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Experimental analysis of comparative temperature and exergy of crystalline (c-Si) and amorphous (a-Si) solar PV module using water cooling method

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Abstract: *The objective of the research is to minimize the amount of water and electrical energy needed for cooling of the solar panels, especially in hot arid environment. A cooling system has been developed based on water spraying of PV panels. A mathematical model has been used to determine when to start cooling of the PV panels as the temperature of the panels reaches the maximum allowable temperature (MAT). Both models, the heating rate model and the cooling rate model, are validated experimentally. Based on the heating and cooling rate models, it is found that the PV panels yield the highest output energy if cooling of the panels starts when the temperature of the PV panels reaches a maximum allowable temperature (MAT). This research work proposes PV (PHOTOVOLTAIC) water base cooling system design by using a mono-crystalline and amorphous silicon PV module as solar absorber. Water cooling of a commercial PV module configured as water cooled solar PV system by forced flow is studied. The energy and exergy performance of the water cooled solar PV system has been experimentally determined approx. at constant mass flow rates. The experimental result shows that the water cooled solar PV system has got better performance than the simple PV.*

Keywords: *Solar photovoltaic, Water, Temperature, Solar intensity, Exergy, Efficiency.*

I. Introduction

Photovoltaic (PV) technology [1] is widely used now a day in different applications [2-4] but due to relatively large initial investments but compare to large investment it low overall efficiency, the number of installed capacities is lower than expected. The other major issue of the commercial solar PV technology is its cleaning issue, i.e. dust impact and other particles accumulated on the front surface of PV panel surface that can significantly reduce the amount of electric generation around 30 percent. Hence to increase in panel electrical efficiency along with solving its cleaning question and aiming to develop thinkable cooling techniques for the PV panel.

It is well known that electrical efficiency of PV systems can be increase if module temperature is decrease. Hence so many cooling techniques have been used in past year for improving performance of PV system. In current day, market available from PV technologies, electrical efficiency drop is due to the high cell temperature which ranges from 0.25%/℃ up to 0.5%/℃ (depending from the specific PV technology used), so electrical efficiency can improve with a proper cooling method and each cooling technique should have improve feasibility. The objective of this experiment was to construct an experimental setup and to analyse a water flow cooling technique. The proposed water flow cooling technique can potentially increase PV module performance due to an evaporation of water and self-cleaning effect, which is also a great benefit in terms of improved feasibility in the long run.

1.1. *Overheating effect on PV efficiency*

One of the main impediment that surface the operation of photovoltaic module (PV) is overheating due to excessive solar intensity and high environment temperatures. Over heating decrease the efficiency of the panels dramatically [5]. The ideal P–V characteristics of a solar panel for a temperature variation between 0 ℃ and 75 ℃ are shown in Fig. 1, which is adopted from Rodrigues et al. [6]. The P–V characteristic is the relation between the electrical power output, P, of the solar PV module and the output voltage, V, while the solar radiation, E, and cell temperature, Tm, are kept constant. If any of those two factors, namely Tm and E, are varied then all characteristics have also change. The maximum power output from the solar cells decreases as the solar panel temperature rise, as can be seen in Fig. 1.

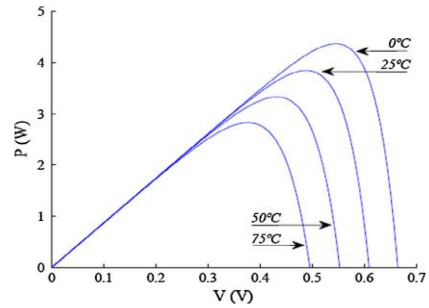


Fig.1. *P–V characteristics as a function of the solar cell temperature Tm, adopted from [2]. The panel temperature varies between 0 ℃ and 70 ℃.*

The temperature coefficient of the photovoltaic cell used in this research [7] is 0.5%/℃, which indicates that every 1℃ of temperature rise corresponds to the drop in the efficiency by 0.5 percent. This shows that high temperature of the PV panels can affect the output of the panels significantly.

