International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 9 Issue 3 Series.II || Mar.2020 || PP 55-65

The Effect ofTemperatureon the Efficiency of aSilicon Solar Cell Shaded bya Mesh as a Function of the Mesh Parameters and Operating Conditions.

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Abstract: *The efficiency of a silicon solar cell shaded by a mesh is studied. The temperature of the mesh subjected to incident solar insolation is estimated as a function of the mesh parameters. The temperature of the solar cell is also evaluated by solving a heat balance equation considering the radiant energy emitted by the mesh and received by the cell as an additional energy source. All the temperature dependent cell parameters are estimated at different local day times. Shading and cooling conditions are also taken into consideration. The variation of the efficiency along the local day time is thus revealed. An illustrative example is given.*

Keyword: *Solar Energy - Silicon Solar Cell –Solar Cell Temperature - Solar Cell Performance- Solar Cell Efficiency - Heat Transfer Model.*

Date of Submission: 14-03-2020 Date of Acceptance: 31-03-2020

I. Introduction

Trials to increase the efficiency of semiconductor photovoltaic solar cells are important for solar technological applications. This objective has aroused the interest of many investigators [1-9].The parameters of such a cell as open circuit voltage $V_{oc}(T)$, dark saturation current $I_o(T)$, short circuit current $I_{sc}(T)$ and energy gap $E_g(T)$ are in general functions of the cell temperature . Moreover, there are someexternal factors affecting the efficiency, such as the solar illumination levels [8] .This factor is associated with other factors as the shading percentage and the cooling conditions [9-12]. The physical, optical and geometrical characteristics of the cell also play an important role in determining the cell performance. The temperature functional dependence of the open circuit voltage of a photovoltaic solar cell is studied by El-Adawi et al. [5].when a solar cell is subjected to incident solar radiations, its temperature increases relative to the ambient temperature. Besides, a part of the absorber solar energy is transformed into electric energy through the photovoltaic effect. The temperature effect on the solar cell performance is considered by different authors [13-16].

The present trial is formulated to consider a solar cell covered with a mesh.

The aim of the study is to evaluate the efficiency of the solar cell as a function of the mesh parameters, such as its material, its thickness the total area of its pores relative to the surface area of the cell. In such a case the mesh plays two roles:

i) As shading agent.

ii) As an additional source function to overheat the solar cell by radiation. So the mesh hastwo compromising effects.

The shading percentage can be varied through varying the number of the holes in the mesh and the area of each hole.

Through a heat balance equation, the temperature of the cell is obtained.

This temperature varies along the local day time. Thus at each temperature the cell parameters are evaluated asa function of the cell temperature T ^oK. A function that predicts the incident global solar irradiance q_o (t), W/m^{2}is also required. There are manytrials to capture sucha function [17-19].

The efficiency (η) is defined as:

$$\eta = \frac{FF \text{ Isc Voc}}{\text{P}_{\text{in}}},$$

Where P_{in} , is the solar energy received by the cell at the considered local day time”t”

The Mathematical Formulation of the Problem.

In setting up the problem one has to consider a system of a silicon solar cell and a mesh which covers the solar cell. The system is subjected to incident solar radiation.

The aim is to evaluate the temperature of the solar cell in the presence of the mesh.

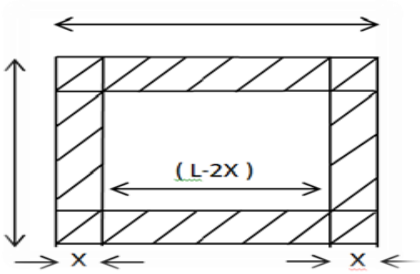
This step is required to estimate the cell parameters and its efficiency. Two steps are required.
First step is to find the temperature of the mesh alone.
Second step is to evaluate the temperature of the solar cell considering the radiant energy received by the solar cell from the mesh. Thus it is suggested that the mesh represents an additional source for heating the solar cell besides that received by the solar insolation.

1- Determination of the mesh temperature:
Let us consider a mesh of a square shape of length "L", m.
The number of its holes is N = (n-1) (m-1),
Where n is the total number of nodes in a horizontal dimension, and "m" is the number of nodes in the other perpendicular dimension.
Let us consider, that each hole is in a square frame of length"l", m. The width of a frame on each side is "x" .Thus the area of the gap in the each hole is $(l-2x)^2$,m^2.
Thus the total area of the gaps in the mesh is $\grave{S}$=N $(l-2x)^2$.
The total area of the mesh subjected to incident solar radiation is $S_n = (L^2 - \grave{S})$.
Let us consider that "d_n" represents the thickness of the mesh material.

The heat balance equation for the mesh can be written in the form:

$$S_n A\, q(t) - S_n h\, \emptyset_n(t) = S_n \rho_n c_{pn} d_n \frac{d\emptyset_n(t)}{dt} \quad (1)$$

Where ,"h",$(W/m^2 K)$ is the heat transfer by convection at the front surface, "ρ_n", (kg/m^3) is the density of the mesh and "d_n", (m) is thickness of the mesh.



