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Effect of Cooling and Determination of Temperature Coefficients of Solar Photovoltaic (PV) Module Using Linear Correlation Model

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Abstract *- In this study, the effect of cooling on temperature coefficient of a 1.08m^2 polycrystalline silicon solar photovoltaic module was investigated. The temperature coefficients were determined using linear correlation approach. The experimental setup comprised of two solar modules - controlled and test modules. The solar modules were subjected to similar uncontrolled external microclimatic conditions between the hours of 09:00 and 16:00. A preset solar module surface temperature of 45°C controlled the submersed DC pump and consequently, the circulation of cooling fluid from a reservoir to an attached heat exchanger to the rear-side of test solar module. The solar module surface temperature was observed to vary linearly with the intensity of radiation with 0.0289°C increase in module surface temperature per 1Wm^{-2} increase in solar radiation for the control solar module and 0.0214°C per 1Wm^{-2} increase in module surface temperature for the test solar module. The results have also indicated that the percentage amount of heat on the surface of solar module was reduced by 4.08% due to the effect of cooling with temperature coefficients, β of 0.008%°C^{-1} and 0.015%°C^{-1} for the control and test solar modules respectively. The reference and mean efficiencies of 11.32% and 8.07% were recorded for the control solar module whereas 16.43% and 9.55% were recorded for test solar module.*

Keywords: solar PV module, temperature coefficient, linear correlation, reference efficiencies

1.0 INTRODUCTION

Energy sources are classified into two groups - non-renewable and renewable (Shelly et al., 2016). These primary sources are converted to electricity, a secondary energy source, which flows through power lines and other transmission infrastructure to your home and businesses (http://energy.gov, 2016). Non-renewable energy sources are more efficient than renewable but the process of converting from non-renewable primary energy to electrical energy is associated with green-house gases emission. As a result of increased concern associated with the use of non-renewable energy sources for energy supply, there has been massive awareness campaign aimed at sensitizing the energy consumers on the advantages of use of renewable primary energy converters like solar photovoltaic (PV) panels. Cumulative worldwide installed photovoltaic capacity reached 1000Megawatts (MW) as at 1999 (USD Energy, 2002). Also, according to Rustemli and Dincer (2011) solar PV market installations reached 7.3 Gigawatt (GW) in 2009, representing growth of 20% over the previous year (Rustemli and Dincer, 2011). Furthermore, between 2004 and 2009, grid connected PV capacity reached 21GW and was increasing at an annual average rate of 62% (Salmi et al., 2012). Currently, solar PV provides around 4800GW (Salmi et al., 2012). This is an indication that solar PV energy converter had relatively gained a wide acceptance as an alternative form of energy supply.

Commercial photovoltaic panels are generally inefficient converting less than 25% of solar radiation into electricity. As seen from Figure 1, except for solar parabolic trough and solar power tower, out of the twenty-five electricity generation technologies presented statistically in term of their efficiencies, photovoltaic cell is the least efficient with its efficiency to be 14% approximately. This implies that approximately 80% of the radiation is transformed into heat energy thereby causing panel’s surface temperature elevation. As intensity of radiation increases, the temperature of the panel tends to appreciate thereby affecting the performance of the panel. Temperature among other factors contributes in affecting the performance of the solar modules. It has been observed from mono-crystalline silicon (c-Si) PV module that for module temperatures above 25°C, the output power appears to diminish by approximately 0.5% per °C (Buday, 2011). Solar PV module temperature coefficient is a determinant for measuring the percentage decrement in output power of solar module as the temperature varies from standard test condition, STC.

