Effect of solar cell temperature on its performance

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Abstract - Effect of solar cell temperature on its performance is studied through the dependence of the solar cell's parameters such as I_{sc} (short circuit current) and V_{oc}(open circuit voltage) on the cell temperature . The two – dimensional Laplace integral transform technique has been used to solve the heat diffusion equation for a solar cell subjected along the local day time to the incident global solar radiation. Mathematical expression for the temperature of the cell is obtained. As an illustrative example computations are carried out on a silicon solar cell at different operating conditions. The obtained results indicate that the increase in solar cell temperature make a degradation in its performance.

Keywords - solar cells temperature, photovoltaic, Heat diffusion equation, solar energy.

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Introduction

Finding alternative sources of energy is a vital issue in the modern word for many reasons .One reason is that traditional energy sources like gas, cool, oil and fossil fuels may be depleted relatively soon. Another reason is that from the environmental point of view burning of fossil fuels causes air and water contamination. Solar energy and other alternative sources are not only renewable but also environmentally friendly .Solar energy can be converted into electricity .Devices that convert solar energy directly 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 [1-26].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 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 of a solar cell subjected to the incident solar radiation and to study its variation with the solar exposure time considering different conditions such as cooling "h" and absorption coefficient "A" at the front surface in addition to the effect of its thickness "ℓ". Also the variation of I_{sc} ,V_{oc} and η with temperature is studied.

I -The mathematical formulation of the problem

Assuming that a 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 A q(t) ,where "A" is the absorption coefficient at the front surface of the considered cell .The heat diffusion equation is given in the form [27]:

$$\frac{\partial^2\theta(x,t)}{\partial x^2} - \frac{1}{\alpha}\frac{\partial\theta(x,t)}{\partial t} = 0 \qquad t > 0 \;,\; 0< x \le \ell \qquad (1)$$

Where:-

θ(x,t)= $T(x,t) - T_0$, K is the excess temperature relative to the ambient temperature T_0 .

$\alpha = \frac{\lambda}{\rho C_\rho}$, m^2/sec is the thermal diffusivity written in terms of :

λ , W/m.K is thermal conductivity, C_ρ , J/kg.K is the thermal capacity and the density ρ, kg/m^3 , of the solar cell material.

Equation (1) is subjected to the following conditions:

$$\text{At } t=0 \qquad q(0)=0 \quad \text{and} \qquad (2)$$

$$\theta(x,0)=0\ . \tag{3}$$

At the front surface x=0 ,

$$Aq(t)= -\lambda\frac{\partial\theta(x,t)}{\partial x}\Big|_{x=0} + h_0\theta\,(0,t) \tag{4}$$

Where:

q(t), W/m^2 is the irradiance of the incident solar radiation which is given elsewhere by [28]:

$$q(t)=q_{max}\ e^{-\frac{(t-t_0)^2}{(t_s-t)(t-t_r)}} \tag{5}$$

Where:

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

t_r , is the sunrise time in hours,

t_0 , is the mid time between sunrise and sunset in hours,

t_s , is the sunset time in hours,

t , is the local day time in hours and

h$_0$, W/m^2.K is the heat transfer coefficient at the front surface.

At the back surface x= ℓ,

The heat balance equation can be written in the form:

$$\int_0^t Aq(t)\mathrm{dt}=\int_0^\ell \rho C_p\theta(x,t)dx+\int_0^t h_0\theta(x,t)dt \tag{6}$$

The L.H.S. represents the total energy absorbed at the front surface during the exposure time , while the R.H.S. first term represents the heat energy stored in the solid target and the R.H.S second term is the energy lost by convection at the front surface.

Applying the two dimensional Laplace integral transform technique on equations (1) and (4) one gets:

$$\left[p^2\tilde{\theta}(p,s) - p\tilde{\theta}(0,s) - \frac{\partial\tilde{\theta}(x,s)}{\partial x}\Big|_{x=0}\ \right] - \frac{s}{\alpha}\ \tilde{\theta}(p,s) = 0 \qquad (7)$$

and

$$-\frac{\partial\tilde{\theta}(x,s)}{\partial x}\Big|_{x=0} = \frac{A}{\lambda}\tilde{q}(s) - \frac{h_0}{\lambda}\tilde{\theta}\ (0,\text{s})$$

(8)

Substituting equation (8) into equation (7) one gets:

$$\tilde{\theta}(\text{p,s}) = \frac{p}{\left[p^2 - \frac{s}{\alpha}\right]}\tilde{\theta}(0,s) + \frac{h_0}{\lambda\left[p^2 - \frac{s}{\alpha}\ \right]}\tilde{\theta}(0,s) - \frac{A}{\lambda\left[p^2 - \frac{s}{\alpha}\ \right]}\tilde{q}(s) \qquad (9)$$

The inverse Laplace transform of equation (9) gives: [29]

$$\tilde{\theta}(\text{x,s}) = \tilde{\theta}(0,s)\cosh\Big(\sqrt{\frac{s}{\alpha}}x\Big) + \frac{h_0}{\lambda\sqrt{\frac{s}{\alpha}}}\tilde{\theta}(0,s)\sinh\Big(\sqrt{\frac{s}{\alpha}}x\Big) - \frac{A}{\lambda\sqrt{\frac{s}{\alpha}}}\tilde{q}(s)\sinh\Big(\sqrt{\frac{s}{\alpha}}x\Big) \qquad (10)$$

Applying Laplace integral transform technique to equation (6) one gets:

$$\tilde{\theta}(0,s) = \frac{A}{h_0}\tilde{q}(s) - \rho C_p\frac{s}{h_0}\int_0^d \tilde{\theta}(x,s)dx \qquad (11)$$

Solving equations (10) and (11) one gets:

$$\tilde{\theta}(x,s) = \frac{A\tilde{q}(s)\cosh\Big(\sqrt{\frac{s}{\alpha}}x\Big)}{\left[\lambda\sqrt{\frac{s}{\alpha}}\sinh\left(\sqrt{\frac{s}{\alpha}}d\right) + h_0\cosh\Big(\sqrt{\frac{s}{\alpha}}d\Big)\right]} \qquad (12)$$

Since $\cosh x = \frac{e^x + e^{-x}}{2}$, $\sinh x = \frac{e^x - e^{-x}}{2}$, equation (12) can be rewritten in the form:

$$\tilde{\theta}(x,s) = \frac{A\tilde{q}(s)\left[\exp(-\sqrt{\frac{s}{\alpha}}(2d-x)+\exp(-\sqrt{\frac{s}{\alpha}}x)\right]}{\left[\lambda\sqrt{\frac{s}{\alpha}}+h_0\right]\left[1-\gamma\exp(-2\sqrt{\frac{s}{\alpha}}d)\right]} \tag{13}$$

Where :

$$\gamma = \frac{\lambda\sqrt{\frac{s}{\alpha}}-h_0}{\lambda\sqrt{\frac{s}{\alpha}}+h_0} \tag{14}$$

