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Thermal Management of Solar Photovoltaic Module to Enhance Output Performance: An Experimental Passive Cooling Approach Using Discontinuous Aluminium Heat Sink

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Abstract- The linear variation of photovoltaic cells with its temperature could affect the performance of the module and also damage the PV material. In order to address this important issue, this study proposed a passive cooling mechanism using designed aluminum sheets mounted at the rear side of the PV module. According to the results, the average temperature for the cooled panel during the entire experimental period was found to be 41.09 ℃, whereas that of the referenced panel recorded 51.08 ℃. This represent a temperature reduction of 10 ℃. The temperature reduction led to an improvement in the efficiency of the PV module by 4%. The average output power for the cooled module is 12.19 W, whiles that of the referenced module is 11.14 W. This translated into an improvement of 9.43% in the power output of the cooled module. The average exergy efficiency for the cooled module is 7.55% against 5.55% for the referenced module. The results also revealed that the cooled panel which incurred an additional investment cost due to the integration of the heat sink still recorded a relatively lower cost, i.e., 0.42 $/kWh, as against 0.45 $/kWh for the referenced panel. In effect, the proposed mechanism proved to be effective, it did not come with extra cost for the power generation, it rather reduced slightly the cost of energy for the power plant due to the high electricity it generated within the period.

Keywords: Thermal management, Solar photovoltaic module, Aluminum fins, Passive cooling, Efficiency enhancement.

1. Introduction

Data from the U.S. Energy Information Administration (EIA) show that primary energy demand globally is projected to increase by some 50% by close of 2040. This demand is expected to be met by 23% renewables and 77% fossil fuel [1–3]. It is however known that, increasing the use of fossil fuel as a source of energy generation will lead to environmental pollution and global warming due to increase in earth temperature [1,4–9]. It is therefore imperative to find more sustainable, clean, and cheap sources of energy generation to meet this projected demand [10,11].

Solar energy is one of the available and inexhaustible renewable energy resources for energy generation and is accessible in both direct and indirect forms. One of the best-known techniques for the direct conversion of solar energy into electrical energy is the photovoltaic (PV) technology [12,13]. The conventional PV technology converts a relatively small percentage of sunlight into direct current electricity, i.e. 10%-20%, and the remaining energy is transformed into heat [14,15]. According to a research by Reddy et al. [16] the temperature of a PV system can reach as high as 80 °C if installed in hot arid areas which can drastically reduce the efficiency of the PV module. The type of module such as thin film or crystalline silicon affects the variation in its conversion efficiency with temperature. In the case of crystalline silicon module, research shows that its conversion efficiency decreases by about 0.5% per every 1°C rise in the operating temperature of the module [17]. However, in the case of thin films, they have a relatively lower negative temperature coefficient as compared to the crystalline silicon. For that reason in the case of thin film technologies, the reduction in efficiency for each 1 °C rise in a module's temperature is as follows: PV modules made of cadmium telluride (CdTe) is 0.25%, amorphous silicon (a-Si) is 0.21% and copper indium gallium selenide (CIGS) is 0.32-0.36% [18]. For this reason, various researchers in the sector are interested in developing the required technique to control the temperature of the module under high temperature conditions which will consequently improve the performance of the PV cell. This may be in the form of a passive or active system of cooling the PV cell.

In existing literature, studies such as Bahaidarah et al. [19] experimentally and numerically investigated the effect of incorporating a heat exchanger at the back of a PV panel under Saudi Arabian weather conditions. According to their results, the temperature of the module reduced considerably due to the active water cooling by 20% which led to an increase of 9% in the efficiency of the PV panel. Schiro et al. [20] investigated the potential of integrating a cooling system to an existing PV unit without varying the original structure of the module. Abdolzadeh and Ameri [21] also assessed a cooling system related to photovoltaic pumping systems. The front section of the module is sprayed with pumped water which led to a significant drop in its temperature and increasing the electrical energy yield by approximately 17%. Elbreki et al. [22] proposed a passive cooling technique for PV systems using planner reflector and lapping fins. Their results showed that the PV system with 18 lapping fins and 27.7 mm fin pitch had an efficiency improvement of 11.2% compared to the bare PV with 9.81% at 1000 W/m^2. Agyekum et al. [23] employed a combination of aluminum fins and ultrasonic humidifier to manage a PV module's temperature. This led to a temperature reduction of 14.61 °C. The difference between the current study and their study is that their study incorporated an ultrasonic humidifier to generate water vapor to cool the aluminum fins.

Furthermore, Lucas et al. [24] also assessed experimentally the electrical and thermal performance of a PV module cooled with evaporative chimney. Their system recorded an 8 °C temperature reduction leading to an improvement in electrical efficiency in the range of 4.9-7.9%. Hachem et al. [25] evaluated the performance of pure and combined phase change material (PCM) for PV module cooling. Results from their study suggest that the combined PCM is the optimum option. The PV module's electrical efficiency increased by 3% averagely for the pure PCM whiles the combined PCM led to an average increase of 5.8%. Aelenei et al. [26] in 2014 studied both experimentally and theoretically the use of PCM in the cooling of PV modules. Their study indicated that the maximum electrical efficiency of the BIPV PCM can reach 10% whiles that of the thermal can be 12%.

