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Output power boosting of a photovoltaic panel based on various back pipe structures: a computational study

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Abstract. The efficiency of photovoltaic panels (PV) drops due to the rise in temperature, which leads to a decrease in the PV output power. A PV/Thermal system is therefore used as a solution to increase the output power from the PV panels. Comsol Multiphysics software program, a simulator-based Finite Element Method (FEM) tool, and Matlab program simulations are used to perform this electro-thermal model. The simulation process for different back pipes follows a serpentine, and a new shape of pipes called (square shapes) which are attached under the PV module. These shapes were specifically chosen for higher conversion efficiency and increase the heat transfer of the system. Additionally, a comparison between electrical parameters and heat transfer characteristics of water and CuO/water nanofluid in a PV cooling system has been studied. The new shape leads to improve the photovoltaic (PV) module parameters, such as short circuit current ISC, open-circuit voltage VOC, and maximum power Pmax for a new shape more than the serpentine shape. These parameters are calculated under Air Mass 1.5 G (AM1.5G) with 1000 W/m2 of irradiance which is considered the average irradiance at the MENA (The Middle East and North Africa) region throughout the year. The results exhibit the PV module's total enhancement by using the new shape with CuO nano-fluid about 24.7 %.

1. Introduction

The PV module is one of the most significant sources of renewable energy in countries that have high-temperature weather. This is due to its cheapness, availability, and eco-friendly behavior. On the contrary, the efficiency of PV modules dropped which leads to the output power reduction in this region. Therefore, the goal is to achieve a high photovoltaic conversion efficiency by reducing the PV module temperature in general,[1].

Reviewing the Previous Works, offered different ways to decrease the PV module temperature. To cope with the rather high module temperature, different passive in addition to the active cooling techniques which have been verified in previous works are investigated [2] and [3]. As for active cooling, the cooling fluid is one of the main factors that affects the system performance [4]. Air, water, and nano-fluids have been recorded as a cooling fluid to decrease the PV module temperature [5],[6] [7][8][8].

Teo et al. investigated a PV module cooling system with an air duct in parallel pipes attached under the modules, where ever the PV modules were cooled down by forced convection. The performance enhanced by about 4-5% [9].

Yang et al. improved a new material called Functional gradient material (FGM) attached as PV layers under the module, copper pipes underneath the layers that were attached by thermal paste under the backside of a PV/T system. Water as a cooling fluid is pumped with different flow rates through the copper pipes to reduce the PV module temperature, therefore, increasing PV/T system electrical power by about 2%. This work also tested the thermal efficiency of the closed system design and the results showed that the electrical efficiency increased to 71% of the output power of the system. Herein, a simulation model for a PV/T open system is introduced. The attached water pipe is heated by the effect of the temperature increase of the PV modules due to the Sun irradiance. The results exhibited an advancement in the total efficiency of the system by raising the temperature of water output [10].

Afroza Nahar et al. enhanced the PV module output performance by a 3D numerical method (Comsol Multiphysics package). The new shape (pancake shape) is attached to the backside of the PV module to increase PV output power by using the water as a cooling fluid. The new channel was made from two different materials (copper & aluminum) under various inlet velocities (0.0009 to 0.05 m/s) and compared with the system without cooling. The simulation results showed an increase in the overall efficiency of about 14.6% for aluminum and 16.3% for copper pipes [11].

Nooshin Karami and Masoud Rahimi introduced a novel method to decrease the temperature of the PV cells experimentally using different shapes of pipes (Straight and Helical) connected in the backside of PV cells. K-type thermocouples were placed in the flow path of nano-fluids (Boehmite AlOOH_xH2O) with a mixture concentration of 0.1 wt% to show the temperature variation when the fluids moved inside the pipes. The temperatures of the cell are reduced by 3˚C in each temperature sensor with a growing in electrical power over the entire day. Whereas the straight shape showed an increase of 20.57% while the helical shape increased by 37.67 %, [12].

