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Numerical Study of the Efficiency of a Solar Panel with Heat Sinks

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ABSTRACT

The electrical efficiency of solar photovoltaic (PV) panels depends on their temperature. One of the significant problems consists in the overheating due to the total radiation energy, the ambient temperature, and the low capacity to dissipate this thermal energy. To improve the efficiency of solar panels, a numerical study was carried out using the ANSYS-Fluent 2021 commercial software in which the heat transfer between a solar panel with and without heat sinks was modelled, determining the incidence of fins in power generated by the photovoltaic cell. For the development of the study, initially, the theoretical calculation of the heat transfer and the generated power that occurs in the cell with and without a heat sink was carried out. Therefore, numerical simulation was conducted to analyse the effect of the geometry of the heat sink on the efficiency of the photovoltaic cells; different arrangements of rectangular fins were taken, varying their height (10 mm, 25 mm, and 50 mm). For the model's configuration, boundary conditions corresponding to physical phenomena such as solar radiation and forced convection were considered. Results show an increase on the solar PV panel efficiency of 0.36%, 0.72%, and 1.07% for the height heat sinks of 10 mm, 25 mm, and 50 mm compared to the commercial PV solar panel without heat dissipation, respectively.

1. Introduction

Nowadays, the application of renewable energies due to the negative impact of fossil oil applications such as global warming, environmental pollution and acid rains is increased [1]. Solar energy is one of the most extensively used energy sources for thermal and electrical energy generation and protecting the environment is a commitment of governments, people, and industries [2]. Therefore, there is currently evidence of significant growth, both in the production of increasingly efficient solar panels and in the implementation of large solar plants connected to the electricity grid [3]. One problem in using photovoltaic panels to extract energy from sunlight is the effect of temperature. As the solar panel heats up, the efficiency of converting light to electrical power

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decreases, reaching an efficiency between 14% and 17% [4]. For this reason, several cooling techniques have been implemented, named active and passive methods. Active method relates an active cooling system that needs external electrical or mechanical energy, such as fans OR PUMPS for air or water circulation on the photovoltaic panel, respectively to heat dissipation [5]. By the other hand, passive heat dissipation systems relate all the natural process and techniques always without an external energy source. The Photo Voltaic and thermal collector are a good solution in terms of economics payback period, lesser space, and the capacity to reuse the wastage heat in other industrials process. To exhaust the heat from the PV panels, different components can be utilized like air, air/water and water collectors [6], nanofluids [7, 8], thermoelectric generators [9, 10], and phase-changing materials (PCM) [11] to improve the efficiency.

In this way, it is of great interest to control this thermal variable and optimize its operation, in this case, by designing air-cooled heat sinks [12]. The thermal process of a photovoltaic panel will be characterized, looking for the most efficient way to dissipate heat and increase its efficiency and useful life due to thermal fatigue due to high temperatures [13].

Studies such as Agrawal and Tiwari [14] presented the concept of serial and parallel airflow arrangement through solar panels using microchannels where a nine-channel arrangement was made for heat dissipation using air as a coolant. Numerical calculations showed an increase in annual thermal gain of 70% and 60%. This study serves as a support in the study of the position of the channels and the geometries of the modeling for greater efficiency.

Agrawal and Tiwari [15] conducted an experimental analysis with hybrid photovoltaic glass, in which they linked three PTV modules and made airflow through them following a pattern where in terms of energy saving analysis. It was concluded that the hybrid photovoltaic collector offers a higher potential than the photovoltaic module. Jin *et al.,* [16] demonstrate a configuration with an air tunnel passage in a rectangular geometry to dissipate heat. Corroborating what was previously said about the decrease in efficiency as the temperature of the cells increases. This analysis was carried out by comparing a model of a photovoltaic panel with a tunnel and another without it, increasing its efficiency by 10% and thermal efficiency by 75%.

Caluianu and Băltăreţu [17] studied the temperature profile and air velocity using a PTV thermal model and validated with experimental data. The simulation was done by applying the Galerkin finite element method to the flow and energy equations, incorporating an implicit convective boundary condition. As the width of the channel increases, the average air temperature varies between 50°C and 30°C in the outlet section. Lee *et al.,* [18] compared simulation and experimental results where they found a 3% difference between both methods. They determined that low fin spacing is important when input speed is low, and high speeds have a more significant effect. when the input speed is high, reducing module temperature.