Additionally, Marinić-Kragić, et al. [27] introduced slits on the surface of PV panel to aid passive cooling of the PV module. Results from their study suggest an average 3°C decrease in the temperature of the PV panel due to their modification. Gomaa et al. [28] proposed two different cooling techniques to enhance the performance of PV system. These techniques are the direct active cooling using water and the second technique is the use of fins to passively cool PV module. Their study found out a 55 °C, 38 °C and 58 °C for the fins, water, and non-cooling module, respectively. Hernandez-Perez et al. [29] studied the thermal performance PV passive cooling mechanism using a discontinuous finned heatsink. The numerical simulation results suggest a temperature reduction of up to 7 °C for their proposed heatsink. The experimental results also recorded a 5 °C drop in the temperature of the PV. Sajjad et al. [30] also proposed a cost effective approach to cool PV modules. They used the duct of a cooled air from an air-conditioner to cool a PV module. According to their results, the cooled module recorded a performance ratio and electrical efficiency of 6% and 7.2%, respectively. Alami et al. [31] studied the effect the evaporative cooling mechanism for the management of a PV module's temperature. They integrated a layer of synthetic clay to the rear surface of a PV panel whiles allowing the evaporation of a thin film of water. Their results suggest that the proposed approach is effective since it led to a maximum increase of 19.4% and 19.1% for the output voltage and output power, respectively. In other studies, Choubineh et al. [32] employed phase change material (PCM) to cool a PV module. The results from their study indicate that the use of a PCM sheet of 6 mm thickness has the potential to reduce the temperature of the panel to 4.3, 3.6, 3.4 and 3.7 °C averagely in a natural air flow mode, medium, forced high-velocity and low velocity, respectively. Agyekum et al. [33] used a dual surface mechanism to cool a PV module. Their cooling approach led to a temperature reduction of 23.55℃.

Based on the literature reviewed supra, it is clear that the cooling of PV to enhance their output is an important area of study especially due to the increasing use of PV systems for energy generation globally. However, in our attempt to develop appropriate mechanisms to cool the modules, it is also important to consider availability of the material as well as the technical and the cost effectiveness of the proposed approach. In most cases, researchers resort to the use of water for the cooling of PV modules, however, water although cheap might not be easily available for use at all sites. For instance some countries in North Africa and Middle East are confronted with water scarcity basically due to climate change, impact of conflicts and economic downturn [34]. This suggest that if human's are unable to meet their water needs due to scarcity of water in those areas, then it safe to suggest that solar PV modules will not have some either for its cooling. Interestingly those are the areas with the high potential for solar energy development due to the high availability of solar radiation throughout the year. High temperatures are also recorded in those areas, which is a concern to the development of the PV technology. It is for this reason that other studies proposed other forms of cooling technologies than the use of water.

In this study, we propose the use of perforated discontinuous aluminum fins with "brush-like" endings to cool the PV system. This study is an improvement of the study by [35] who used similar approach but without perforation and brush-like fins, this approach is a modification of that study. Our approach is expected to be more effective for the cooling process of PV panels due to the modifications made on the heat sink. The key contribution of the current study is to provide a passive approach in cooling PV systems which can easily be integrated into the manufacturing of PV panels at the level of production.

The rest of the paper is presented as follows: the materials and methodology used for the study are presented in section 2, the results and discussions are presented in section 3, and section 4 covers the conclusion and discussions.

2. Materials and methodology

The objective of this study is to use passive mechanism for thermal management of a PV module, this was done experimentally using an aluminum sheet carefully designed to aid in the quick dissipation of heat at the edges of the fins. The reason why aluminum was selected over other possible metals is discussed in section 2.1. The other sections will present the experimental procedure used for the analysis..

2.1. Characteristics of aluminum

Aluminum is durable, corrosion-resistant, lightweight, high in thermal conductivity and malleable metal found naturally on earth. Aluminum's thermal conductivity is approximately 50 to 60 percent that of copper. Its high thermal conductivity is approximately 62 percent of the International Annealed Copper Standard (IACS) which renders it good for use, it also has approximately a third of copper's specific gravity [36]. Aside the characteristics of aluminum listed earlier in this section, it is a material that is also easily available and relatively cheaper than other such materials with high level of heat conduction that is required for this kind of studies.

2.2. Mathematical modelling for solar cell

The fall of solar radiation on solar cell generates voltage (V) and current (I). About 47 percent of solar radiation (i.e., visible light 400 nm – 800 nm) on a PV module is converted into electricity whiles the rest is converted into heat which negatively affect the characteristics of the PV module. The open circuit voltage V_{OC} and the short circuit current I_{SC} are the maximum voltage and current, respectively, that is obtainable from the PV module that defines its theoretical maximum power [37]. The solar PV panel's current can be evaluated by assessing the equivalent circuit of the solar cell. A solar cell under illumination has an I-V equation as presented in Eq. (1) [38]:

$$I_{total} = I_0\left(e^{\frac{qv}{nKT}} - 1\right) - I_L \tag{1}$$

Where, $I_L = qAG(L_n + L_p + W)$, represent the light generated current that shows that the carriers produced inside the volume of cross-sectional area A as well as the length $(L_n + L_p + W)$.