1.2. Cooling techniques

The main function of cooling technology in solar PV is to keep the cool and reduce cell temperature uniformly. From thermal point of view, water cooled solar PV system one of the effective method for cooling solar PV cell. The main speciality of hybrid PV/T is to always connect with cooling system uniform cooling. Various ideas to decrease solar reflection from the surface of panel, but various have drawbacks: antireflective-coatings are not durable and structured surfaces are costly, lay up dust and are arduous to clean. Yet refractive index of water is 1.3, is a viable mediate between glass (n_{glass}=1.5) and air (n_{air}=1.0). In addition it help making the panel surface clean and water reduces radiation reflection by 2–3.6% hence decreases cell temperatures up to 22℃ and the electric current yield can return a overplus 10.3%; a overall-gain of 8–9% can be achieved even when accounting for power needed to run the pump. [8].

Water cooled solar PV system is one of the most popular methods for cooling the photovoltaic panels nowadays [9]. The hybrid system consists of a solar photovoltaic panels combined with a cooling system. The cooling agent, i.e., water or air, is flow on the surface of PV panels for cooling the solar cells, such that the heated water or air remove from the PV system and may be used for domestic applications such as domestic heating. Akbarzadeh and Wadowski [5] developed a hybrid PV/T system connected it with cooling system and using water as a cooling agent for rise efficiency and power output of solar PV system. Chanitakis [9] developed a hybrid PV/T solar system and worked on both air and water medium as a cooling agent and found that solar PV with water cooling agent be more effective and gave impressive result with respect to air technique.

II. Experiment and methodology

The experiments were investigated according to the meteorological conditions of Bhopal (latitude of 23.16ºN; longitude of 77.24ºE) in India from 09.00 a.m. in the morning to 5.00 p.m. in the evening. Water is used as a coolant in the system with a varying the water temperature from 15℃ to 23℃. Ambient temperatures, relative humidity, V_w, G, V_{oc}, I_{sc}, P_{max}, front side and rear side temperature of panel, fill factor, voltage and current at maximum power, and exergy of solar PV system were measured every one hour for both normal solar PV and water cooled solar PV systems.

2.1. Experimental Setup

The water cooled solar PV system is constructed using 5W monocrystalline silicon and amorphous (Thin) silicon solar panel. The area of panel is 0.1455 sq. m. of both silicon cell i.e. monocrystalline and amorphous. The enclosure is acting as an absorber. A 12V DC water pump is used to circulate the water on the system. Flow of water uniformly on the front surface of PV panel for uniform cooling on the front surface of the panel Fig.2 and Fig.3.

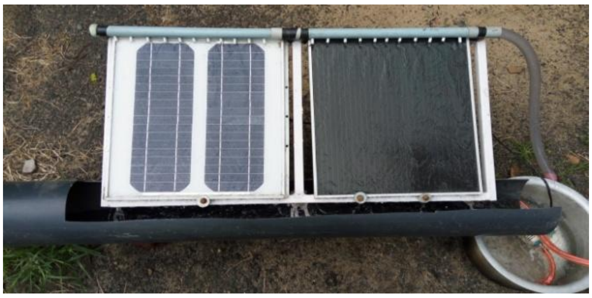


Fig.2. *Experimental setup*

Fig.3. *Close-up of the flowing film of water at the PV module surface*

2.2. Mathematical modelling

Combination of efficiency terms describes the performance of water cooled solar PV system. Thermal efficiency and electrical efficiency are show performance of solar system. Thermal efficiency is the ratio of thermal gain of the system to the incident solar irradiation and the energy efficiency of a water cooled solar PV system is defined as the ratio of the output energy of the water cooled solar PV system to the input energy received on photovoltaic surface. Overall efficiency is the sum of thermal and electrical efficiency and is used to evaluate the overall performance [10].