Hole figure

Equation(1) can be written in the form:

$$\frac{d\emptyset_n(t)}{dt} + \frac{h\, \emptyset_n(t)}{\rho_n C_{pn}\, d_n} = \frac{A\, q(t)}{\rho_n c_{pn}\, d_n} \quad (2)$$

The solution is obtained in the form:

$$\emptyset_n(t) = e^{\int_0^t -\frac{h}{\rho_n c_n d_n}dt}\left[\frac{A}{\rho_n c_n d_n}\int_0^t q_o(t)\, e^{\int_0^t \frac{h}{\rho_n c_{pn} d_n}dt}\, dt + c\right] (3)$$

at t=0 , $q_o(t)$ =0 and thus c =0

In the present trial $q_o(t)$ is considered in the form [20]:

$$q_o(t) = q_{max}\left(\frac{t}{t_{max}}\right)\left(\frac{t_d - t}{t_d - t_{max}}\right) (4)$$

Where, A is the absorption coefficient of the mesh,q_{max} ,$W/m^2$is the maximum irradiance at $t = t_{max}$, $t_d$is the length of the solar day in hours, given by [21]:

$$t_d = \frac{24h}{180^0} cos^{-1} (\tan \delta \tan L) \quad (5)$$

Where,

$$\delta = 23.45 \sin 360 \left(\frac{284+n}{365}\right), \quad (6)$$

δ is the solar declination angle, and "n" is the day number of the year starting from 1 January i.e., $(1 \le n \le 365)$, L is the latitude.
Substituting the expression of q_0 (t), W/m^2in eq. (4) and performing the entire required integrations one finally gets the solution in the form [22]:

$$\emptyset_n(t) = \frac{b_n q_{max}}{(t_{max}\, t_d - t_{max}^2)}\left\{\left[t_d\left(\frac{t}{a_n} - \frac{1}{a_n^2}\right) + \frac{e^{-at}}{a_n^2}\right] - \left[\left(\frac{t^2}{a_n} - \frac{2t}{a_n^2} + \frac{2}{a_n^3}\right) - \frac{2}{a_n^3} e^{-at}\right]\right\} (7)$$

Where:

$$a_n = \frac{h}{\rho_n c_{pn} d_n} \quad , \quad b_n = \frac{A}{\rho_n c_{pn} d_n} = \frac{A\, S_n}{m_n c_{pn}}$$

2- **Determination of the temperature of the solar cell in the presence of the mesh:**
One can write the heat balance equation in the form:

$$S(1-\varepsilon)\bar{A}q(t) - S(1-\varepsilon)\, h\, \theta(t) + \sigma S_n {\emptyset_n}^4(t) = S(1-\varepsilon)\rho d c_p \frac{d\theta}{dt} \quad (8)$$

Where:

$\varepsilon = \frac{S_n}{S}$, isthe percentage of shading of the metal mesh on the solar cell.

$\sigma = 5.67 * 10^{-8}$, is the Stefan's Bolthmann constantand $\bar{A}$is the absorption coefficient of the solar cell.

Equation (8) can be written in the following form:

$$\frac{d\theta}{dt} + \frac{h\,\theta(t)}{S\rho d c_p} = \frac{\bar{A} q_o(t)}{S\rho d c_p} + \frac{\sigma S_n {\emptyset_n}^4(t)}{S(1-\varepsilon)\rho d c_p} \quad (9)$$

Equation (9) can be written in the following form:

$$\frac{d\theta}{dt} + a\,\theta(t) = Q(t) \quad (10)$$

Where:

$$a = \frac{h}{d\rho\, c_p},\ Q(t) = \left[\frac{\bar{A}}{d\rho\, c_p} q_o(t) + \frac{\sigma S_n}{S d\rho\, c_p} {\emptyset_n}^4(t)\right]$$

Equation (10) has an integrated factor exp $\left(\int \frac{h}{d\rho\, c_p} dt\right)$

Thus the solution is obtained in the form [23].

$$\theta(t) = e^{-\int_0^t \left(\frac{h}{d\rho\, c_p} t\right) dt} \left[\int_0^t Q(t)\, e^{\int_0^t \left(\frac{h}{d\rho\, c_p} t\right) dt}\, dt\right] \quad (11)$$

Substituting the values of,Q (t) from eq. (10) one gets:

$$\theta(t) = \exp\left(\frac{-ht}{d\rho\, c_p}\right)\left[\int_0^t \left(\frac{\bar{A}}{d\rho\, c_p} q(t) + \frac{\sigma S_n}{S(1-\varepsilon) d\rho\, c_p} {\emptyset_n}^4(t)\right)\right] \exp\left(\frac{ht}{d\rho\, c_p}\right) dt \quad (12)$$

Substituting the values of q (t) from eq. (4) &${\emptyset_n}^4$ from eq. (7) in equation (12) one gets:

$$\theta(t) = \frac{\bar{A}}{d\rho\, c_p} e^{-at} \int_0^t q_{\max} \frac{(t t_d - t^2)}{(t_{\max}\, t_d - t_{\max}^2)} e^{at} dt + + \exp\left(\frac{-ht}{d\rho\, c_p}\right) \frac{\sigma S_n}{S(1-\varepsilon) d\rho\, c_p} \int_0^t \left(\frac{S_n A q_{\max}}{m_n c_n (t_{\max}\, t_d - t_{\max}^2)}\right)^4 * \left\{\left[\frac{t_d}{a_n}\left(t - \frac{1}{a_n} + \frac{e^{-at}}{a_n}\right)\right] - \left[\frac{1}{a_n}\left(t^2 - 2\left(\frac{t}{a_n} - \frac{1}{a_n^2} + \frac{e^{-at}}{a_n^2}\right)\right)\right]\right\}^4 \exp\left(\frac{ht}{d\rho\, c_p}\right) dt$$

(13)

By integrating eq. (13)by the aid of the related references [22] and well established computer programs [mat lab – version :Febuary23,2017] one gets The expression of the temperature of the solar cell in the presence of a mesh. It can be written in the form:

$$\theta(t) = \frac{b q_{\max}}{(t_{\max}\, t_d - t_{\max}^2)} \left\{\left[t_d\left(\frac{t}{a} - \frac{1}{a^2}\right) + \frac{e^{-at}}{a^2}\right] - \left[\left(\frac{t^2}{a} - \frac{2t}{a^2} + \frac{2}{a^3}\right) - \frac{2}{a^3} e^{-at}\right]\right\} +$$

$$+ \exp\left(\frac{-ht}{d\rho\, c_p}\right) \frac{\sigma S_n}{S(1-\varepsilon) d\rho\, c_p} \left(\frac{S_n A q_{\max}}{m_n c_n (t_{\max}\, t_d - t_{\max}^2)}\right)^4 *$$

$$* \int_0^t \left\{\left[\frac{t_d}{a_n}\left(t - \frac{1}{a_n} + \frac{e^{-at}}{a_n}\right)\right] - \left[\frac{1}{a_n}\left(t^2 - 2\left(\frac{t}{a_n} - \frac{1}{a_n^2} + \frac{e^{-at}}{a_n^2}\right)\right)\right]\right\}^4 \exp\left(\frac{ht}{d\rho\, c_p}\right) dt$$