Parameters such as fill factor (FF), V_{OC}, I_{SC} and efficiency (η) are used to compare solar cells. The V_{OC} depends on the PV panel's temperature, this can be seen from Eq. (2) [39].

$$V_{OC} = V_{OC}(T_0) - \left[\frac{E_{g0}}{e} - V_{OC}(T_0)\right]\left[\frac{T}{T_o} - 1\right] - \frac{3kT}{e} In\frac{T}{T_o} \tag{2}$$

When the temperature increases by 40 K and T_o = 300 K, then T = 340 K becomes the PV panel's temperature. The Boltzmann constant is k, E_{g0} is the band-gap energy. These can be ignored: $\frac{T}{T_o}$ = 0.125 and $\frac{3kT}{e} In\frac{T}{T_o}$ = 10 mV. V_{OC} varies with temperature as presented in Eq. (3).

$$\frac{dV_{OC}}{dT} = -\frac{\left[\frac{E_{g0}}{e} - V_{OC}(T_0)\right]}{T_O} - \frac{3kT}{e} \tag{3}$$

Where E_{g0} = 1.21 eV and T = 300 K and V_{OC} = 0.55 V, which is a characteristic of a silicon solar cell, it reduce in V_{OC} with a rise in T of $\frac{dV_{OC}}{dT}$ = -2.45 mVK^{-1} at 25 °C [40].

2.2.1. *Efficiency and power and temperature of solar PV system*

Increase in I_{SC} with increasing temperature is rather small whiles the V_{OC} and the FF reduce significantly. The efficiency of the PV can be expressed as a ratio of the energy output to the energy input as presented in Eq. (4) [22,41].

$$\eta = \frac{E_{out}}{E_{in}} \tag{4}$$

Similarly, the efficiency of the module can be found using Eq. (5).

$$\eta = \frac{P_m}{G * A} \tag{5}$$

The solar irradiance is denoted by G, the maximum power is also denoted with P_m and the area of the PV module is represented with A.

The net effect between the slight increase in the I_{SC} and the significant reduction in the FF and the V_{OC} results in a linear relationship which is in the form of Eq. (6) [33,42].

$$\eta_c = \eta_{ref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right) + \gamma log_{10} G_T\right] \tag{6}$$

The efficiency of the module under reference temperature T_{ref} is denoted by η_{ref} at a solar radiation flux of 1000 W/m^2. β_{ref} denotes the temperature coefficient, γ denotes the solar coefficient, the two coefficients are usually 0.004 K^{-1} and 0.12, respectively [43]. The solar coefficient is usually taken as zero and as a result Eq. (6) becomes Eq. (7), this is the conventional linear equation for the electrical efficiency of the PV module.

$$\eta_c = \eta_{ref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right] \tag{7}$$

The improvement in the efficiency of each PV panel i.e., cooled and the referenced panels can be computed using Eq. (8).

$$improvement = \frac{\eta_{cooled\ pv} - \eta_{ref\ pv}}{\eta_{ref\ pv}} \times 100\% \tag{8}$$

2.2.2. *Exergy efficiency analysis*

Exergy is the maximum amount of useful work that a system can produce as it comes to equilibrium with a reference environment. It is not subject to the law of conservation (with the exception of ideal, or reversible, processes). Unlike energy, exergy is destroyed or consumed because of irreversibility in real process [44]. A PV module's overall exergy balance can be represented by Eq. (9a) and (9b) [45].

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{9a}$$

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} + \sum \dot{E}_{loss} + \sum \dot{E}_{irreversibility} \tag{9b}$$

The exergy efficiency for a PV system can be expressed mathematically as indicated in Eq. (10) [46].

$$\psi_{system} = \frac{Ex_{out}}{Ex_{in}} \tag{10}$$

Where the PV module's input exergy takes into the solar radiation intensity exergy as expressed in Eq. (11) [46,47].

$$\dot{Ex}_{in} = \left(1 - \frac{T_a}{T_s}\right) I_s A \tag{11}$$

The output exergy can also be computed with the help of Eq. (12) [46].

$$\dot{Ex}_{out} = V_m I_m - \left(1 - \frac{T_a}{T_{cell}}\right) h_c A (T_{cell} - T_a) \tag{12}$$

The PV module's exergy efficiency can therefore be calculated using Eq. (13) [48].

$$\psi_{system} = \frac{V_m I_m - \left[\left(1 - \frac{T_a}{T_{cell}}\right) \cdot \left(h_c A \cdot (T_{cell} - T_a)\right)\right]}{\left(1 - \frac{T_a}{T_s}\right) \cdot I_s \cdot A} \tag{13}$$

Where the maximum power voltage and current of the system are represented by V_m and I_m, respectively. The ambient temperature is symbolized with T_a (K), the module surface temperature is denoted T_{cell} (K), T_s signify the sun surface temperature assumed to be 5762 K. The global solar radiation (W/m^2), and the module area is denoted by A (m^2), the area of the module used in this study is 0.4275 m^2. The convective heat transfer is denoted by h_c, it depends on the velocity of wind v and can be calculated using Eq. (14) [49].

$$h_c = 5.7 + 3.8v \tag{14}$$

2.3. *Experimental setup*

The passive mechanism that is used in the cooling of PVs are normally done by attaching a heat sink at the rear side of the PV panel. In the case of this experiment, the PV module and heat sink is cooled by air. This mechanism of cooling PVs comes with a number of advantages such as the non-use of water which would have come as an extra cost and also the mechanism is relatively simple to construct.

