The influence of irradiance concentration using an asymmetric reflector on the electrical performance of a PVT hybrid collector with standard monocrystalline cells

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Abstract

The objective of this thesis was to study the effect on a concentrating photovoltaic-thermal (CPVT) collector caused by a non-homogeneous radiation, specifically on the electrical performance. In order to accomplish the objective of this work, it was implemented a mating model using a raytrace software and two electric models using the one diode model with 5 parameters and with 3 parameters. The model divides the whole solar cell into small elements considering each of this elements as a unique solar cell, which in the case of the higher number of divisions the small elements has an area of 0.65mm^2. Some simulations were carried out changing the number and size of the elements, comparing the results with the experimental values obtained by a CPVT from the company Solarus. It was demonstrated that increasing the number of elements will lead to a power closer to the measured one. The solar cell will work at different temperatures due to the non-homogeneous radiation, thus, the integration of a thermal model is necessary and the approach employed was to test different discrete temperature levels and analyse the sensibility of the models to the temperature. It was observed that a higher variation of temperature will lead to a power reduction. This is because the zone where most of radiation reaches is at a higher temperature than expected. It was seen that a variation in temperature of 15°C and 20°C will lead to a poor forecast of the power. A non-homogeneous radiation affects the I-V curve, specifically the fill factor, which is translated in a reduction of the maximum power. However, this decrease, for this experimental tested conditions, does not exceed 1.3% in relation to an homogeneous irradiance.

Keywords: non-homogeneous radiation, hybrid PVT, electrical PV cells models, electrical PV performance.

1 Introduction

The objective of this project is to determine how the non-homogeneous radiation affects the electric performance of a collector, particularly, a CPVT collector. It is necessary to measure the distribution of energy that can be concentrated by a collector. In this sense, the use of raytrace software will help to cover this topic. It is difficult to obtain experimental data on the distribution of the irradiance on the solar cells. Therefore, the use of a model can be an useful analysis tool which results can be compared with experimental data to validate it. Then, a previous objective to the main goal is to generate a proper model to simulate the collector behaviour, forecasting the power, current and voltage for a given conditions. The collector that is subject of study in this thesis is a CPVT collector from Solarus Sunpower B.V. Its collector was designed and tested in Sweden (Solarus Sunpower B.V., 2015).

Table 1: Comparison between raytrace software

	Interface Design	**Price**	**Post-processing**	**Material Libraries**
TracePro	Excellent	N/A	Own analysis feature	Excellent
Opticad	Good	3500 USD	Own analysis feature	N/A
SolTrace	Could be improved	Free upon registration	Exportable data	N/A
Tonatiuh	Excellent	Free	Exportable data	Poor

Nomenclature

FF	Fill factor.
I_D	Diode current [A].
I_L	Light current [A].
I_{max}	Maximum power point current [A].
I_o	Reverse diode saturation current [A].
I_s	Saturation current [µm].
I_{sc}	Short circuit current [A].
I_{sh}	Shunt current [A].
P_{max}	Maximum power [W].
R_s	Series resistance [Ω].
R_{sh}	Shunt resistance [Ω].
V_{max}	Maximum power point voltage [V].
V_{oc}	Open circuit voltage [V].
V_T	Thermal voltage [V].
m'	Diode's ideality factor.

This document presents a literature review on raytrace software and electrical models. An own mating model using a raytrace software and two electric models using the one diode model with 5 parameters and with 3 parameters is presented and is used to simulate the radiation over a solar cell.

2 Literature review

2.1 Raytrace Software

Four raytrace software are compared, namely TracePro (Lambda, 2016), OptiCAD (OptiCAD Corp., 2016), SolTrace (National Renewable Energy Laboratory, 2003) and Tonatiuh(Blanco et al., 2009). Table 1 shows a comparison between the four available software packages, where it is demonstrated the advantage of Tonatiuh over others: user friendly, easy to add own scripts and geometries, exportable data capability and free.

2.2 Electrical Models

The equivalent circuit of a solar cell using one diode is presented in Figure 1. Duffie et al. (2013) determined the I-V characteristic where they use 5 parameters described by (1).

