Effect of Solar Cell Temperature on its Photovoltaic Conversion Efficiency

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Abstract - The solar energy conversion is investigated theoretically. The variation of the temperature of the solar cell subjected to the incident global solar radiation along the local daytime is determined.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 cooling coefficient*(h), th*e optical parameters, physical parameters, and the geometrical parameters of the cell .The temperature dependence of the short circuit current I_{sc},the dark saturation current I_0 , 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 different operating conditions and different astronomical locations (Egypt and Hong Kong) as illustrative examples are given.

Keywords - Solar Cell Temperature, Photovoltaic Conversion Efficiency , Solar Cell Performance , Solar Energy , Heat Transfer Equation

I NTRODUCTION

The study of the efficiency of the solar cell with the aim to increase its value has aroused the interest of many investigators [1-21]. The efficiency is a measure of the cell performance, which in turns depends on many parameters. Many of such parameters are temperature dependent. Such a study is very important for different theoretical and technological applications of photovoltaic solar cells. The photovoltaic solar energy conversion is investigated theoretically over a temperature range 273-673^{0}K, using semiconductor materials with band gab varying from 0.7-2.4 eV [1]. It is concluded that maximum conversion efficiency occurs in materials with higher band gab as the temperature is increased.

In evaluating the efficiency of a solar cell, some authors assume that the increase of the short circuit current I_{sc} with temperature is negligible [2] and accept its temperature rate of variation to be zero.

El-Adawi et al. [13] studied the temperature functional dependence of a Silicon solar cell without neglecting the temperature rate of variation of I_{sc} and the open circuit voltage V_{oc}. An expression for $\frac{d\eta}{dT}$ is also given, where η is the efficiency of the solar device. It is concluded that the temperature dependence of I_{sc} has not to be neglected, in evaluating the solar device efficiency. It is revealed also that the efficiency behaves as a slowly varying function with temperature along the local daytime. The same result is obtained in the reference [15]. It is concluded that the temperature variation of the solar cell along the daytime is significant and must be considered. While the efficiency decreases slightly with temperature.

The temperature dependence of a solar cell performance is studied in the temperature range 273-523^{0}K [17]. The temperature dependence of the cell parameters I_{sc}, and V_{oc} are considered.

It is concluded that the efficiency decreases with increasing the cell temperature.

The efficiency of a Silicon solar cell as a function of the doping degree and the incident solar spectral photon flux is studied in [18].It is revealed that the efficiency depends not only on the doping ratio

$\frac{N_d}{N_a}$, but it does depend on their absolute values.

Where, N_d , m^{-3} is the concentration of the donor atoms, and

N_a , m^{-3},is the concentration of the acceptor atoms. At room temperature, computations show that a small value 11.67% for the efficiency is obtained. In the same trend, a relation is established between the recombination velocity at the metallurgical interface within the depletion layer and the current density [19].It decreases with the increase of the recombination velocity. This in turn leads to the decrease in the efficiency. The temperature of a solar cell is determined theoretically by solving the heat energy equation using Laplace Integral Transform technique [20]. The dependence of the cell parameters on its temperature is considered in evaluating its efficiency. The temperature and the efficiency are computed along the local daytime.

It is revealed that the diurnal cell temperature variation is significant, while the efficiency is revealed to be slowly varying function of temperature. It decreases with increasing the cell temperature. For the considered operating conditions, computations for a silicon solar cell of thickness 0.02m show values of the efficiency in the range 21-28% .

The effect of the temperature on the silicon solar cell parameters is also studied [21] in the temperature range 293-353^{0}K. It is shown that I_{sc}.

Increases with temperature while V_{oc} decreases regularly with temperature. It is also revealed that the efficiency decreases with temperature. Maximum efficiency $\eta = 18.34\%$ is achieved at thickness $\ell = 100\ \mu$m at cell temperature 293 ^0K. It is established that the efficiency is proportional to I_{sc} and V_{oc} .

The aim of the present trial is to find theoretically the temperature field within the solar cell subjected to incident solar radiation and to study its variation with the solar exposure time considering different operating conditions such as cooling ,the absorption coefficient at the front surface in addition to its thickness. The variation of the cell parameters such as (I_{sc}),(V_{0c}) with its temperature along the local day time is also studied in relation to the efficiency . This will make it possible to support one or more of the published trends concerning the variation of the cell parameters and its efficiency with the cell temperature. Suitable recommendations to increase the solar cell efficiency are given.

II 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. Assuming that the active part of the solar cell is of a small thickness one can consider a homogeneous field to be built within the considered thickness [15]. Neglecting the heat losses by radiation because of the low level of its temperature during the exposure time and considering only heat losses by convection at the front surface, one can write the heat balance equation in the form:

$$S^1 A\, q(t) - S^1 h\, \theta(t) = S^1 \ell \rho c_p \frac{d\,\theta(t)}{d\,t} \qquad (1)$$

Where :

$\theta(t) = (T(t) - T_0)$, $\overset{0}{K}$ is the excess temperature of the cell relative to the ambient temperature T_O , $S^1(m^2)$ is the area of the cell front surface , h $(W/m^2\ \overset{0}{K})$ is the heat transfer coefficient at the front surface , $\ell(m)$ is the cell thickness , $\rho(kg/m^3)$ is the density of the solar cell material, and $c_p(J/kg.\ \overset{0}{K})$is the specific heat of the cell material .

Equation (1) can be rewritten as :

$$\frac{d\,\theta(t)}{d\,t} + B\theta(t) = D\, q(t) \qquad (2)$$

Where, $B = \dfrac{h}{\ell \rho c_p}$ *and* $D = \dfrac{A}{\ell \rho c_p}$

Equation (2) represents a first order non-homogenous equation . It can be solved by the integrating factor as follows [22] :

$$\theta(t)\, e^{\int B\,dt} = \int_0^t D\, q(t)\, e^{\int B\,dt}\, dt \qquad (3)$$

$q\,(t)$ was given by the authors [23] in the following form :

$$q(t) \;=\; q_{\max}\; e^{-\frac{(t-t_0)^2}{(t_s-t)(t-t_r)}} \tag{4}$$

Where $q_{\max}$ was suggested by the authors of the present work in terms of the solar constant S in the form [23]:

$$q_{\max} \;=\; \alpha\, S\,(\,1+0.033\,\cos\frac{360\,n}{365}\,) \tag{5}$$

n is the day of the year starting from 1 January ($1 \le n \le 365$) .

