Effect of non-uniform illumination and temperature distribution on concentrating solar cell - A review

Guiqiang Li[1]*, Qingdong Xuan[1], Gang Pei[1], Yuehong Su[2]*, Jie Ji[1]

[1] *Department of Thermal Science and Energy Engineering, University of Science and Technology of China, 96 Jinzhai Road, Hefei City 230026, China*

[2] *Institute of Sustainable Energy Technology, University of Nottingham, University Park, Nottingham NG7 2RD, UK*

Abstract

Concentrated photovoltaic (CPV) technology as a typical PV application is becoming popular due to its advantages of high conversion efficiency and low cost etc. However an important issue for CPV technology is the non-uniformity on the illumination and the temperature which can finally influence the overall electrical efficiency of solar cells. This study presents the feature of the non-uniform illumination and temperature, and reviews the cause and harm of the non-uniform illumination and temperature. Then the specific effect on cell parameters of different solar cells is analyzed, and finally the improving methods for reducing this negative effect on concentrating solar cells are proposed. This review will help researchers to learn the effect of the non-uniformity on the illumination and the temperature, and common improvement method, which will benefit CPV design and optimization.

Keywords: non-uniform illumination; concentrating solar cell; non-uniform temperature; cooling technology

*Corresponding authors. Tel/Fax: +86 551 63607367. E-mail: ligq@mail.ustc.edu.cn; Yuehong.Su@nottingham.ac.uk

Contents

1. Introduction

Energy is one of the vital factors for any country development. Till date the coal as one of the major sources of electricity production has the share of electricity by 42% and it will still be the main source of electricity in many countries in the next few decades [1]. But the problems of worldwide energy shortage and environment pollution are becoming more serious, so renewable energy has been encouraged by many countries due to the advantages of being sustainable and not contributing to the world's CO_2 greenhouse gas emissions [2]. Solar energy as an abundant and large potential renewable energy source in the world has no pollution [3], so it has been widely used. According to 2015's data, solar photovoltaics (PV) contribute about 227 GW, and concentrating solar power (CSP) technologies contribute about 4.8 GW in electricity generation capacity [4]. However, the major limitation of PV technology still remains at lower performance price ratio compared to the conventional power generation techniques. Only part of the solar radiation can be converted into the electricity while the remaining solar radiation is either converted into the heat or is reflected back [5]. Concentrating photovoltaic (CPV) can overcome these problems because of its lower cost and higher electrical efficiency [6]. The expensive PV material is replaced by lower cost mirrors and/or lenses, reducing the system cost but maintaining the total value of the energy captured [7]. If the cell cost can be reduced to be a small portion of the whole system cost, it can be advantageous to employ a cell with a higher efficiency, making the investment in the optics more valuable [8]. Although with the concentration ratio increasing the solar cell temperature will increase, which will lead to the PV efficiency and lifespan decrease, this problem can be solved by using a proper cooling technology [9]. In addition, the photovoltaic/concentrated solar power hybrid system can attain the better power quality electricity compared to the PV-alone system [10].

Concentrating solar cell is the core part of a concentrating photovoltaic system. There are many kinds of solar cells, about 90% of which are monocrystalline and multi-crystalline silicon solar cells [11], and others include III–V compound solar cells (such as single-junction GaAs and multi-junction concentrators), thin film cells (such as cadmium telluride (CdTe) thin-film photovoltaics, copper indium gallium diselenide (CIGS) solar cells, and amorphous silicon cells, dye-sensitized solar cells, organic solar cells, etc. [12] and since 1960 semiconductors (III–V and II–VI) based solar cells were studied and new technology for polycrystalline Si (pc-Si) and thin-film solar cell have been establish in order to lower the material cost and energy input but increase the production capacity [13]. Silicon wafer-based solar cells are believed as 'first generation' while 'second generation' are lower cost thin-film solar cells, and the concentrating solar cell was regarded as the third generation solar cells [14]. There are two ways to widen the application of solar cells: one is to decrease the costs, but many ways have been tried on this [15] and it can't achieve an effective progress in a short period of time, and the other is to improve the efficiency of the cells, which has also become the focus of the study of concentrating photovoltaic.

However, there are several factors that can affect the efficiency of cells in the CPV system, such as the kind of cells, concentration ratio, non-uniform illumination, non-uniform temperature, cooling structure and so on. In this paper, the main purpose is to summarize the effect of non-uniform illumination and non-uniform temperature on concentrating solar cells, and to analyze the performances on different cells and to illustrate the improvement methods to overcome the negative influences.

2. Concentrating solar cell overview

Solar cell is the core component of the CPV system, and its characteristic plays an important role on the overall performance of the CPV system. Low concentration photovoltaic (LCPV) systems can adopt the conventional high performance silicon solar cells [16] which can be used under the concentration ratio of 2 to 10 suns [17]. But for medium and high solar concentrating PV systems, because of the high operating temperature of cell which will influence its several parameters, it needs the specially designed solar cells which could further employ the sun-tracking device and cooling technique [18]. Medium and high concentrator PV technology is still in a deployment stage [19]. Silicon-based solar cells may be not much proper, and III–V multi-junction solar cells are more suitable for the solar concentrating system because of the lower base electrical resistivity [20]. Multi-junction solar cells used for CPV systems could deliver the electrical power with a lower cost compare to the traditional one [21] and the PV conversion efficiency will increase with a high solar concentration ratio until the series resistance limits the performance [22]. Xing et al. [23] used finite element method to calculated the thermal performance of silicon vertical multi-junction (VMJ) solar cell under 1D non-uniform illumination of 500 suns, and used SPICE software to calculated the PV electrical performance based on the thermal simulation results and founded that it had a better performance than silicon planar junction cell under the same conditions of 500 suns which means multi-junction solar cells have a good potential in CPV. In recent years, the electrical efficiency of the III–V triple-junction solar cells has been increased significantly [24], and according to Ref. [25], [26], [27], the highest efficiency can reach 28.3% [25], 40% [26], and 41.1% [27].

2.1 Difference from traditional solar cells

The computing and testing of traditional cells are carried out under the assumption of the uniform condition, and the deviation is acceptable for the practical application. However, for concentrating photovoltaic cells, especially with the increase of solar concentration ratio, the non-uniformity can cause a significant difference on different solar cells with the decline in the overall performance. So in the analysis of the concentrating solar cells, the effect of non-uniformity on cells has the great significance. And in the process of analysis, there is a lot of limitations when using the analysis methods of traditional cells, since the characteristics of the concentrating solar cell itself must be taken into consideration. For example, using the light intensity and temperature function with a Gaussian distribution takes the place of that with the uniform distribution; or using a 2-d or 3-d cell model replaces the one dimensional diode model.

2.2 Current Cell models

The traditional parallel circuit model consists of the diode and the current source is widely used to characterize the electrical characteristics of solar cells. But high concentration solar cells have specific characteristics different from those of conventional flat-plate solar cells [28]. The traditional model ignores the non-uniformity of light intensity and temperature on the cell, but this influence on the CPV cells has become very significant. Also, different illumination spectra, angles of impinging light and chromatic aberrations should be taken into consideration [29]. So in order to increase the performance of such concentrating solar cells, a modeling as accurate as possible is necessary to achieve realistic results [30]. The circuit network model to analyze the solar cell electrical characteristics under non-uniformity can be used. In recent years, the scientists have also devoted considerable efforts in developing models that reproduce the electrical behavior of solar concentrating under different operating conditions [28]. The important issue of establishing the model is to minimize the series resistance due to the loss of the voltage caused by large generated currents. And when a cell is designed for concentration, the design of the front metal grid spacing is important to reduce the resistance of the emitter region.

Franklin and Coventry designed a two-dimensional cell model under an average concentration ratio of 20-50 suns, and the net generated intensity is given by Eq. (1) [31]. Generated current was considered to gradually vary only in the x-direction and the emitter resistance could result in a junction voltage that increases with the distance from the finger.

$$I_j(x,y) = I_0(x,y)(e^{\frac{q \cdot V_j(x,y)}{K \cdot T(x,y)}} - 1) - I_L(x,y) \tag{1}$$

where $I_j(x, y)$, $I_0(x, y)$, $I_L(x, y)$, $V_j(x, y)$, $T(x, y)$ stand for the net current flowing across the junction, the reverse saturation current, the photocurrent, the p-n junction voltage and the temperature respectively for the given element position (x, y).

Mellor, et al. presented another two-dimensional model of the current distribution in the front surface of the cell which took into account the distributed diode effect [32]. The cell model can be seen as consisting of a series of the same fingers and it doesn't limit the vertical current flowing from the emitter to the fingers. The illumination intensity falls on the PV cell is given by:

$$G(x) = G_0 A_0 \exp(-\frac{x^2}{2{s_0}^2}) \tag{2}$$

And the current generated in the emitter region is given by:

$$Q_j = C_1 G + C_2 T^3 \exp(\frac{-E_g}{k_b T})[\exp(\frac{q_e V_j}{n k_b T} - 1)] \tag{3}$$

While in the dark finger and bus-bar region is given by:

$$Q_j = C_2 T^3 \exp(\frac{-E_g}{k_b T}) \left| \exp(\frac{q_e V_j}{n k_b T} - 1) \right| + C_3 V_j \quad (4)$$

G_0 is the mean illumination across the cell, S_0 controls the width of the curve; T is the cell temperature; V_j is the junction electric potential; q_e is the electron charge, k_b is the Boltzmann constant; E_g is the bandgap energy; n is the diode ideality factor, and C_1, C_2 and C_3 are coefficients specific to a given cell.

A useful 3D model based on the distributed circuit units for concentrating solar cells was established by Galiana, et al. [33] which had a greatly improvement compared with the conventional model [34] in greater detail. The model considered the various influence factors, such as all of the series resistances and even the parallel resistances. The whole solar cell could be modeled based on the electrical circuit attained by the interconnection of every unit circuit. There are three main types of elementary units in the model [33]: (a) illuminated area; (b) dark area (bus bar and front grid); and (c) perimeter region. The equivalent circuit for the illuminated areas is the only unit where photo-generation takes place and that for the dark areas (beneath the busbar and fingers) considers the recombination in the neutral regions as well as in the depletion region with two diodes. The equivalent circuit for the perimeter regions (beneath the busbar) has basically the same electrical circuit concerning in the ohmic losses.

3. Effect of non-uniform illumination on solar cells

3.1 Characteristics of the non-uniform illumination

In CPV systems, concentrators are used to concentrate the sunlight on solar cells. It is hoped that the illumination is uniform, but in reality, a part of the area of solar cells may be accepted by the excessive light, or rarely be exposed to the light.

There are two distinctive features of the non-uniformity: a single solar cell with the non-uniform illumination or a series of cells connected together with different illumination on each cell surface [35]. In the first case, some parts of a single cell surface be illuminated and some are rarely illuminated, so the part which accepts excessive exposure to the light may generate the huge current and heat. In the second case, because the cells in the CPV system often exist in series, and one shaded could affect the whole system, causing the system performance to decrease significantly and leading the cell to damage due to reverse-bias operation and overheating [36]. Solar cells are often used in series, since each cell cannot maintain the absolute same performance, the total power output is less than the sum of individual power, which is called 'current mismatching'.

There are many reasons that will cause non-uniform illumination, here they are summarized below in Table 1 [31, 35, 37, 38].

From the table 1, it can be found that the concentrator optics play an important role on the illumination on cells, so the improper design may lead to severe non-uniformity. Meanwhile, unbefitting position, shading, spectral response also can cause this phenomenon. However, this non-uniformity can affect the whole CPV system on the overall economic benefits, the electrical performance of the solar cell, thermal features and so on.

3.2 Cell parameters analysis under non-uniform illumination

Solar cells performance is mainly characterized by the four basic parameters: Short Circuit Current I_{sc}, Open Circuit Voltage V_{oc}, Fill Factor FF (defined as the ratio of the maximum power from the solar cell to the product of I_{sc} and V_{oc}) and the energy conversion efficiency η, and they will all be affected by illumination conditions. For the purpose of experimental or numerical analysis, it is difficult to reproduce a non-uniform illumination distribution caused by a real solar concentrator, so a localized illumination in experiments and a standardized illumination such as Gaussian distribution or a simulated distribution are usually employed, as detailed in the following.

3.2.1 Localized illumination

It is known that there are two distinctive performances of non-uniformity in section 3.1, and the first case that the inhomogeneous illumination intensity on a single cell is analyzed here.

- Partitioned uniform illumination

In Coventry's study, a monocrystalline silicon solar cell was employed to indicate the effects of the non-uniformity on the *I-V* characteristics experimentally [39]. An experiment was conducted on a single solar cell in two cases: 30 X concentration ratio over the whole cell, and 90 X concentration ratio over the middle third of the cell. The results showed that there is a reduction in open circuit voltage of 6.5 mV (Fig. 1) and an obvious deviation of the *I-V* curves is observed under the uniform and non-uniform illumination conditions, and the author pointed out an efficiency drop from 20.6% with uniform illumination to 19.4% with non-uniform illumination [40].

Katz et al. [41] used a 100 mm² triple-junction GaInP2 /GaAs/Ge cell with the uniform front metallization under a localized illumination procedure. Solar illumination on the cell P_{in} was provided from 0.1 to 8 W. The short-circuit current I_{sc} was proportional to P_{in} with a photocurrent generation ratio $G = I_{sc} / P_{in}$. The V_{oc}, FF and η will all get a decline affected by the local illumination compared with the uniform illumination. With P_{in} increase, the decline of the V_{oc}, fill factor FF and dependence of energy conversion efficiency η will also gradually increase and the deviation values seems to be larger with P_{in} at the higher level. However, especially, the position of the local illumination on cell have little influence on the decline of the parameter FF.

