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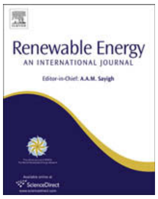

Technical Note

Theoretical and operational thermal performance of a ‘wet’ crystalline silicon PV module under Jamaican conditions

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the results of the impact of a gravity-fed cooling technique applied to a photovoltaic module. The experiment shows that the technique increases the power output of the module by reversing the negative effects of elevated cell temperature on open circuit voltage, and this without the use of a circulating pump. The cooling technique employs the hydraulic head of water from an upstream source as the driving force that passes water over the back of the module, and this keeps the module temperature constant. The experimental results and the results of mathematical model on which it is predicated on are in very close agreement.

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1. Introduction

A major portion of the research in the photovoltaic field focuses on the thermal control of the cell (Cordero et al.; Ronnelid et al. [1,2]). Hence, effective cooling of PV cells is seen as part of the advances in the technology and this paper presents the findings from the application of a cooling technique to crystalline silicon (c-Si) photovoltaic cells.

Photovoltaic (PV) is the use of certain types of material, which are called semiconductors, to convert light energy (e.g. sunlight) directly into electricity. Only a portion of the light energy that enters the cell is converted to electricity; the rest converts to heat. Photovoltaic applies no moving part, is totally environmentally friendly, silent, a reliable technology and has the potential of addressing a significant portion of the world’s energy needs. Gallium arsenide (GaAs), cadmium sulfide (CdS), silicon (Si) and germanium (Ge) are examples of semiconductor materials used to fabricate photovoltaic cells; and from among the PV cells manufactured crystalline silicon cells predominate (Carabe and Gandia; Radziemska, [3,4]). One reason for this domination is that silicon, in the form of silica (high grade sand, quartz rock), abounds in nature. So having a cheap source of raw material the next step is to improve the conversion efficiency of the cell.

It has been established that the conversion efficiency, which translates to power output of PV cells, falls as the cell temperature is elevated. This phenomenon, according to Maycock and Stirewalt [5], is more pronounced in silicon cells than other cells such as gallium arsenide. The phenomenon, though, seems puzzling if one assumes power output is solely dependent on electrical conductivity ($P = IV$). In addition, quantum physics shows that the increase in conductivity of a semiconductor is directly proportional to temperature.

To further make the point, Goetzberger, et al. [6] state that electrical conductivity in the form of free electrons per unit volume, n, in the conduction band of a semiconductor, depends decisively on temperature as demonstrated by the formula

$$n = 2\left\{\left(2\pi m_n^* kT\right)/h^2\right\}^{3/2}\exp\left[\left(E_f - E_c\right)/kT\right] \qquad (1)$$

where the term before the exponential function is the effective density of state of the electrons in the conduction band. The fermi level energy (E_f) is less than the conduction band energy (E_c), which shows that the exponential term is greatly influenced by temperature.

Goetzberger, et al. [6] further point to the fact that at absolute zero semiconductors become insulators, and only as temperature increases is conductivity seen. This fact seems to suggest that the conductivity of a PV cell as a function of temperature would be limited only by how high temperature a PV cell can sustain; and by implication so too is power output. But Maycock and Stirewalt [5] show that power output of PV cells is not solely dependent on electrical conductivity but, at a given insolation, is inversely proportional to temperature.

This inverse relationship of power output (conversion efficiency) to temperature is due to the dependence of the open circuit voltage, V_{oc}, on temperature, according to Angrist, Hu and White, and Graff and Fischer [7–9].

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Nomenclature

C_p	specific heat (kJ/kg K)
e	electronic charge
E_c	energy in the conduction band
E_f	energy at the Fermi level
E_g	band gap energy
$f(x)$	temperature of slab at time zero
F_n	transient temperature coefficient
h	Planck's constant
I_o	saturation current
I_{sc}	short circuit current
k	Boltzmann constant, thermal conductivity (W/m °C)
L	thickness of (PV cell) silicon slab (m)
L_p	diffusion length
m_n^*	effective mass of electrons
q	elementary charge
q_0	solar irradiance on cell (position $x = 0$) (W/m^2)
t	time
T	temperature (K)
U	temperature of cell (°C)
U_L	temperature of cooling water (°C)
U_T	thermal voltage (kT/q)
V	transient cell temperature (°C)
x	position along cell thickness (m)
Greek	
α	thermal diffusivity of silicon (m^2/s)
φ	steady state cell temperature (°C)
ρ	density of silicon (kg/m^3)
ρ_n	electrical resistivity (ohm-cm)
μ	mobility of charge carrier
Subscripts	
n	electron
p	hole

Goetzberger et al. [6] give the development of the open circuit voltage as

$$V_{oc} \approx U_T \ln(I_{sc}/I_o) \tag{2}$$

(where $U_T = kT/q$, thermal voltage) and they state that the efficiency of a PV cell is essentially reducing the saturation current, I_o.

