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Heat Response Model for Phase Layered Topology in a Photovoltaic Thermal System

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Abstract

The electrical and thermal energy generated by a Photo-voltaic (PV) module is based on the amount of the solar radiation directed on the PV module. In this study, a Photo-voltaic Thermal (PVT) system is constructed to maximize the electrical energy generation through the fast removal of heat through a new phase layered topology. The combinations of aluminum plate and heatsinks are used to transfer heat generated by sunlight radiation on PV modules to heat transfer thermal container. The aluminum plate is attached beneath the PV module and heatsinks welded beneath the alumni plate making it as a phase layered heat removal. The heat transfer on each layer of the photovoltaic thermal system is investigated with the phase changing topology and also investigated for its performance with a heat removal agent. In both cases, with and without water as coolant in the thermal container, the experimental outcome is analysed for performance analysis. It is found the PV temperature reduced by about 10 degrees which is cirtical for the PV performance reducing the wasted thermal energy and thereby increases the electrical energy conversion.

Keywords: *heat transfer, phase layered topology, photovoltaic thermal, heat response model*

1. Introduction

Solar energy is one of the most sustainable and renewable sources of energy. It is well recognized that solar energy availability is significantly more than the global energy demand [1]. The available technology has limited capabilities of harnessing this boundless and free energy. The solar radiation generates electrical energy on the PV elevate the temperature of the PV module significantly and hence resulted in a drop in PV output efficiency. This considerable generated thermal energy is wasted as heat reducing the electrical efficiency conversion. The proposed photovoltaic thermal collector design system harness both electrical and thermal energy simultaneously from a single solar collector shown in Figure 1.

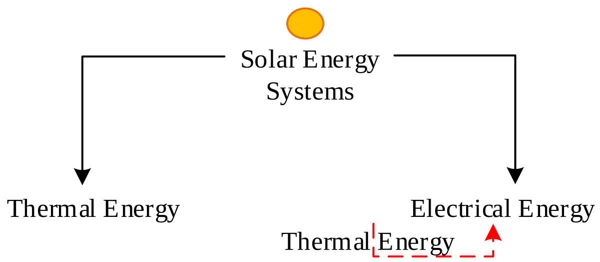

Figure 1. Effects of selecting different switching under dynamic condition

In the past, many different types of topology are proposedto increase the efficiency of a PVT system. The PV module cell temperature is a function of physical properties of the PV cell material, the module and its configuration, the prevailing weather conditions and the surrounding

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environment [2]. The performance dependent on environmental conditions and the output varies with the temperature change of the PV cell. The effect of the temperature on the PV cell are as follow:

1. The increase in PV module temperature decreases the output voltage of the PV cell
2. The rising cell temperature causes the declining in the open circuit voltage due to increase in reverse saturation current
3. The increase in the PV module temperature reduces peak power output

Therefore, it is important to know the temperature of a solar PV panel to predict its power output and its efficiency. The temperature dependence of a PV material is described with a temperature coefficient [3]. For polycrystalline PV panels, if the temperature decreases by one degree Celsius, the voltage increases by 0.12 V so the temperature coefficient is 0.12 V/C [4]. The open circuit voltage of PV module at a given temperature is shown in the Equation (1).

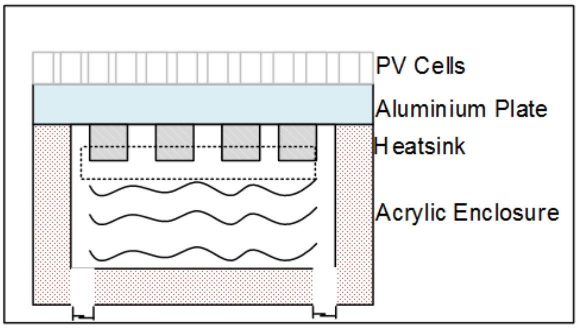
$$V_{OC,mod} = T\alpha * (T_{STC} - T_{ambient}) + V_{OC,rated} \quad (1)$$

