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Solar Conversion Efficiency Improvement of a Photovoltaic Module by Hybrid Active and Passive Cooling Techniques

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Research Article

Abstract

Energy is becoming more demanding and a security to the continual existence of human race in different aspects. Renewable energy being the most clean and reliable energy sources have attracted the attention global researchers towards a high efficiency energy conversion interface of the most desired source; solar energy. The main aim of this research is efficiency improvement of PV system through the application of hybrid active and passive cooling techniques. A locally available and designed porous pot has been selected to be part of the forced water circulation technique because of its high cooling capacity without any necessary maintenance. The circulation was achieved with the aid of low energy powered fabricated centrifugal pump with flow rate of 0.01litres/sec. 5% concentration of Ethylene glycol in the cooling fluid to further aid the cooling capacity of the water. The pot was designed to ensure cooling down of circulating fluid before subsequent recycling process to a temperature below room temperature even at the hottest hours of a day. The technique was integrated with back surface aluminum heat sink, supported with an insulative cover. The result shows about 28% temperature fall and 4.04Watts power increase of the module relative to reference module.

Keywords
PV Module, Cooling techniques, Porous pot, Efficiency

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1. Introduction

Pollution free, minimal maintenance, high power density, low operational cost among other factors are the primary reasons why among other sources of renewable energy solar energy has been seen as the most clean, reliable and most effective source of electrical and thermal energy (Andris *et al.*, 2009). The high demand on electrical energy for domestic and industrial needs at urban and rural areas serves the fundamental reason for harnessing solar renewable energy through photovoltaic (PV) cell technologies in addition to the current united nations effort in creating safe, clean and conducive environment against the current global warming (Siecker *et al.*, 2017) by greenhouse effect due to over dependence on nuclear and fossil fuels as the sources of energy, thus PV cell technology is seen as the outstanding solution to these challenges (Boxwell *et al*., 2012). Solar energy is converted to electrical energy by PV cells or solar cells; most commonly silicon wafer (Brownea *et al.* 2014), Solar cells form the building blocks of PV module (Andris, *et, al.*, 2009). The solar energy is converted to electrical energy in the cell by electron-hole pair generation, separation and transportation across P-N junction by incidence solar radiation with photons having energy greater than band gap energy (Kozan, *et, al*., 2019). It has been well documented that only about 31% of the incidence solar radiation is converted in to useful electrical energy, the remaining energy is converted and absorbed as thermal energy by the module (Brownea et al. 2014), (Koteswararao *et al*., 2016). This results in rise in temperature of the cell and thus exponential rise in carrier recombination and hence low conversion efficiency of the module (Wurfel, 2005), subsequently shorten the life span of the module due to technical destruction (Andris, *et al.*, 2009). Every 1℃ module temperature rise above the standard test condition (STC) results in conversion efficiency fall by 0.5% (Evans and Florschuetz, 1978; Kumar, *et al.*, 2007). Thus the major setback in PV cell technology is has been its low conversion efficiency primarily due to rise in module temperature (Irwan, *et al*., 2015). To achieve this, the PV module needs to be cooled to STC temperature by removing an excess thermal energy from the module efficiently.

(Dua, *et al.* 2012) Used back surface water cooling technique with aluminum metal tubes on a concentrated silicon solar cell, although the power output realized was 4.7 to 5.2 times that of reference cell, but the efficiency improvement was below 9%. (Moharram, *et al.* 2013) Cools the module by spraying water on a PV power plant, the water was allowed to drain and recycled through a buried aluminum water tank in the ground, with the aim of cooling down the water before subsequent recycling. About 5% of the water was lost due to evaporation, 12.5% efficiency improvement was achieved. (Haidara et al., 2018) Adopted back surface cooling with a wetted cloth evenly spread and well fixed, aluminum tubes serve as the passage for the water wetting the cloth, channeled through the cloth. The evaporating water was also assumed to be cooling the water by convection. 10-14.5% increase in efficiency was achieved.

