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Thermodynamic Simulation of Photovoltaic Panels Installed in Surfaces with Different Albedo Indices using the Finite Element Method

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Abstract. High temperatures decrease the output voltage in photovoltaic panels, interfering in the energy generation process. This article presents simulation results that demonstrate the interference of the surface material on which the photovoltaic panels are installed in the panels operation temperature. The study was developed from the thermodynamic simulation model using the finite element method. The cases were analyzed from the construction of a three-dimensional design with two photovoltaic panels installed on a surface of galvanized steel of 80m², which had 20m² of area covered by a reflective paint. Ten simulation routines were performed considering the different indices of solar irradaytion in a period of 18 hours. The simulation results confirmed that the surface of the panels installation was cooled to 20°C after the coating application. Measurements from a thermal camera was presented showing the heat transfer in the materials, and the temperature profile of the panels and the surface of the roof with and without the reflective paint.

Key words
Energy Efficiency, Finite Element Method, Photovoltaic Panel, Thermodynamic Simulation, Reflective Paint.

1. Introduction

The sunlight that reaches the Earth's surface is capable of deliver 7900 times more energy than it is actually used [1, 2, 3, 4].

The solar energy has low representativity in the world energy matrix compared to the generation potential of much of the globe. Among the factors that contribute to the fact presented, the low efficiency of photovoltaic cells that convert solar energy into electric energy is one of them. [5, 6].

High temperatures reduce the energy efficiency of solar cells. Only a fraction of the incidente sunlight that hits the photovoltaic panel (PV) cell is converted into electric energy. The rest of the absorbed energy is converted to thermal energy in the cell, increasing the junction temperature [7, 8].

The surface of a roof can reach temperatures of up to 90°C while a photovoltaic panel surface can reach up to 60°C in the Brazilian summer, resulting in an efficiency loss of 18% over its generation capacity [9, 10].

Thus, photovoltaic panel cooling techniques are becoming more widespread in order to maximize output power.

In the cooling of photovoltaic panels by water application on the front surface, the heat transfer from the panel surface to the water will occur. The water will absorb heat from the photovoltaic panel by the conduction of heat, causing improvements in power and voltage levels, and improving the panel efficiency [11].

In [12] is presented a study about photovoltaic panels cooling using water. Two solar panels prototypes were mounted, one without cooling system and another with cooling system in which the water is sprayed by a fan. The results showed that the cooled solar panels by water generated more energy than the panel without cooling system. However, the study results indicated that the method used is not efficient because the spray applied for cooling the panels did not cover the whole area of the module.

Still on PV cooling techniques, in [13] an approach is presented about the reduction of temperature of the photovoltaic panels using air-cooled heat sinks.

The heat dissipation to the environment can guarantee that the energy not absorbed by cells does not turn into heat, and that the cells work under normal operating conditions [7].

White and reflective paints promote the surface cooling through heat dissipation to the environment by infrared rays [14].

Considering that the ideal conditions of installation of the PV correspond to locals with high indices of solar radaytion and low temperatures, this study purposes the analysis of computational simulations, evaluation of the interference of the material of the installation surface in the operating temperature of the PV. Therefore, an experiment was simulated that consists of the installation of two sets of photovoltaic panels installed on the surface with and without reflective paint. The simulation results are compared with thermal images obtained using a thermal camera.

2. Methodology

The simulation was carried out from an experiment installed on the galvanized steel roof at the laboratory of the Nucleus of Experimental and Technological Studies and Research of the Federal Institute of Goias (IFG), Goiania campus, Goiania, Goiás, Brazil. The experiment consists of two photovoltaic (PV) systems installed on surfaces with different coverage layers (with and without reflective paint). The total area of the roof is 995.55m².

Figure 1 shows the location of the roof on IFG Goiania campus named “1”. Figure 2 ilustrates the arrangement of two areas used to install the two sets of PV described in the image as areas A and B.