The value of the solar constant S is taken as S =1353 [24], α is taken as [25,26]:

$$\alpha = \frac{(\,\gamma^{+}-\gamma^{-}\,)}{(\,1+G\,)\,(\,\gamma^{+}+A-B\,R\,)}\; e^{\gamma^{-}\tau}\;\mu_0\;\;,$$

$$\gamma^{\pm} = \frac{1}{2}\;(\,C-A\,)\;\pm\frac{1}{2}\,[\,(\,C+A\,)^{2}\;-\;4\,B\,D^{\backslash\backslash}\;]^{\frac{1}{2}}\;,$$

$$A=(\;\frac{2-\omega_0}{2\,\mu_0}\;)\;,\;\; B=\omega_0\;,\;\; C=(\,2-\omega_0\;)\;,\;\; D^{\backslash\backslash}=\frac{\omega_0}{2\,\mu_0}\;,\;\;\omega_0=\frac{\tau^{S}}{\tau}$$

τ^{s} , τ are the optical thickness due scattering and total optical thickness

(scattering and absorption)

$$G=-[\,\frac{\gamma^{-}+A-B\,R}{\gamma^{+}+\;A-B\,R}\,]\,e^{(\gamma^{-}-\gamma^{+})\tau}\quad,\quad \mu_0=\cos Z\quad,\quad Z=\left|\,D'\;-\;L'\,\right|\quad;$$

Z is the solar zenith angle , D' is the solar codeclination, which is the complementary angle of the declination , L' is the observer colatitude which is the complementary angle of the latitude.

t_r, is the sunrise time in hours.

t_s ,is the sunset time in hours,

$t_0 (= t_d / 2)$, 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 [27]:

$$t_d = \frac{12}{15} \cos^{-1}(-\tan\phi \tan\delta),$$

ϕ, *is* the latitude and δ is the solar declination angle given as:

$$\delta = 23.45 \sin 360\left(\frac{284 + n}{365}\right).$$

The solution of equation (2) can be written in the following form *:*

$$\theta(t) = D\, q_{\max}\, e^{-Bt} \int_0^t e^{\frac{Bt(t_s - t)(t - t_r) - (t - t_0)^2}{(t_s - t)(t - t_r)}}\, dt \qquad (6)$$

Equation (6) represents the temperature of the considering cell after an exposure time *"t"* along the solar day time .The solution revealed that the cell temperature $\theta(t)$ is a function of*:* $\{ q_{\max}, A, h, \ell, \rho, c_p, t_0, t_s ;\ t \}$.

III The efficiency temperature dependence for the solar cell

The efficiency (η) of the solar cell is defined as follows [2] :

$$\eta = \frac{V_{0c}\, I_{sc}\, FF}{P_{in}} \qquad (7)$$

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Where :

P_{in} (W/m^2) is the input total solar power received by the solar cell , V_{0c} is the open circuit voltage which is given as[2] *:*

$$V_{0C} = \frac{k\,T}{e}\ \ln\left(\frac{I_{SC}}{I_0} + 1\right) \qquad (8)$$

Where :

$k(J/{}^0K)$ is the Boltzmann constant , $T\,({}^0K)$ is the cell temperature , ($e = 1.6 \times 10^{-19}$ *coulomb*) is the electron charge , I_0 (amp/m^2) is the reverse saturation current and its dependence on temperature is revealed through the following equation *[2] :*

$$I_0 = \varepsilon\, n'\, T^{\gamma}\, e^{\left(\frac{-E_g}{k\,T}\right)} \qquad (9)$$

Where :

$\varepsilon = 179$ amp/K^3m^2 for Silicon solar cell [17] , n' is non-ideality factor of the cell and is taken as unity , the value of γ is accepted as $\gamma = 3$ [2] , E_g is the energy band gap . The dependence of energy band gap ofa semiconductor on temperature can be described as [28,29]:

$$E_g = E_g(0) - \frac{\bar{\alpha}\, T^2}{T + \beta} \qquad (10)$$

$E_g(0)$ is the energy band gap of the semiconductor at $T \approx 0\ {}^0K$, for Silicon $E_g(0) = 1.16\ eV$ [29] , $\bar{\alpha} = 7 \times 10^{-14} eVK^{-1}$ and $\beta = 1100\ {}^0K$ which are constants for each semiconductor material [29] , I_{sc} is the short circuit current given as [1] *:*

$$I_{sc} = Q\,(1 - R(T))\,(1 - e^{-\mu \ell})\, e\, n_{photons} \quad (11)$$

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] :

$$R(T) = 0.322 + 3.12 \times 10^{-5}\ T \quad (12)$$

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

$$\mu = a \exp\left(T / T_S\right) \quad (13)$$

where $a = 3.17 \times 10^4\ m^{-1}$ and $T_1 = 346\ \overset{0}{K}$, 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 day time is given as :

$$n_{photon} = \frac{q(t)}{E_g} \quad (14)$$

IV COMPUTATIONS

The silicon solar cell temperature as a function of the local day time *"t"* is calculated using equation (6) ,the physical parameters of Silicon are

$$\rho = \mathbf{2280}\ \mathrm{kg/m^3} \quad , \quad c_p = \mathbf{840}\ \mathrm{J/kg}$$

The hourly incident global solar radiation $q(t)$ (eq.(4)) is considered for Egypt and Hong Kong as illustrative examples .For each cell temperature the corresponding values of I_{sc} , I_0 , and V_{0c} are determined.

Hence the efficiency " η " of the cell as a function of the solar local day time " t " is estimated for both considered locations.

For Egypt (July) [31] the $q(t)$ parameters are :

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

1) Different thicknesses $\ell = 1 , 5 , 10\ \mu m$ are considered at $h = 1\ W/m^2K$, $A = 0.6$

The obtained results are illustrated in Fig . 1(a)

2) Different cooling conditions $h = 1, 4 , 8\ W/m^2K$ are considered at thickness $\ell = 1\ \mu m$, $A = 0.6$.

The obtained temperature $T(t)$ is illustrated in Fig.1(b).

3) Different absorption coefficients $A = 0.6 , 0.7 , 0.8$ are considered at thickness $\ell = 1\ \mu m$, $h = 1\ W/m^2K$

The obtained results are illustrated in Fig.1(c) which show that the temperature of the solar cell increases as the absorption coefficient at the front surface increases.

For Hong Kong (July [32]) the above same steps (1),(2),(3) are carried out , where :

$q(t)$ Parameters are: $q_{max} = 788\ W/m^2$, $t_d = t_s = 14$hours ,

$t_0 = 7\ hours$, $t_r = 0\ hours$.

The obtained results are illustrated in Fig.2(a, b, c) respectively .

The variations of I_{sc} , V_{oc} and the efficiency η for the case $\ell = 10\ \mu m$, $h = 1\ W/m^2K$, $A = 0.6$ for Egypt (July) are computed and are illustrated in Figs.3(a, b, c), computations for $\ell = 1\ \mu m$, $h = 1\ W/m^2K$, $A = 0.8$ are made and are also illustrated in Figs.4 (a,b,c). The same functions for

Hong Kong (July) are computed and are illustrated in Figs.5 (a, b, c) and Figs.6 (a, b, c).

The obtained results revealed that I_{sc} increases with increasing the temperature and vice versa .This variation for most semiconductors, is attributed to the fact that as the temperature increases the band gap decreases.

Moreover, the dependence of the efficiency of the considered solar cell on the thickness " ℓ " , heat transfer cooling coefficient " h " and the absorption coefficient" A " are clarified .