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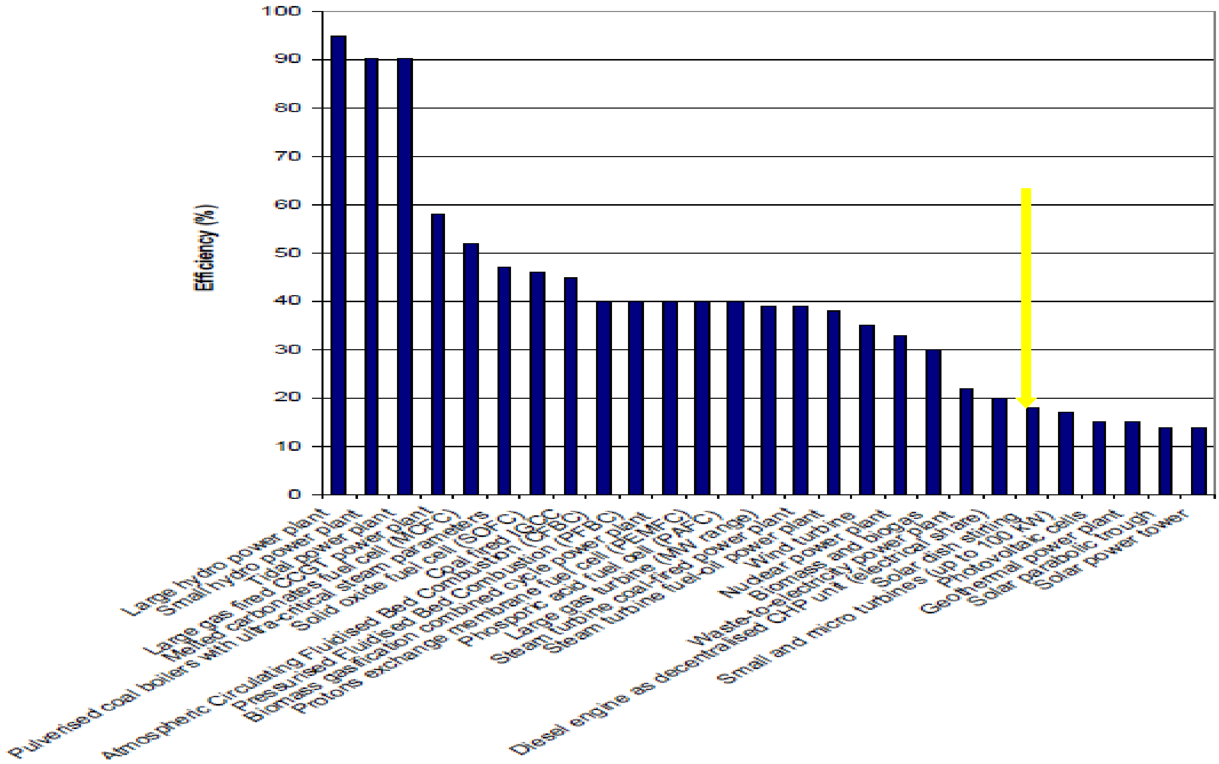


Figure 1: Efficiency in Various Electricity Generation Technologies (Source: Bauerschmidt, 2003)

A study carried out by Dash and Gupta (2015) on the effect of temperature on power output from different commercially available photovoltaic modules has shown that the average temperature coefficient of power for mono-crystalline, multi-crystalline and CdTe based modules are -0.446 %/°C, -0.387 %/°C and -0.172 %/°C respectively. In case of amorphous silicon module, only one sample is measured and the temperature coefficient was -0.234 %/°C. In their study, the output power for different commercially available solar PV modules were compared as a function of their respective temperature coefficients.

A study carried out by Tobnaghi et al., (2013) on the effect of temperature on electrical parameters of solar cells has shown that the most significant change by temperature is voltage which decreases with increasing temperature while output current slightly increase by temperature. It was also reported that reduction in the open-circuit voltage for silicon solar cells is about 2mV/°C. In addition, increase in temperature causes reduction in maximum power output by 0.005mW/°C. In this study, temperature coefficient was established using direct method.

Dinçer and Meral (2010) studied some of the critical factors that affect the efficiency of solar cells. They named these factors cell temperature, maximum power point tracking (MPPT) and energy conversion efficiency. However, the percentage change in current, voltage and output power with respect to change in temperature were not determined. Rjyadhara et al. (2013) analyzed solar photovoltaic cell performance with changing irradiance and temperature and came to conclusion that with increase in temperature the rate of photon generation increases rapidly and this results in reduction in band gap. Hence this leads to marginal changes in current but major changes in voltage.