Discussing the orders of magnitudes in equation (14) for low cooling one finds that γ tends to unity. Thus equation (13) can be rewritten in the form :

$$\tilde{\theta}(x,s) = \frac{A\tilde{q}(s)\left[\exp(-\sqrt{\frac{s}{\alpha}}(2d-x)+\exp(-\sqrt{\frac{s}{\alpha}}x)\right]}{\left[\lambda\sqrt{\frac{s}{\alpha}}+h_0\right]\left[1-\exp(-2\sqrt{\frac{s}{\alpha}}d)\right]} \tag{15}$$

To get the inverse Laplace transform of $\tilde{\theta}(x,s)$ one has to make use of the convolution theorem [30]:

$$L^{-1}\ \{f_1\ (\mathrm{s})\ f_2(s)\}=\int_0^t f_1(\tau)\ f_2(\mathrm{t}-\tau)\mathrm{d}\tau. \tag{16}$$

Where:

$$f_1\ (\mathrm{s})=\ \tilde{q}(s) \tag{17}$$

$$f_2(s)= \frac{\left[\exp(-\sqrt{\frac{s}{\alpha}}(2d-x)+\exp(-\sqrt{\frac{s}{\alpha}}x)\right]}{\left[\lambda\sqrt{\frac{s}{\alpha}}+h_0\right]\left[1-\exp(-2\sqrt{\frac{s}{\alpha}}d)\right]}\ . \tag{18}$$

Considering the relation

$$\frac{1}{1-x} = \sum_{n=0}^{\infty} x^n \qquad |x| < 1 \qquad [29], \tag{19}$$

one can get the temperature of the cell in the following form:

$$\theta(x,t) = A\,\frac{\sqrt{\alpha}}{\lambda}\quad \mathrm{q}_{\max}\quad \int_0^t \Bigg[\exp\left(\frac{-(\tau-t_0)^2}{(t_s-\tau)(\tau-t_r)}\right).\sum_{n=0}^{\infty}\Bigg[\frac{exp\left(\frac{-(2dn+x)^2}{4\alpha(t-\tau)}\right)}{\sqrt{\pi(t-\tau)}} + \frac{exp\left(\frac{-(2d(n+1)-x)^2}{4\alpha(t-\tau)}\right)}{\sqrt{\pi(t-\tau)}} - \frac{\sqrt{\alpha}}{\lambda}h_0\Bigg[exp\left(\frac{(2d(n+1)-x)h_0}{\lambda}+\frac{\alpha {h_0}^2}{\lambda^2}(t-\tau)\right).erfc\left(\frac{(2d(n+1)-x)}{\sqrt{4\alpha(t-\tau)}}+\frac{h_0}{\lambda}\sqrt{\alpha(t-\tau)}\right) + exp\left(\frac{(2nd+x)h_0}{\lambda}+\frac{\alpha {h_0}^2}{\lambda^2}(t-\tau)\right).erfc\left(\frac{(2nd+x)}{\sqrt{4\alpha(t-\tau)}}+\frac{h_0}{\lambda}\sqrt{\alpha(t-\tau)}\right)\Bigg]\Bigg]d\tau\Bigg] \tag{20}$$

II- The efficiency of the solar cell

Equation (20) is used to find the efficiency of the solar .

The efficiency (η) of the solar cell is defined as the ratio between the maximum power P_{max} , generated by a solar cell and the received power P_{in} as follows [2]:

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{I_m V_m}{P_{in}} = \frac{V_{0c}\ I_{sc}\ FF}{P_{in}} \tag{21}$$

Where:

P_{in} , W is the total input solar power received by the solar cell ,

V_{0c} is the open circuit voltage which is given as [2] *:*

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

(22)

Where:

k ,($J/{}^{0}K$) is the Boltzmann constant , T (^{0}K) is the cell temperature , (e=-1.6×10^{-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] :

$$I_0 = \varepsilon\, n'\, T^{\gamma'} e^{\left(\frac{-E_g}{k\,T}\right)} \qquad (23)$$

Where:

$\varepsilon = 179$ amp/K^{3}m^2 for Silicon solar cell [14] , 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 of a semiconductor on temperature can be described as [31-32]:

$$E_g = E_g(0) - \frac{\bar{\alpha}\, T^2}{T+\beta} \quad \text{, where} \qquad (24)$$

$E_g(0)$ is the energy band gap of the semiconductor at $T \approx 0\ {}^{0}K$, for silicon $E_g(0) = 1.16\ eV$ [30] , $\bar{\alpha} = 7 \times 10^{-14}\ eV\,K^{-1}$ and $\beta = 1100\ {}^{0}K$ which are constants for each semiconductor material [31] , I_{sc} is the short circuit current given as [1] :

$$I_{sc} = Q\,(1 - R(T))\,(1 - e^{-\mu\,\ell})\; e\, n_{photons} \qquad (25)$$

Where:

Q is the collection factor , $R(T)$ is the reflection coefficient at the front surface of the cell and its value is given as [33] :

$$R(T) = 0.322 + 3.12 \times 10^{-5}\ T \tag{26}$$

μ, is the attenuation coefficient and its value is given as [33] :

$$\mu = a\, e^{\frac{T}{T_1}} \tag{27}$$

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

$$n_{photon} = \frac{q(t)}{E_g} \tag{28}$$

III- Computations

The silicon solar cell temperature " T " as a function of the local day time "t" is calculated using equation (20) .The physical parameters of the silicon are:

ρ =2280 kg/m^3 , C_ρ=840 J/kg.K°, λ=1.5×10^2 W/m.K and α =9.2×10^{-5} m^2/sec .The hourly incident global solar radiation q(t) (eq.(5)) is considered for Egypt and Hong Kong .For the considered values of the temperature "T" the values of $I_{sc}(T)$,$V_{oc}(T)$ are computed using equations (25 and 22). Then the efficiency η(T) (eq. 21) is estimated for different operating conditions as follows:

First: For Egypt (July) (1980) [34]

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

(1)The effect of cooling conditions on the efficiency:

Three values of h= 1, 4 and 8 W/m^2.K, are considered for ℓ=1 μm and A = 0.6 as parameters. The obtained results as a function of the shifted time t´ = (t-t_r) are shown in fig. (1).

(2)The effect of thickness on the efficiency:

Three values of ℓ= 1 μm, 1and 5 mm, are considered for h=1 W/m^2.K and A = 0.6 as parameters. The obtained results as a function of the shifted time t´ = (t-t_r) are shown in fig. (2).

(3)The effect of absorption coefficient on the efficiency:

Three values of A= 0.6, 0.7 and 0.8, are considered for ℓ=1 μm and h=1 W/m^{2}K as parameters. The obtained results as a function of the shifted time t´ = (t-t_r) are shown in fig. (3).

Second: For Hong Kong (July [35]) the above same steps (1), (2), (3) are carried out, where the profile parameters are:

q_{max}= 788 W/ m^2 , $t_r = 0$ $hours$, t_0= 7 hours,$t_d =$ 14 hours , t_s = 14 hours.

The obtained results are shown in Figures (4, 5, 6) respectively.

