Romanian Journal of Civil Engineering, Volume 16 (2025), Number 4

Efficiency Enhancement of Photovoltaic Panels through Passive Heat Pipe Technology

Creșterea eficienței panourilor fotovoltaice prin utilizarea tehnologiei pasive cu țevi termice

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DOI: 10.37789/rjce.2025.16.4.10

Abstract- Photovoltaic (PV) technology is a key renewable energy source; however, its performance is significantly hindered by overheating, which reduces efficiency and output. This study investigates passive cooling solutions for PV panels, with a focus on heat pipe integration. The research builds upon previous simulation-based work by extending experiments to real outdoor operating conditions, enabling a more accurate assessment of thermal and electrical behavior. Two types of heat pipes-narrow copper water-based pipes and flat aluminum acetone-based pipes—were integrated into aluminum transfer plates and tested against a conventional PV panel. Measurements were conducted over multiple days under comparable irradiance and ambient conditions, with performance indicators including panel surface temperature and electrical output. Results demonstrate that while the conventional PV panel reached average temperatures of 46.31 °C and produced 38.65 W, the narrow heat pipe–cooled module reduced the temperature to 44.28 °C and delivered 43.32 W. The flat heat pipe–cooled module achieved the best performance, lowering the temperature to 41.20 °C and increasing power output to 55.45 W. These findings confirm that passive heat pipe cooling is a practical and efficient method to mitigate PV panel overheating, significantly improving energy output and long-term system reliability.

Index Terms - Energy efficiency, Heat pipes, Passive cooling, Photovoltaic Panels

A. Introduction

Photovoltaic conversion is currently considered as the most promising renewable energy technology for electricity generation, as a clean and sustainable energy source. It is not harmful to the environment; photovoltaic (PV) panels have a long lifetime and no associated CO2 emissions and low loss in transmission of electricity due associated to onsite production [1], [2].

Overheating of PV panels is a major obstacle to their operation, since just a temperature rise of 1 °C can lead to a reduction in power output by 0.65–0.85 % [3]. This

The article was received on 24.10.2025, accepted on 27.10.2025 and published on 27.11.2025

issue is intensified during the summer season, when the PV temperatures can reach 40–70 °C, resulting in a significant 7.5–22.5 % decline in conversion efficiency [4]. There are a lot of passive cooling PV methods that along the time were proved or simply considered theoretical. To discuss about the new ways to cool a PV panel there are some references done in the past few years.

It is important to mention that there are two types of passive cooling systems for PV solar panels: direct and indirect. Direct cooling involves a heat sink that is directly attached to the PV panel. Indirect cooling, however, utilizes an intermediate medium, like heat pipes, to transfer heat from the panel to a remote heat sink or in the air.[5]

In 2021 A.M. Elbreki et al., experimentally analyzed the cooling of a PV module using fins and a planar reflector at the geographical location of the National University of Malaysia. Two different heat sink configurations including longitudinal and lapping fins were chosen as the passive cooling system. Economic analysis has also been done to find out the shortest payback period of each cooling system compared with the reference module. In the latter study, under an average solar irradiance of 1000 W/m² and ambient temperature of 33 °C, passive cooling with lapping fins was used, which resulted in a mean PV module temperature, electrical efficiency, and power output of 24.6 °C, 10.68%, and 37.1 W, respectively, as the best performance. [6].

Another article written in 2023 by S.N. Razali et. al. presents another way of passive cooling a PV panel using multidirectional tapered fin heat sinks to improve the efficiency by utilizing aluminum alloy material as heatsinks. After readings and measuring the results S.N. Razali et. al. obtains some considerable changes in PV panel by lower temperature by 12 °C and increases the efficiency by 1.53% difference compared with a normal PV panel measured in the same conditions. In conclusion the integration of multidirectional tapered fin heat sinks proves to be a promising solution for managing PV module temperatures, enhancing electrical efficiency, and optimizing the performance of solar modules in tropical climates. [7]

To get along with the studies about our main topic about passive PV panel cooling using heat pipes, there are some things already know about this process and well presented below.