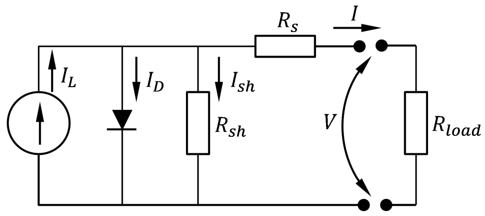

Figure 1: One diode equivalent circuit

$$I = I_L - I_o \left[\exp\left(\frac{V + IR_s}{m'V_T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

Most models use the manufacturer information and need some extra data that should be obtained from experiments. As stated by Hejri et al. (2016) it is possible to use a set of equations with only manufacturer's data. This proposal doesn't need to evaluate the solar cell experimentally, making the calculations and modelling a fast and easier way than other models. Hejri et al. (2016) got three equations with three unknowns R_s, R_{sh} and γ. They called γ to the ideality factor.

These equations, as any other one diode model, has to be solved by a numerical method namely Newton-Raphson. However, using Newton-Raphson must ensure to have a good initial guess. Hejri et al. (2016) arrived to (2), (3) and (4), that give good initial values for R_s, R_{sh} and γ. Using Newton-Raphson to solve Hejri equations, it is possible to get the solar cell parameters and obtain its I-V curve.

$$\gamma = \frac{2V_m - V_{oc}}{V_T \left[\ln\left(\frac{I_{sc} - I_m}{I_{sc}} \right) + \frac{I_m}{I_{sc} - I_m} \right]} \qquad (2)$$

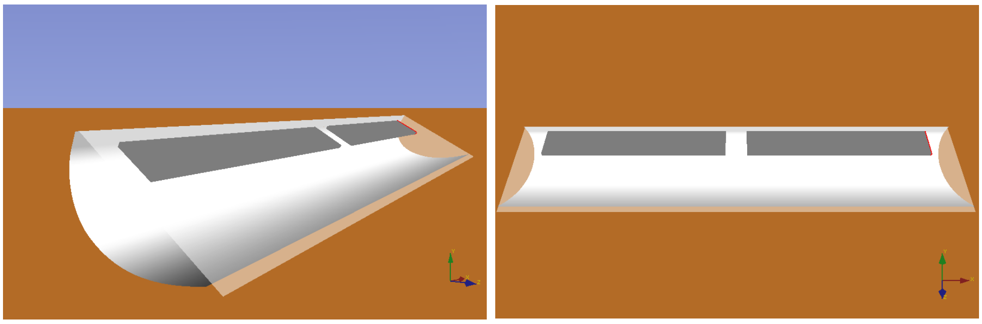

Figure 2: Final geometry using Tonatiuh

$$R_s = \frac{V_m}{I_m} - \frac{\frac{2V_m - V_{oc}}{I_{sc} - I_m}}{\ln\left(\frac{I_{sc} - I_m}{I_{sc}}\right) + \frac{I_m}{I_{sc} - I_m}} \tag{3}$$

$$R_{sh} = \sqrt{\frac{R_s}{\frac{I_{sc}}{\gamma V_T} \exp\left(\frac{R_s I_{sc} - V_{oc}}{\gamma V_T}\right)}} \tag{4}$$

The most common procedure to study a cell under non-uniform radiation is to divide the cell in sub-cells which will act as a one diode model or two diode model (Baig et al., 2012; Chenlo and Cid, 1987; Franklin and Coventry, 2002). Each of the elements is connected in series or parallel depending in the model selected. Models proposed by some authors include two dimensional current flow (Heizer and Chu, 1976; Mitchell, 1977), this means that current generated by a single element could travel horizontally or vertically adding its current to the next element until reach a finger and finally the busbar.

