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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 $q_{\max}$, 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_{sc}, the dark saturation current I_o, the open circuit voltage V_{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 interest of many investigators [8]-[22].

The efficiency (η) 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 sitting up the problem it is assumed that solar radiation of irradiance $q(t)$ W/m^2 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:

$$SA_{ab}q(t) - Sh\theta(t) = S\rho lc_p \frac{\mathrm{d}\theta}{\mathrm{d}t} \tag{1}$$

where:

$\theta(t) = (T(t) - T_O), \mathrm{K}$ is the excess temperature of the cell relative to the ambient temperature T_O, S (m^2) is the area of the cell front surface, h (W/m^2·K) is the convection heat transfer coefficient at the front surface, l (m) is the all layer thickness, ρ (kg/m^3), c_p (J/kg·K) are density and the specific heat of the solar cell material respectively.

Equation (1) can be written as:

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} + a\theta(t) = Bq(t) \tag{2}$$

where,

$$a = \frac{h}{\rho lc_p} \quad \text{and} \quad B = \frac{A}{\rho lc_p}$$

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

$$\theta(t)\mathrm{e}^{\int_0^t a\mathrm{d}t} = \int_0^t Bq(t)\mathrm{e}^{\int_0^t a\mathrm{d}t} \tag{3}$$

$q(t)$, (W/m^2) is the irradiance of the incident solar radiation given in the form [24]:

$$q(t) = q_{\max}\left(\frac{1}{t_0}\right)^2\left(\frac{1}{t_d - t_0}\right)^2 t^2(t_d - t) \tag{4}$$

where:

$q_{\max}$, W/m^2 is the maximum irradiance of the incident solar radiation;

$t_0 = (t_d/2)$, 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:

$$t_d = \frac{2}{15}\cos(-\tan\phi\tan\delta) \quad [25]$$

where:

ϕ, *is* the latitude and δ 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 ($1 \le n \le 365$) starting from 1 January.

The solution is obtained as the form [26]:

$$\theta(t) = Bt_d^2\left[\left(\frac{t^2}{a}-\frac{2t}{a^2}+\frac{2}{a^3}\right)-\frac{2}{a^3}e^{-at}\right]-2Bt_d\left[\left(\frac{t^3}{a}-\frac{3t^2}{a^2}+\frac{6t}{a^3}-\frac{6}{a^4}\right)+\frac{6}{a^4}e^{-at}\right] + B\left[\left(\frac{t^4}{a}-\frac{4t^3}{a^2}+\frac{12t^2}{a^3}-\frac{24t}{a^4}+\frac{24}{a^5}\right)-\frac{24}{a^5}e^{-at}\right] \quad (5)$$

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 (η) of the solar cell is defined as the ratio between the maximum power $P_{\max}(=FFV_{oc}I_{sc})$, generated by a solar cell and the received power P_{in} as follows [2]:

$$\eta = \frac{FFI_{sc}V_{oc}}{P_{in}} \quad (6)$$

P_{in} (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]:

$$V_{oc} = \frac{KT}{e}\ln\left(\frac{I_{sc}}{I_o}+1\right) \quad (7)$$

where:

$K(\mathrm{J/K})$ is the Boltzmann constant, $T(\mathrm{K})$ is the cell temperature ($e = 1.6 \times 10^{-19}$ Coulomb) is the electron charge, I_o (amp/m^3) is the reverse saturation current and its dependence on temperature is revealed through the following equation [2]:

$$I_o = \epsilon n T^{\gamma} e^{\frac{-E_g}{KT}} \quad (8)$$

where:

$\epsilon = 179\ \mathrm{amp/K^3 \cdot m^2}$ 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 semiconductor on temperature can be described as [27] [28]:

$$E_g = E_g(0) - \frac{\alpha T^2}{T + \beta} \tag{9}$$

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

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

Which are constants for each semiconductor material [28], I_{sc} is short circuit current given as [8],

$$I_{SC} = Q\left(1 - R(T)\right)\left(1 - \text{expel}(\mu l)\right) e n_{\text{photons}} \tag{10}$$

