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DESIGN AND DEVELOPMENT OF A SOLAR SIMULATOR FOR EFFICIENCY IMPROVEMENT IN PHOTOVOLTAIC PANELS

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Abstract. *Tests of PV panels efficiency follow IEC 61215, which defines optimal conditions of irradiation, temperature and ventilation for these procedures, resulting always in values tending to the optimal that difficultly are achieved in real conditions of use. Therefore, it was developed a solar simulator to provide the study and evaluation of PV efficiency under adverse climatic conditions, emphasizing the impact of temperature on their performance. The solar simulator was developed based on the following criteria: the use of artificial lamps with spectrum similar to the sun, adjustment of environment temperature and control of irradiation and its spreading homogeneity on PV surface. However, after performing some tests was observed that the irradiation homogeneity on the surface was worse than desired, with high values of irradiation in the center and low values in the peripheral areas, encouraging some redesigns of the apparatus until a more homogeneous distribution of irradiation was achieved. After this, the solar simulator was considered suitable for the desired proposal, which is the study and evaluation of future technological solutions aimed to increase PV efficiency by control or reduction its temperature.*

Keywords: *Photovoltaic, Energy, Efficiency, Temperature, Solar simulator*

1. INTRODUCTION

Photovoltaic (PV) efficiency tests follow the international standard IEC 61215 and are conducted in climatic chambers at 25 ° C, air mass of 1.5 and irradiation of $1000\ Wm^{-2}$. The radiation is generated by a solar simulator usually using xenon lamps, whose spectrum has larger amplitudes in the range of more efficient power conversion and lower amplitudes in the infrared band, just to avoid the temperature rise on PV panels. Thus, the efficiency of the manufacturers are always a value tending to the optimal, whose similar results are hardly achieved in real conditions. In order to decrease the discrepancy between the PV efficiency in real conditions and in climate chambers, a new standard was established called NOCT (Nominal Operating Cell Temperature), with radiation tilt 45 °, ambient temperature of 20 ° C, wind speed of $1\ ms^{-1}$ and irradiation of $800\ Wm^{-2}$. Although this allows an approximation of the standard tests under actual operating conditions in Europe, in Brazil the difference is increased, since the ambient temperature and irradiation in this country are even higher then NOCT values (VILLALVA e GAZOLI, 2012) (BLOEM, 2008) (WEISS, AMARA e MENEZO, 2012) (REIS, 2011) (TIEPOLO, 2011).

Differently from the tests carried out by manufacturers, experimental studies aimed at improving the PV efficiency are performed under real conditions, influenced by climatic adversities such as the different conditions of irradiation during the day and position of the sun during the year partial shadows because of the clouds, variation of ambient temperature and wind speed. According to (SKOPLAKI and PALYVOS, 2009), these features require special attention in the prediction of PV efficiency (PÓ, 2011) (WEISS, AMARA e MENEZO, 2012).

According to (PO, 2011), in a controlled environment (indoor) for testing and evaluation of PV panels, the possibility of controlling the temperature and irradiation reduces the uncertainties about the results. While evaluations in an uncontrolled environment (outdoor) can only be performed reliably when its temperature during the measurements have not vary by more than 2 K and irradiation and wind speed are virtually constant. These implications result in the need for a large amount of data acquisitions to determine important parameters of PV panels in an outdoor evaluation, whereas this could be simplified in an indoor environment where there is less uncertainty about the measures.

In this context, was developed an indoor environment for experimentation, evaluation and comparison of proposals aimed at increasing the PV efficiency by controlling or decreasing its temperature, using some of thermal and radiative properties. In Figure 1, (Weiss et. al., 2012) proposes the model of a photovoltaic panel highlighting for its thermal properties and some constructive. This environment, which is called solar simulator, was developed in climatic chamber of the Thermal Systems Laboratory (LST) of the Pontifical Catholic University of Paraná (PUCPR) where is possible to control the ambient temperature, ventilation and irradiation.