Photo Electric conversion efficiency, $\eta_e = \frac{Im.Vm}{G.A}$ (1)

Thermal Efficiency, $\eta_{th} = \frac{mCp\,(To-Ti)}{GA} = \frac{Q_{useful}}{A_{module} \times G}$ (2)

However, this definition of energy efficiency is conditioned to theoretical cases. Where S is the solar absorbed flux and it is given by:

$S = G \times A_{module}$

The fill factor is defined as:

$FF = \frac{VmIm}{VocIsc}$

$V_m I_m = FF \times V_{oc} I_{sc}$

Where,

m is mass flow rate of air in kg/sec,

C_p specific heat of air (1005 J/KgK),

C_p specific heat of water (4.2 KJ/KgK)

G is the daily global solar radiation/ intensity on the collector surface,

T_i is inlet air temperature and

T_o is the outlet air temperature

2.2.1. **Energy Efficiency Analysis of Solar Panel**

According to first law of thermodynamics,

$E_{in} = E_{out}$ (3)

General equation for the exergy balance:

$EX_{in} - E_{out} = E_{loss}$ (4)

The energy efficiency of a water cooled PV system is defined as the ratio of the output energy of the water cooling PV system to the input energy received on solar PV module surface.

The energy efficiency of a water cooled PV system is given as

$\eta_{energy} = \frac{Voc.Isc}{G.Amodule} \times FF$

And the energy efficiency of a water cooled PV system at maximum power is defined as the ratio of actual electrical output and input solar radiation PV surface area.

$\eta_{energy} = \frac{Vm.Im}{G.Amodule}$

2.2.2. **Exergy Efficiency analysis of Solar Panel**

Exergy analysis includes a consideration of energy quality or capability, which permits evaluation of the most effective, not just most efficient, use of energy potential. For the steady-state flow process during a finite time interval, the overall exergy of the solar PV can be written as follows.

Exergy Input = Exergy Output + Exergy Loss + Irreversibility (5)

This degradation in the quality of energy is called exergy loss (availability loss). The exergy loss is also called irreversibility.

Exergy efficiency is the ratio of total output exergy to total input exergy. An exergy efficiency of the PV module may be defined as the ratio of the exergy gained by the solar PV to the exergy of the solar radiation.

$\eta_{ex} = \frac{Ex_{output}}{Ex_{input}}$ (6)

Inlet exergy of a PV system includes only solar radiation intensity exergy.

$$E_{x\ input} = AG\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a^4}{T_s^4}\right)\right] \quad (7)$$

The exergy output of the system can be calculated as

$$E_{x\ out} = E_{x\ thermal} + E_{x\ electrical} \quad (8)$$

Thermal Energy

$$E_{x\ thermal} = Q \times \left[1 - \frac{T_a}{T_m}\right] \quad (9)$$

Where,

$$Q = UA\ (T_m - T_a) \quad (10)$$

Overall heat loss coefficient of a PV module

$$U = h_{conv} + h_{rad} \quad (11)$$

Convective heat transfer coefficient

$$h_{conv} = 2.8 + 3V_w \quad (12)$$

Radiative heat transfer coefficient between PV array & surroundings

$$h_{rad} = \varepsilon\sigma(T_{sky} + T_m)(T_{sky}^2 + T_m^2) \quad (13)$$

Temperature of the sky

$$T_{sky} = T_a - 6 \quad (14)$$

Temperature of the module based on NOCT value.