The variation of I_{sc} ,V_{oc},and the efficiency η for ℓ= 10 μm ,h= 1 W/ m^2, A= 0.6 for Egypt (July) are computed and are shown in Figures(7, 8, 9).Computations for ℓ= 50 μm ,h= 1 W/ m^2 , A= 0.8 are made and are also illustrated in Figures (10, 11, 12). The same computations for Hong Kong (July) are made and are shown in figures (13, 14, 15) and figures (16, 17, 18).

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^2.K at thicknesses ℓ = 10 ,20,50 µm and 1mm is computed for Egypt (July) and Hong Kong (July) and are illustrated in Figs.19 and 22 respectively

ii) The efficiency at: A= 0.8 , ℓ = 50µm at different cooling conditions h = 1 , 4 and 8 W/m^{2}K is computed for Egypt (July) , and Hong Kong (July) and are illustrated graphically in Figs. 20 and 23 respectively.

iii) The efficiency at: h = 1W/m^2.K , ℓ= 50 µm 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.21 and 24 respectively.

IV- Results and Discussions

The obtained results illustrated in figure (1) reveal that, the cell temperature decreases as the heat transfer cooling coefficient at the front surface increases.

The obtained results illustrated in figure (2) reveal that, the cell temperature decreases as the thickness of the cell increases and this is attributed to the increase of the mass of the heated bulk as its thickness increases.

The obtained results illustrated in figure (3) reveal that, the cell temperature increases as the absorption coefficient "A" increases due to the increase of the absorbed solar power.

Moreover, the short circuit current I_{sc} increases with increasing temperature and vice versa and this behavior is like the behavior shown in [26].Since as the temperature increases for most semi-conductors, the energy band gab decreases according to (eq.24) and hence I_{sc} increases [36].

In addition the open circuit V_{oc} starts to increase with temperature within the small rang of temperatures where the linear proportionality is predominate (eq.22). Then its value decreases with higher temperatures due to the behavior of the logarithmic function with temperature (eq.22) [37].

As a result the efficiency "η " in general decreases with increasing the temperature .This increase behavior is nearly the same as the behavior of the open circuit voltage with temperature.

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

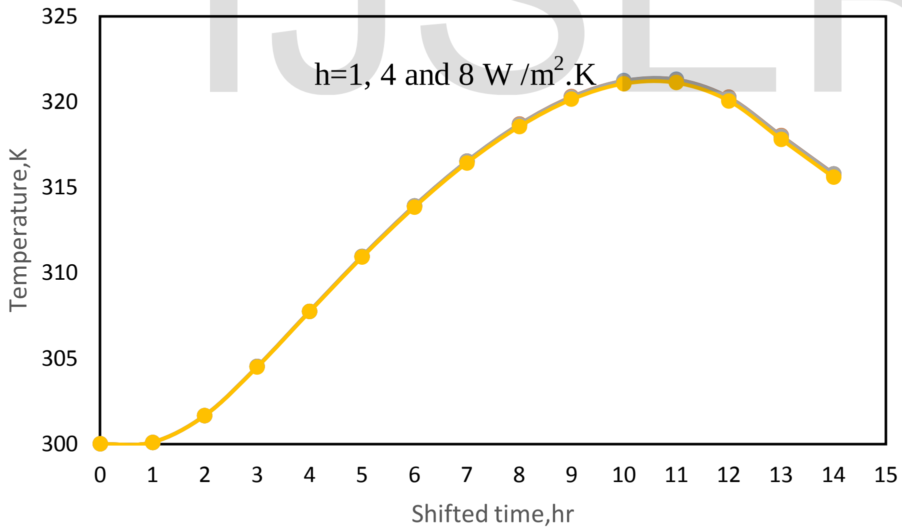

Fig . (1): The temperature of the cell as a function of the local daytime at ℓ=10^{-6} m and A=0.6 for different values of the cooling coefficient at the front surface.

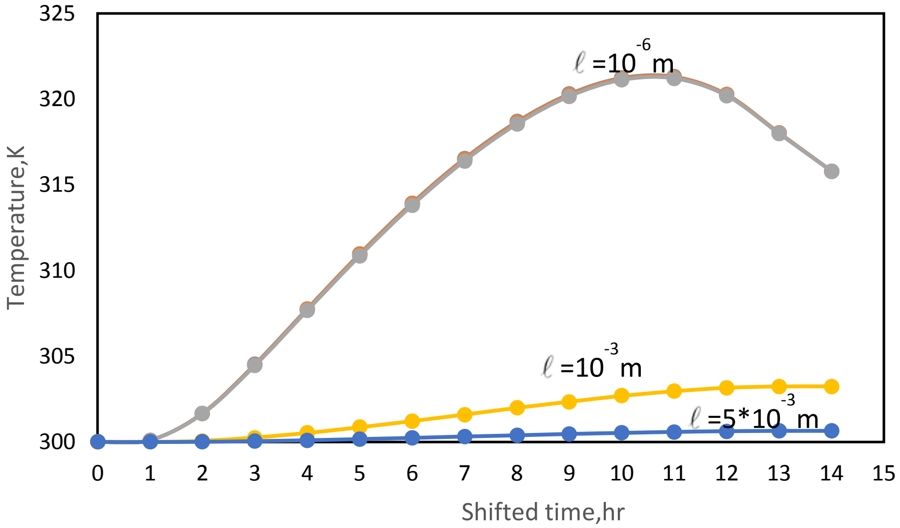

Fig.(2): The temperature of the cell as a function of the local daytime at h=1W/m^2.K and A=0.6 for different values of the thickness.

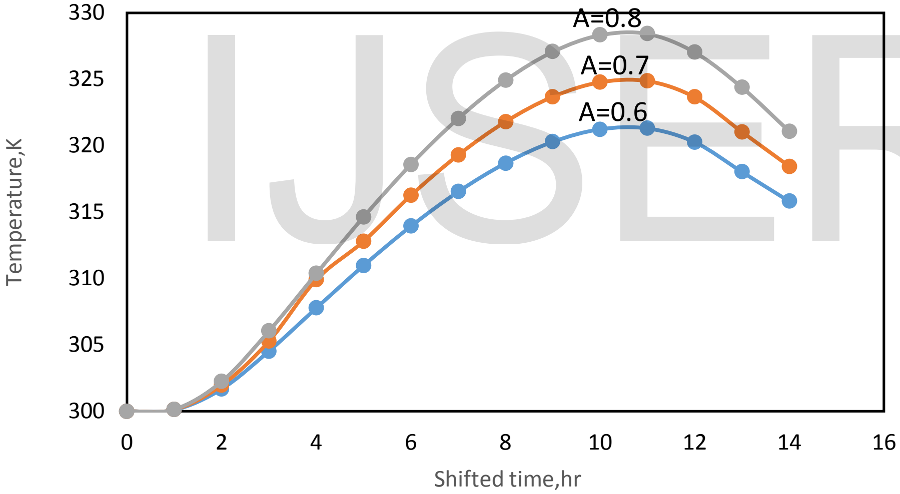

Fig.(3):The temperature of the cell as a function of the local daytime at ℓ =10^{-6} m and h=1W/m^2.K for different values of the absorption coefficient at the front surface.