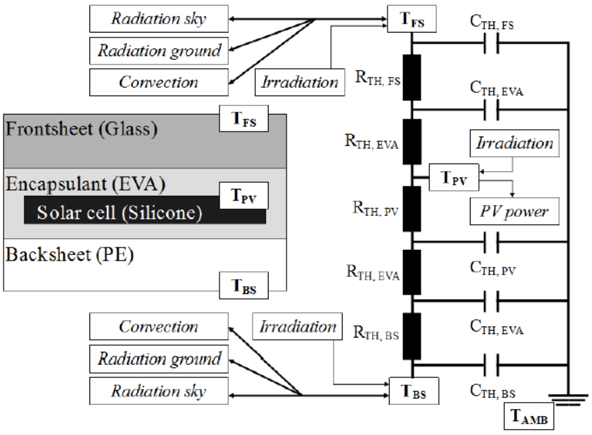


Figure 1. Thermal and radiative properties of a PV cell

2. DEVELOPMENT

The main objective of this project was to propose and construct a solar simulator using the climated chamber of LST-PUCPR, for testing and evaluation of PV panels under adverse weather conditions, in which the most important parameter is the influence of temperature on their efficiency.

The development of the solar simulator was performed into two main objectives: design and development; and definition of lamps.

2.1 Design and development of solar simulator

The solar simulator was built with the following dimensions: 1250 x 1850 x 2100 mm (width x length x height) so that it could fit most PV panels available commercially. Irradiation is generated by lamps arranged as a 4 x 6 array, totaling 24 lamps (Fig. 2). This amount of lamps is to be no large gaps between them, which can generate regions with low irradiation on the panel surface.

Figure 2. Design and development of solar simulator structure

The circuit was connected to a 220 V voltage source to prevent significant losses of power by Joule effect in the conductors and reduce spending on oversizing of conductors and protective devices, and it was connected to a power controller (dimmer) using PWM (pulse-width modulation) with a maximum voltage and 220V-12kW for the purpose of controlling the lamp power and therefore the irradiation on the surface of PV panels (Fig. 3).

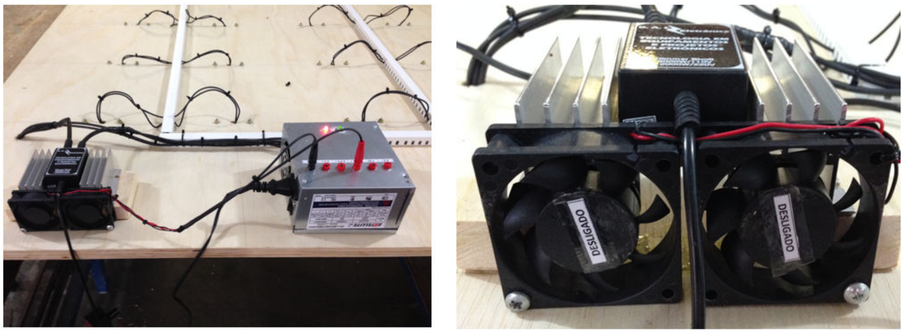


Figure 3. Dimmer to control the irradiation on PV panels

The solar simulator was mounted within the climated chamber of the LST, which has the following characteristics:

- dimensions (3000 x 3000 x 3000) mm;
- temperature range: -10°C a 65°C;
- humity range: 10 a 95%.

2.2 Definition of lamps

The choice of lamps was an important step in the construction of solar simulator. At this stage the following requirements have been established:

- the lamp spectrum should be as close as possible to the solar radiation spectrum, with one band being transformed into electrical energy and the other into thermal energy;
- the lamp power should be sufficient for:
    - cause significant heating in the PV panel;
    - result in an irradiation bigger or equal to a 1000 Wm^{-2}.

After a research comparing the spectrum of different lamps commercially available, it was decided to use halogen lamps as irradiation source, because of its similar spectrum to the solar radiation. In Fig. 3 are compared the spectrum of the halogen lamp with the spectrum of solar radiation and others lamps.