Chaabane *et al.,* [19] analyzed computational and experimentally a concentrating photovoltaic/thermal system but having water as fluid as a coolant in photovoltaic panels. They determined that the computational model adequately presents the physical phenomenon. Baloch *et al.,* [20] used a converging channel and analyzed the influence of the channel on panel temperature for one month. Experimentally, they took the results between a photovoltaic panel without a channel and another with channel converging with 2° deviation, which had a decrease in temperature of up to 25.8℃. Then they conducted a computational study [21] using the Fluent software where they took the same channel angle, corroborating experimentally the previous numerical results found.

Ahmad *et al.,* [22] analyzed the effects of fin spacing, fin height, and fin thickness on the heat transfer properties of a novel truncated multi-level fin heat sink (MLFHS) was investigated numerically using finite element analysis (FEA). The parametric study was conducted to compare the thermal performance of the MLFHS with the conventional rectangular plate-fin heat sinks by varying the fin spacing (p = 10–35 mm), fin height (h = 60–120 mm), and fin thickness (t = 0.5–1.5 mm). The findings were promising with an optimized fin heat sink showing a decrease in the average PV module temperature as high as 6.13% and improved power output by 2.87%.

Mankani *et al.,* [23] studied analyses by CFD simulations, the cooling performance of air-cooled heat sinks for the climate of Dubai, UAE. A stepwise optimization study was conducted to investigate the effects of varying fin spacing, baseplate thickness, fin height and fin thickness on the heat dissipation rate. The means results were a lower temperature of 27°C of the PV panel in an ambient temperature of 42°C and a reduced the average panel temperatures by 9%.

Elbreki *et al.,* [24] studied by experimental test a new different design of the heat sinks, namely lapping and longitudinal. Design of Experiment (DOE) approach technique was employed to identify the optimum design parameters in terms of fin height, fin pitch, fin thickness, number of fins, and tilt angle. Results showed that passive cooling with lapping fins demonstrates the best performance with a mean PV module temperature 24.6°C lower than the reference PV module. Hence, the achieved electrical efficiency and power output are as high as 10.68% and 37.1 W, respectively. Finally, Life Cycle Cost Analysis (LCCA) was conducted. The analysis showed that the payback period for PV modules with longitudinal, lapping fins and bare PV modules are 4.2, 5, and 8.4 years respectively. Therefore, PV module cooling using a passive technique, particularly with a lapping fins design, is the preferred option.

The study of the best geometric configurations of the heat sinks is an excellent way to enhance the efficiency of PV panels, especially heat sinks with simple and easy to manufacture shapes to decrease the ratio between cost and benefice. The objective of this study is to numerically determine by CFD simulations the incidence of efficiency with different arrangements of heat sinks, varying the heights of 0, 10, 25, and 50 mm, and the number of sinks between 9 and 18.

2. Methodology

2.1 Governing Equations

The analysis in this study employs the following assumptions proposed by Murray-Gardner [25]:

(i) The airflow is steady, laminar, and incompressible.
(ii) The temperature at the base of the fin and the surrounding temperature is uniform.
(iii) The convective heat transfer coefficient of the fin is constant over the entire surface.

The governing equations describing the fluid flow are called the Navier-Stokes, represented by the following differential form. Continuity (1):

$$\frac{\partial p}{\partial t} + \nabla.(\rho\vec{u}) = 0 \quad (1)$$

where ∂p/∂t is the rate of change of pressure, and $\nabla.(\rho\vec{u})$ describes the divergence of the flow velocity vector at a particular point. Momentum (2):

$$\rho\frac{\partial\vec{u}}{\partial t} + (\rho\vec{u}\,.\,\nabla)\vec{u} = -\nabla p + \rho b + \nabla.\tau \quad (2)$$