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

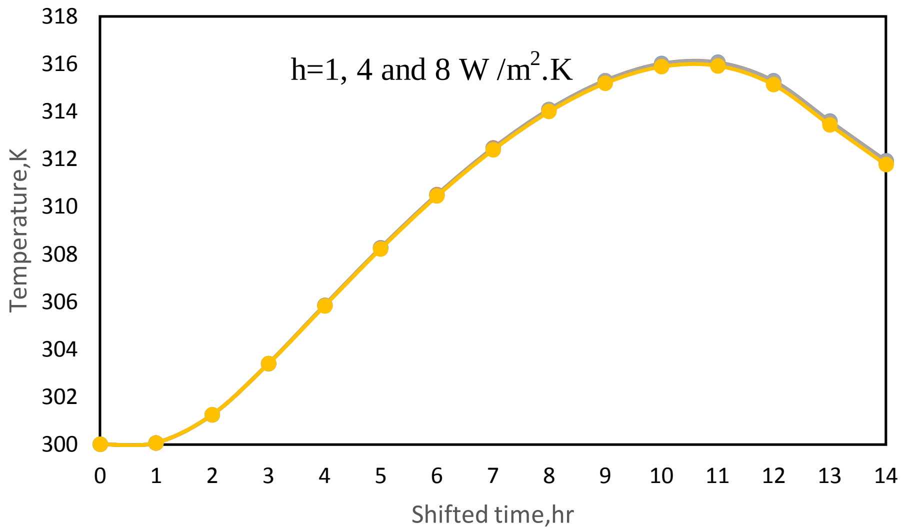

Fig.(4): The temperature of the cell as a function of the local daytime at $\ell=10^{-6}$ m and A=0.6 for different values of the cooling coefficient at the front surface.

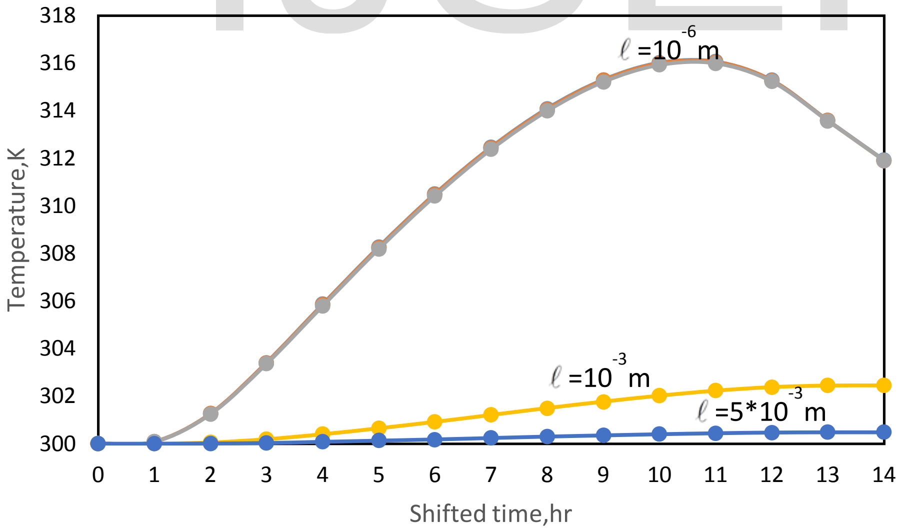

Fig.(5): The temperature of the cell as a function of the local daytime at h=1W/m^2.K and A=0.6 for different values of the thickness.

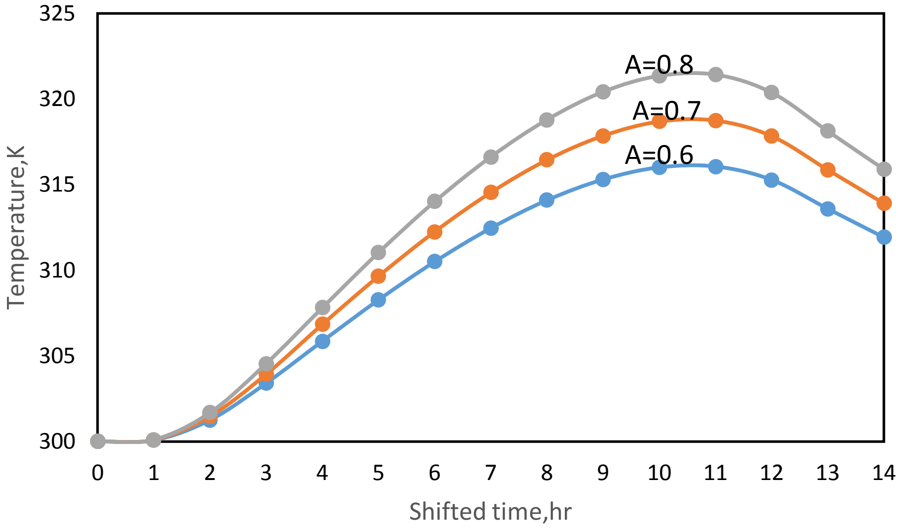

Fig. (6): The temperature of the cell as a function of the local daytime at $\ell=10^{-6}$ m and h=1W/m^2.K for different values of the absorption coefficient at the front surface.

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

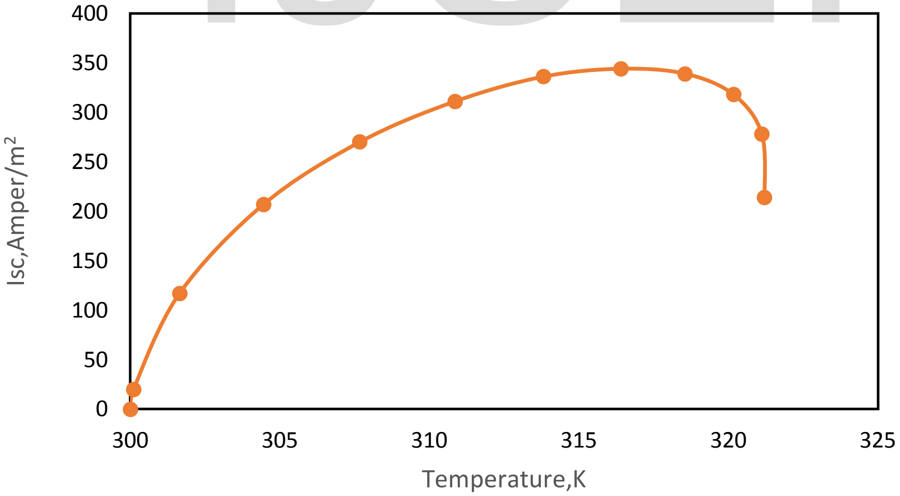

Fig.(7): The temperature dependence of I_{sc} at ℓ=10μm, h=1W/m^2.K and A=0.6.