This work aims to enhance the output power of the PV panels in the MENA region [13]. This study shows an innovative simulation model for a PV panel with attached different backside pipe structures (Serpentine and square). The shapes of pipes by the Comsol Multiphysics package are illustrated. The suggested simulation model is capable of simulating the water and CuO nano-fluid thermal behavior and expressing its effect on the PV module performance.

2. Model Description

A computational-based model using the Comsol Multiphysics package for a Photovoltaic/Thermal hybrid system (PV/T) is executed as given in Figure ***1***. It is divided into a closed technique laminar flow and sequence heat transfer physics package, which is being connected to show the convective heat exchange of the fluid inside the copper pipes from the PV panel to cool it by finite Element Method (FEM). In this studied model, a mesh independence test of 0.00542 m and a maximum size of 0.212 m has been utilized [14].

The simulated system includes a mono-crystalline PV panel with a total area of 1.5013 m^2 and the maximum output power of 280 Watt as shown in Figure ***1a***. Various shapes of pipes bonded on the copper plate as the same area of PV panel with 0.001 m thickness. The copper plate is attached to the backside surface of the PV panel to allow the fluid to move through the pipes under the PV panel. All suggested shapes of pipes are made from copper with dimensions 0.005 m and 0.006 m for both inner and outer diameters. The copper pipes are chosen because of their high thermal conductivity and wide use [15]. The volumetric flow rate inside the pipe 10 L/m to speed up the enhancement performance. ***Figure 1***-b exhibits the structure of the first backside water pipe, serpentine shape, with a length of 16.1 m long and a total area of 0.631 m^2. Figure ***1***- c shows the second type, square shape, with an area of 1.193 m^2 and length 31.78 m long. The nano-fluid is a mixture of water and CuO nanoparticles. In the present study, the concentration of nano-particles by about 0.01 wt% is used. The goal for selecting CuO nano-particles is for higher thermal properties [16].