The aluminum sheet was cut into several pieces and holes were then created into them to enable the flow of air through them. The edges of the various sheets were also cut into small fins, this was strategically done to reduce the surface area at the edge of the sheet to enable quick dissipation of heat, this and the perforated holes are missing in [35]. These sheets were then placed at the rear side of the panel as shown in **Fig. 1a**, the referenced panel which is uncooled or unmodified is presented in **Fig. 1b**. In order to get effective contact as well as conduction of heat from the panel to the aluminum sheets, a thermal grease (HY 710) was applied in between the panel and the point of contact with the sheets. Also, in order to get the sheets firmly on the back of the panel, a universal silicone gel was used applied to each of them. The pieces of aluminum fins were positioned in no specific other but were positioned such that greater section of the PV string were covered or attached with a string.

In total, seven K-type thermocouples were used to record the temperature at different sections of the two panels, the thermocouples have a temperature range of -200 ℃ - 1370 ℃. Its temperature resolution is 0.1 ℃ with an accuracy of ±0.3%. The solar pyranometer (Tenmars TM-207) was used to record the solar radiation on the day of the experiment. A channel K-type thermometer SD logger 88598 was used to record the temperatures of the various thermocouples. It has a typical accuracy of ±10 W/m^2 [±3 BTU/ft^{2}h] or ±5% and an additional ±0.38 W/m^2/°C. The GM 1362-EN-01 thermometer with temperature range from -30℃ - 70 ℃ was used to take the readings of both the humidity and the ambient temperature for the day, it has an accuracy of ±2%. The experimental test rig is as presented in **Fig. 2.** The clamp meter used to record the voltage and current of the two panels has uncertainty that range from ±1.5 – 2.0%. The anemometer has an accuracy of 0.2 % with a range of 0–25 m/s. The PV panel used for the experiment has a dimension of 95 × 45 cm and is a 30 W polycrystalline module with referenced efficiency of 15%. An infra-red thermal imager camera was also used to analyze the temperature distribution of the two panels.

2.4. Uncertainty analysis

Analyzing the uncertainties in an experimental data is key because it give confidence in the results obtained in the experimental process. The accuracy of the various equipment used for the recording of experimental data during the experimental process are all presented supra. The uncertainties in the obtained data were evaluated using Eq. (15)-(17) [50].

$$standard\ deviation\ (SD) = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}} \quad (15)$$

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_N}{N} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad (16)$$

$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N(N-1)}} = \frac{SD}{\sqrt{N}} \quad (17)$$

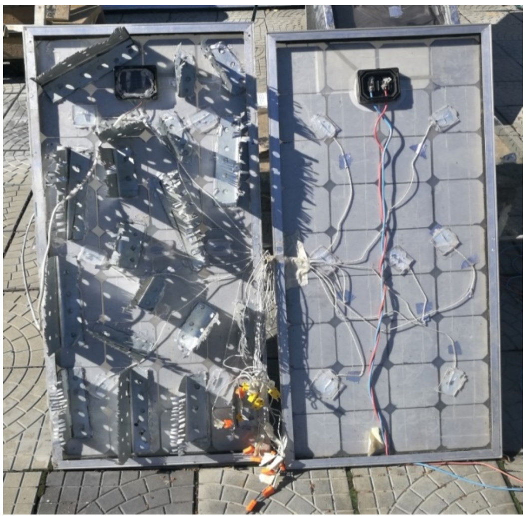
Where the number of measurements is denoted by N, the uncertainty or standard error is denoted by σ_m and the observations are denoted by x_i.

3. Results and Discussions

The obtained experimental results are presented in this section. The section consist of the weather characteristic, thermal management, and the electrical improvement due to the integration of the proposed cooling mechanism.

3.1. Weather characteristics

This experiment was conducted at the Ural Federal University in Russia in the month of July 2021 which is the peak of the summer period. The weather characteristics on the day of the experiment is as presented in Fig. 3. The average solar radiation for the day was recorded as 976.35 W/m^2 with an average ambient temperature of 33.78 °C. The highest solar radiation intensity of 1345 W/m^2 was recorded at 12:30pm. The average humidity for the day is 43.75%. The air relative humidity during summer periods usually decreases with the day's hours, this is mainly due to the increase in ambient temperature in the course of day. This is manifested in the results recorded as the humidity decreases with increasing hours and temperature. The average wind speed recorded is 5.29 m/s.



