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TEMPERATURE ANALYSIS IN A PHOTOVOLTAIC ARRANGEMENT: AN EXPERIMENTAL APPROACH

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Abstract. *The aim of this work was realized an energy balanced, using collected parameters in an experimental project and perform an electrical and thermal analysis of a photovoltaic panel. Developed a photovoltaic panel, through the manufacture of its components, being installed thermocouples behind the solar cells and on top of the glass to determine respectively the temperature in the cells and the temperature on the surface. The other data were made through the compact meteorological station and two pyranometers that measured the ambient temperature, wind speed, the horizontal global radiation and the global tilted radiation with an inclination equal to latitude in Brasília-DF. To register the voltage data used if an open circuit system connected directly in the Datalogger. The efficiency of a photovoltaic panel is influenced by solar radiation and temperature. Therefore, it is important to perform analysis of the energy balance to cover all its components. It was possible to verify the temperature variations in the cell through three different methods: collected by the experimental apparatus, calculated by the mathematical model and calculated by Kalogirou (2016). The results showed a great approximation with the Kalogirou equations. The methodology is based on data collection in an experimental project and analysis will be developed through the software MATLAB® R2016a.*

Keywords: *Temperature, photovoltaic panel, energy balance*

1. INTRODUCTION

The perspective of population growth has as consequence the increase of energy demand. The generation of electricity to meet this growing demand through the use of non-renewable sources, mainly fossil fuels, would be imprudent, because their contribution to climate change as the burning of fossil fuels releases carbon dioxide (CO2) and other gases. Fossil fuels accounted for 87.43% in 2005 and 86% in 2015 of the global matrix of electricity generation showing a drop of 1.6%, in 10 years (BP, 2016).

In this context, photovoltaic solar energy has been growing, with the reduction of the prices of photovoltaic panels, which converts the solar radiation into electric current. The process is carried out by photons contained in sunlight that when reaching the cell create an electric field, this occurs in the union of the modified semiconductor materials.

The power generated by a photovoltaic (PV) panel is related to the amount of incident radiation and temperature. Increasing the temperature causes losses in the efficiency of converting solar radiation into electrical energy. The heating of the panel is caused by climatic variations, by the solar cell through the reverse current or even by its degradation. The temperature of the photovoltaic cell is a consequence of the energy exchange in the various forms between the panel and the environment in which it is inserted. For a better understanding of the parameters that influence these exchanges, an experiment was established with the measurement of several variables that participate in the energy balance of a PV panel.

2. MATERIALS AND METHODS

For measurement the variables of energy balance, a PV panel was constructed and instrumented, with temperature sensors (thermocouples) mounted on the solar cells, on the glass and on the backsheet. Furthermore, a resistive circuit for measuring the electrical power generated by the panel. In addition to specific panel variables, meteorological parameter such as air temperature, humidity and irradiance (direct and diffuse, both horizontal and in the plane of the pa nel) were measured. These variables will be used in the modeling of the terms the energy balance of the panel in order to know the relative relevance of each plot. The tests were performed in Brasília – DF.

Brasília is located in the center of Brazil with a latitude of 15° 36' 03" S, longitude de 47° 42' 47" and altitude of 1023 m, and presents an altitude tropical climate, characteristic of plateaus and mountains, the region has a well-defined rainfall regime. The rainy season starts in October and lasts until March. The dry season takes place in the rest of the year, from April to September (Sonda, 2018). That is, it has a period of greater diffuse radiation, between October and March with the accumulation of rain clouds in the summer, and clear sky from April to September with greater direct radiation.

Through the compact weather station, the climatic variations can be checked throughout the day, the most relevant is the ambient temperature, and wind speed.

2.1 Mathematical model

In order to improve the methodology of the mathematical model, power analysis and heat transfer were established and the energy balance was then developed.

