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Real Profiles of the Temperature and the Photovoltaic Parameters in an Uncooled Silicon PV cell Submitted to an Increasing Light Concentration

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ABSTRACT: The main objective of this study is to determine the real impact of light concentration increase on the parameters of an uncooled PV cell. To obtain results close to the reality, this study takes into consideration the effect of the PV cell heating inherent to light concentration and which is characterized by temperature increase. On the Basis of the thermal model, the temperature profile versus light concentration is determined. And photovoltaic parameters are extracted from the electrical model. Subsequently concentration ratio influence on these photovoltaic parameters is studied. The results indicate that the PV cell's temperature increases rapidly with light concentration. It appears that diffusion parameters rise when concentration ratio varies from C = 1 Sun where the temperature is T=323.31 K to C = 12.51 Suns where the temperature is T=507.32 K. Beyond C = 12.51 Suns, these diffusion parameters decrease. The results also indicate a strong increase in current density with concentration ratio. This is explained by the fact that concentration ratio and temperature increase are favorable factors for the current. Contrary to many authors, this work shows that the photo-voltage and the conversion efficiency decrease with increasing concentration. This is explained by the antagonism of the effects of concentration and temperature increase on photo-voltage. For concentrations ranging from C = 1 Sun to C = 6 Suns the maximum power increases and decreases beyond C = 6 Suns. For an uncooled silicon PV cell, these results reflect the performance drop with increasing light concentration ratio.

KEYWORDS: Thermal model, Temperature profile, Concentration ratio, Photo-voltage, Conversion efficiency, operating point.

1 INTRODUCTION

Many authors have worked on light illumination level influence on photovoltaic parameters. Some of them realized their works under illumination levels lower than one Sun [1-7]. Others have also worked under illumination levels higher than one Sun, where the illumination is said to be concentrated [8-19].

Geisz et al. [8], Chancerel et al. [9], Peters et al. [10], Zoungrana et al. [11] and Khan et al. [15] showed in their works that the light concentration increase leads to the rise of the open-circuit voltage, to that of the conversion efficiency and to that of the fill factor. Zhe Li et al. [1] and Glowienka et al. [2] also obtained the same results under non-concentrated illumination levels. Zoungrana et al. [11] and Khan et al. [15] showed that short-circuit current increases linearly with increasing light concentration ratio. This result was also confirmed under non-concentrated illumination by Zhe Li et al. [1] and Glowienka et al. [2]. However, in the studies listed above, the PV cell is cooled and its temperature is assumed to be constant and equal to ambient temperature.

Indeed, a concentration photovoltaic system is often associated to a cooling system to obtain a concentrated photovoltaic-Thermal (CPV/T) hybrid system. A coolant fluid circulating in the cooling system collects the heat from the photovoltaic device. The PV panel or cell can thus be cooled. The hybrid concentration photovoltaic-thermal system (CPV/T) therefore provides energy not only in electrical form but also in the form of heat [20-24]. But, conventional cooling fluids (air and water) present a low thermal conductivity. One of the most recent methods of improving heat transfer is the use of nano-enhanced paraffin and nanofluids. Numerous studies showed that this new technique considerably improves the electrical and the thermal efficiency of the PVT hybrid system [25-30].

However, when the PV cell is uncooled, authors like Wang et al. [12] and Cui Min et al. [13] showed the rapid rise of the PV cell's temperature with light concentration increase. This was also showed by Nicoletti et al. [3] under non-concentrated illumination. In addition, several studies highlighted the temperature negative impact on the photovoltaic parameters. Thus, Elias et al. [4], Ciulla et al. [5], Singh et al. [7], Savadogo et al. [14] and Khan et al. [16] showed that temperature increase leads to a very small rise in current density and a strong drop in voltage, electric power and conversion efficiency. It therefore appears that a study of illumination level influence which does not consider the temperature variation impact, cannot lead to realistic results.

In one of our previous researches [18], we examined the influence of the light concentration on carriers' density. There, we took into account the PV cell's heating linked to the light concentration rising. It resulted that carriers' density is maximum at the rear-side of the PV cell's base. This conclusion contradicted with several studies by different researchers who worked on the same topic. In fact, these ones had assumed that the temperature remained constant and shown that carriers' density is maximum near the illuminated face.