Manor et al. [42] used a large photoactive area organic cell with poly(3-hexylthiophene) (P3HT)/PCBM BHJ. The cell parameters was measured under various concentrations of uniform and localized illumination. The results indicate that the localized illumination of different part over the cell area gives identical results as mentioned above using the triple-junction cell. For the V_{oc}, from Fig. 2(b), it can be seen that there exists a decline when the cell is exposed to the localized illumination and the decline has remained at about 0.1V. In addition, it is clearly that the results in the localized mode show the superior I_{sc}, FF and η values in Fig. 2(a), Fig. 2(c) and Fig. 2(d). With the increase of light intensity, FF and η both show the tendency of decline. This seems to be a special situation which demands more attention.

- Gaussian distribution

In the process of modeling, the distribution profile of the non-uniform illumination needs to be confirmed. And the cell parameters can be observed by experiment after the correct choice.

In the cell circuit modeling analysis, most linear concentrators usually have the non-uniform illumination profiles in the finger direction, such as a Gaussian function [43]. This distribution can be instead of the actual circumstances, especially for the Fresnel lens concentrating device [44].

The rough graph is shown in Fig. 3 [45]. The model based on Gaussian illumination incident on the cell on the x axis, which is also the finger direction:

$$R_g(x) = R_0 \exp(-\frac{(x - x_0^R)^2}{2S_R^2}) \tag{5}$$

where R_0 entangles the normalisation factor which ensures the desired mean irradiance across the cell, x_0^R controls the Gaussian illumination center, and S_R is the width of the illumination curve [45].

In the study by Franklin and Coventry [31] in 2002, the solar cell efficiency reduced from 17.3% under the uniform illumination and temperature, to 16.8% under the distributed illumination and uniform temperature and the open circuit voltage experiences a decline of about 5mV under the identical total illumination in each case (Fig. 4). Also, it is concluded that open circuit voltage and efficiency both experience a significant decline with increasingly centralised illumination profile (Fig. 5). This can also be proved in Algora [46]'s experiment which used the 3D model mentioned above in Section 2.2. He tested this GaAs single junction solar cell under two types of illumination: (a) a 100× uniform illumination; or (b) a non-uniform illumination going from 0 at the bus bar and linearly increasing until reaching 4000×at the center, so that the average illumination on the cell was 1000×. The FF has a decline of 0.003 and the η has a decline of 0.4% and the V_{oc} also experienced a decline with the increase of the non-uniformity.

Mellor et al. [32] established a two-dimensional finite element model of cell as introduced in Section 2.2. The whole cell is considered as consisting of a number of identical finger elements with identical emitter sections along each side of the finger, taking into account its corresponding busbar sectors. The model was used to compare the cell parameter under 12 suns uniform and non-uniform illumination. The V_{oc} has a reduction of 0.007V, and the FF has a 0.06 reduction and the η has a 1.7% reduction with a peak illumination ratio of 10X compared to those under the uniform illumination (Table 2, Fig. 6 and Fig. 7). And form the results, it can been gotten that with the increase of the peak illumination ratio, the declination of the FF and efficiency of the PV cell tends to be larger. The authors also conducted the analysis of the effect of the finger number on the V_{oc} of the cell which was founded that at different peak illumination ratio, the optimised fingers varied a lot (Fig. 7). This is an interesting conclusion which provides an effective way to improve the cell structure to better suit the Gaussian illumination profiles.

Domenech-Garret [45] analyzed the cell behaviour under different conditions through the model established by Mellor A et al. [32] (Fig. 8). The model was used to get the $I-V$ curve of a cell under a 15 suns, with three conditions: (1) Gaussian Radiation (GR) distribution together with a Gaussian temperature (GT) profile; (2) GR distribution and uniform equivalent temperature(UT); (3) both uniform radiation and uniform temperature(URT). It is pointed out that the decline of FF is 0.01 and V_{oc} is 10mV under the UT situation compared to URT situation (Fig. 9).

Herrero et al. [44] investigated the performance of multi-junction solar cells under the non-uniform illumination and the result is shown in Fig. 10. The increase in the non-uniformity decreases the fill factor, which is mainly because of the increase of series resistance losses that leads to the solar cell efficiency decrease in operation. Goma et al. [47] studied the effect of concentration distribution on cell performance to calculate the fill factor FF using the c-Si solar cells. The study was conducted under various incident light intensities. The effect of non-uniform distribution tended to be larger with the decrease in irradiance (Fig.11). Araki and Yamaguchi [48] studied the concentrator cells performance under non-ideal illumination. Fig. 12 shows the $I-V$ curve under Gaussian illumination compared to that under the uniform illumination using the AlGaAs/GaAs 2-junction solar cell. The deviation in the *FF* and the cell efficiency is very large between the Gaussian illumination and the uniform illumination.

3.2.2 Shaded cell

Segev and Kribus [36] used the vertical multi-junction cells to make an experiment under non-uniform illumination. The non-uniform illumination on the vertical multi-junction (VMJ) cells was along one direction and nearly uniform illumination along another vertical direction [49]. They simulated the CPV module performance which is made of concentrating monolithic silicon VMJ cells [50], electrically connected in parallel under non-uniform illumination produced by a parabolic dish concentrator. From the experiment, dense array CPV modules based on VMJ cells connected in parallel feature very low sensitivity to non-uniform illumination, when the homogenizer is short or even doesn't exist, the decline of the efficiency is not obvious. Modules with as high as 25 VJs in each VMJ cell have shown configuration efficiencies above 0.98 with no homogenizing optics. This capability of the VMJ cells array can lead to several practical advantages.

As listed in Table 1, shading is an important reason for non-uniform illumination, too. Dolara et al. [51] used the poly-crystalline and mono-crystalline PV module to investigate the influence of partial shading. Three shading scenarios are applied to the PV modules (Fig. 13). From their experiment results, the FF and η all get a significant reduction, especially under horizontal shading scenarios for poly-crystalline PV module (Fig. 14). With the increase of degree of shading, the generated current is decreasing, too. Wang et al. [52] used the PV module to determine the effects of frame shadows in two cases: a series circuit and a parallel circuit (Fig. 15). Even the shadow area is very small, it can have a serious influence on PV modules. The parallel circuit has a better performance than series one. It should be noted that for the PV modules, the shading effect may be even much more serious, it was found that the maximum and minimum drop in short circuit current of module is observed to be 84.2% and 34.6% when the solar cells of high and low spectral response are shaded [53].

Here a comparison of the cell performance between the uniform and non-uniform illumination is listed in Table 3.

Seen from the above experiment, it can be found that non-uniform illuminations have certain influence on the solar cell parameters which cause a decline on the open circuit voltage V_{oc}, fill factor FF and efficiency η in most instances, so it needs to find ways to decrease the influence.

3.3 Methods to alleviate the effect

There are many methods to reduce the effects of the non-uniformity, including optimizing the design for solar cells, the concentrator optics and the tracking system etc. Among them, from the perspective of optimizing the structure of the solar cell itself, firstly, the concentrator cells need to have the right size and shape depending on the illuminated region in concentrating systems [35]; secondly, the surface of the cells can be dealt with. Also, when the modular design was employed, it can reduce resistance through improving routing architecture, narrowing cells interval or strengthening the arrangement density of cells.

3.3.1 Cell structure

Mellor et al. [32] indicated that the optimization of the front contact pattern, by increasing the number of fingers to suit the degree of non-uniformity, can mitigate the cell efficiency decrease significantly. When the number of fingers on a cell is increased from 184 to 287 under the illumination with a peak value ratio of 10, the efficiency drop is decreased from over 1.7% to less than 0.7% compared to the uniformly illuminated cell. The influence of the front contact can also be seen. The worse the quality of the front contact, the greater the decrease in the cell parameters [46]. Silva et al. [54] indicated that the device fabrication processes is important for the solar cell efficiency. For example, the silicon surface texturing process can reduce the optical reflection by increasing the surface absorption area of the incident radiation on the cell and finally increase the cell efficiency. Another technique is called the laser grooving buried gate (LGBC) (Fig. 16). This metallization process and the connecting grid design can help the solar cell to decrease their series resistance values and increase cell efficiency under the concentrated illumination. The LGBC cells can be optimized depending on the type of the concentrating system [55]. For InGaP/InGaAs/Ge triple-junction solar cell, the solar cell's structure can be optimized by changing the cell size or grid electrode pitch, for reducing the series resistance and reducing the effects of the non-uniform illumination [56].

3.3.2 Concentrator choice

The incident solar irradiance on solar cells depends mainly on the optical elements [57]. An important factor to affect the overall CPV system performance is the intensity and illumination distribution from the optical elements [58], so the choice of the concentrator will affect non-uniform illumination, too. We can promote cell efficiency through the optimization of the concentrator. For concentrator silicon solar cells, when the concentration ratio increases, the tracking and cooling system will be difficult. The luminescent concentrator is made by down converter materials and can absorb incident sunlight by the species luminescent and emitted with the high quantum efficiency. Employing the down converter materials to realize concentration could reduce the demand of tracking, because the effect of the non-uniform illumination on the luminescent concentrator was less compared to that on optical elements such as reflectors and Fresnel lens [59] so it can offer an attractive approach to combine spectral and spatial concentrations of both direct and diffuse light without the expensive tracking system [60]. The up converter materials could be placed at the bottom of the bifacial illuminated cell under concentration to further improve the efficiency [61]. In Araki et al.'s [48] study above, they also proposed a simple method to anticipate non-ideal illumination effect for concentrator cells. They found that the presence of the chromatic aberration can improve the *FF* of the solar cell from Fig. 17 [48]. The chromatic aberration (CA) losses could be minimized by Fresnel elements that alternately focus red and blue light or use a secondary optical device [62]. Hatwaambo et al. [63] used semi-diffuse rolled reflective elements in low concentrating photovoltaic system to improve the system performance. Perez-Enciso et al. [64] proposed a method to achieve a uniform flux distribution with a multi-faceted point focus concentrator, which can be used in different types of receiver and no additional device is required to homogenize the flux. Yeh [65] illustrated the solar radiation distribution of a two-stage solar concentrator combining the Fresnel lens (FL) and the compound flat concentrator (CFC), and demonstrated the way that a 2nd stage reflector of right dimension has the function of enhancing flux intensity and uniformity at the same time. Li et al. [66] proposed a lens-walled compound parabolic concentrator (CPC) as shown in Fig. 18 [66] which has an advantage of more uniform flux distribution than mirror CPC with the same geometrical concentration ratio. They did outdoor experiment [67] and indoor experiment [68] using a lens-walled CPC PV and found that the lens-walled CPC PV still has a large value of the open circuit voltage, the short circuit current and optical efficiency at the incidence angle larger than 15° and a better fill-factor than mirror CPC PV which indicated their hypothesis [67]. Based on the experiment results, they further performed structure optimization by simulation and experiment [69]. They did a further research in 2014 and proposed a novel lens-walled CPC with air gap as shown in Fig. 19 which set an air gap with the lens structure and maximize the total internal reflection [70]. This structure can improve optical efficiency by more than 10%

and is more uniform compared to the original lens-walled CPC [71].

4. Effect of non-uniform temperature on solar cells

4.1 Characteristics of the non-uniform temperature

Non-uniform temperature indicates that the cell temperature is different among different parts. It can be arisen by several reasons, such as the non-uniform illumination, the inconsistency of each cell, the cooling mechanism and so on. And it often cause the excessive temperature which is harmful to the solar cell and the whole system.

Non-uniform temperature distribution can affect the PV system performance in two ways: (1) cells efficiency loss due to power output loss; (2) the thermal fatigue induced by temperature variation because of large amount of the thermal cycles and stresses [72].

When a cell is exposed to the non-uniform illumination, the effect of the non-uniform solar radiation distribution will significantly lead to the temperature distribution on the solar cell, and the area which has a larger flux intensity will surely have a higher temperature or even get hot spots [73]. Coventry et al. [39] found that the central illuminated region of the cell may be as much as 14°C hotter than the edges of the cell through the experiment. Furthermore, the reduction of the illuminated area will cause an increasing temperature gradient. Secondly, each cell can't be exactly the same, so the differences between them will cause the differences in their performance and therefore may cause the temperature difference. Finally, in order to avoid the damage of cells caused by the excessive temperature when using them, every system will have a heat sink. However, even if the solar cell is uniformly illuminated, temperature non-uniformities are always existed because of the imperfections in the cell-to-substrate bond, and the temperature gradient may exist along its diameter because of the properties of the heat sink geometry [74].

In all the consequences about the non-uniform temperature, the excessive temperature is the primary problem. It can bring many harm, and with the increase of the concentration ratio, this problem will become more obvious [75]. So in the discussion of the harm, we mainly discuss the efficiency loss caused by the excessive temperature and the solution to this problem.

The effect of temperature can be concluded in two ways: (1) for solar cells, it may exhibit a short-time degradation due to the local overheating, resulting in loss of efficiency [76], and it will also cause long-term irreversible damage and reduce the lifespan rapidly [77] and the PV cells, much like the high-performance CPUs and GPUs, failures are always instantaneous and catastrophic[78]; (2) for the whole system, it will affect the system reliability and the whole economic benefits.

4.2 Cell parameters analysis under non-uniform temperature

4.2.1 Temperature distribution profile

A Gaussian illumination profile has been used as the actual temperature profile as shown in Fig. 20 [31]. It is assumed that three fourths of the total energy can reach on the front surface of the cell. And if most heat generation occurs in the central region of a cell, this region will get the highest operating temperature, so there exists a temperature difference between the center and the outer edge of the cell [31].