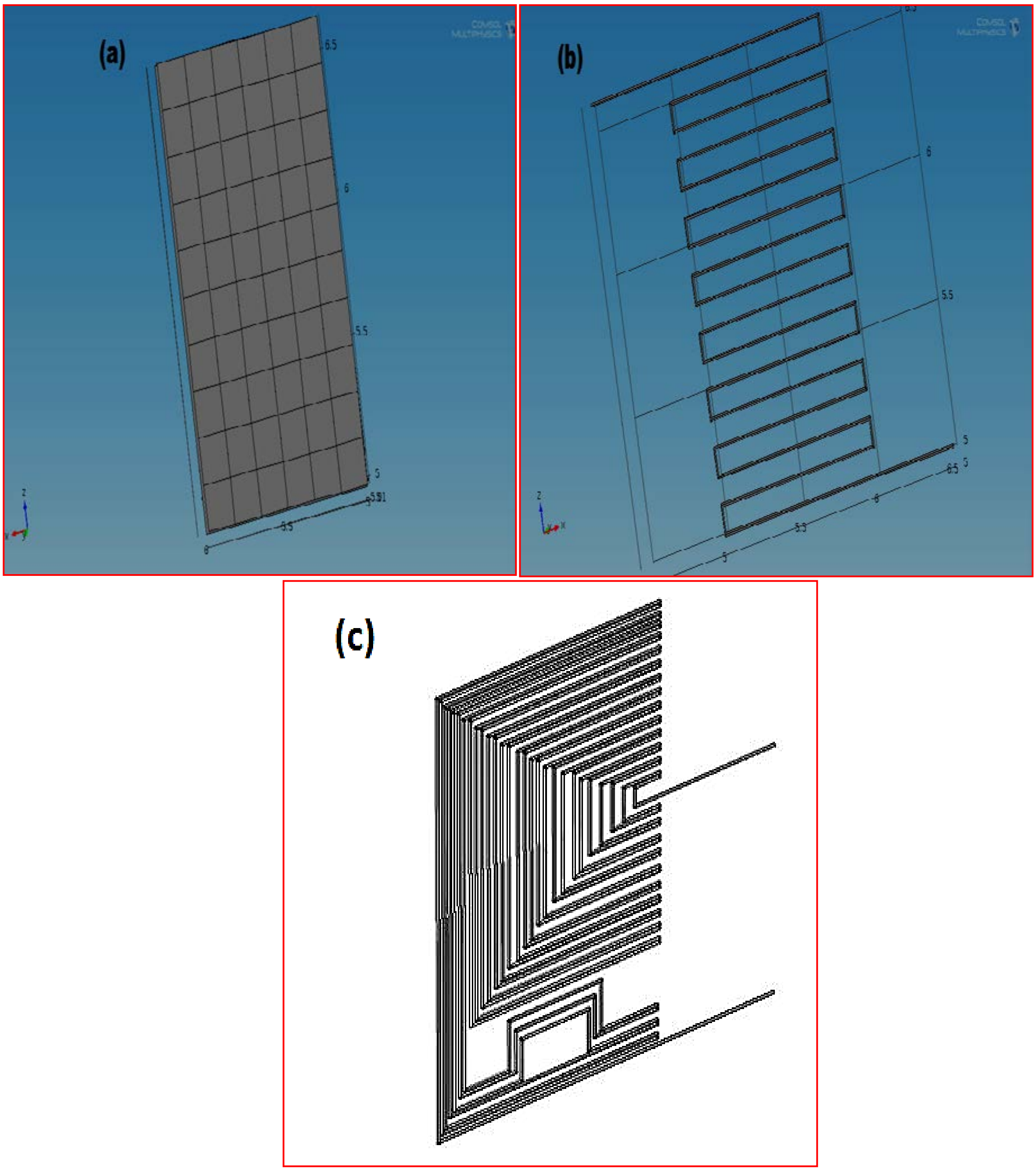

Figure 1: (a) Comsol software program model for a PV panel, (b) Serpentine back pipes, and(c) Square back pipes.

3. Methodology

The modeling in this work is divided into two parts. Firstly, the thermal modeling to decrease the PV module temperature. Secondly, the electrical modeling to show the enhancement in $\mathbf{I_{sc}}$, $\mathbf{V_{op}}$, and the output power of the system.

In the thermal modeling, the sun irradiance under (AM1.5G) standard is increased the silicon PV panel temperature which is the body (PV panel) passes through its heat to the copper plate and pipes (external and internal) by conduction. At last, the cooling liquid (water or nano-fluid) is heated by convection. The thermal parameters are calculated for a closed thermodynamic technique [17]. The overall heat transfer coefficient is given by equations (1, 2, and 3) and the rate of heat transfer is calculated by equation (4) for an open thermodynamic system [18].

$$\frac{1}{U\,A} = \frac{t_{th}}{K_{Si}\,A} + \frac{t_{th}}{K_{cu}\,A} + \frac{ln(\frac{r_{in}}{r_{out}})^2}{2\,\pi\,K_{Pipe}\,L} + \frac{1}{h_f\,a} + \frac{1}{h_{air}\,a} \tag{1}$$

$$A = l \text{ x } w \tag{2}$$

$$a = 2\pi\,r\,L \tag{3}$$

$$Q^{\cdot} = A\,U\,\Delta\,T \tag{4}$$

The electrical parameters are calculated after the thermal parameters to show the influence of the improvement in the output power on the PV performance. PV module efficiency $\boldsymbol{\eta_{PV}}$ is calculated by dividing the output electrical power (at maximum output power) by the total input power under the AM1.5G standard. The short current based on FEM is calculated by using equation (5) [19]:

$$I_{sc} = I_{PV} - I_{01}\left(eq\frac{V}{K_BT} - 1\right) - I_{02}\left(eq\frac{V}{K_BT} - 1\right) \tag{5}$$

The open-circuit voltage is given by equation [19](6) as follow:

$$\mathrm{V_{oc}} = \mathrm{n}\,\frac{\mathrm{KT}}{\mathrm{q}}\ln[\frac{\mathrm{I_{PV}}}{\mathrm{I_{o1}}} + 1] \tag{6}$$

The solar cell efficiency can be represented as a variation in the solar output electrical power, the module surface area, and the solar irradiance (see equation (7))[19].