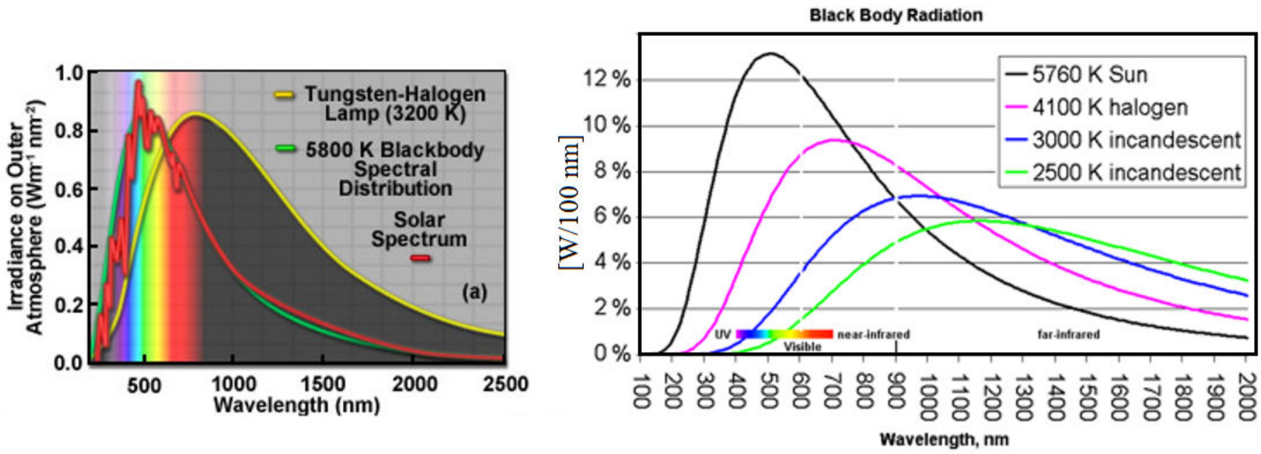


Figure 3. Comparison between the halogen lamp spectrum and: solar spectrum (left side); others incandescent lamps spectrum (right side) (ZEISS, 2015).

An apparatus was constructed to examine the ability of the halogen lamp to generate energy in a PV cell and at the same time, heats it. This apparatus (Fig. 4 - left) consisted of a base containing, on one side, a 500 W halogen lamp, and on the other hand, a PV cell. The distance between the lamp and the cell was 1 meter. In addition to this apparatus, we used a voltmeter and a thermal camera to check the capacity of power generation and thermal energy in the cell.

After testing, it was found the generation of electricity and thermal energy by the cell, resulting in an increase in temperature of 19.2 °C to 33.3 °C.

Figure 4. Apparatus to evaluate the generation of electricity and heat by halogen lamp (left side) and thermal imaging of PV cell (right side).

To define which power of lamps should be used in the solar simulator (300 W or 500 W), there were two more specific evaluations: the heat generated in PV cell and the intensity of irradiation at a distance of 1 meter.

The evaluation of heating generated in PV cell was carried out in the LST chamber with temperature stabilized at 25 °C. This evaluation consisted in measuring the temperature of the PV cell, using a T-type thermocouple, when irradiated by 300 W and 500 W lamp. During the evaluation the whole temperature inside the chamber was also recorded (Fig. 5).