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]:

$$R(T) = 0.322 + 3.12 \times 10^{-5} T \tag{11}$$

μ is the attenuation coefficient and is value given as [30]:

$$\mu = a \exp(T/T_S) \tag{12}$$

where:

$a = 3.17 \times 10^4\ \text{m}^{-1}$; and

$T_S = 346\ \text{K}$, l in meter is the thickness of the solar cell,

n_{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:

$$n_{\text{photon}} = q(t)/E_g \tag{13}$$

4. Computations

The silicon solar cell is considered with dimensions (5.5 cm × 11 cm × 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_{sc}, I_o, and V_{oc} corresponding to each value of T at a certain time "t" are determined.

Hence the efficiency "η" 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:

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

Different thickness l = 10^{-3}, 3 × 10^{-3}, 5 × 10^{-3} m are considered at h = 1 W/m^2·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·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 W/m²·K for different value of the thickness.

shifted time t, hr.	T, K		
	$l = 10^{-3}$ m	$l = 3 \times 10^{-3}$ m	$l = 5 \times 10^{-3}$ 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 $l = 10^{-3}$ m and A = 0.7 for different value of the cooling.

shifted time t, hr.	T, K		
	h = 3 (W/m²·K)	h = 5 (W/m²·K)	h = 10 (W/m²·K)
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

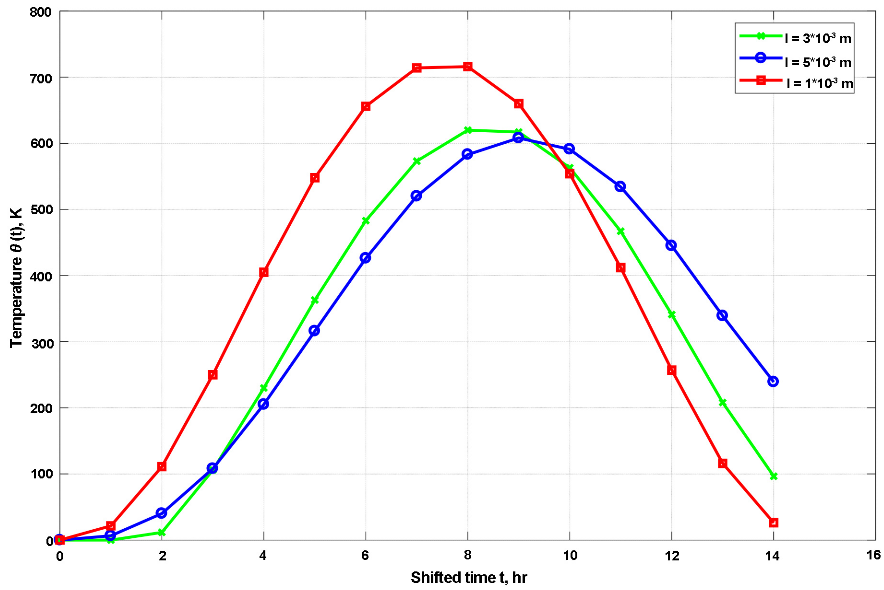

Figure 1. The variation of the temperature of the cell as a function of the local day time in $h = 1$ W/m^2·K and $A = 0.7$ for different thickness.

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 $l = 10^{-3}$ m, $h = 3$ W/m^2·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:

$l = 5 \times 10^{-3}$ m, $A = 0.7$, $h = 1$ W/m^2·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 vic versa.

Moreover, the dependence of the efficiency of the considered solar cell on the thickness l, are clarified.

The efficiency at: $h = 1$ W/m^2·K, $A = 0.7$ and thickness $l = 10^{-3}$, 3×10^{-3}, 5×10^{-3} m is computed and is illustrated in **Figures 6-8**.