Figure 1 – Location of the roof at IFG campus Goiania.

Figure 2 – Arrangement of the areas used to install the PV sets.

For the study was used the finite element method that maintains the properties of the original environment and uses mathematical analysis to desintegrate a continuous element into small elements, described by differential equations solved by mathematical models [15]. The steps were simulated in the software Comsol 5.2b.

Initially it was necessary to define the location of the area to be simulated. The software requires the local geographic coordinates, which were obtained to [16], being: -16.665166 and -49.255851. The study was carried out from the analysis of ten simulations with different values of solar irradaynce, according to each hour of the day. For the definition of the equipament materials, the albedo indices and emissivity of the materials used were inserted into the software.

Figure 3 ilustrates the roof geometry drawn in three dimensions into the software Solidworks and imported to the Comsol software. The drawing consists in three distinct objects, two photovoltaic panels, a galvanized steel roof where the surface material is maintained, and a galvanized steel plate where layers of reflective paint are applied, consisting of microspheres of hollow ceramic.

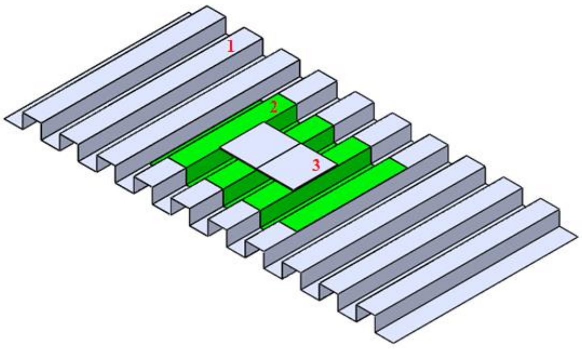

Figure 3 – Simulated roof geometry

Three distinct domains were assigned in the image of Figure 3. The surface of the roof without the reflective paint with 80m² is represented by number 1 the area of 20m² painted with reflective paint is represented by number 2, and the two photovoltaic panels with an area of 1,2m² are represented by number 3.

For each domain is defined the index of emissivity (ε) and absorptivity (α), as shown in the Table 1. The values of ε and α of the galvanized steel roof was defined by [17] and the [18]. The values of ε and α of the reflective paint used were defined from the technical bulletin which deals with the specificities of the product [19]. The absorptivity and the emissivity of the panel were defined by [20] and by [21], respectively.

The mean solar irradaynce (Ee) of the seven days of measurement, measured at the Meteorologial Station of the Federal University of Goias, located in Goiania, was used to simulate heat transfer and temperature behavior in the materials composing the geometry.

Table 1 – The emissivity and absorptivity indices of each domain used in simulation

Domain	Description	Emissivity index (ε)	Absorptivity index (α)
1	Galvanized steel roof	0.25	0.65
2	Galvanized steel roof with reflective paint	0.87	0.15
3	Photovoltaic Panel	0.25	0.85/0.91

The mean values shown in the last column represent the values inserted in Comsol for the simulations of the respective schedules.
Figure 4 ilustrates the thin tetrahedral mesh used in simulation.

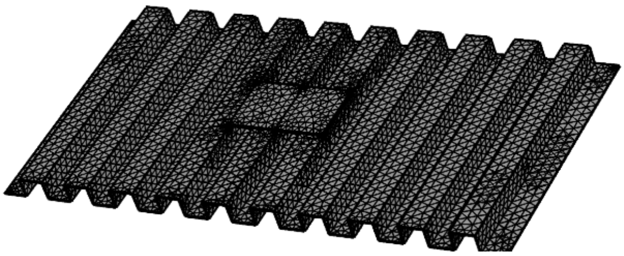

Figure 4- The tetrahedral mesh used in simulation

The average values of the solar irradaynce from the seven days to the 10 hours of measurement are listed in Table 2.