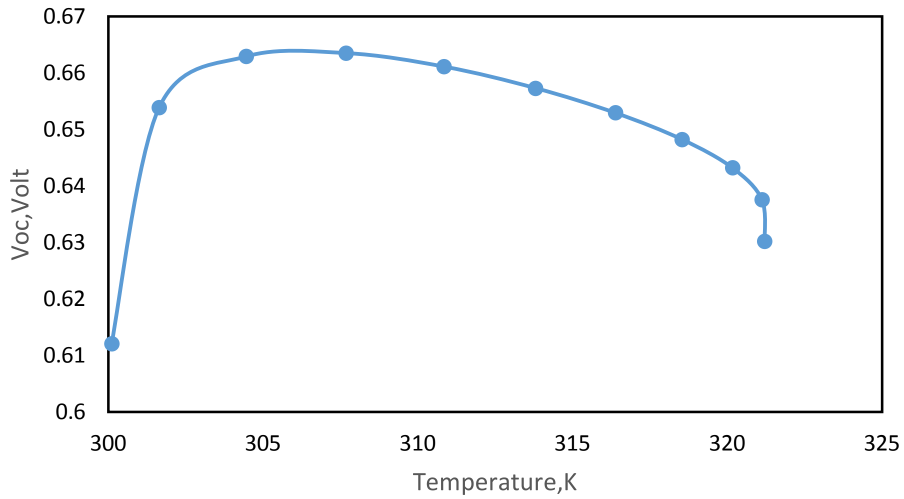

Fig.(8): The temperature dependence of V_{oc} at ℓ=10μm, h=1W/m^2.K and A=0.6.

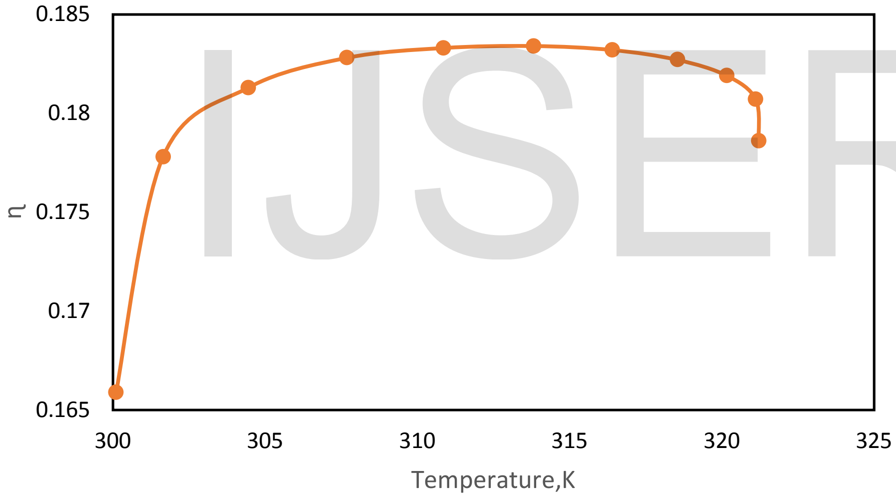

Fig. (9): The temperature dependence of η at ℓ=10μm, h=1W/m^2.K and A=0.6.

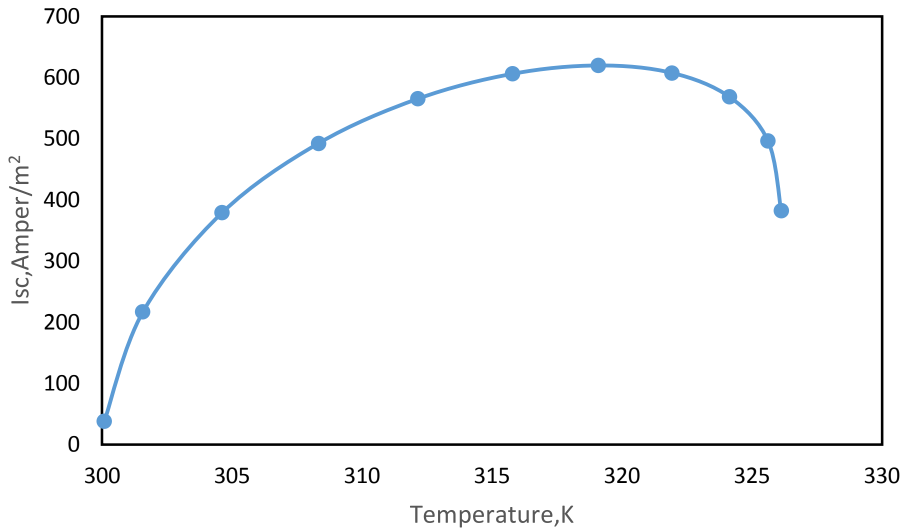

Fig.(10) :The temperature dependence of I_{sc} at ℓ=50μm , h=1W/m^2.K and A=0.8

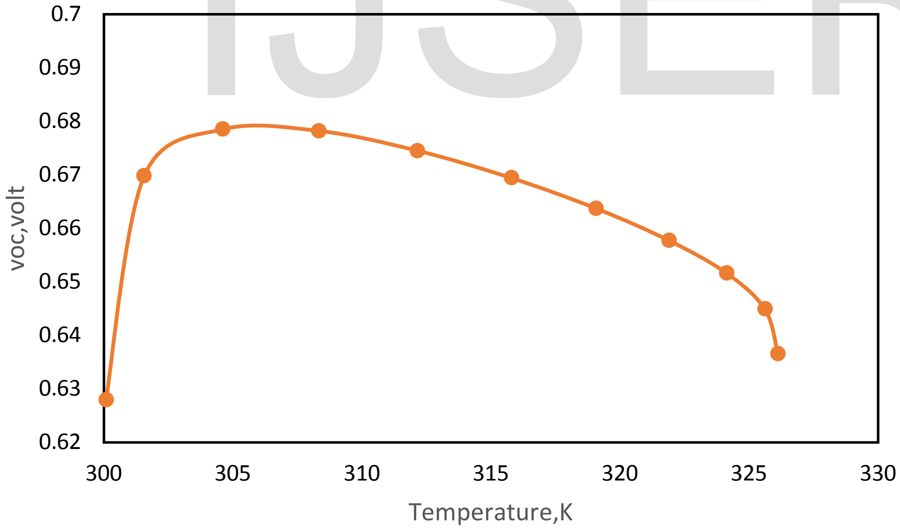

Fig.(11): The temperature dependence of V_{oc} for Egypt July at ℓ=50μm, h=1W/m^2.K and A=0.8.

