JJMIE

Volume 19, Number 2, June. 2025
ISSN 1995-6665
Pages 387– 394
https://doi.org/10.59038/jjmie/190211

Jordan Journal of Mechanical and Industrial Engineering

Experimental Study for Cooling Enhancement of PV System by Using a Heat-Sink Integrated with PCM

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Received 22 June 2024 *Accepted 1 Mar 2025*

Abstract

This study investigates the cooling of a Photovoltaic module using Phase Change Material (PCM) heat sink. Three modules with different cooling methods were compared against each other by applying a constant heat flux to simulate the sun irradiance. The first module, the reference module, is cooled by natural convection without any attachments, the second module is cooled by aluminum fins heat sink, and the third module is cooled by aluminum container equipped with internal and external fins. Two different orientations for finned heat sinks have been studied: one with vertical orientation and the other one with horizontal orientation. In the heat sink with horizontal finorientation; the air-cooled heat-sink case, a maximum temperature difference of 4.2 ^oC and an efficiency enhancement of1.89% is observed when compared to the reference module. Alternatively, in the PCM module case, a maximum temperature difference of 18.8 ^oC and an efficiency enhancement of 8.46% is observed when compared to the reference module. On the other hand, in the heat-sink with vertical fin orientation; in the air-cooled heat-sink case, a maximum temperature difference of 5.7 ^oC and an efficiency enhancement of 2.57%is observed when compared with the reference module, whereas a maximum temperature difference of 23.0 ^oC and an efficiency enhancement of 10.35% is observed in the PCM module when compared to the reference module..

Keywords: photovoltaic, efficiency, cooling technique, PCM, fins cooling, infraredcamera.

1. Introduction

Energy demands worldwide are growing fast, and the energy consumption will increase by 33% between the years 2010 and 2030[1]. The energy demand increase is accompanied by a rise in the renewable forms of energy generation to limit the greenhouse emissions and decrease dependence on fossil fuels. Solar energy has been widely used in thermal and electric power generation due to its availability and ease of energy production. For electric power generation, PV panels are one of the leading alternative technologies. As solar irradiance hits the PV surface, electric current is generated within the semiconductor materials inside solar panel layers, however, PV panels are only about 15-20% efficient which means most of the solar irradiance is absorbed by the panel and its temperature rises, and this in-turn leads to a further decrease in the PV cells efficiency[2]–[4]. Hence, thermal management is required to limit the drop in power output. PCM have been widely used in thermal management[5] and thermal energy storage systems[6].PCMs have the capability to absorb large amount of latent heat at nearly isothermal conditions; and they are commercially available in different types with varying physical properties including density, latent heat of fusion and melting range.

In recent years, many studies investigated the performance of PCM-based heat sinks both experimentally and numerically. Using numerical simulation, Zhao et al.[7] studied the effect of PCM thickness on PV temperature. By adding PCM, an increase by 11.02% in power generation with reduction of 24.9 °C in temperature is obtained. Huang et al.[8] studied the performance of PV using PCM-based heat sinks both experimentally and numerically. Their results showed significant improvement in PV performance when using PCM-based sinks with internal fins. Khanna et al. [9], presented a mathematical model to enhance the internal fin geometry and spacing of a PCM based heat sink, the model focused on the effects of fins spacing, length and thickness and PCM container depth on the heat transfer rate between the PCM and the PV module. Two different irradiance levels were considered (3 kW/m^2 and 5 kW/m^2). They found out that the optimum fins spacing was 25 cm, the optimal fin thickness was 2 mm, the optimal fins length is equal to the heat-sink width, and the PCM optimal depths are found to be 2.3 cm and 3.9 cm for the irradiance levels of 3 kW/m^2 and 5 kW/m^2 respectively. Soares et al. [10] experimentally tested three real scale solar PVs: two panels equipped with a movable PCM based thermal energy storage system(TES) with different cavity orientation (PV/PCM1 vertical cavities and PV/PCM2 horizontal cavities) and one without PCM as a reference