Table 2 – Solar irradaynce [W/m²] data obtained by the measurement period average

Hours	1° day	2° day	3° day	4° day	5° day	6° day	7° day	Avarege
8 to 9	221.85	221.90	222.28	101.66	195.13	101.01	218.32	183.16
9 to 10	438.32	436.74	437.75	383.88	415.91	422.91	459.10	427.80
10 to 11	622.59	622.38	617.05	214.88	607.64	605.48	608.29	556.90
11 to 12	743.36	740.76	738.28	742.88	732.12	726.19	602.22	717.97
12 to 13	911.00	802.10	827.24	801.64	793.86	791.08	818.88	820.83
13 to 14	194.89	793.86	806.79	790.41	773.73	786.15	883.37	718.46
14 to 15	819.62	715.12	711.24	707.79	694.18	820.72	211.67	668.62
15 to 16	623.06	579.22	576.69	571.47	564.85	153.26	685.64	536.31
16 to 17	254.22	386.65	379.69	381.10	344.88	440.33	124.53	330.20
17 to 18	181.61	160.42	169.52	157.00	138.81	178.78	81.77	152.56

The simulation was performed using solar irradaynce data in the interval between 8 a.m to 6 p.m**.** Data from ten different times were used. The images shown in the results presented here refer to the simulation of schedules and values of solar irradaynce specific to the intervals: 8 a.m to 9 a.m; 9 a.m to 10 a.m; from 10 a.m to 11 a.m, and so on until the measurement from 5 p.m to 6 p.m**.**

The simulation results were compared to the images obtained from a thermal camera. The images were recorded keeping a distance of 10 meters from the experiment. The measurement with the thermal camera was performed between 1 p.m to 2 p.m. For purposes of comparison, the simulation step will be used in this period.

3. Results

The results obtained in the simulations are presented from Figure 5 to Figure 14. The images show, through the color differentiation, the temperature values of the surfaces analyzed.

Figure 5 shows the behavior of the average temperature of the roof and the photovoltaic system between 8:00 a.m and 9:00 a.m.

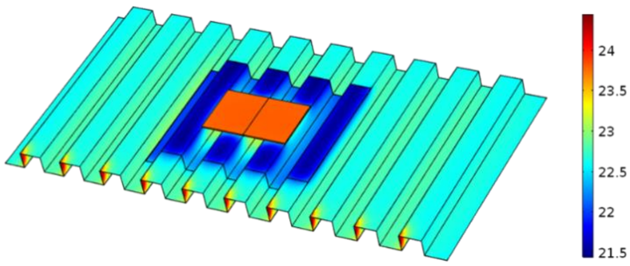

Figure 5 –Thermodynamic simulation from 8 a.m to 9 a.m

The temperature of the roof without reflective paint was 23°C, except for the edges of the roof that had a higher heating (between 23.5°C and 24°C), factor to be assigned to the solar position of each time. The temperature of the roof with reflective paint was 21.5°C, except the area under the photovoltaic panel that had a heating above 1.5°C. The temperature of the photovoltaic panel was the highest, reaching a value of approximately 24°C, a factor attributed to the composition of the materials of this surface.

Figure 6 shows the average temperature behavior of the roof and the photovoltaic system between 9 a.m and 10 a.m..

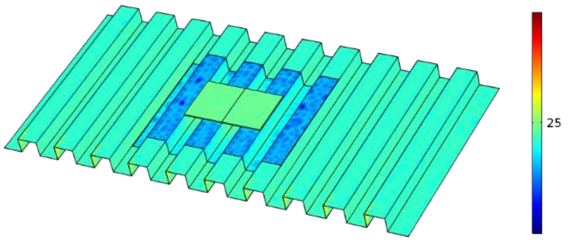

Figure 6 - Thermodynamic simulation from 9 a.m to 10 a.m

In this measurement the temperature of the materials did not exceed 25°C, so, in the three surfaces where different materials were assigned, the temperature variation is centesimal, and the temperature of the roof with the reflective paint is lower than the temperature of the roof without paint.