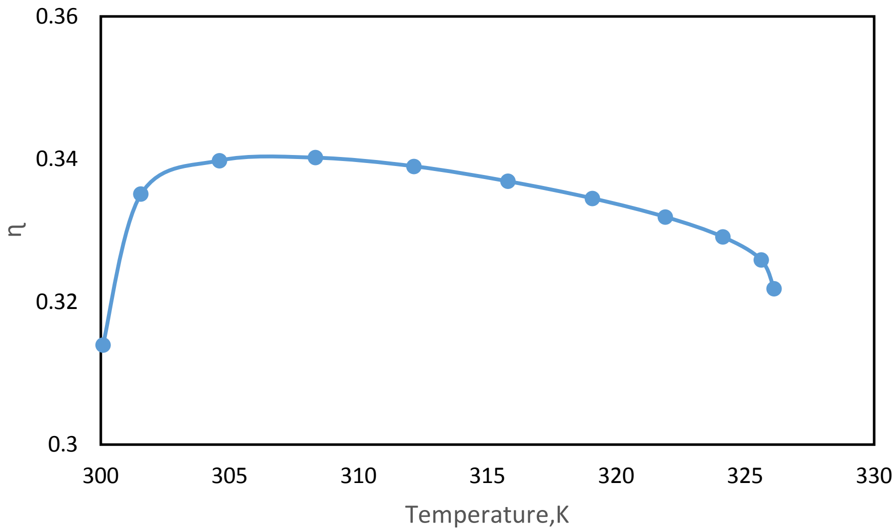

Fig .(12): The temperature dependence of. η for Egypt July at ℓ=50µm , h=1W/m^2.K and A=0.8.

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

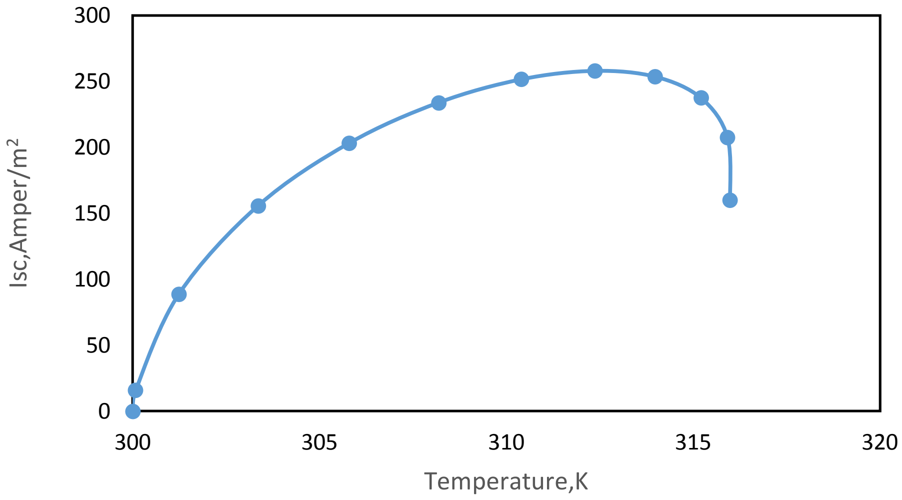

Fig.(13): The temperature dependence of I_{sc} at ℓ=10μm , h=1W/m^2.K and A=0.6.

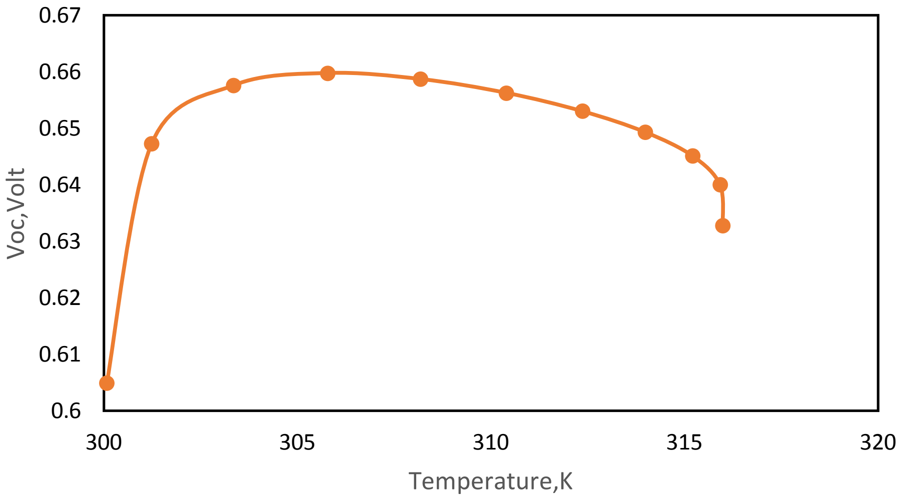

Fig.(14): The temperature dependence of V_{oc} at ℓ=10μm, h=1W/m^2.K and A=0.6.

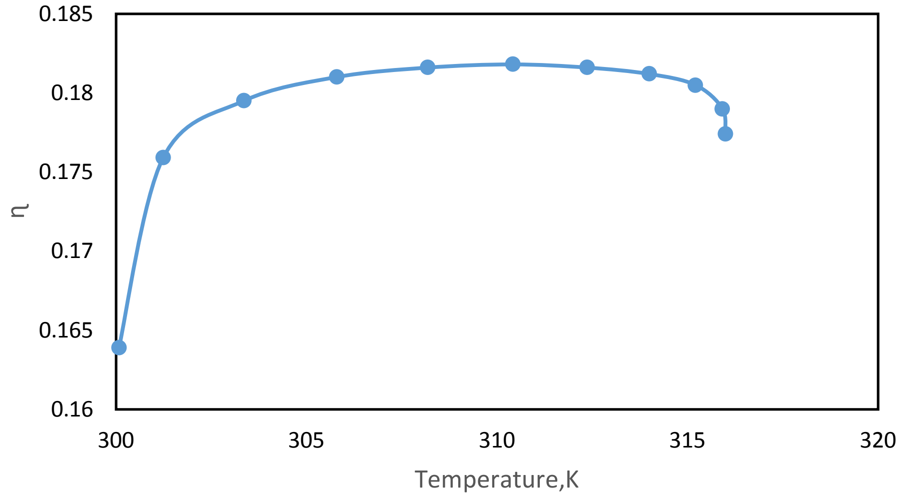

Fig. (15):The temperature dependence of η at ℓ=10μm,h=1W/m^2.K and A=0.6.

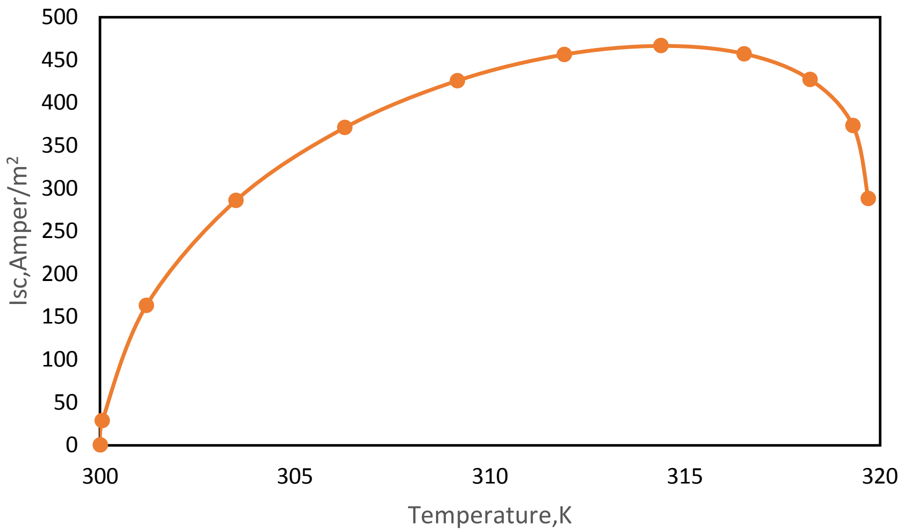

Fig.(16): The temperature dependence of I_{sc} at ℓ=50µm , h=1W/m^2.K and A=0.8.