3 Model

3.1 Tonatiuh

The Solarus collector consists of a reflector and a receiver. The reflector has a parabolic and a cylindrical part (asymmetric through). The receiver element has PV cells at the upper and lower side, while in the middle it has tubes for the heat transfer. This geometry was translated into Tonatiuh coupling basic geometries such as cylinders, parabolic solids and rectangles. Tonatiuh is capable of showing the amount and distribution of the rays reaching a desired area. This data is then exported to a binary file for post-processing. The environment in Tonatiuh was set to match the conditions of the day when Solarus ran its test. It was selected a Pillbox sunshape in order to have the same solar intensity in every point of the sun and it was defined to have an irradiance of 921 W/m^2. The location of the sun was established using Tonatiuh's sun position calculator, requiring only the date input. The collector was facing south with a tilt of 30°. Figure 2 shows the final geometry output in different views.

3.2 Electrical model in Matlab

First of all, it is necessary to translate the binary files from Tonatiuh in order to have the distribution of the photons and be able to work with the data. Knowing the amount of photons, location and their energy it was successfully determined the local radiation per each finite element. The cell is divided in finite elements and each element is modelled as a one single cell. Each element will produce its own current, different from the other elements since the radiation reaching each subcell is different. The solar cell could be divided as many elements as necessary. Some assumptions to take in consideration are: No current transfer between rows and, radiation on a single element is homogeneous. Each element is modelled using the one diode model with 5 parameters since it is more accurate than the 3 parameters model. The numerical proposal from Hejri et al. (2016) will be used to obtain the 5 parameters of the one diode model. The equivalent circuit of the cell using the one diode model is shown on Figure 3. As stated previously, the current generated by an element is added to the next one until it reaches the finger and then it flows into the busbar. This approach will lead to have tiny elements of 0.65 mm x 1 mm, for the 38 cells, a total of 224,960 elements need to be simulated.

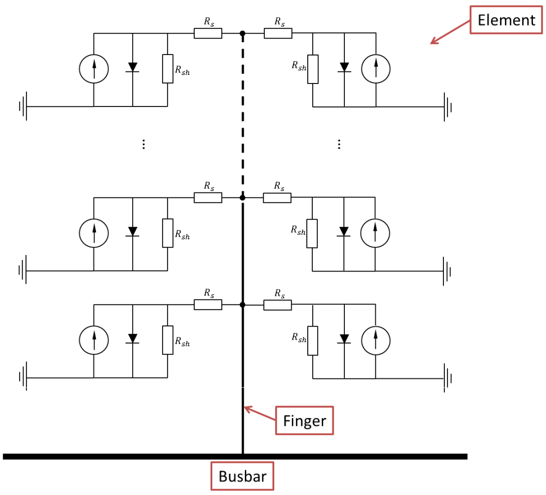

Figure 3: Equivalent circuit of a cell

The small elements will have the same electrical properties between them but different to the original solar cell because they have a different area.
When cutting a solar cell, its V_{max} and V_{oc} remain constant. In the other hand, the current and temperature coefficients are proportional to the area. For each element (1 mm x 0.65 mm) R_s, R_{sh}, I_s, I_o and V_T were computed, where all of them except R_s depend on irradiance and will need to be evaluated with the irradiance obtained by Tonatiuh. In order to obtain the values it is used (2), (3) and (4) and the Newton Raphson method to solve them.
Having all parameters it is possible to evaluate each element. However, some parameters depend on radiation and/or temperature and still need to be defined. V_T, I_o depend on temperature and I_{sc}, R_{sh} depend on irradiance while I_s, V_{oc} depend on both temperature and irradiance.
For every radiation reaching the cell, a different temperature will appear. It is important to highlight that the temperature used in the simulation is an average of the whole cell and not a temperature for each element.
The next step is to obtain the values of current generated by each element for a given voltage. In this way, it is possible to get the I-V curve and the maximum points of the solar cell arrangement. For now, since only one cell is being modelled, the current generated is assume to be the same in the 38 cells of a string and since the cells are connected in series, the voltage will be multiplied by 38.
Then, since there are two strings connected in parallel, the current doubles. The procedure is repeated for values of voltage from 0 V to .5 V where it is found that no more current is generated as if the arrangement was in open circuit.
With the values of current and voltage it is calculated the power generated and the maximum power point is obtained. This step was done calculating the power for a given voltage and moving to the right or left depending where the highest point was until reaching a maximum point. The open circuit voltage was obtained giving values to the voltage and increasing it until the current obtained was close to zero. After this procedure, it is obtained the P_{max}, I_{max}, V_{max}, I_{sc}, V_{oc} of the two strings connected in parallel, each string made of 38 cells dividing each cell in small elements of 0.65 mm x 1 mm as stated previously.
The same process is now done using the one diode with 3 parameters model and the results are compared. The simulation using only 3 parameters is to observe and compare the results and computing time. Notice that the difference between 5 and 3 parameters is the use of series and shunt resistances in the 5 parameters model.
A series of simulations were done using the one diode with 5 parameters model but now changing the number and size of the elements. Table 2 shows the total of simulations done with their respective number of elements and size. The objective of this simulations is to determine if the final results are affected by changing size and number of elements.
Since it is difficult to implement a detailed thermal model, and thus, obtain the temperature for every element, it was decided to use a much simple model that could observed the influence of establishing different variations of temperature and different temperature discretization.
There are included more simulations but now specifying "hot" and "cold" zones in the cells. The "hot" zone will be above average temperature and "cold" zone will be below. For example, if average temperature is 40.5°C and defining a $\Delta T = 5$°C, the "hot" zone will be 45.5°C and the "cold" will be 35.5°C.