Graff and Fischer further explain that, in a cell, the current–voltage characteristics obtained in the dark is of equal importance as that of the photocurrent. They state that this is due to the fact that when power is drawn from a cell the 'dark current' which exists across the junction opposes the photocurrent. The most important contribution to the 'dark current', they state, is that from the saturation current, I_o, which comes from the injection of minority carriers crossing the p–n junction.

In establishing the impact of the saturation current, I_o, on conversion efficiency (power output), Angrist [7] shows that current density, $J_o = I_o/A$, which is saturated current per unit area, is given by

$$J_{o(p)} = 2.23 \times 10^{31} T^3 \rho_n \mu_n \mu_p k T e L_p^{-1} \exp[-E_g/(kT)] \tag{3}$$

which shows the strong dependence of J_o on temperature since the term before the exponential is influenced by the fourth power of temperature. Likewise, the exponential varies according to temperature fluctuations for a given semiconductor material. Angrist notes that the smaller J_o is the more efficient the cell becomes, and concludes that the lower the operating temperature of a PV module the better its performance.

In general, the literature shows a lowering in open circuit voltage, V_{oc}, of −0.41%/K and reduction in conversion efficiency of the same order of −0.4%/K at temperatures above 298 K (King et al.; Sweelem et al.; and Hu and White [8,10,11]). Therefore, in addressing the problem of reduction in conversion efficiency of PV cells due to elevated operating temperature, some form of cooling mechanism has to be employed for the cells.

Various techniques have been used in an attempt to cool PV cells. The following are some of the techniques used:

1. A string module with the cells laminated on a copper fin absorber with a water tube welded on to the back was used by Brogren and Karisson [12].
2. A heat spreader made of 3 mm thick aluminum plate attached to a module was proposed by Araki et al. [13].
3. Farahat [14] employed the evaporative cooling method based on the theory of heat pipes. He designed the PV cell as a controlled gas heat pipe with variations in the shape of the evaporator.
4. Increasing thermal mass of modules by attaching them to small water filled tanks is a method used by Ronnelid, et al.; and Krauter [2,15]. Krauter found, though, that this technique greatly increases the weight of the module in the order of 200 kg/module.
5. Sweelem et al. [11] blew air across the back of the cell through an adjustable air-gap.

From the literature, of all the techniques adapted to cool PV cells, circulating water over the cell, usually at the back, prove to be the most effective (Brogren and Karisson [12]). Krauter [15], though, circulated water over the front of the cell with very good effect, but this technique runs the risk of depositing scales on the face of the cell and thus reducing its effectiveness. The circulating water technique has one major draw back and that is the 'parasitic' power required to run the pumps. This means that part of the power gained in cooling the cell is "lost" in running the pump.

In an attempt to negate the 'parasitic' power problem, Furushima and Nawata [16] devised a system which utilizes siphonage. By using the city mains to get water to the supply tank on top of the building, they bypassed the use of a pump. For circulating the water over the back of the cells they employed a piping system with a controller for valve openings which induces siphonage in the piping from the top level to the ground level of a building.

This technique, besides being somewhat complex with controllers and synchronizing valves, will also require the maintenance of airtight seals in the piping. So, in assessing the effectiveness of any cooling system, simplicity of design and net power gains (increase power from cooling minus parasitic power for circulating pump) are issues to be considered.

With the aim of achieving design simplicity and maximizing power gains of a cooling system for a PV module, this investigation uses a Gravity-Fed Technique. That is, water being diverted from an upstream source such as a river, or from any elevated position, including catchments of rain water, is channeled across the back of a PV module ('wet' module), cools the module and is returned to the river downstream.

The power required to drive the water through the system comes from the hydraulic head of the flow stream under gravity, due to the difference in elevation. (It must be noted that this cooling technique limits the system to regions that have water supply. Hence it is envisioned that this system will be coupled to remote or semi-remote PV power generation).

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