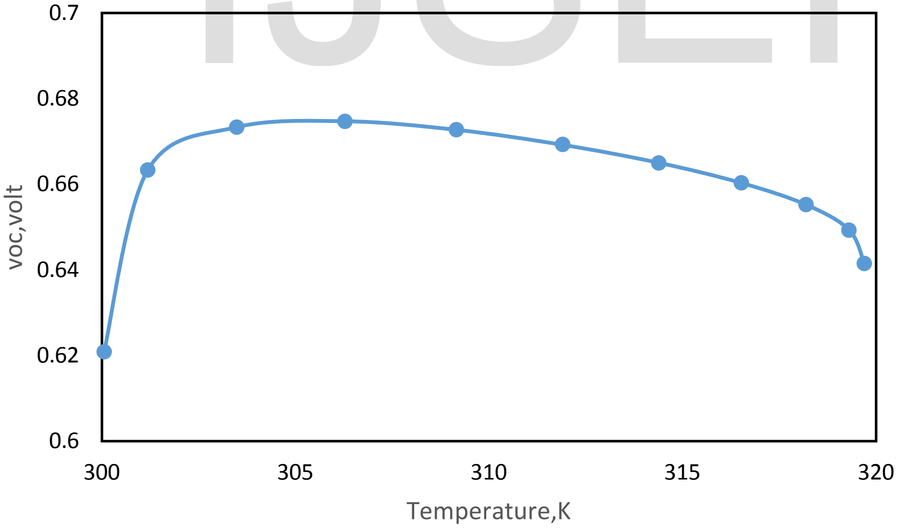

Fig.(17): The temperature dependence of V_{oc} for Hong Kong July at ℓ =50µm, h=1W/m^2.K and A=0.8.

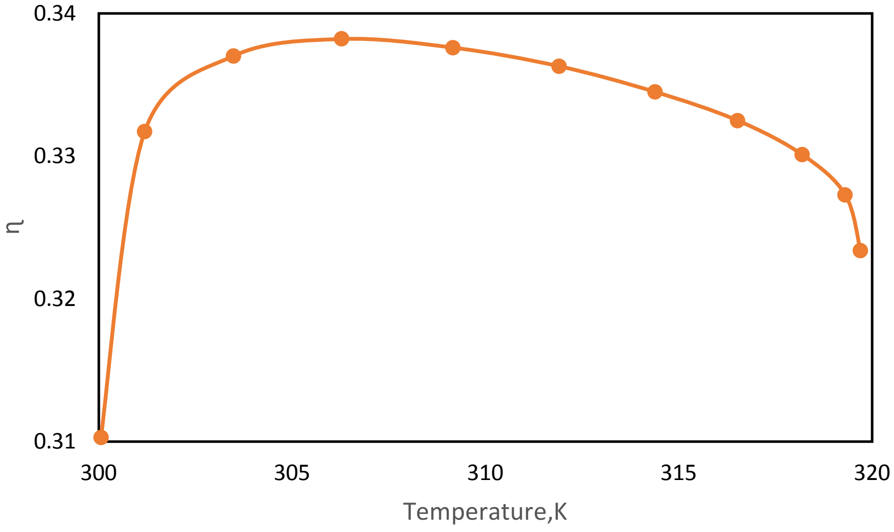

Fig . (18): The temperature dependence of. η for Hong Kong July at ℓ =50µm, h=1W/m^2.K and A=0.8.

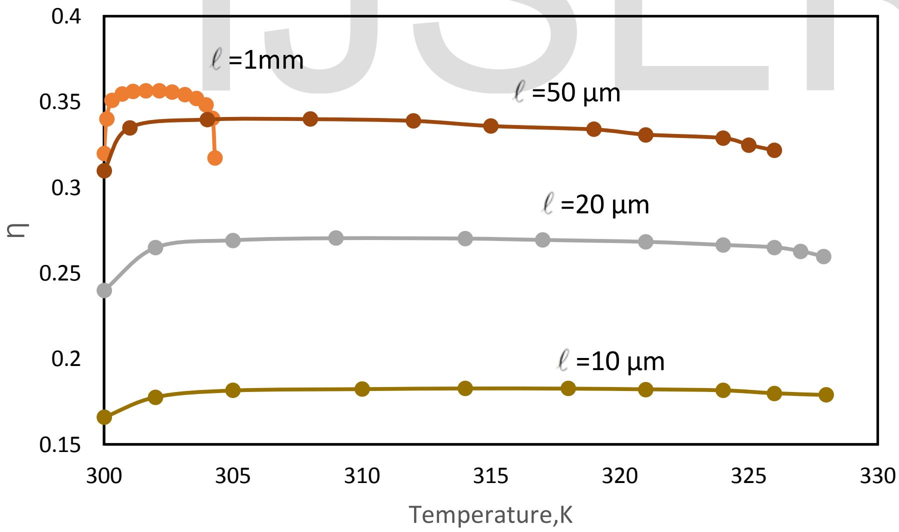

Fig.(19): Effect of thickness on the efficiency of a solar cell at A=0.8 and h=1W/m^2.K

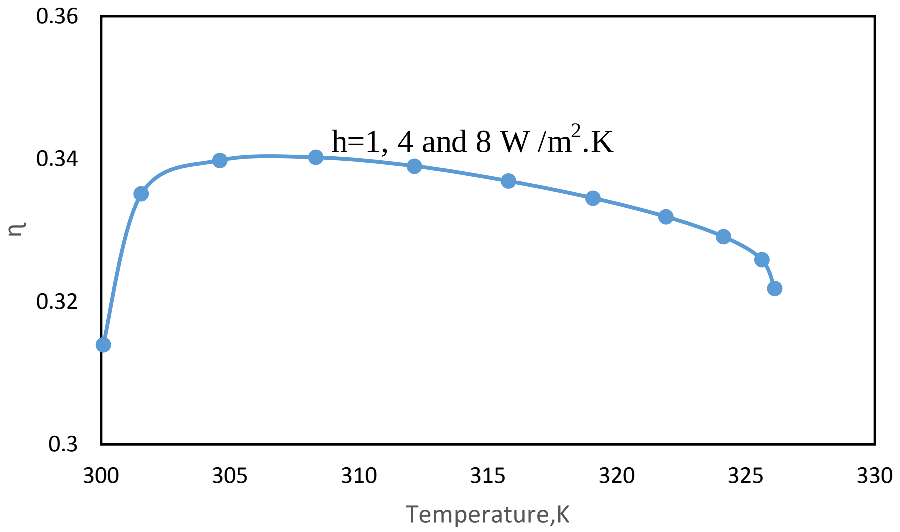

Fig . (20): Effect of cooling on the efficiency of a solar cell at A=0.8 and ℓ=50μm.