This present study represents the continuation of our previous researches [18]. The main objective of this present work is to study the influence of light concentration ratio on the diffusion and the electric parameters of an uncooled silicon PV cell (diffusion coefficient, diffusion length, photocurrent, photovoltage, electric power and efficiency). We first determine the PV cell's temperature profile versus light concentration ratio. Thereafter, we study light concentration ratio influence on the photovoltaic parameters. The temperature variation effect which is a direct consequence of the light concentration ratio variation is also taken into consideration.

2 MATERIALS AND METHODS

2.1 THERMAL MODEL AND THE PV CELL TEMPERATURE PROFILE DETERMINATION

The Figure 1 illustrates a PV cell under light concentration. A convergent optical system placed before the PV cell allow the concentration of the incident light. The light concentration PV cell therefore receives the light power which is partially converted into electrical power. The rest of the power received is dissipated in thermal forms by natural convection and by radiation.

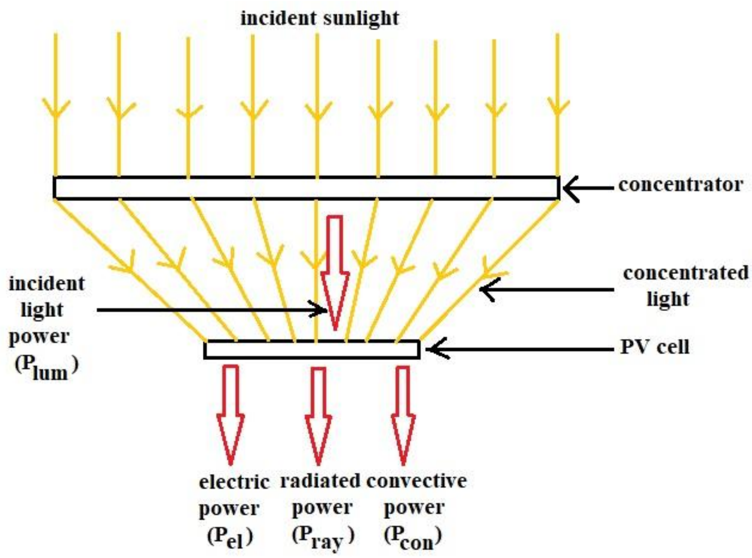

Fig. 1. Light concentrated PV cell's thermal model

The heat exchanges by convection and radiation take place at the front and back of the cell and are neglected on the lateral edges. The thermal convection coefficient is assumed to be the same at the front and the back of the cell. The emissivity is also assumed to be the same at the front and back of the cell. Due to its thin thickness, the PV cell's temperature is assumed to be uniform.

On the basis of these assumptions, the powers exchanged by the PV cell are:

- The absorbed light power: $P_{lum} = \tau_0 \alpha_0 A_0 C P_{in}$ (1)
- The output electric power: $P_{el} = \eta \tau_0 \alpha_0 A_0 C P_{in}$ (2)

η gives the conversion efficiency [13,18]: $\eta = a(1 - bT)$ with a = 0.425 and b = 0.00176 (3)

- The power dissipated by radiation: $P_{ray} = A_{ray} \varepsilon \sigma (T^4 - T_0^4)$ (4)
- The power dissipated by convection: $P_{con} = A_c h (T - T_0)$ (5)

In steady-state, the light power absorbed by the PV cell is the sum of the output electric power and the powers dissipated in thermal forms. This results in the following thermal equation 6:

$$A_t \cdot T^4 + D_t \cdot T + E_t = 0 \quad (6)$$

With $A_t = -A_{ray} \varepsilon \sigma$; $D_t = \tau_0 \alpha_0 A_0 C P_{in} ab - A_c h$ and $E_t = \tau_0 \alpha_0 A_0 C P_{in} (1 - a) + A_r \varepsilon \sigma T_0^4 + A_c h T_0$.