The rate of change of fluid momentum is equal to the sum of surface forces (viscous forces and pressure) and body forces, derived by applying Newton's second law of motion. Energy (3):

$$\frac{\partial(\rho E)}{\partial t} + \nabla.\left(\rho E\,\vec{U}\right) = \nabla.(k\nabla T) - p\nabla.\vec{u} + \nabla\vec{u}\!:\tau + S \quad (3)$$

where E denotes internal energy, T is the temperature, k is the thermal conductivity of the fluid, $k\nabla T$ is the heat flux given by Fourier's Law, ∇u, τ is defined as the irreversible transfer of mechanical energy into heat, and S is the heat source. To know the maximum power reached by the panel, we have the solar energy converted by the photovoltaic panel and delivered. Eq. (4) describes the maximum power that the solar panel reaches:

$$P = VI = \eta G \quad (4)$$

Where P is the electrical power, V is the voltage, I is the electrical current, η is the electrical efficiency, and G is the incident radiation. Similarly, the equation can be described as follows:

$$P = P_{max}(1 + \frac{\Upsilon}{100} * (T_{cell} - 25)) \quad (5)$$

Where P_{max} is the maximum power rating, Υ is the thermal power coefficient, and T_{cell} is the cell temperature. On the other hand, the internal generation of heat is produced because a certain amount of energy incident on the panel is absorbed, and the rest is lost in the internal heat of the panel. To characterize this behavior of internal heat, the following equation was Eq. (6).

$$Q = \frac{T_{cell} - T}{R} = G - P \quad (6)$$

Where T is the ambient temperature and R is the thermal resistance of the module. Figure 1 graphically represents the incident radiation (G), heat (Q), and electrical power (P).

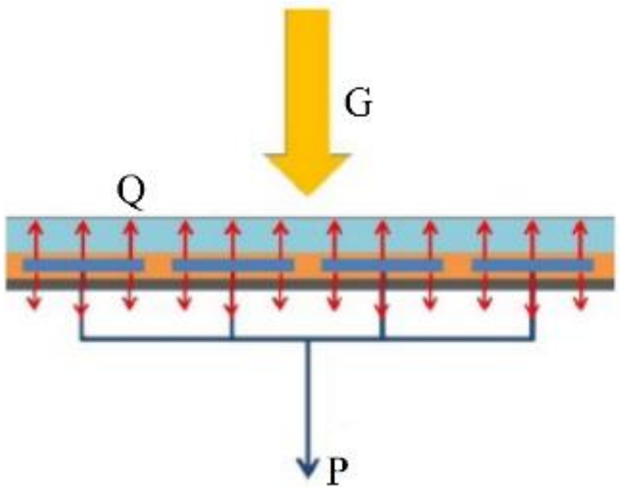
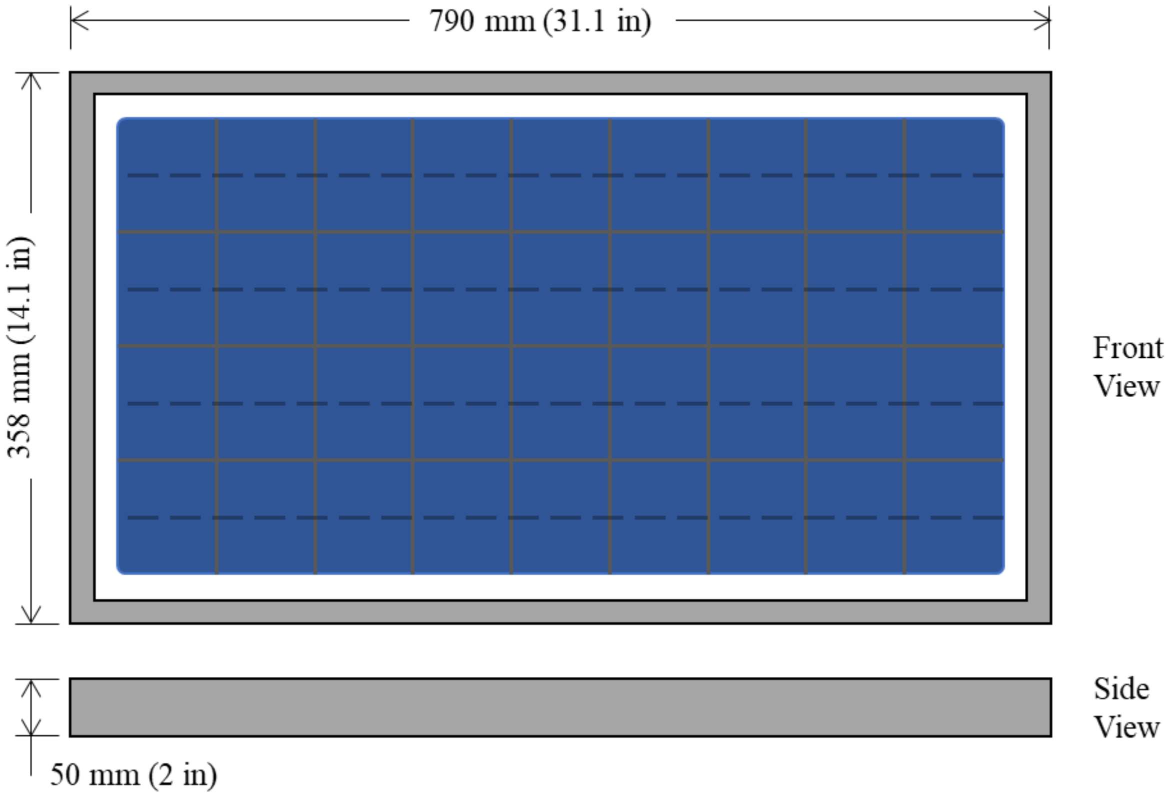