Figure 7 shows the behavior of the average temperature of the roof and the photovoltaic system between 10 a.m and 11 a.m..

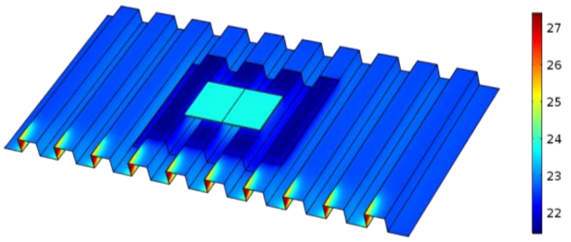

Figure 7 - Thermodynamic simulation from 10 a.m to 11 a.m

The maximum temperature obtained was 26°C and it can be seen at the edges of the roof without relfective paint. The minimum temperature was approximately 22°C, and it can be seen in the part of the roof painted with reflective paint. In the photovoltaic panels the temperature was 24°C.

Figure 8 shows the behavior of the average temperature of the roof and the photovoltaic system between 11 a.m and 12 a.m.

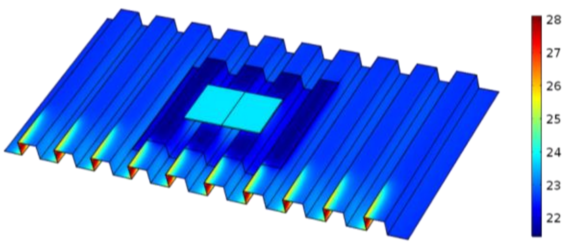

Figure 8 - Thermodynamic simulation from 11 a.m to 12 a.m

The results obtained in this simulation was similar to the results of the previous simulation shown in Figure 7, differing only by the edge of the roof without reflective paint, which had the most part of the roof heated.

Figure 9 shows the behavior of the average temperature of the roof and the photovoltaic system between 12 a.m and 1 p.m.

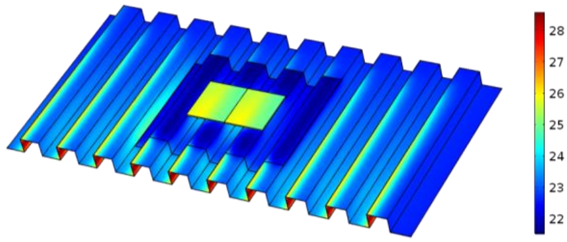

Figure 9 - Thermodynamic simulation from 12 a.m to 1 p.m

As shown in the image presented above, the maximum temperature covered the lower and upper parts of the roof without reflective paint, with a temperature range between 25°C and 28°C. The temperature of the roof with the reflective paint was 22°C, with a small heating under the photovoltaic panels. The highest temperature corresponds to the panels, varying between 25°C and 26°C.

Figure 10 shows the behavior of the average temperature of the roof and the photovoltaic system between 1 p.m and 2 p.m..

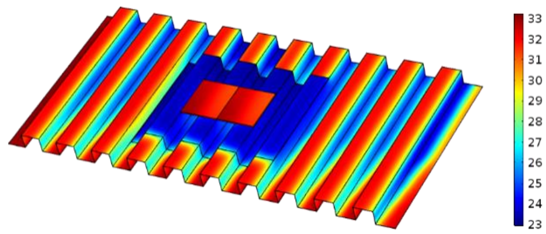

Figure 10 - Thermodynamic simulation from 1 p.m to 2 p.m

In the simulation from 1 p.m to 2 p.m the photovoltaic panels had the highest temperature, reaching 33°C, and the roof with reflective paint had the lowest temperature, equal to approximately 23°C.

A fact did not occur in the precious simulations and can be seen in the simulation of the 1 p.m to 2 p.m, the thermal gradient represented by a line of thin thickness between the painted surface and the roof without paint. The variation of the temperature in the roof without paint also did not occur with high intensity in the images already shown, fact that could have occurred only in this image by the solar position as well as by the increase of the solar irradaynce at certain time.