Numerical simulation in observing the cooling effect of Aluminum heat sink using adjustable Aluminum ribs and angles was conducted by (Popovicia, et al. 2016) the ribs height was increased in steps of 0.01m to 0.05m and a 0.003m diameter perforated hole on each step with the angle of the ribs with respect to module back surface was also adjusted up to 135°. The result shows that the highest efficiency was achieved at 0.05m ribs height and 45° angle. (Munzer, *et al*. 2018) Carried out an experimental investigation with active back surface cooling technique with two nanofluids namely TiO_2 and Al_2O_3 of different concentration and flow rates. These with the aid of two rectangular heat exchangers and heat sink were placed at the back of the PV module. About 50% efficiency improvement was achieved.

For the same aim, silicon oil of varying thickness was used by (Nikhil, *et al.*, 2012) on the surface of the PV module for six steps with step size of 0.1mm, the result shows highest improvement of 23.23% at 0.2mm thick. (Shukla, *et al.*, 2017) conducted a simulation on conductive and convective heat transfer and also phase change material under some certain fixed conditions concerning the PV panel structure, atmospheric conditions etc the result shows about 5% improvement. (Kelebekler, et al., 2017)conducted an indoor experiment with the of maintaining the PV module temperature fixed with the range of 23OC-49OC with the aid of PI controller and thus monitored the effect of temperature on the module output, voltage loss from 0.44 to 0.39 was observed.

Passive photonic technique was adopted by (Li, *et al.*, 2017) the technique works on selective spectrum absorption on $Al_2O_3/SiN/TiO_2/SiN$ alternating layers on a glass substrate, 1% efficiency improvement was recorded. An immersion cooling was carried out by (Antony, *et al.*, 2017) using water and silicon oil for comparative cooling efficiency, where water shows best cooling capacity over silicon oil, although the water cooling system has some disadvantages over silicon.

Thus this research aimed at lowering the temperature of a 20W 18V photovoltaic module in order to achieve maximum electrical efficiency output, by improving the power output, open circuit voltage (Voc), short circuit current (Isc), and the fill factor (FF) by first observing their magnitudes with module that is not under cooling and then module under cooling

2. Temperature dependence of a solar Cell

It has been stated clearly in the above theory that temperature plays a vital role in the operation of PV cell. The temperature rise on a PV module is greatly due to infrared component of solar radiation spectrum resulting from the fact that of all the solar radiation incidence on the PV module only about 20% are converted to electricity by solar cell(Tzuc, *et al.* 2018), and other photons with energy greater than band gap are absorbed at the lattice sites of the crystals and resulted in increase in thermal energy of the cell, the dark color of PV panel surface increases the thermal absorption by the cell, the electron-hole pair generation due to thermal excitation process etc. And each degree rise in temperature of the PV module reduces the overall cell V_{oc}, I_{sc} and η by 2.2mV, 0.1% and -0.5% respectively (Tzuc, *et al.* 2018) with a reverse saturation current increase by multiple of four per every ten degrees rise in temperature (Neaman, *et al.*, 2012). The overall effect of temperature can be well understood on I-V characteristics curve with three distinct temperature values (25ºC, 45ºC and 60ºC) as shown in Figure 2.