τ_0 is the concentrator transmissivity and α_0 the cell's absorption coefficient, A_0 the PV cell's surface, C light concentration ratio. P_{in} the incident solar light power density which is $P_{in} = 1000\ W/m^2$ under AM 1.5 standard conditions [11,14]. A_{ray} is the radiative surface, ε its emissivity and $A_{ray} = 2A_0$. $\sigma = 5,67 \times 10^{-8}\ W/m^2 K^4$ is the Stefan-Boltzmann coefficient. A_c is the convective surface, h its convection coefficient and $A_c = 2A_0$.

Table 1. Nomenclature

Input parameters		N_b	the doping density (cm^{-3})
τ_0	concentrator transmissivity	A_n	constant linked to intrinsic density ($cm^{-3}.K^{-\frac{3}{2}}$)
α_0	PV cell absorption coefficient	ε	PV cell surface emissivity
A_0	PV cell surface (m^2)	T_0	ambient temperature (K)
A_{ray}	radiative surface (m^2)	**Output parameters**	
A_c	convective surface (m^2)	T	PV cell temperature (K)
h	PV cell surface convection coefficient (W/m^2. K)	D^c	diffusion coefficient ($cm^2.s^{-1}$)
k	The Boltzmann coefficient (J/K)	L^c	diffusion length (cm)
q	Elementary charge (C)	J_{ph}	current density ($A.cm^{-2}$)
C	light concentration ratio (Suns)	V_{ph}	photovoltage (V)
P_{in}	incident solar light power density (W/m^2)	P	electric power *($mW.cm^{-2}$)*
a, b	coefficient in electric efficiency expression	P_{max}	*maximum power ($mW.cm^{-2}$)*
C_{th}	Coefficient linked to the thermal-generation rate	P_{inC}	*absorbed power ($mW.cm^{-2}$)*
σ	Stefan-Boltzmann coefficient (W/m^2K^4)	η	conversion efficiency (%)

2.2 ELECTRICAL MODEL AND DETERMINATION OF THE PV CELL DIFFUSION AND ELECTRIC PARAMETERS

In this study, we use a back-surface field (BSF) PV cell of (n^+-p-p $^+$) type [14,18]. The PV cell is illuminated with an incident light of variable concentration C (in Suns). The contribution of the emitter to the current density is neglected and we only consider the base contribution [14,18]. In the cell base, electrons distribution is non-uniform because of the illumination high level [14,18]. The non-uniform distribution of the electrons in the cell base leads to the taking into account of the electric field related to electrons concentration gradient in the base [11,14,18]. Figure 2 shows how the electric field of the concentration gradient of the electrons is oriented.

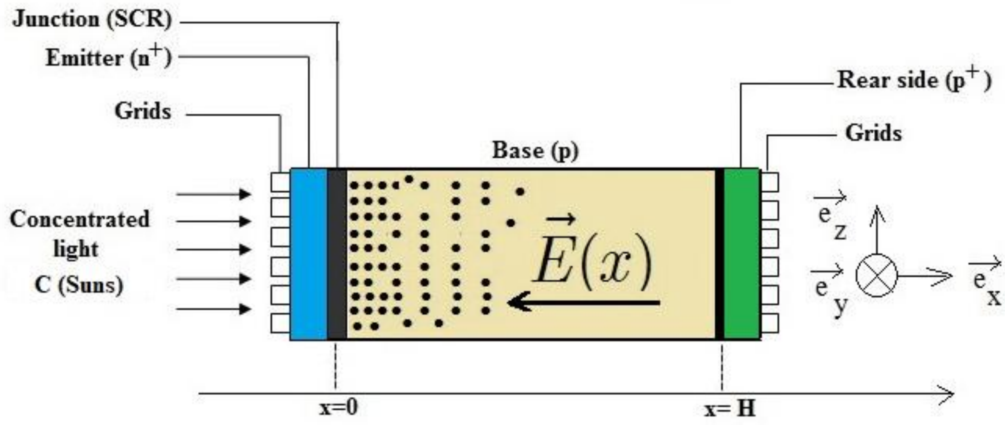

Fig. 2. Electrical model of a silicon PV cell under light concentration

The electric field of the concentration gradient of the electrons is expressed by the equation 7 below [11,14,18]:

$$E(x) = \frac{D_p - D_n}{\mu_n + \mu_p} \cdot \frac{1}{\delta(x)} \cdot \frac{\partial \delta(x)}{\partial x} \tag{7}$$