Figure 11 shows the behavior of the average temperature of the roof and the photovoltaic system between 2 p.m and 3 p.m..

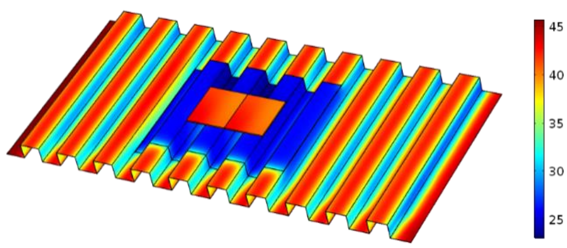

Figure 11 - Thermodynamic simulation from 2 p.m to 3 p.m

By analyzing the figure it is possible to see that the temperature of the roof without the reflective paint reached 45°C, the photovoltaic panels varied between 40°C and 45°C, and the temperature of the painted surface of the roof was approximately 28°C.

Figure 12 shows the behavior of the average temperature of the roof and the photovoltaic system between 3 p.m and 4 p.m.

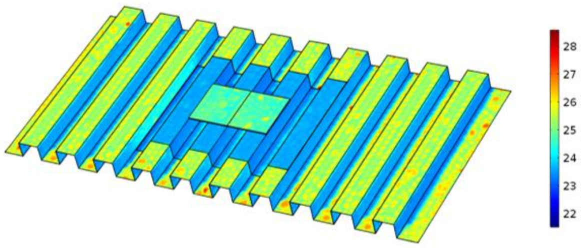

Figure 12 - Thermodynamic simulation from 3 p.m to 4 p.m

The three surfaces analyzed had similar temperatures, approximately 25°C. As in the other simulations, the painted area had a temperature lower than the area without paint and the photovoltaic panels.

Figure 13 shows the behavior of the average temperature of the roof and the photovoltaic system between 4 p.m and 5 p.m..

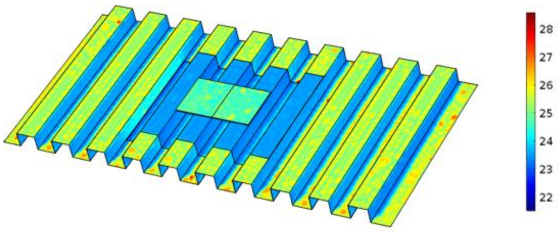

Figure 13 - Thermodynamic simulation from 4 p.m to 5 p.m

The analysis of the Figure 13 is similar to the Figure 12. It is possible to see by the color scale that the surfaces temperature had the same behavior and the same value in both simulations, even with different levels of irradaynce imputed in the software.

Figure 14 shows the behavior of the average temperature of the roof and the photovoltaic system between 5 p.m and 6 p.m.

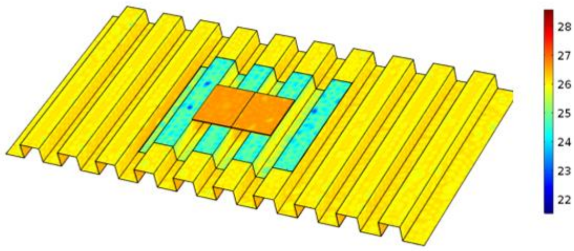

Figure 14 - Thermodynamic simulation from 5 p.m to 6 p.m

From the color scale it can be observed that the photovoltaic panels were the hottest surfaces under analysis, and the temperature of the roof with reflective paint representes the coldest part.

The results obtained by the simulation steps were compared with thermal images captured by a thermal camera (FLIR TG 165). For comparison purposes, the measurements with the camera on a sunny day with maximum radiation rates of 900 W/m² were made at 2 p.m.

Figure 15 shows the behavior of the temperature in the photovoltaic panels and the roof surface in the set A (photovoltaic system without reflective paint), recorded by the thermal camera. The temperature lines (L1 and L2) in the image indicates the temperature profile on these surfaces.