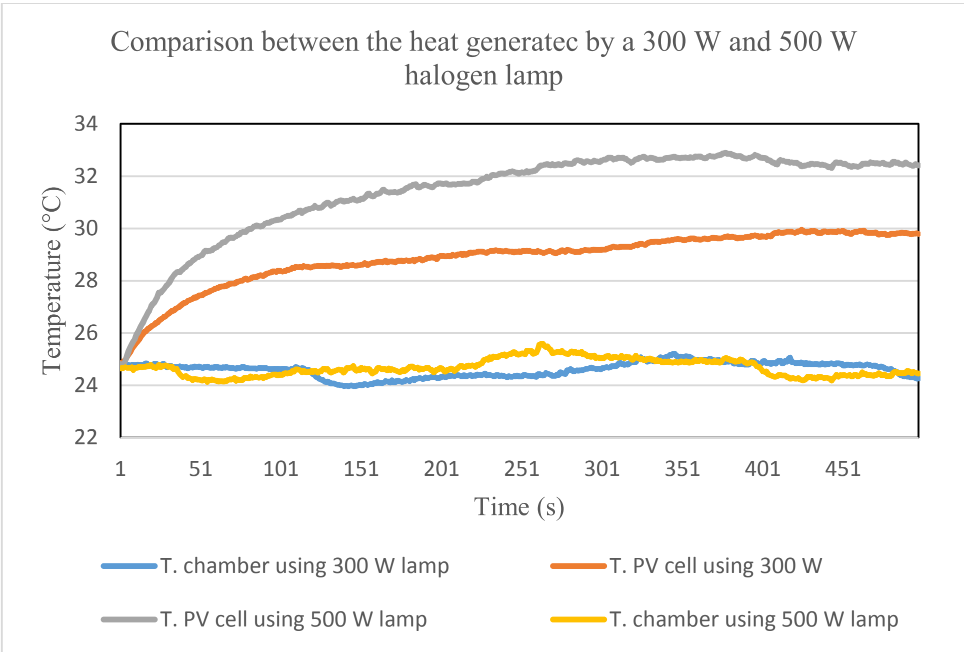


Figure 5. Comparison between the heat generated by a 300W e 500W lamp.

Considering the use of 24 halogen lamps in the solar simulator for irradiating an area of approximately 2,3 m^2, it was concluded that both lamps have power enough to cause a significant increase in the temperature of the PV cell. Therefore, the choice of lamp power was decided only in the evaluation of irradiation.

Using the same apparatus, the PV cell was replaced by a CMP calibrated pyranometer model 6 - Kipp & Zonen (sensitivity of 12,24 $\mu V m^2 W^{-1}$ and impedance of 43 Ω) to evaluate the irradiation. After the acquisition of the radiation generated by the lamps of 300 W and 500 W were plotted graphs of Fig. 6.

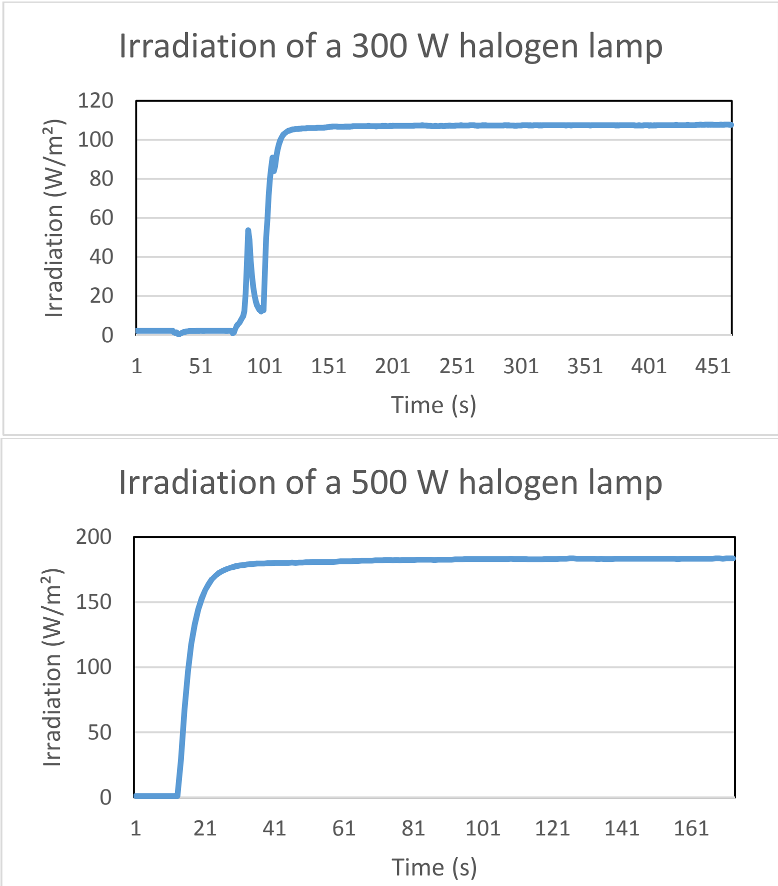


Figure 6. Irradiation of halogen lamps 300 W (left) and W 500 (right).

According to the Figure 6, it was possible to observe that, although the 500 W lamp has presented much higher irradiation, the irradiation of approximately 110 Wm^{-2} generated by the lamp 300 W reaches the requirements, since, as mentioned above, the conceptual design of the solar simulator expect the utilizations of 24 in an area of only approximately 2,3 m^2.