On the Basis of our assumptions, we determine the carrier's continuity equation given by:

$$\frac{\partial^2 \delta(x)}{\partial x^2} - \frac{\delta(x)}{(L^c(T))^2} = -\frac{G_n}{D^c(T)} \tag{8}$$

- **The diffusion parameters**

In equation 8, $\delta(x)$ represents the carrier's density at the PV cell base depth x. $D^c(T)$ and $L^c(T)$ respectively represents the diffusion coefficient and length versus temperature T given by equation 9 and 10:

$$D^c(T) = \frac{\mu_n(T)\left[2D_n(T) - D_p(T)\right] + \mu_p(T)D_n(T)}{\mu_n(T) + \mu_p(T)} \tag{9}$$

$$L^c(T) = \sqrt{D^c(T) \times t} \tag{10}$$

In these equations 9 and 10, $D_n(T)$ and $D_p(T)$ respectively represents electrons and holes intrinsic diffusion coefficients versus temperature. $\mu_n(T)$ and $\mu_p(T)$ are respectively electrons and holes mobility coefficients versus temperature. G_n represents carriers generation rate which corresponds to the sum of two components as show in equation 11 [14,18, 31]:

$$G_n = G(x) + G_{th} \tag{11}$$

- $G(x)$ is the photo-generation rate: $G(x) = C \cdot \sum_{i=1}^{3} a_i e^{-b_i x}$ (12)

- G_{th} is the thermal-generation rate: $G_{th} = C_{th} \times n_i^2$ (13)

C_{th} is given by $\tau = \dfrac{1}{C_{th} N_b}$ with N_b the doping density. n_i represents electrons intrinsic density and is expressed by [14,18,20]:

$$n_i = A_n \times T^{\frac{3}{2}} \times \exp\left(-\frac{Eg(T)}{2kT}\right) \quad (14)$$

A_n is a constant and for the silicon $A_n = 3.87 \times 10^{16}\ cm^{-3}.K^{-\frac{3}{2}}$. k is the Boltzmann constant. $Eg(T)$ represents the energy gap and is expressed by [14,18, 32]:

$$Eg(T) = 1.1557 - \frac{7.021 \times 10^{-4} T^2}{T + 1108} \quad (15)$$

- **The current density**

The current density expression given by following equation 16 is obtained from Fick's law [11,14, 31].

$$J_{ph}(Sf, C) = q \cdot D^c(T) \cdot \left.\frac{\partial \delta(x, Sf, C)}{\partial x}\right|_{x=0} \quad (16)$$

- **The voltage**

The voltage expression is determined by applying Boltzmann relation and is given by equation (17) [11,14, 31]:

$$V_{ph}(Sf, C) = V_T \cdot \ln\left[\frac{\delta(x = 0, Sf, C)}{n_0} + 1\right] \quad (17)$$

In this expression, $V_T = \dfrac{kT}{q}$ is the thermal voltage and $n_0 = \dfrac{n_i^2}{N_b}$ represents carriers concentration at the thermodynamic equilibrium.

- **The electric power**

The output electric power resulting of the PV cell is given by equation (18) [11,14, 31]:

$$P(Sf, C) = V_{ph}(Sf, C) \times J_{ph}(Sf, C) \quad (18)$$

- **The conversion efficiency**

The conversion efficiency at different concentration ratios is calculated by using the following formula [11,14, 31]:

$$\eta(C) = \frac{P_{\max}(C)}{P_{inC}(C)} \quad (19)$$

$P_{\max}(C)$ and $P_{inC}(C) = \tau_0 \alpha_0 C P_{in}$ are respectively the maximum output power and the absorbed power density at light concentration C.