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panel. The results showed PV reference produced more power than PCM1 and PCM2, and they found out that PCM-based movable TES units do not enhance the thermal efficiency of PV panels and also PCMs with higher melting range are required for the Mediterranean climate; besides, the experiment showed that PCM1 with vertical configuration seems more efficient than PCM2 with horizontal configuration. Waqas et al.[11]conducted an experimental investigation to cool down the PV panel with a PCM put inside a movable shutter mechanism. During the night period, the shutter opens to increase cooling rates of the PCM to increase the solidification in very hot climate and closes during sunshine. The efficiency was observed to increase by 9% in summertime with PCM melting point 35 ^{o}C and increased by 2.2% in wintertime with PCM melting point 30 ^{o}C. Ma et al. [12]used ANSYS Fluent software to study finned rectangular chamber (internal aluminum fins), filled with PCM. Five different PV-PCM models were investigated, model I, II and III filled with30 mm PCM (type RT35, RT35HC and RT42 respectively), each type has different heat capacity, and the model IV and V filled with 40 mm and 50mm depth of PCM RT35HC respectively. The best model efficiency is model II, which maintained the temperature below 45 ^{o}C for 318 min thereby the electricity output increase by 6.35%.Atkin et al. [13]experimentally studied and computationally simulated (using Matlab)four different PV thermal regulation techniques: a PV cell without any attachment, a PV cell with a PCM heat sink, a PV cell with fins and a PV cell with a PCM container fitted with external fins, all these modules subjected to natural convection. The study showed that PCM-heat sink equipped with extended surfaces was the most effective thermal regulation method with an overall efficiency improvement by 12.97%.Rajvikram et al.[14]used a PCM-based heat-sink fitted with a flat aluminum sheet that serve as a thermal conductivity enhancer to improve thermal regulation and increase the power output of the PV panel, the experiment was conducted under direct sunlight. The conversion efficiency was enhanced by 24.4%and the temperature was reduced by 10.35 ^{o}C when compared to un-cooled panels, they also concluded that the PCM holds and shifts the peak of temperature and the aluminum plate accelerates the heat diffusion rate from the heat-sink to the surroundings. Wongwuttanasatian et al. [15], tested a polycrystalline PV solar panel equipped with a PCM-based heat sink. Three container geometries with the same volume (3000 cm^{3}) were considered: grooved box, tubed box, and fined box. Initially, they were tested without PCM and then they were filled with the low-cost Palm wax. The finned box provided the best efficiency over the grooved box and tubed box with overall efficiency 9.33% without Palm wax and 9.82 % with Palm wax.El Mays et al.[16] tested a PCM-Based heat-sink fitted with internal fins compared with reference PV panel, the system enhanced the electric efficiency by an average of 1.75%, and the front temperature of the solar panel was reduced by an average of 6.1 ^{o}C.Soliman et al. [17]experimentally investigated the performance of Aluminumheat-sink attached to PV module subjected to indoor halogen lamps radiation. Modules were tested under both natural convection and forced convection using a draft fan which simulate windy conditions. Temperature of the cell was reduced by 5.4% when the heat sink was cooled naturally and reduced by 11% when fan was used as a forced cooling heat sink. Sathe et al. [18] simulated slanted PCM-Based heat-sink fitted with internal and external fins, transient computation at, varying different cavity depths (20 mm, 30 mm and 40 mm), varying tilting angle (30^{o}, 45^{o} ,60 ^{o} and 90^{o}), different number of fins (2, 3 and 4). They found out that melting time is inversely proportional to inclination angle and directly proportional to the number of fins. However, the average PCM temperature is directly proportional to the inclination angle. Besides, addition of more than 3 fins doesn’t significantly improve the melting time although is enhances the heat transfer within the PCM. Interestingly, the Nusselt number was increased by (6-9) times for the 30^{o} inclined configuration and (2-3) times for other configurations.