Where $V_{OC,mod}$ is open circuit voltage at module temperature, $T\alpha$ is temperature coefficient, T_{STC} is the temperature at Standard Test Conditions (STC), 25 °C and $V_{oc,\ rated}$ is open circuit voltage at STC. The production of electricity is the main priority, therefore it is necessary to operate the PV module at low temperature in order to keep PV module cell electrical effciency at a suffcient level. The generated heat on the Photovoltaic caused by the solar radiation decreases the power output of the PV consequently in a certain range. The increase in cell's temperature causes a linear decrease in the open circuit voltage leading to decrease in cell efficiency [5]. Understanding how the solar panels react to these different conditions is essential for engineers to develop a solution accordingly [6, 7].

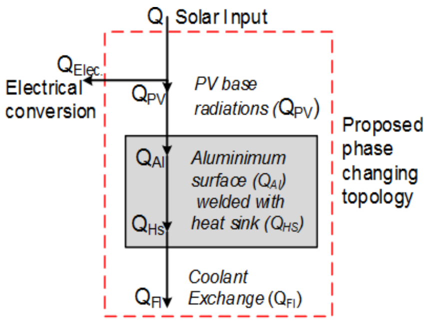
2. Phase Layered Topology

2.1. Systems Configurations and Topology

The designed system consisted amorphous panel PV, aluminum plate, heatsinks and thermal container. The aluminum plate is attached beneath the PV module via thermal glue to absorb a good portion of the thermal energy from the PV module. The heatsinks are point welded on the bottom layer of the aluminum plate to further remove the heat from the aluminum plate. The thermal container is made of acrylic to hold coolant. The assembled unit is placed inside a thermal container, which the unit perfectly sat on the top of the thermal container. The heatsinks also fit inside the container which is immersed in the coolant. Each layer of the PVT system is shown in Figure 2.



(a) Phase layered system setup



(b) Phase changing topology

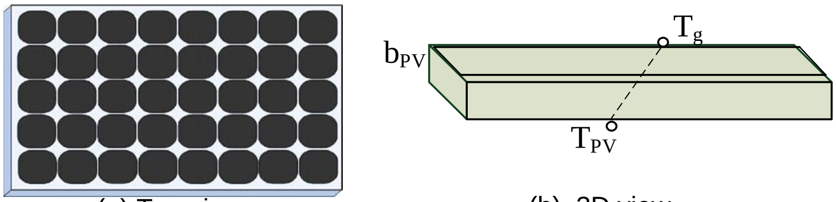
Figure 2. PVT System with thermal container

2.2. System Heat Transfer Process

Newton's law of cooling states the convective energy exchange from a surface to the surrounding fluid is proportional to the overall temperature difference between the surface and the fluid. Temperature differences cause the flow of heat from a higher temperature to a lower temperature material, liquid or gasses. There are three modes of heat transfer radiation, convection and conduction. The basic microscopic mechanism of conduction is the motion of molecules and electrons. It can occur in solids, liquids and gasses [4]. For a PV module in air, the total convective energy exchange from a module surface is shown in Equation (2).

$$q_{conv} = h_c . A. (T_{module} - T_{ambient}) \quad (2)$$

Where h_c is the convective heat transfer coefficient and A is the surface area of the PV module [2]. The process of the heat transfer in this experiment started from the top glass layer of the PV down to the heatsinks, which are shown in Figure 2. The top view of the PV is shown in Figure 3(a). The thin glass layer under the PV module block the solar radiation reverse to the the top layer of the PV as shown Figure 3(b).