Fig. 1. Incident variables in the photovoltaic panel

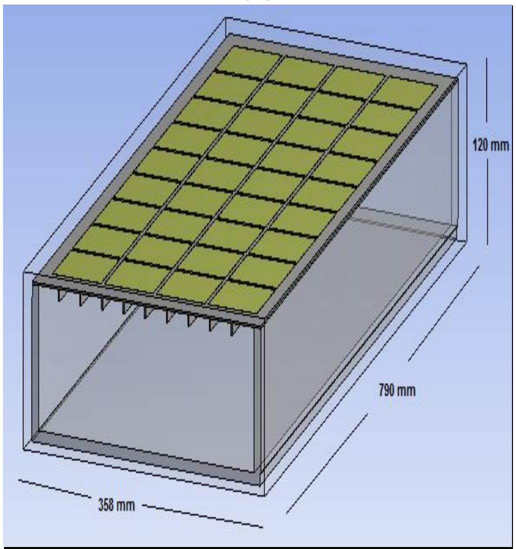
2.2 Computational Method and Grid Generation

There is theoretical support for the case study through articles replicating similar cases. These modeling and computational analyses will be carried out using ANSYS Fluent. The software contains the necessary modules that allow the simulation where a thermo-structural interaction is carried out.

In addition, the finite element analysis method will be used with the Meshing module to get reliability in the results. Then the boundary conditions are configured, such as the characteristics of the materials such as density, viscosity, and coefficient of thermal expansion. In addition to external factors, all these boundary conditions are configured using the Fluent computational fluid dynamics module [26, 27]. A 330 W photovoltaic panel was selected, from which the physical characteristics were taken for the validation of the computational and mathematical models; it also has 36 of 3 in polycrystalline cells. Figure 2(a) represents the model selected for this study and Figure 2(b) represents the modeling of the panel.



(a)



(b)