$$T_m = T_a + (NOCT - 20) \times \left(\frac{G}{800}\right) \quad (15)$$

Electrical exergy in the power output of PV module

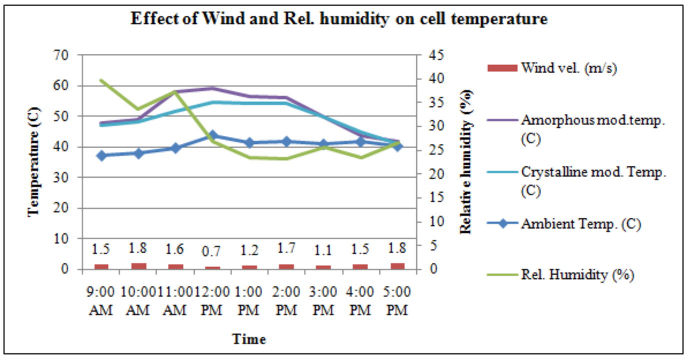
E_x electrical = V_{oc} x I_{sc} x FF

2.3 Instruments used

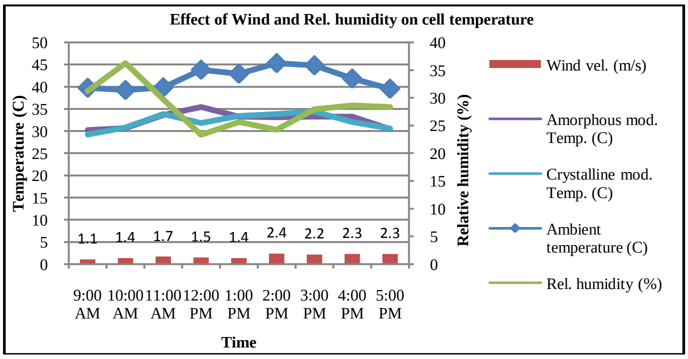
Total Instantaneous Global Solar intensity was measured by using portable Solar Power meter (Tenmars TN-207, Taiwan) with an uncertainty of ±10 percent. The ambient (environmental) temperature and humidity was measured with digital thermo hygro meter. An electrical characteristic of water cooled solar PV was measured with Solar Module Analyzer (MECO 9009). Ambient temperature of atmosphere was measured with digital thermometer. Front side and rear side temperature of water cooled solar PV system was measured by using IR Thermometer.

III. Result

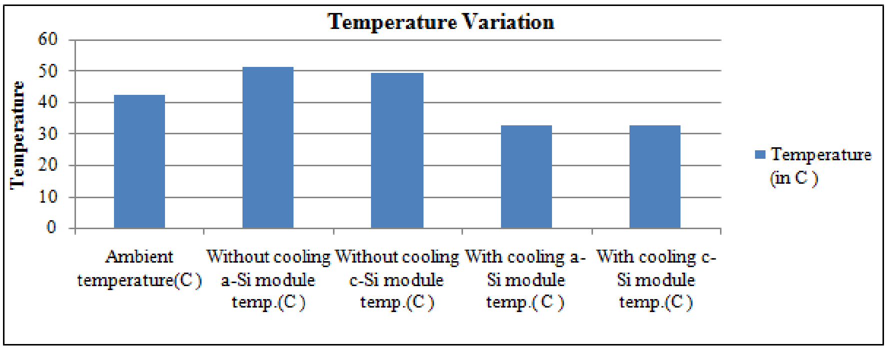
3.1. Effect of Wind and Relative humidity on PV module temperature during without cooling process with the help of line graph



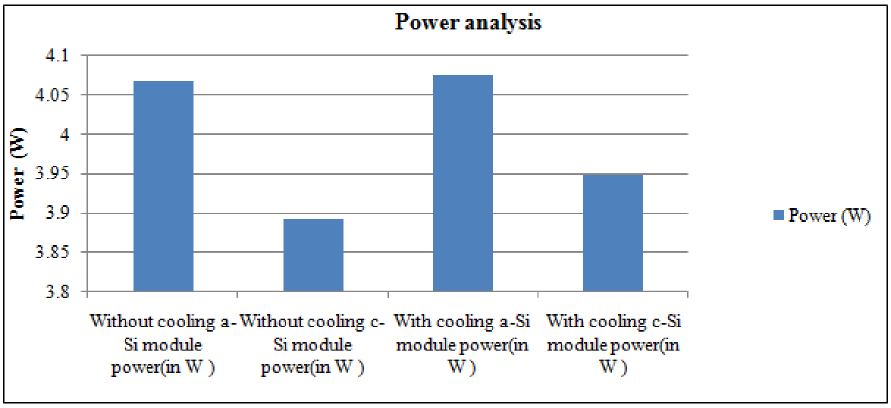
2.3. Effect of Wind and Rel. humidity on PV module temperature during cooling process with the help of line graph



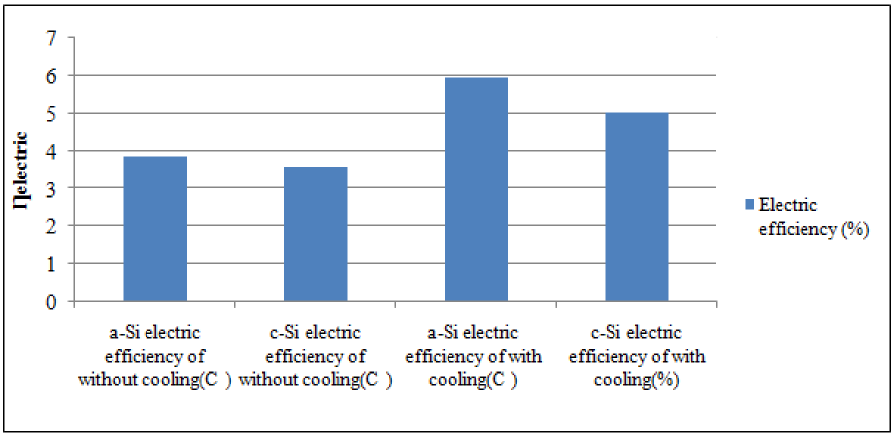
3.3. Effects of ambient temperature on module under water cooling technique and comparison it with non-cooling module-