$$\eta_{\mathrm{PV}} = \frac{\mathrm{Pout}}{\mathrm{Pin}} = \frac{\mathrm{V_{oc}I_{sc}FF}}{\mathrm{q_{rad}\,A}} \tag{7}$$

The tested nanofluid is considered a mixture between the water and the CuO nanoparticles. In the present study, the CuO oxide of 0.01% mass concentration is used. The purpose for selecting Copper Oxide is that openly known thermal properties and easy dispersion [20]. The nano-material properties have a density = 6400 kg/m^3, size = 40 nm, thermal conductivity = 40 W/m.K, the specific heat 892 J/kg.K and the shape type of particles is a spherical shape. The nano-fluid density is determined from Pak and Cho's equation (8) [21].

$$\rho_{\mathrm{nf}} = \rho_f(1\text{-}\emptyset) + \rho_p.\,\emptyset \tag{8}$$

The specific heat of the nano-fluid is deduced from Xuan and Roetzel's equation (9).

$$(\mathrm{C_P}\rho)_{\mathrm{nf}} = (\mathrm{C_P}\rho)_f(1\text{-}\emptyset) + (\mathrm{C_P}\rho)_p\emptyset \tag{9}$$

The nano-fluid thermal conductivity is calculated from Maxwell's equation (10) [22].

$$\mathrm{k_{nf}} = \mathrm{k_f}\frac{(\mathrm{k_p} + 2\mathrm{k_f} - 2\emptyset\,\mathrm{k_f} - (\mathrm{k_p}\,)}{((\mathrm{k_p} + 2\mathrm{k_f} + \emptyset\,\mathrm{k_f} + (\mathrm{k_p}\,)} \tag{10}$$

At the results, the mixture of nano-fluid properties are density= 1201.7 kg/m^3, thermal conductivity= 0.7431 W/m.K and specific heat= 5202.11 J/kg.K.

4. Results and Discussion

This section demonstrates the results and the descriptive analysis included in the present work. The calculation of the thermal parameters of backside temperatures is performed to improve the performance of the PV system. Figure 2 shows the comparison of the module temperature (with (square and serpentine shapes) without cooling (STC) at different shapes attached in the backside of the PV module by using water along with daytime. This is to study the influence of the fluid used to minimize the temperature of the PV/T performance by using water and to show the best shape that can be performed by nano-fluid by comparing with (STC) Standard Temperature Condition without cooling the PV panel temperature reduced by water flew inside the backside pipes attached under the module. The temperature of the PV module backside without cooling reached 53.9°C while the PV module temperature with cooling by using serpentine shape decreases by 5.1°C and the same PV module temperature with square shape reduces by 15.2°C. Surly, the square shape enhanced the PV module performance by about 17.7%. The system improved due to a rise in the total area of pipes of square shape.