Table 2: Simulations done with the electrical model

Simulation	Horizontal divisions	Vertical divisions	Number of elements	Size of an element	Area of an element
1	148	1520	224,960	1 mm x 0.65 mm	0.65 mm^2
2	1	38	38	26 mm x 148 mm	3848 mm^2
3	5	38	190	26 mm x 29.6 mm	769.6 mm^2
4	10	38	380	26 mm x 14.8 mm	384.8 mm^2
5	20	380	7600	2.6 mm x 7.4 mm	19.24 mm^2

Table 3: Temperatures used for "Hot" and "Cold" (2 zones)

Sim.	ΔT (°C)	Hot zone temp. (°C)	Cold zone temp. (°C)
a	5	45.5	35.5
b	10	50.5	30.5
c	15	55.5	25.5
d	20	60.5	20.5

Table 4: Temperatures for different radiation ranges (5 zones)

Radiation ranges (W/m^2)	Temperature (°C)
10102.8-12628.5	45.5
7577.1-10102.8	43
5151.4-7577.1	40.5
2525.7-5051.4	38
0-2525.7	35.5

This experiment has as an objective to see how different temperatures in the same solar cell could affect its behaviour. For the temperature variations done in these simulations see Table 3. This simulation is repeated but now considering five zones instead of two. The temperature range was set to be 35.5°C to 45.5°C divided in five sections as well as the radiation. Since data from radiation is known, it is obtained the maximum and minimum radiation reaching the surface and divided in five sections as well. Table 4 shows the defined temperature for every range of radiation.

Please notice that the simulation using five temperature zones was only done for the 148 x 1520 elements.

4 Results

A simulation using the 5 and 3 parameters was done. Figure 4 shows the I-V curves for both simulations. It is observed that the one diode with 3 parameters model have a higher power and current, this is because it is not taking into account the losses in the series and shunt resistances. Table 9 shows the percentage difference for the 5 and 3 parameters model and Solarus estimation if we take as reference the measured values. The one diode with 5 parameters model has the closest values to the measured ones and thus, the smallest percentage difference.

The model using 3 parameters is much more faster than the 5 parameters, i.e. a simulation to obtain current points for 148 x 1520 elements last 494 seconds, this is around 8 minutes, while a simulation using 5 parameters can last up to 21609 seconds, this is, 6 hours. The one diode with 5 parameters model incorporates the series and shunt resistances and takes much time because it needs to solve simultaneous equations.

As seen on Figure 5, it is possible to see with high accuracy the location where the concentration occurs since the number of elements is very high. As seen on Figure 6 a higher variation of temperature will lead to a power reduction. This is because the zone where most of radiation reaches is at a higher temperature than expected.

In Table 5, the five temperature zones approach forecast a higher power. The main observable reason for this to happen is that for a certain radiation range, the temperature associated does not correspond to it. Another reason, that could be happened at the same time, is that the temperature does not change 5°C, but 10°C.