The following cases are considered:

i)The efficiency at : $A = 0.8$, $h = 1\ W/m^2K$ and $FF = 0.85$ at thicknesses $\ell = 1, 10, 20\ \mu m$ is computed for Egypt (July) and Hong Kong (July) and is illustrated in Figs.7 and 10 respectively .

ii) The efficiency at : $A = 0.6$, $\ell = 10\mu m$ and $FF = 0.85$ at different cooling conditions $h = 1, 4$ and $8\ W/m^2K$ is computed for Egypt

(July) , and Hong Kong (July) and are illustrated graphically in Figs.8 , and 11 respectively.

iii) The efficiency at : $h = 1W/m^2K$, $\ell = 10\ \mu m$ and $FF = 0.85$ at different absorption coefficients $A = 0.6$, 0.7 and 0.8 is computed for Egypt (July) and Hong Kong (July) and is illustrated graphically in Figs.9 , and 12 respectively.

VI RESULTINS 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[33] .

In addition the open circuit V_{oc} increases in the small rang of temperature. At this stage the proportionality with T is predominant in the expression of V_{oc} given in equation (8) .Then its value decreases with higher temperatures , since the saturation current density I_0 increases rapidly with temperature (Eq.9) faster than I_{sc}*[34]* .

As a result the efficiency " η " in general decreases with increasing the temperature .This behavior is nearly the same as that of V_{oc} for the same reasons discussed before. It's dependence on the solar cell thickness" ℓ " reveals that it increases with the increase of the thickness since it is related to lower cell temperature. It also increases with cooling nevertheless such increase is not pronouncing within the small range of temperature. As the absorption coefficient " A " increases the efficiency decreases .Since as " A " increases, the solar power absorbed increases , hence the cell temperature increases . The effect is not pronouncing within the small range of temperatures.

VII CONCLUSIONS

The introduced trial is promising in studying the efficiency of a solar convertor . The efficiency of a solar cell depends on its temperature and thus its value changes along the local day time.

Higher efficiencies are obtained for lower cell temperatures. Hence increasing the thickness and the cooling conditions at the front surface increases the efficiency of the cell.

Moreover, an optimum value for the absorption coefficient may be suitable to achieve maximum efficiency of the solar cell.

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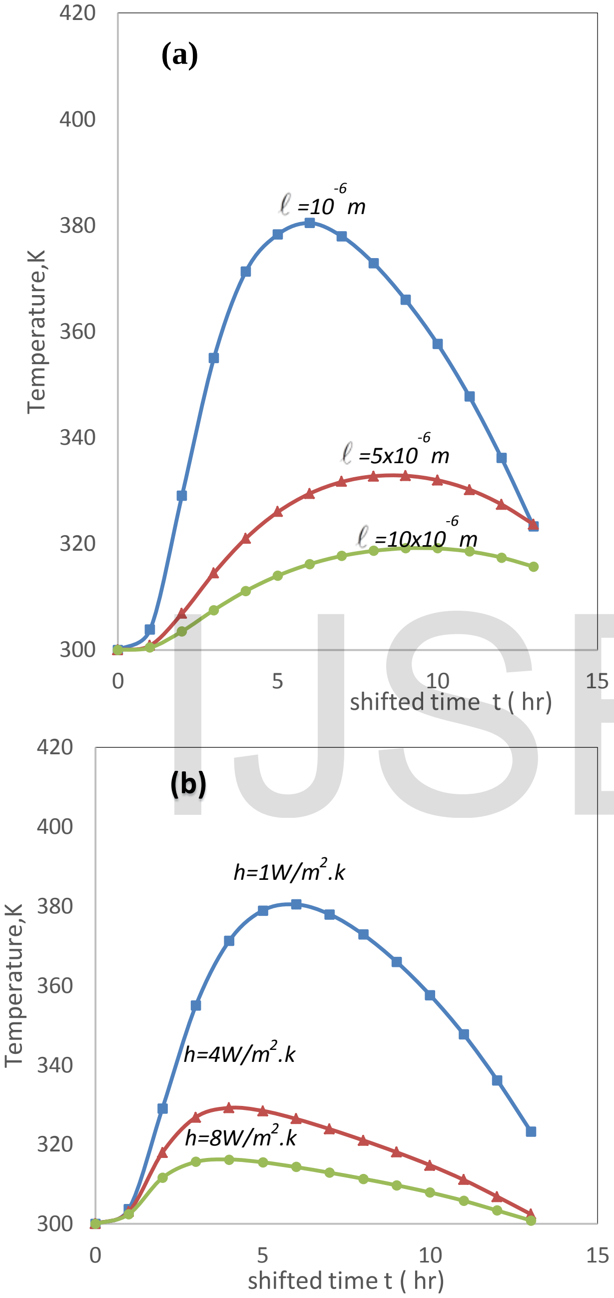
Egypt (July) (1980) located at 23̊ 58` N



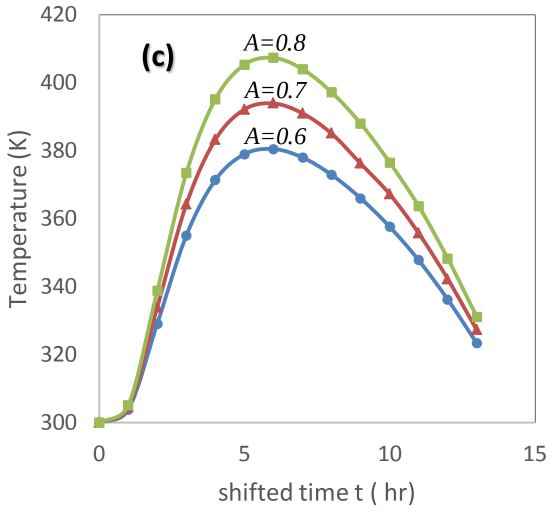


Fig. 1: The temperature of the cell as a function of the local daytime. In(a)*h=1W/m²/.K* and *A=0.6* for different values of the thickness. In (b) $\ell=10^{-6}$ *meter* and *A=0.6* for different values of the cooling coefficient at the front surface. In (c) $\ell=10^{-6}$ *meter* and $h=1W/m^2.K$ for different values of the Absorption coefficient at the front surface