In 2024 Yahya Sheikh et. al. designed and performance assessed a solar PV panel integrated with heat pipes and bio-based phase change material. This study presents a hybrid way of cooling a PV panel (passive and active). The choice of utilizing heat pipes, rather than directly attaching phase change material PCM based heat sink to the PV panel is because of low thermal conductivity of PCMs. The aluminum flat sheet, which is attached to condenser sections of heat pipes, further enhances the system by providing increased contact surface area, facilitating efficient convection heat transfer to the surrounding air. The study had some impressive results, there were 4 cases and the most efficient one reduced the temperature of PV panel by 37 °C under a radiative heat flux of 1000W/m² . But even so the study demonstrates an efficiency enhancement of up to 17.3% beating the other ways of PCM and heat pipes cooling techniques studied. In conclusion with this hybrid technique of colling a PV, Yahya Sheikh et. al succeeded in giving us proper and usefull information. [5]

Passive cooling methods for photovoltaic panels

PCM - Based Cooling

Different from the heat pipe cooling methods, the PCM-based cooling methods for PV panels introduced in this section refer to cooling methods which utilize solid–liquid phase change [8]. The typical PV/PCM integrated system mainly comprises a PV panel and a PCM container made of high-thermal-conduction metal [9].

Pure PCM - Based Cooling

For typical simulation studies on PV panel cooling based on pure PCMs, Kant et al. [10] studied the effects of convection inside melted PCMs, wind speed, and tilt angle of the PV panel on the cooling performance of a PV system (see Figure 1) with PCM cooling through simulations. The PCM was assumed to be RT35. The simulation results indicated that when both the convection and conduction heat transfers in the PCM were considered, the PV panel temperature could be reduced by 6.0 °C.

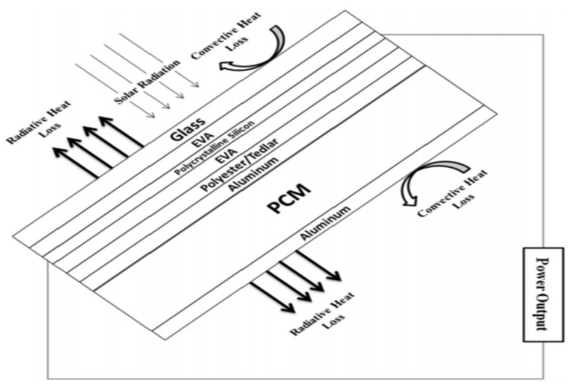

Figure 1. Diagram of a PV system using PCM cooling studied by Kant et al. [10]

For typical experimental studies, Ranawa and Nalwa [11] evaluated the cooling performance of PV panels using different multi-layer PCM cooling schemes through the experimental method. Figure 2 presents the diagrams and experimental device for PV panels with multi-layer PCM cooling. OM37 and OM42 were used as the PCMs.

The results revealed that compared with the PV panel with only single-layer OM42, the temperature reductions of the panels using OM37/OM37/OM42 and OM37/OM42/OM42 were 3.0 ◦C and 1.9 °C, respectively.

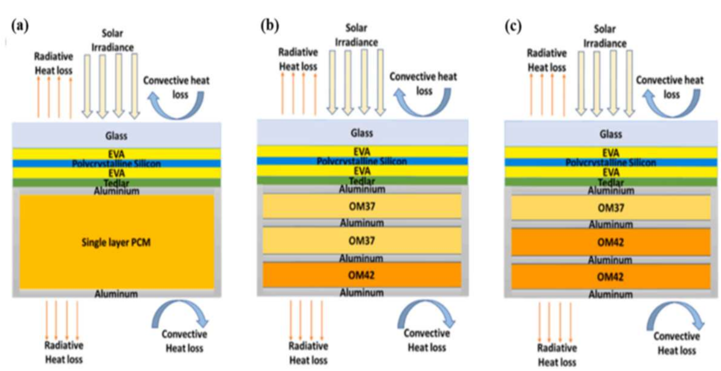

Figure 2. Diagrams of PV panels with multi-layer PCM cooling studied by Ranawa and Nalwa: (a) OM42, (b) OM37/OM37/OM42, and (c) OM37/OM42/OM42 [11].