The generated power of a photovoltaic panel is intrinsically related to the temperature and incident radiation. Therefore, to measure the power generated by the panel a resistive circuit was connect to the PV panel terminals. The power output by the panel is given by Ohm's law, eq (1):

$$P = V.I = V^2/R, \tag{1}$$

where V is the voltage (continuously measured) and R is the resistance (measured in the lab prior to the experiment).

The incident radiation and temperature have a significant impact on the energy produced. The output power decreases with the increment of the temperature, but raises with increasing incident radiation. And the tension decreases with the temperature and the current raises linearly varying with the incident radiation (Oliveira, 2008).

The thermal analysis is performed by estimating the several terms of the energy balance by calculating the heat transfer rate for each component of the panel from physical properties and measured temperature. Convection occurs mainly between the top and bottom surfaces of the panel and the atmospheric air. It is expressed by Newton's Law of cooling in eq. (2), where the convection coefficient (h) is proportional to the surface area (A) and the temperature difference between the surface (Ts) and the environment ($T\infty$).

$$Q_{conv} = -h.A(T_s - T_\infty) \tag{2}$$

Jones (2001) determines that the convection coefficient should be considered as natural and forced convection. The cooling in the natural convection occurs by the temperature difference between the module and the environment. Duffie and Beckman (2013) present considerations for determining the coefficient of heat transfer by forced convention through the wind.

The heat transfer by radiation can be estimated by separating incident solar radiation and thermal radiation exchanges, in short waves and long waves, respectively. In Equation (3), it shows the solar radiation as short wave, where it is related to the absorptivity (αs), the area (A), the global radiation (G) and the albedo (ρ). Equation (4), the long wave, accounts for the exchange of thermal radiation between PV and ambient, through emissivity (ε), Stefan Boltzmann's constant (Σ) and the variation of the ambient temperature (T∞) with that of the surface (TS).

$$Q_{rad,SW} = \alpha_s.A.G.(1 - \rho) \tag{3}$$

$$Q_{rad,LW} = \varepsilon.\sigma.A.(T_\infty^4 - T_s^4) \tag{4}$$

With the variables measured and the physical properties of the materials a reasonably accurate estimate of the terms of the energy balance will be possible. The energy balance of a photovoltaic panel was developed as a function of temperature. The equation is based on the balance between the thermas inertia $\left(mc\frac{dT_{PV}}{dt}\right)$ and the heat exchange by radiation in short waves $(Q_{in,SW})$ and long waves $(Q_{out,LW})$ convection $(Q_{out,conv})$ and the power generated (P_{PV}). The energy balance is described in. Eq. (5).

$$mc\frac{dT_{PV}}{dt} = Q_{in,SW} + Q_{out,LW} + Q_{out,conv} - P_{PV} \tag{5}$$

The inertia term on the left side of equation (5) is given by eq. (6). This is determined by the mass of the glass (m_{gl}) and the solar cell (m_{cell})in the photovoltaic module, with their respective specific heat (c_{gl} e c_{cell}).

$$mc\frac{dT_{PV}}{dt} = m_{gl}c_{gl}\frac{\Delta T_{gl}}{\Delta t} + m_{cell}c_{cell}\frac{\Delta T_{cell}}{\Delta t} \quad (6)$$

According to Jones (2001), the specific heat and density of a monocrystalline solar cell and the glass are described in Table (1).

Table 1. Specific density and heat values of the components of a solar module (Jones, 2001).

Solar Module	ρ (Kg/m³)	c (J/KgK)
Monocrystalline solar cell	2330	677
Glass	3000	500

2.2 Experimental apparatus

In order to obtain a comparative analysis of the proposed model, a prototype of a photovoltaic panel is developed capable of providing data. The materials used for the construction and analysis of the prototype are presented below:

Table 2. Solar module components and description of materials used in experimental design.