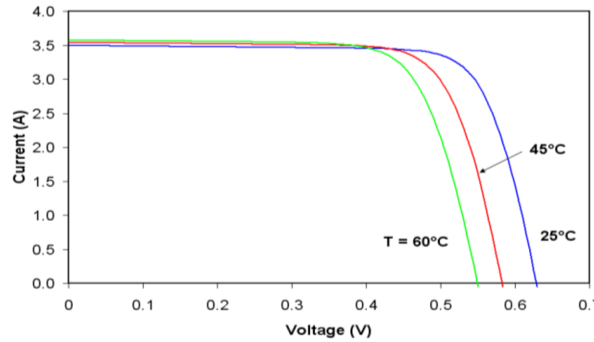

Figure 2: Temperature Effect On I-V Characteristics Curve of a solar Cell

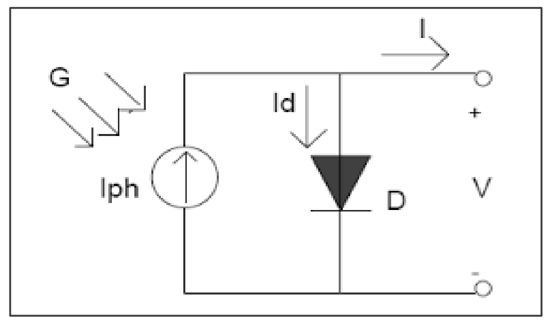

Figure 3: Equivalent Circuit of a solar cell.

It follows that in high quality solar cell short circuit current is equal to photo generated current when the external voltage is zero and is in the direction of electric field(Wurfel, 2005) i.e. $I_{sc} = I_L$ (see Figure 2.4 above). Open circuit voltage (V_{oc}) is the voltage across the output of a PV cell when the net current is zero; in an ideal case R_s and R_{sh} effects are negligible. Thus it could be seen that no power can be extracted from a PV cell under I_{sc} or V_{oc}. When the forward bias current is to be taking in to account, then the net current can be expressed as (Wurfel, 2005);

$$I = I_L + I_d \quad (12)$$

Where I_L is the light generated current and I_d is the forward bias current, which can be expressed in terms of reverse saturation current I_0 (the current formed due to movement of minority carriers from neutral region to depletion layer) (Wolfe, *et al.* 2013) is given by;

$$I_d = I_0 \left[Exp\left(\frac{eV}{K_B T}\right) - 1 \right] \quad (13)$$

Thus, (13) becomes;

$$I = I_L + I_0 \left[Exp\left(\frac{eV}{K_B T}\right) - 1 \right] \quad (14)$$

Since V_{oc} measures when I_{sc} equals zero then;

$$V_{oc} = \frac{K_B T}{e} \ln\left(\frac{I_L}{I_0} + 1\right) \quad (15)$$

It could be seen from (15) that higher value of I_o lowers V_{oc}. Thus to operate solar cell with lower value of I_o a semiconductor material with higher band gap should be chosen, this will make carrier concentration (n_i) to be low, and affects the reverse saturation current as;

$$I_0 = n_i^2 e \left[\frac{D_P}{L_e N_A} + \frac{D_h}{L_h N_D}\right] \quad (16)$$

It then follows that as a solar cell absorbs solar energy its temperature rises, this lead to increase in V_{oc} and fill factor FF (measure of how high series resistance is and how small shunt resistance is) decrease substantially while I_{sc}only slightly increases as seen from Fıgure 3.

The overall effect affect the output power, fill factor and electrical efficiency respectively as;

$$P_m = I_m V_m = V_{oc} I_{sc} FF \quad (17)$$

Thus;

$$FF = \frac{P_{max}}{I_{SC} V_{OC}} \quad (18)$$

$$\eta = \frac{V_{oc} I_{sc} FF}{QA} \times 100\% \quad (19)$$

$$P_{in} = Q \times A \quad (20)$$

Where Q is the solar intensity and A is the area of the PV module surface.

3. Materials and Methods

The method and materials used were fundamentally objected to ensuring high cooling effect, necessary measures were taking to ensure that thermal energy was not added to the system by ambient temperature or any other cooling component.

3.1 Materials

The cooling systems comprise the 20W, 18V PV Module with characteristics given in Table 3.1 below, other materials used were Porous pot which is designed traditionally with burnt pottered clay for water cooling purpose. The pot was obtained at the pottery industry in local market. The performance of the pot has been evaluated by measuring the day-time temperature of the water. The maximum temperature measured was 14oC at ambient temperature of 39oC, 3V Centrifugal pump was also designed with a minimum power rating in order to reduce excessive power consumption while operating, Drain pipes for collecting the water in and out of Porous pot, Insulative back surface cover, Gum, Cupper tubes (6mm external diameter), Ethylene glycol ($C_2H_2O_2$), Aluminum metal strips, Thermal grease, Pot shield and Pot stand. Other measuring instruments are k-type thermocouple thermometer, Pyranometer device for solar irradiance measurement, digital multimeter, infrared thermometer and liquid in-glass thermometer. The experiment will be conducted in an area free from shedding.