5. Results and Discussions

The obtained results reveal that: The cell temperature decreases as the transfer coefficient for cooling increases, also it decreases as the thickness of the cell increases while it increases as the absorption coefficient "A" at its front surface increases. This is because when "A" increases the value of the solar power absorbed by the cell increases.

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 gab decreases [19].

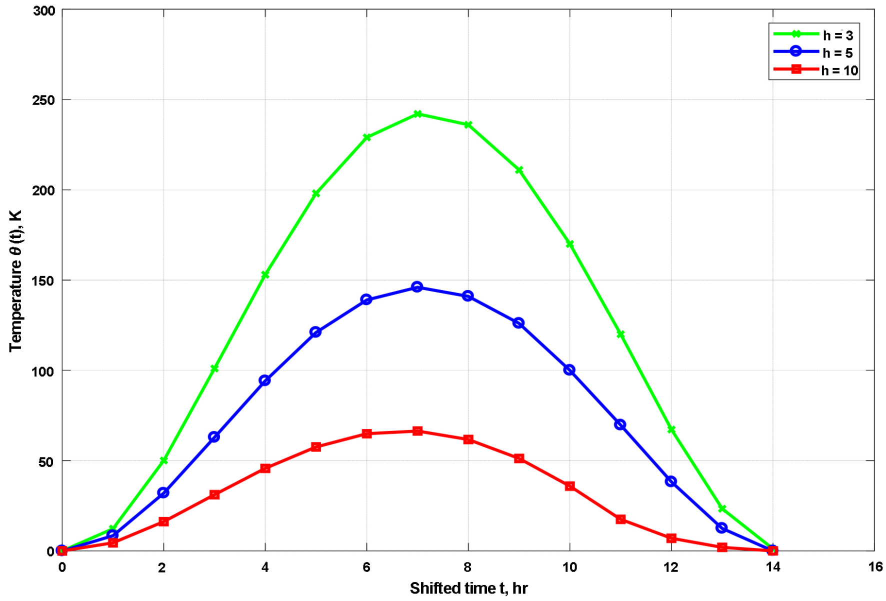

Figure 2. The variation of the temperature of the cell as a function of the local day time in $l = 10^{-3}$ m and $A = 0.7$ for different values of the cooling coefficient.

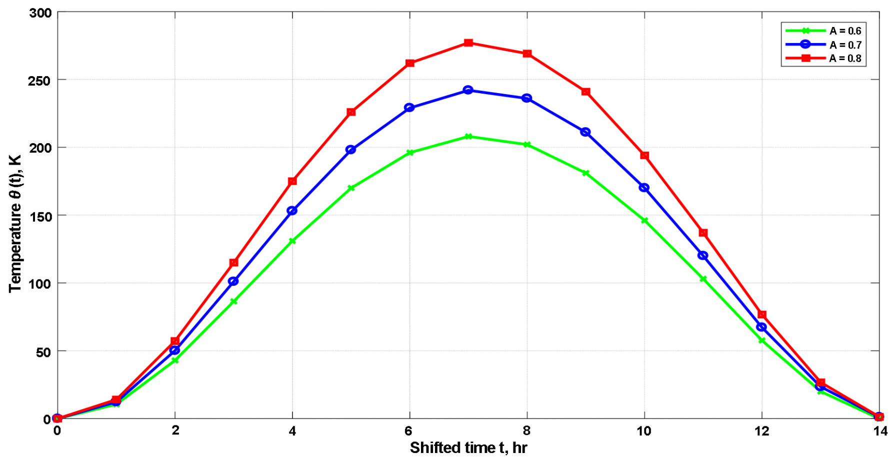

Figure 3. The variation of the temperature of the cell as a function of the local day time in $l = 10^{-6}$ m and $A = 0.7$ for different values of the cooling coefficient.