Components	Description
Photovoltaics cells	Monocrystalline silicon solar cell, with dimension of 156 156mm, power of 4.8 W, grade A and efficiency of 19.8%.
Glass	The glass used has 3 mm thickness and high transparency. Its density, expressed in the official system of units, is 2.500 kg/m³.
Film encapsulating for Solar Panel – EVA	Ethylene Vinyl Acetat is a material that protects photovoltaic cells
Backsheet	hick white plastic film that goes on the back of the solar panel
Junction box Or Connection box	to electrically connect the photovoltaic panel
Frame	The frame, in general, remains exposed to the weather.

The PV panel was assembled by grouping the solar cells, connected by a tin band, and welded at the points of copper contacts in the solar cell itself, whose function is to carry the current. The thermocouples are installed underneath the solar cells in order to measure the temperature variation in the solar cell itself. The PV panel built consisted a system of 3x3 solar cells. The mounting of the PV panel was made with the layers of glass, EVA, solar cells, EVA and backsheet, as shown in Fig. (1). The frame was added to fix the glass and the junction box that provides the power output in the system employed.

In Figure (2), there are the positions of thermocouples mounted on solar cells. The front view is represented on the left image (Figure 2), where two thermocouples were installed on top of the glass, to verify the temperature variation on the glass surface of the photovoltaic panel. The right image (Figure 2) represents the thermocouples installed in the back of the solar cells in order to verify the temperature variation in the three positions of the solar panel. To record the data a Datalogger was used, programmed to collect the temperature information in each thermocouple installed in the photovoltaic panel. A weather station was employed in order to collect the ambient temperature and wind speed. Two pyranometers to measure the incident global radiation, installed in the horizontal position and another inclined together with the photovoltaic panel.

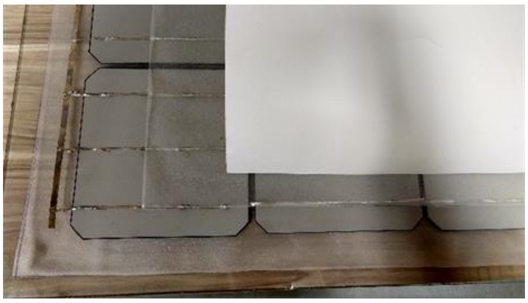

Figure 1. Assembly process with the glass layers, EVA, solar cells, EVA and backsheet, respectively.

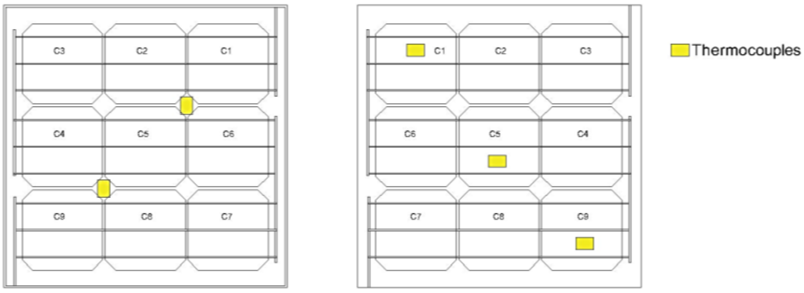

Figure 2. Thermocouple positions in solar cells, respectively with front and rear view.

The experimental apparatus diagram with its instrumentation for data collection is described in Figure 3. In addition, data from a complete solarimetric station installed in the Energy and Environment Laboratory, close to the test site is available.

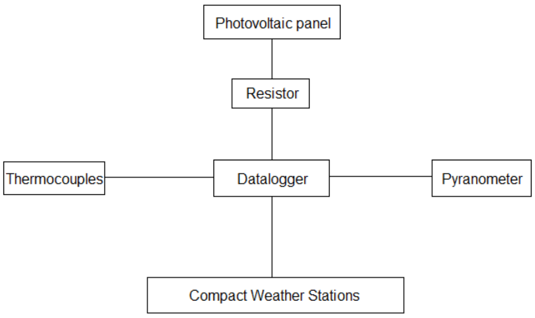

Figure 3. Diagram of the experimental apparatus.