Hong Kong (July) located at 22° 19` N,114° 10` E

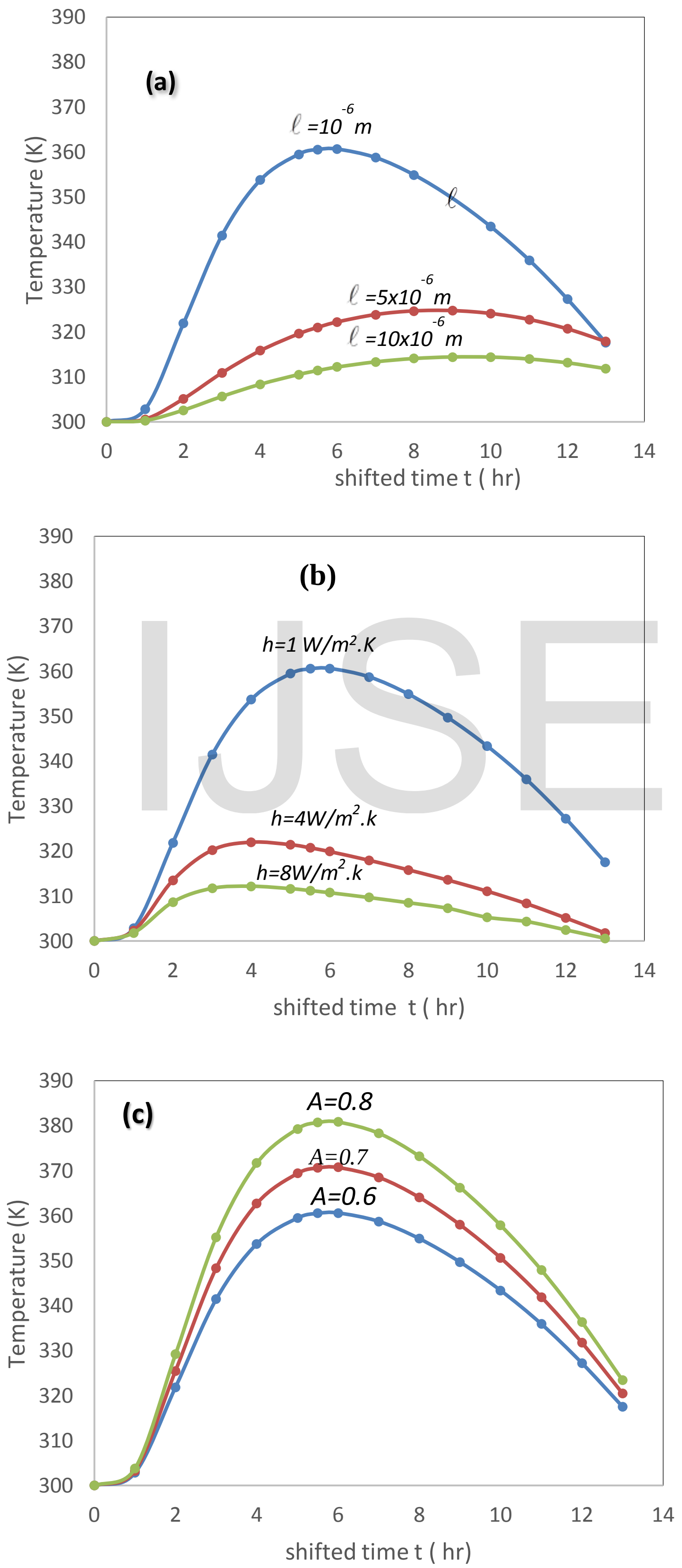
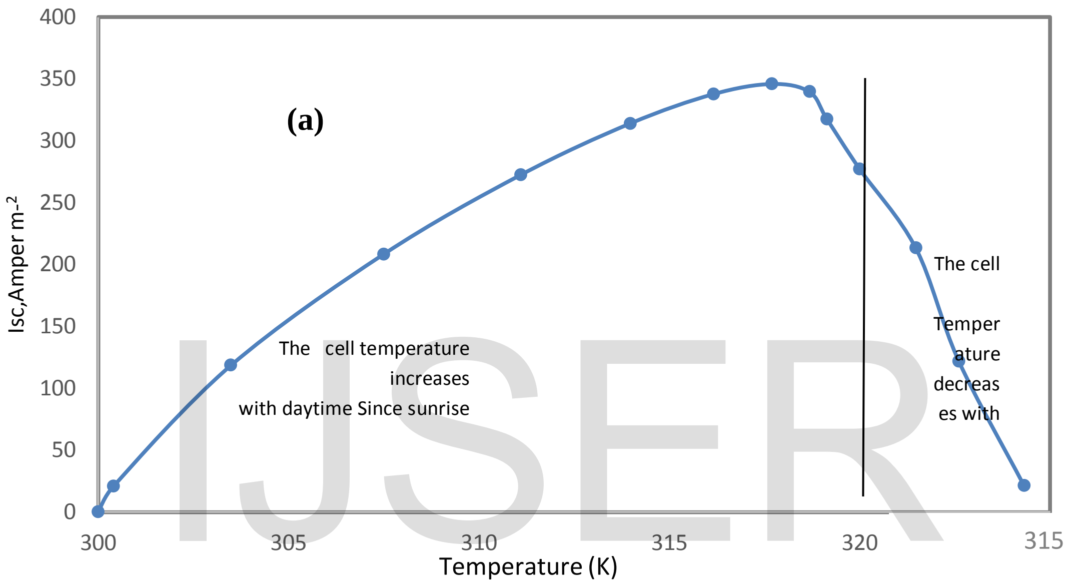
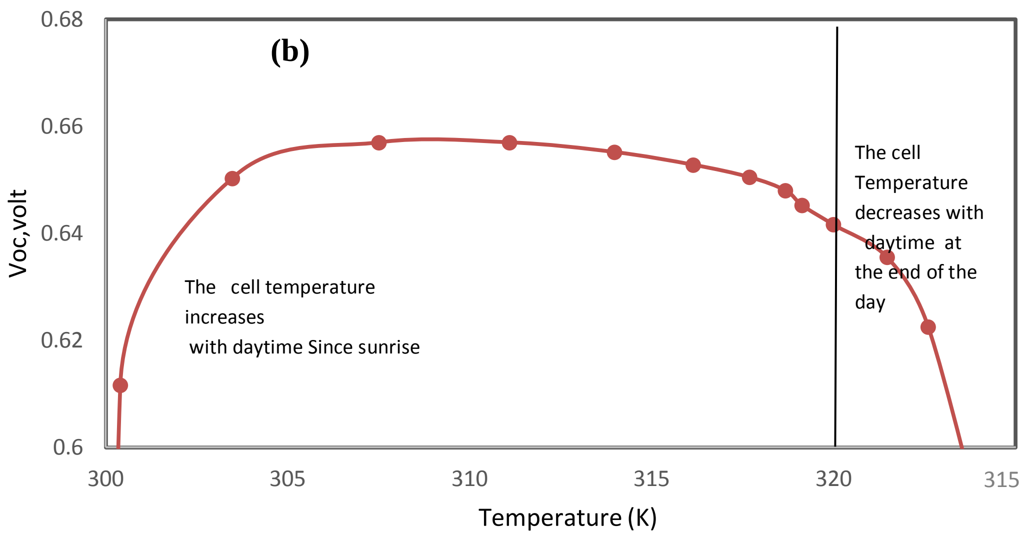


Fig. 2: The temperature of the cell as a function of the local day time. In (a) $h=1W/m^2.K$, $A=0.6$ for different values of the thickness. In (b) $\ell=10^{-6}$ *meter*, $A=0.6$ for different values of the cooling coefficient at the front surface. In (c) $\ell=10^{-6}$ *meter* and $h=1W/m^2.K$ for different values of the Absorption coefficient at the front surface.

