Technical Note

Develop of a system for the mensuration of the energy efficiency of solar cells

Desarrollo de un sistema para la medición de la eficiencia energética de celdas solares

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MSc. Ivelisse Almanza-Fundora [I*], Lic. Regla Ramona García-Fernández [I], Dr.C. Francisco García-Reina [I]

[I]Universidad de Ciego de Ávila Máximo Gómez Báez, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba.

ABSTRACT: This document deals with the development of a system for the measurement of the solar power and the electric power generated by the solar cells of a photovoltaic panel, in order to assess energy efficiency in the conversion of light energy into electrical energy. So the first thing is to calibrate the light power emitted a tungsten lamp, taking into account the temperature of the filament and the emittance of the tungsten as a function of temperature and wavelength. The temperature of the filament is determined by measuring the resistance as a function of the voltage and amperage of the filament power and using the dependence of the resistivity of tungsten with temperature. The luminous power that emits the filament is calibrated with phototransistors and photodiodes patterns Siemens, photoelectric units (Lux, lx) and in unit of energy (W/m2). With the I-v characteristics of the cell, the Voc open circuit voltage and intensity of current in short circuit Isc determines the maximum electrical power supplied by the cell, which divided between the light output provides the efficiency rating conversion of light energy into electricity by the photovoltaic cell. Studied cells have an open circuit (Voc) of 4.6 V voltage, intensity of current in short circuit (Isc) of 87 mA and efficiency of 12.4% with irradiation of 399,6 W/m2. Key words: solar cells, energy efficiency measurements.

Keywords: power luminous lot, electric power, photovoltaic panel.

RESUMEN: El presente trabajo muestra el desarrollo de un sistema para la medición de la potencia luminosa solar y la potencia eléctrica generada por las celdas solares de un panel fotovoltaico, con el fin de evaluar la eficiencia energética en la conversión de la energía luminosa en energía eléctrica. Para esto lo primero es calibrar la potencia luminosa que emite una lámpara de tungsteno, teniendo en cuenta la temperatura del filamento y la emitancia del tungsteno en función de la temperatura y la longitud de onda. La temperatura del filamento se determina midiendo la resistencia en función del voltaje y el amperaje de alimentación del filamento y usando la dependencia de la resistividad del tungsteno con la temperatura. La potencia luminosa que emite el filamento es calibrada con fototransistores y fotodiodos patrones Siemens, en unidades fotoeléctricas (en lux, lx) y en unidades energéticas ($W/m^{2)}$. Con las características I-V de la celda, el voltaje a circuito abierto *Voc* y la intensidad de la corriente en cortocircuito *Isc* se determina la potencia eléctrica máxima suministrada por la celda, la cual dividida entre la potencia luminosa proporciona el valor de la eficiencia de conversión de energía luminosa en eléctrica por la celda fotovoltaica. Las celdas estudiadas tienen un voltaje a circuito abierto (*Voc)* de 4,6 V, una intensidad de la corriente en cortocircuito (*Isc)* de 87 mA y una eficiencia de 12,4% con una irradiación de 399,6 W/m^2.

Palabras clave: potencia luminosa solar, potencia eléctrica, panel fotovoltaico.

[*]Author for correspondence: Ivelisse Almanza-Fundora, e-mail: ivelisse@unica.cu

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INTRODUCTION

In the search for alternative energy sources, but at the same time, to protect the environment, contemporary governments have taken the decision to use the Sun as a great source of energy because it is infinite and inexhaustible . In Cuba, from the energy revolution motivated by Commander in Chief Fidel Castro Ruz, since the beginning of the last decade, a great effort is being developed in the development of systems for the use of solar energy, both for the direct heating, as in its conversion into electricity in solar photovoltaic panels. The importance of this issue is such today that it has been reflected in the guideline No. 253 of economic policy and Social Revolution drawn in the 6th Congress of the Communist Party of Cuba PCC (Partido Comunista de Cuba) (2011), in terms of the development of reliable and accurate systems to measure energy resources that the country has, with special relevance to solar energy.

In photovoltaic systems, it is essential to measure the efficiency of solar cells, since this lets to know how much power of solar radiation (W/m2) each of them absorbs, which also requires to know exactly, how much solar energy reaches each location per unit area in one second (Daniels, 1981). Then, the amount of solar energy and conversion into electric energy efficiency are the two fundamental parameters to measure and control in all photovoltaic solar energy system (Böer, 1979; Green, 1982; Alan *et al.*, 1990; Bacus, 2001; Doherty y Malone, 2001; Ginley *et al.*, 2008).