3 RESULTS AND DISCUSSION

3.1 PV CELL TEMPERATURE PROFILE VERSUS LIGHT CONCENTRATION RATIO

This study is numerically conducted with the Matlab software. The extracted data are then used to plot the temperature profile by using the OriginPro 8 software. As shown by the thermal equation above, the heating of the light concentration PV cell is linked to the light concentration ratio. It is then possible to study the profile of the PV cell temperature, and so its heating through the light concentration ratio.

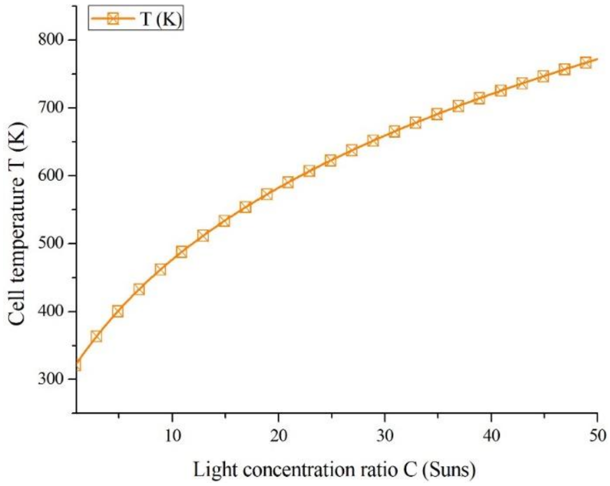

Fig. 3. The PV cell temperature profile versus light concentration ratio

Figure 3 gives the PV cell temperature profile versus light concentration ratio. Figure 3 shows an increase of PV cell temperature with the increasing light concentration ratio. Indeed, when the light concentration ratio increases, the heat quantity received by the PV cell rises and so does its temperature. When the concentration ratio goes from C = 1 Sun to C = 50 Suns, the PV cell temperature increases from 323.31 K to 771.97 K. This is equivalent to an increase of 157.32% in the PV cell's temperature. As the temperature increase in the bulk of the PV cell leads the decrease of its electric parameters [4, 5, 14,16], this significant variation rate of the temperature must necessarily be taken into consideration to obtain results close to reality.

3.2 INFLUENCE OF CONCENTRATION RATIO ON SILICON PV CELL DIFFUSION PARAMETERS

Figures 4 and 5 give respectively variations of the diffusion coefficient and the diffusion length in the PV cell base and under a variable light concentration ratio.