(14)

3. The efficiency temperature dependence for the solar cell in the presence of a mesh:

The efficiency (η) of the solar cell is defined as the ratio between the maximum electricpowerP_{max} = (FF $V_{oc} I_{SC}$), generated by a solar cell and the received solar power P_{in} as follows [24]:

$$\eta = \frac{FF\, I_{SC}\, V_{oc}}{Pin} \quad (15)$$

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 [24]:

$$V_{oc} = \frac{kT}{e} \ln\left(\frac{I_{sc}}{I_o} + 1\right) \quad (16)$$

Where:

k (J/ ^oK) is the Boltzmann constant, T (^oK) is the cell temperature,

(e=1.6*10^{-19} Coulomb) is the electron charge, Io(amp/m^2) is the reverse saturation current and its dependence on temperature is revealed through the following equation [24]:

$$I_o = \xi\, n T^{\gamma} e^{\frac{-E_g}{KT}} \quad (17)$$

Where:
The value of γ =3[24], ξ= 179 amp/K^3m^2 for silicon solar cell [25], n is non-ideality factor of the cell and is taken as unity, E_g is the energy band gap. The dependence of energy band gap of a semiconductor on temperature can be described as [26-27]:

$$E_g = E_g(0) - \frac{\alpha T^2}{T+\beta} \quad (18)$$

$E_g(0)$ is the energy bandgapof the semiconductor at T$\approx 0\ ^oK$
For silicon $E_g(0)$ =1.16 eV [28],
α =7*10^{-14} eVK^{-1} and β= 1100 ^oK
Which are constants for each semiconductor material [27], I_{SC} is short circuit current given
As [29],

$$I_{SC}=Q\ (1-R\ (T))\ (1-\exp\ (\mu\ d))en_{photons} \quad (19)$$

Where:
Q = 0.8, is the collection factor, R (T) is the reflection coefficient at the front face of the cell and its value is given as [30]:

$$R\ (T) = 0.322 + 3.12 * 10^{-5}\ T \quad (20)$$

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

$$\mu = a \exp\ (T/T_S) \quad (21)$$

where :

a=3.17x10^4 m^{-1} ,T_S =346 ^oK, d in meters, is the thickness of the solar cell *and*
$n_{photons}$ is the number of photons with energy ($E_g \geq h\upsilon$) and for simplicity its value for a given temperature T at a certain local daytime is given as:

$$n_{photon}=q\ (t)/E_g \quad (22)$$

3-Computations
***The mesh temperature**
The mesh temperature and its variation along the local day time are estimated using Eq. (7) at different levels of cooling (h =5 W/$m^2\ ^oK$, h = 10 W/$m^2\ ^oK$ and h = 50W/$m^2\ ^oK$) and at different thicknesses of mesh frame (d_n =2mm, 3.5mm and 5mm) for different materials: copper, iron, and Bakelite.

The hourly incident global solar radiation q (t) (eq. (4)) is considered for Makah [31] as an illustrative example·
The following parameters are also considered:
$q_{max} = 971\ , W/m^2$ is the maximum irradiance at $t = t_{max}$,
$t_d = 12, hr$ is the length of the solar day in hours,

t_{max} = 6, hr.
The following physical properties of Copper, iron and Bakelite areused in computations [32].

	Copper	iron	Bakelite
$\rho, Kg/m^3$	8900	7897	1273.5
$C_p, J/Kg.K$	380	452	1590

Different thicknessesd_n =2*10^{-3}, 3.5*$10^{-3}$and 5*10^{-3} m are consideredat
h=10 W/$m^2\ ^oK$, A=0.7.The obtained results are illustrated graphically in figs. (1), (2) and (3) for Copper, iron and Bakelite respectively. The obtained data Show that the temperature of the mesh increases as the thickness decreases.
Different cooling conditions h = 5, 10 and 50, W/$m^2\ ^oK$ are considered at thicknessd_n= 3.5*10^{-3} m, A =0.7. The obtained results are illustrated graphically in fig. (4), (5) and (6) for Copper, iron and Bakelite. Which show that the temperature of the grid increases as the cooling conditions decreases. The relation of the temperatureof the grid along the local day time for different materials is considered ath=10W/$m^2\ ^oK$, d_n=3.5*10^{-3}m and A=0.7.The obtained results are illustrated graphically in fig. (7)