(a) Top view (b) 3D view

Figure 3. PV Module with glass layer and transfer

The temperature value on the PV module is calculated using Equation (3).

$$T_{PV} = T_A + \frac{\mathbf{T_{NOCT} - 20}}{\mathbf{0.8}} * \mathbf{G} \quad (3)$$

Where T_A is the ambient temperature, G is solar radiation W/m^2, T_{NOCT} is nominal operating cell temperature at open circuit with the following conditions: ambient temperature of 20 ºC and G = 800 W/m^2 [2]. The system is attached together in which thermal energy flow from the top layer of PV to an aluminum plate and down to the heatsinks. If coolant existed in the thermal container the thermal energy further travel from heatsinks to coolant where heatsinks are immersed into it. Further investigation of the designed PVT system is to be performed when the coolant circulates through the heat exchanger located in the water of the thermal tank. The pump aims the circulation of the coolant in the thermal container into heat exchange and back to the thermal container as a closed loop system. The circulation of the coolant causes the heat exchanger unit to raise its temperature. The heat exchanger is manufactured into a spiral shape and is immersed in the water stored in the insulated tank. This process aims to release the heatsinks' thermal energy to the lower temperature water in the tank. This continuous process raises the temperature of the water in the tank and helps to lower the PV temperature. The system is designed as a closed loop in which the water in the thermal container never mixes with the water presented in the tank. The acquired high-temperature water in the tank can be used for domestic and industrial purposes.

2.3. Heat Transfer from the PV to the Aluminium Plate

The heat traveled through the glass at the top layer of the PV to the bottom layer of the PV later transferred to the aluminum plate attached to the bottom layer of the PV module. The heat added in the aluminum plate further transferred to the heatsinks attached below the aluminum surface and further into the water in the thermal container. It is noted that portion of the radiation reflects back to the sky and portion of the sun energy on the PV wasted to the surrounding atmosphere via conduction by the PV and the edges of the aluminum plate to the surrounding air. It is noted here that if the ambient temperature is more than the PV thermal temperature, the PV absorb more heat energy from the surrounding atmosphere. In the process of the heat transfer through the layers, at this stage, the heat absorbed by the top layer of the aluminum plate moves to its bottom layer as shown in Figure 4. In this process, a small portion of heat is lost from the edge of the aluminum plate to the surrounding air. The overall thermal energy of the aluminum plate is calculated using Equation (4).

$$Q_{Al} = Q_{PV} - Q_{RAl} \quad (4)$$

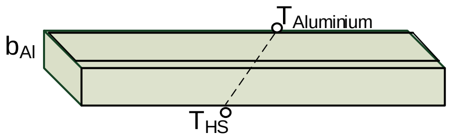


Figure 4. Aluminium plate layer

Where Q_{Al} is the thermal energy of aluminum plate, Q_{PV} is the net thermal energy of PV and Q_{RAl} is the thermal resistance of aluminum plate.

The solar radiation directed to the PV module is mostly absorbed by PV and about 5% of it reflected back to the environment. The radiation on the PV causes the rising temperature of the PV surface. The heat collected by the PV module transfers to the aluminum plate which is attached directly to the bottom of the PV module. The estimated temperature of the aluminium plate is calculated using Equation (5).

$$T_{Al} = T_{PV} - \frac{b_{PV} * Q_{PV}}{K_{PV} * A_{PV}} \quad (5)$$

Where T_{Al} is aluminum thermal plate temperature (K), T_{PV} is PV temperature (K), b_{PV} thickness of PV (m), Q_{PV} thermal Energy of PV (W), K_{PV} thermal conductivity of PV (W/m^2) and A_{PV} surface area of PV [4].

2.4. Heat Transfer from the Aluminum Plate to the Heatsinks

The heat collected on the aluminum plate transfers to the heatsinks attached to the bottom layer of the aluminum plate as shown in Figure 5. The heatsinks are only point welded on the four corners to the aluminum plate which are not perfectly attached together. As a result of this gap between aluminum plate and heatsinks, the thermal energy is prevented from transferring perfectly the thermal energy from aluminum plate to the heatsinks.