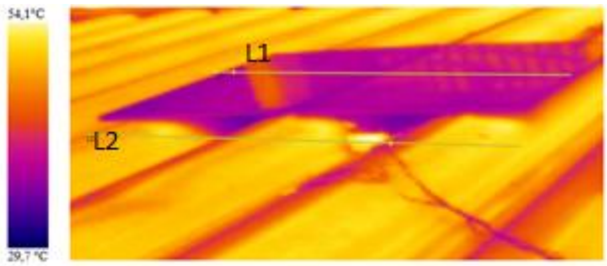

Figure 15 – Temperature behavior of the photovoltaic panels and the roof surface in the set without reflective paint

Table 3 presents the maximum and minimum values of temperature at the two measurement points (roof and the photovoltaic panels) on the surface of the unpainted roof

Table 3 – Temperature values obtained by the thermal images of the set without reflective paint

Score	ºC Maximum	ºC Minimum
L1	49.1°C	38.4°C
L2	53.9°C	41.7°C

Figure 16 shows the thermal image of set B (with reflective paint), where the lines L1 and L2 represents the temperature profile on the roof and panels surfaces.

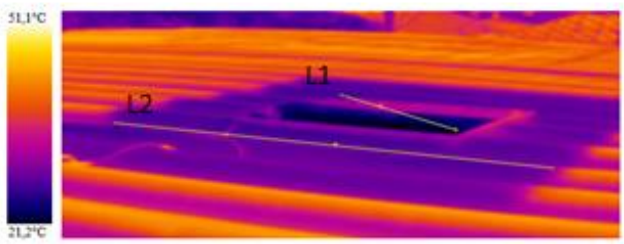

Figure 16 - Temperature behavior of the photovoltaic panels and the roof surface in the set with reflective paint

Table 4 presents the maximum, minimum and average values of the surfaces of the photovoltaic panels installed on the roof covered by reflective paint (L1) and the roof painted (L2).

Table 4 – Temperature values obtained by the thermal images of the set with reflective paint

Score	ºC Maximum	ºC Minimum
L1	49,1°C	38,4°C
L2	53,9°C	41,7°C

The results of the thermal camera show the reliability of the simulation results in relation to the surface temperatures, since the results of the two measurements at the same time were similar.

The maximum temperature of the roof recorded by the thermal camera was 51,1°C in the area without the reflective paint. In the thermodynamic simulation, the maximum value of the roof was 45°C. On the surface of the painted roof the thermal camera recorded approximately 22°C, while the temperature simulation was 25°C. The panels temperature showed the greatest disparity with a difference of 10°C between the value simulated and measured by the thermal camera. The difference can be attributed to the difference between the absorbance and reflectance indices and those provided by the software in which the simulation routinvai es were performed.

4. Conclusion

This paper presented thermodynamical simulation results of two photovoltaic systems installed on a galvanized steel surface with and without reflective paint. The simulation was done using the finite element method and had the objective to show the influence of the surface material where the photovoltaic panels are installed at their operating temperature.

The results of the simulation as well as the measurement made by the thermal camera showed that the surface painted with reflective paint reached lower temperatures than the adjacente areas where the original characteristics of the roof. From 2 p.m to 3 p.m, when the solar incidence is very high, the difference between the maximum and minimum temperature reaches 20°C.

The material used on the installation surfaces of the photovoltaic panels can help to reduce the operating temperature of the panels and consequently increase the energy production, improving the energy efficiency.

The solar reflectance of the paint directly affects the thermal performance of the painted surfaces, proving that to a higher solar reflectance of the paint (or the lower is the absorption), lower is the surface temperature of the coating.

The reflective paint has a high emissivity index and a low absorption index, so that the solar irradaynce reaching a certain surface is not absorbed, resulting in the temperature reduction of the surface and environment.

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