Spectral Beam Splitting - Based Cooling

An important characteristic of PV cells is that they have spectral response curves [12]. This means that only a certain part of the full solar spectrum can be utilized by PV panels to generate electricity, and the rest absorbed by PV panels can only become waste heat and makes the panel temperature increase, thereby reducing photo-electric efficiency [13].

Though traditional PV/T systems can solve this problem to a certain extent, the temperature of the outlet working fluid is limited by the PV panel temperature [14]. Solar PV/T systems using beam splitting technology can not only reduce the PV panel temperature but also eliminate the limitation of PV panel temperature on working fluid temperature.

The operating principle of solid beam splitter-based PV/T systems is shown in Figure 3. Regarding studies on beam splitting PV/T systems with solid beam splitters, Liang et al. [15] conducted experiments on a solar beam splitting PV/T system using a SiO_2/TiO_2 film beam splitter. They found that the use of SiO_2/TiO_2 film reduced the PV panel temperature by 3.0 °C.

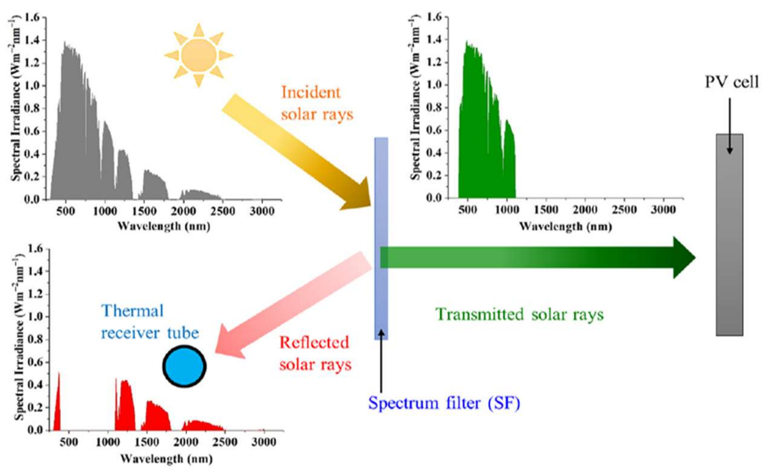

Figure. 3. Operating principle of solid beam splitter-based PV/T systems.

Heat Pipe Cooling

Heat pipe is an effective passive heat transfer element which utilizes phase change in a medium inside a fully enclosed vacuum pipe for heat transfer. It mainly consists of three parts, namely, evaporation, insulation, and condensation sections [16]. The heat transfer inside a heat pipe primarily depends on the gas–liquid phase change in the working fluid and does not require a large temperature difference between the heat source and the heat sink. It can have high temperature uniformity, high thermal conductivity, and variable heat flux without additional energy consumption [17]. Additionally, heat pipes also have advantages of low cost, high reliability, long service life, and diverse structure and can be freely designed according to the heat dissipation requirements and structural characteristics of different PV systems. Concentrated solar photovoltaic (CPV) systems with heat pipe cooling can not only obtain effective cooling effects for PV panels but also collect some heat for thermal utilization. When heat pipes for PV systems are designed, water, ethanol, ammonia, toluene, pentane, and other materials can be selected as the working fluid.

Air Cooling

The natural circulation air cooling method belongs to the passive cooling technology. It takes heat away from PV panels through natural circulation flow on the front or back of the PV panels, reducing the PV panel temperature. An effective method for the natural circulation air cooling of PV panels is to add heat sinks on the back of the PV panels to further enhance the cooling effect [18]. The heat sink is normally a thermal conductor (e.g., fin) which can absorb heat from PV panels and dissipate it to the surrounding environment [19]. Appropriately increasing the heat transfer area of fins or adjusting the fin layout can enhance the PV panel cooling effects [20]. Bayrak et al. [21] analyzed the influences of fin parameters on the temperature and electrical power of PV panels under the natural convection condition through experiments. The experimental devices in the study are presented in Figure 4. They found that the PV panel using fins with 7.0 cm × 20.0 cm dimensions had the best cooling performance, with the output power being 9.4 W higher than that of the PV panel with no fins. Another similar experimental study was conducted by Selimefendigil et al. [22], who cooled PV panels by porous fins. The results indicated that the use of porous fins brought an increase of 7.26 W in output power.