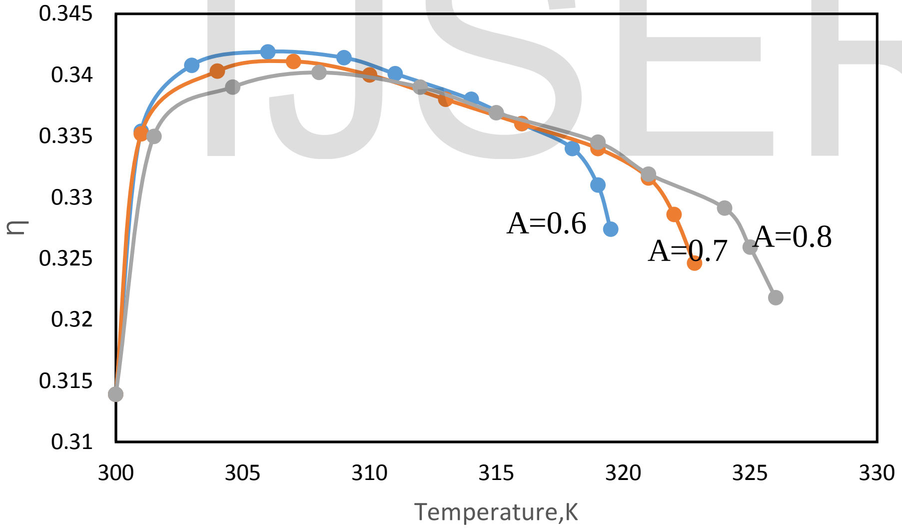

Fig . (21). Effect of Absorption on the efficiency of a solar cell h=1W/m^2.K and ℓ=50μm.

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

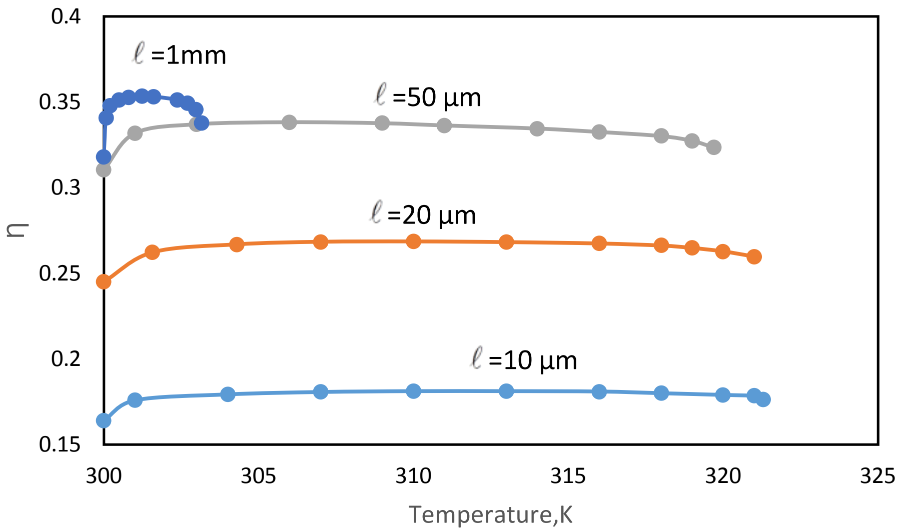

Fig. (22): Effect of thickness on the efficiency of a solar cell at A=0.8 and h=1W/m^2.K

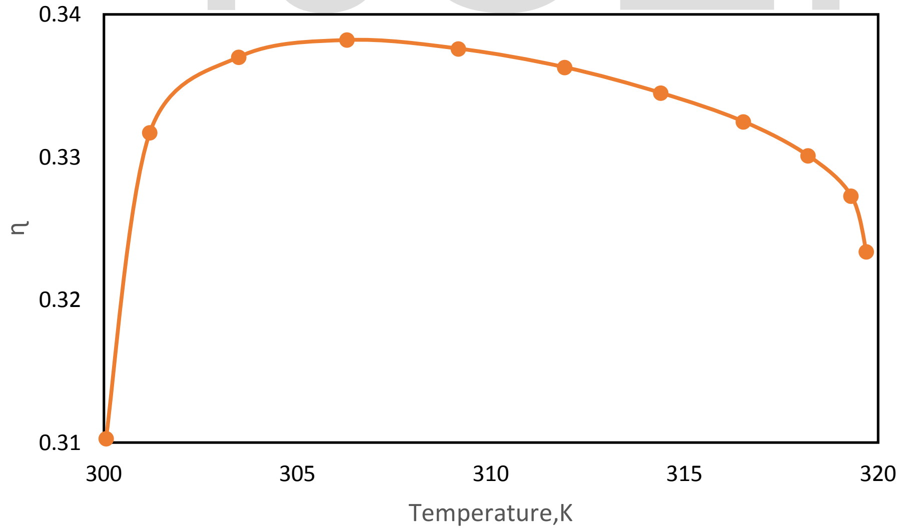

Fig. (23): Effect of cooling on the efficiency of a solar cell at A=0.8 and ℓ=50µm.

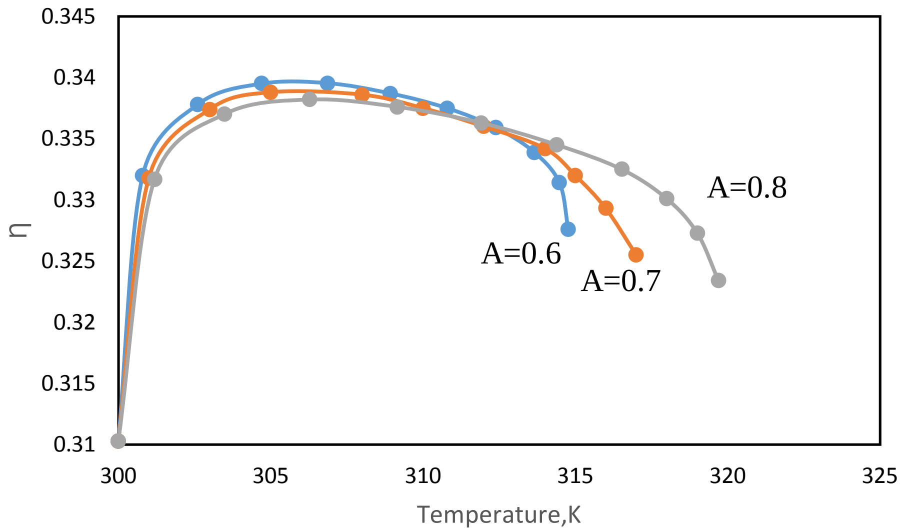

Fig. (24): Effect of Absorption on the efficiency of a solar cell h=1W/m^2.K and ℓ=50μm.

VI- Conclusion

The efficiency of a solar cell depends on its temperature and thus its values change along the local day time.

Higher efficiency are obtained for lower cell temperature. Hence increasing the thickness of the cell, increases the efficiency of the cell. Also increasing the absorption coefficient at front surface, decrease the efficiency of the cell.

As the temperature increases, the short circuit current (I_{sc})increase while the open circuit voltage (V_{oc}) decreases.

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