4.2.2 Variation of cell parameters

Studies present that the operating temperature is a key factor to influence the conversion efficiency. The increase in the cell temperature cause a reduction of the open circuit voltage, which affects the maximum power output delivered by the cell and leads to the cell efficiency decrease. Tiwari et al. [79] summarized the cell efficiency changed by the cell temperature during a day. It can be concluded that the cell efficiency decreases along with the cell temperature increase and at the end of the day it will again increase due to the decrease in cell temperature (Fig. 21). Pérez-Higueras et al. [19] also observed that the efficiency of the cell decreased when the temperature rose using a multi-junction cell (Fig. 22). Skoplaki and Palyvos [80] indicated that for most of the silicon-based PV cells with the temperature of 25 °C, the average decrease in efficiency is of the order of 0.45% per degree rise in operating temperature. Under the concentrating condition, the influence of temperature on the cells will surely become larger. Since the cell efficiency decreases with increasing temperature, the cell at the highest temperature will limit the whole string cells efficiency [29].

The influence of the temperature of mono-Si solar cells with the p–n junction on different cell parameters was studied by Meneses-Rodrígueza et al. [81]. It can be found that the open circuit voltage and fill factor FF have significantly decreased with the increase of temperature while the short-circuit current I_{sc} has no significant change (Fig. 23).

For InGaP/InGaAs/Ge triple-junction solar cells, from Fig. 24, the V_{oc}, FF and η all decreased with the increasing temperature. It can be found that the decline of V_{oc}, FF and η have about 0.5, 0.04 and 0.03 with 140 °C compared to 20 °C at 200 suns. And the I_{sc} remain almost the same when the concentration ratio is not much high. Under the concentration ratio at 200 suns, the I_{sc} has a small increase of 200mA. Therefore the InGaP/InGaAs/Ge triple-junction solar cells have an advantage over crystalline-silicon solar cells under high-temperature conditions [56].

Peharz et al. [24] also investigated the temperature impact on different CPV modules with GaInP/GaInAs/Ge triple-junction solar cells. An indoor sun simulator was used [82] which was investigated in recent years to control the various temperature. The $I-V$ curves and consequences of different parameters (Fig. 25 and Fig. 26). The open circuit voltages decreases linearly by 0.18%/K of temperature increase and the FF shows a relative decrease of 0.16%/K. In contrast, the I_{sc} is expected to increase of 0.13%/K with increasing module temperature. It is concluded that the temperature dependence of Fresnel lenses and thermal expansion of the CPV modules would reduce the positive short circuit current temperature coefficient of the solar cells [83]. Siefer et al. [84] did a further study in the same circumstances. The data shown in Fig. 27 revealed that the energy conversion efficiency η, *Voc* and *FF* also decreased with the increased temperature. The main reason for the decline is that the open circuit voltage V_{oc} will decrease when operated at a high temperature under concentration.

The results of the Gaussian temperature profile and an equivalent temperature T_0 = 323 K and a temperature peak ΔT = 20 K (ΔT is the temperature amplitude with respect to the temperature baseline T_0) were shown in Fig. 8 in Section 3.2.2 above. And when the temperature peak ΔT = 40 K and the equivalent temperature rose to T_0 =334K, the decline of FF is 0.05 and V_{oc} is 7mV under the Gaussian temperature situation compared to UT situation from their data (Fig. 28 [45]). Two conclusions can be gotten from the two results shown respectively: (1) the fill factor FF and the open circuit voltage V_{oc} all decrease when the temperature distribution is more uneven; (2) the fill factor FF and the open circuit voltage V_{oc} all decrease with the increasing temperature.

And here a comparison of the cell performance between the uniform and non-uniform temperature is listed in Table 4.

4.3 Improvement methods

For multi-junction solar cells such as the GaInP/GaAs/Ge solar cell, under concentrated sunlight, about 37% of the absorbed energy is used for generating electrical power whereas 63% of it is dissipated in heat. Heat dissipation is important because V_{oc} which is related to the efficiency of solar cells has a negative correlation with the temperature [21]. So two kinds of methods can be employed to improve this problem, and one is to control the generation of heat by cells and the other is to use the cooling system. In the first case, we can reduce the internal resistance of the cell pack or improve the charging and discharging efficiency of cell under high temperature. But the inherent chemical heat produced by cell inside can't be avoided, so just consider for the adjustment of the cell may cannot effectively solve the problem. Therefore, another case which gains further efficiency is accomplished by a cooling system to reduce the cell temperature [87] and [88] and the heat dissipated from the solar cells can be further utilized at the same time where hybrid technologies were developed for combined heat and power (CHP) cogeneration since the 1970s [89]. Cooling of photovoltaic cells is paid more attention when designing concentrating photovoltaic systems. The cooling mechanism should be chosen for the proper thermal regulation. The type of cooling technology depends upon various parameters such as the area available for cooling, the fluid flow rate and the heat transfer coefficient. It needs to follow this principle as follows: the reliability of the system, the security of starting and running, the cooling efficient and cell temperature uniformity, whether the system can save energy and the system should meet different needs [90]. The cooling technology can be divided into passive and active, and the passive one have advantages of low cost and simple structure. But it is insufficiently used for LCPV systems and almost cannot be used for commercial. The active system has a better cooling effect and reliability [91] and for the active cooling, the heat exchanger design can be optimized to obtain uniform temperature distribution [72], but it is complex and not safe [92]. And the main goal of this section is to introduce and provide the current work in the field of CPV cooling technology.

4.3.1 The traditional cooling methods

Traditional cooling methods are mainly consisted of air cooling technology and water cooling technology.

- Air cooling technology

Air can take heat away to keep cell's temperature in a low level by convection passively or actively from the back of the solar cell. Hussain et al. [93] established a cooling channel under the absorber plate in which the air can flow to take away the heat. Araki et al. [94] studied the single solar cell cooling problems under 500 X concentrator, and the results showed that the thermal contact between solar cell and aluminum plate is also the key to keep its low temperature.

- Water cooling technology

Water cooling offers a good performance because of its high convection coefficient and thermal capacity. The key to design is to guarantee the good heat transfer and electric insulation between the solar cell and the heat exchanger. Verlinden et al. [95] described an integral water cooling technology using a monolithic silicon concentrator module consisted of 10 cells (Fig. 29). The module got a 0.8% growth of efficiency when operated at 25°C compared to 39°C. Verlinden [96] reported an active water cooling system based on the reflective parabolic dish and set up parallel narrow flow on the back of the solar cell. The PV receiver is composed of 16 modules, each with

24 series-connected silicon solar cells. The cell efficiency can reach 24% and the system comprehensive energy utilization efficiency can surpass 70%.

The advantages and disadvantages of the two kinds of cooling technology are obvious. The air cooling technology is cheap and safe while the water cooling technology is complex and expensive but the thermal properties of water make it far more efficient as a coolant medium than air.

4.3.2 The new cooling technology

Nowadays, a lot of new cooling technology has risen up and plays an increasingly important role in the field. They include the heat pipe cooling technology, the micro-channels technology, the liquid immersion cooling technology, the impingement jet cooling technology and the phase change material technology, etc.

- Heat pipe cooling technology

Heat pipes are common and efficient heat transfer device. One end is stick to the solar cell and absorb the heat, and another is exposed to cooling environment (Fig. 30) [97] and [98]. This technology has many advantages, such as the high thermal conductivity, the good temperature uniformity, the heat flux variability, the reversible flow direction, the temperature steady characteristics and the good environment adaptability [90]. Tarabsheh, et al. [99] put forward the pipe line layout for effective cooling cell method and the cooling pipes beneath each PV string can enhance the performance of the PV module.

- Micro-channels technology

The size of micro-channels are small and can directly cool the millimeter level heat source, but the temperature gradient and the pressure loss is large, so it is needed to find ways to improve its structure. The work is concentrated on the optimization of the micro-channel heat sink [100]. Walpole and Missaggia [101] demonstrated an alternating-channel-flow micro-channel heat sink which can reduce the surface temperature variations compared to a conventional one with one-directional flow (Fig. 31) [101]. Yang and Zuo [102] presented a novel multi-layer manifold microchannel cooling system and the experiment results showed that the surface temperature difference of the CPV cells was below 6.3 °C which also indicated that multi-layer manifold micro channel had a heat transfer coefficient of 8235.84 W/m^2 K and its pressure drop was lower than 3 kPa.

- Liquid immersion cooling technology

Liquid immersion cooling means that solar cells can be immersed directly into the circulating liquid and the liquid can take the heat away from both the front and back surface of the PV string [7]. Liu [103] studied the liquid immersion cooling on cell modules under moderately intensified illuminations. The temperature distribution of cell module is fairly uniform within 3 °C under turbulent flow mode.

- Impingement jet cooling technology

Impingement jet cooling technology can obtain the low thermal resistance and has been widely used in many industrial fields [104]. For solar cell cooling, the impinging jets can extract a large amount of heat due to the very thin thermal boundary layer that is formed in the stagnation zone directly under the impingement. Royne et al. [105] explored a jet impingement cooling device for arrays of densely packed PV cells. Combined with a model for cell performance at different temperatures, it was found that there exists a broad optimal operating region for any system of photovoltaic cells and cooling device at a given illumination level.

- Phase change material technology

PCMs can stored the excess heat through melting change in phase and at the same time it has a constant temperature during the phase change process. Based on this this feature PV cells can achieve the uniform temperature operation condition. Researchers have used PCMs in different energy conversion systems, including PV systems to maintain a high efficiency [106]. Sharma et al. [107] presented an experimental employing the phase change materials (PCM) to enhance performance of low-concentration Building-Integrated Concentrated Photovoltaic system via thermal regulation. The results showed that the relative electrical efficiency can increase by 7.7% due to PCM incorporation and the module centre temperature has an average reduction of 3.8 °C compare to the naturally ventilated system without PCM.

Here a comparison of the different cooling methods is listed in Table 5.

5. Dual effect

In the realistic use of the CPV systems, the most common situation is that the non-uniform illumination and temperature which have been found to affect the cell efficiency and overall system performance in a negative way are both existed. Non-uniform illumination could produce the significant local heating in concentration solar cells and therefore also cause non-uniform temperature. So the comprehensive effects of them is discussed here.

First the effects on cells in the majority situations due to the non-uniformity are summarized below:

- Increase in cell temperature.
- Increase in series resistance.
- Increase in short circuit current.
- Decrease in open circuit voltage.
- Decrease in fill factor.
- Decrease in efficiency.

It is worth mentioning two points in particular. One is that the short circuit current is hardly affected by non-uniform illumination, but the temperature influence on it is positive, especially in high concentrator photovoltaic systems [19]. Fernández, et al. [108] did the research on the performance of lattice-matched and metamorphic triple junction solar cells under different temperatures and spectral conditions and they also presented the temperature coefficients of the *IV* parameters of different multi-junction (MJ) cells at different concentration ratios [109] and found that the incident spectrum during a spectrometric characterization has a significant influence on Isc and P_{mpp} but only marginal on Voc. Another is there exists a special circumstance that for organic solar cells, the FF and η increase under the localized illumination compared to the uniform one [41]. Maybe people could do further research of this characteristic and make full use of it. Other kinds of solar cells could have some other special characteristics which are worth being explored in the future too.

Luque et al. [110] established a cell model under inhomogeneous illumination which takes into account the temperature inhomogeneity (Fig. 32). It is concluded that the illumination inhomogeneity increased the temperature and the series resistance, therefore reduced the efficiency. But the strong internal ohmic drops will switch off all the poorer parts of the solar cell and leave only the outstanding central part of it, causing the efficiency reduction to be much less of what it might have been expected. Meneses-Rodrígueza et al. [81] studied the simultaneous influence of both the temperature and the illumination (Fig. 33). It can be found that on the whole, the efficiency increased with the increase of the illumination and the decrease of the temperature. So in order to obtain a proper efficiency, it needs to select the proper combination of illumination and temperature. Franklin and Coventry [31] made a contrast among the conditions of uniform illumination and temperature, non-uniform illumination and uniform temperature, and non-uniform illumination and temperature. It can be found that there is a further reduction of V_{oc} when the cell is exposed to non-uniform illumination and temperature. They also pointed out that the cell efficiency η decreases from 17.3% under uniform illumination and temperature, to 16.8% under non-uniform illumination and uniform temperature, and 16.7% under non-uniform illumination and temperature. So it can be conclude that for monocrystalline silicon solar cells, both non-uniform illumination and non-uniform temperature may have a negative impact on the efficiency of the cell and the effect of non-uniform illumination is greater.

Refer to the analysis by Domenech-Garret [45], it can found that both non-uniform illumination and non-uniform temperature will decrease the FF and V_{oc} of the cell model shown in Fig.7. By comparison, the temperature had a greater impact on FF and the illumination played a more important role on V_{oc}.

To compensate for the effects of non-uniform illumination, among the several improvement methods, the changes for cells have smaller benefits and the cost may be larger. The design for concentrator can lead to considerable modification which could provide significantly enhancement on FF and the cost is much lower. The concentrator can be improved from the material, the processing technology, the concentrating way and so on.