The slope usually used is that of the latitude of the site and with the upper surface facing north. A resistor was installed to limit the current along with a fan to cool the system. And in the photovoltaic panel has the output of the positive and negative wires through a junction box up to the Datalogger. In Figure (4) it shows the experimental apparatus during its operation on a sunny day and its respective systems for data collection.

Figure 4. Experimental Project in a sunny day and the system for data collection.

The results were analyzed based on a scheme of energy types in a photovoltaic panel, as shown in Fig. (5). It is observed that it has an influence mainly of convection, radiation and power.

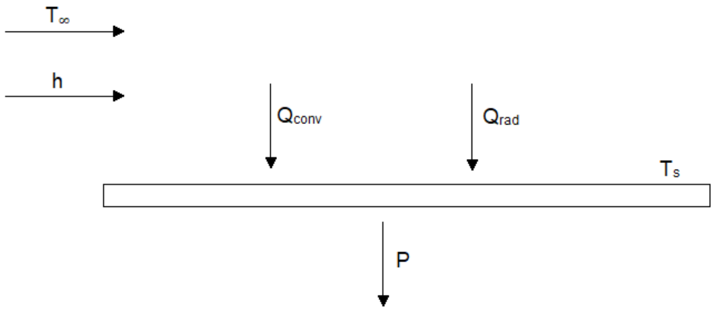

Figure 5: Scheme of energy types in a photovoltaic panel

In the convection, the flow can be influenced by different means: through the flow generated on the surface of the module caused by the difference of its temperature and the environment, the so-called natural convection and through the wind that the module is exposed, called forced convection. According to Jones (2001) to determinate the convection coefficient both have to be considered.

In this work the natural convection is determined by Holman (2010), through a constant with the cubic root of the variation of the temperature of the module with the environment.

The forced convection is determined by Duffie and Beckman (2013), where it presents considerations to determine the coefficient of heat transfer by wind. The roof, trees and nearby buildings influence the wind flow. Grounded in a collector installed in a house, Mitchell (1976) investigated heat transfer and were often well represented as a sphere when the diameter is equivalent to cubic root of volume, assuming a house is a sphere. However, the calculations for the heat transfer coefficient by the wind are not established, and it is recommended when forced and natural convection occurs simultaneously.

The balance of solar radiation energy on the surface is the energy absorbed from the sun with the difference of the absorbed from the environment and the emitted. From this energy balance provide the radiation of short waves and long waves. Short-wave radiation is the term referring to the incident energy absorbed from the sun, which is the difference between received and reflected energy. The received energy is the amount of absorption of the photovoltaic panel, according to Jones (2001), the average absortivity of a PV is approximately 77%. The reflected energy is characterized by the albedo of the soil, according to Silva et al. (2016) for the region of the Federal District in urban area the maximum albedo is 19.5%.

The long-wave exchange has to account for the radiation from the surface and from the atmosphere. The emissivity of the module by Jones (2001) is 0.9 for clear sky conditions.

The experimental project was placed in the sun in the morning and collected data until the afternoon when solar radiation was minimum. All equipment was leveled, and the panel with its upper surface facing north with the angle of inclination equal to that of local latitude. To power the equipment was used a 12 V battery.

3. RESULTS AND DISCUSSION

The solar radiation collected by the experiment is shown in Fig. (6), which shows the variation of the horizontal and inclined (tilted) global radiation, in Brasília – DF. The global radiation in inclined plane has an inclination of 15.8°, this angle increases the intercepted radiation and reduces the loss of reflection.

In this same test it is possible to verify, in Fig. (7), the variation of the temperatures in the thermocouples installed in the photovoltaic panel. Thermocouples C1, C5 and C9 correspond to those mounted on the back of the solar cell and the C1F and C9F on the front of the glass surface, from their respective positions on the solar cells, as shown in Fig. (2).