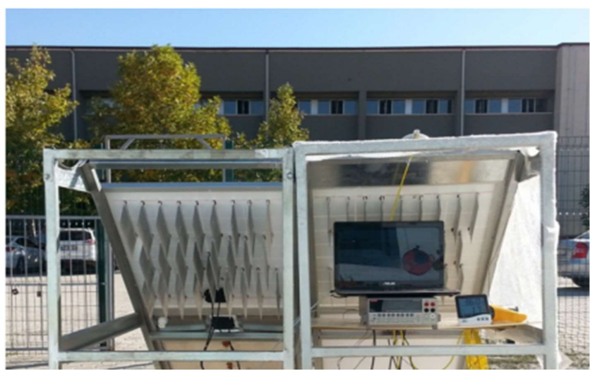

Figure 4. Experimental devices of fin-based natural circulation air cooling method for PV panels [21].

This research focuses on the passive cooling of photovoltaic (PV) panels through the use of flat and narrow heat pipes, a technique aimed at enhancing both the electrical efficiency and the overall reliability of PV systems. The experimental stand employed in this study was initially designed and constructed by Dr. Eng. Marius Branoaea within the framework of his doctoral dissertation entitled “Numerical and Experimental Research for Improving the Energy Efficiency of Solar Systems with Simultaneous Production of Electricity and Heat”. In that work, the PV modules were tested under controlled conditions using a solar simulator, and the results demonstrated promising improvements in performance.

While simulator-based experiments provide valuable insight under repeatable and well-defined irradiation and thermal conditions, they cannot fully reproduce the variability and complexity of outdoor environments. For this reason, the present article extends the scope of investigation by testing the heat pipe–cooled PV panels under real operating conditions. The objective is to evaluate their thermal and electrical behavior under real outdoor operating conditions and to assess the potential of passive heat pipe cooling as a practical solution for improving the long-term efficiency of PV installations.

B. Methods

The PV (photovoltaic) panels will be fixed to a metal frame made of square steel profiles witch cross-section of 300mm x 30 mm. The frame has height 1740 mm and a width of 1.0 mm. From the base of the frame to the level of the wheels, the vertical bars have a length of 240 mm, resulting in a total height of 1980 mm. Further details are shown in Figure 5.

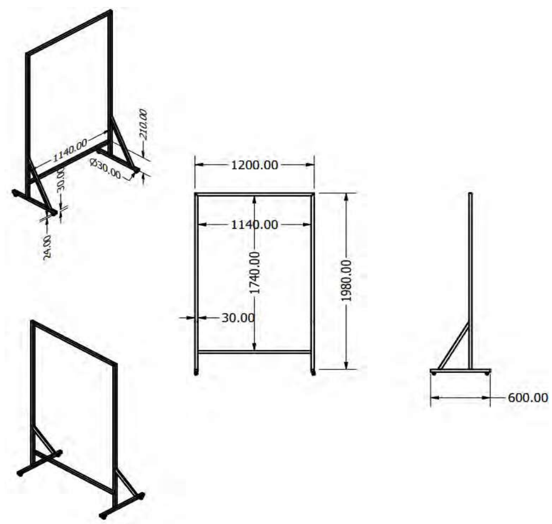

Figure 5. Metal frame of the PV panel

For ease of transportation, each frame is equipped with four wheels with a diameter of 30 mm. To improve the thermal efficiency of PV(photovoltaic) panels it was considered the use of heat pipes technology because these devices have high thermal properties and few disadvantages. For this purpose, two types of heat pipes were selected, both presenting favorable characteristics in terms of constructive parameters as well as heat transfer efficiency.

The heat pipes used for extracting heat from the surface of the photovoltaic panel are of two types: wide heat pipes with a rectangular cross-section, and narrow heat pipes with an oval cross-section and flat sides.The narrow heat pipes are manufactured by Advanced Thermal Solutions Inc., are made of copper, and use distilled water as the working fluid.