Egypt (July) (1980) located at 23° 58` N





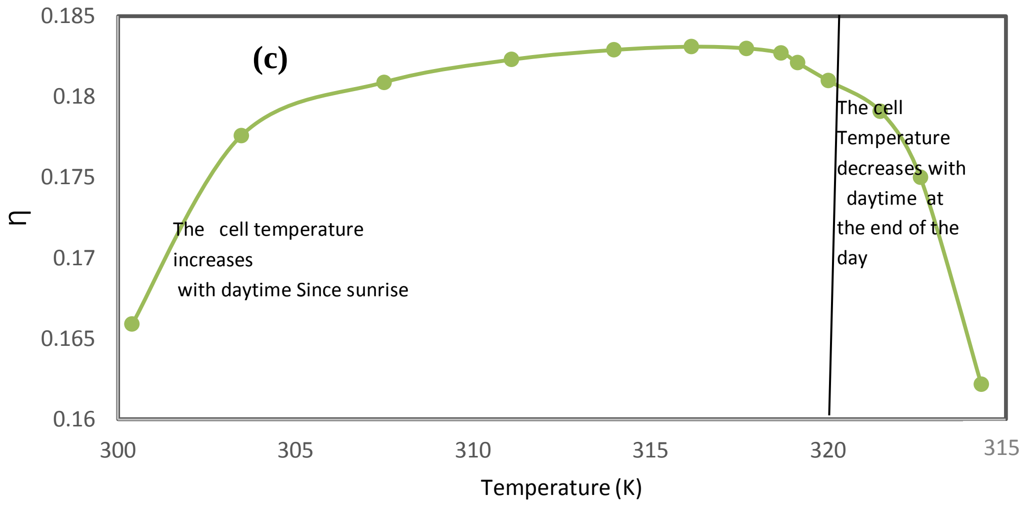
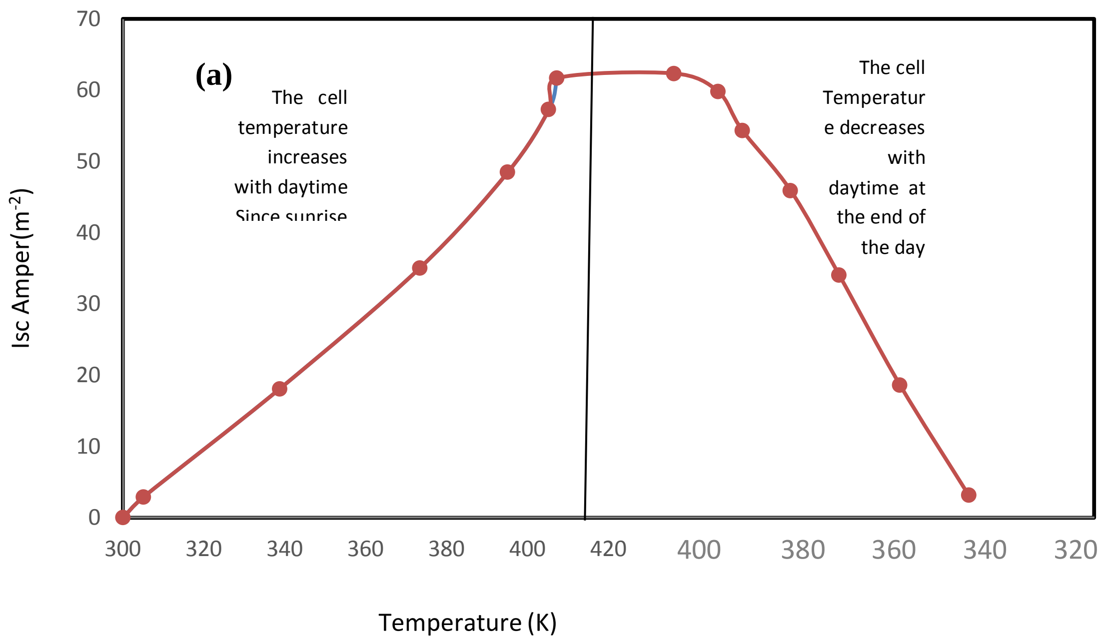
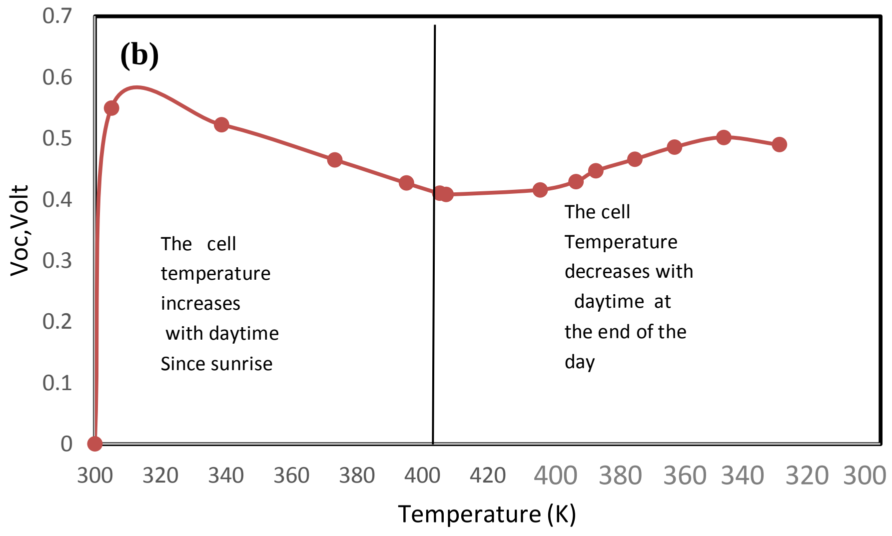
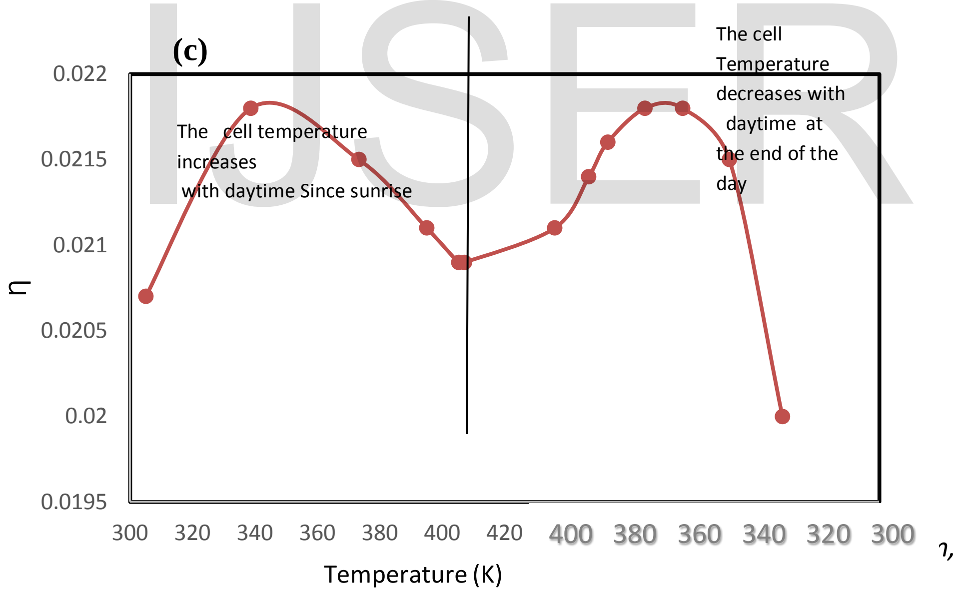


