The Solar Cell Parameters as a Function of Its Temperature in Relation to Its Diurnal Efficiency

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Abstract

The variation of the temperature of the solar cell subjected to the incident global solar radiation along the local daytime in relation to its efficiency is studied. The heat balance equation is solved. The solution revealed that the cell temperature is a function of the maximum value of the daily incident global solar radiation $q_{\text{max}}$, the convection heat transfer coefficient ($h$), the optical, physical and the geometrical parameters of the cell. The temperature dependence of the short circuit current $I_{\text{sc}}$, the dark saturation current $I_{\text{d}}$, the open circuit voltage $V_{\text{oc}}$, and the energy band gap $E_g$ characterizing a Silicon solar cell is considered in evaluating the cell efficiency. Computations of the efficiency concerning operating conditions and astronomical locations (Egypt) as illustrative examples are given.

Keywords
Solar Cell Performance, Solar Energy, Solar Cell Temperature, Heat Transfer Model

1. Introduction

Heating a solar cell subjected to the incident global solar radiation affects its photovoltaic performance [1]-[7]. The solar p-n cell is a semiconductor photovoltaic device.

Solar energy can be converted into electricity are termed as the photovoltaic devices or solar cells. At present this solar cell is the most important long-duration power supply for satellites and space vehicles. Solar cells have also been successfully employed in small-scale terrestrial applications. Due to this the study of the efficiency of the solar cell with the aim to increase its value has aroused the in-
interest of many investigators [8]-[22].

The efficiency (\(\eta\)) is a measure of the cell performance which depends on many parameters. Many of such parameters are temperature dependent.

The performance of a solar cell is determined by parameters as a short circuit current \(I_{sc}(T)\) and open circuit voltage \(V_{oc}(T)\). It has been shown earlier that \(I_{sc}\) increases with increasing the temperature whereas open circuit voltage \(V_{oc}\) decreases with increasing the temperature.

The aim of the present work is to find theoretically the temperature field within the solar cell considering different optical, physical, geometrical conditions. The temperature functional dependences of the cell parameters \(V_{oc}\), \(I_{sc}\) and the efficiency are also taken into consideration.

2. The Mathematical Formulation of the Problem

In setting up the problem it is assumed that solar radiation of irradiance \(q(t)\) W/m² is incident on the front surface of the solar cell, where it is partly absorbed and partly reflected.

The absorbed quantity is \(Aq(t)\), where “\(A\)” is the absorption coefficient at the front surface of the considered cell. The heat diffusion equation is given in the form:

\[
SA_{a}q(t) - Sh\theta(t) = S\rho c_{p}\frac{d\theta}{dt}
\]

where:

\[
\theta(t) = (T(t) - T_{o}), \text{K} \quad \text{is the excess temperature of the cell relative to the ambient temperature } T_{o}, \text{, } S (m²) \text{ is the area of the cell front surface, } h \text{ (W/m²-K) is the convection heat transfer coefficient at the front surface, } l \text{ (m) is the all layer thickness, } \rho \text{ (kg/m³), } c_{p} \text{ (J/kg-K) are density and the specific heat of the solar cell material respectively.}
\]

Equation (1) can be written as:

\[
\frac{d\theta}{dt} + a\theta(t) = Bq(t)
\]

where,

\[
a = \frac{h}{\rho c_{p}} \quad \text{and} \quad B = \frac{A}{\rho c_{p}}
\]

Equation (2) can be solved using the integrating factor \([23]\) as follows:

\[
\theta(t)e^{\int adt} = \int_{0}^{t} Bq(t)e^{\int adt} dt
\]

\(q(t), \text{ (W/m²)}\) is the irradiance of the incident solar radiation given in the form \([24]\):

\[
q(t) = q_{max}\left(\frac{1}{t_{o}}\right)^{2}\left(\frac{1}{t_{o} - t}\right)^{2}t^{2}(t_{o} - t)
\]