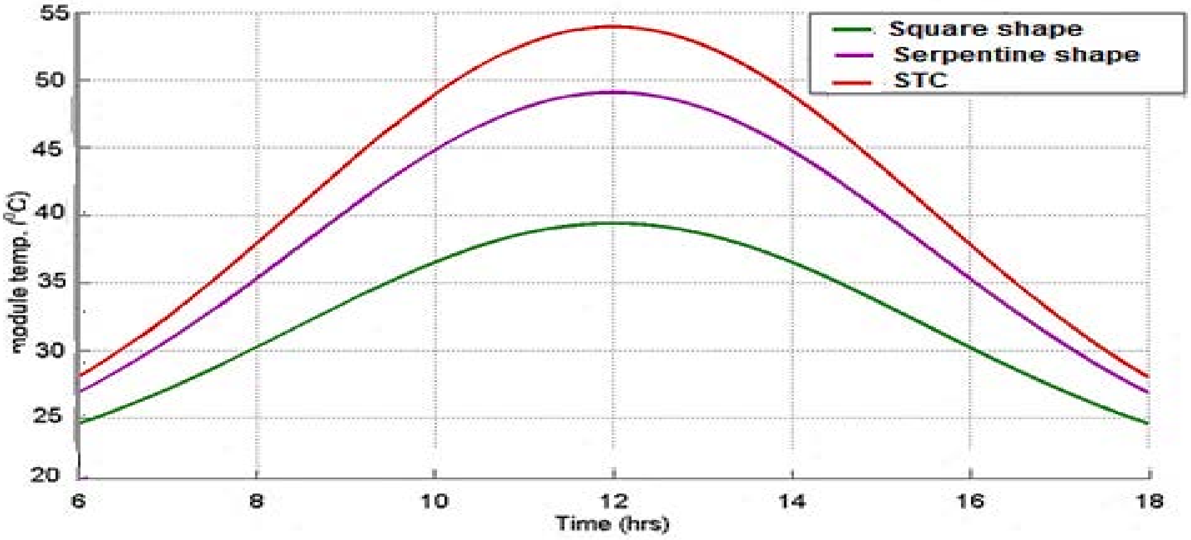

Figure 2. A comparison of the module temperature (with (square and serpentine shapes)/without cooling (STC)) at different shapes attached in the backside of the PV module by using water along with the daytime.

Figure 3 presents the **I-V** and **P-V** curves to compare among different shapes of pipes by water as a cooling fluid, concerning the standard curve. The **I-V** curves in Figure 3-a show only the variation across the voltage range from 0 to 15**V** and the current from 8 to 9.5**A** to observe the fluctuations in the short circuit current, as the open-circuit voltage is almost maintained constant for all the simulated shapes concerning standard curve (not shown) [12]. By comparing with STC module performance, the Figure shows an increase in module output power by using serpentine shape 0.2**A** while with square shape the system output power raised about 0.64 **A**. That increase happened due to the reduction of PV module temperature by using a square shape.

The P-V curves in Figure 3-b showed the power variation across the maximum power point from 26 to 29**V**. The short circuit current at STC condition without any cooling reached 8.29**A** and output power of 219.26**W** while $\mathbf{I_{sc}}$ of serpentine shape enhanced to a maximum of about 8.49**A** at the output power of 223**W**. The new shape with a larger area than the serpentine one has $\mathbf{I_{sc}}$ = 8.95**A**, and $\mathbf{P_{out}}$ = 236**W** by about a 5.7 % increase compared with the serpentine shape. The results show the best performance was the square shapes of pipes to enhance the PV output power.