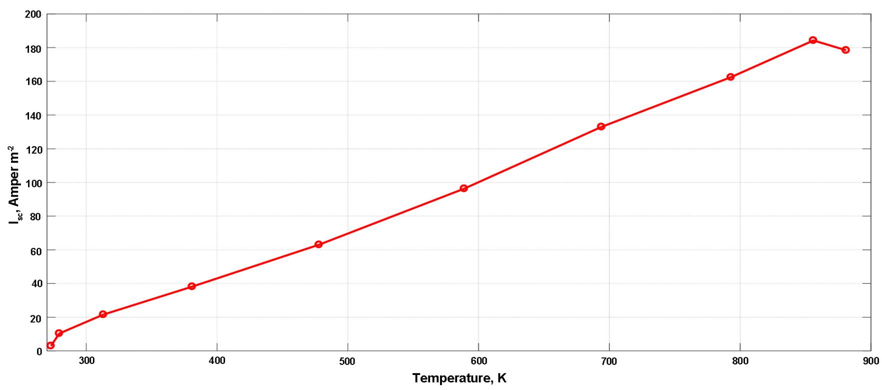

Figure 4. The variation of I_{sc} at $l = 5 \times 10^{-3}$ m, $h = 1$ W/m^2 and $A = 0.7$.

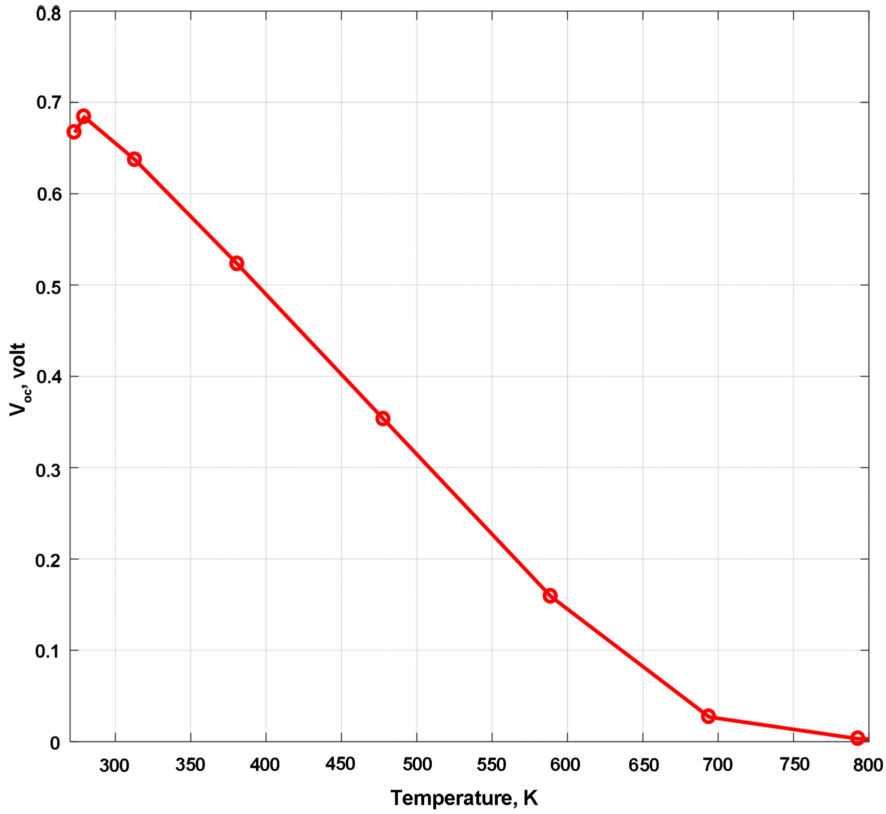

Figure 5. The variation of V_{oc} at $l = 5 \times 10^{-3}$ m, $h = 1$ W/m^2·K and $A = 0.7$.