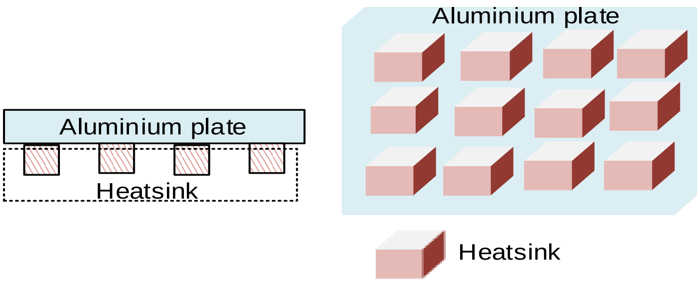


Figure 5. Aluminium plate and Heatsinks

The heat absorbed by the aluminum plate further travel to the heatsinks that are point welded on the bottom surface of the aluminum plate. The aluminum type heatsinks are a good thermal conductor, which removes the heat from the aluminum plate that is attached to the top of the heatsinks. The estimated amount of heat in heatsinks are calculated using Equation (6).

$$T_{Hs} = T_{Hs} + \frac{Q_{Hs}}{N * K_{Hs} * A_{Hs} * n * \tanh(n*L)} \quad (6)$$

Where T_{Hs} is the temperature of the heatsink, KHs is thermal conductivity of heatsink, QHs is the thermal energy of heatsinks below [8].

2.5. Heat Transfer from Heatsink to the Coolant

Water is selected as a coolant in the thermal container to further remove the heat from the heatsinks. The heat sinks are submerged in the water and as the result of direct contact of the many surface layers of the heatsinks and the water, the heat from the heatsinks is removed faster via conduction compare to the heat transfer from the upper layer heat transfer. Figure 7 above shows the consistency of very narrow gap between the heatsinks temperature and the water in the thermal container. It is intended to use a different concentration of the nanofluid as a coolant in the future experiment to analyze the effectiveness of its heat removal compared to the water.

Heat is characterized as the type of energy that is exchanged between two systems' temperature contrast [9, 10]. When the thermal container is filled with water as a coolant, heatsinks are immersed in stored water in the container. The water in the thermal container further removes and in turn absorbs the heat from the heatsinks, which assist in removing the heat from the top layer of PV modules. The heatsink is a passive heat exchanger that cools a device by dispersing heat into the surrounding medium. In computers, the heatsink is used to cool down central processing units or graphics processors. A heatsink transfers thermal energy from a higher temperature device to a lower temperature medium. The medium in this experiment is selected as air and water. The material of the heatsink is aluminum with thermal conductivity (K) 220 W/m [11]. Therefore, the designed system remove the thermal energy from the surface of PV module to aluminum plate attached bellow it and from aluminum plate to aluminum heatsinks that are point welded to the aluminum plate and finally to the coolant in the thermal container. This process help to cool down the PV module, which not only increases the efficiency of the module but also save the wasted thermal energy of the PV module that caused by sun radiation.

3. System Design

In the experimental portion, Pyranometer is used to measure the sun radiation. A Pyranometer measures broadband solar radiation on a flat surface which can also measure the solar radiation flux density. In conjunction with measuring the radiation of the sun, thermocouple sensor is used to measure the ambient temperature, PV, aluminum plate, heatsinks and coolant temperature. The data logger is utilized to collect the measured data for specified length of time. These data are collected by data logger which further analyzed and calculated the thermal response of each layer in relation to the solar radiation and ambient temperature. The data logger is set to measure and collect the data for the frequency of 10 seconds for the duration of two hours from 11:30 AM to 1:30 PM which the solar radiation continues to increase suitable for analyzing the data. The entire system setup used for this experiment is shown in Figure 6. Although minimizing the reflection of solar radiation is a crucial part of achieving a higher electrical power efficiency of PV, it generates heat on PV module which reduces the efficiency of the PV. The amount of light absorbed by the PV module depends on the optical path length and the absorption coefficient of PV module [7]. The PV module is exposed to the solar radiation, which in turn generated electrical power and raised the temperature of the PV module. The PVT system removed the collected thermal energy from the PV module which is caused by solar radiation.