(a) (b)

Fig. 1 Photograph of the back of the two panels – cooled with aluminum fins (a) and referenced panel (b)

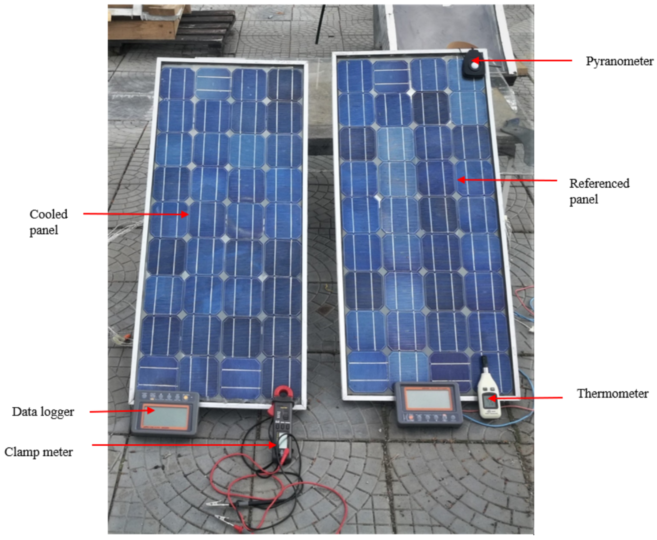


Fig. 2 Experimental test rig - cooled or modified panel (left) referenced panel (right)

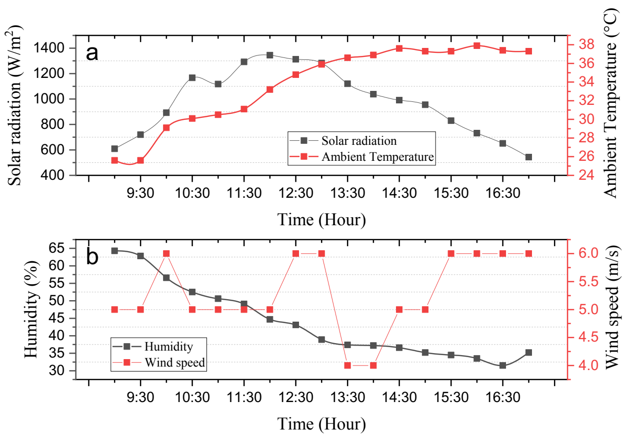


Fig. 3 Weather characteristics on the day of experiment

3.2. Thermal management of the PV system due to cooling

The K-type thermocouples were used to take the temperature of the panel at seven different locations of the panel at each reading time, i.e., every 30 minutes from 9:00 am to 17:00 pm. The temperatures for the cooled and referenced panels are presented in **Fig. 4.** The average temperature for the cooled panel during the entire experimental period is 41.09 °C, whereas that of the referenced panel was 51.08 °C. The difference between the cooled and reference is 9.99 °C. The highest temperature for the cooled panel was 52.53°C and this occurred at 2:30 pm whiles during that same period the referenced module recorded a temperature of 63.60 °C. This indicates that the proposed cooling method used in this study was effective when it was needed most. In order studies, Arifin et al. [51] conducted both numerical and experimental study on a proposed aluminum heat sink for the cooling of PV panels. According to their study, the heat sink was able to contribute to a reduction in the PV module's temperature from 85.3° C to 72.8° C, which is a 12.5 °C reduction. Hasan [52] also obtained a difference of 5.7 °C between a cooled and uncooled panel using fins as heat sink. Mojumder et al. [53] obtained a temperature reduction of 3–8 °C using fins as cooling mechanism for PV system. It can therefore be said that the proposed heat sink in the current study has proven to be effective and the results obtained relative to its ability to reduce temperatures is relatively higher than most studies conducted using similar approach.

3.3. Thermal management of the PV system due to cooling

The testo infrared thermal imager was also used to assess the temperature distribution of the two panels at mid-day, i.e., 12:00 pm. The results from that exercise is presented in **Fig. 5 and Fig. 6**. The cooled panel recorded an average temperature of 37.2 °C with maximum temperature of 40.5 °C, whiles in the case of the referenced panel, the average temperature is 40.8 °C with maximum temperature of 54.6 °C. There are slight differences in terms of the average values of the thermal imager and that recorded using the thermocouples. The difference can be due to the fact that the thermocouples are closer to the panel than the thermal imager and as a result has the potential to give a relatively accurate results, hence the variations.

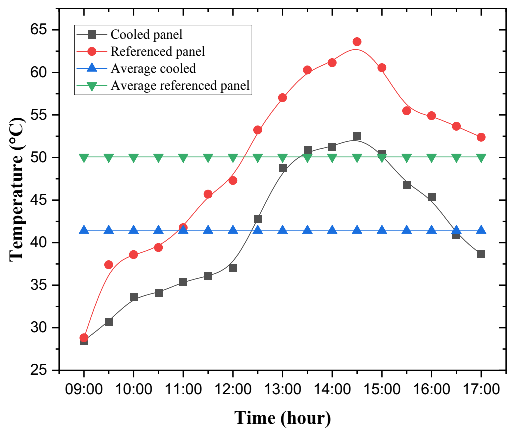


Fig. 4. Temperature characteristics of the two panels

3.4. Electrical efficiency and power characteristics of the two panels

In the case of the current, the difference between the referenced panel and that of the cooled panel was relatively insignificant as shown in **Fig. 7a.** The two modules recorded almost the same current, the average current difference between the modules is 0.005 A. The average current for the cooled panel is 0.646 A as against 0.641 A for the referenced module.