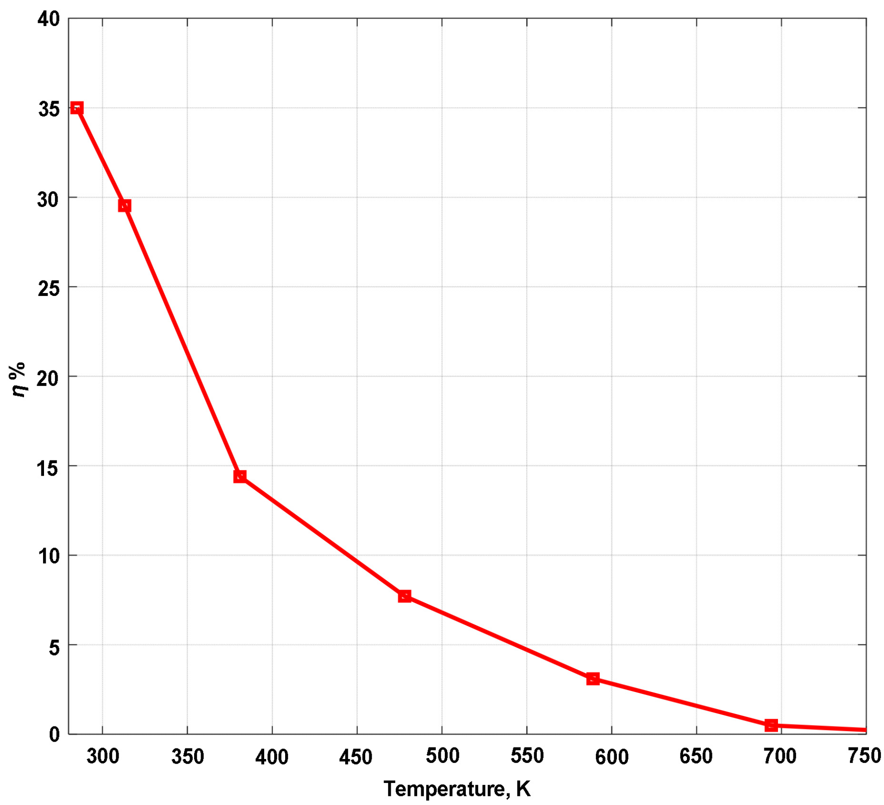

Figure 6. The temperature dependence of n at $l = 5 \times 10^{-3}$ m, $h = 1$ W/m^2·K and $A = 0.7$.