At the same time, under these negative influence, the cell temperature is considered to increase a lot, and the solutions to the problem, especially the cooling methods, are discussed above in Section 4.3. It can be concluded that a reasonable cooling system design is significant in CPV systems. A good cooling system can not only reduce cell temperature, but also decrease the negative influence of non-uniform illumination and cell temperature. Among all the cooling methods, they each have their own advantages and disadvantages. The traditional cooling methods are more mature, the air cooling technology is mainly used on single cell and the water cooling technology is used in LCPV systems which has a better cooling effect. For the new cooling methods, micro-channels technology and impingement jet cooling technology are used for HCPV systems for their high heat transfer coefficient. While heat pipe cooling technology has a wide scope of application and liquid immersion cooling technology can be applied in linear concentrating systems for its good heat-sinking capability.

6. Conclusion

In this paper, the performance of concentrator cell under non uniform illumination and temperature and the improvement methods have been presented. An overview of concentrating solar cells is introduced. Nowadays, solar cells have a widely use in CPV systems and have lots of differences with each other. And when these cells are used to investigate the effect of non-uniformity, models need to be established by using theoretical and finite element methods in 1-D, 2-D or 3-D.

The non-uniform illumination can be caused by the concentrator design, the improper relative position of the solar cell etc. It displays in two aspects of localized illumination and the inhomogeneous of the whole cell. And it can lead to an obvious decrease in open circuit voltage, fill factor and efficiency, especially for multi-junction solar cells. These problems can be partially solved by changing cell surface pattern, choosing proper cell material and concentrator. Non-uniform temperature is mainly caused by the non-uniform illumination, and other factors such as the arrangement of the cell among a cell pack, and the cooling mechanism etc. The greatest danger of it is the local excessive temperature which cause decrease in the open circuit voltage, the fill factor and the efficiency. Particularly, the short circuit current will increase with the increased temperature, especially in HCPV systems. People often use different cooling technology to reduce this influence. However, in reality, these two cases are usually co-exist, scientists can search for the influence of various parameters further by experiments to seek a better solution to reduce the influence of the non-uniformity.

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Figure captions

Fig.1. $I-V$ curves for uniform and non-uniform illumination of a solar cell

Fig.2. A comparison between the key parameters of uniformly and localized illuminated cells: (a) I_{sc}, (b) V_{oc}, (c) FF, and (d) PCE(η)

Fig.3. Rough illumination profile related to a Gaussian distribution

Fig.4. Simulated $I-V$ Curves: average concentration ratio = 22.7, average temperature = 69°C

Fig.5. Open circuit voltage and efficiency variation with peak illumination intensity

Fig.6. (a) Fill factors and (b) cell efficiencies of cells simulated under Gaussian illumination profiles

Fig.7. Open circuit voltage of cells simulated under Gaussian illumination profiles

Fig.8. Sketch of the cell element used in the model

Fig.9. Comparison of the $I-V$ curves of a cell under three conditions

Fig.10. $I-V$ curves related to multi-junction (MJ) solar cell under uniform and non-uniform illumination

Fig.11. FF under uniform and non-uniform conditions depend on incident light intensity

Fig.12. Calculated $I-V$ curves under non-uniform flux. The solid lines correspond Gaussian-distributed flux density. The dotted lines correspond uniform flux

Fig.13. Shading scenarios: (a) Vertical shading; (b) Horizontal shading; (c) Diagonal shading

Fig.14. (a) current–voltage curve and (b) power–voltage curve of poly-crystalline PV

module under horizontally shading process

Fig.15. Circuit diagrams

Fig.16. LGBC technology structure of solar cell

Fig.17. Influences of synthesized chromatic aberration of 3-junction solar cell

Fig.18. (a) Structure of mirror CPC, (b) Structure of lens-walled CPC

Fig.19. Structure of lens-walled CPC with air gap

Fig.20. An example of cell temperature profile depend on cell position

Fig.21. Cell temperature and cell efficiency for a typical day of summer

Fig.22. Differences in the efficiency under various temperature of the multi-junction cell

Fig.23. The performance of (a) $I-V$ curves, (b) cell parameters under different temperatures

Fig.24. The relationship of temperature and (a) V_{oc} (b) I_{sc} (c) FF (d) conversion efficiency η of InGaP/InGaAs/Ge triple-junction solar cells

Fig.25. The $I-V$ curves of the investigated modules

Fig.26. The module's electrical parameters dependent on temperature

Fig.27. Open circuit voltage V_{oc}, fill factor FF and efficiency η of the $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction cell at different temperatures

Fig.28. Comparison of the $I-V$ curves of a cell under three conditions

Fig.29. Cooling structure of the PV module

Fig.30. Heat pipe based cooling system

Fig.31. A cross-sectional view of a portion of the microchannel heat sink

Fig.32. Schematic of the cell grid for series resistance calculations

Fig.33. Efficiency of solar cells under simultaneous influence of temperature and solar concentration

Table captions

Table 1.The causes of non-uniform illumination

Table2. Cell parameters under 12 suns uniform illumination

Table 3. Comparison between uniform and non-uniform illumination.

Table 4. Comparison between uniform and non-uniform temperature.

Table 5. Comparison of different cooling methods.

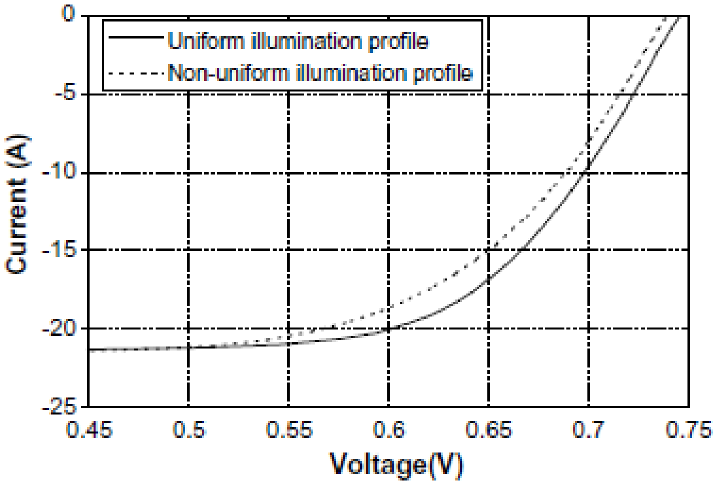

Fig.1. $I - V$ curves for uniform and non-uniform illumination of a solar cell [40].

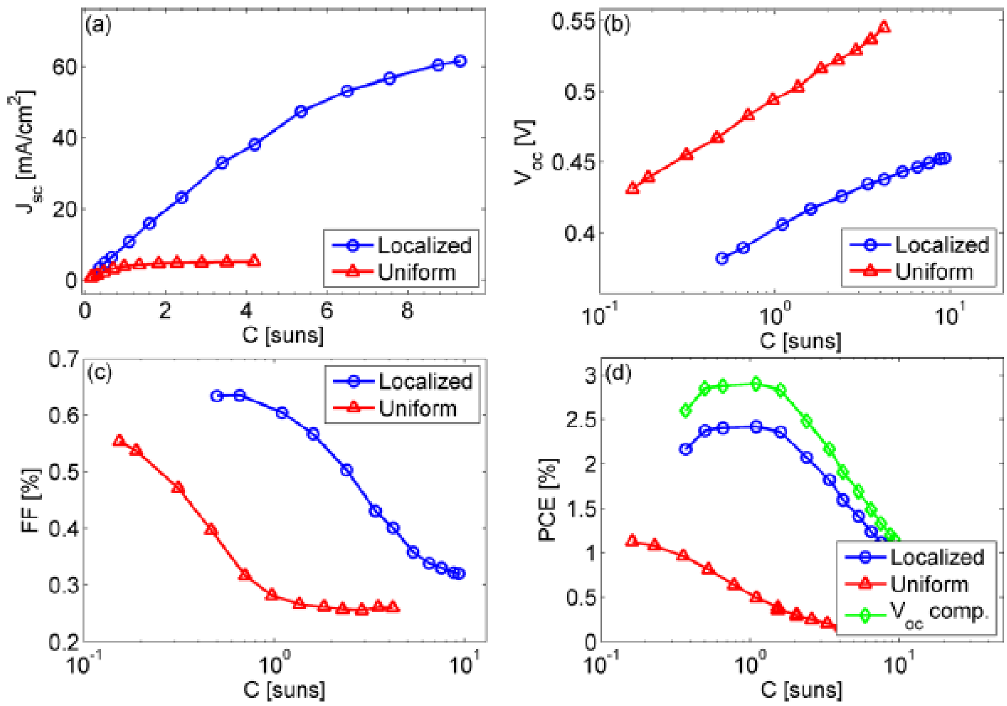

Fig.2. A comparison between the key parameters of uniformly and localized illuminated cells: (a) I_{sc}, (b) V_{oc}, (c) FF, and (d) PCE(η) [42].

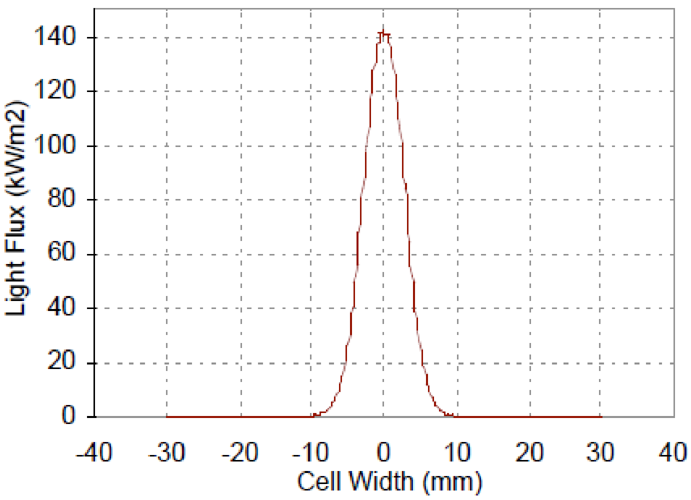

Fig.3. Rough illumination profile related to a Gaussian distribution [45].

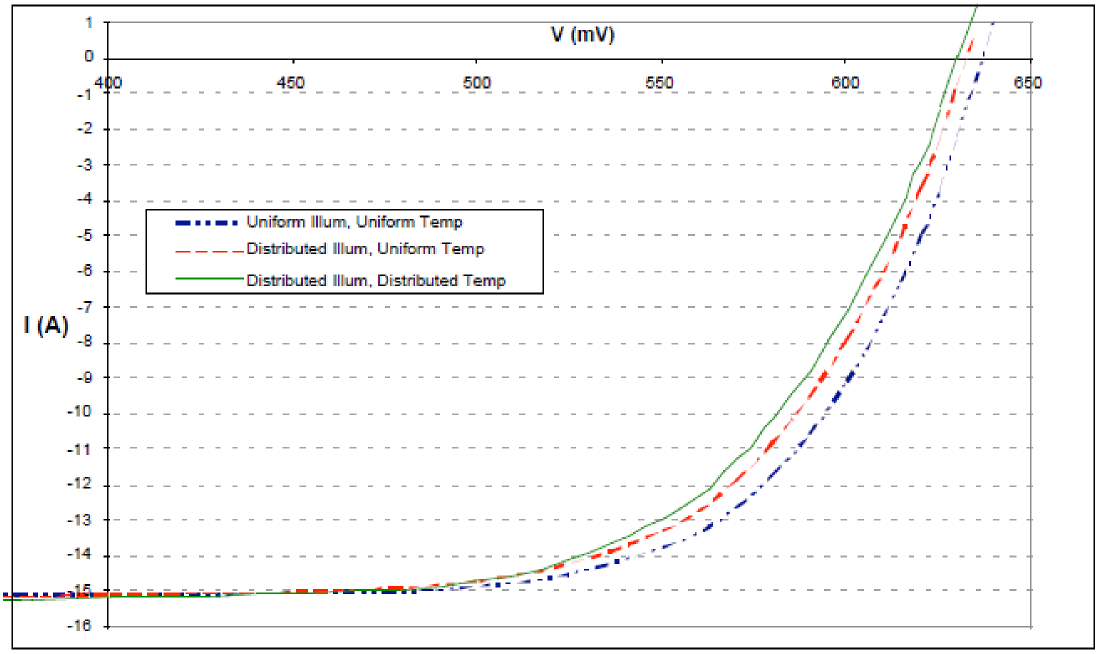

Fig.4. Simulated $I-V$ Curves: average concentration ratio = 22.7, average temperature = 69°C [31].

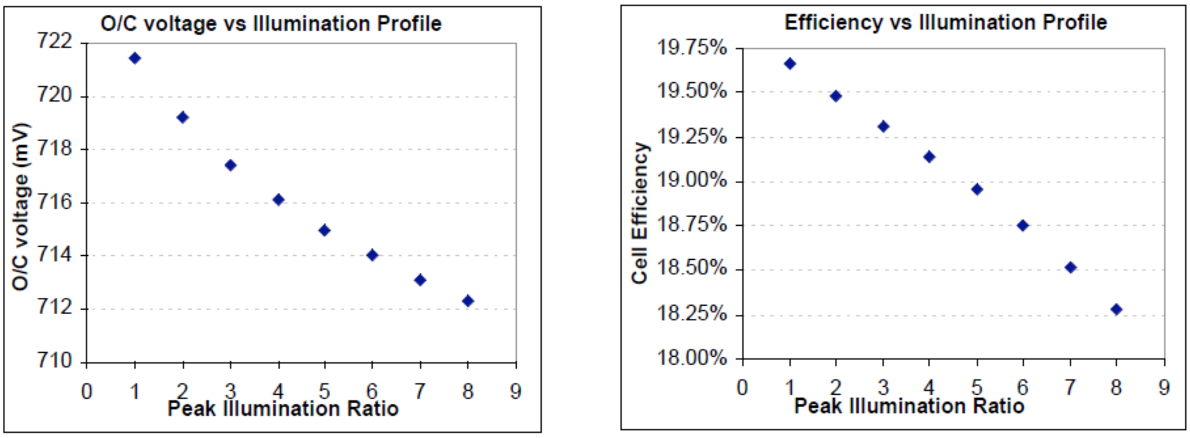

Fig.5. Open circuit voltage and efficiency variation with peak illumination intensity [31].