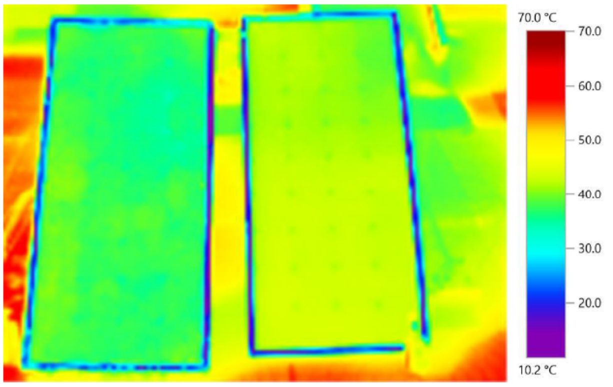
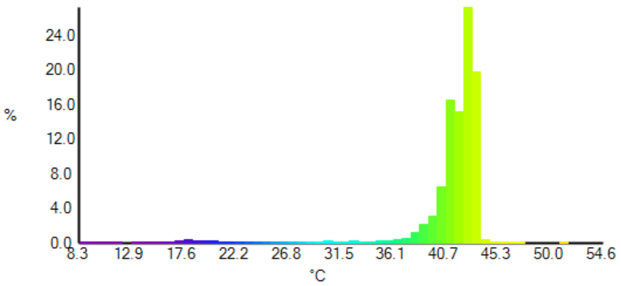
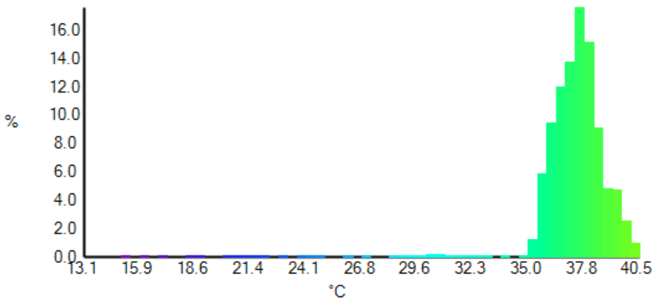


Fig. 5 Thermal image of the two panels - cooled (left) referenced (right)



(a)



(b)

Fig. 6 Thermal profile for: (a) referenced (b) cooled

The effect of temperature on the voltage of the PV module is clearly demonstrated in **Fig. 7b.** As stated earlier, temperature has a significant effect on the voltage of PV modules, in this case, the average voltage of the cooled panel is 18.85 V whiles the referenced panel recorded 17.39 V. It can be said that the modification of the panel which led to the cooling of same resulted in a 1.46 V increment in its voltage compared to the referent panel. The difference in voltage between the referenced and cooled panels at the start of the experiment when humidity was high and the temperature relatively colder was not much. However, as the temperature rose and the humidity fell, the referenced panel's voltage dropped quiet significantly. The reduction in the voltage of the referenced panel is as a result of the high temperatures it recorded during the entire experimental period. The comparison for the output power from the two PV panels is shown in **Fig. 8**. The highest power of 13.24 W and 12.08 W for the cooled and referenced modules, respectively, were both recorded at 12:30 pm. The effect of the cooling mechanism proposed in this study can be seen throughout the experimental period, this is because the output power for the cooled at any time during the experiment was higher than the referenced module. The average output power for the cooled module is 12.19 W, whiles that of the referenced module is 11.14 W. This translates to an improvement of 9.43% in the power output of the cooled module. This level of improvement is expected in this kind of cooling system since there is no form of water but only depend on the ambient wind speed and temperature for its cooling purposes.

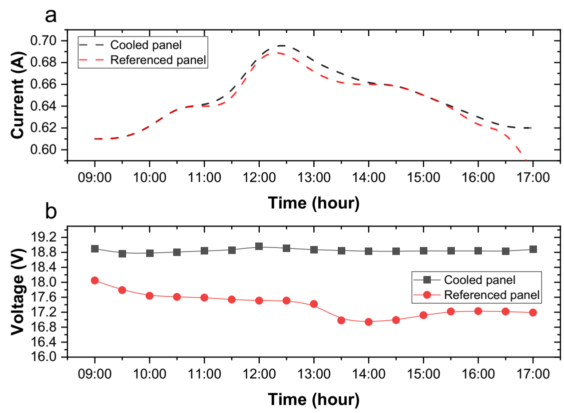


Fig. 7 (a) Current and (b) voltage variations for the two panels

The efficiency of the two modules over the entire study period is illustrated in **Fig. 9a.** These were obtained by using Eq. (7) and a referenced or manufacture efficiency of 15% for the panel. The results obtained shows that the cooled panel recorded an average efficiency of 14% as against 13% for the referenced module. The improvement in the efficiency of the panel is presented in **Fig. 9b.** The average improvement in the efficiency was obtained using Eq. (8), and it was identified to be 4.0%. The obtained values for both the power and improvement in efficiency are all consistent with some studies that adopted similar approach to cool PV modules and in some cases better. For instance, Hasan and Farhan [54] obtained an average improvement in the power output of 4.9% and a temperature reduction of 8.4% using copper metal foam fins. Kim et al. [55] had an improvement of 1.44% in the efficiency of the panel using aluminum mesh. Similarly, Hernandez-Perez et al. [56] proposed a new passive PV heatsink design that according to them would minimize efficiency losses. They obtained an electrical efficiency improvement of 4% using their mechanism. . Finally, AlAmri et al. [57] found out that the power of a solar PV module can increase by 8.7% and 6.5% in summer and winter, respectively, using optimized heat sinks. In effect the results obtained from the proposed heat sink in this study served its purpose and improved upon both the efficiency and power output of the panel.