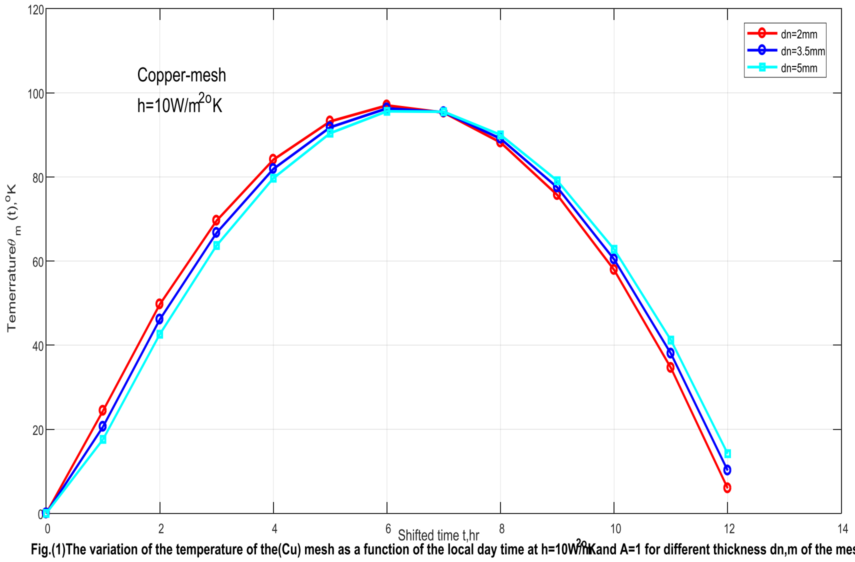


Fig.(1)The variation of the temperature of the(Cu) mesh as a function of the local day time at $h=10W/m^{2o}K$and A=1 for different thickness dn,m of the mesh

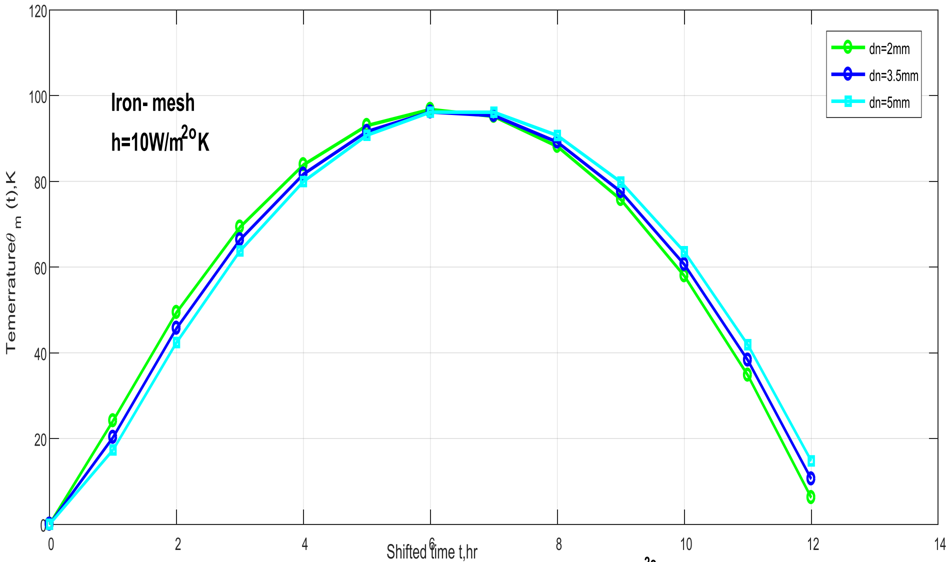


Fig.(2):The variation of the temperature of the(Fe) mesh as a function of the local day time at $h=10W/m^{2o}K$ and A=1 for different thicknesdn,m of the mesh

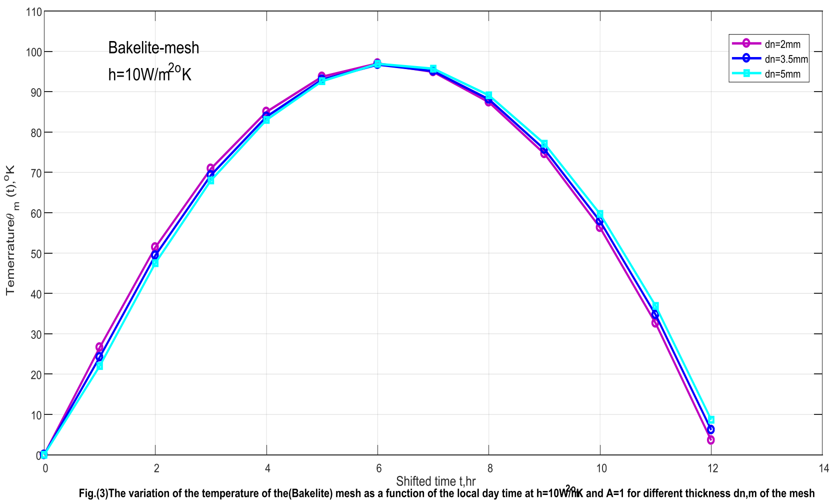


Fig.(3)The variation of the temperature of the(Bakelite) mesh as a function of the local day time at $h=10W/m^{2o}K$ and A=1 for different thickness dn,m of the mesh