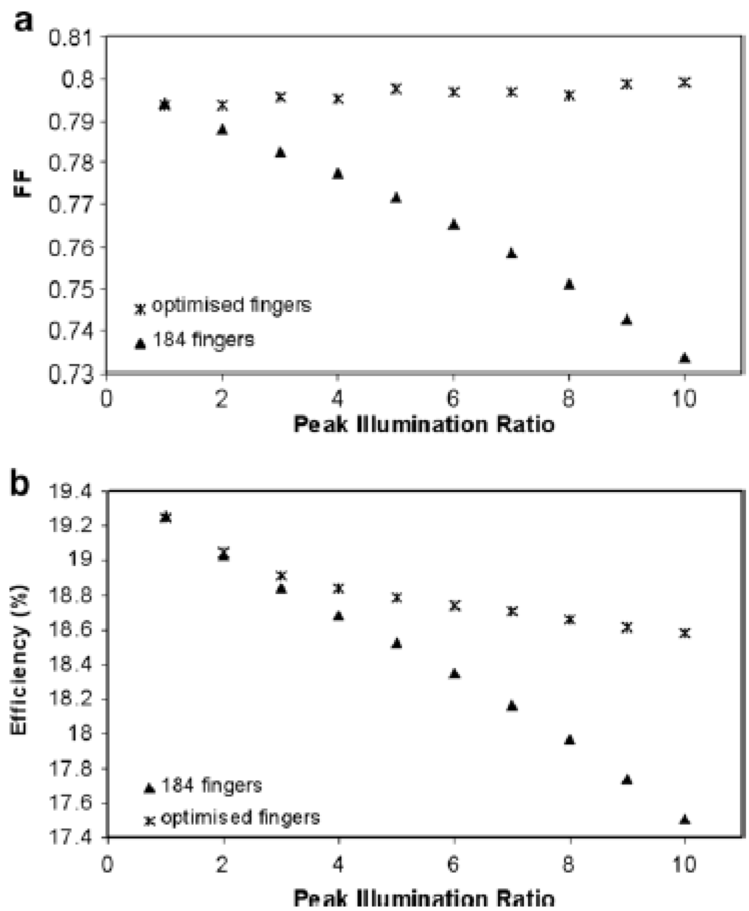

Fig.6. (a) Fill factors and (b) cell efficiencies of cells simulated under Gaussian illumination profiles [32].

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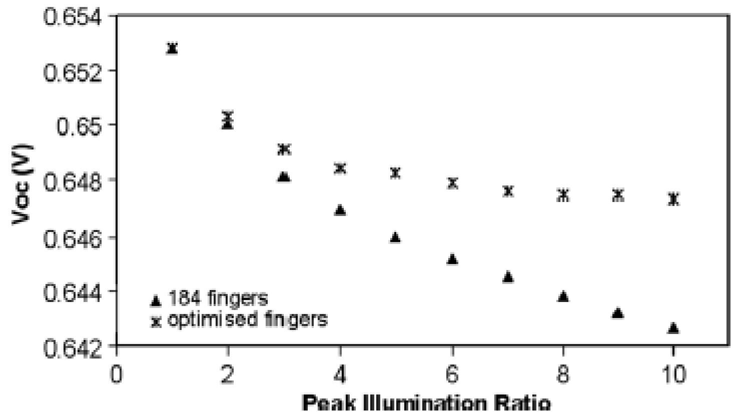

Fig.7. Open circuit voltage of cells simulated under Gaussian illumination profiles [32]

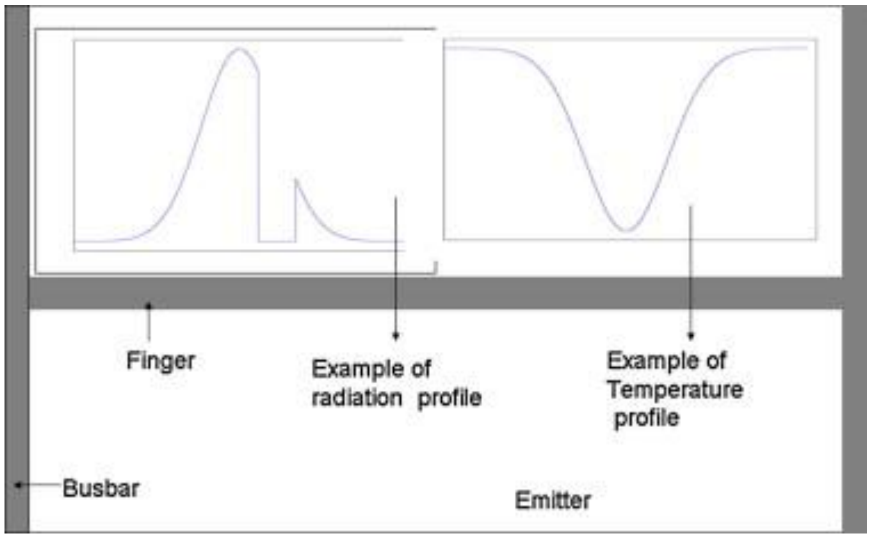

Fig.8. Sketch of the cell element used in the model [32].

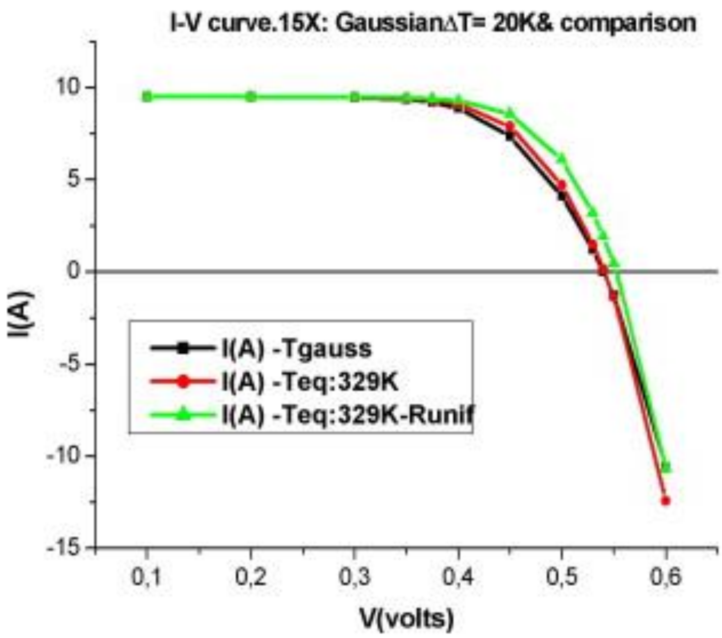

Fig.9. Comparison of the $I-V$ curves of a cell under three conditions [45].

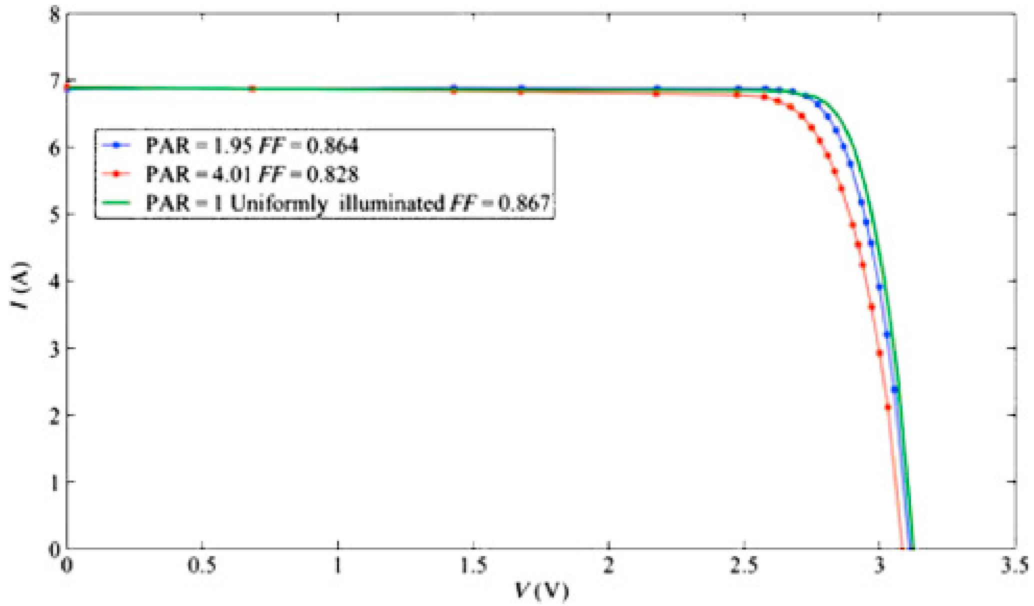

Fig.10. $I-V$ curves related to multi-junction (MJ) solar cell under uniform and non-uniform illumination [44].

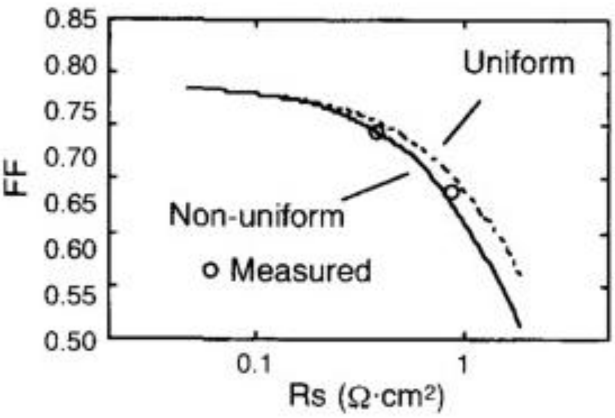

Fig.11. FF under uniform and non-uniform conditions depend on incident light intensity [47].

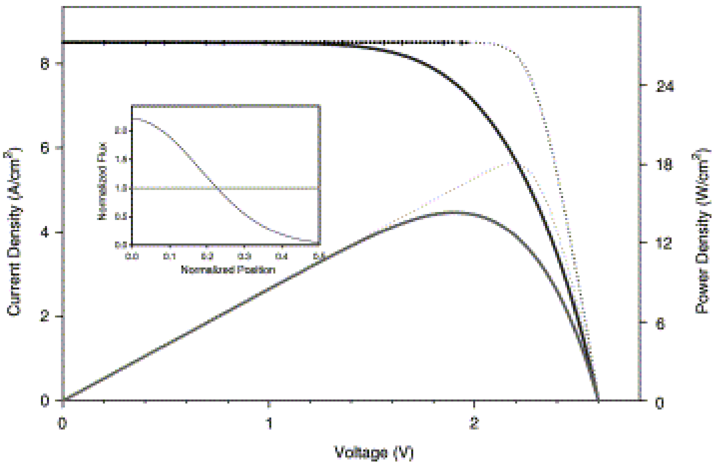

Fig.12. Calculated $I-V$ curves under non-uniform flux. The solid lines correspond Gaussian-distributed flux density. The dotted lines correspond uniform flux [48].

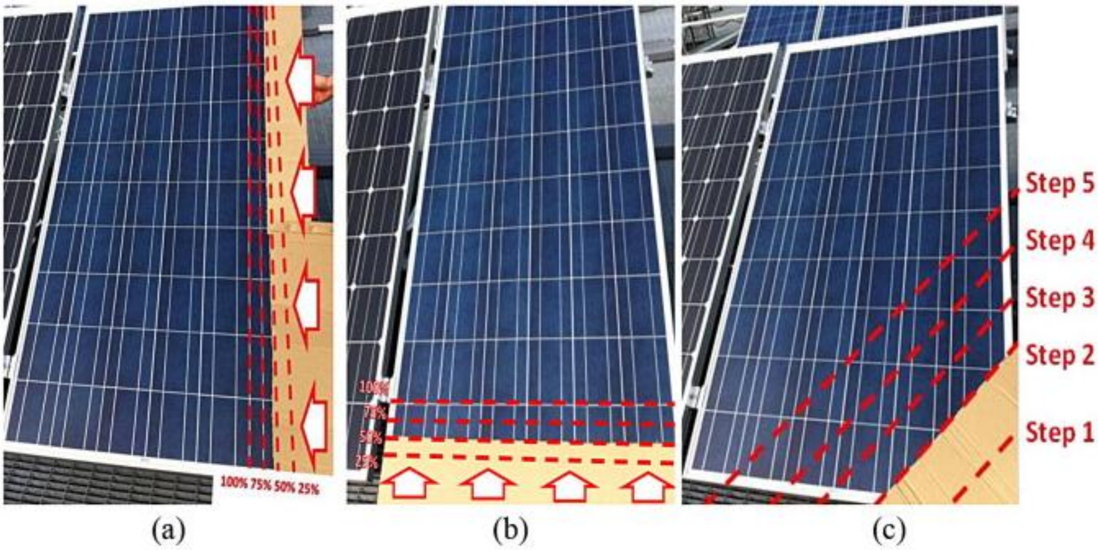

Fig.13. Shading scenarios: (a) Vertical shading; (b) Horizontal shading; (c) Diagonal shading [51].