The heat pipe model ATS-HP-F8L300S21W is made of copper and uses distilled water as the working fluid. It has a width of 10.65 mm, a thickness of 4 mm, and a length of 300 mm ± 2.0%, operating within a temperature range of 30–120 °C. Its thermal performance varies with effective length, with a maximum heat transfer capacity (Q_{max}) of 25.7 W at 180 mm and a recommended Q_{max} of 20.6 W at 225 mm. The power of the heat pipe fluctuates depending on the distance between the evaporator and the condenser, with the relationship between distance and power expressed in equations (1) and (2).

$$Q_{max} = \frac{Q_t}{L_{eff}} \times 1000 \qquad (1)$$

$$L_{eff} = L - \frac{L_e + L_c}{2} \qquad (2)$$

Q_t = amount of thermal energy transferred per unit [W/m]
Q_{max}= maximum power of heat pipe [W]
L_{eff} = effective operating length [mm]
L – length of the heat pipe [mm]
L_e= evaporator length [mm]
L_c= condensator length [mm]

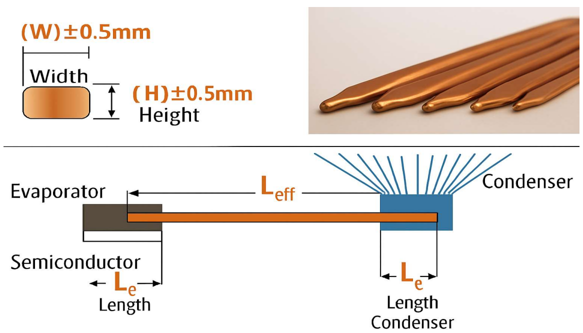

Figure 6. Constructive details of narrow heat pipes

The flat heat pipes are manufactured by AMEC THERMASOL, made of aluminum, and use acetone as the working fluid. These heat pipes were considered because, due to their constructive design, they have a larger contact surface with the photovoltaic panel.

The ATS-HP-F8L300S21W heat pipe is made from Aluminum 1070 and uses acetone as the working fluid. It has dimensions of 50 ± 0.5 mm width, 2.5 ± 0.5 mm thickness, and 250 ± 0.5 mm length, with a working temperature range from -40 °C to 100 °C. It supports heat transfer rates between 75 and 300 W, operates at angles between 0° and 90°, and has a thermal resistance of less than 0.2 °C/W.

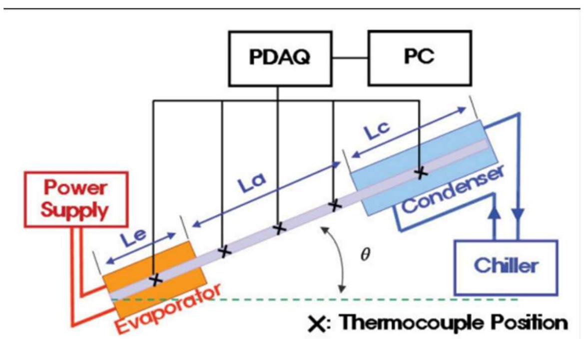

Figure 7. Constructive details of flat heat pipes

To improve the heat transfer from the photovoltaic panel to the heat pipes and to secure the pipes in place, two metal plates for enhancing thermal transfer were designed. Depending on the type of heat pipe used, the plate was constructed in two variants: one for wide pipes and the other for narrow pipes. The width and height of the plates match the dimensions of the panel, while their thickness is 10 mm.

The thermal transfer plates are made of aluminum because aluminum is a metal with a thermal conductivity of 237 W/(m·K) for pure aluminum or approximately 160 W/(m·K) for most alloys.

Design of a PV panel cooled with narrow heat pipes:

In this version of the photovoltaic panel cooling system, the dimensions of the photovoltaic panel and the narrow heat pipes were taken into account to design the thermal transfer plate in which the heat pipes will be integrated.

The thermal transfer plate is made from an aluminum sheet measuring 1620 mm in height, 960 mm in width, and 10 mm in thickness. At the upper part of the plate, a rectangle measuring 150 mm × 130 mm was cut out at a distance of 415 mm from the sides, corresponding to the location of the photovoltaic panel junction box.