3. RESULTS

Several tests of the solar simulator were carried out in order to evaluate:

- ability to control the irradiation intensity on the PV surface;
- spreading of irradiation homogeneously on the panel surface.

Before performing the tests, the surface of the solar simulator to be irradiated was divided in the form of a 10 x 7 array (row x column), resulting in 70 quadrants. The columns were labeled with the letters "A" to "G" and the lines with the numbers "1" to "10".

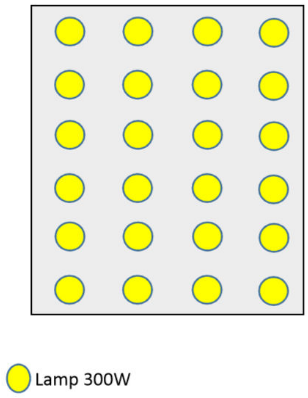
The pyranometer was placed in the center of the simulator (D5 quadrant) and the irradiation power was adjusted using the dimmer, until it reaches the irradiation of approximately 1000 Wm^{-2}.

After adjusting the irradiation, was measured the irradiation intensity in each of quadrants of solar simulator surface. All irradiation values were collected and stored by data acquisition equipment Agilent 34970A, which was configured to perform the pyranometer readings at 10 seconds.

Three modifications and improvements have been made in the solar simulator based on the results obtained during the tests, which modifications are described below as case A, B and C.

3.1 Case A

In the Case A Fig. 7 was generated containing irradiation in each of quadrants of the simulator. In this figure is evident the poor distribution of irradiation generated on the surface of the solar simulator. The irradiation in the central quadrant was close to the desired value (999,01 Wm^{-2}), but in border regions the irradiation value was much lower than the desired, reaching values of only 33.72% of D5.



A)

	A	B	C	D	E	F	G
1	435,1797	503,8491	561,9952	593,8255	573,3333	529,4629	470,4994
2	554,0726	647,344	714,1991	733,8277	723,9245	662,9705	576,097
3	642,3839	754,1653	813,7156	848,5894	839,7575	783,4704	649,3621
4	682,8402	804,4755	889,6796	911,8069	895,016	823,7578	706,7747
5	733,546	855,4291	941,6247	970,2128	956,6563	887,9084	768,4009
6	745,7466	879,7604	966,8119	999,0143	969,3785	888,0854	767,8114
7	690,8242	807,4145	875,6752	900,2709	876,7975	805,3243	701,1751
8	657,8586	756,665	831,4494	864,4425	849,5253	769,5757	665,6003
9	585,9951	688,9709	748,2478	774,4616	774,4616	700,9581	604,9519
10	470,3128	542,9565	602,2919	611,873	596,6945	563,0187	483,2322

B)

Figure 7. a) configuration of the lamps in the solar simulator (Case A); b) irradiation spreading on the surface of the solar simulator.

In this Case A we conclude that:

- the solar simulator was able to adjust the irradiation on the surface with satisfactory precision, with a variation of only 0.1% below the desired value;
- irradiation in each quadrant of the simulator surface is strongly influenced by the side lamps (neighborhood), and this has influenced in the peripheral areas of the simulator, making its surface with low homogeneity of irradiation.

This problem of non-homogeneity in the simulator can generate the same effect occurred in panels with partial shading. That is, some cells generate electrical currents more intense than others and can negatively polarize cells that generate less current, significantly affecting the performance of the entire panel (DOLARA, LAZAROIU, *et al.*, 2013), (LOPES, 2013) (ISHAQUE, 2011).

3.2 Case B

Because of the problem occurred in the Case A, it was executed the redesign of the solar simulator in which the solution found to fix the problem of bad spreading of irradiation was to surround the perimeter of the simulator with a reflective surface (95% reflection), creating virtual images in all sides of the simulator, as shown in Fig. 8, to increase the irradiation mainly in the peripheral regions.