Table 6 shows a comparison between the five simulations using different size and thus, number, of elements. The power obtained when simulating at 224,960 elements is very close to the reference values measured by Solarus. It is demonstrated that increasing the number of elements will lead to a closer value, of P_{max}, I_{max} and V_{max}, with low difference error as seen on Table 7. If we compare the results of Table 8 to the measured ones, it is seen that a variation in temperature of 15°C and 20°C will lead to a poor forecast of the power.

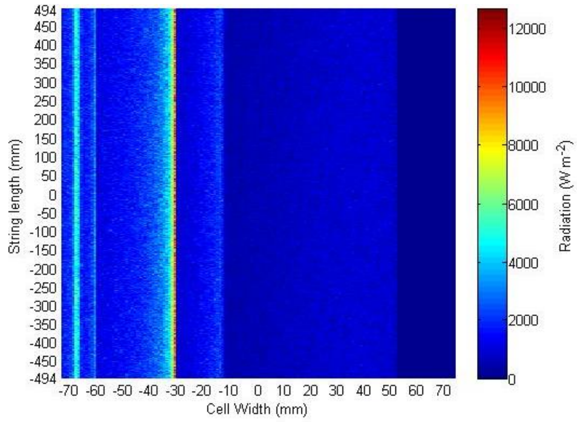

Figure 5: Radiation map with 148 x 1520 elements

Table 5: Comparison between 2 and 5 "hot" and "cold" zones at $\Delta T = 5°C$

	2 zones	**5 zones**
P_{max} **(W)**	47.62	48.98
I_{max} **(A)**	3.30	3.22
I_{sc} **(A)**	3.53	3.54
V_{oc} **(V)**	18.68	18.93
V_{max} **(V)**	14.44	15.20

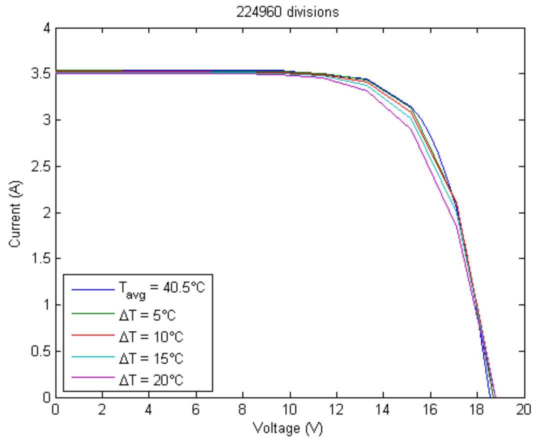

Figure 6: I-V curves for 148 x 1520 elements

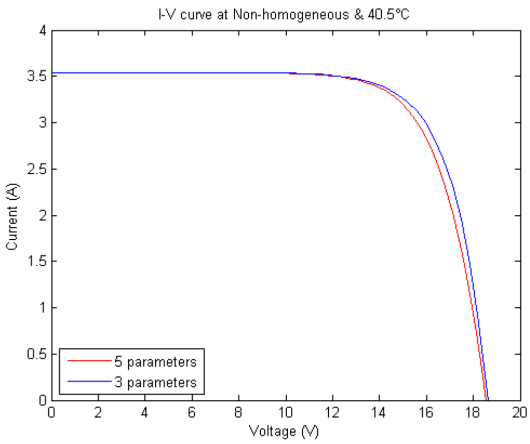

Figure 4: I-V curves using 5 and 3 parameters model

Table 6: Comparison between number of elements

	Number of elements				
	224,960	**7600**	**380**	**190**	**38**
P_{max} **(W)**	47.66	48.25	47.66	47.75	47.92
I_{max} **(A)**	3.14	3.26	3.22	3.22	3.23
I_{sc} **(A)**	3.54	3.54	3.50	3.50	3.50
V_{oc} **(V)**	18.56	18.57	18.56	18.57	18.60
V_{max} **(V)**	15.20	14.82	14.82	14.82	14.82

Table 7: Percentage difference of number of elements with respect to the measured values