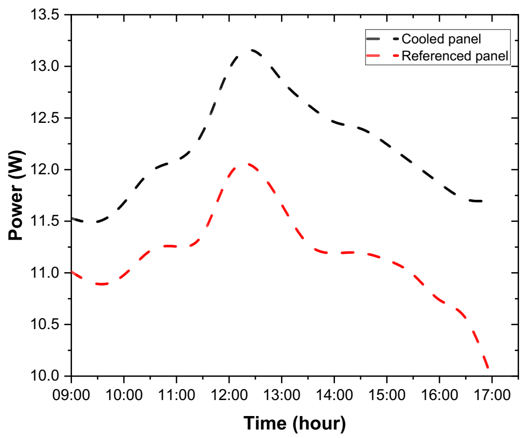


Fig. 8 Power variation for the two modules

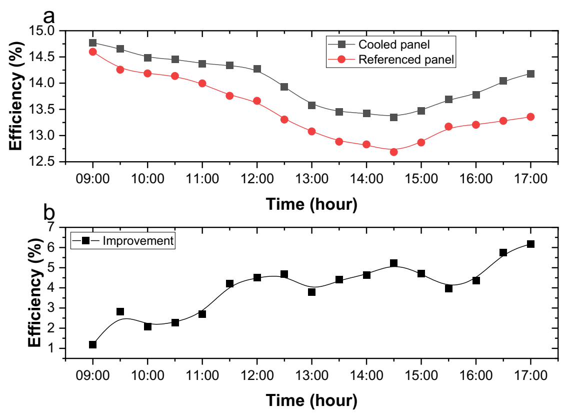


Fig. 9 Efficiency variations and improvement for the panels

The exergy efficiencies for both panels are presented in **Fig. 10**. As can be seen from the figure, the level of solar radiation plays a key role on the exergy efficiency, the higher the solar radiation the lower the exergy efficiency. A PV module's exergy efficiency generally shows the quality index of the energy, and this is dependent on the thermodynamic principles. This accounted for the continuous reduction in the exergy and thermal efficiencies for both panels up until when the intensity of the solar radiation started reducing. The average exergy efficiency for the cooled and referenced panels are 7.55% and 5.56%, respectively. The relatively low exergy efficiency recorded by the referenced module is as a result of the high cell temperatures it recorded during the day. It also indicate the positive effect the fins had on the panel. In general, the highest exergy efficiency of 13.6% for the cooled PV module was recorded at 5:00 pm, whiles that of the referenced module which is 11.6% was recorded in the morning at 9:00 am.

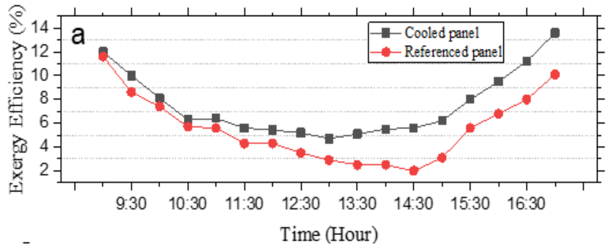


Fig. 10 (a) Exergy efficiency (b) thermal efficiency for both panels

Results from other studies that proposed other forms of mechanisms for the cooling of PV modules are presented in **Table 1**. It can be observed from the other literatures reviewed that apart from those whose mechanism make use of water for the cooling of the PV panels, results from this study performed better relative to the level of temperature reduction for the cooled panel. For instance, the temperature reduction for [58] is 6 °C, [59] recorded a reduction of 6.1 °C, and [60] also recorded a reduction of 6.1 °C. The current study however recorded a temperature reduction of 10 °C which is higher than the reviewed literature presented supra. The improvement in the temperature reduction in this paper can be attributed to the brush-like nature of the fins which helps to speed up the dissipation of the heat along edges of the fins, this technic is missing in those studies.

3.5. Economic analysis

The economics for the two studied panels, i.e., cooled and referenced panel has been carried out using the levelized cost of energy (LCOE) approach. The LCOE is accepted as the primary metric for accessing the cost of energy generated by renewable energy power plants. The LCOE is taken as the constant price for each unit of energy (kWh) which causes an investment to have a present value of zero or just break even. İn other words, it is price at which the generated power or energy must be sold in order to break even over the technology's life time peroid. İt is expressd mathematically as [61]:

$$LCOE = \frac{LC_{inv} + LC_{O\&M} + LC_{fuel}}{E_{annual}} \quad (18)$$

Table 1. Comparison of other studies using other cooling mechanisms with results of current study

No	Ref	Mechanism used	Panel temperature		Electrical Efficiency	
			Average panel temperature without cooling	Average panel temperature with cooling	Electrical efficiency of the panel without cooling	Electrical efficiency of the panel with cooling
1	[22]	Lapping fins and planner reflector	64.3 °C	39.73 °C	9.81%	11.2%
2	[58]	Rectangular fins	64 °C	58 °C	-	14.5%
3	[62]	Mounting aluminum fins at the back surface	71.0 °C	63.5 °C	11.09 %	13.43 %
4	[59]	Aluminum fins	56 °C	49.9 °C	15.9%	17.7%
5	[55]	Fins on PV using CFD simulation	62.78 °C	47.65 °C	13.24%	14.39%
6	[60]	PCM heat sinks	57.9 °C	51.8 °C	9.33%	9.82%
7	[63]	Capillary action burlap cloth	66.4 °C	49.3 °C	9%	14.75%
8	[64]	Water spray cooling technique	56 °C	24.1 °C	13.92%	15.92%
9	[65]	Cotton wick structures is developed for standalone flat PV modules	65 °C	45 °C	9%	10.4%
10	[66]	Spraying cooling system	61 °C	49 °C	11.8%	13.27%

