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The Efficiency of a SiliconSolar Cell as a Function of the Thermal, Shading and Cooling Conditions-Theoretical Approach.

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Abstract: *The temperature of a silicon solar cell subjected to incident solar radiation is determined through solving a heat balance equation. The temperature dependent cell parameters as $V_{oc}(T)$, $I_{sc}(T)$, $I_o(T)$,and$E_g(T)$ are evaluated at each local day time "t". The performance and efficiency of the cell at different local day times and operating conditions as shading and cooling are revealed.*
Computations to reveal such functional dependences for a certain solar cell are performed as an illustrative example.
Keyword: *Solar Energy- Silicon Solar Cell –Solar Cell Temperature- Solar Cell Performance- Solar Cell Efficiency - Heat Transfer Model.*

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I. Introduction:

Solar energy is not only renewable but also environmentally safe. A solar cell is a tool that converts solar energy directly into electricity.

The factors affecting the efficiency of a solar cell have received great attention in research [1-5] with the aim to increase such efficiency. The considered silicon solar cell is made of semiconductor material and it is simply a (p-n) junction of such materials. When a solar cell absorbers solar radiation with quantum photon ($h\boldsymbol{v}$ $\geq E_g$) where E_g is the energy gap of the semiconductor, an electron-hole pair is formed through the photovoltaic phenomenon[6-10].

As the temperature changes the band gap widthE_g (T) changes. Thus the cell temperature dependent parameters, such as V_{oc} and I_{sc}alsochange with different dependences.

The aim of the present article is to determine theoretically, the cell temperature as a function of the received global solar insolation q_o(t), W/m^2.

Then the characteristic values of V_{oc}(T), I_{sc}(T), I_o(T),andE_g(T) are estimated at eachconsidered local day time"t". This makes it possible to evaluate the cell efficiency η(t), defined as:

The ratio between the energy gained per second per unit area to the received input solar light irradiance p_{in} , W/m^2.

i. e $$\eta = \frac{FF \text{ Isc Voc}}{\text{P}_{\text{in}}} \quad (1)$$

Where, I_{SC}, is the short circuit current,

Voc, is the open circuit voltage and FF is the filling factor.

It is worth to note that shadow conditions also affect the performance of the considered solar cell [11-13].

Indeed, the photovoltaic panels are often partially shaded due to cloudsand dust that build up on the surface of the panel [11].

In the present trial,the efficiency of a silicon solar cell at different illuminations and cooling conditions is estimated.

II. Cell Temperature

According to the suggested model, the received solar irradiance q_o(t), W/m^2 at the front surface of the solar cell is partly absorbed A q_0 (t), and partly reflected. Where, A is the absorption coefficient.

Assuming the solar cell to be of small thickness such that a homogeneous temperature field is built through the cell material.

One can write the heat balance equation in the form:

$$S\, A_{ab}\, q\,(t) - S\, h\, \theta(t) = S\, \rho\, l\, c_p \frac{d\theta}{dt} (2)$$

The term S h$\theta(t)$, represents, the quantity of heat lost by convection.

θ (t) = (T (t) – T_O), $^{O}K$is the excess temperature of the cell relative to theambient temperature T_O. Heat losses by radiation are neglected since; the temperatures attained by the cell along the local day time are not of high values.
S, m^2 is the area of the cell front surface,
ρ, (kg/m^3) is the density of the solar cell material and c_p , (J/kg. ^{O}K) is the specific heat of the solar cell material.
Equation (2) can be rewritten in the form:

$$\frac{d\theta}{dt} + \frac{h}{\rho\ l\ c_p}\theta(t) = \frac{\xi\ A}{\rho\ l\ c_p} q\ (t) \quad (3)$$

Equation (3)has an integrated factor$e^{\int_0^t \frac{h\ dt}{l\ \rho c_p}}$
Thus the solution is obtained in the form [14]:

$$\theta(t) = e^{-\frac{h\ t}{\rho\ l\ c_p}} \left[\int_0^t \frac{\xi\ A}{\rho\ l\ c_p} q(t)\ e^{\frac{h\ t}{\rho\ l\ c_p}}\ dt\ \right] (4)$$

Where,$\xi$is the shading ratio, $= \frac{\text{dark portion area}}{\text{total illuminated cell surface area}}$
q_0 (t), W/m^2 is the solar irradiance issuggested in the form [15]for the first half of the day time:

$$q\ (t) = q_{\max} \left(\frac{t}{t_{max}}\right) \quad 0 \le t \le t_{max} \quad (5)$$

For the second half, the relation is written in the form:

$$q\ (t) = q_{\max} \left(\frac{t_d - t}{t_d - t_{max}}\right) t_{max} \le t \le t_d \quad (6)$$

For symmetrical distribution ($t_{max} = \frac{t_d}{2}$):

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

Where,
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 [16]:

$$t_d = \frac{24h}{180^0} cos^{-1}\ (\tan\delta\ \tan L) \quad (7)$$

Where,

$$\delta = 23.45 \sin 360 \left(\frac{284+n}{365}\right), \quad (8)$$

δ is the solar declination angle,
and "n" is the day number of the year starting from 1 January i.e.,
(1 ≤ n ≤ 365), Lis latitude.
Substituting the expression of q_0 (t), W/m^2in eq. (4) and performing all the required integral one finally gets the solution in the form[17]:

$$\theta\ (t) = \frac{Hq_{max}}{t_{max}} \left[\frac{t}{b} - \frac{1}{b^2} + \frac{e^{-at}}{b^2}\right] \quad 0 \le t \le t_{max} \quad (9)$$

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

$$+ \left(\frac{Hq_{max}}{t_{max}}\right) \left[\left\{\left(\frac{t_{\max}}{b} - \frac{1}{b^2}\right) + \frac{e^{-bt_{\max}}}{b^2}\right\}\right] t_{max} \le t \le t_d \quad (10)$$

Where:

$$H = \frac{\xi\ A}{\rho\ l\ c_p}, \quad b = \frac{h}{\rho\ l\ c_p}$$

III. Efficiency estimation

According to the accepted definition for the efficiency (Eq.1) the temperature functional dependences of the parameters are clarified in the following:
$V_{oc}$is the open circuit voltage which is given as [18]:

$$V_{oc} = \frac{KT}{e} \ln\left(\frac{Isc}{Io} + 1\right) \quad (11)$$

Where:
k(J/^{O}K) is the Boltzmann constant,
T (^{O}K) is the cell temperature,
(e=1.6*10^{-19} coulomb) is the electron charge,I_o(amp/m^2) is the reverse saturation current and its dependence on temperature is revealed through the following equation [18]:

$I_o = \epsilon\, nT^{\gamma} e^{\frac{-E_g}{KT}}$ (12) where:

n is non-ideality factor of the cell and is taken as unity for simplicity, the value of γ =3 [18],
ϵ = 179 amp/K^3m^2 for silicon solar cell [19],
The dependence of energy band gap of a semiconductor on temperature can be described as [20]:

$$E_g = E_g(0) - \frac{\alpha T^2}{T+\beta} \quad (13)$$

$E_g(0)$ is the energy bandgapof the semiconductor at T≈ 0 ^0K,
For silicon material$E_g(0)$ =1.16 eV [21], α =7*10^{-14} eVK^{-1} and β= 1100 ^0K, thereare constants for each semiconductor material [21],
Iscisthe short circuit current given as [22],

I_{SC}=Q (1-R (T)) (1-exp (μ l)) (14)

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 [23]:

$$R(T) = 0.322 + 3.12 \times 10^{-5}\, T \quad (15)$$

μ, is the attenuation coefficient and its value is given as [23]:

μ= a exp (T/T_S) (16)

where :

a=3.17x10^4 m^{-1} andT_S =346 ^oK[23]

l, *in meter is the thickness of the solar cell,*
$n_{photons}$ is the number of photons with energygreater than the band gap ($E_g \geq h\upsilon$) and for simplicity its value for a given temperature T at a certain local daytime is given as:

n_{Photon} = q (t)/Eg(17)

IV. Computations

The cell temperature without shading and its variation along the local day time is estimated using Eq. (9) and Eq. (10) at different levels of cooling:
h = 5 W/m^2 ^0K , h = 10W/m^2 ^0Kandh = 50 W/m^2 ^0K
The following parameters are also considered:
l, = 0.035 m is the thickness of the solar cell material.
ρ =2280 kg/m^3 is the density of the solar cell material.
c_p = 840 (J/kg. ^0K) is the specific heat of the solar cell material.
The obtained results are given in table (1) andare illustrated in Fig. (1).

Table (1): The unshaded solar cell temperature θ (t) [Eq.(9) &Eq.(10)] at different cooling conditions (h=5, 10 and 50W/m^2 ^oK).

Shifted local day time t, hr.	h=5W/m² °K	h=10W/m² °K	h=50W/m² °K
	θ(t), °K	θ(t), °K	θ(t), °K
1	14.78	9.23	2.18
2	36.88	20.55	4.44
3	59.47	31.88	6.71
4	82.10	43.21	8.97
5	104.74	54.54	11.23
6	127.37	65.87	13.49
7	120	61.15	11.48
8	107.9	49.151	9.21
9	84.7	38.18	6.95
10	62.04	26.85	4.68
11	39.4	15.51	2.42
12	16.8	4.18	0.161

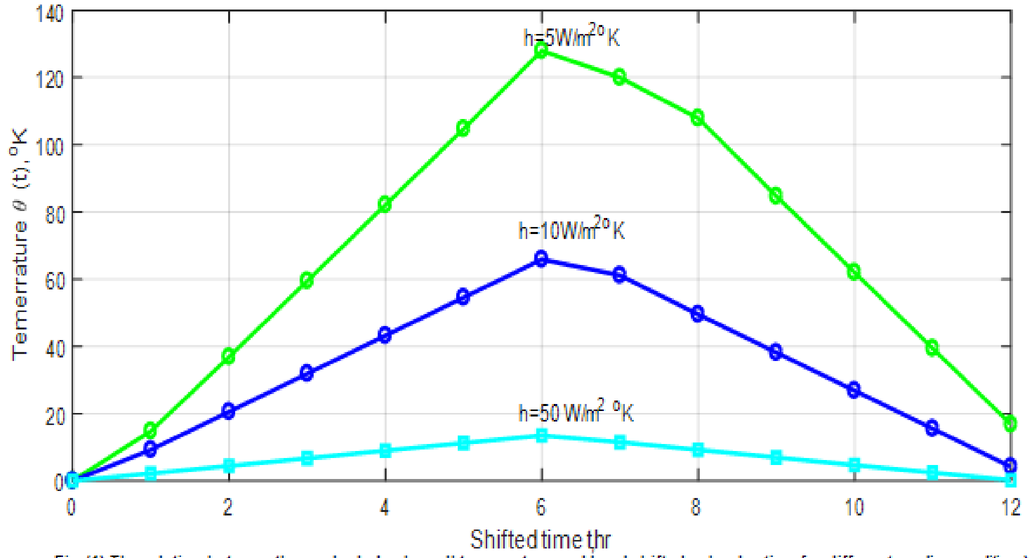
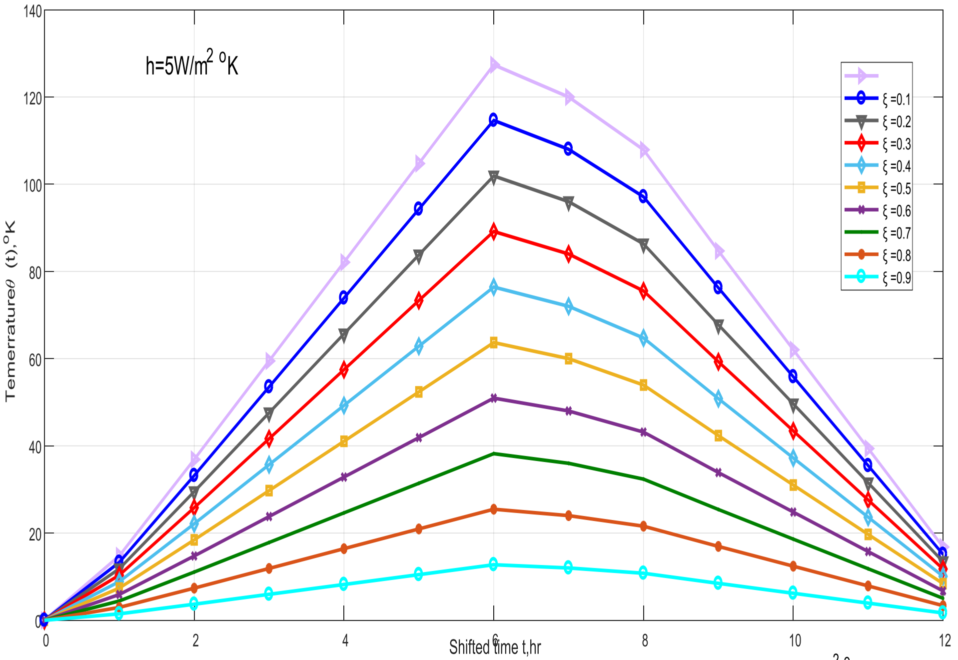


Fig.(1):The relation between the unshaded solar cell temperature and local shifted solar day time for different cooling conditions)

The cell temperaturewithshadingeffects and its variation along the local day time is estimated using Eq. (9) and Eq. (10) at different ratios of shading.
The obtained results are tabulated in table (2) and illustrated graphically in Fig. (2), (3) and Fig. (4).