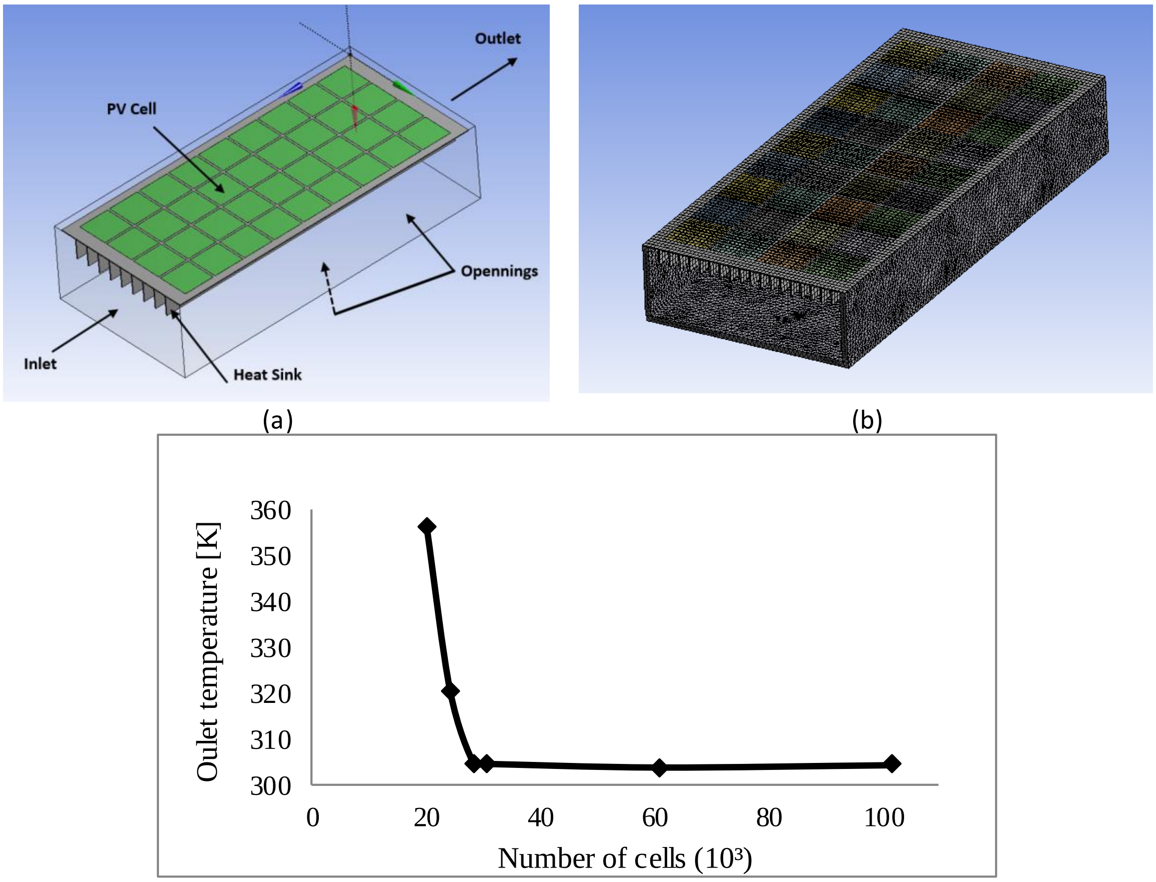
Fig. 2. PV dimensions and CAD model; (a) Commercial PV panel selected, (b) PV Solar panel CAD

Figure 3(a) represents the mesh that was made for the selected photovoltaic panel. Modeled PV was commercial PV 30W power of Solar Electric Supply Inc. Company. In this figure, it can be seen the boundary conditions, such as fluid inlet and outlet and walls and the heat source as detailed in

Table 1. In addition, air inlet velocity, internal heat generation, and heat transfer by convection and radiation are also configured. The turbulence model selected was the Spalart-Allmaras [28, 29], due to its low computational cost and the fact that it solves an equation that models the transport of turbulent kinematic viscosity. Figure 3(b) represents the mesh study carried out for this study. It can be seen how the results do not vary more than 5%, guaranteeing confident results [30-32], concerning the number of elements. The study was conducted from approximately 2E5 to 5.5E5 items. For better computational performance, the mesh of approximately 3E5 elements was established.

Table 1
Initial configuration

Parameter	Symbol	Value	Unit
Irradiance	G	800	W/m^2
Ambient temperature	T_∞	25	°C
Air velocity	U_∞	1	m/s
Air density	ρ	1.12	Kg/m^3
Forced convective coefficient	h	8	W/m^{2}K
Natural convective coefficient	h	0.9	W/m^{2}K
Reynolds number	Re	2346	-
Nusselt number	Nu	284	-



(c)

Fig. 3. Boundary conditions (a); Boundary conditions, (b) mesh of PV panel and (c) mesh independence study