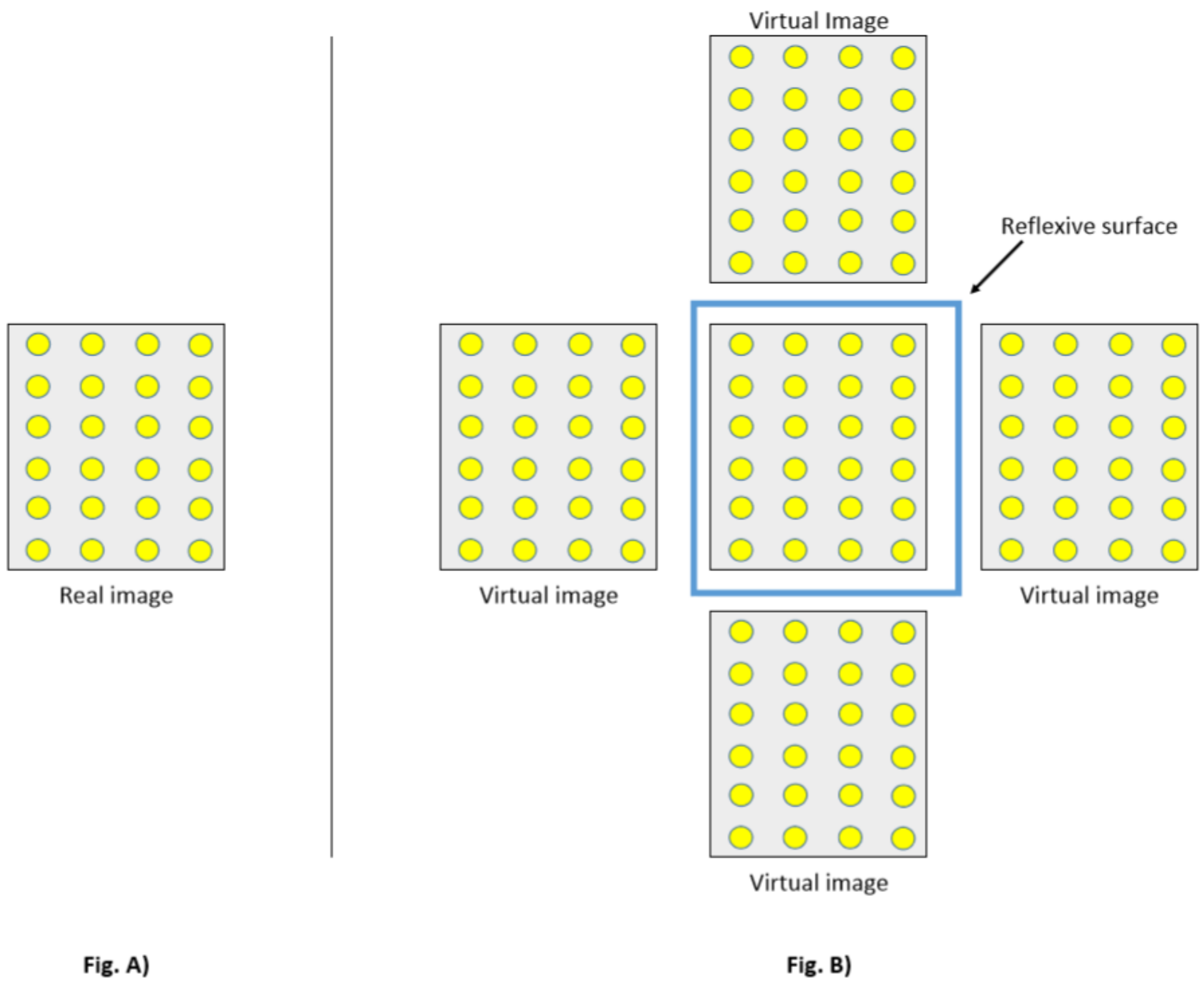


Figure 8. a) solar simulator without the reflective surface on the sides; b) solar simulator surrounded by reflective material creating virtual images on the sides.

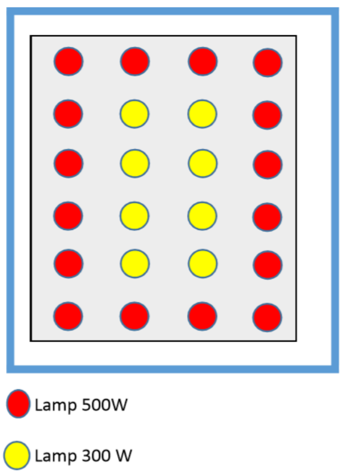
This modification improves significantly the spreading of radiation on the simulator surface (Fig. 9). However, it can be observed several values reaching less than 900 Wm^{-2} (90% of the desired irradiation), exclusively in the peripheral regions of the simulator.

