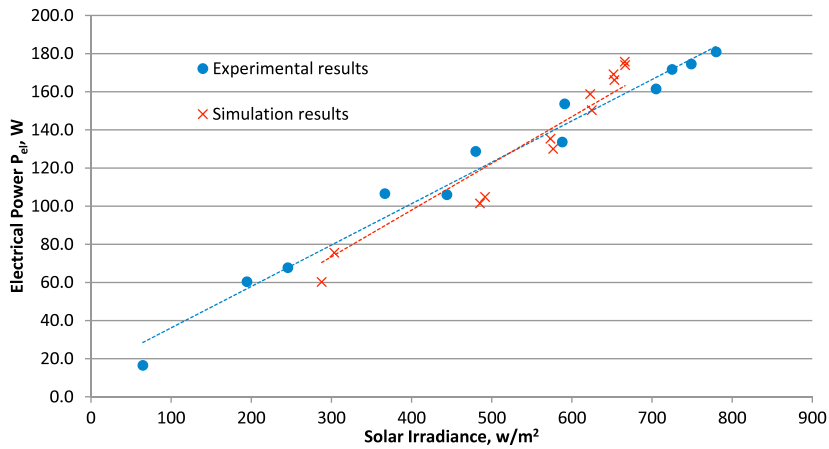


Fig. 9. Comparison of the PV system electrical power numerical and experimental results.

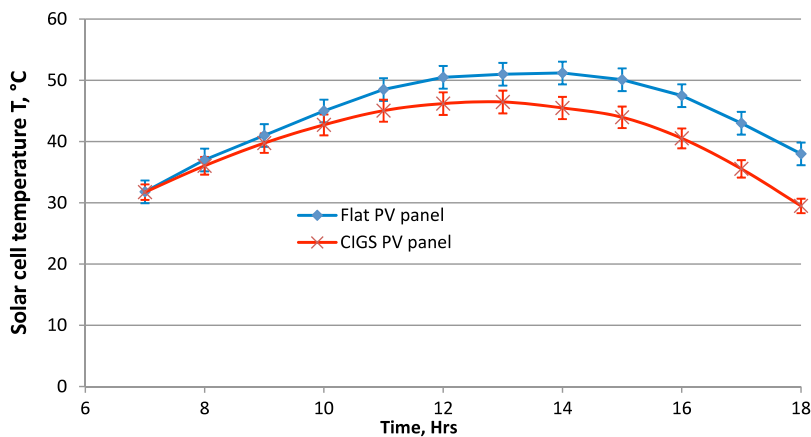


Fig. 10. Comparison of the cells temperature in the CIGS PV panel to that in the flat one.

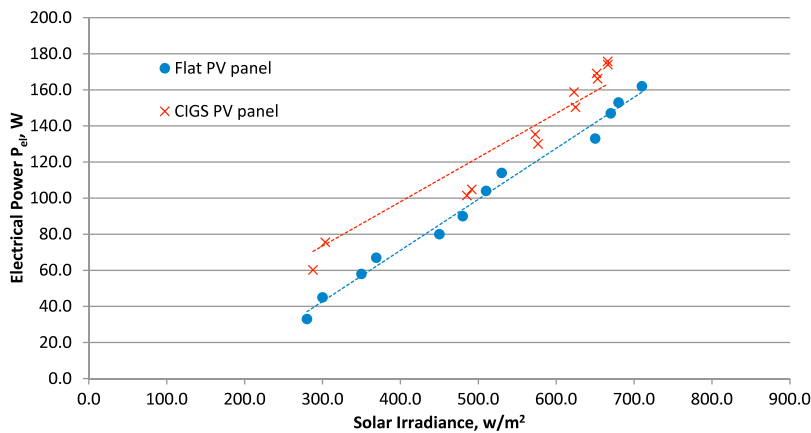


Fig. 11. Comparison of the electrical power in the CIGS PV panel to that in the flat one.

4. Conclusion

The electrical performance of a particular photovoltaic system was experimentally evaluated under a spring day in the Tunisian Saharan city Tozeur. This solar system consists of 40 spaced solar cells made of CIGS and of cylindrical shapes. Due to its open design, this solar system allows the solar cells cooling by natural ventilation. The measurements were taken for an horizontal and inclined panel, and for a gray and white soil. Experimental results

showed the advantage of the inclined system which collects higher intensity of the solar radiation, resulting in higher electrical production of the PV panel. Concerning the effect of the nature of the soil on which the panel is placed, a higher electrical production was obtained for the white soil which, unlike the gray one, allows the panel to operate with an additional part of the solar radiation which is that reflected by this soil. A 3D CFD model interpreting this solar system's operating was then developed and simulation results showed a good agreement with the experimental data.

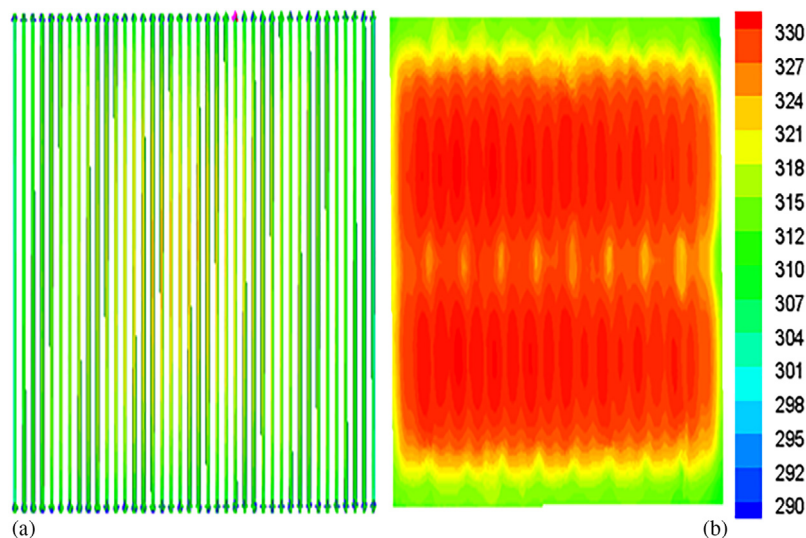


Fig. 12. Temperature contours for a cross section of the CIGS (a) and the flat (b) PV panels.

This solar system's performance was then compared to that of the flat PV panel and numerical results showed the effect of the CIGS system ventilation and its lower temperature in its performance improvement. The developed and validated CFD model can be later used for the CIGS PV panel's performance optimization, especially for the evaluation of the optimum tubes spacing in order to reduce the PV panel surface.

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