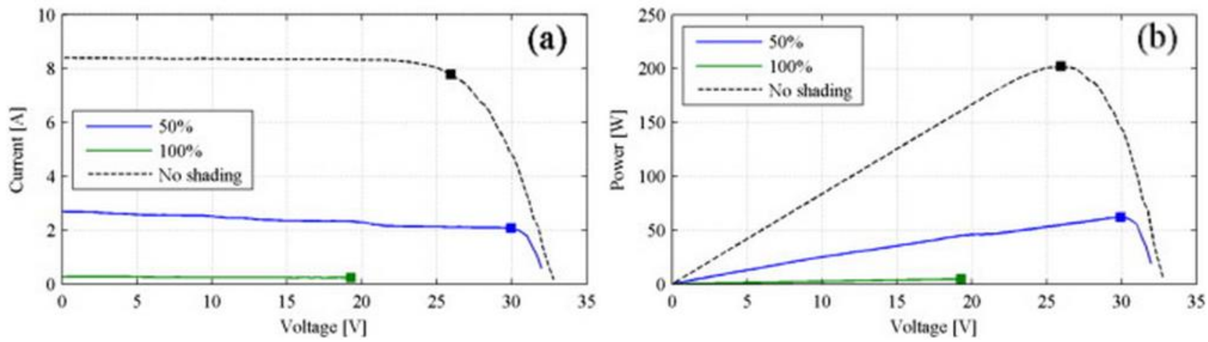

Fig.14. (a) current–voltage curve and (b) power–voltage curve of poly-crystalline PV module under horizontally shading process [51].

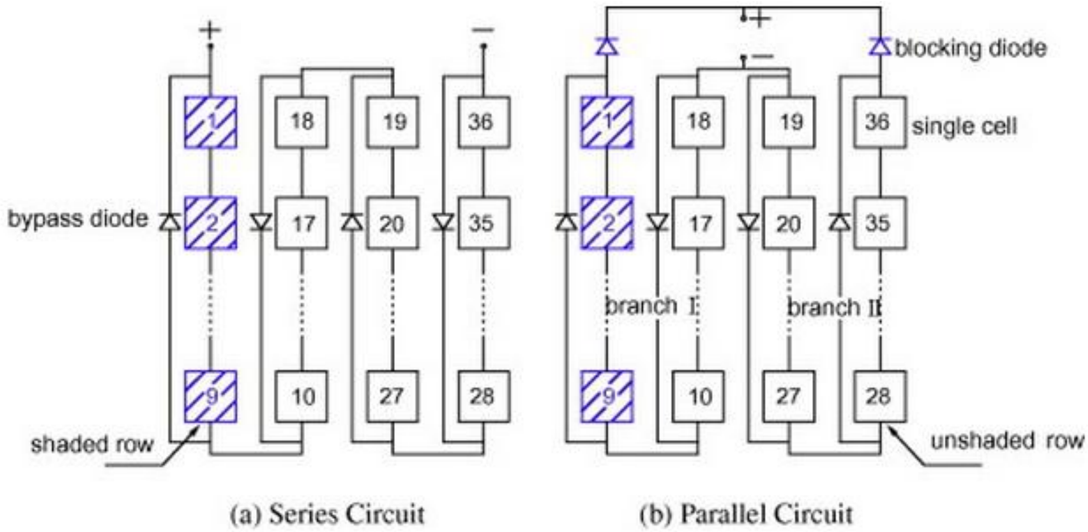

Fig.15. Circuit diagrams [52].

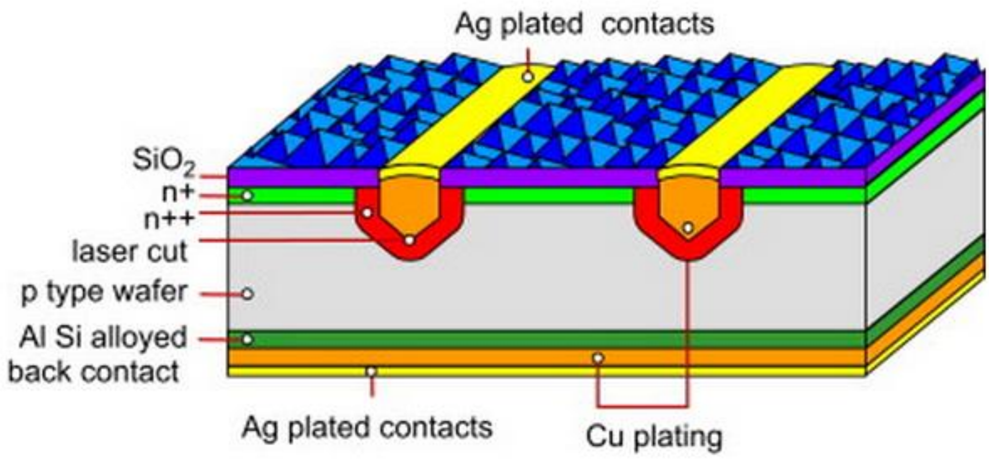

Fig.16. LGBC technology structure of solar cell [54].

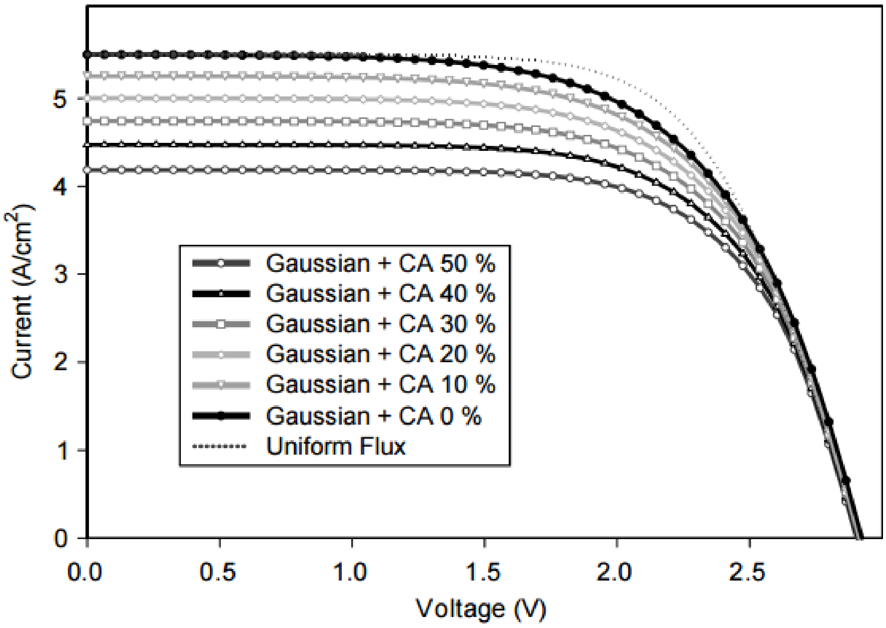

Fig.17. Influences of synthesized chromatic aberration of 3-junction solar cell [48].

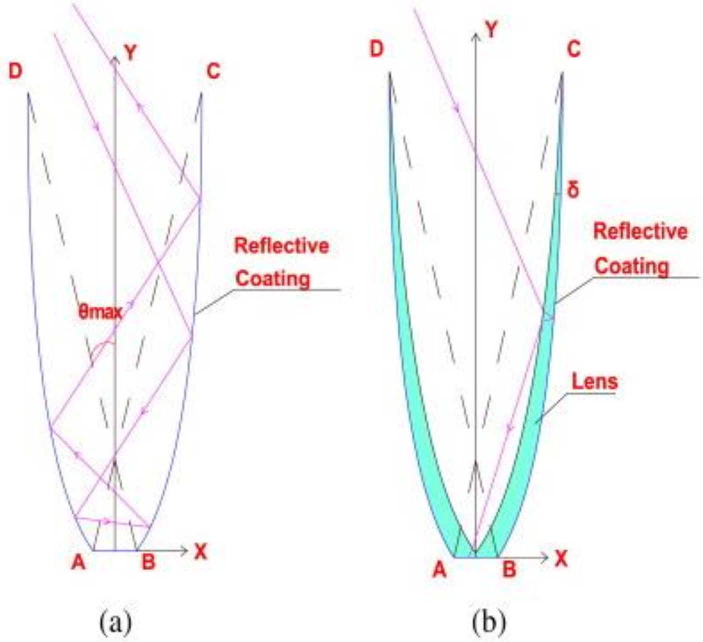

Fig.18. (a) Structure of mirror CPC, (b) Structure of lens-walled CPC [66].

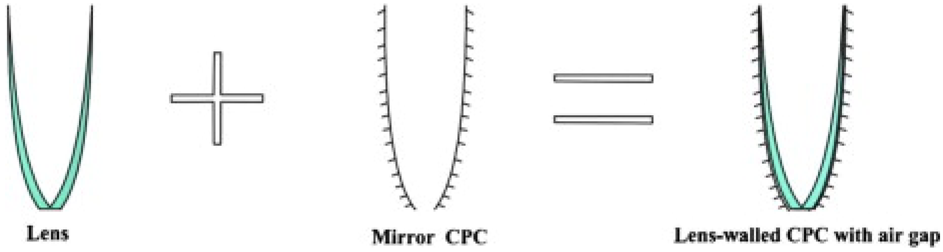

Fig.19. Structure of lens-walled CPC with air gap [70].

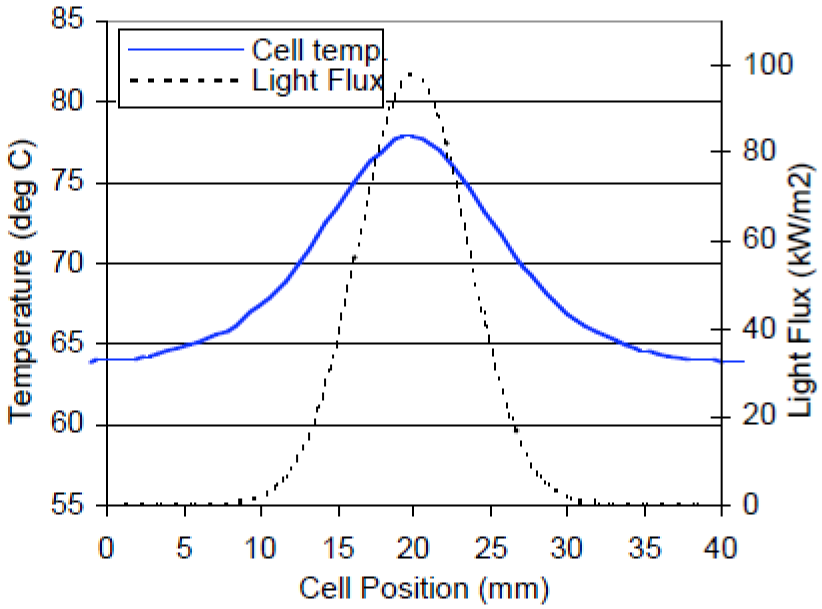

Fig.20. An example of cell temperature profile depend on cell position [31].

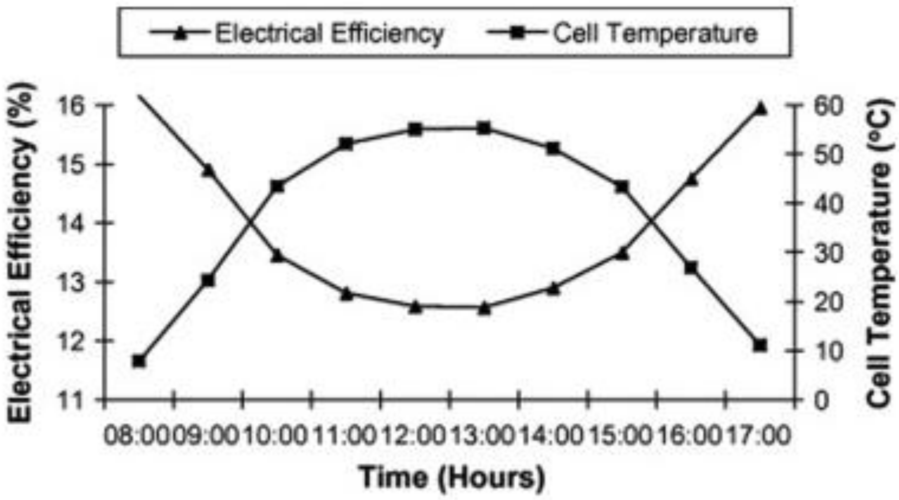

Fig.21. Cell temperature and cell efficiency for a typical day of summer [79].

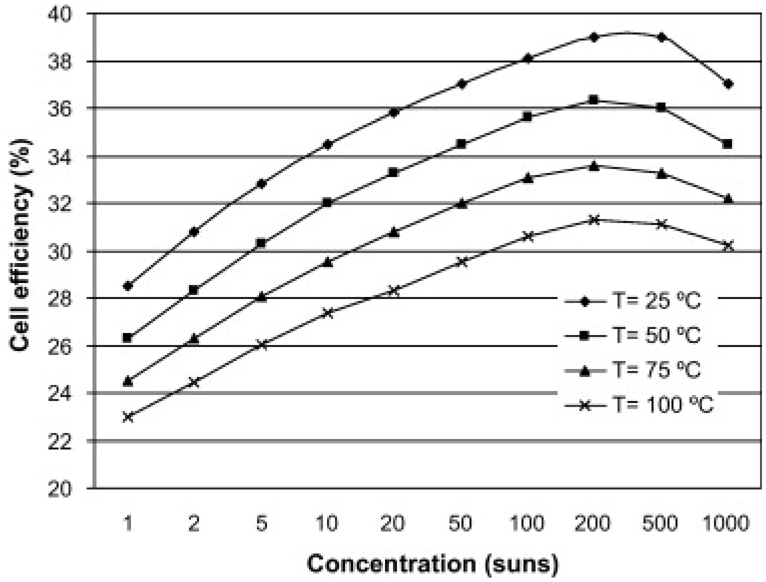

Fig.22. Differences in the efficiency under various temperature of the multi-junction cell [19].