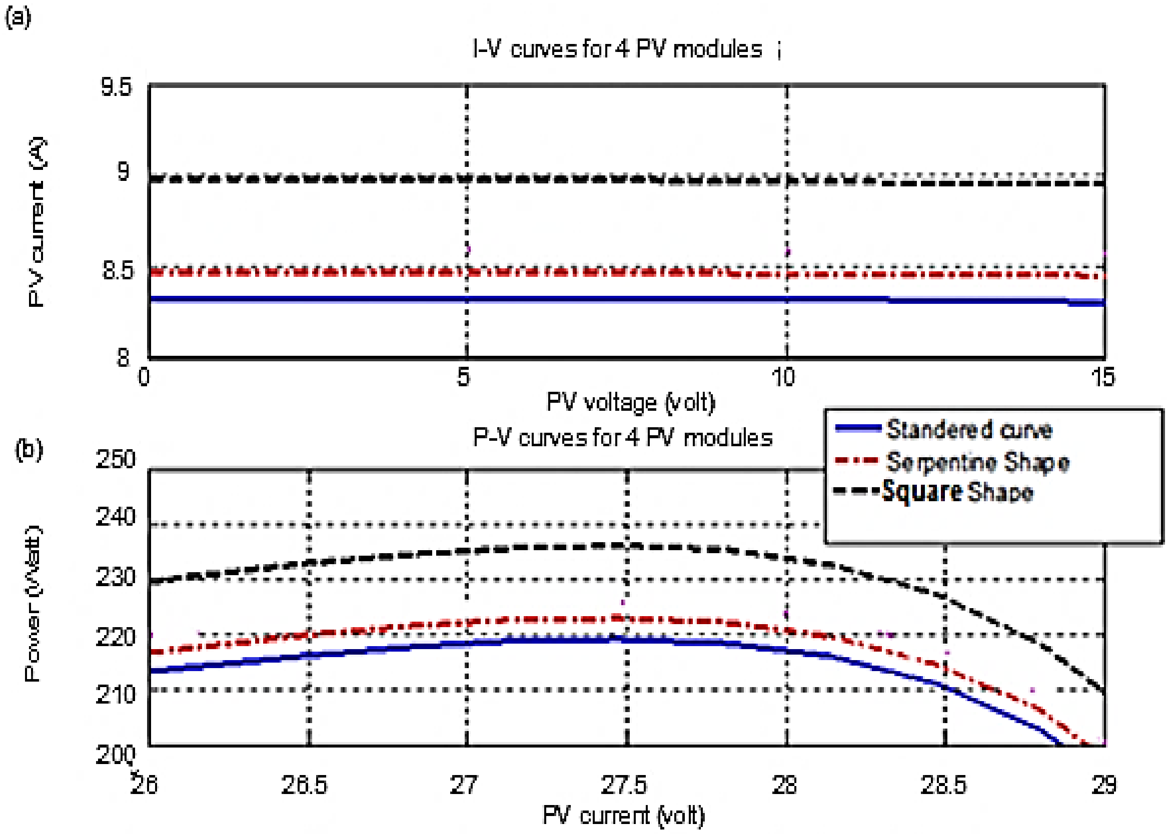

Figure 3 Simulation results for I-V and P-V characteristic curves without cooling besides with cooling by using water with different shapes attached in the backside of PV modules.

Figure 4-a shows the comparison between water and nano-fluid (CuO) cooling technique through the best shape of pipes (square shape). By comparing the results with water that introduced the I_{sc} of serpentine shape with nano-fluids observed to 9.35**A** and Pout = 246**W**. All graphs of I-V and P-V characteristics curves are plotted using the Matlab program [15]. The results showed an enhancement in the PV panel by using nano-fluid with a new shape of about 5**%** in the output power compared with water as a cooling fluid as shown in Figure 4-b.