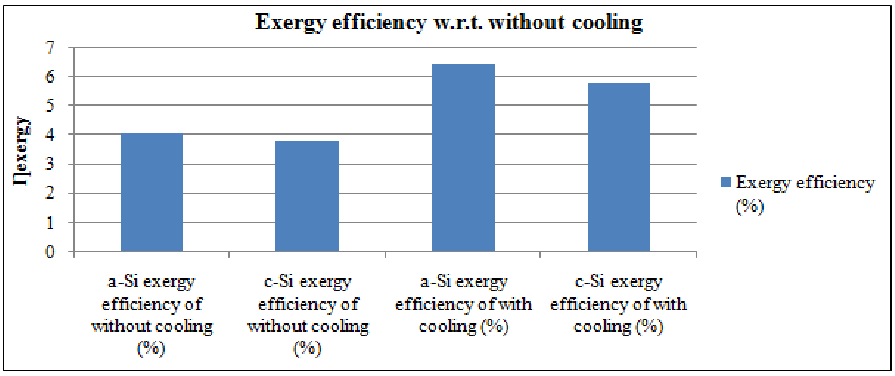
2.4. Effect of water flow cooling method on power output



2.5. Effect of water cooling technique on module electric efficiency –



3.6**.** Comparison of with and without cooling base exergy efficiency between two different modules-



IV. Conclusion

The main goal of this research is to uniform cool the PV panels by using the least amount of water and energy. A uniform cooling system has been developed based on water flow on the PV panels by uniformly. A cooling rate model has been made to evaluate how time it will take to cool the PV panels by water flow to its operating temperature. A mathematical model has been used to find the heating rate of the PV panels, in order to determine when to start cooling. An experimental setup has been constructed to validate both models, i.e., the heating and the cooling rate models, experimentally, and to study the effect of cooling method on the operation of PV panels. It can be concluded from the results of this study that;

1. It is used to cool and clean the PV cell or module using the proposed cooling system in hot and dusty regions.
2. The cooling rate for the solar cells is 2℃/min based on the concerned operating conditions, which means that the cooling system of PV will be analysis every hour, in order to decrease the module temperature around 10℃. The result of the uniform water cooling model has shown better agreement with the experimental measurements.
3. The PV panels yields the highest output energy if cooling of the cells starts when the hotness of the solar PV cells reaches the maximum allowable temperature (MAT). The MAT is a deal temperature between the actual output energy from the PV panels and the energy needed for cooling.
4. Under water cooling method amorphous array gave better performance as compare to mono-crystalline array.

Nomenclature:-

A_{module}	Area of PV/T module
V_{OC}	Open circuit voltage
I_{SC}	Short circuit voltage
V_m	Maximum voltage (V)
I_m	Maximum current (A)
FF	Fill factor
U_{loss} (U)	Overall heat loss coefficient of PV/T module
$h_{convection}$	Convective heat transfer coefficient
$h_{radiative}$	Radiative heat transfer coefficient
V_{wind}	Wind velocity (m/s)
T_{ambent} (T_a)	Ambient temperature
T_{sky}	Effective sky temperature (= T_a- 6)
$E_{X\ input}$	Input exergy
$E_{X\ output}$	Output exergy
$\eta_{electric}$	Electric efficiency
$\eta_{thermal}$	Thermal efficiency
S	Solar absorbed flux
T_{sun} (T_s)	Sun temperature (= 5780K approx.)
T_m	Module temperature
G	Solar radiation intensity
a-Si	Amorphous silicon cell
c-Si	Crystalline silicon cell

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