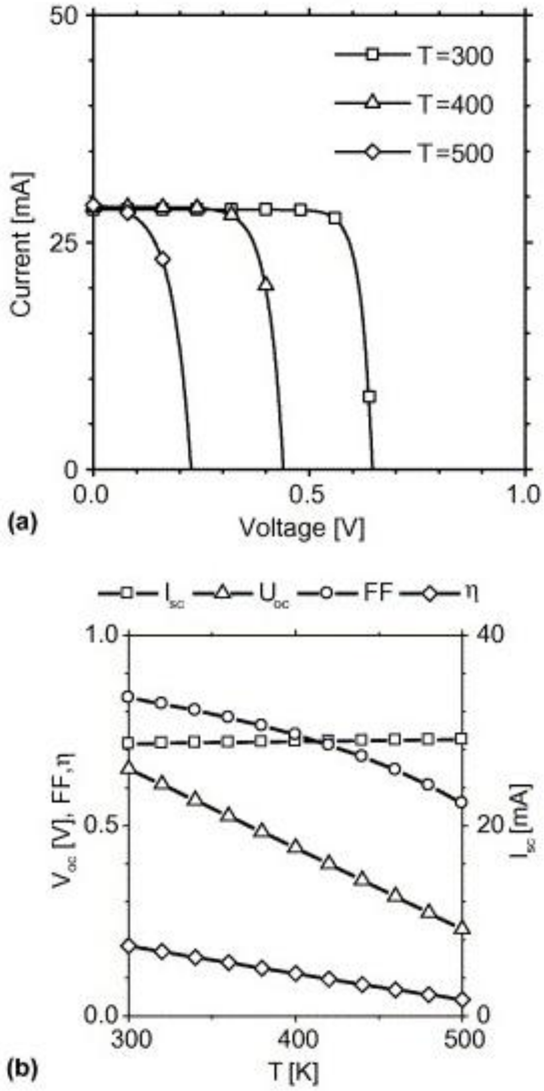

Fig.23. The performance of (a) $I-V$ curves, (b) cell parameters under different temperatures [81].

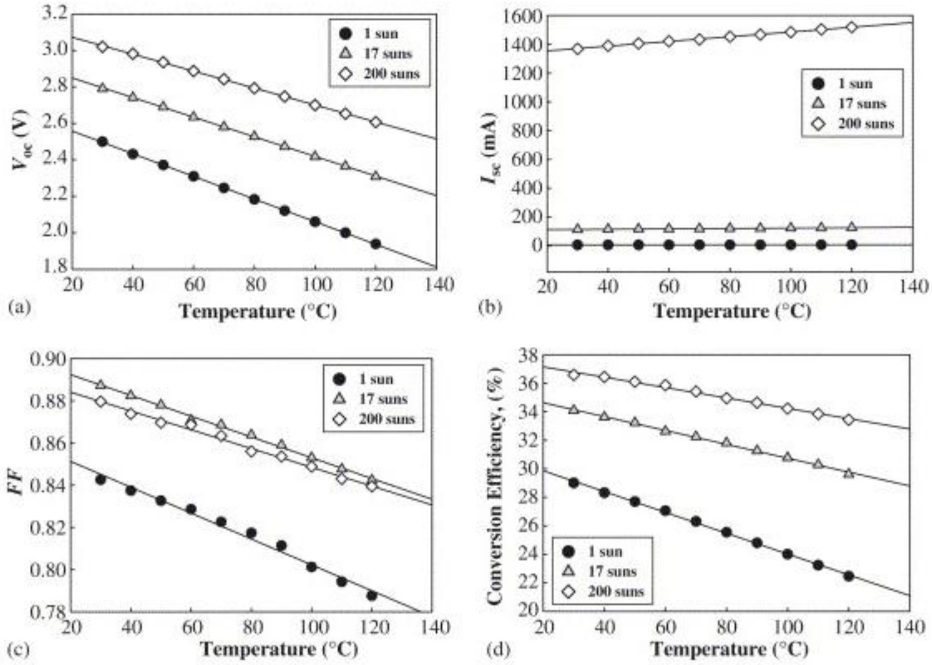

Fig.24. The relationship of temperature and (a) V_{oc} (b) I_{sc} (c) FF (d) conversion efficiency η of InGaP/InGaAs/Ge triple-junction solar cells [56].

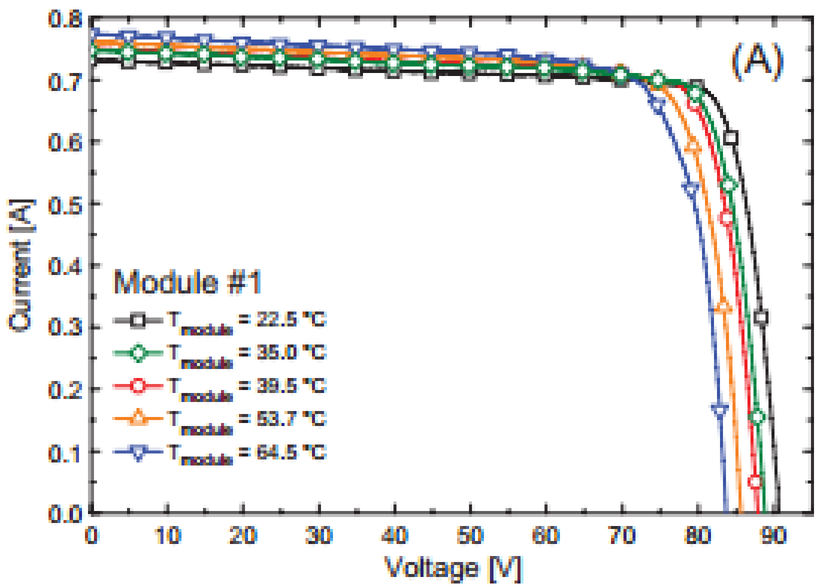

Fig.25. The $I-V$ curves of the investigated modules [82].

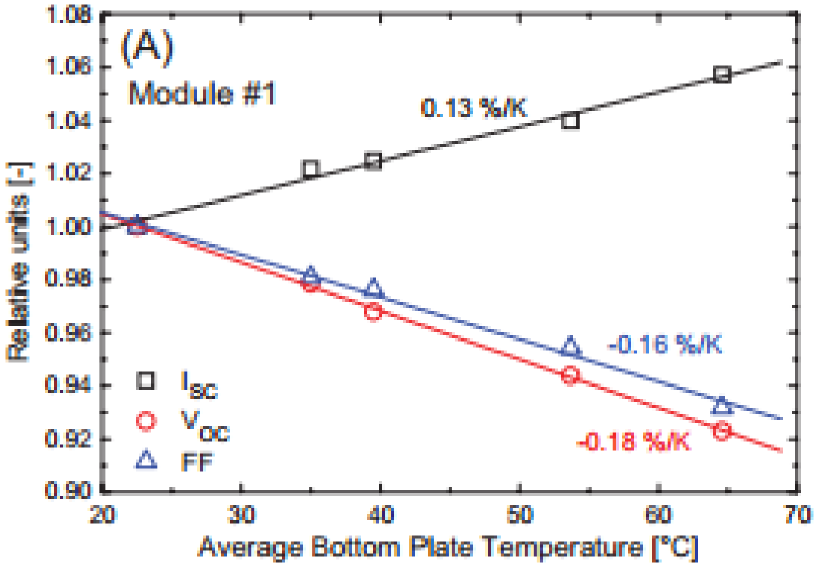

Fig.26. The module's electrical parameters dependent on temperature [82].

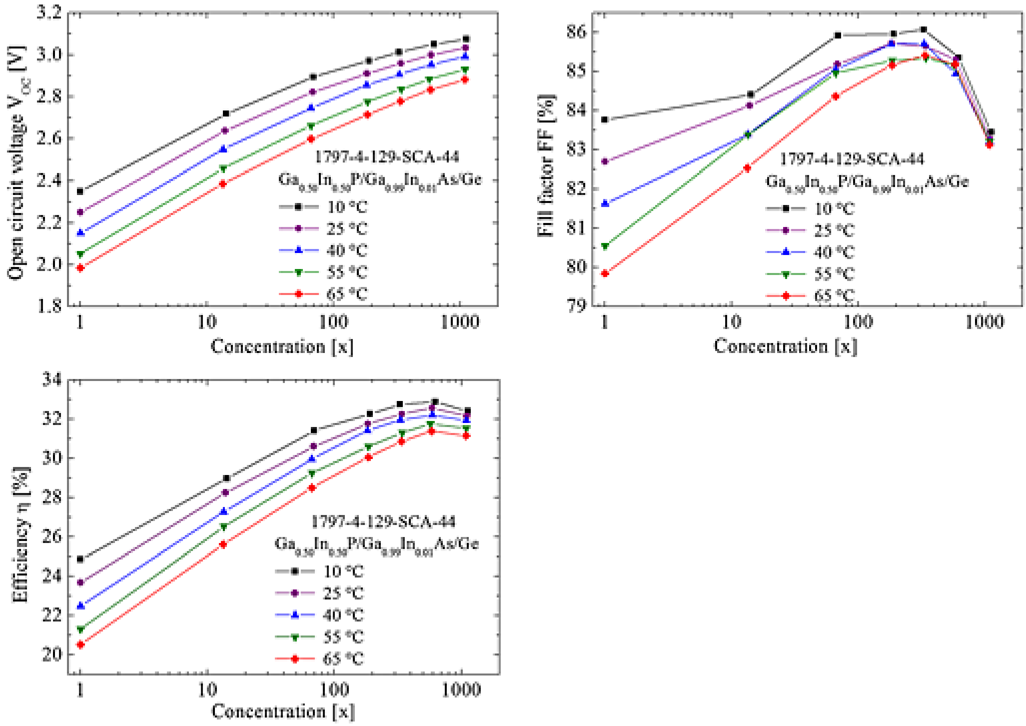

Fig.27. Open circuit voltage V_{oc}, fill factor FF and efficiency η of the $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction cell at different temperatures [84].

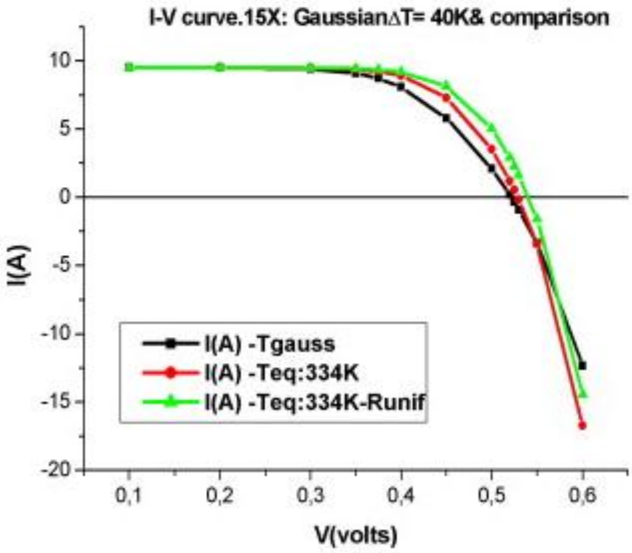

Fig.28. Comparison of the $I-V$ curves of a cell under three conditions [45].

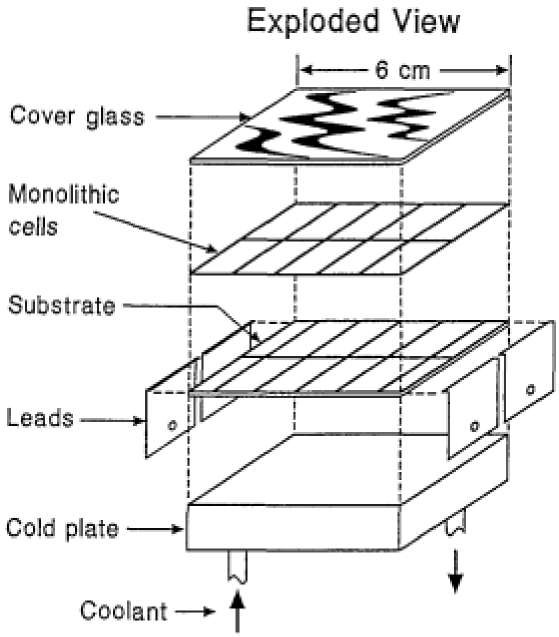

Fig.29. Cooling structure of the PV module [95].

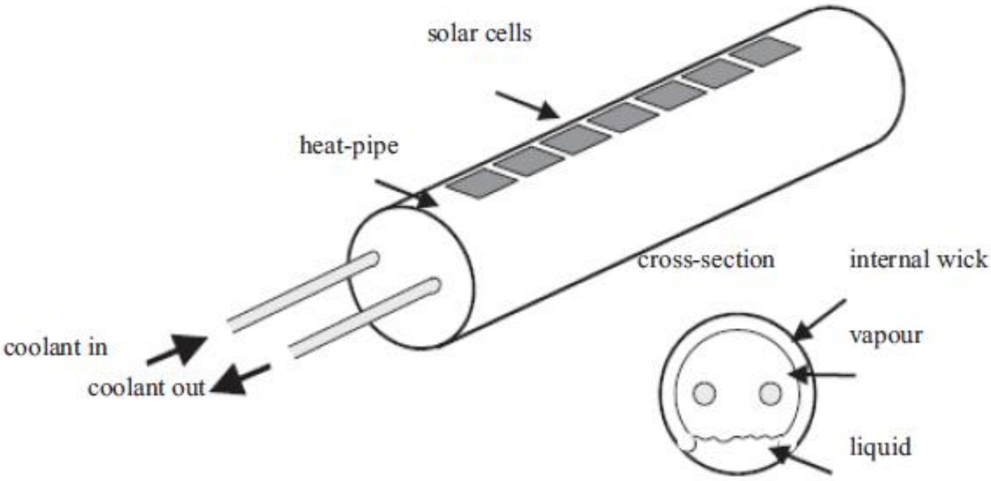

Fig.30. Heat pipe based cooling system [90].