Table 2. Economics parameters used for the analysis

Parameter	Cooled PV	Referenced PV
Levelized cost of fuel ($\boldsymbol{LC_{fuel}}$), \$/kWh	0	0
Investment cost ($\boldsymbol{C_{inv}}$), \$	62.88	60.00
Annual operation and maintenance cost ($\boldsymbol{C_{O\&M}}$), \$	3.00	3.00
Lifetime of the plant (n), years	30.00	30.00
Effective discount rate ($\boldsymbol{i_{eff}}$), % **[61]**	5.00	5.00
Nominal escalation rate ($\boldsymbol{r_n}$), % **[61]**	1.00	1.00
$\boldsymbol{K_{O\&M}}$	0.96	0.96
Capital recover factor (CRF), (%)	6.50	6.50
Constant-escalation levelization factor O&M, (CELF)	1.10	1.10

$$LC_{inv} = CRF \times C_{inv} \quad (19)$$

$$CRF = \frac{i_{eff} \cdot (1 + i_{eff})^n}{\left((1 + i_{eff})^n\right) - 1} \quad (20)$$

$$LC_{O\&M} = C_{O\&M} \times CELF \quad (21)$$

$$CELF = \left(K_{O\&M} \times \frac{1 - K_{O\&M}^{n}}{1 - K_{O\&M}} \right) CRF \quad (22)$$

$$K_{O\&M} = \frac{1 + r_n}{1 + i_{eff}} \quad (23)$$

Where the capital recovery factor (%) is represented by CRF, the investment cost is denoted with C_{inv}, $C_{O\&M}$ is the annual cost of operations and maintenance, n is the plant's lifetime, $CELF$ is the constant-escalation levelization factor, i_{eff} is the effective discount rate and r_n is the nominal escalation rate (%).

With the poor weather conditions in Russia particularly during the months of September to April each year, we assume that the panel would work effectively only in the summer period. Therefore, for the purposes of economic analysis the months of May, June, July, and August were considered as effective months for PV module operation for the entire year. As a result, it is assumed that the PV plant worked for 120 days per year. The energy that is generated by both panels per year can therefore be projected to be 17.554 kWh and 16.042 kWh for the cooled panel and referenced panel per year, respectively. By using data provided in Table 2, the LCOE is calculated for the various panels. The cost of the aluminum sheet is 640 rubles equivalent to \$8.64, however, only one-third of the aluminum sheet was used which translates to \$ 2.88 this adds to the investment cost of the cooled panel. An assumed cost of \$50 and other installation cost of \$10 were used as the cost of investment for the 30 W PV panel. The cost of fuel in Eq. (18) is taken as zero since the panel required no fuel to operate.

The results shows that the cooled panel which incurred an additional investment cost due to the integration of the heat sink still recorded a relatively lower cost, i.e., 0.42 \$/kWh, as against 0.45 \$/kWh for the referenced panel. It is important to note that, the LCOE is hugely affected by the level of solar radiation at a locality. The LCOE recorded in this study seems to be higher due to the low insolation recorded on the day of the experiment, which had an impact on the output power of the two panels.

4. Conclusion

The current study presents an experimental work on a passive cooling approach for a solar PV module using simple aluminum sheets designed to help to dissipate the heat at the rear side of the panel using natural wind.. The edges of the pieces of aluminum sheet attached at the real side of the panel which serve as heat sink were designed to be brush-like with perforated holes on the surface. These were done to minimize the surface area for heat conduction and enhance its fast dissipation. The following conclusions were arrived at:

- The average temperature for the cooled panel during the entire experimental period is 41.1 °C whereas that of the referenced panel was 51.1 °C. This represent a temperature reduction of 10 °C.
- The temperature reduction led to an improvement in the efficiency of the PV module by 4%. The average output power for the cooled module is 12.19 W, whiles that of the referenced module is 11.14 W. This translate to an improvement of 9.43% in the power output of the cooled module.
- The average exergy efficiency for the cooled module is 7.55% against 5.55% for the referenced module.
- The results shows that the cooled panel which incurred an additional investment cost due to the integration of the heat sink still recorded a relatively lower cost, i.e., 0.42 \$/kWh, as against 0.45 \$/kWh for the referenced panel.

In effect, it can be concluded that the proposed cooling approach has demonstrated to be effective, as the improvement in the power output in this study is among the highest in previous studies that used similar cooling approach. This kind of cooling comes with some advantages, i.e., it has low investment cost, zero water consumption, noiseless and simple to construct. It however comes with a relatively less temperature reduction. This study did not take into consideration the effect of the thickness of the aluminum sheet on the heat dissipation process, it is therefore recommended to assess the effect of the aluminum thickness on the effectiveness of this cooling approach. This is because the thickness of the aluminum may have an effect on the efficiency of the cooling process.

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