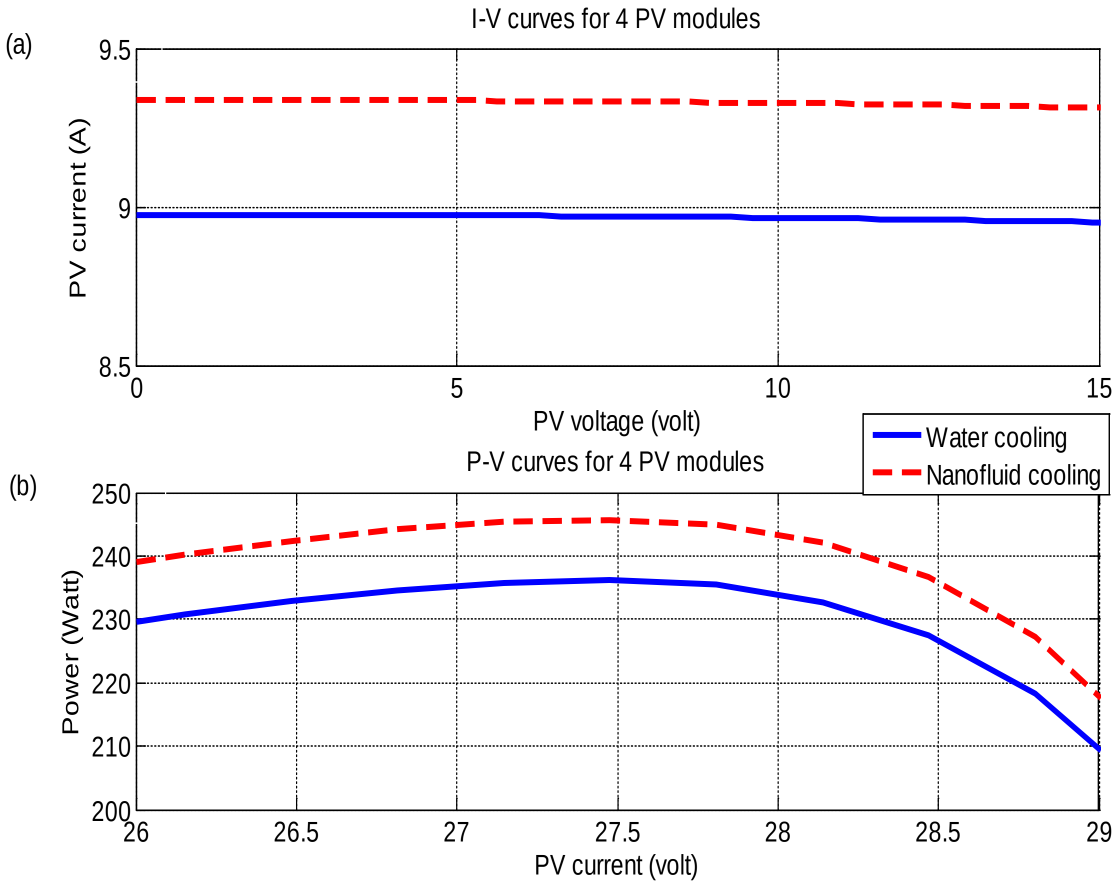

Figure 4 A comparison between water and nano-fluids (CuO) by using a square shape attached to the backside of the PV panel.

5. Conclusion

This study demonstrates the effect of an active cooling system with water and CuO nano-fluid as a cooling fluid. Two different shapes of pipes (serpentine and square) were presented with the insertion of a structured targeting maximum thermal heat transfer and output power of the **PV/T** system. The main conclusions are summarized as follow:

- By using water as a cooling technique, the results showed that the module temperature with serpentine and square shapes decreased about 8.4% and 17.7% compared with STC conditions.
- This increase reflects on the maximum output power which reaches 223 Watt for serpentine shape and 236 Watt for a square shape.
- After choosing the square shape (the best cooling one), the CuO nanofluid is the solution to investigate the system output power.
- By comparing the output power of square shape by using CuO nanofluid with water as a cooling fluid, the results exhibit an improvement in overall system performance by about 24.7**%.**
- The results in this paper showed a fair agreement with what is published in the literature.

Nomenclature

Symbol	Description	Units

U	Overall heat transfer coefficient	W/m^2*K
A	Plate surface area and PV area	m^2
t_h	The thickness of the plate	m
A	Pipe surface area	m^2
K_{si}	Silicon thermal conductivity	W/m^2*K
K_{cu}	Copper thermal conductivity	W/m^2*K
K_{Pipe}	Pipe thermal conductivity	W/m^2*K
h_f	fluid thermal conductivity	W/m^2*K
h_{air}	Air thermal conductivity	W/m^2*K
r_{in}	Pipe inner radius	m
r_{out}	Pipe outer radius	m
L	Plate length	m
W	Plate width	m
l	Total pipe length	m
$Q^{\cdot}$	The rate of heat transfer	W
I_{sc}	Short circuit current	A
I_{PV}	PV current	A
I_{01}	Dark saturation Current	A
V	Voltage	Volt
K_B	Boltzmann constant	$1.38 \times 10^{-23} m^2 . kg \times s^{-2} \times K^{-1}$
I_{02}	Reactive current	A
V_{oc}	Open circuit voltage	V
q	The electron charge	1.6×10^{-19} C
η_{PV}	PV efficiency	%
Pout	The maximum power output	W
Pin	The input power	W
FF	Fill factor	%.
ρ_{nf}	Density of nano-fluid	Kg/m^3
ρ_f	The density of cooling fluid	Kg/m^3
ρ_P	Density of nano-particles	Kg/m^3
$\emptyset$	Volume concentration	%
C_{pnf}	Specific heat of nano-fluid	J/kg.K
C_{pf}	Specific heat of cooling-fluid	J/kg.K
C_{Pp}	Specific heat of nanoparticles	J/kg.K
k_{nf}	Thermal conductivity of nano-fluid	W/m.K
k_f	Thermal conductivity of cooling-fluid	W/m.K
k_p	Thermal conductivity of nanoparticles	W/m.K
q_{rad}	Sun irradiance at MENA region	1000 W/m^2

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