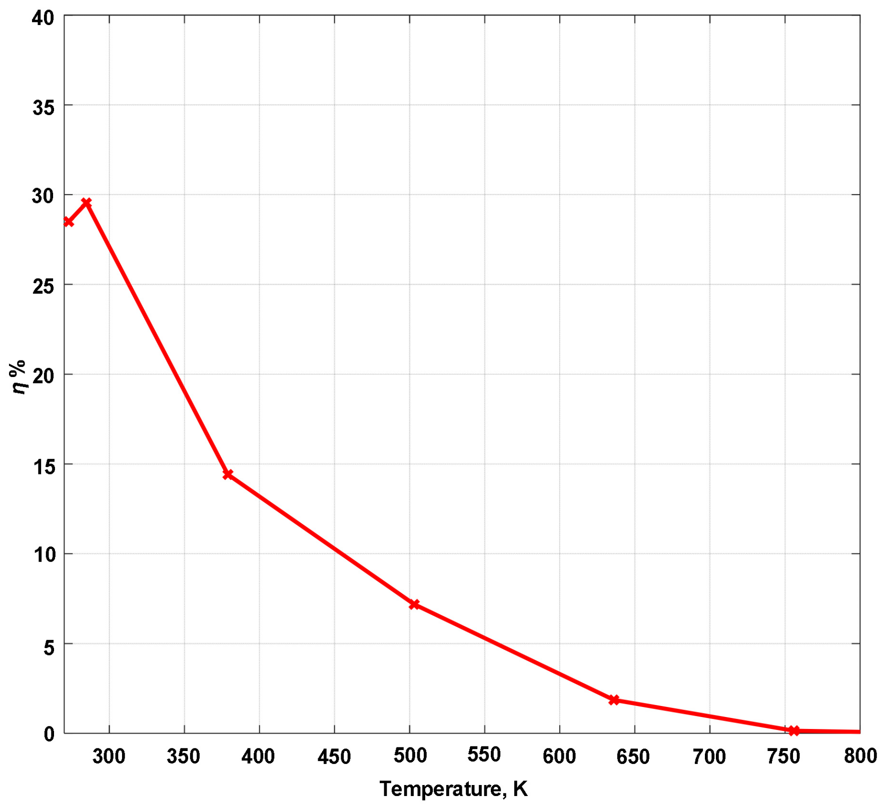

Figure 7. The temperature dependence of n at $l = 5 \times 10^{-3}$ m, $h = 1$ W/m^2·K and $A = 0.7$.

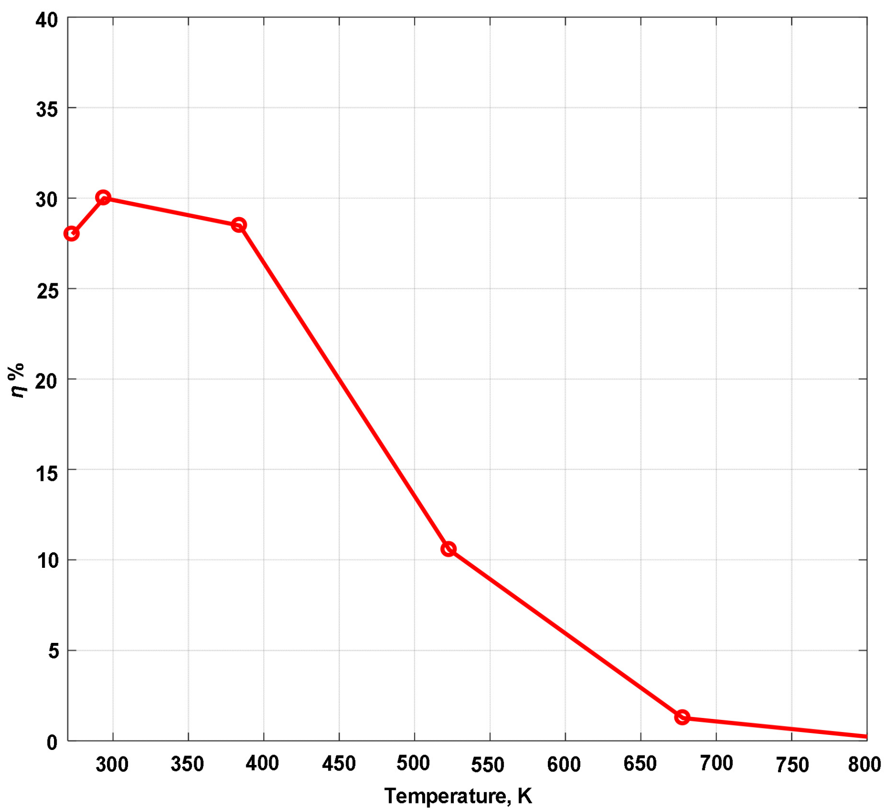

Figure 8. The temperature dependence of η at $l = 10^{-3}$ m, $h = 1$ W/m^2·K and $A = 0.7$.

Table 3. The temperature of the cell as a function of the local day time at $l = 10^{-3}$ m and h = 3 W/m^2·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
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 $\ln\left(\frac{I_{sc}}{I_o}+1\right)$. The first factor suggests a linear relation on (T) while is relation deviated due to the presences of the logarithmic function $\ln\left(\frac{I_{sc}}{I_o}\right)$ grows slowly with T than the function $\frac{kT}{e}$.

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

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_{sc}, and the efficiency η are functions of the cell temperature with different degrees.

The efficiency η 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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