On the surface of the plate, 63 (7 × 9) heat pipes are evenly spaced, with a vertical distance of 55 mm and a horizontal distance of 106 mm between them. Based on the heat pipe dimensions from the manufacturer's datasheet and by verifying the correspondence between technical data and reality, the narrow heat pipe was modeled with a 45° inclination and an evaporator length of 70 mm to maximize its efficiency.

For the placement of a heat pipe on the plate, it was necessary to design two rectangular-section holes. The first hole measures 70 mm in height, 14 mm in width, and 6 mm in depth, serving to hold the pipe in position, while the second hole measures 35 mm in height, 14 mm in width, and 10 mm in depth, allowing the heat pipe to pass through the plate.

Design of a PV panel cooled with flat heat pipes:

In the case of flat heat pipes, similarly to the plate for narrow heat pipes, the design started from an aluminum plate measuring 1620 mm in height, 960 mm in width, and 10 mm in thickness, with a rectangle of 150 mm × 130 mm cut out at the upper part. On the surface of the plate, 40 (5 × 8) heat pipes are arranged, with a vertical spacing of 80 mm and a horizontal spacing of 108 mm. Similar to the narrow heat pipes, a wide heat pipe bent at 45° was designed, with an evaporator length of 50 mm.

Considering the dimensions of the heat pipes, the mounting hole on the plate measures 60 mm in height, 52 mm in width, and 4 mm in depth, while the plate penetration is made through a section measuring 40 mm in height and 52 mm in width.

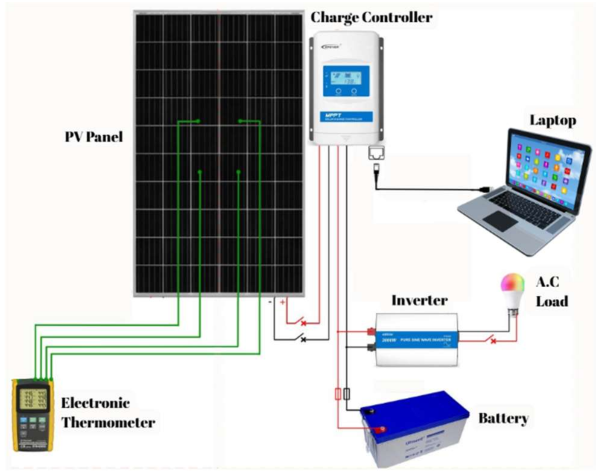

Figure 8. Operating principle of the experimental setup

In Figure 8 we have the operating principle of the experimental setup:

The EPSolar – EPEver XTRA2210N MPPT controller measure the parameters of the PV panel, directs the electrical energy to the inverter and to the storage battery. The device connects to a computer and transmits information about the PV panel parameters.

The off-grid pure sine wave inverter convert electrical energy from DC (direct current) into AC (alternating current).

The Lutron Electronic thermometer, model BTM-4208SD measures the temperatures of the photovoltaic panel at four distinct points using K-type thermocouples for surface temperature measurement.

C. Data presentation

In this subsection, we present the results obtained from the experiments. The experiments were carried out over six separate days, with two days assigned to each type of PV (photovoltaic) panel: the conventional panel, the panel with narrow heat pipes, and the one with flat heat pipes. To ensure the reliability of the findings, we compared only the time intervals during which the testing conditions were most similar.

The measurements transmitted by the controller were recorded every minute, obtaining clearer results regarding the power output, the same approach was applied to the PV panel temperature.

The analysis was conducted over the time interval between 9:00 and 10:00 a.m., during which the measured parameters-such as solar irradiance and ambient temperature-exhibited comparable values.

The general results obtained from the measurements are presented in Table I.