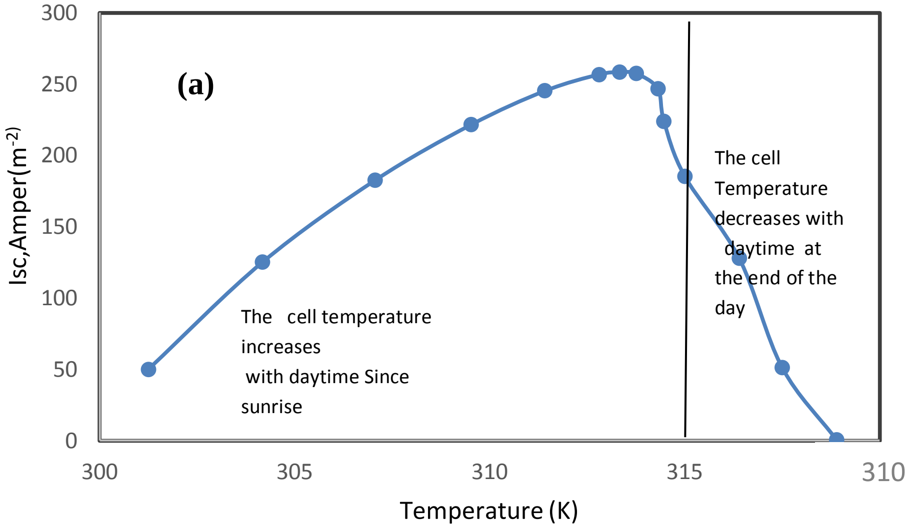
Fig.3: The temperature dependence of. (a) $I_{sc.}$(b)*Voc* . (c)*η*for Egypt July at *ℓ =10μm, h=1W m*$^{-2}$*.K,A=0.6*

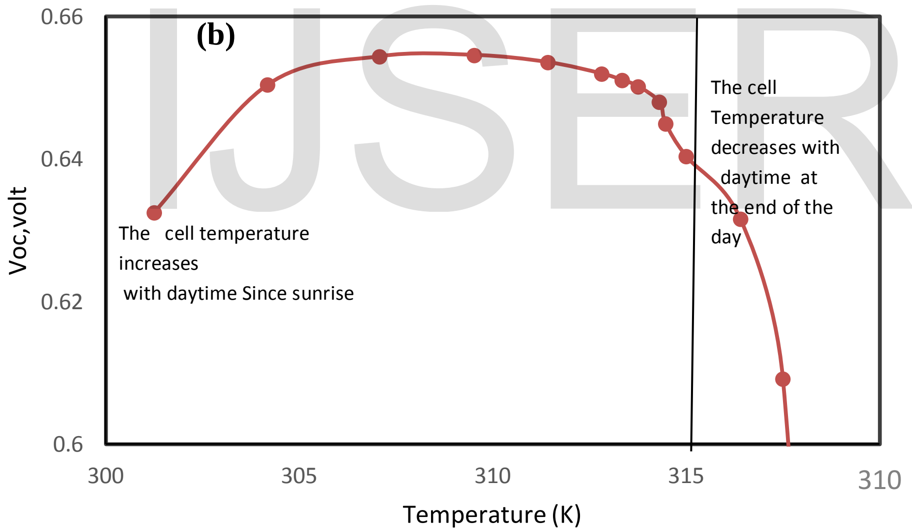



(b)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Voc,Volt
The cell temperature increases with daytime Since sunrise
The cell Temperature decreases with daytime at the end of the day
300 320 340 360 380 400 420 400 380 360 340 320 300
Temperature (K)


(c)
0.022
0.0215
0.021
0.0205
0.02
0.0195
η
The cell temperature increases with daytime Since sunrise
The cell Temperature decreases with daytime at the end of the day
300 320 340 360 380 400 420 400 380 360 340 320 300
Temperature (K)

-


300
250
200
150
100
50
0
Isc,Amper(m-2)
(a)
The cell
Temperature
decreases with
daytime at
the end of the
day
The cell temperature
increases
with daytime Since
sunrise
300
305
310
315
310
Temperature (K)


0.66
0.64
0.62
0.6
Voc,volt
(b)
The cell
Temperature
decreases with
daytime at
the end of the
day
The cell temperature
increases
with daytime Since sunrise
300
305
310
315
310
Temperature (K)