Table (2): The relation between the solar cell temperatureθ(t) according tothe[Eq.(9)&Eq.(10)]at different shading levels ξ for (h=5W/m^2 ^{o}***K***, l=35mm, A=1).

t,hr	ξ =0.0 θ(t), ^{o}***K***	ξ =0.1 θ(t), ^{o}***K***	ξ =0.2 θ(t), ^{o}***K***	ξ =0.3 θ(t), ^{o}***K***	ξ =0.4 θ(t), ^{o}***K***	ξ =0.5 θ(t), ^{o}***K***	ξ =0.6 θ(t), ^{o}***K***	ξ =0.7 θ(t), ^{o}***K***	ξ =0.8 θ(t), ^{o}***K***	ξ =0.9 θ(t), ^{o}***K***
1	14.78	13.30	11.82	10.35	8.87	7.39	5.91	4.43	2.96	1.48
2	36.88	33.19	29.50	25.82	22.13	18.44	14.75	11.06	7.37	3.69
3	59.47	53.52	47.58	41.63	35.68	29.74	23.79	17.84	11.89	5.95
4	82.1	73.89	65.68	57.47	49.26	41.05	32.84	24.63	16.42	8.21
5	104.74	94.27	83.79	73.32	62.84	52.37	41.89	31.42	20.95	10.47
6	127.37	114.63	101.89	89.16	76.42	63.69	50.95	38.21	25.47	12.74
7	120	108	96	84	72	60	48	36	24	12
8	107.9	97.11	86.32	75.53	64.74	53.95	43.16	32.37	21.58	10.79
9	84.7	76.23	67.76	59.29	50.82	42.35	33.88	25.41	16.94	8.47
10	62.04	55.836	49.632	43.428	37.224	31.02	24.816	18.612	12.408	6.204
11	39.4	35.46	31.52	27.58	23.64	19.7	15.76	11.82	7.88	3.94
12	16.8	15.12	13.44	11.76	10.08	8.4	6.72	5.04	3.36	1.68



Fig(2): The relation between solar cell temperature according to (Eq.9 and Eq.10) and local solar time at different Shading levels for (h=5 W/m^2 ^{o}k, d=.035m, A=1)

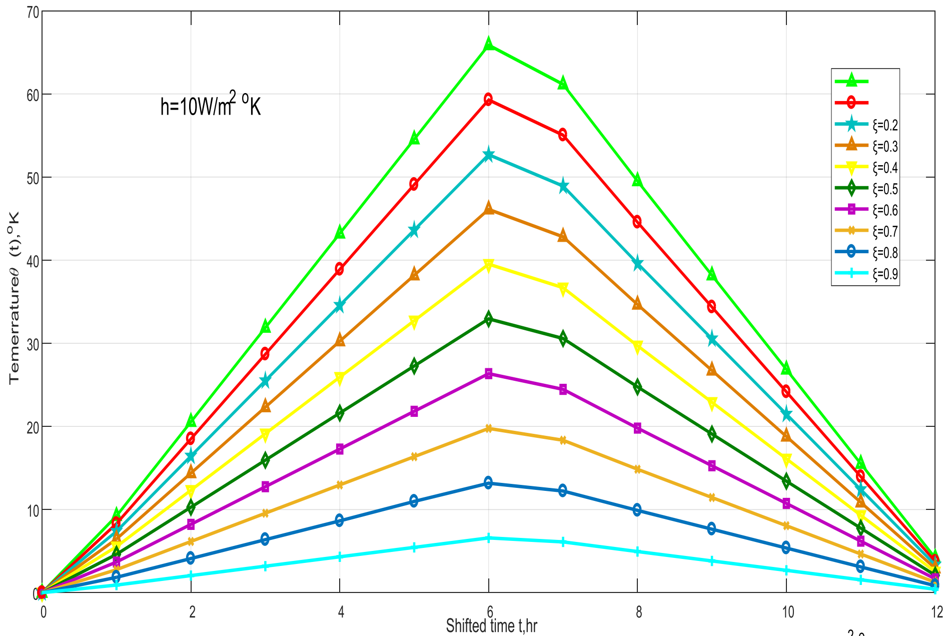


Fig.(3): The relation between solar cell temperature according to(Eq.9 and Eq.10) and local solar time at different Shading levels for (h=10W/m^2 ^{o}k, d=.035m, A=1)

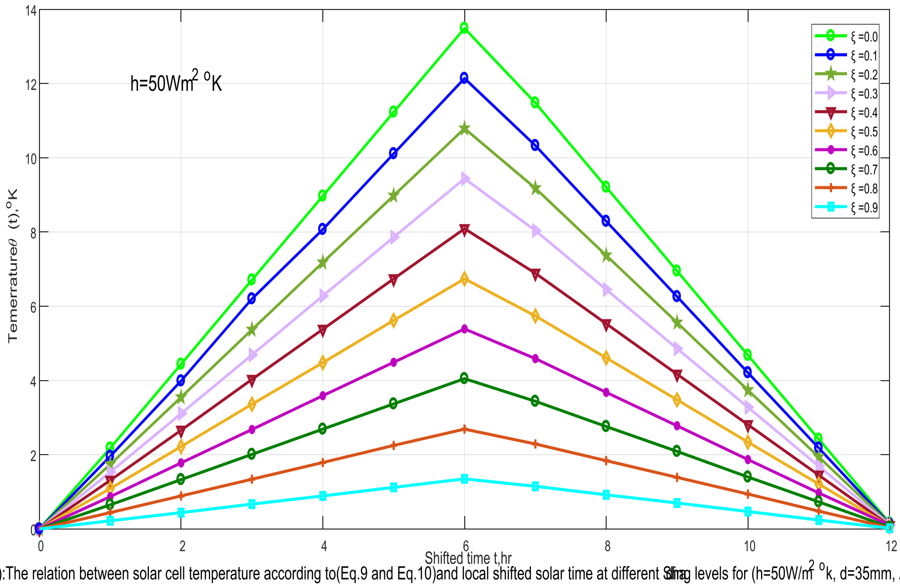


Fig.(4):The relation between solar cell temperature according to(Eq.9 and Eq.10)and local shifted solar time at different Shading levels for (h=50W/m^2 ^{o}k, d=35mm, A=1)

V. Efficiency Estimation:

For a certain local day time (t), the parameters E_g (T), I_{sc}(T), and V_{oc}(T) are estimated. From which the efficiency ηis evaluated.