Table I

Technical specification of wide heat pipes

Parameters	***Conventional PV panel***	***PV panel cooled with narrow heat pipes***	***PV panel cooled with flat heat pipes***
Solar irradiance	794 W/m²	835 W/m²	848 W/m²
The ambient temperature measured	18.33°C	21.00°C	19.67°C
PV panel temperature	46.31°C	44.28°C	41.20°C
Power measured (W)	38.65 W	43.32 W	55.45 W

It should also be emphasized that the efficiency of a photovoltaic module is generally influenced by its operating temperature, since the output power decreases as the module temperature increases. In this regard, Figure 9 illustrates the average temperature variation (resulted from the 4 temperature sensors which were installed on the PV panel) of the tested modules as a function of their configuration (cooled or uncooled).

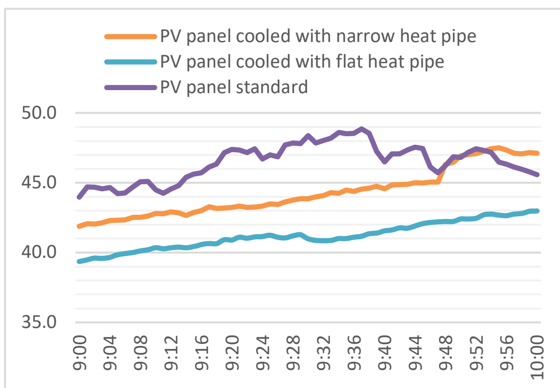

Figure 9. Average temperature variation of the PV panel

The temperature of the PV panels is between 39.5 °C and 48.85 °C. The highest value is for the standard PV panel, and the lowest one is for the PV panel cooled with flat heat pipes.

The initial power values corresponded to the average power measured during the 9:00–10:00 a.m. interval. For a more detailed analysis and to observe the fluctuations of the PV panel, Figure 10 presents the power measured every minute.

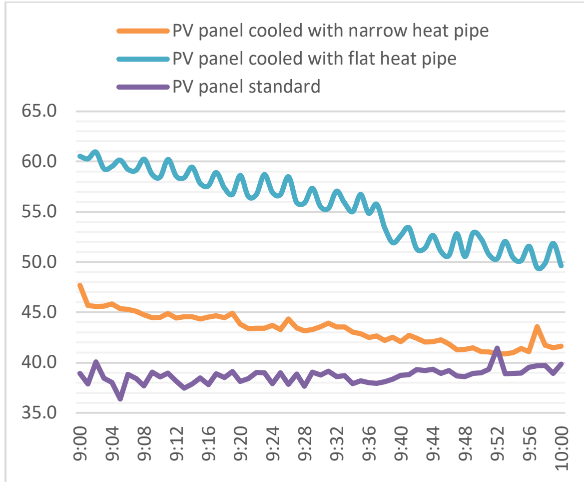

Figure 10. Average power variation of the PV panel

The power of the PV panels is between 36.38 W and 60.94 W. The highest value is for the PV panel cooled with flat heat pipes, and the lowest one is for the conventional PV panel.

D. Conclusions

This work shows that passive heat-pipe cooling can keep PV modules cooler and raise power in real outdoor use. In side-by-side morning tests, both cooled panels ran at lower temperatures than the standard panel, and the flat heat-pipe design performed best. These results support a simple idea: if we move heat away from the back of the cells more effectively, we recover electrical output without adding fans, pumps, or extra controls

Over the 09:00–10:00 window, the reference panel averaged 46.31 °C and 38.65 W, the narrow copper/water design reached 44.28 °C and 43.32 W, and the flat aluminum/acetone design reached 41.20 °C and 55.45 W. Even after accounting for small differences in sun (using power-per-irradiance), specific power improved by ~6–7% for the narrow pipes and ~34% for the flat pipes versus the reference, which points to real thermal gains rather than irradiance alone.

The flat heat-pipe layout proved to be the better solution, because is likely has better contact with the module rear and lower interface resistance, which spreads heat more evenly and reduces hot spots.

Although the results confirm that passive cooling solutions are effective, the study has some limitations. The analysis focused only on a one-hour testing window on selected days, which does not reflect the full daily or seasonal performance of the panels. In addition, the influence of wind speed was not considered. Future research should extend testing over full days and across different seasons, while also accounting for wind effects and other environmental variables, in order to provide a more complete picture of the long-term benefits and practical applications of passive heat-pipe cooling in PV systems.

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