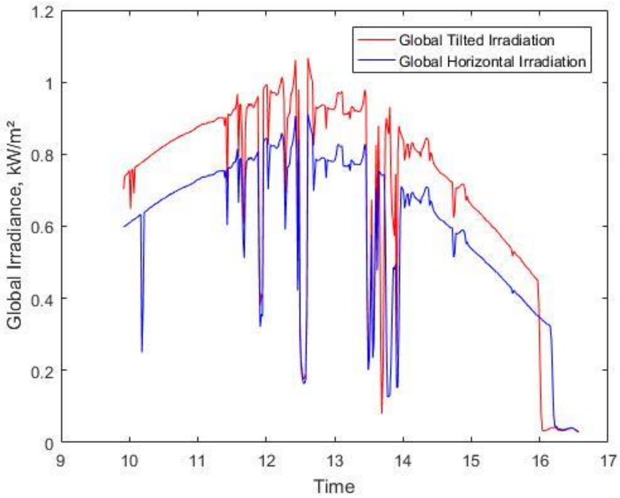

Figure 6. Global radiation in a horizontal plane and inclined with the latitude of the site.

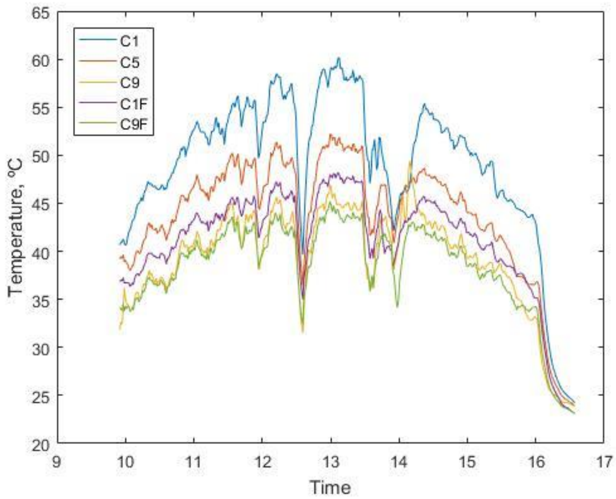

Figure 7. Temperature in tehrmocouples

It is possible to observe that there is a pattern from the largest to the lowest temperature among the thermocouples installed in the solar cells. At C1 with its highest temperature, it presented a difference between thermocouple C9 of approximately 13.75ºC. And the two thermocouples on the surface of the glass showed a difference of 1.42ºC, the highest temperature being the C1F, that is, the measurement of the temperature on the surface of the glass, does not describe the actual values in the solar cells. According to Solheim (2013) and Santolin (2016), this occurs due to reverse current, which even under cloudy day conditions heating can occur.

To identify the temperature changes an infrared camera was used as show in Figure 8 to caputure a thermal image in color scale along the solar panel. The image was captured on a clear day. The figure shows spatial heterogeneity in temperature distribution probably due to two factors, photovoltaic hotspot and different convection heat transfer.

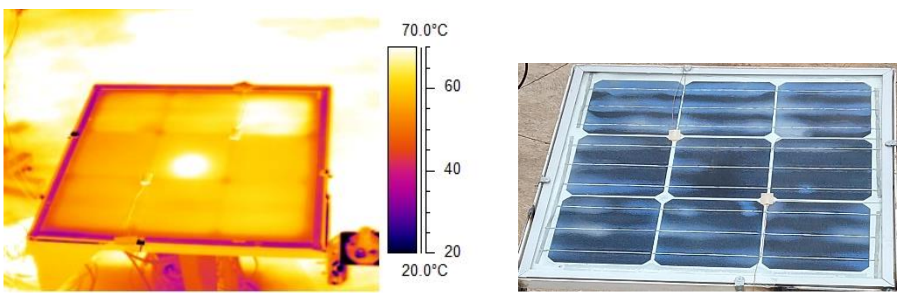

Figure 8. Temperature variation captured by an infrared camera and photovoltaic solar panel photo on a clear day

Kalogirou (2016), describes approximate equations to determine the cell temperature of a photovoltaic panel operating under the nominal cell operating temperature conditions (NOCT). The calculated values were performed by the energy balance, as described above in eq. (5). The values used are wind speed and ambient temperature. The measured values were recorded in the Datalogger by thermocouples within the solar module