The efficiency against the shading ratios are tabulated in tables (3)and are illustrated graphically in Fig. (5), (6) and Fig. (7), with cooling level(h) as a parameter.

These curves reveal that, the efficiency increases slightly with shading at constant cooling conditions.

Moreover, the efficiency at a certain shading ratio (ξ =0.4) and at a certain cooling level (h=10W/m^2 $^o\boldsymbol{K}$), is evaluated along the local day time.

The obtained results are illustrated graphically at Fig.(8) from which it is clear that the efficiency(η)decreases along the solar day time.

From computed values of I_{sc}(T), and V_{oc}(T), a relation between each of these two physical quantities and the shading ratios at three specified local day times 3,6 and 9,hr is graphically illustrated as shown in figures 9,10,11,12,13,14 .

From which, it is revealed thatI_{sc} decreases markedly with shading ratio, while V_{oc} increases slightly with shading ratio.

VI. Power Computations

From the obtained values of I_{sc}(T), and V_{oc}(T)the cell power defined as: P=($I_{sc} * V_{oc}$) is computed at different cooling levels and at different shading ratios.

The obtained results are graphically illustrated in fig.15,16 and 17from which it can be concluded that shading has negligible effect on the efficiency at higher levels of cooling.

Table (3): The relation between the shading ratio ξ and the efficiency at three specified local day time at: (Q=0.7,l=35mm,A=1,h=10W/m^2 $^o\boldsymbol{K}$).

Shading ratio ξ	t=3,hr		t=6,hr		t=9,hr	
	θ(t), ^oK	η %	θ(t), ^oK	η %	θ(t), ^oK	η %
0.00	31.88	16.363	65.87	8.252	38.18	5.699
0.1	28.69	16.388	59.28	8.309	34.36	5.704
0.2	25.50	16.411	52.69	8.343	30.54	5.706
0.3	22.32	16.432	46.11	8.371	26.73	5.712
0.4	19.13	16.451	39.52	8.396	22.91	5.714
0.5	15.94	16.468	32.94	8.416	19.09	5.716
0.6	12.75	16.483	26.35	8.432	15.27	5.717
0.7	9.56	16.497	19.76	8.444	11.45	5.718
0.8	6.38	16.508	13.17	8.452	7.64	5.717
0.9	3.19	16.518	6.59	8.457	3.82	5.716

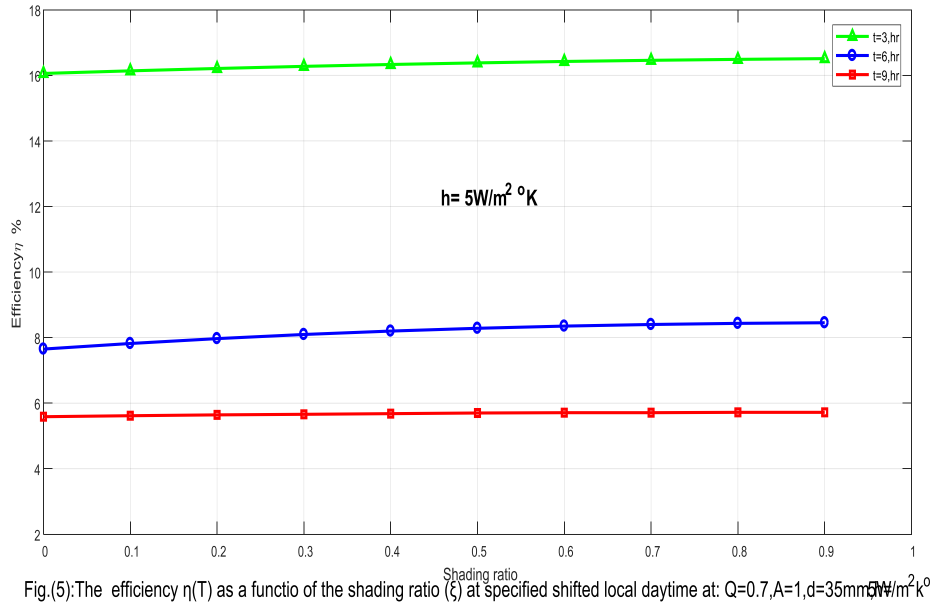


Fig.(5):The efficiency η(T) as a functio of the shading ratio (ξ) at specified shifted local daytime at: Q=0.7,A=1,d=35mm,h=5W/m^{2}k^o

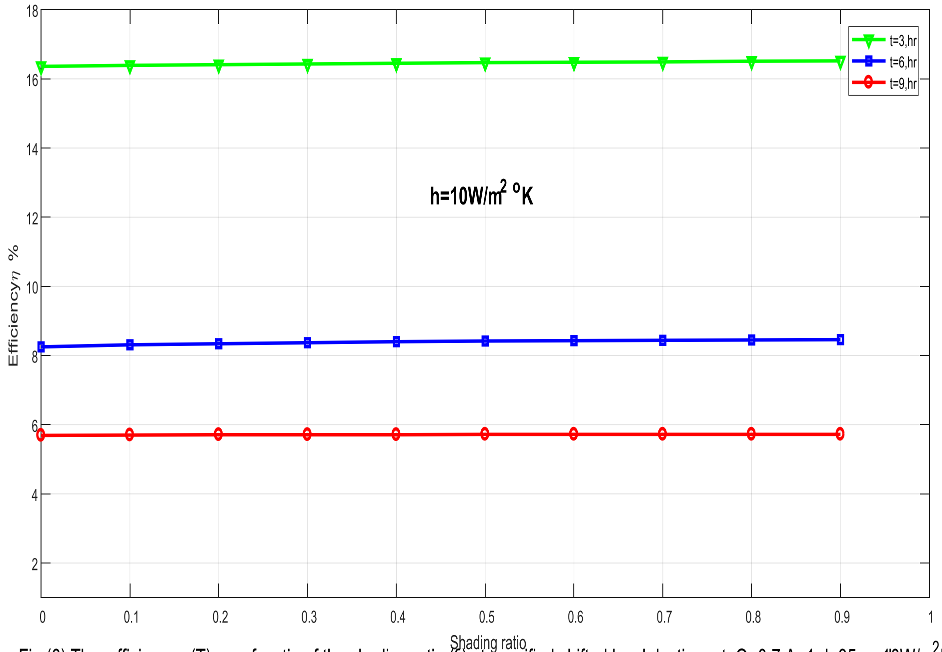


Fig.(6):The efficiency η(T) as a functio of the shading ratio (ξ) at specified shifted local daytime at: Q=0.7,A=1,d=35mm,h=10W/m^{2}k^o