Fesharaki et al. (2011) reported in their study of the effect of temperature on photovoltaic cell efficiency that as the temperature increases, the efficiency of the PV module decreases. However, the percentage of variation of solar cell conversion efficiency was not reported. A study carried out by Guda and Aliyu (2015) on the effect of temperature on photovoltaic array conversion efficiency and fill factor has shown that PV array has its highest energy conversion efficiency of 13.14% during harmattan, while having least efficiency of 12.43% during the clear sunny season. It was also reported that the PV array exhibits its highest fill factor of 0.756 during harmattan while its least fill factor of 0.708 was recorded during the clear sunny season. The conversion efficiency of the array is reported to have dropped by $7356x10^{-5}$%, $7262x10^{-5}$% and $7427x10^{-5}$% per 1°C rise in solar cell temperature during harmattan, cloudy and clear sunny seasons respectively whereas the fill factor dropped by $116x10^{-5}$%, $109x10^{-5}$% and $116x10^{-5}$% per 1°C rise in temperature. While this study covered both the temperate (clear sunny season) and cold (harmattan) weather, this however cannot form the basis for analyzing the effect of cooling on the temperature coefficient of solar cells.

The current study adopts Florschuetz linear correlation model equation in determining the solar cells' temperature coefficient, β. In addition, the effect of cooling on temperature coefficient, β of solar cells was further carried out. However, a new approach for the solar cells cooling process is employed, i.e., the fluid circulation by a DC submersible pump was control based on the preset solar cells' temperature.

2.0 MATERIALS AND METHOD

As shown in Figure 2, the setup comprised of two (2) polycrystalline solar PV module of 1.08 square meter.

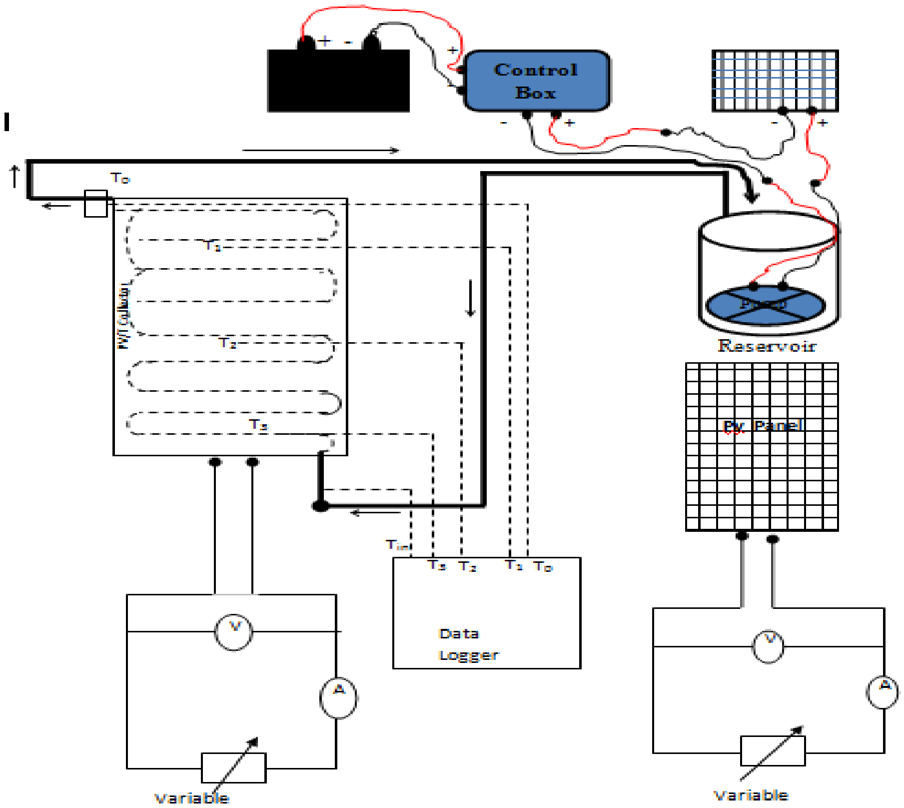


Fig. 2: Experimental setup for investigating the effect of cooling on temperature coefficient of PV module

The solar modules were oriented south-facing at tilt angles of 15°C each. A DC submersible pump in a reservoir of water was connected in series with a control unit, and two serially connected 12V monocrystalline silicon modules as shown in Figure 2. The equivalent circuit diagram for a solar PV module with cooling systems is shown in Figure 3.