where:
\( q_{\text{max}}, \text{W/m}^2 \) is the maximum irradiance of the incident solar radiation;
\( t_0 = (t_s/2) \), is the mid time between sunrise and sunset in hours;
\( t_d = (t_s - t_r)\), is the length of the solar day given as:
\[
t_d = \frac{2}{15} \cos(-\tan \phi \tan \delta)
\]
where:
\( \phi \), is the latitude and \( \delta \) is the solar declination angle given as:
\[
\delta = 23.45 \sin \frac{284 + n}{365}
\]
\( t_r \) is the sunrise time in hours;
\( t_s \) is the sunset time in hours;
And “n” is the day of the year \((1 \leq n \leq 365)\) starting from 1 January.
The solution is obtained as the form [26]:
\[
\theta(t) = B_t \left[ \left( \frac{t^2 - 2t + 2}{a} \right) - \frac{2}{a} e^{-at} \right] - 2B_t \left[ \left( \frac{t^3 - 3t^2 + 6t - 6}{a} \right) + \frac{6}{a} e^{-at} \right] \\
+ B \left[ \left( \frac{t^4 - 4t^3 + 12t^2 - 24t + 24}{a} \right) - \frac{24}{a} e^{-at} \right]
\]
Equation (5) represents the temperature of the considering cell after an exposure time “t” along the solar day time.

3. The Efficiency Temperature Dependence for the Solar Cell

The efficiency \( \eta \) of the solar cell is defined as the ratio between the maximum power \( P_{\text{max}} \) \( (= FFV_{oc} I_{sc} \) \), generated by a solar cell and the received power \( P_{in} \) as follows [2]:
\[
\eta = \frac{FFI_{oc} V_{oc}}{P_{in}}
\]
\( P_{in} \) \( \text{(W/m}^2 \) is the input total solar power received by the solar cell;
\( V_{oc} \) is the open circuit voltage which is given as [2]:
\[
V_{oc} = \frac{KT}{e} \ln \left( \frac{I_m}{I_o} + 1 \right)
\]
where:
\( K \) \( \text{(J/K)} \) is the Boltzmann constant, \( T \) \( \text{(K)} \) is the cell temperature \((e = 1.6 \times 10^{-19} \text{ Coulomb})\) is the electron charge, \( I_o \) \( \text{(amp/m}^2 \) is the reverse saturation current and its dependence on temperature is revealed through the following equation [2]:
\[
I_o = \epsilon n T^n e^{\frac{-E_g}{kT}}
\]
where:
\( \epsilon = 179 \text{ amp/K}^3 \cdot \text{m}^2 \) for silicon solar cell [18], \( n \) is non-ideality factor of the cell and is taken as unity, the value of \( \gamma = 3 \) [2];
\( E_g \) is the energy band gap. The dependence of energy band gap of a semicon-
ductor on temperature can be described as [27] [28]:

\[
E_g = E_g(0) - \frac{\alpha T^2}{T + \beta}
\]  

(9)

\(E_g(0)\) is the energy band gap of the semiconductor at \(T \approx 0\) K;

For silicon \(E_g(0) =1.16\) eV [29], \(\alpha = 7 \times 10^{-14} \) eV\(\cdot\)K\(^{-1}\) and \(\beta = 1100\) K.

Which are constants for each semiconductor material [28], \(I_n\) is short circuit current given as [8],

\[
I_{sc} = Q(1 - R(T))(1 - \exp(\mu l))en_{\text{photons}}
\]  

(10)

where:

\(Q\) is the collection factor, \(R(T)\) is the reflection coefficient at the front face of the cell and its value is given as [30]:

\[
R(T) = 0.322 + 3.12 \times 10^{-5} T
\]  

(11)

\(\mu\) is the attenuation coefficient and is value given as [30]:

\[
\mu = a \exp\left(\frac{T}{T_S}\right)
\]  

(12)

where:

\(a = 3.17 \times 10^4\) m\(^{-1}\); and

\(T_S = 346\) K, \(l\) in meter is the thickness of the solar cell,

\(n_{\text{photons}}\) is the number of photons with energy greater than the band gap and for simplicity its value for a given temperature \(T\) at a certain local daytime is given as:

\[
n_{\text{photons}} = \frac{q(t)}{E_g}
\]  

(13)

4. Computations

The silicon solar cell is considered with dimensions (5.5 cm \(\times\) 11 cm \(\times\) 0.35 cm) is considered [31]. The silicon solar cell temperature as a function of the local day time “\(t\)” is calculated using Equation (5), the physical parameters of Silicon are:

\[
\rho = 2280 \text{ kg/m}^3, \ c_p = 840 \text{ J/kg}
\]

The hourly incident global solar radiation \(q(t)\) (Equation (4)) is considered for Egypt [32] as an illustrative example. The values of \(I_n, I_a\) and \(V_{oc}\) corresponding to each value of \(T\) at a certain time “\(t\)” are determined.