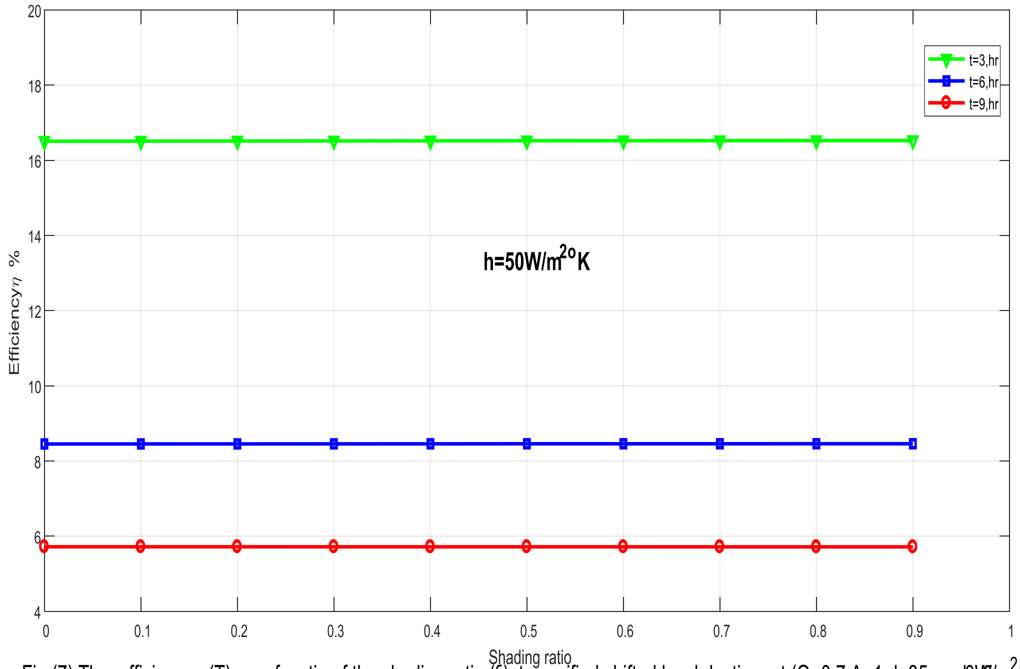


Fig.(7):The efficiency η(T) as a functio of the shading ratio (ξ)at specified shifted local daytime at:(Q=0.7,A=1,d=35mm,h=50W/m^{2}k^o)

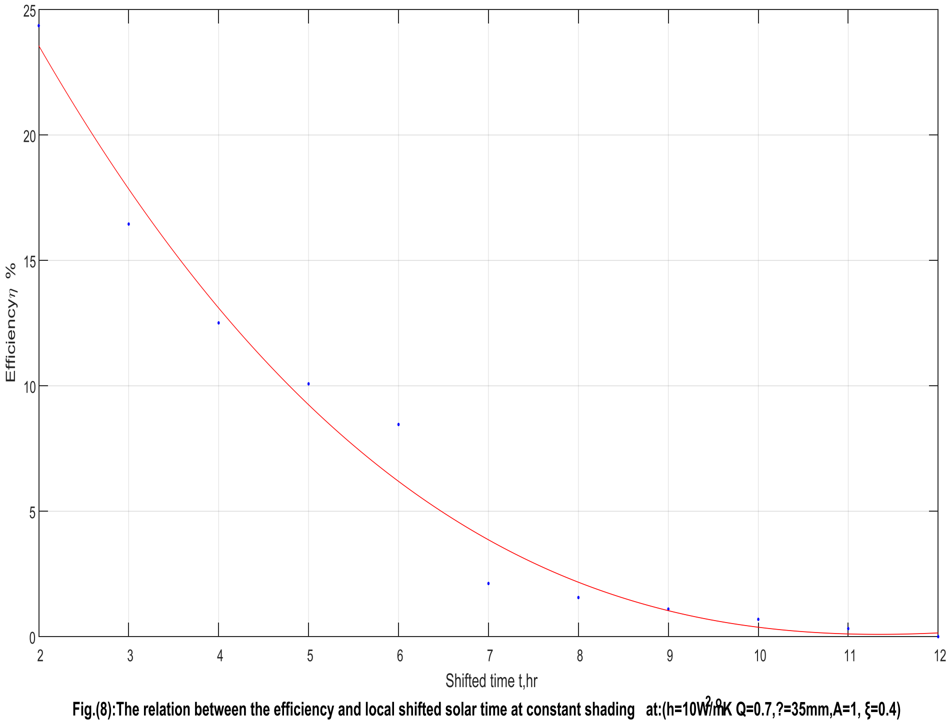


Fig.(8):The relation between the efficiency and local shifted solar time at constant shading at:(h=10W/m^2^{o}K Q=0.7,?=35mm,A=1, ξ=0.4)