3.2. Methods

Integrated active and passive cooling techniques were chosen in order to cover a high cooling efficiency for the experimental set up. Prior to use of cooling systems, the experiment was conducted with PV module at normal environmental conditions for reference readings, the ambient temperature, cell temperature, solar irradiance, open circuit voltage and short circuit current readings were taken on hourly bases, starting from 9:00am to 4:00pm being the hours of a day with highest solar intensity; the readings were taking for three days involving cooling systems and the reference system. The overall average readings were determined. Origin software was used to plot the graphs of the readings measured from the two PV module configurations.

The active part comprises back surface water cooling method which was equipped with limited power consumption components, such as low voltage centrifugal pump (3Volts), porous pot or mud pot which is traditionally fabricated pot for water cooling purpose, thus no external energy would be required to lower the temperature of the recycling fluid, it is poor conductor so the ambient temperature effect on its operation is negligible, the pot was be prevented from direct solar radiation through the use of shed (see fig. C below). The cooling system set up allowed for the use of thermal energy extracted from the module for other vital needs, outlet and inlet drain tubes were carefully fixed on the pot and the pot rose above the ground in order to avoid heating due to earth. This is aimed at mitigating increase in temperature of the porous pot due to environmental factors. The tubes were connected to the looped copper tubes at the back of the 20W PV module, the module was raised to some height and tilted to angle 15o south as recommended for the experiment located between latitude 0º and 15º (Idoko, *et al*. 2018). Centrifugal pump fixed between the copper tube water outlets to the pot was used to aid the water circle process (see Figure B below). Copper loop tube fixed at back surface of the module for the water passage, has an inlet and outlet ports to allow the in and out flow of the fluid. Cooling with water and heat sink was first observed before the cooling fluid would be aided with organic compound; ethylene glycol. Ethylene glycol ($C_2H_2O_2$) is an Organic Compound known for polyester polymer manufacturing and cooling/anti freezing ability. It helps in increasing the thermal conductivity of water by lowering its surface tension (known as surfactant) (Idoko, *et al*. 2018). And these complete the back surface cooling technique using fluid flow. The physical and electrical characteristics the PV module is summarized in Table 1.

Table 1: Characteristics of the PV module used

Module size	350mm×480mm
Model number	AP-PM-20
Power rating (P_{max})	20W
Output tolerance	± 5%
Current at maximum power (I_{max})	1.14A
Voltage at maximum power (V_{max})	17.5V
Short-circuit current (I_{sc})	1.27A

Open-Circuit voltage (V_{oc})	22.05V
Nominal operating cell temperature	25°C
Solar irradiance	1000W/m^2
Maximum series fuse rating	1000V DC
Maximum system voltage suitable for the panel	12V DC

4. Results and Discussion

The module used was made with polycrystalline Silicon wafers with description given in table 3.1 above. The experiment focuses on the use of porous pot (commonly known as Tulu). It is a traditional Pot specifically designs for water cooling. The Pot used cools the water to as low as 12℃ at 10:00am just before the system startup and the average temperature of the outlet water measured was 28℃ by adopting constant fluid flow of 0.01liters/second; based on the constructed centrifugal pump capacity. Thus the system was found to cool down the cell temperature up to about 14.48℃ (28.24%) using water and aluminum heat sink. The cooling process was found within an ambient temperature of 31 to 39℃ down to 13.52℃ (26.37%) using Ethylene glycol in water base (5% concentration) with Aluminum heat sink within the ambient temperature of (26 to 41℃). This is a high cooling rate compared to other active cooling methods that often require cooling down the water.