PCMs have low thermal conductivity in the range of (0.2 -0.7) W/m.K which limits the heat transfer rate within the PCM, and the challenge is to adopt some innovative techniques to enhance heat transfer such as increasing the heat transfer surface area by adding fins with different geometrical parameters such as shape, size, and spacing using metal foams or by adding nano-particles with high thermal conductivity into the PCM [19]. Ababneh et al. [20] demonstrate that the temperature of the storage medium remains within a narrow range during thermal energy storage, which implies minimal internal entropy generation.

In this paper, a PV module will be first experimentally tested and investigated under different operating parameters. The experimental approach will consider three different types of cooling methods; First Type: PV module with the back side is subjected directly to the atmosphere that is considered as a reference module, Second Type: PV module equipped with an aluminum fins heat sink cooled by natural convection, and the Third Type: PV module equipped with Aluminum heat sink and a Phase Change Material (PCM) container integrated with internal and external fins cooled by natural convection. The heat sink configuration will be tested with the fins being oriented horizontally and vertically.

2. Experimental study

The cooling is quantified by comparing the temperature by reference surface. Three polycrystalline PV modules were set up and tested simultaneously under the same operating conditions: The first module is the baseline or the reference module (without any attachments effects on model temperature). The second module is attached with aluminum fins heat sink, the fins are attached to the backside of the module using silicon adhesive bond with Silver-base thermo-paste to fill the gaps between the heat sink and the PV module backside. The third module is equipped with an aluminum container with internal and external fins and filled with PCM material (Paraffin Wax 37^{o}C melting point). The PCM heat sink (a container with internal and external fins) was fabricated as one piece to eliminate any gaps through heat transfer walls series. Figures (1 and 2) show the experimental setups for the three study cases. In all cases, the module is tilted by 30° with the front surface of the PV panel subjected to artificial solar radiation and natural convection on the back surface.Two different orientations (horizontal and vertical) for the external fins array (as shown in Figure 3) are tested experimentally.

The heat sinks are machined from one-piece aluminum plate and air cooler heat sink that has thickness 25 mm slotted by 21 mm fins depth and 5 mm thickness and 5 mm gap between the finsas illustrated in Figure 4. The PCM heat sink is a plate of aluminum which has 50 mm thickness, 21 mm fins depth and 5 mm fins thickness and 5 mm gap between the fins, this is air cooled side fins, the other side was grooved to create PCM chamber with 25 mm depth and internal longitudinal fins with thickness 3 mm and 14 mm spacing between the fins (PCM cavity). Both heat sinks were engraved to make space for PV module terminal box to increase contact area around the terminal box, Figure 5 shows the PCM heat sink specifications.