The estimated PV energy is calculated using Equation (7).

$$Q_{PV} = \frac{(k_{PV} \cdot A_{PV})}{b_{PV}} (T_{Al} - T_{PV}) \quad (7)$$

Where Q_{PV} is the thermal energy of PV (W), K_{PV} is thermal conductivity of PV (W/m^2), A_{PV} is the area of PV (m^2), b_{PV} is the thickness of PV (m) and T_{Al} is aluminum thermal plate temperature (K) [9].

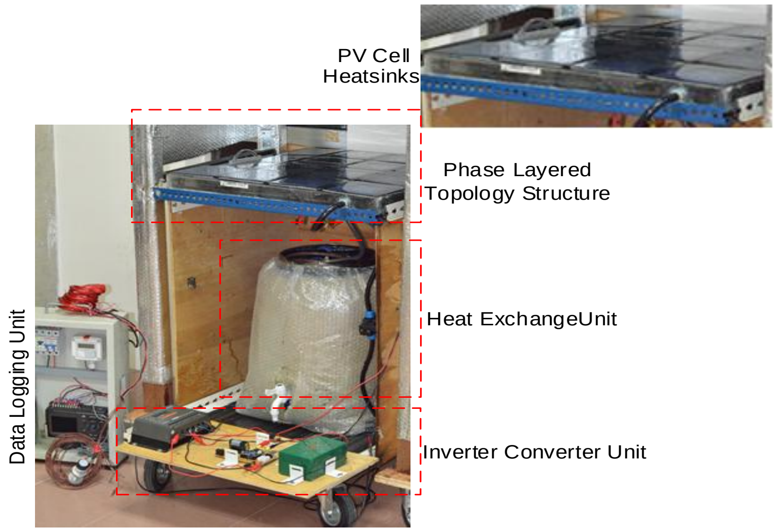


Figure 6. Proposed System Module

The flowchart for the measurement point evaluation are shown in Figure 7 and Figure 8 respectively. The flowchart in Figure 7 shows the heat transfer process on each layer from the PV top surface to heatsinks. The measurement is taken from each measuring point MP1, MP2, MP3. The MP1 is the measuring point for aluminium plate, MP2 is the measuring point for heatsinks and MP3 is the measuring point for the coolant. The flowchart in Figure 8 below shows the experimental potion process of this design. Two tests are conducted, water in the thermal container and no water in the thermal container. The measurement is taken from each measurement point MP. The obtained data is further compared for analyzing the system performance under those two conditions.