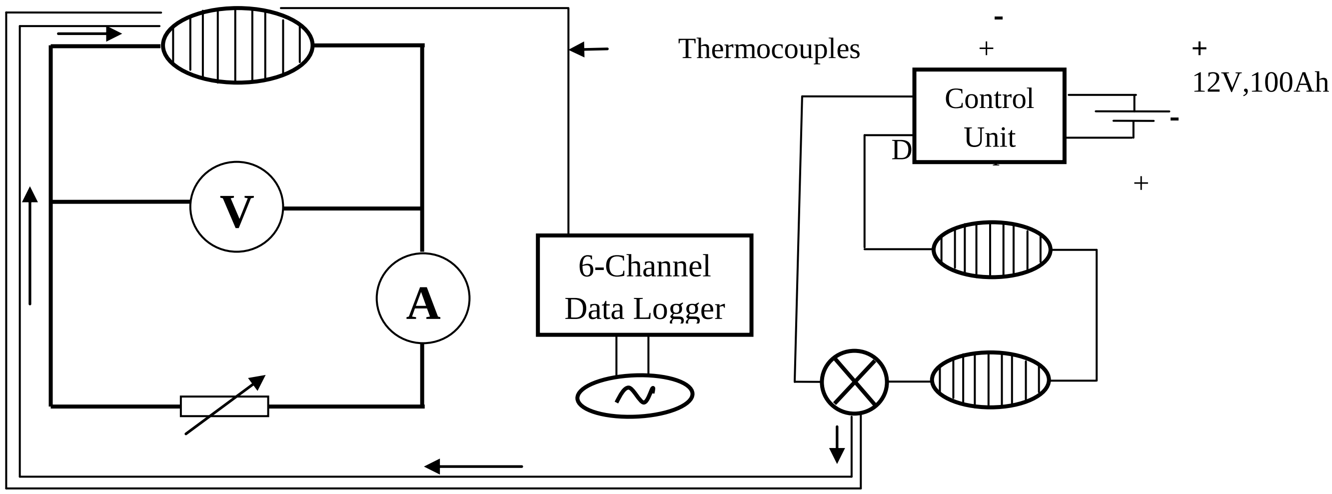


Fig. 3: Equivalent circuit diagram for investigating the effect of cooling on temperature coefficients of PV modules

The controller unit was powered by a 12V, 100Ah deep cycle battery whereas a six-channel data logger was powered by AC output from an inverter, The DC pump controller was preset to control the DC pump (i.e., fluid circulation) at module surface temperature, T_{surf} of 45°C; that is, at $T_{surf} \leq 45°C$, DC pump was enabled and disabled at $T_{surf} > 45°C$.

Solar radiation, ambient, absorber, water inlet and water outlet temperatures and surface temperature were measured by pyranometer, six-channel data logger and infrared thermometer (as shown in Plate 1) and recorded.

Plate 1: Data collection setup at Sokoto Energy Research Centre.

The rheostat slider positions were varied at seven different positions and the respective currents and voltages were measured and tabulated. In addition, short circuit currents Isc and open circuit voltages Voc were measured and recorded. The data were collected between the hours of 09:00 and 16:00 with an inter-data interval of 30 minutes for the months of May, June and July respectively.

3.0 RESULTS AND DISCUSSION

Solar radiation and temperature have effect on current and voltage. Figure 4 shows a plot of solar radiation and PV module temperature.