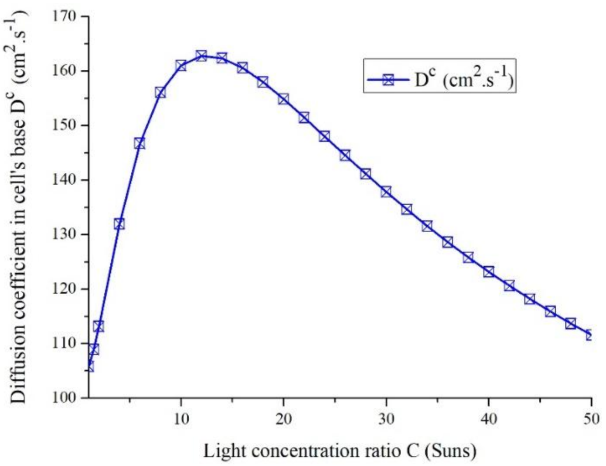

Fig. 4. Diffusion coefficient variations versus light concentration

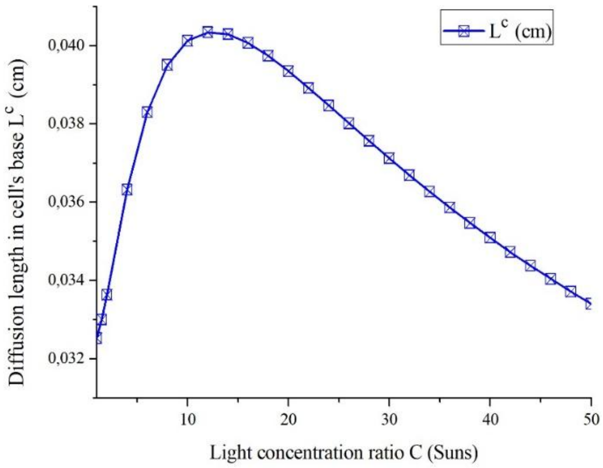

Fig. 5. Diffusion length variations versus light concentration

Figures 4 and 5 show that, when light concentration increases, the diffusion parameters rise to reach their maximums at C = 12.51 Suns which corresponds to the temperature T=507.32 K. At this value of light concentration, the maximum values of the PV cell diffusion parameters are respectively: $D_{\max}^{c} = 162.83\ cm^2.s^{-1}$ for the diffusion coefficient and $L_{\max}^{c} = 0.04\ cm$ for the diffusion length. This increase of the diffusion parameters with increasing light concentration can be explained by the increase of carrier density maxima shown in our previous study [18]. The increase of the carrier density maxima induces at the junction, an increase of the slope of the density curves. This translates into an increase in the number of carriers diffusing through the junction. This is equivalent to the diffusion parameters increasing with light concentration.

The increase of the diffusion coefficient characterizes that of the quantity of electrons which can cross the junction to participate to the photocurrent. This behavior of the diffusion coefficient suggests an increase of the current and a decrease of the voltage with the rise of concentration ratio. The increase of the diffusion length means that of average distance traveled by carriers before recombining. These results characterize a reduction of recombinations in the PV cell bulk, and then leads to the improvement of its performance.

Beyond C = 12.51 Suns, the diffusion parameters values drop with light concentration increase. The decrease in diffusion parameters beyond C = 12.51 Suns (the PV cell temperature is T = 507.32 K) is essentially explained by the negative effect of temperature on charge carrier diffusion. The decrease in carrier diffusion was shown in our previous article [18]. It so appears that beyond C = 12.51 Suns, an increase of light concentration causes the reduction of the PV cell electric parameters and then its performance.

The concentration ratio presents a positive effect on diffusion parameters for its values up to C = 12.51 Suns. The value C = 12.51 Suns of light concentration ratio which coincides to a temperature T=507.32 K corresponds to the maximum values of diffusion parameters. In the rest of our study, we consider light concentration ratios between C = 1 Sun (T=323.31 K) and C = 12 suns (T=501.32 K) to stay in the positive domain of light concentration ratio. In this interval, we work under temperatures $T \le 501.32\ K < \theta_D = 645\ \mathrm{K}$ where equations 14 and 15 remain valid [32, 33].

3.3 INFLUENCE OF LIGHT CONCENTRATION RATIO ON CURRENT DENSITY PROFILE

The curves in figure 6 give the current density profile for different values of light concentration ratio.

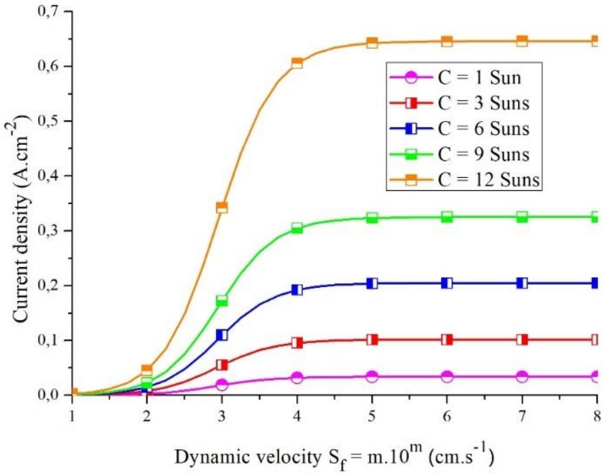

Fig. 6. Current density profile for different concentrations

We observe on these curves, an increase of current density with that of light concentration ratio. This increase in photo-current can be explained by the increase in diffusion parameters with concentration. This was shown in the previous sub-section for concentration ratios below 12.51 Suns (C ≤ 12.51 Suns).

Thus, the increase of current density agrees with the behavior of the PV cell diffusion parameters under concentration ratio presented above. The increase of diffusion parameters with the rise of the light concentration ratio will lead to the augmentation of the quantity of electrons that can cross the junction and then the PV cell photocurrent.