Figure 2. Experimental setup: Back-side

Figure 1. Experimental setup: Front side

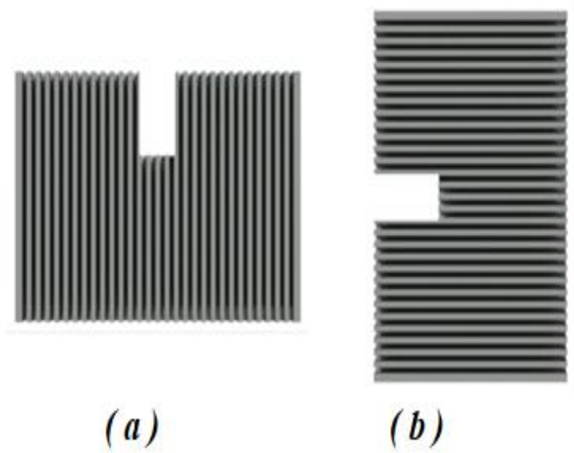

Figure 3. Fin orientation: (a) Vertical, (b) Horizontal

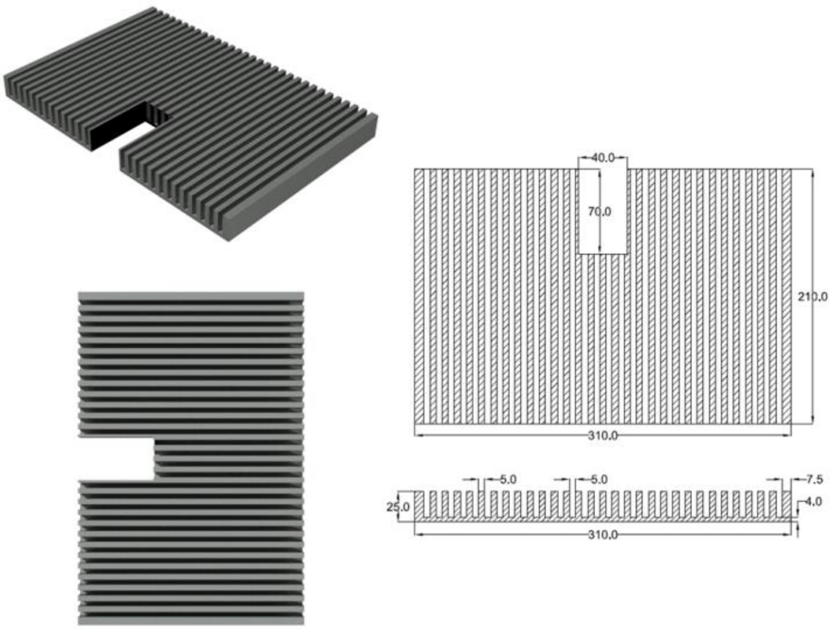

Figure 4. Air based Heat Sink, Module 2

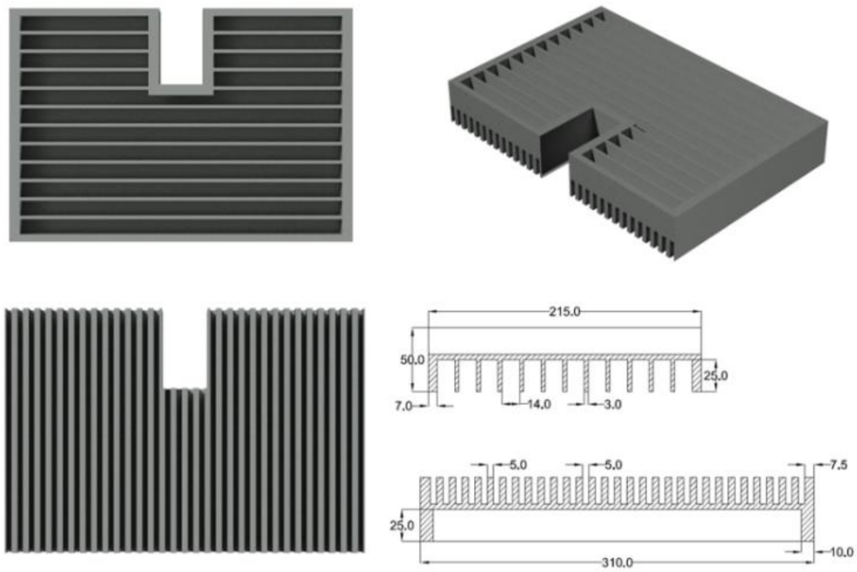

Figure 5. PCM based Heat Sink, Module 3

The system is equipped with Arduino data acquisition and data logger. Thermocouples are placed at selected locations at the back side of the module and inside the PCM container to read and record temperatures variation with time at these locations. An infrared camera (IR-camera) with 0.04 °C and 480×360 PPI resolution (equivalent to 172800 thermo-couple array) is used to read temperatures distribution and accurately detect the hot spots on the backside of the module.