	Number of elements				
	224,960	**7600**	**380**	**190**	**38**
P_{max} **(W)**	0.8%	2.0%	0.8%	1.0%	1.3%
I_{max} **(A)**	16.1%	20.6%	19.1%	19.3%	19.7%
I_{sc}**(A)**	14.3%	14.3%	12.8%	12.8%	12.8%
V_{oc} **(V)**	15.7%	15.6%	15.6%	15.6%	15.5%
V_{max} **(V)**	13.2%	15.4%	15.4%	15.4%	15.4%

Table 8: String arrangement using 148 x 1520 elements

	T = 40.5° **C**	ΔT = 5° **C**	ΔT = 10° **C**	ΔT = 15° **C**	ΔT = 20° **C**
P_{max} **(W)**	47.66	47.62	47.20	46.26	44.78
I_{max} **(A)**	3.14	3.30	3.19	3.20	3.02
I_{sc} **(A)**	3.54	3.53	3.52	3.51	3.50
V_{oc} **(V)**	18.56	18.68	18.76	18.79	18.76
V_{max} **(V)**	15.20	14.44	14.82	14.44	14.82

Table 9: Percentage difference between 5 parameters, 3 parameters and Solarus simulation with respect to the measured values

	5 par.	**3 par.**	**Solarus**
P_{max} **(W)**	0.8%	3.5%	77.0%
I_{max} **(A)**	16.1%	19.3%	39.6%
I_{sc} **(A)**	14.3%	14.3%	28.1%
V_{oc} **(V)**	15.7%	13.6%	11.7%
V_{max} **(V)**	13.2%	13.2%	26.7%

5 Conclusions

The one diode model with 3 parameters is faster than the one diode model with 5 parameters. However, using the 5 parameters model provides a more accurate result. The one diode model with 3 parameters can be used only to know a fairly value of the power that can be obtained. It is recommended to be used when an approximation of the power, voltage and current is needed. For a more precise forecast the one diode with 5 parameters model is used.

When simulating at "hot" and "cold" zones, it was demonstrated that the maximum and minimum temperatures of the cell is near the average point, ±10°C but no more than ±15°C where it was seen that the power, current and voltage have a higher percentage difference.

The use of more than two "hot" and "cold" zones can be used. For the case of having a maximum and minimum temperatures 5°C higher and lower respectively, the five temperature zones approach forecast a higher power. This is why it is really necessary to have a point where for a given radiation its temperature is known, so it can be used as a reference and to be able to divide in proper regions. Moreover, the maximum temperature of the cell could be higher than 5°C above the average, this assumption implies the use of other temperatures, i.e. 10°C.

It is also demonstrated that having an homogeneous distribution of radiation, will lead to slightly improvement of the performance of the collector. Under non-homogeneous radiation the V_{max} increase while the I_{max} decrease, which lead to a lower power output. V_{oc} also decreases as other authors suggest.

An electrical model using 3 or 5 parameters was built and coded in Matlab. With the help of Tonatiuh, it was possible to compute the distribution and energy of the photons reaching a surface. The simulations and forecast are close to the reference measures and could be considered as a helpful model if one wants to know the order of magnitude of the generated power.

As a final conclusion, it is observed that the radiation affects the parameters which are used to model the collector, I_{sc}, R_{sh}, I_s and V_{oc}, however, this impact is not as significant as the effect produced by the temperature, which includes parameters such as, V_T, I_o, I_s and V_{oc}, but more important is the impact on the I-V curve, FF and finally in the maximum power, voltage and current. A non-homogeneous radiation affects negatively, and indirectly, the electrical performance of the collector. It is said indirectly because the impact received by the parameters are almost insignificant. Nevertheless, a non-homogeneous radiation will lead to a temperature distribution in the solar cell, which will cause a modification in the performance of the solar cell.

As a proposed future work, the thermal module needs to be added to the current model. In order to have a more accurate model, it is required to make the calculations of a single element using a temperature closer to the real one. This implies that the thermal and electrical models need to be solved simultaneously. Including the thermal model in the CPVT, it could be possible to forecast the final temperature of the fluid that is being heated only knowing the inlet temperature and the radiation reaching the collector as inputs.

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