The turbulence model selected for the simulation was Spalart Allmaras; this is a single equation model. This turbulence model is a choice where turbulent effects are not of great importance in the system. A SIMPLE algorithm is used, which uses a ratio between velocity and pressure corrections to obtain the pressure fields in the fluid. With this algorithm, a discrete correlation is obtained for the pressure correction in each of the cells. For the evaluation of gradients and derivatives, the scheme called least square cell based is used, where it is assumed that the solution for a variable varies linearly from one cell to another. Additionally, to resolve momentum and energy, a 'second order Upwind' system is used, which takes information from the flow's origin and increases the precision of the results. They are 1E-3 for continuity and velocity (U, V, W), and 1E-6 for energy.

3. Results and Discussion

Table 2 presents the thermal resistance of a fin (Rfin) and of the heat sink (Rsink) for the height of the sink and the efficiency of the fin (nfin). This table shows how thermal resistances decrease as the height between heat sinks increases—presenting variations between 5% and 10% for Rfin and Rsink, respectively. Table 2 shows that the height of the panels does not have a more significant influence on the thermal resistance since it is more affected by the thickness of the fin. If the thickness of the fin increases (leaving the number of fins fixed), the distance between them will be less, and this affects the airflow as it does not have enough space to circulate.

Table 2
Rfin and Rsink with different heights

Sink height (m)	Rfin	Rsink	ηfin (%)
0	17.44	197.66	99
0.01	4.55	0.49	50
0.02	4.31	0.44	21
0.05	4.25	0.41	11

Figure 4 and Table 3 show the comparison in the theoretical and numerical model of the temperature (K) for the PV as the initial case (without heatsink) and with heatsinks (at the three different heights). It is observed a variation of 7% in the three cases with a heat sink. In a theoretical model, it can be observed how with a 10 mm heatsink, the temperature increases to a maximum point (336.4 K) and then begins to decrease at a constant rate (7%) as the height of the heatsinks increases. Figure 5 shows the temperature contours of the panel with heat sinks and the base case without a heat sink. This figure shows how the temperature decreases with the heat sinks and decreases as the height of the heat sinks increases.