Thus the cooling system used in this experiment has the following advantages;

i - The mud pot is relatively cheap and available
ii - Higher cooling efficiency over other methods was observed
iii - It does not require routine maintenance
iv - mmm It does not require any external power supply for its operation
v - Its cooling efficiency is relatively less affected on its exposure to solar radiation
vi - Continuous water replenishment is not required unless the warmed water has been tapped out of the system for other needs.

The cooling with the organic compound in water base gives a better and more stable curves compared to other cooling techniques.

(A)

(B)

(C)

Figure 4: A; complete experimental set up, B; measuring devices, C; Porous pot shed.

In Figures below, the graph of power has a linear relation with increasing irradiance and solar conversion efficiency has inverse relation with ambient temperature. The curves having their minimum values recorded at early and late hours of the experimental day, and peak at mid-day could be theoretically explained by understanding the fact that solar irradiance depends on position of the sun or wavelength of the solar spectrum (Idoko, *et al.* 2018). In other words, the path length of solar spectrum is a function of an angle subtended by the sun relative to earth and that angle varies with time of a day (Nelson, et al. 2007). Thus minimum solar irradiance is recorded at early and late hours of a day, and maximum at the zenith of the sun.

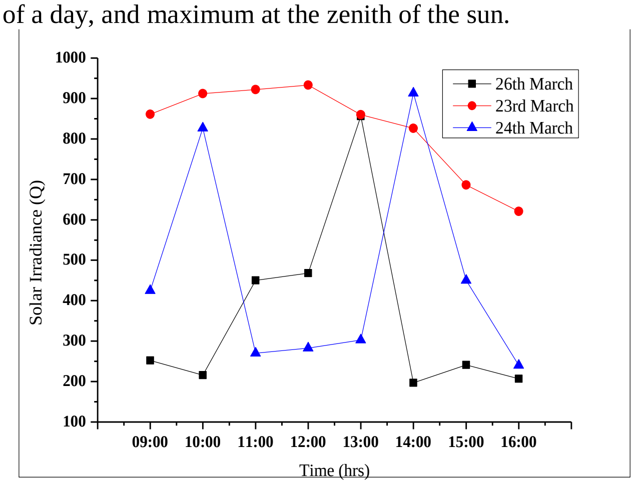

Figure 5: Solar irradiance versus Time

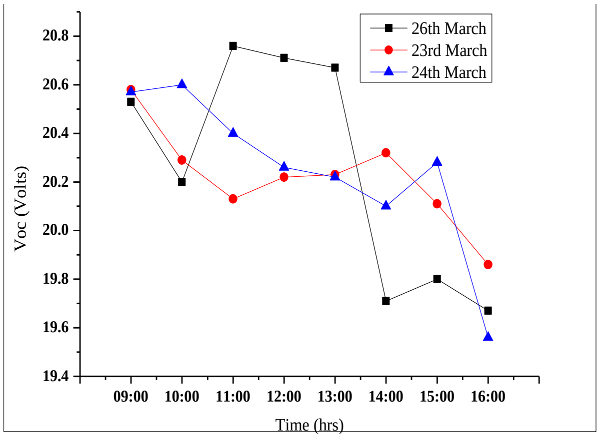

Figure 6: Open circuit voltage versus Time

4.1 Discussions

The experiments were conducted between the months of March to April in open space on the top of faculty of natural and applied sciences, under the weather conditions of Katsina, Nigeria. The experiments were conducted following the same materials and methods. The experiments were conducted just before rainy seasons; experiencing irregularities in solar radiation.

The panel was tilted to 15oSouth in order to capture the maximum incidence solar radiation over a wider time frame of a day with readings taken on hourly bases within the brightest hours of a day. The readings were taken for three days for the three phases of experimental setups and averages were taken.

It could be seen clearly from the figure 5 below that solar radiation has its peak at almost same intensity in all the experimental days above 900W/m2. Highest instabilities from the curves were highest on 26th and 24th.

The temperature of the PV module depends on incident solar radiation among other factors; hence the pulsating effect in solar radiation could contribute to the module temperature.