Also, the rise of current density with concentration ratio observed in this study is greater than that observed by Zoungrana et al. [11] who have worked with a cooled concentration PV cell. Indeed, under concentration C = 25 Suns Zoungrana et al. [11] obtained a short-circuit current density of 0.783 $A.cm^{-2}$ whereas at only C = 12 Suns, a short-circuit current density of 0.646 $A.cm^{-2}$ is obtained in this present study. The strong increase of current density in this present study is due to temperature increase linked to the heating caused by concentration ratio increase. Both, temperature and concentration ratio increase, favor current density. Thus, under concentration and without cooling, the effects of concentration ratio and temperature combine to give a very strong current density.

3.4 Influence of light concentration on the photovoltage profile

Figure 7 shows for different concentration ratio, the photo-voltage profile versus the junction dynamic velocity (Sf).

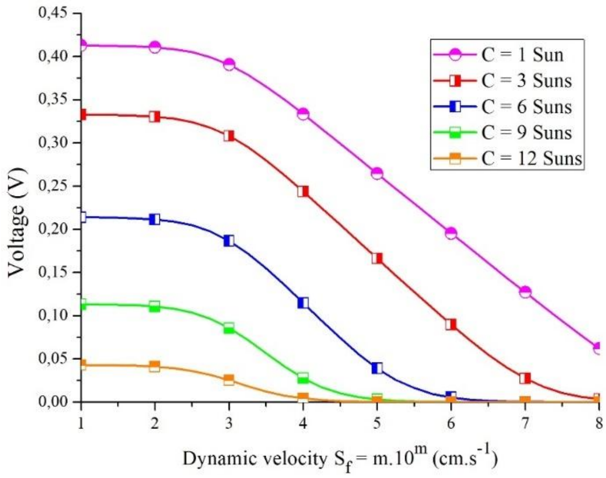

Fig. 7. Photo-voltage profile for different concentrations

It appears on curves of Figure 7, that the PV cell photovoltage decreases with the increase of light concentration ratio. This result agrees with the variation of diffusion parameters under concentration ratio which predicted a decrease in photo-voltage. This result disagrees with Geisz et al. [8], Chancerel et al. [9], Peters et al. [10] and Zoungrana et al. [11] who showed an increase in photo voltage with increasing concentration ratio. Indeed, in their works these authors did not take into consideration the temperature effect which is inherent to light concentration increase. As shown by many works [4,5,14,16], the temperature has a negative effect on the photo voltage. This negative effect of temperature increases with light concentration increasing. The temperature profile plotted above shows that cell temperature goes from 332.31 K to 501.32 K when concentration ratio goes from C = 1 Sun to C = 12 Suns.

The decrease in photo voltage is explained by the negative effect of temperature. Admittedly, the concentration of light has a positive effect on photo-voltage, which increases. However, the temperature negative effect turns out to be more important than concentration ratio positive effect, which is supposed to increase the photo-voltage.

3.5 Influence of light concentration on the power output profile

The curves in figure 8 give for different light concentration ratios, output power profile versus dynamic velocity (Sf).

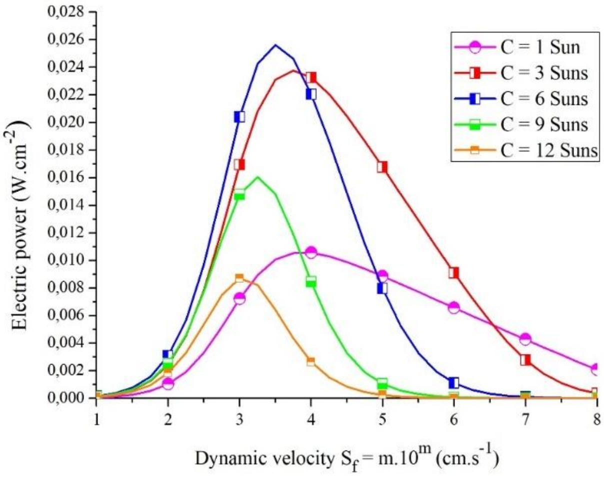

Fig. 8. Electric power output profile for different concentration ratios

Figure 8 shows that when the concentration ratio varies from C= 1 Sun to C = 6 Suns, the maximum output power increases. However, from C = 6 Suns to C = 12 Suns, this maximum power decreases. Indeed, from C = 1 Sun to C = 6 Suns, the increase in photocurrent is greater than the decrease in photo-voltage and therefore the output power increases. Beyond C = 6 Suns, the increase in photo-current becomes less important than the decrease in photo-voltage and therefore the power decreases with concentration ratio increase.