Solar radiation was imitated using a heated plate equipped with quartz tube heaters parallel to front surface of the PV panel. Radiation heat flux flows from the 136.6 °C hot plate to the PV panel setup and the spacing between the hot plate and the panel was 17 cm; besides, plate surface area was equal to that of the three panels (71cm × 31cm); the heat flux was calculated by Stefan-Boltzmann equation[21]:

$$q = \varepsilon\sigma F_{ij}\left(T_i^4 - T_j^4\right) \quad (1)$$

Here, q represents the heat flux in W/m^2, $\varepsilon$is the emissivity of the emitter plate (0.95 for rough painted plate), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W.m^{-2}.K^{-4}), F_{ij} is the view factor for aligned parallel rectangles, and T is the absolute surface temperature in K.

The heat sink container is filled with molten PCM (petroleum jelly, melting point 37 °C) and then it was allowed to freeze, heat sinks “aluminum based and PCM based” were attached to 2nd and 3rd modules respectively; PCM temperature is recorded using three thermocouples placed inside the PCM without touching the Aluminum boundary and surroundings temperature is also recorded using another thermocouple and the IR-camera takes snapshots of the temperature distribution of the outer surface of the modules.

Data were recorded for the two different fins orientations, the ambient and PCM temperatures were recorded every one-minute and every five-minutes for the front surface of the panel. Each thermal image was processed by special software (FLIR TOOL®) and recorded the average temperature for each panel.The Poly-Crystalline Silicon Module that are used in the experiments, the PCM properties and the heat sink specifications are summarized in Tables 1, 2 and 3 respectively.

Table 1. PV Panels Specifications:

Type	Poly-crystalline Silicon
Module Efficiency at STC	14.50%
Maximum Power Output (Pmax)	10 W
Optimum Operating Voltage (Vmp)	18V
Optimum Operating Current (Imp)	0.59 A
Open Circuit Voltage (Voc)	21.2 V
Short Circuit Current (Isc)	0.55 A
Temperature Coefficient of (Pmax)	- 0.45/°C
Module Area Include the Frame	250 mm × 350 mm
Weight	0.85 kg
Nominal Operating Cell Temperature (NOCT)	46±2°C
Front side Emissivity ε (measured)	0.84
Backside Emissivity ε (measured)	0.93

Table 2. PCM Properties

Property	Value
Melting Range (°C)	37-38
Density (kg/m3) @ 60 °C (liquid)	865
Heat of Fusion (kJ/kg)	194
Specific Heat (kJ/kg.°C)	2.8
Thermal Conductivity (W/m-°K)	0.21
Flash Pint (°C)	183-220

Table 3. Heat Sink Specifications

	Fins-Only Heat Sink	PCM Heat Sink
Material	Aluminum	
Bulk Dimensions (W×L×H) [mm]	210 × 310 × 25	210 × 310 × 50
External Fins Dimensions (W×L×H) [mm]	5 × 210 × 21	5 × 210 × 21
Internal Fins Dimensions (W×L×H) [mm]	-	3 × 310 × 25
External Area [m^2]	0.281	
Internal Fins Area [m^2]	-	0.142
PCM Cavity Volume [cc]	-	1100
Weight [kg]	2.5	3.6 excluded PCM
Emissivity	0.24	

3. Results and Discussions

The performance of PV module has been studied under three different natural cooling mechanisms, i.e., PV module without fins, PV module with fins, and PV module with PCM heat sink with internal and external fins. Two different orientations for fins array (horizontal and vertical) were also investigated. During the experiment, the data were recorded every one minute for the temperature and every five minutes for the IR images.

A continuous rise in PV surface temperature is observed for all modules after applying heat flux. However, the rate of temperature rise is strongly related to the modules' design and orientation. For instance, in the reference module (without fins), temperature starts increasing rapidly for the first 15 minutes after that it slows down to a maximum steady-state temperature of 75.9 °C for vertical orientation and 71.9 °C for horizontal orientation as shown in Figures 6 and 7 respectively.