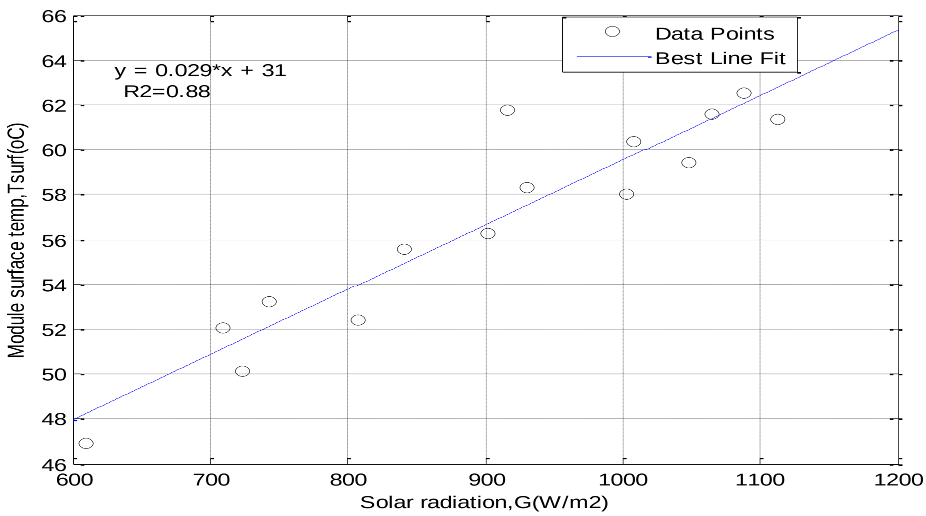


Fig. 4: Solar radiation - solar PV module temperature interaction

There exists a positive relationship between solar radiation and modules surface temperature with R^2 - value of 0.88. From the model equation

$$T_{Surf}^{PV} = 0.029G + 31; R^2 = 0.88 \quad (1)$$

The result in Figure 4 shows that for 1Wm^{-2} increase in solar radiation, solar module's surface temperature is expected to increase by 0.029°C. This clearly has shown that module's surface temperature increases with increase in solar radiation. In order to regulate solar modules elevated temperature as intensity of solar radiation increases, the cooling process by a DC submersible pump was controlled at preset temperature of 45°C. The effect of cooling is presented in Figure 5.

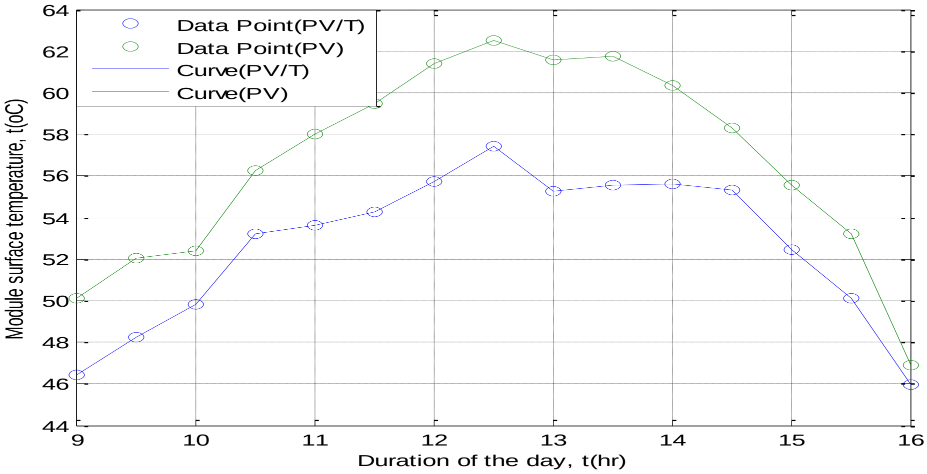


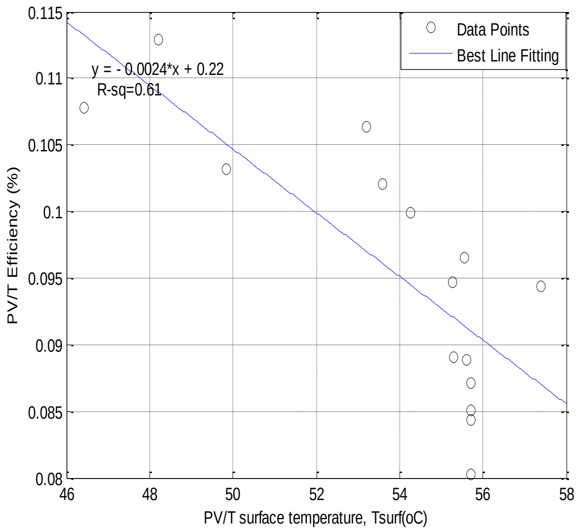
Fig. 5: Effect of cooling on PV module surface temperature

The area under the curve for Figure 5 was determined from the modeled equations 2 and 3 of the curve fittings for Figure 5, with lower and upper limits of 9 and 16.