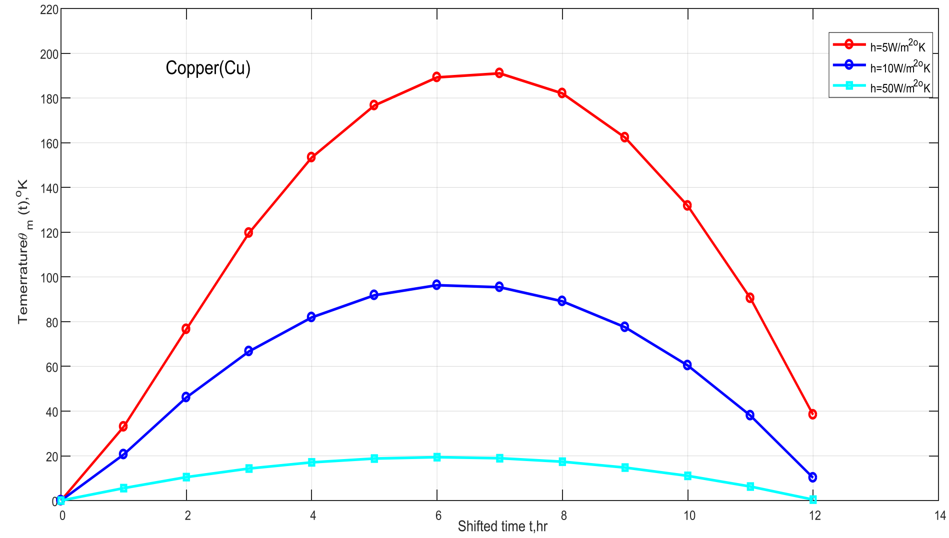
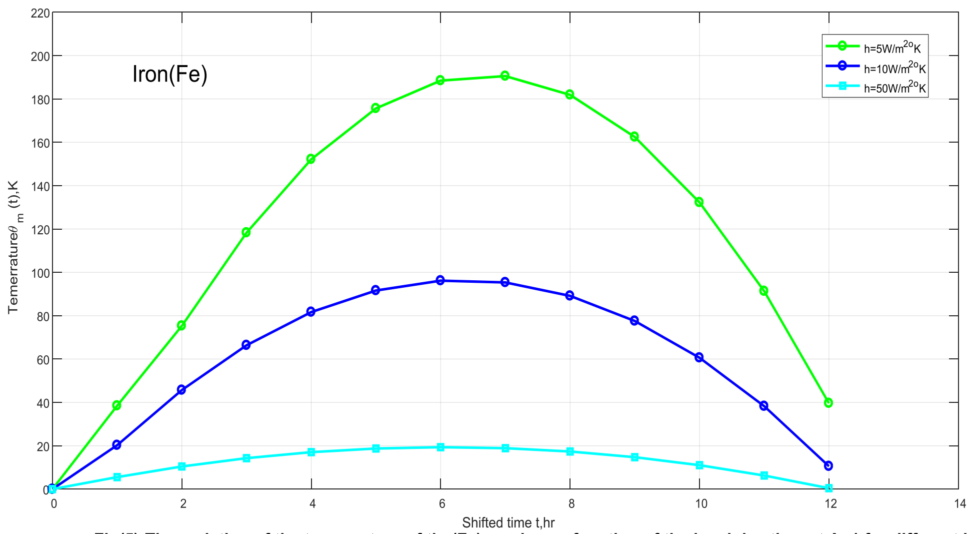


Fig.(4):The variation of the temperature of the(Cu) mesh as a function of the local day time at A=1 for different h



Fig(5):The variation of the temperature of the(Fe) mesh as a function of the local day time at A=1 for different h

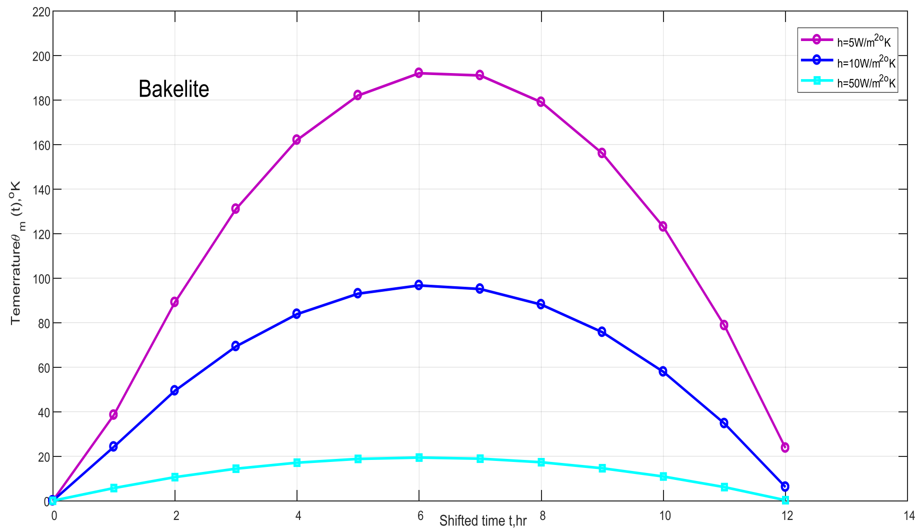


Fig.(6)The variation of the temperature of the(Bakelite) mesh as a function of the local day time at A=1 for different h

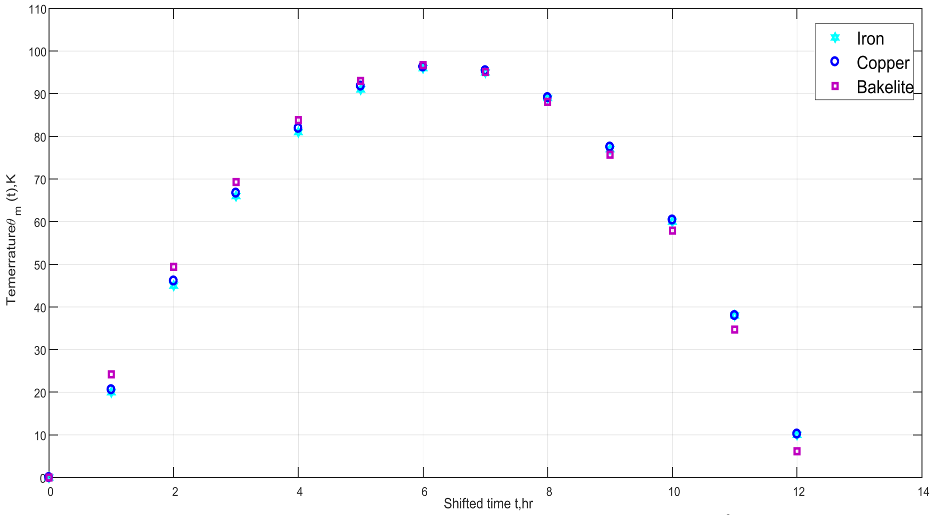


Fig.(7):The variation of the temperature of the mesh as a function of the local day time at h=10W/m^2 ^{o}K and A=1 for different metals

The temperature of the solar cell in the presence of a mesh.