The same trend for temperature rise is also observed in PV module with finned heat sink, however, the temperature rise rate is gradually increasing to a maximum value of 70.2 °C for vertical orientation and 67.4 ºC for horizontal orientation. The gradual increase in PV surface temperature and the reduction in the maximum values of temperature is expected due to the increase in heat transfer area which enhances natural convection rate between the back surface of the PV module and the surrounding air.

In the case of PCM-based heat sink, the increase in temperature rise is even slower than the rates observed in the previous two cases and the maximum surface temperature is also lower. In this case, a maximum temperature of 56.4.2 ºC for vertical orientation and 53.7 ºC for horizontal orientation is reached (see Figures 6 and 7).

Heat flows from the PV surface towards the heat sink outer boundaries, though the metal enclosure and the internal fins and this adds heat to PCM causing its temperature to rise and once the melting point is reached PCM starts melting. As further heat is added to the PCM, the molten region gets bigger. Moreover, convection currents and vortices are formed due to buoyancy effects that are induced by density gradients which are caused by temperature difference, consequently mixing is improved as well as heat transfer within the PCM.

The Melting process of PCM is nearly isothermal and the PCM temperature rise is determined by its solidification and melting temperatures during the process. On the other hand, The PV surface temperature will always be greater than that of the average PCM temperature but at the interface thermal equilibrium always exists.