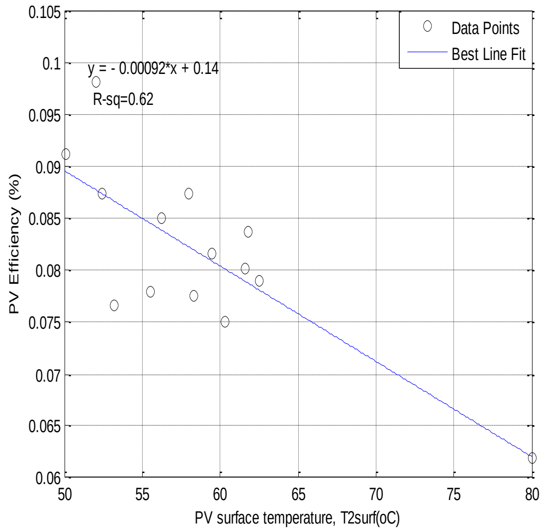
$$T_{Surf}^{pvt} = -0.81t^2 + 20t - 73 \quad (2)$$

$$T_{Surf}^{pv} = -1.1t^2 + 27t - 110 \quad (3)$$

The respective area under the PV and PV with cooling curve fittings were 357.93unit^2 and 329.91unit^2. Hence, there was a 4.08% reduction in heat developed on the surface of PV module as a result of cooling process. The effect of 4.08% reduction in thermal energy in the form heat is presented in Figures 6(a) and 6(b), i.e., the relationships between solar module conversion efficiency and module surface temperature (with and without cooling).



(a)



(b)

Fig. 6: Solar module efficiency - surface temperature interaction with and without cooling.

The modeled equations from Figures 6(a) and (b) are

$$\eta_{PVT} = 0.22 - 0.0024T_{Surf}^{PVT} \quad (4)$$

$$\eta_{PV} = 0.14 - 0.00092T_{Surf}^{PV} \quad (5)$$

The reference efficiency, η_{ref} at the reference temperature and the PV module efficiency temperature coefficient, β were determined from a linear correlation given by Florschuetz (Tonui and Tripanagnostopoulos, 2006).

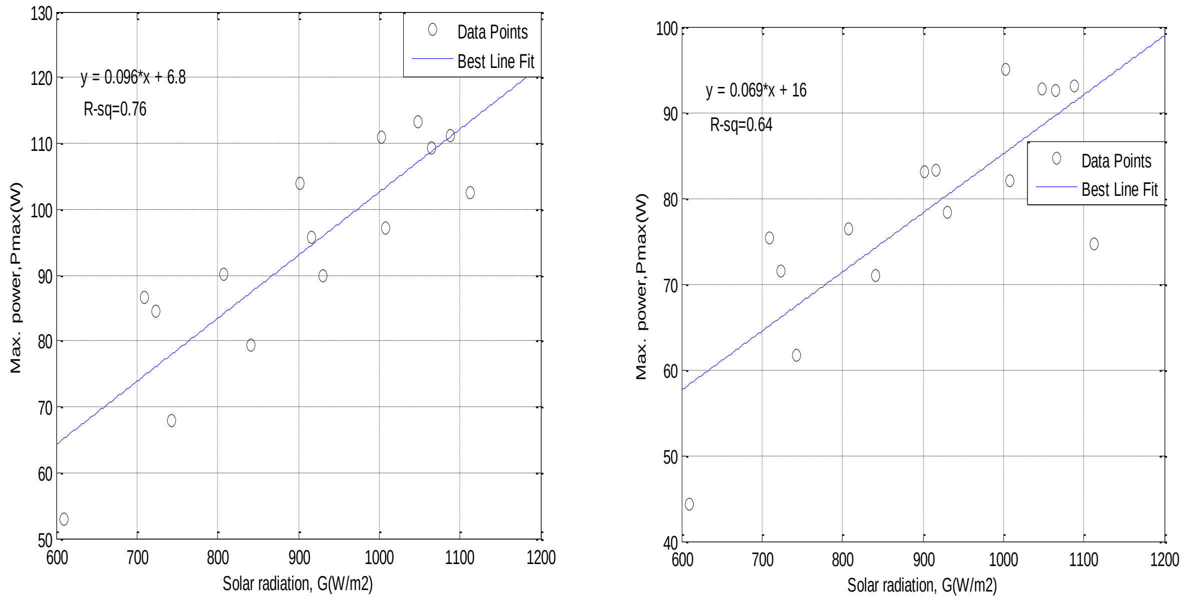
$$\eta_{el} = \eta_{ref}\left[1 - \beta\left(T_{PV/T} - T_{ref}\right)\right] \quad (6)$$