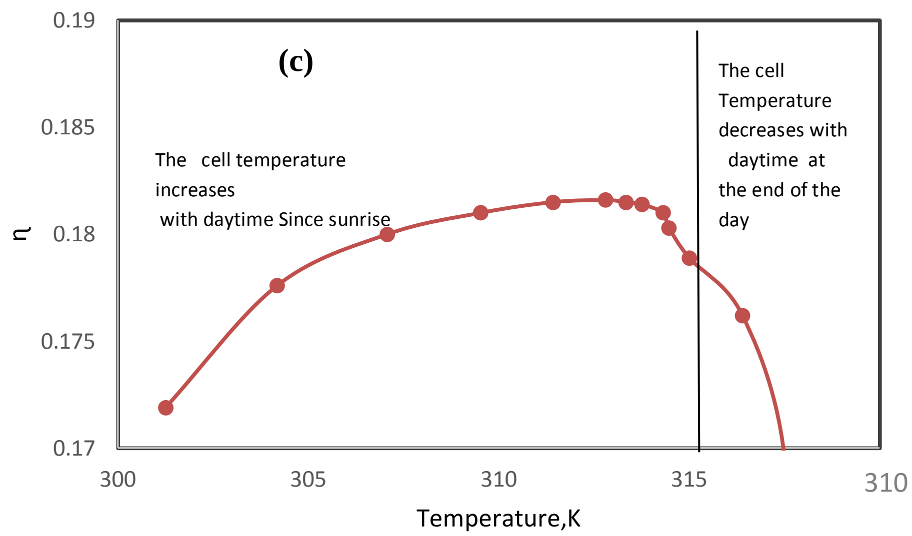
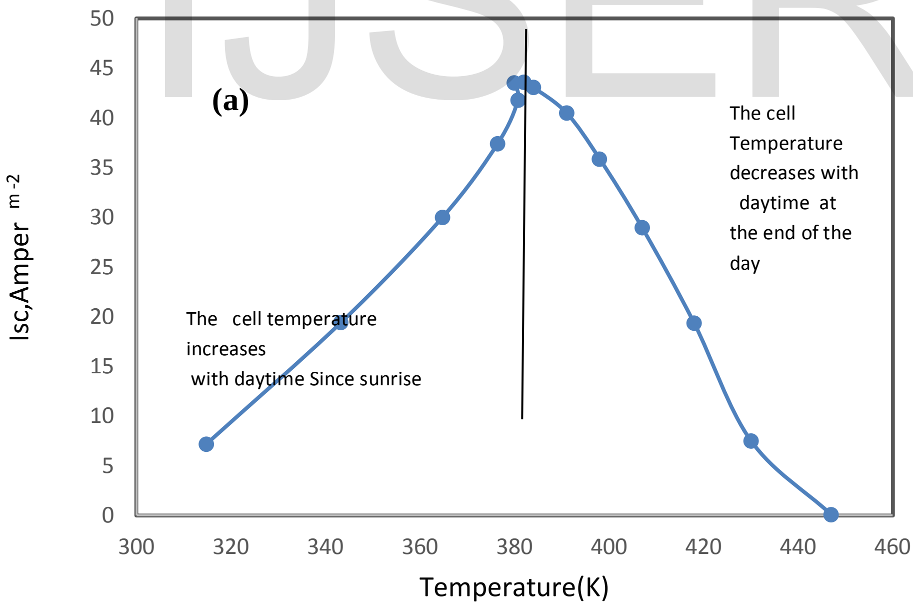
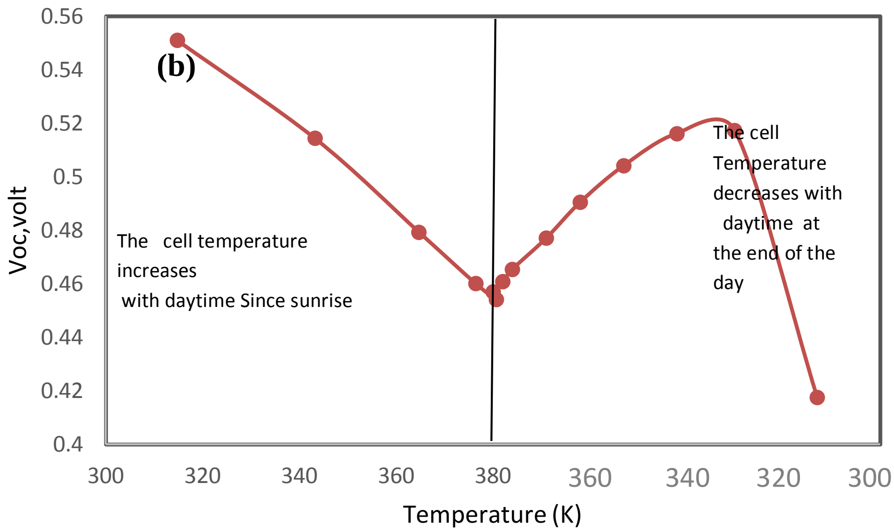


Fig.5 The temperature dependence of .(a)I_{SC}.(b)*Voc* .(c)η for Egypt July at ℓ *=10μm,h=1W m^{-2}.K,A=0.6*





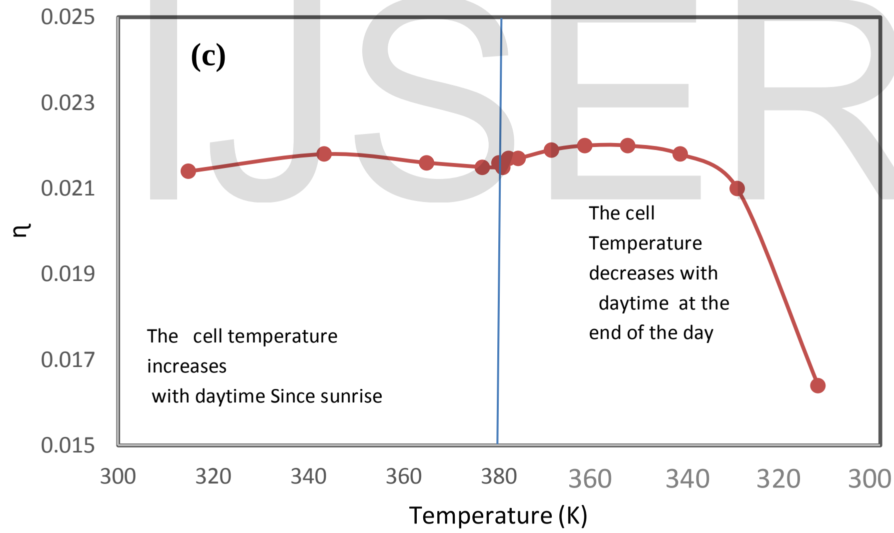


Fig.6: The temperature dependence of.(a)$I_{sc.}$(b)Voc .(c)η for Hong Kong July at ℓ =1µm,h=1W m^{-2}.K,A=0.8

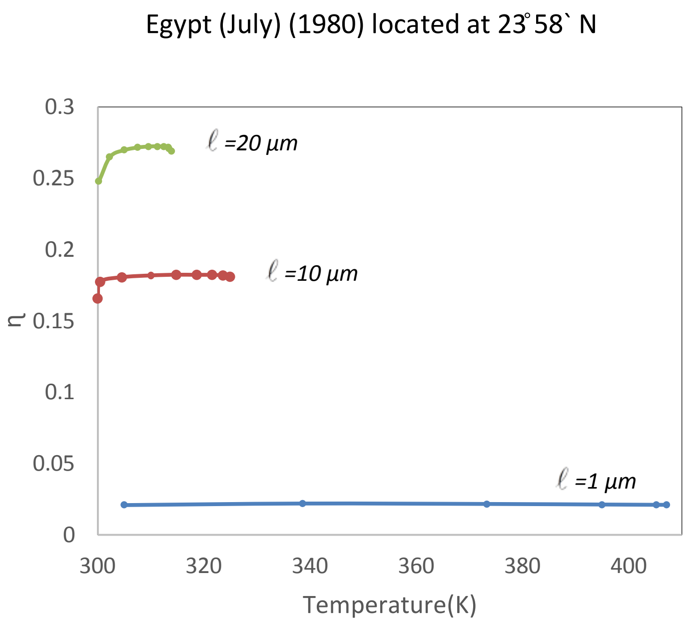


Fig.7: Effect of thickness on the efficiency of a solar cell for Egypt(July) at *A=0.8,h=1W/m²̲.K*