Hence the efficiency “\(\eta\)” of the cell as a function of the solar local day time “\(t\)” is estimated for considered location.

For Egypt (July) [32] the \(q(t)\) parameters are:

\(q_{\text{max}} = 1045\) W/m\(^2\), \(t_d = 14\) hours, \(t_r = 0\) hours, \(t_0 = 7\) hours.

Different thickness \(l = 10^{-3}, 3 \times 10^{-3}, 5 \times 10^{-3}\) m are considered at \(h = 1\) W/m\(^2\)\(\cdot\)K, \(A = 0.7\).

The obtained results are given in Table 1 and illustrated graphically in Figure 1 showing that the temperature of the solar cell increases as the thickness decreases.

Different cooling conditions \(h = 3, 5, 10\) W/m\(^2\)\(\cdot\)K are considered at thickness \(l = 10^{-3}\) m, \(A = 0.7\) the obtained results are given in Table 2 and illustrated graphically...
Table 1. The temperature of the cell as a function of the local day time at $A = 0.7$ and $h = 1 \text{ W/m}^2\cdot\text{K}$ for different value of the thickness.

| shifted time $t$, hr. | $T$, K | $I = 10^{-3} \text{ m}$ | $I = 3 \times 10^{-3} \text{ m}$ | $I = 5 \times 10^{-3} \text{ m}$ |
|----------------------|--------|------------------------|------------------------|------------------------|
| 0                    | 0      | 0                      | 0                      |
| 1                    | 21.5   | 0                      | 6.4                    |
| 2                    | 111    | 11.7                   | 40.1                   |
| 3                    | 250    | 106                    | 108                    |
| 4                    | 405    | 230                    | 205                    |
| 5                    | 548    | 363                    | 316                    |
| 6                    | 656    | 483                    | 426                    |
| 7                    | 714    | 573                    | 520                    |
| 8                    | 716    | 620                    | 583                    |
| 9                    | 660    | 617                    | 608                    |
| 10                   | 554    | 563                    | 591                    |
| 11                   | 412    | 467                    | 534                    |
| 12                   | 257    | 341                    | 445                    |
| 13                   | 116    | 208                    | 339                    |
| 14                   | 26.5   | 96.4                   | 239                    |

Table 2. The temperature of the cell as a function of the local day time at $l = 10^{-3} \text{ m}$ and $A = 0.7$ for different value of the cooling.

| shifted time $t$, hr. | $T$, K | $\dot{h} = 3 \ (\text{W/m}^2\cdot\text{K})$ | $\dot{h} = 5 \ (\text{W/m}^2\cdot\text{K})$ | $\dot{h} = 10 \ (\text{W/m}^2\cdot\text{K})$ |
|----------------------|--------|----------------------------------|----------------------------------|----------------------------------|
| 0                    | 0      | 0                                | 0                                | 0                                |
| 1                    | 12.3   | 8.44                             | 4.52                             |
| 2                    | 50.1   | 32                               | 16.2                             |
| 3                    | 101    | 62.9                             | 31.1                             |
| 4                    | 153    | 94.2                             | 45.7                             |
| 5                    | 198    | 121                              | 57.6                             |
| 6                    | 229    | 139                              | 64.9                             |
| 7                    | 242    | 146                              | 66.4                             |
| 8                    | 236    | 141                              | 61.7                             |
| 9                    | 211    | 126                              | 51.2                             |
| 10                   | 170    | 100                              | 35.9                             |
| 11                   | 120    | 69.7                             | 17.5                             |
| 12                   | 67.2   | 38.2                             | 0                                |
| 13                   | 23.4   | 12.5                             | 0                                |
| 14                   | 1.15   | 0                                | 0                                |
Figure 1. The variation of the temperature of the cell as a function of the local day time in $h = 1 \text{ W/m}^2\cdot\text{K}$ and $A = 0.7$ for different thickness.

in Figure 2 which show that the temperature of the solar cell increases as the cooling conditions at the front surface decreases.