The solar cell temperatureθ (t),^{o}K (equation (14))along the local solar day time (t, hr) shaded by the mesh of different materials (Copper, iron and Bakelite) of thickness d_n=1mm and h=10W/m^2 ^oKat different widths (x) of the frame of each hole are considered. The obtained results are given in tables (1), (2) and (3) and are illustrated graphically in figs. (8), (9) and (10) which show that the temperature of the solar cell in the presence of a mesh decreases as the widths (x) of the frame of each hole increases.

Table (1): The solar cell temperatureθ (t),^{o}K(equation (14)) along the local solar day time (t, hr) shaded by the mesh of copper (Cu) of thickness dn=1mm and h=10W/m^2 ^oK at different widths of the frame of each hole**.**

Shift time t, hr	θ, ^oK X=0	θ, ^oK X=1mm	θ, ^oK X=2mm	θ, ^oK X=3mm	θ, ^oK X=4mm
1	20.6	10.97	6.17	2.74	0.68
2	46.1	22.29	12.53	5.57	1.39
3	66.7	31.21	17.53	7.79	1.95
4	81.9	37.7	21.18	9.41	2.35
5	91.8	41.78	23.48	10.43	2.61
6	96.3	43.44	24.41	10.84	2.71
7	95.4	42.68	23.98	10.66	2.66
8	89.1	39.51	22.2	9.86	2.47
9	77.5	34	19.21	8.67	2.36
10	60.4	25.9	14.61	6.54	1.71
11	38	15.47	8.7	3.87	0.98
12	10.2	2.62	1.47	0.65	0.16

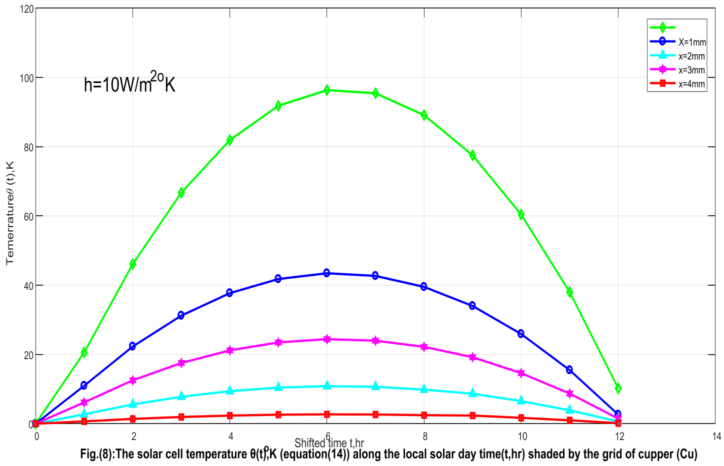


Fig.(8):The solar cell temperature θ(t),^{o}K (equation(14)) along the local solar day time(t,hr) shaded by the grid of cupper (Cu) of thickness dn=1mm and h=10W/m^2 ^{o}K at differen width of the frame of each hole.

Table (2): The solar cell temperatureθ (t),°K(equation (14)) along the local solar day time (t, hr) shaded by the grid of Iron (Fe) of thickness dn=1mm and h=10W/m^2 ^oK at different widths of the frame of each hole.

Shift time t, hr	θ, ^oK X=0	θ, ^oK X=1mm	θ, ^oK X=2mm	θ, ^oK X=3mm	θ, ^oK X=4mm
1	20.26	10.97	6.166	2.74	0.68
2	45.7	22.29	12.526	5.56	1.39
3	66.36	31.21	17.534	7.79	1.95
4	81.67	37.7	21.184	9.41	2.35
5	91.61	41.78	23.475	10.43	2.61
6	96.16	43.44	24.408	10.84	2.71
7	95.34	42.68	23.982	10.66	2.66
8	89.14	39.51	22.197	9.86	2.47
9	77.56	33.98	19.19	8.64	2.32
10	60.6	25.93	14.6	6.53	1.69
11	38.27	15.47	8.7	3.87	0.98
12	10.56	2.62	1.472	0.65	0.16

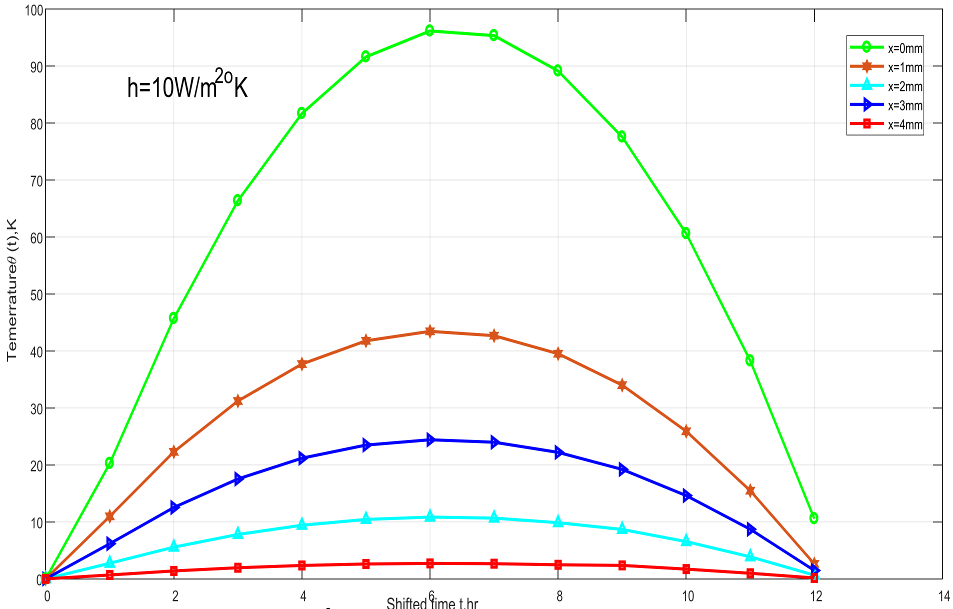


Fig.(9):The solar cell temperature θ(t)K (equation(14)) along the local solar day time(t,hr) shaded by the mesh of Ferric(Fe) of the thickness dn=1mm and h=10W/m^2 °K at different width of the frame of each hole.