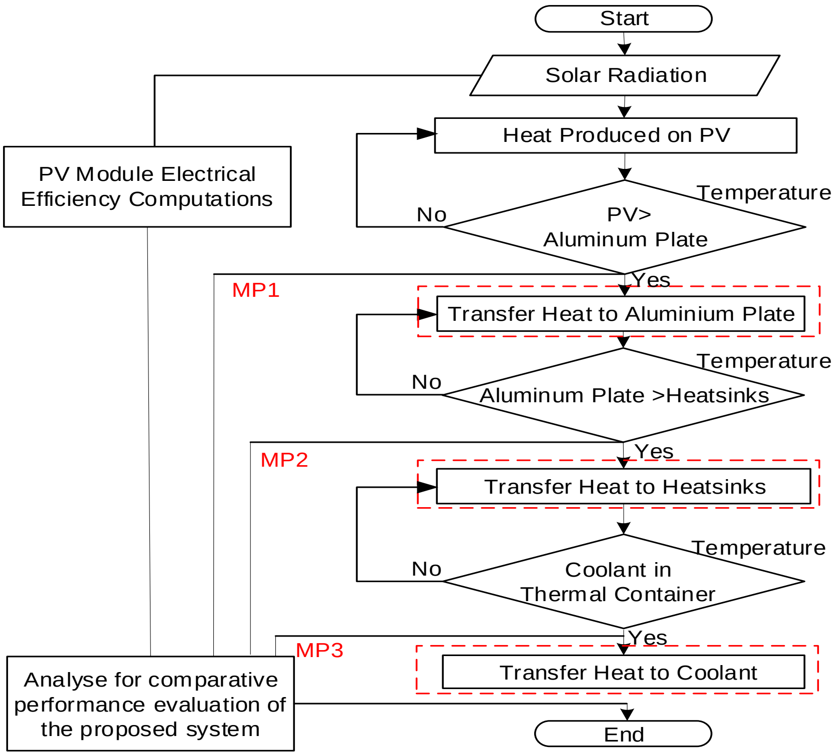


Figure 7. Thermal flow through different layers of PVT system

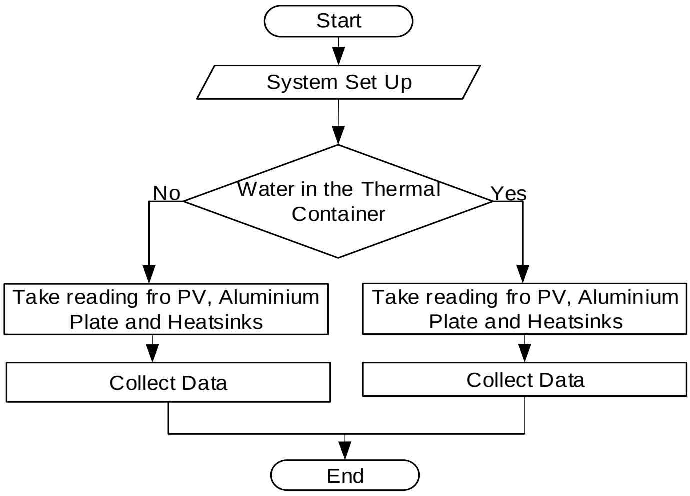


Figure 8. Heat flow transfer through different layers of PVT system

4. Results and Analysis

When no heat removal agent as coolant in the thermal container, the temperature of the heatsinks seems to follow closely to the PV temperature than when water existed in the thermal container. This is because heatsinks only able to releases their thermal energy to the surrounding trapped air in the thermal container. The trapped hot air does not allow the heatsinks to further release their thermal energy freely. Figure 9 below shows the temperature of each layer during this experiment which shows that the heatsinks temperature slowly increases and hold their thermal energy after the temperature of the PV and aluminum plate drops. This is due to the fact that heatsinks do not have any heat conduction material or coolant in the thermal container. From the figure it can be observed that the aluminum plate's temperature closely follow the PV temperature with a narrow gap. The gap is due to the deformation of the aluminum plate caused by high heat during welding of heatsinks to the aluminum plate.

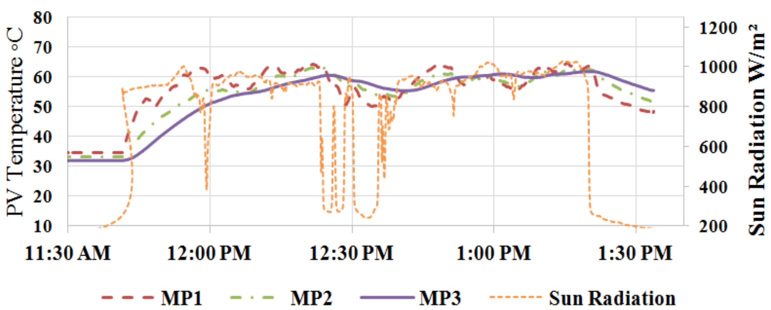


Figure 9. Experimental temperature respond of PVT layers without coolant

The system set up for this portion of the research is the same as the previous set up except water is included as a coolant in the thermal container, where the heatsinks submerged into the water. The pyranometer and the thermometer are connected to the systems as in the previous set up without water in the thermal container. The data is collected by the data logger and Excel program is employed to generate the figure of temperature value of each layer in sequence PV, aluminum plate, heatsinks and water in the thermal container. The temperature of each layer experimentally with water as a coolant in the thermal container is shown in Figure 10.