	A	B	C	D	E	F	G
2	911,1182	897,5	888,8999	893,1668	872,198	863,3252	834,9049
3	921,0601	912,5745	915,4888	923,3277	916,524	924,275	885,7183
4	937,0577	925,6543	940,4566	947,2214	953,1105	957,1063	901,7165
5	941,4431	929,804	942,3485	975,043	986,2519	991,102	936,952
6	971,4413	962,9673	995,9444	1030,956	1024,943	1022,104	972,1874
7	963,664	970,8863	990,8983	1006,089	1030,988	1046,25	1021,291
8	954,214	952,4385	967,5424	981,2222	996,048	1000,217	987,5044
9	912,3754	929,3979	939,7165	950,6154	964,9863	975,1529	969,9011
10	907,7274	917,6608	937,135	950,4706	937,9734	922,0921	895,1157
11	845,6823	903,8654	915,6039	938,5521	939,0965	932,2921	912,0675

Figure 9. irradiation spreading on the surface of the solar simulator (Case B).

3.3 Case C

In the Case C, in order to increase the irradiation in the peripheral areas of the simulator, it was investigated the use of the reflective surface and, and the replacement of peripheral lamps of 300 W for 500 W (Fig. 10a).



A)

	A	B	C	D	E	F	G
1	879,5414	904,5144	928,4788	933,6772	949,953	936,6145	923,477
2	915,3315	948,4623	965,2829	969,7899	970,7771	949,9679	936,1783
3	942,8088	948,0032	964,9691	972,4257	968,1786	966,4366	944,7065
4	923,1835	940,548	966,2561	968,7287	976,2772	1013,933	1006,676
5	996,7995	1010,406	1025,044	1019,462	1026,149	1015,518	1019,788
6	990,6141	990,9718	1000,441	1016,493	1027,168	1020,689	1018,722
7	978,1939	980,7192	977,62	987,1059	983,5618	974,033	945,5527
8	985,7651	983,4776	987,1087	1000,335	998,7246	986,5065	980,8177
9	968,5224	986,4484	990,0034	1011,427	993,2442	983,0808	964,071
10	939,9453	972,3458	985,8303	993,3983	977,525	958,1174	931,7112

B)

Figure 10. a) configuration of the lamps in the solar simulator (Case C); b) irradiation spreading on the surface of the solar simulator.

Figure 10b indicates an improvement in the irradiation spreading on the surface of the solar simulator. Even though the results indicate the presence of a quadrant (A1) with irradiation below 900 Wm^{-2}.

4. CONCLUSIONS

Assuming the dependence of PV efficiency in relation to operating temperature, ambient temperature, irradiation, and wind speed, a solar simulator was proposed for testing and evaluations of the photovoltaic panel efficiency through adverse conditions.

In the development of solar simulator, irradiation spectrum and the homogeneity of the surface are essential prerequisites to perform the PV evaluations with the desired fidelity.

To simulate sunlight, halogen lamps have a spectral distribution with satisfactory levels of correlation, carrying a band with wavelength greater than $1.15\ \mu m$, heating the panel, and a band above this value, responsible for the formation of electron-gap pair, resulting in electric current.

Provide the uniformity of irradiation on the panel surface is a more complex requirement because the solar simulator has 24 different irradiation points. Even though IEC 60904-9 standard defines that the variation of irradiation on the surface must be less than ± 2% in manufacturer efficiency evaluations, which applies only a flash irradiation in a short period of time, it is important to emphasize that this project has a different purpose, which include heat the panel and simulate several real operation conditions. Considering this, the result shown in the Case C of the solar simulator was considered satisfactory for this purpose.

Some improvements may be used to improve the distribution of irradiation in the solar simulator, such as the use of ambient lighting software or neural networks to help decide on the best placement of reflectors, in which the main objective is to create conditions to promote the development of new technological solutions to increase PV efficiency by decreasing or controlling its temperature (SCHNEIDER, 2008).

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