Table (3): The solar cell temperature θ, ^oK (equation (14)) along the local solar day time (t) shaded by a grid of Bakelite of thickness dn=1mm and h=10W/m^2 ^oK at different widthsof the frame of each hole.

Shift time t, hr	θ, ^oK X=0	θ, ^oK X=1mm	θ, ^oK X=2mm	θ, ^oK X=3mm	θ, ^oK X=4mm
1	24.2	10.96	6.17	2.75	0.68
2	49.4	22.3	12.55	5.58	1.39
3	69.3	31.2	17.6	7.81	1.95
4	83.8	37.7	21.2	9.44	2.36
5	93	41.8	23.5	10.5	2.61
6	96.7	43.4	24.44	10.9	2.72
7	95.1	42.7	24.02	10.7	2.67
8	88.1	39.5	22.2	9.89	2.47
9	75.7	34	19.2	8.66	2.32
10	57.9	25.9	14.6	6.55	1.69
11	34.7	15.5	8.71	3.88	0.98
12	6.16	2.62	1.47	0.65	0.16

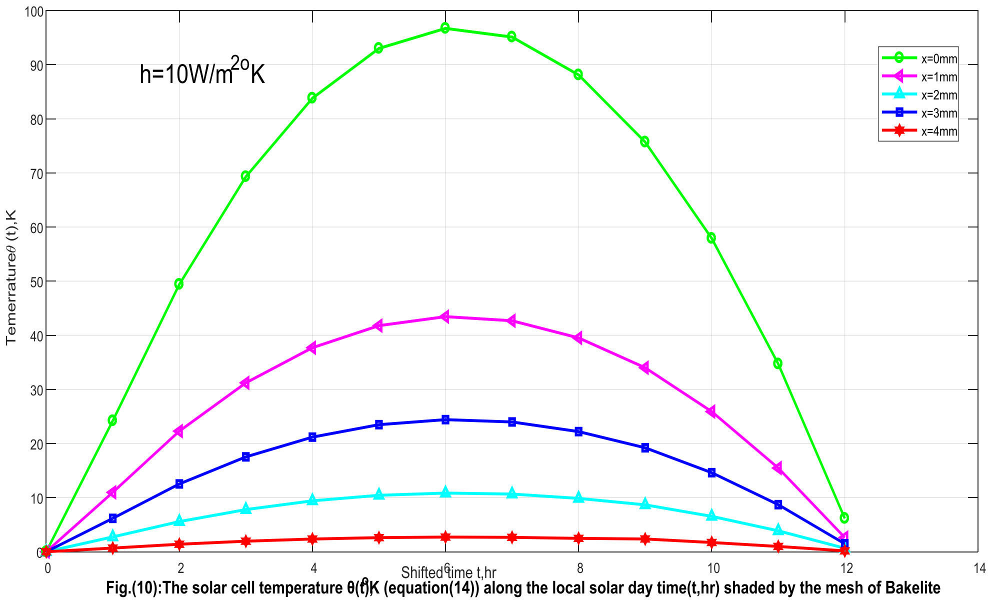


Fig.(10):The solar cell temperature θ(t)K (equation(14)) along the local solar day time(t,hr) shaded by the mesh of Bakelite of thickness dn=1mm and h=10W/m²K at different width of the frame of each hole.

The efficiency of the solar cell in the presence of a mesh.

The silicon solar cell temperature in the presence of a mesh as a function of the local day time *"t"* is calculated using equation (14).

The physical parameters of Silicon are:

ρ=2280 kg/m^3 c_p =840J/kg

The hourly incident global solar radiation q (t) (eq. (4)) is considered for Makah[31] as an illustrative example .The valuesof I_{sc} ,I_0andV_{0c} corresponding to each value of θ(t) at a certain time"t" are determined.

Hence the efficiency " η "of the cell in the presence of a mesh as a function of the solar local day time "t" is estimated for considered location.

For Makah [31] the q (t) parameters are:

q_{max} = 971W/m^2, t_d = 12 hours, tr = 0 hours, t_0 = 6 hours

The solar cell efficiency equation (15) along the local solar day time shaded by the mesh of (Cu, Fe and Ba) of thickness dn=1mm, h=10 W/m^2 $^oK$and (A=0.7) at different widths of the frame of each hole$X$ =10^{-3}, 2*10^{-3}, 3*10^{-3} and 4*10^{-3}m are considered.

The obtained results are given in figs. (10), (11) and (12)

The obtained results show that the efficiency of the solar cell shaded by mesh of (Cu, Fe and Bakelite) increases slightly as the thicknesses of the frame increases.