Figure 8 also shows that increasing concentration ratio causes a displacement of the maximum power point towards the open circuit. This displacement of the maximum power point is due to temperature effect. Indeed, Zoungrana et al. [11] worked on the concentration ratio influence and assumed a constant temperature and equal to ambient temperature (T=300 K). In their work these authors did not notice the operating point displacement. However, Savadogo et al. [14] worked on the temperature influence on a solar cell subjected to a constant light concentration (C = 50 Suns). Contrary to the first ones, these authors showed the displacement of the maximum power point toward the open circuit with temperature increase.

3.6 INFLUENCE OF LIGHT CONCENTRATION ON THE CELLS OPERATING POINT AND CONVERSION EFFICIENCY

Table 2 gives, for various concentration ratios the corresponding values of the maximum output power, absorbed light power and conversion efficiency.

Table 2. Concentration ratios and corresponding values of maximum output power, absorbed light power and conversion efficiency

C (Suns)	1	3	6	9	12
Maximum power Pmax (mW.cm^{-2})	10.60	23.77	25.62	16.05	8.74
Absorbed power PinC (mW.cm^{-2})	56	168	336	504	672
Conversion efficiency η (%)	18.93	14.15	07.63	03.18	01.30

Table 2 shows that the conversion efficiency decreases with light concentration increase. Also, the study of the electric power showed an increase of the maximum power which goes from 10.60 mW.cm^{-2} to 25.62 mW.cm^{-2}, when light concentration varies from C = 1 Sun to C = 6 Suns. This increase in maximum power corresponds to a variation rate of 141.70%. However, in the same concentration interval, the absorbed light power goes from 56 mW.cm^{-2} to 336 mW.cm^{-2}. This is equivalent to a 500% increase in light power absorbed. It appears that maximum power output increase is slower compared to that of the absorbed light power. This fact induces the decrease of the conversion efficiency with concentration ratio increase. This decrease of the conversion efficiency is explained by temperature negative impact mainly on the photo-voltage and the maximum output power.

This result also disagrees with Geisz et al. [8], Chancerel et al. [9], Peters et al. [10], Zoungrana et al. [11] and Pérez-Higueras et al. [34] who did not take into account temperature effect and showed an increase of conversion efficiency with light concentration ratio.

4 CONCLUSION

In this work, we have investigated the influence of light concentration ratio on the performance of an uncooled silicon PV cell. This study is based on two models: a thermal model and an electrical one. On the Basis of the thermal model, the temperature profile of an uncooled PV cell submitted to a variable concentration ratio is determined. The diffusion and the electric parameters were extracted from the electrical model. Subsequently light concentration ratio influence on these parameters is studied. This study takes into account effect of heating caused by concentration ratio variation and which is characterized by the temperature increase.

The results indicate that the PV cell temperature increases very rapidly with light concentration. It also appears that diffusion parameters increase when concentration ratio varies from C = 1 Sun where temperature is T=323.31 K to C = 12.51 Suns where temperature is T=507.32 K. Beyond C = 12.51 Suns, these diffusion parameters decrease. The results also indicate a strong increase in current density with concentration ratio of an uncooled PV cell. This result is explained by the fact that current increases not only with concentration ratio but also with temperature. Concentration ratio and temperature are favorable factors for the current density.

Contrary to many authors, this work shows that the photovoltage and conversion efficiency decrease with increasing concentration ratio in an uncooled photovoltaic system. This is explained by the antagonism of the effects of light concentration and temperature on voltage. Indeed, light concentration contributes to increase the voltage while the generated temperature contributes to the reduction of this voltage.

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