Comparing equations 4 and 5 with equation 6, the PV module temperature coefficients, β of 0.0146%°C^{-1} and 0.0080%°C^{-1} were determined for PV module with and without cooling process. The respective reference efficiencies are 16.43% and 11.32%. This is an indication the process of cooling has a significant effect of the conversion efficiency of solar cell. This is because at reference temperature of 25°C for both solar modules (with and without cooling system), there was an improvement in the conversion efficiency by 5.11% (as determined from Florschuetz equation).

In previous studies, Dash and Gupta (2015) reported temperature coefficients for monocrystalline, multi-crystalline and CdTe solar modules as -0.446 %/°C, -0.387 %/°C and -0.172 %/°C. The percentage decrease in conversion efficiencies per 1°C for monocrystalline, multi-crystalline and CdTe solar modules are greater compared to what is obtained from the current study. The implication is that, the efficiency is improved. However, one of the solar module for this study is subjected to cooling process.

Guda and Aliyu (2015) reported solar cell temperature coefficients of 7356x10^{-5}%, 7262x10^{-5}% and 7427x10^{-5}% per 1°C rise during harmattan, cloudy and clear sunny seasons respectively. However, an approach different from Florschuetz correlation model was used in their study at arriving solar cells temperature coefficients.

The effect of temperature coefficients, β on the performances of two modules are shown in Figures 7(a) and (b).



(a) (b)

Fig. 7: Effect of temperature coefficient on power outputs (with and without cooling)

Figure 7(a) and (b) is the output power - solar radiation scattered line plots with best line fittings for PV module with and without cooling. The respective modeled equations are

$$P_{\max}^{PVT} = 0.096G + 6.8 \quad (7)$$

$$P_{\max}^{PV} = 0.069G + 16 \quad (8)$$

The results presented in Figures 7(a) and 7(b) have shown that as solar radiation increases, the output power of solar modules also increases. However, the percentage of increase varies for the two solar modules. The output power for solar module subjected to cooling process increases by 9.6x10^{-2}W per 1Wm^{-2} increase in solar radiation, where as the output power for a solar module without cooling system increases by 6.9x10^{-2}W per 1Wm^{-2} increase in solar radiation. The reviewed works limited their studies on the effect of temperature on solar module output power, i.e., established relationship between solar module output power and temperature. However, the relationship between solar modules' output power and intensity solar radiation for both solar module with and without cooling system are linearly correlated. Furthermore, the reference efficiencies for solar modules' with and without cooling were determined to be 16.43% and 11.32% respectively.

Moreso, solar modules output power increased by $9.6x10^{-2}$W and $6.9x10^{-2}$W per $1Wm^{-2}$ for solar module with and without cooling system.
In other words, the percentage decrease in solar modules' conversion efficiency per unit degree Celsius rise in modules' temperature for solar modules with cooling and non-cooling system were determined to be 0.008% and 0.015% respectively. The percentage decrease in conversion efficiency for solar module with cooling system is less than that of solar module without cooling system.

4.0 CONCLUSION

It has been established that as the intensity of solar radiation increases, solar module's temperature also increases. However, the elevated solar module's temperature was regulated by an electronic controller unit at a preset temperature of 45°C. The solar module temperature however was greater than 45°C due to inability of the microcontroller based fluid circulation control unit to regulate the flow rate of the cooling fluid. In addition, the inability to control the initial temperature of cooling fluid was also a contributing factor for solar module temperature to be greater than 45°C. Although, solar module's temperature was reduced by 4.08% as a result of cooling process despite the initial temperature range for cooling fluid. The maximum recorded temperature for solar module with and without cooling system were 57.3°C and 62.7°C respectively.
The temperature coefficients were determined as 0.008%°C and 0.015%°C for solar module with cooling and non-cooling system respectively. The overall effect of cooling process was an improved output power.

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