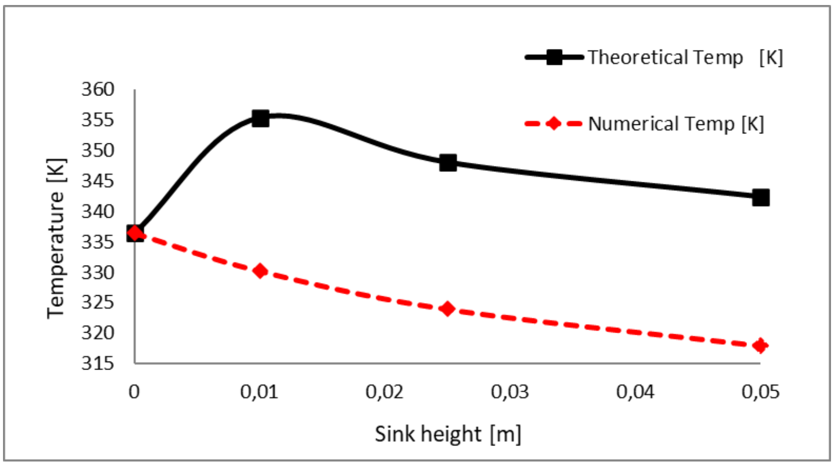
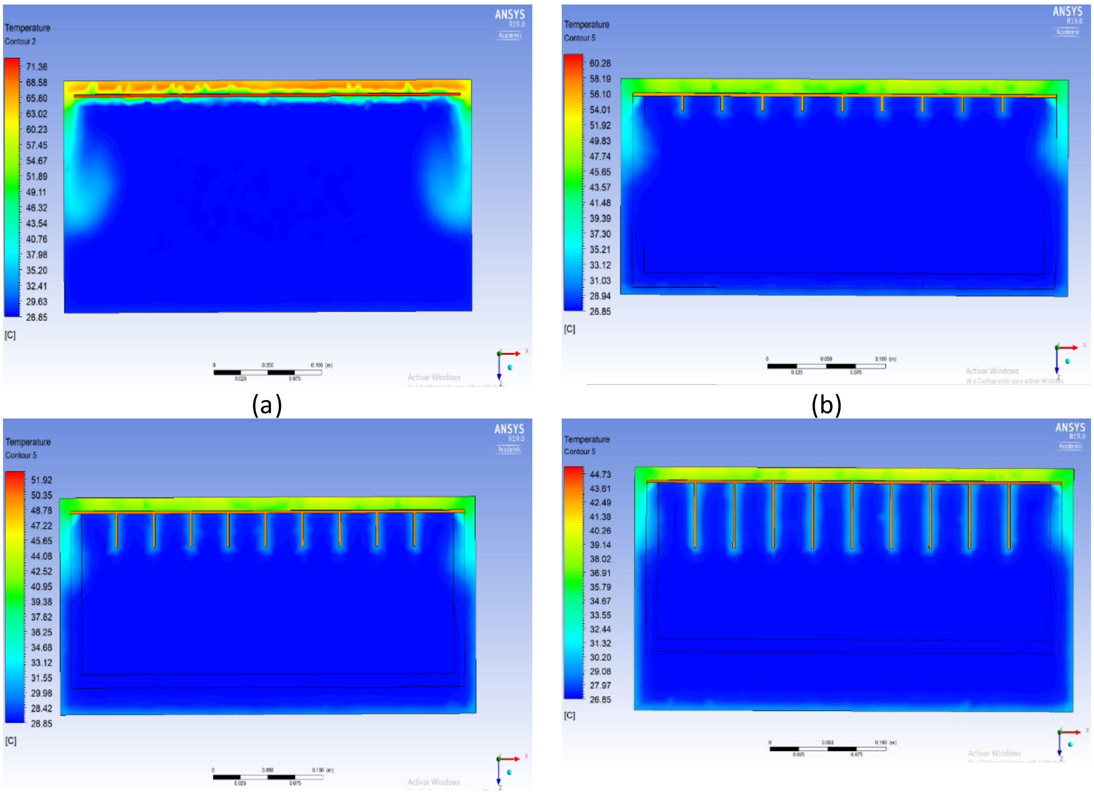


Fig. 4. Numerical and theoretical comparison of temperature of PV with and without a heatsink

Table 3
Numerical and theoretical comparison of temperature of PV

Sink height [m]	Theoretical Temp [K]	Numerical Temp [K]	Error [%]
0	336.38	336.38	0.0
0.01	355.28	330.19	7.1
0.02	348.00	323.94	6.9
0.05	342.38	317.95	7.1



(a) (b) (c) (d)

Fig. 5. Temperature contour; (a) Initial case without sink, (b) Sink 10 mm, (c) Sink 25 mm, (d) Sink 50 mm

Table 4 presents panel power and efficiency for heat sink height and its area. In Figure 5, it can be seen how the power increases as the area of the heat sink increases. The increase in efficiency at low compared to the rise in the heat sink area. The case with an area of 0.43 m^2 presents an efficiency of 11.06%, and for an area of 0.99 m^2 the efficiency only increased 0.11%.

Table 4
Power and efficiency with different sink height

Sink height (m)	Area (m^2)	P (W)	N (%)
0,000	0,00	17,88	10,70
0,010	0,43	18,49	11,06
0,025	0,64	19,09	11,42
0,050	0,99	19,68	11,77

4. Conclusion

In the development of the study, different heights of heat sinks for photovoltaic panels were simulated. The performance of the PV System was compared to the module without cooling; based on these results, it was validated mathematically through the thermal resistance model, which corroborated the effect of temperature on the panels' efficiency and how its decrease can affect their performance. The maximum thermal efficiency achieved by the cooling module is 11.77% when the sink heat is 0.05 m high.

The computational model represents the mathematical model, in which it is observed that by increasing the height of fins, there is a greater exchange of heat with the outside and a reduction in temperature. In addition, a maximum error of 7.7% was found, which is an acceptable value to replicate the electrical performance model; it increases its useful life since it does not present different temperature gradients. According to the study, the PV module's efficiency increases when the temperature of the module decreases. An interesting future work for further improvement efficiency will be the analysis of the cooling effect of rainfall.

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