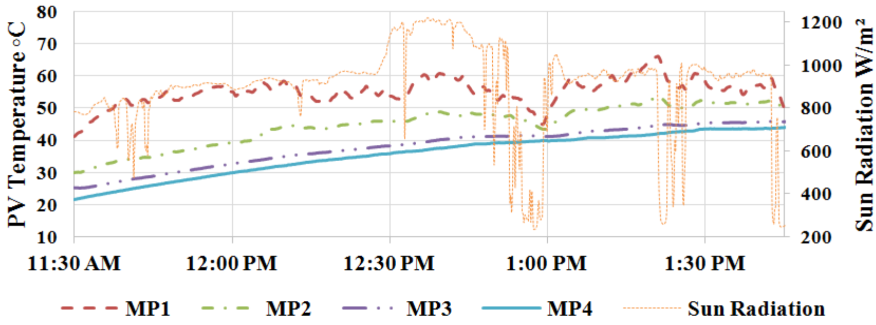


Figure 10. Experimental temperature respond of PVT layers with coolant

Since water is used in the thermal container as a coolant, the figure shows that the PV temperature maintained at temperature just below 60 ºC. The reason is the heat transfers from PV module down to each layer and finally absorbed by the water in the thermal container. Also, the temperature difference between the heatsinks and water in the thermal container shows a rapid heat transfer from the heatsinks to the water around 1:00 PM. This indicates the heatsinks are well considered for this design. The temperature on the heatsinks slowly and steadily raised up while the temperature of the PV and the aluminum plate drops. This is noticed clearly at the end portion of the figure. In this experiment, it is observed that the water in the coolant has a good mediator to absorb the thermal energy on the PV which is caused by the solar radiation. Table 1 shows some of the data taking to clarify the changes in the temperature according to the solar radiation.

Table 1. Solar Radiation's Effect on the Photovoltaic Panel Surface.

Solar Radiation(W/m^2)	PV Temperature (°C) With Coolan	Without Coolant	Δt
862	50.3	60.8	10.5
900	53.4	62.8	9.4
1033.3	55.7	64.9	9.2

The data clearly shows that the temperature of the PV is lower in all three cases with different solar radiation ranging from 862 W/m^2 to 1033.3 W/m^2. In average the PV temperature is less than 9.7 ºC which means the system is effective to remove the temperature of the top layer of PV. In this experiment, it shows the changes of the PV module temperature depends solely on the solar radiation. It also identifies that the temperature of PV panel is less when water is being employed in the system, thus resulting in better performance of PV panel. This is because the water absorbs more heat away from the panel. Moreover, it is also observed that the temperature difference (Δt) is decreasing, as the coolant is absorbing more heat over time until it reaches saturation and cannot absorb more. The solar panel temperature output voltage increases if solar panel temperature decreases so cooling of the PV panel is necessary for the improvement the efficiency of the PV panel [10].

5. Conclusion

The solar radiation generates electrical energy and thermal energy when directed on the PV module. The excessive heat collected on the PV lower the efficiency of the PV and the same time has a negative effect on the life duration of the PV module itself. The excessive heat collected on the PV are utilized in the proposed design. Two different set up are considered by engaging PV module, aluminum plate and heatsinks with and without water as coolant in the thermal container. The data are analyzed and are noticed that the temperature of the heatsinks rises which is higher than the aluminum plate and the PV module due to heat trapped in the last stage of heat transfer. The heatsinks temperature dropped significantly compare to the PV and aluminum plate when water is used as a coolant in the thermal container where the heatsinks submerged in the coolant. The reason for this significant drop and difference temperature is the use of water as a coolant. The water collected the heat from the heatsinks and after a while, the temperature of the heatsinks and the temperature of the water in the thermal container are approximately the same. The solar panel output voltage increases if solar panel temperature decreases. Therefore, cooling the PV panel is necessary for the improvement of PV efficiency. It is found the PV temperature reduced by about 10 degrees which is cirtical for the PV performance reducing the wasted thermal energy and thereby increases the electrical energy conversion.

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