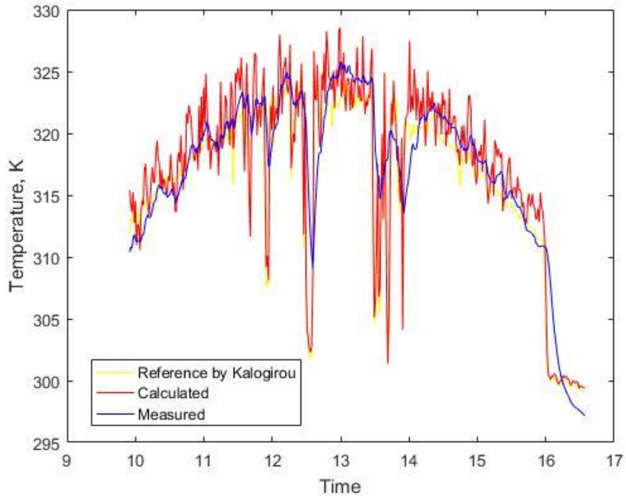

Figure 9. Solar cell temperature.

A polynomial curve fitting was performed in order to adjust a curve for a better approximation between the temperature calculated by the Kalogirou (2016) model, those calculated by the mathematical model established in this article, through heat transfer and power and data collected by the experimental design. It is observed that in Fig. (10), the approximation of the data by the curves, shows a better approximation between the calculated values of the energy balance and the equations determined by Kalogirou (2016).

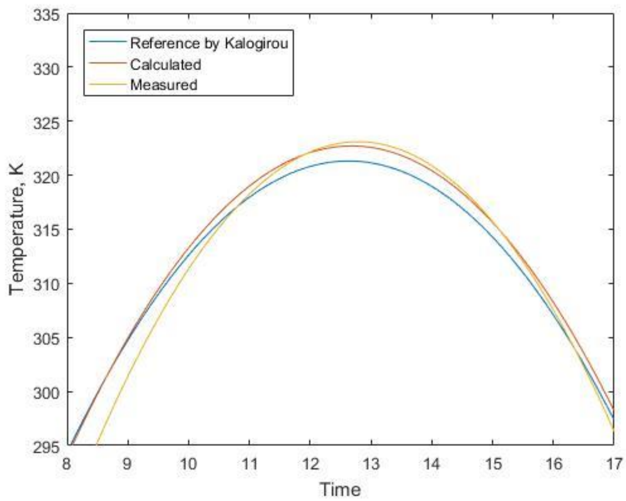

Figure 10. Polynomial temperature curve adjustment

These results show that the mathematical modeling calculated by an energy balance presents a better approximation than the Kalogirou equations. So, to check these temperatures more accurately, it is necessary to develop a mathematical model that determines the temperature variations in each component of a photovoltaic module.

4. CONCLUSIONS

This work presented an energy balance in a photovoltaic panel through the temperature measurements of the several panel components, solar radiation and power generation. The heat transfer process, characterized by solar radiation heating, the energy losses by convection and the long wave exchange between the panel and earth surface and atmosphere.

To characterize the established mathematical model, an experimental design was performed, in which temperature data were collected, through thermocouples placed on the back of the solar cells, the top of the glass and the back of the panel backsheet, coupled global solar irradiance, both horizontal and on inclined surface, and the ambient temperature and wind speed through the compact weather station.

The results presented allowed to visualize the differences of temperatures in the solar cells, and their respective time variations in a clear day of sky. The considerable increase of the panel temperature is attributed to thermal charge due to the incident solar radiation in Brasília - DF. It is noteworthy that the modeling is a simple approximation and the terms of the energy balance were determined in order to have a better knowledge of its relative contributions. Such knowledge will allow the construction of more reliable models of thermal balance of photovoltaic panels and thus better estimates of their electric power generation.

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