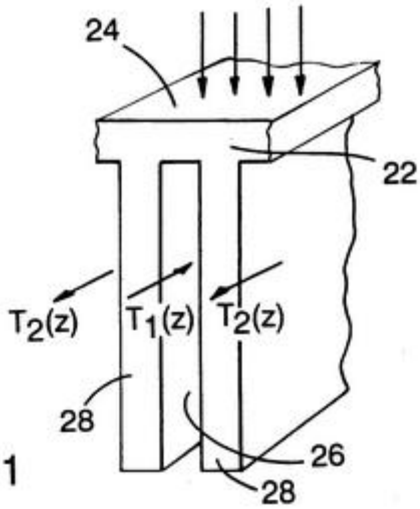

Fig.31. A cross-sectional view of a portion of the micro-channel heat sink [101].

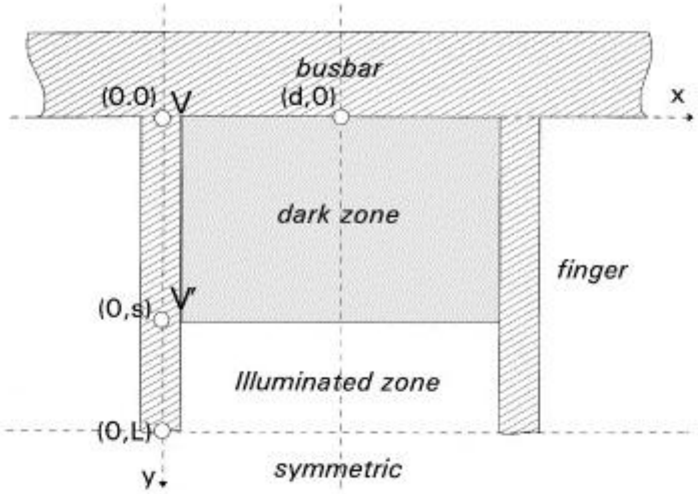

Fig.32. Schematic of the cell grid for series resistance calculations [110].

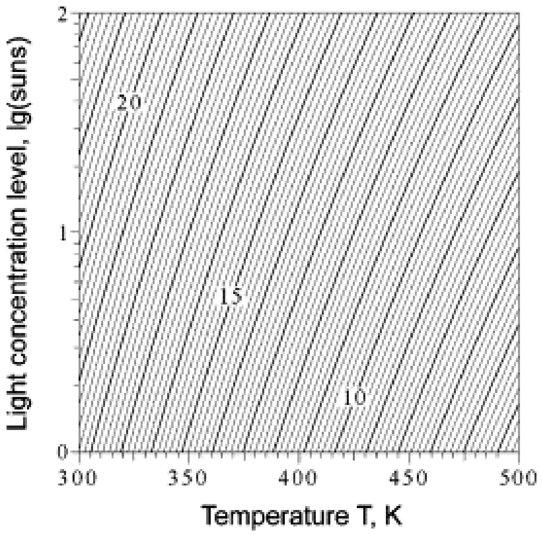

Fig.33. Efficiency of solar cells under simultaneous influence of temperature and solar concentration [81].

Table 1.The causes of non-uniform illumination [31], [35], [37] and [38].

Causes	Concentrator design	Relative position of the solar cell and the sun	Other factors
1	Unreasonable design	Improper tracking system	Shading
2	Material	Deviation of optics and cell	Spectral response
3	Profile errors	(the cell isn’t in the right	
4	Manufacturing problems	position of the optics’	
		absorbers)	

Table2. Cell parameters under 12 suns uniform illumination [32].

IV characteristics for cell simulated under 12 suns uniform illumination	
I_{sc}	20.97A
V_{oc}	0.65V
FF	0.79
Efficiency	19.25%

Table 3. Comparison between uniform and non-uniform illumination.

Researcher	**Type of cell**	**Type of PV system**	**Cell parameters**				**Key findings**
			I_{sc}	V_{oc}	FF	η	
Coventry [39]	monocrystalline silicon	LI, CPV90×, middle third	-	6.5 mV reduction	-	1.2% reduction	Reductions are unavoidable without secondary

		of cell					flux modifier.
Katz, et al.[41]	GaInP2/GaAs/Ge triple-junction uniform front metallization	LI, illuminated fraction: 0.00785	no obvious change	0.09V reduction under $P_{in}=8W$	0.2 reduction under $P_{in}=8W$	8% reduction under $P_{in}=8W$	The position of the LI on cell have little influence on FF.
Manor A, et al.[42]	organic cell	LI, non-CPV to CPV10×	increase, linear growth	decrease, reduction almost be same	decrease, largest at CPV1×, 0.3	decrease, largest at CPV1×, 2%	LI of different part over the cell area gave identical results.
Franklin and Coventry [31]	distributed resistance, cell model	Gaussian illumination, Average concentration ratio of 22.7	-	5mV reduction	-	0.5% reduction	Reductions become larger with increasingly centralized illumination profile.
Mellor, et al.[32]	two-dimensional, front surface currentflow, cell model	Gaussian illumination, mean illumination intensity CPV12×	-	0.007V reduction under PIR of 10	0.06 reduction under PIR of 10	1.7% reduction under PIR of 10	Increasing the number of fingers of the front contact can mitigate the decrease in each parameters.
Domenech-Garret [45]	silicon monocrystalline ASE solar cell	Gaussian illumination, CPV15×	-	10mV reduction	0.01 reduction	-	The illumination profile spoils the fill factor.
Herrero, et al.[44]	multi-junction	Gaussian illumination	-	-	0.003 reduction under PAR of 4.01	-	Reduction is due to an increase in series resistance and lead to efficiency decline.
Algora [46]	3-D, distributed circuit units, cellmodel	average illumination CPV1000×	-	slight decrease	0.003 under good contact, 0.059 under medium contact	0.4%under good contact, 1.63% under medium contact	The worse the quality of the front contact, the greater the decrease in both FF and V_{oc}.
Goma, et al.[47]	c-Si	CPV, different incident light intensity	-	-	0.03 reduction	-	To reduce the effect of concentration distribution, it is necessary to control the R_s.
Araki, et al.[48]	AlGaAs/GaAs 2-junction	Gaussian illumination CPV500×	-	-	significant reduction	-	FF can be partially recovered by chromatic

							aberration.
Pozner, et al.[50]	monolithic silicon, vertical multi-junction	non-uniform, by parabolic dish concentrator	-	-	-	-	Dense array CPV modules based on VMJ cells connected in parallel feature very low sensitivity to non-uniform illumination.

Table 4. Comparison between uniform and non-uniform temperature.

Researchers	**Type of cell**	**Type of PV system**	**Cell parameters**				**Key findings**
			I_{sc}	V_{oc}	FF	η	
Meneses -Rodríguez, et al.[85]	crystalline silicon	CPV, elevated temperature	no obvious change	0.4 V reduction from 300K to 500K	0.25 reduction from 300K to 500K	6% reduction from 300K to 500K	Reduction of efficiency is mainly due to the reduction of the V_{oc} and FF, the influence of the current value could be neglected.
Nishioka, et al.[56]	InGaP/InGaAs/Ge triple-junction	CPV, elevated temperature	slight increase under 200 suns	0.4 V reduction under 200 suns	0.04 reduction under 200 suns	3% reduction under 200 suns	This solar cells have an advantage over crystalline-silicon solar cells under high-temperature conditions.
Peharz, et al.[86]	GaInP/GaInAs/Ge triple-junction	CPV, elevated temperature	increase of 0.13A%/K	decrease linearly by 0.18V%/K	decrease of 0.16%/K	decrease of 0.1%/K	The temperature dependence of Fresnel lenses and thermal expansion of the CPV modules will reduce the positive short circuit current.
Siefer, et al.[84]	GaInP/GaInAs/Ge triple-junction	CPV, elevated temperature	-	-	-	decrease	The main reason for the decline is that the open circuit voltage will

							decrease when operated at a high temperature under concentration.
Domenech-Garret [45]	silicon monocrystalline ASE solar cell	Gaussian temperature profile	-	18mV reduction	0.03 reduction	-	The increasing and uneven temperature both have an effect on cell parameters.

Table 5. Comparison of different cooling methods

Types of cooling method	Characteristics	Researchers	Type of system	Working principle	Key findings
Air cooling technology	Air can take heat away to keep cell's temperature in a low level by convection passively or actively from the back of the solar cell.	Hussain, et al.[93]	Enerworks Heat Safe (EHS) residential solar collector integrated with a back mounted air channel.	Ambient air was introduced between the absorber plate and the back insulation thereby allowing the natural convection cooling of the collector absorber plate	A solar collector integrated with a well designed back mounted air cooling channel and a control valve at the outlet opening would be able to provide suitable heat transfer rates
		Araki, et al. [94]	500 X concentrator module made by printed epoxy and copper sheet on aluminum plate.	Aluminum plate was used to attached to the solar cell which diffused heat at the concentrated region and transferred the heat into the air.	Good thermal contact between solar cell and aluminum plate is the key to keep the concentrator low temperature.
Water cooling technology	Water cooling offers a good performance because of its high convection coefficient and thermal capacity.	Verlinden, et al [95]	Monolithic silicon concentrator module consisted of 10 cells	Monolithic PV module was mounted on a cold plate of the same size, and the heat generated by the solar cells was absorbed by the coolant in the cold plate.	The module got a 0.8% growth of efficiency when operated at 25°C compared to 39°C.
		Verlinden etal. [96]	250 X reflective parabolic dish whose receiver is composed of 16 modules, each with 24 series-connected silicon solar cells.	The PV modules were laminated onto the ceramic substrate and ceramic substrate was attached on a water cold plate for active cooling.	The cell efficiency can reach 24% and the system comprehensive energy utilization efficiency can surpass 70%.

Heat pipe cooling technology	Heat pipes are high heat flux transformation devices and has a good temperature performance at the same time. One end is stick to the solar cell and absorb the heat, and another is exposed to cooling environment	Tarabsheh, et al. [99]	PV string with the cooling pipes beneath it.	The module is cooled by a fluid flowing through pipes underneath the PV module backside. The fluid serves as both heat sink and solar heat collector.	Implementing cooling pipes underneath each PV string improves the performance of the PV cells
Micro-channels technology	Small size and it can directly cool the millimeter level heat source, but the temperature gradient and the pressure loss is large.	Missaggia and Walpole [101]	Alternating-channel-flow micro-channel heat sink.	The micro-channel heat sink was used by making the thermal contact between the device and the heat sink and the coolant will absorber and remove the heat.	It can reduce the surface temperature variations compared to a conventional one with one-directional flow.
		Yang and Zuo [102]	CPV cells with multi-layer manifold microchannel cooling system.	The water was filled in the manifolds, and then was forced to flow into microchannels and took waway the heat from heat sources.	surface temperature difference of the CPV cell was below 6.3 C and multi-layer manifold microchannel had a heat transfer coefficient of 8235.84 W/m2 K and its pressure drop was lower than 3 kPa.

Liquid immersion cooling technology	Liquid immersion cooling involves the immersion of solar cells directly into the circulating liquid and the heat is absorbed by the circulating coolant form both the front and back surface of the PV string [7].	Liu, et al. [103]	Common silicon cells 2CR immersed into a dielectric liquid.	The direct-contact heat transfer between both the front and back surfaces of the module and the dielectric liquid.	The temperature distribution of cell module is fairly uniform within 3 ℃ under turbulent flow mode under the condition that heat is removed from both the back and front of the panel in a dielectric fluid.
Impingement jet cooling technology	Impingement jet cooling technology can obtain the low thermal resistance and has been widely used in many industrial fields at present [95].	Royne, et al. [105]	Arrays of densely packed PV cells.	Liquid was drained in a direction normal to the heated surface around the edges of the central array of jets.	A broad optimal operating region for any system of photovoltaic cells and cooling device at a given illumination level was found.
Phase change material technology	PCMs, also called latent heat storage devices with a constant temperature during the phase change process which can result in the PV surface to be remained at uniform temperature.	Hasan, et al. [106]	Building integrated photovoltaics.	Excess heat is absorbed by PCMS during melting change in phase from solid to liquid at a stable transition temperature thus to regulate the temperature of the PV.	A maximum temperature reduction of 18 ℃ was achieved for 30 min while 10 ℃ temperature reduction was maintained for 5 h at 1000 W/m2 insolation.
		Sharma, et al [107]	Building-Integrated Concentrated Photovoltaic (BICPV) systems	Excess heat is absorbed by PCMS during melting change in phase from solid to liquid at a stable transition temperature thus to regulate the temperature of the PV.	An increase in relative electrical efficiency by 7.7% with PCM incorporation. An average reduction in module centre temperature by 3.8 ℃ was recorded in the BICPV–PCM integrated system as compared to the naturally ventilated system without PCM.