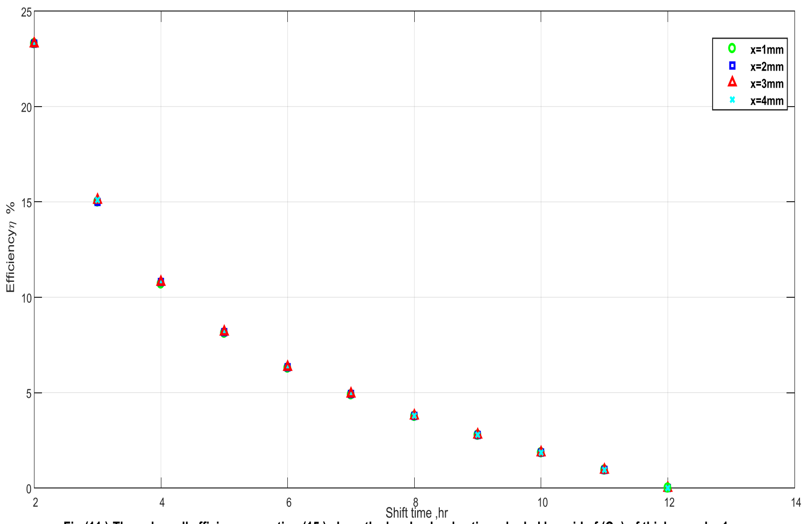


Fig.(11):The solar cell efficiency equation (15) along the local solar day time shaded by grid of (Cu) of thickness dn=1mm at different width of the frame of each hole

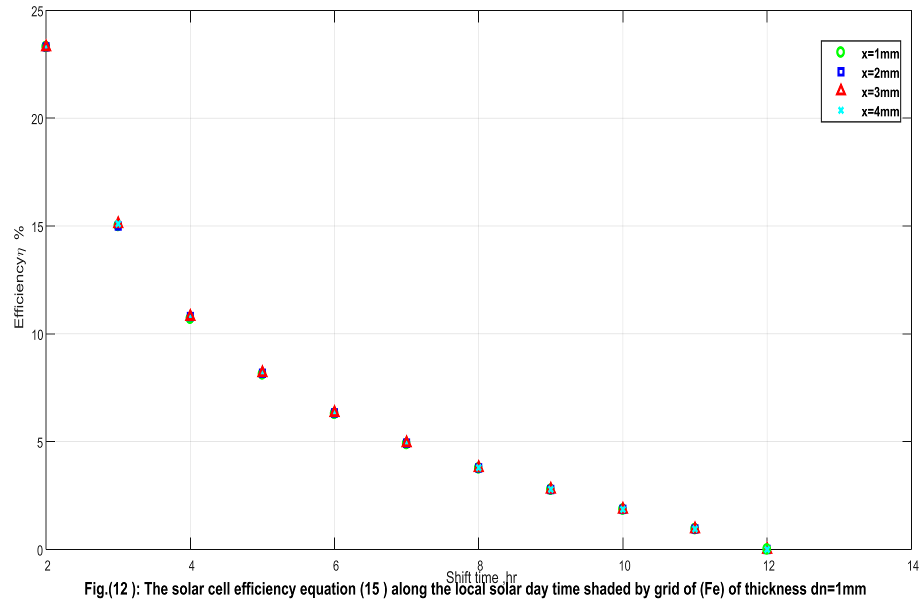


Fig.(12): The solar cell efficiency equation (15) along the local solar day time shaded by grid of (Fe) of thickness dn=1mm at different width of the frame of each hole.

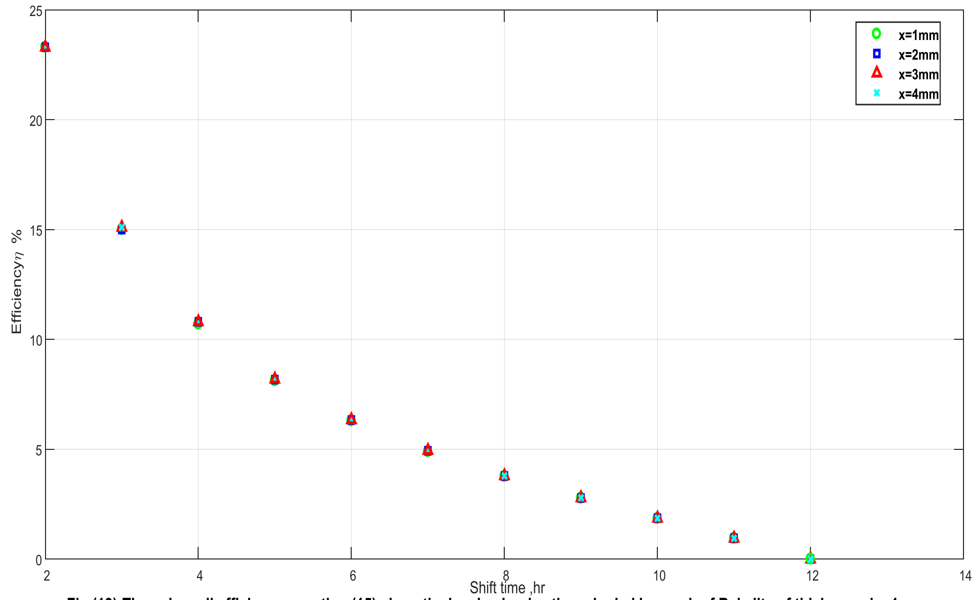


Fig.(13):The solar cell efficiency equation (15) along the local solar day time shaded by mesh of Bakelite of thickness dn=1mm at different width of the frame of each hole.

Results and Discussions

The obtained results reveal that:

* The mesh temperature decreases as the thickness of the mesh increases.

* The meshtemperature decreases also as the heat transfer coefficient"h" for cooling increases.

*The temperature of the solar cell in the presence of a mesh decreases as the widths (x) of the frame of each hole increases this is associated with increasing the shading percentage. This in turn increases the cell efficiency.

*The efficiency of the solar cell shaded by a mesh changes slightly as the material of the mesh changes that is clear for the materials considered (Cu, Fe and Bakelite).This is also important for economic and technological applications.

Acknowledgement:
The authors would like to thank professor Dr.M.K.El-Adawi for his advice, interest and vision concerning the present work.

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S.S.Mustafa "The Effect of Temperatureon the Efficiency of aSilicon Solar Cell Shaded by a Mesh as a Function of the Mesh Parameters and Operating Conditions." *International Journal of Engineering Science Invention (IJESI)*, Vol. 09(03), 2020, PP. 55-65.