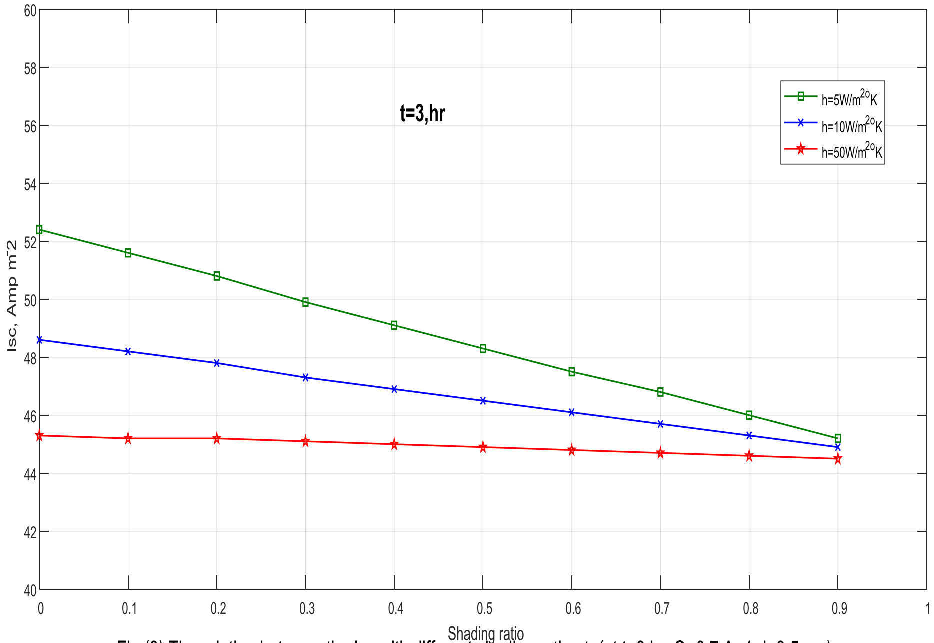


Fig.(9):The relation between the Isc with different shading ratio at: (at t=3,hr, Q=0.7,A=1,d=3.5mm)

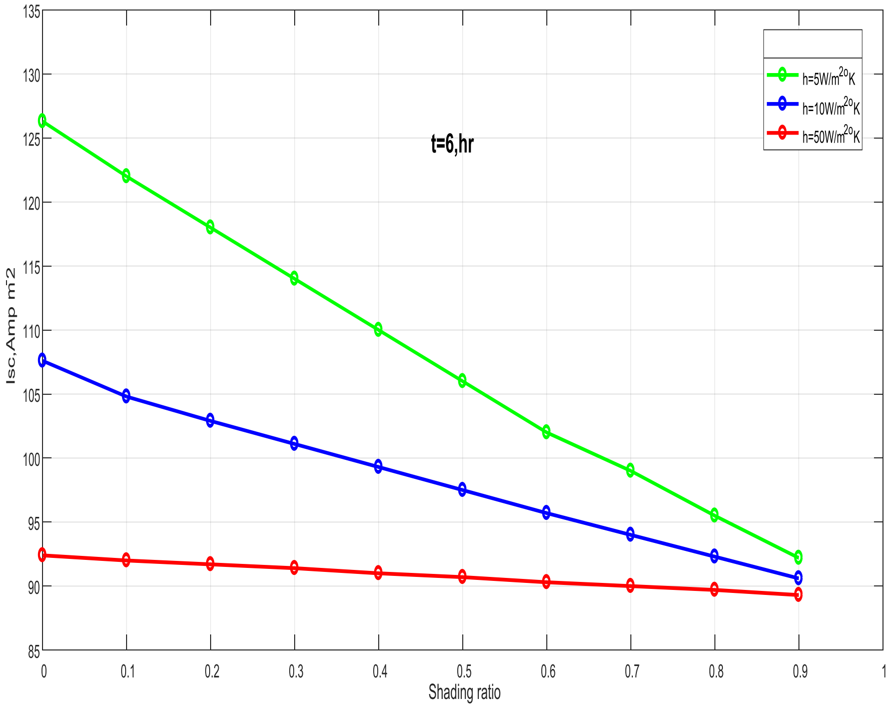


Fig.(10):The relation between the Isc with different shading ratio at:(t=6,hr,Q=0.7,A=1,d=35mm)

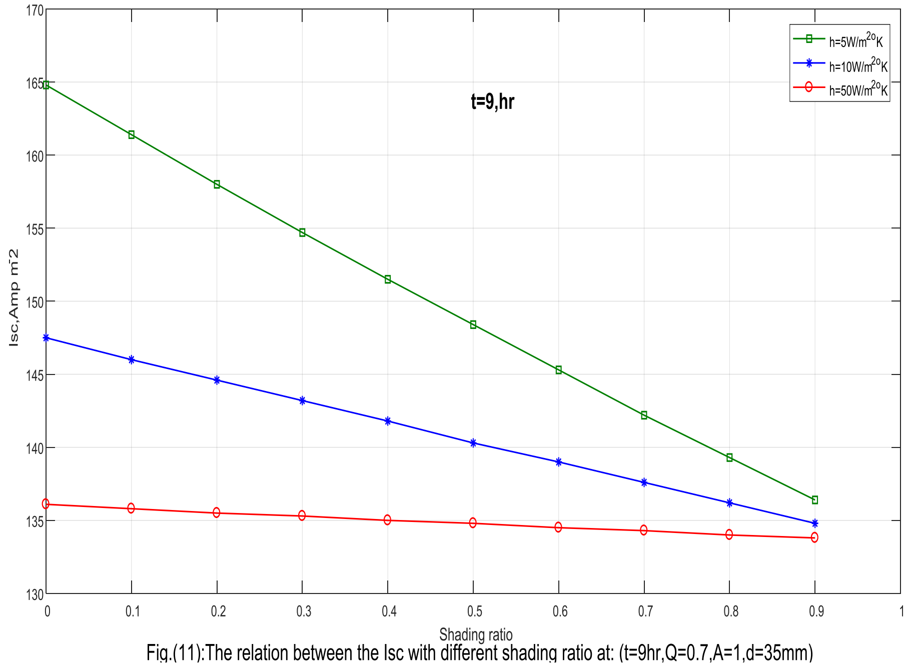


Fig.(11):The relation between the Isc with different shading ratio at: (t=9hr,Q=0.7,A=1,d=35mm)