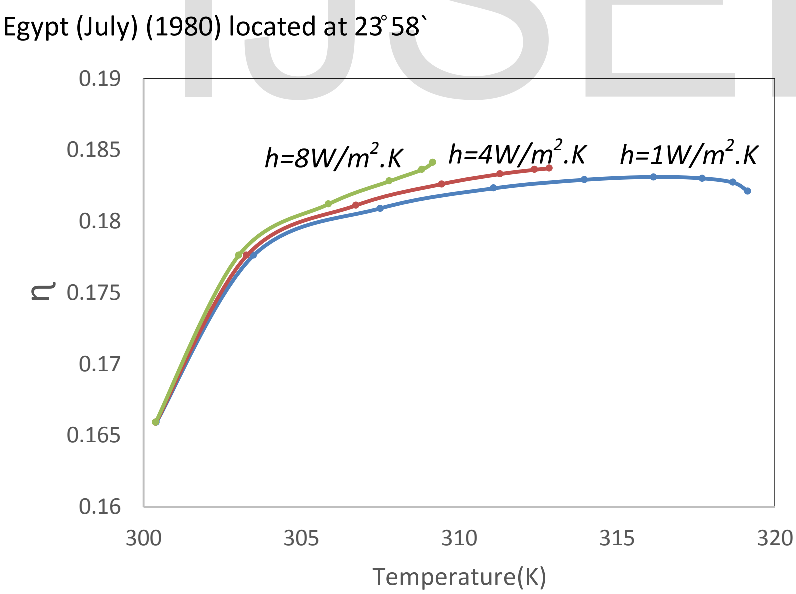


Fig.8: Effect of cooling on the efficiency of a solar cell for Egypt (July) at *A=0.6, ℓ =10µm*

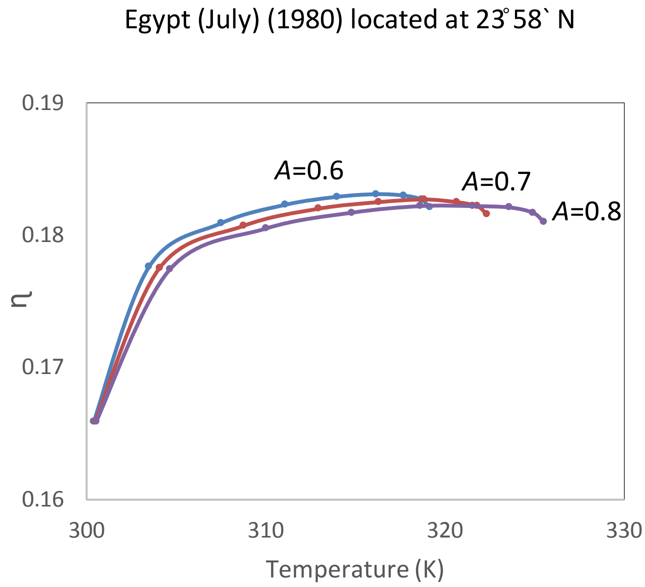


Fig.9: Effect of absorption on the efficiency of a solar cell for Egypt(July)at *h=1W/m²*.*K* , *ℓ =10μm*

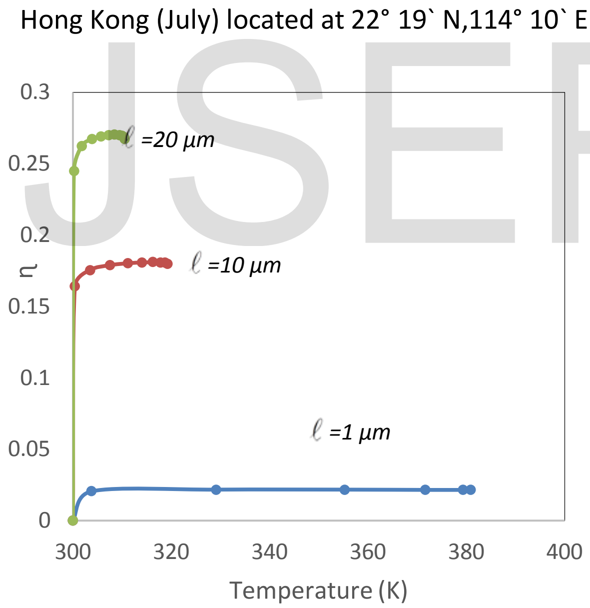


Fig.10: Effect of thickness on the efficiency of a solar cell for Hong Kong (July) at *A=0.8,h=1W/m²*.*K*

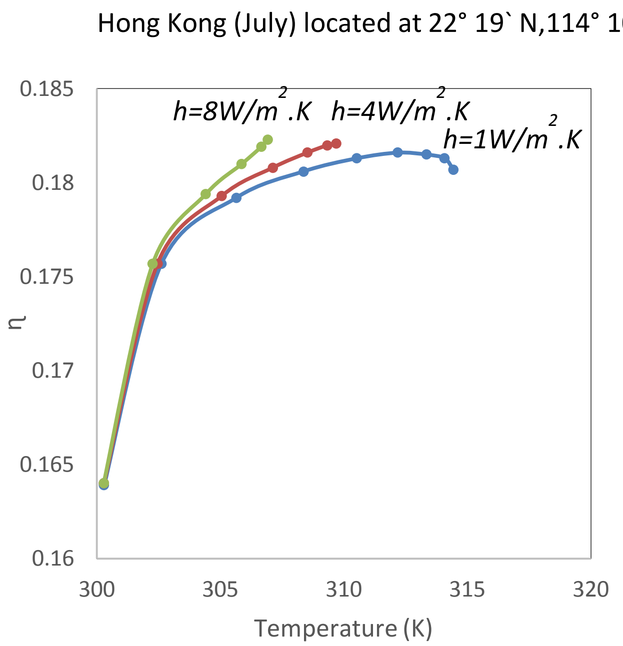


Fig.11: Effect of cooling on the efficiency of a solar cell for Hong Kong (July) at *A=0.6*, *ℓ =10 μm*

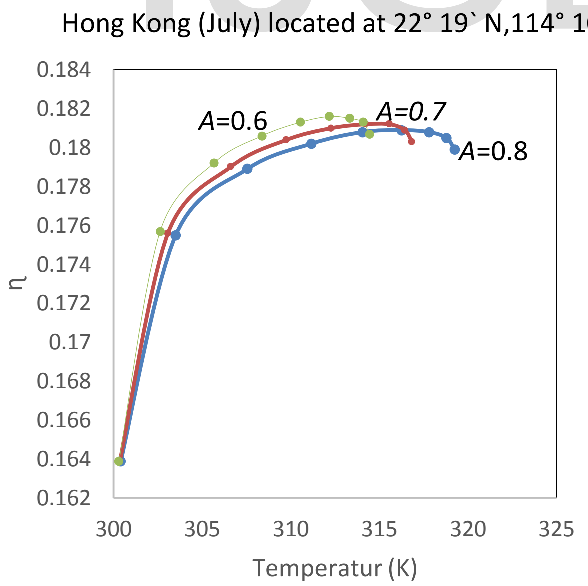


Fig.12: Effect of Absorption on the efficiency of a solar cell for Hong Kong (July)

at *ℓ =10 μm ,h=1W/m*^{2}.