For the three experiments, V_{oc} drops with increasing module temperature and recorded almost same value at the first hour for all the experimental days with about 20.60V and then continue to drop with raising module temperature (Figure 6 above). The drop observed in V_{oc} at 10:00am is due to shed formed by cloudy weather which can clearly be seen on solar irradiance curve on the same experimental day, as the sun gets brighter at about 800W/m^2 while the ambient temperature fairly maintained its value V_{oc} reaches its maximum at 11:00am with about 20.80V before it continue to slightly drop with raising module temperature. Sudden drop is then seen to occur due to shed. The shed dominates for the rest of the experimental values of V_{oc} for the day.

The experimental days with integrated cooling systems recorded the highest ambient temperature with 37℃ and 30℃ on 23rd and 24th days with resulting cell temperature of 38℃ and 31℃ respectively on same days at 9:00am (Figures 7 and 8), and have their maximums for the days to be 43℃ and 38℃ accordingly. Hence the temperature dominates the V_{oc} and continue to drop with raising module temperature and now remains insensitive to incidence solar radiation fluctuations, even though the irradiance recorded highest on 23rd march but V_{oc} maintained its leas value because of its highest module temperature recorded and 26th March recorded the highest peaks for the lowest temperature recorded. The experimental results with cooling systems sustained to highest degree the temperature effect on the module.

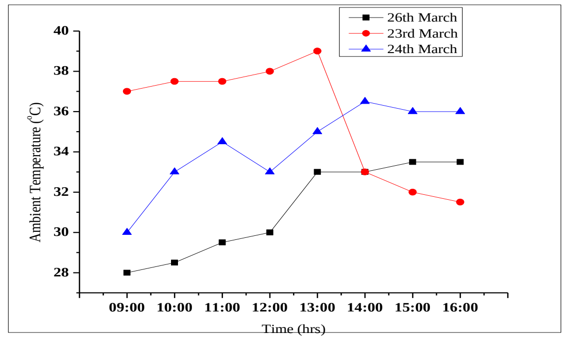

Figure 7: Ambient Temperature versus Time

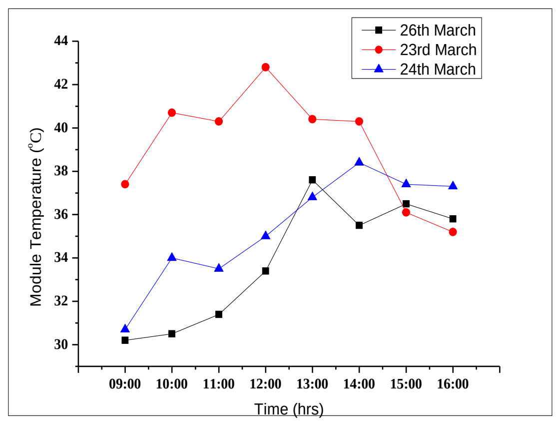

Figure 8: Module Temperature versus Time

The power output curves are simply like a picture of incident solar radiation curves (see Figure 10 below), the maximum power has been recorded at the maximum solar radiation on 23rd March having the highest radiation among others with 20.09Watts at noon hour with the solar radiation being highest to about 933W/m^2. The two cooling systems recorded the highest power values.

5. Conclusion

Integrated active and passive cooling techniques have greatly enhanced conversion efficiency of PV module of polycrystalline silicon wafer and overall output of the module. The system recorded highest improvement while cooling the module under high solar irradiance and hence high ambient temperature conditions. That attributes to the role of traditional cooling tool to improve the cooling effect of water. Power output and efficiency of 4.04 Watts and 18% respectively were obtained during. Furthermore cooling with Ethylene glycol in water base and aluminum heat sink further enhances the efficiency and power output high and relatively stable with power increase to 4.63Watts, efficiency up to 18.78% relative to reference module. In addition to improved efficiency the life span of the module will be raised because of the reduced destructive temperature rise.

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