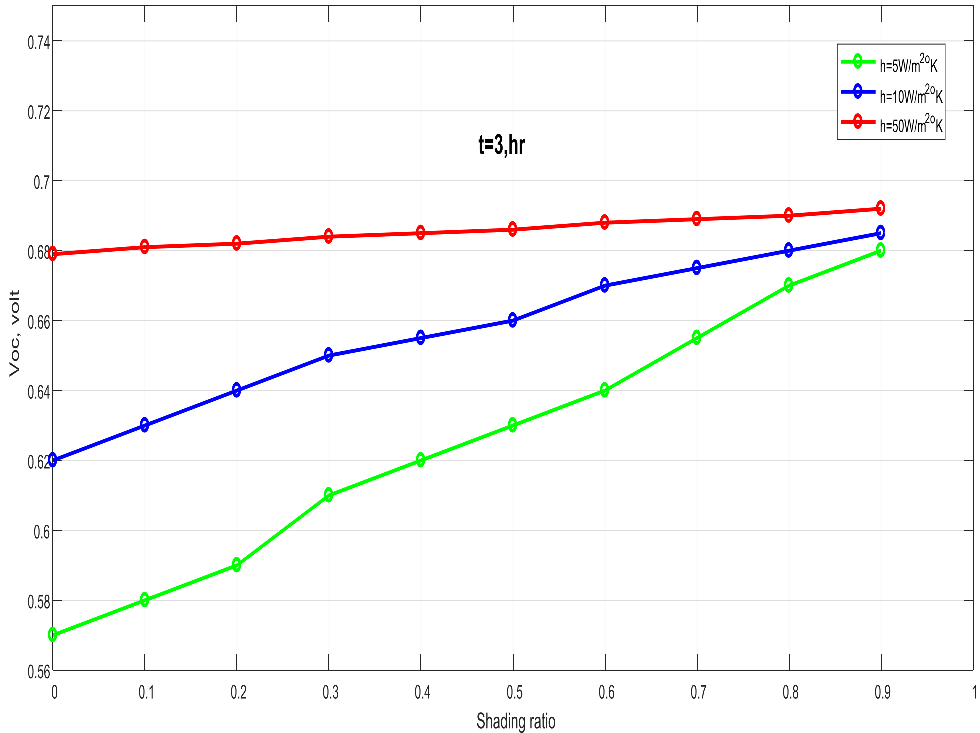


Fig.(12):The relation between the Voc with different shading ratio at:(t=3,hr,Q=0.7,A=1,d=35mm)

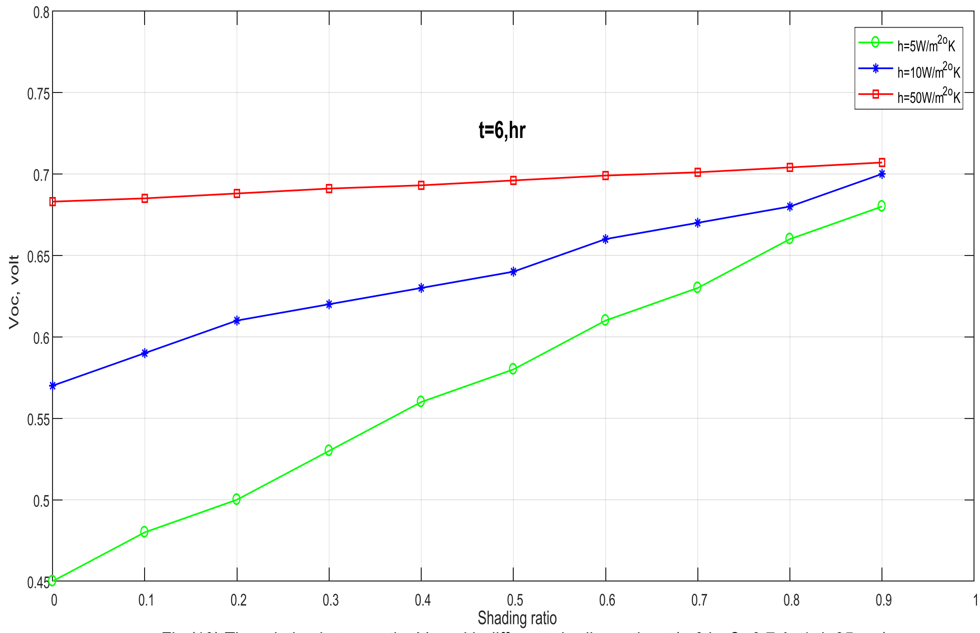


Fig.(13):The relation between the Voc with different shading ratio at:(t=6,hr,Q=0.7,A=1,d=35mm)

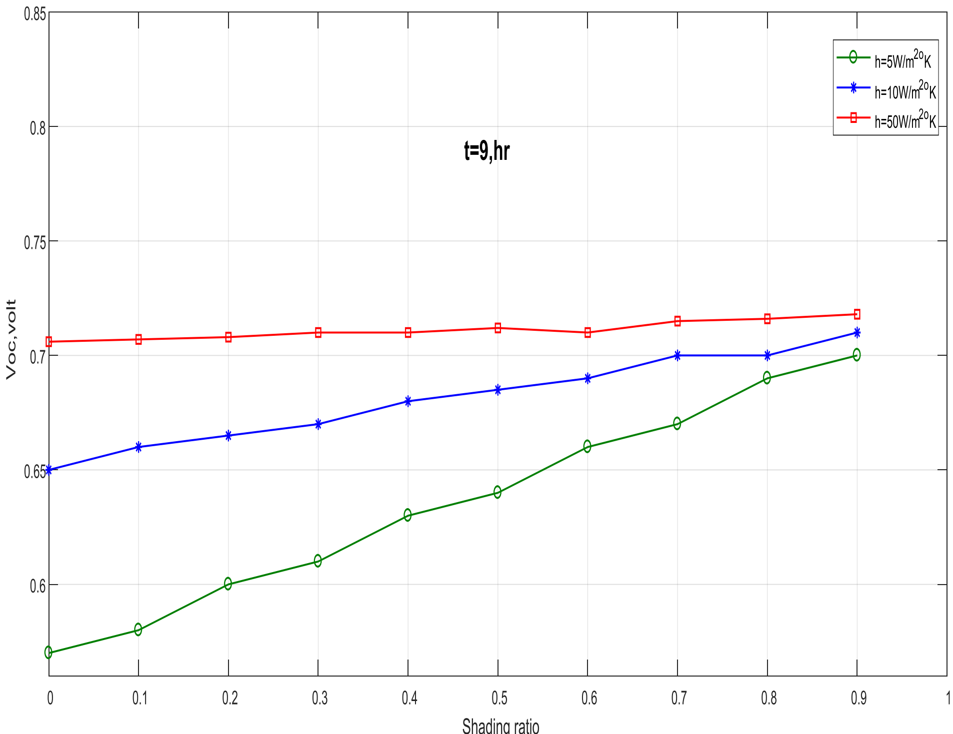


Fig.(14):The relation between the Isc with different shading ratio at:(t=9,hr,Q=0.7,A=1,d=35mm)