Different absorption coefficients $A = 0.6, 0.7, 0.8$ are considered at $l = 10^{-3} \text{ m}$, $h = 3 \text{ W/m}^2\cdot\text{K}$. The obtained results are given in Table 3 and illustrated graphically in Figure 3 which show that the temperature of the solar cell increases as the absorption coefficients at the front surface increases.

The variation of $I_{sc}$, $V_{oc}$ for the case:

$I = 5 \times 10^{-3} \text{ m}$, $A = 0.7$, $h = 1 \text{ W/m}^2\cdot\text{K}$ are computed and are illustrated in Figure 4 and Figure 5.

The obtained results revealed that $I_{sc}$ increases with increasing the temperature and vice versa.

Moreover, the short circuit current $I_{sc}$ increases with increasing temperature and vice versa. This variation may be attributed to the fact that for most semi-conductors, as the temperature increases, the energy band gap decreases [19].
Figure 2. The variation of the temperature of the cell as a function of the local day time in $l = 10^{-3}$ m and $A = 0.7$ for different values of the cooling coefficient.

Figure 3. The variation of the temperature of the cell as a function of the local day time in $l = 10^{-6}$ m and $A = 0.7$ for different values of the cooling coefficient.

Figure 4. The variation of $I_{sc}$ at $l = 5 \times 10^{-3}$ m, $h = 1$ W/m$^2$ and $A = 0.7$. 
Figure 5. The variation of $V_{oc}$ at $I = 5 \times 10^{-3}$ m, $h = 1$ W/m$^2$K and $A = 0.7$.

Figure 6. The temperature dependence of $n$ at $I = 5 \times 10^{-3}$ m, $h = 1$ W/m$^2$K and $A = 0.7$.
**Figure 7.** The temperature dependence of $n$ at $l = 5 \times 10^{-3} \text{ m}$, $h = 1 \text{ W/m}^2\cdot\text{K}$ and $A = 0.7$.

**Figure 8.** The temperature dependence of $\eta$ at $l = 10^{-3} \text{ m}$, $h = 1 \text{ W/m}^2\cdot\text{K}$ and $A = 0.7$. 
### Table 3. The temperature of the cell as a function of the local day time at $l = 10^{-3}$ m and $h$ = 3 W/m²·K for different value of the absorption coefficient at the front surface.

| Shifted time $t$, hr. | $T$, K | $A = 0.6$ | $A = 0.7$ | $A = 0.8$ |
|-----------------------|---------|------------|------------|------------|
| 0                     | 0       | 0          | 0          | 0          |
| 1                     | 10.6    | 12.3       | 14.1       |            |
| 2                     | 42.9    | 50.1       | 57.2       |            |
| 3                     | 86.4    | 101        | 115        |            |
| 4                     | 131     | 153        | 175        |            |
| 5                     | 170     | 198        | 226        |            |
| 6                     | 196     | 229        | 262        |            |
| 7                     | 208     | 242        | 277        |            |
| 8                     | 202     | 236        | 269        |            |
| 9                     | 181     | 211        | 241        |            |
| 10                    | 146     | 170        | 194        |            |
| 11                    | 103     | 120        | 137        |            |
| 12                    | 57.6    | 67.2       | 76.7       |            |
| 13                    | 20      | 43.4       | 26.7       |            |
| 14                    | 0       | 1.15       | 1.31       |            |

Equation (7) reveals that the behavior of $V_{oc}$ with temperature is controlled by two factors $\frac{kT}{e}$ and $\ln\left(\frac{I_{oc}}{I_o}+1\right)$. The first factor suggests a linear relation on $(T)$ while is relation deviated due to the presences of the logarithmic function $\ln\left(\frac{I_{oc}}{I_o}\right)$ grows slowly with $T$ than the function $\frac{kT}{e}$.

$V_{oc}$ has weak dependence on "$T$" than $I_{oc}$.

### 6. Conclusions

The temperature of the solar cell subjected to incident solar insolation increases with local day time and passes through a maximum value then it decreases gradually toward sunset. The cell parameters $V_{oc}$, $I_{oc}$, and the efficiency $\eta$ are functions of the cell temperature with different degrees.

The efficiency $\eta$ of the cell decreases with the cell temperature in general. Thus cooling, the solar cell is recommended.

The open circuit voltage $V_{oc}$ is less dependent on the temperature than the short circuit current $I_{sc}$.

### Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.
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