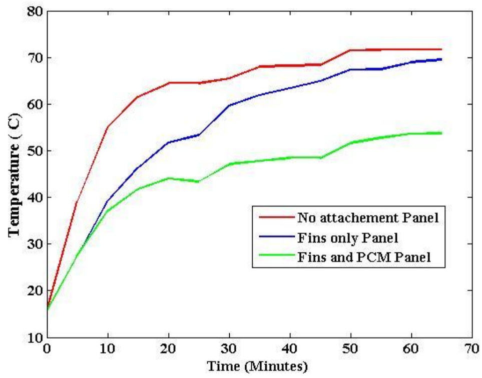

Figure 6. Horizontal Orientation Curves for PV under Different Cooling Methods

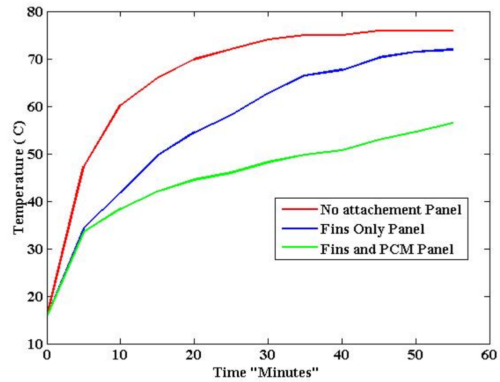

Figure 7. Vertical Orientation Curves for PV under Different Cooling Methods

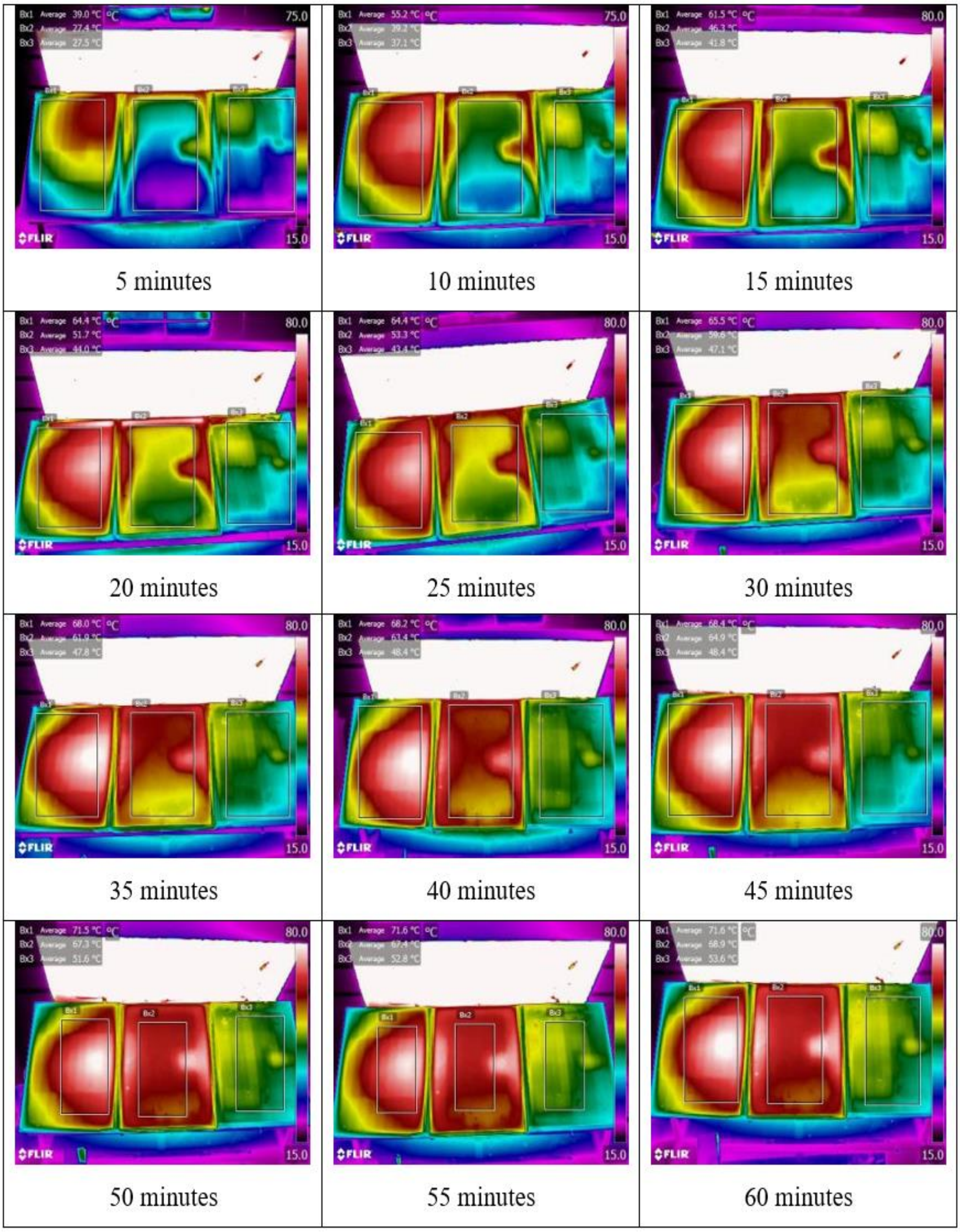

Figure 8. Thermal Image of the Horizontal Orientation Experiment Results

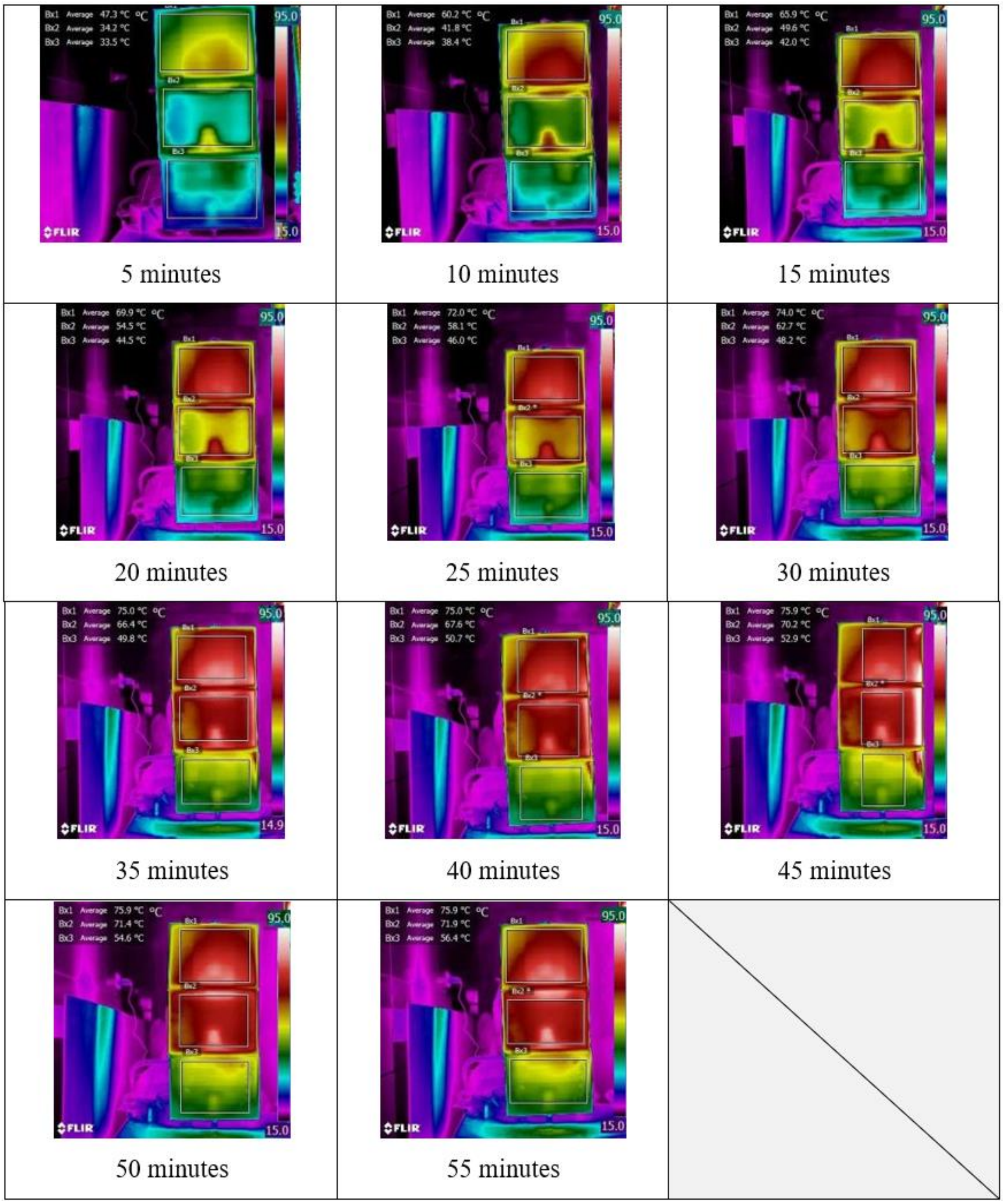

Figure 9. Thermal Image of the Vertical Orientation Experiment Results

4. Conclusions

An efficient cooling mechanism in PV module is necessary to enhance its performance and improve power output. Controlling PV module surface temperature is strongly related to the heat sink design and operating conditions.

Heat sinks with fins and/or PCM significantly reduces the surface temperature of PV surface which improves its performance. For instant, a heat sink with horizontal fins orientation and PCM reduces the average PV surface temperature by 18.8 ^oC when compared to the reference module. However, a reduction by 23.0 ^oC in the average PV surface temperature is observed for vertical fins orientation.

The heat absorbed by PV causes the PCM to melt in a near isothermal process and this doesn't allow the PV surface to overheat as long as the PCM is not totally molten, at the same time the internal fins allow for the heat flux to flow out of the heat sink and consequently maintaining a more uniform temperature distribution within the heat sink.

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