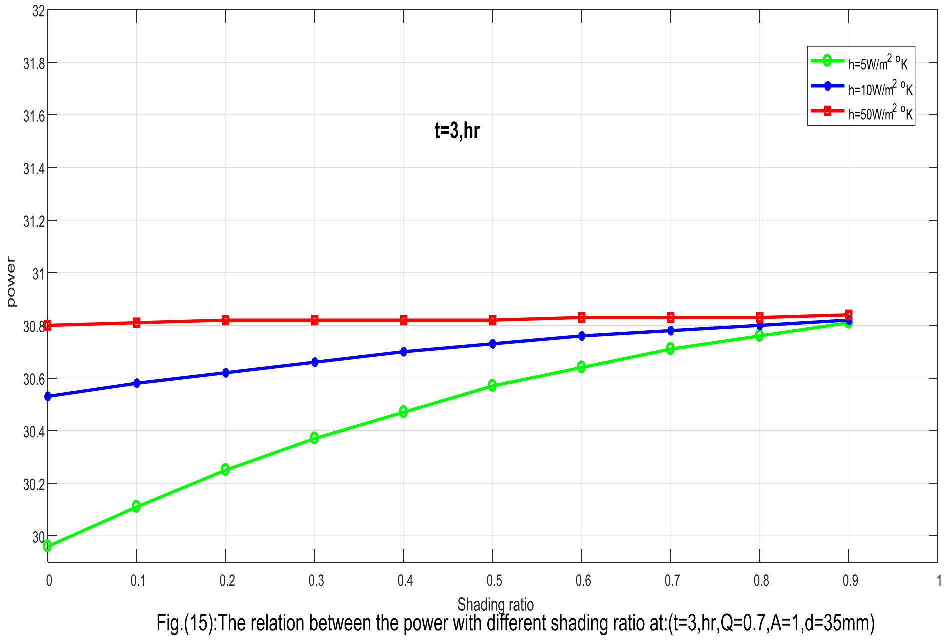


Fig.(15):The relation between the power with different shading ratio at:(t=3,hr,Q=0.7,A=1,d=35mm)

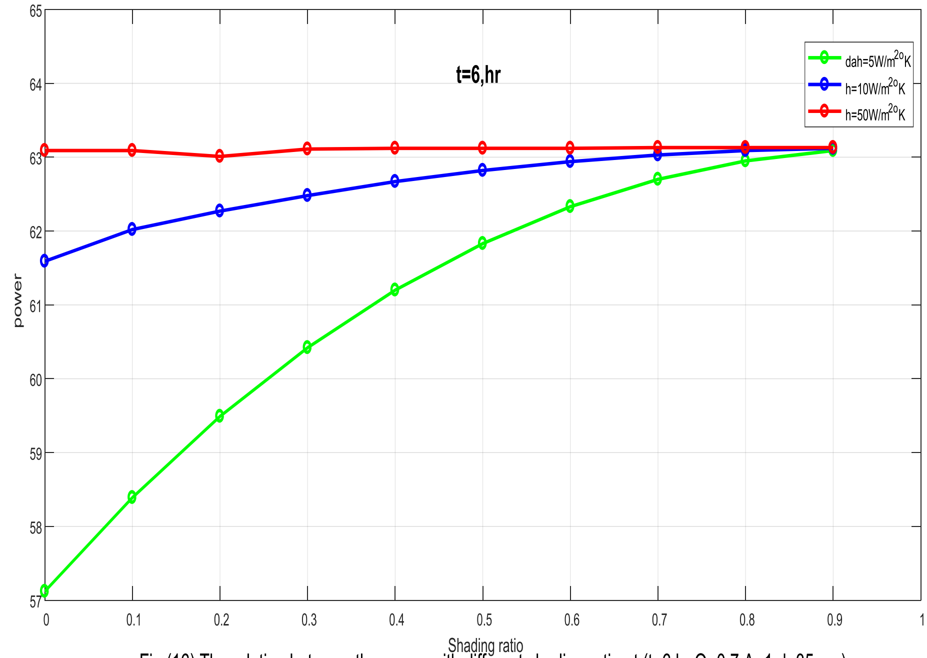


Fig.(16):The relation between the power with different shading ratio at:(t=6,hr,Q=0.7,A=1,d=35mm)

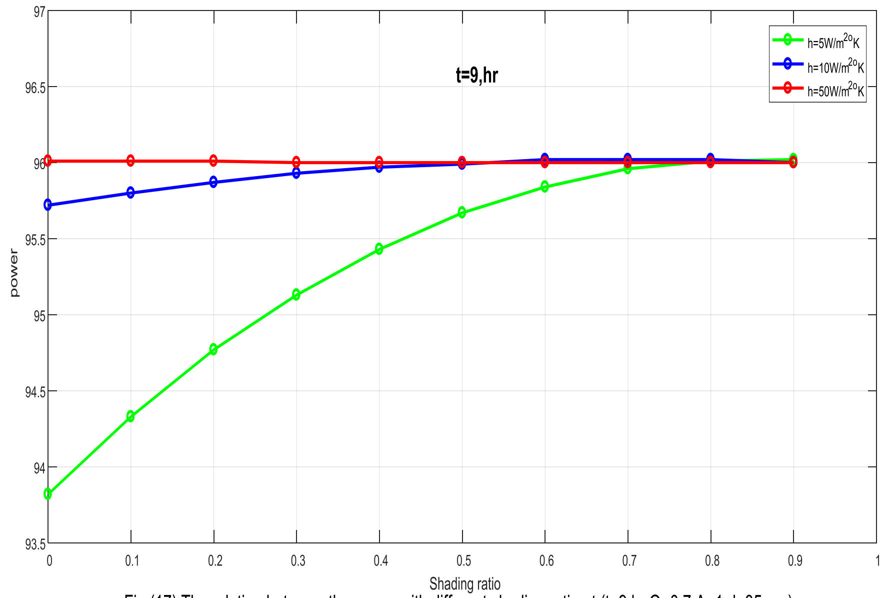


Fig.(17):The relation between the power with different shading ratio at:(t=9,hr,Q=0.7,A=1,d=35mm)

VII. Conclusion

The obtained expressions and results reveal the following conclusions:

1 The obtained mathematical expressions reveal that the dependence of the cell temperature on q_{max} is linear while the dependence on the physical and geometrical properties is not linear.

2 Shading leads to a decrease in the cell temperature.

3Shading causes a slight increase in cell efficiency.

4 At constant shading and cooling the efficiency decreases markedly through the solar day time.

5 $V_{oc}(T)$,increases slightly with shading while $I_{sc}(T)$, decreases markedly with shading.

6 Shading has negligible effect on the cell efficiency at higher levels of cooling.

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