To better understand the essence of this work, it is convenient to wonder: what is solar energy? It is the radiant energy produced in the Sun, as a result of nuclear fusion reactions, which arrives on Earth through space in packets of energy called photons (light), that interact with the atmosphere and Earth surface. Life on Earth would not exist without the presence of the Sun (Kreith y Kreider, 1978; Iqbal, 1983; Manrique, 1984; Nelson, 2003; Espejo Marín, 2004). The planet would be too cold, plants do not grow or it would not have any life, except some bacteria. Energy resources come directly or indirectly from the Sun. Fossil fuels are plants and very old trees, which grew thanks to the sunlight and have been compressed over millions of years. Wind energy and hydraulics are generated through processes driven by the Sun. The fuel wood is obtained from trees, which could not grow without sunlight (Kreith y Kreider, 1978; Böer, 1979; Daniels, 1981; Espejo Marín, 2004; Berri, 2014). The conversion of solar radiation into electrical energy is done by means of photovoltaic cells (Bacus, 2001; Doherty y Malone, 2001; Ginley *et al.*, 2008).

The efficiency of solar cells is crucial to reduce the costs of PV systems, since their production is the most expensive of the whole system. (Iqbal, 1983).The photovoltaic effect occurs when the solar cell material (silicon or other semiconductor material) absorbs part of the photons from the Sun. Then, the absorbed photon liberates an electron, which is located in the interior of the cell. The efficiency of the cell is really the relationship between the amount of electrons released to electrical conduction and the amount of photons of light that reach the cell and it is called internal quantum efficiency (Böer, 1979; Harper, 2000; Doherty y Malone, 2001; Bahnemann, 2004; Berri, 2014).

Hence, it is clear that it is necessary to measure with precision and reliability, energy efficiency and electric power delivered solar panels for each specific application.

Therefore, it is determined as problematic situations, the low utilization of solar energy in Cuba and the province, the ignorance of the basic parameters of the solar cells and its mode of use, the lack of measurements of energy variables solar, equipment and methodologies to measure solar energy and the efficiency of cells and solar panels (Kreith y Kreider, 1978; Espejo Marín, 2004; Meinel y Meinel, 2013; Berri, 2014).

Therefore, it is declared as a research problem: how to measure with precision and accuracy the energy efficiency of cells and solar panels?

As objective of research, it is defined to develop a system for measuring the energy efficiency of solar cells, to be used in the design and installation of photovoltaic panels for a rational and efficient use of solar energy.

The photovoltaic phenomenon is determined at atomic level, as a photon falls on the bond between two atoms and breaks it. To achieve that break in a link with little energy, it is necessary that the atom is unstable, that is, it has incomplete its valence band and the number of electrons there, is different from eight (Shah *et al.*, 1999; Harper, 2000; Wolfgang, 2002; Würfel, 2005; Ginley *et al.*, 2008). Materials that have this feature in their atoms are semiconductors (Boer y Bhattacharya, 1994). In a pure semiconductor current produced by the movement of electrons is negligible due to the low value of free carriers. Therefore, impurities are added to the material to increase the free carriers and the new material obtained is called extrinsic semiconductor. Light is composed of a set of electromagnetic radiation of high frequency, this range is called light spectrum (García y Boix, 1996; Shah *et al.*, 1999; John y William, 2006; Meinel y Meinel, 2013).

METHODS

Determination of the Radiation Intensity Emitted by the Filament

The intensity of the radiation, or irradiance *E*, emitted by a blackbody is proportional to the absolute temperature raised to four, according to Stefan-Boltzmann law:

$$E = E = \sigma \cdot T^4 \quad (1)$$

Where:

σ is the Stefan-Boltzmann constant. For gray bodies as the tungsten filament:

$$E = E = \varepsilon(T) \cdot \sigma \cdot T^4 \quad (2)$$

Where ε (T) is the emittance of tungsten, which is also a function of temperature.

Then, knowing the temperature of the filament, irradiance or luminous power radiated per unit area of the filament can be determined (in units of W/m^2).

Determination of the Filament Temperature T

The measurement of the temperature of the filament is made indirectly, by measuring its resistance according to the temperature. For a tungsten filament, its resistance is related to the temperature according to the equation.

$$R(T) = R0(1 + \alpha T + \beta T2) \quad (3)$$

Where:

T is the temperature in degrees Celsius and the α and β, coefficients valid for Wolfram are α = 4.82 10-3 / K and β = 6.76 10-7 /K^2 , respectively.

The resistance of the filament R (T) is calculated by applying Ohm's law, from the voltmeter and ammeter indications.

The power of the lamp is the V•I product

Clearing t and bearing in mind that the absolute temperature T of the filament is T = t + 273, it is obtained

And the resistance at 0 ° C is:

The emissivity of the filament is given by

$$\varepsilon(T) := -0.02071284 + 1.73311816 \cdot 10 -4 \cdot T + -1.99182555 \cdot 10 - 8 \times T2 \quad (4)$$

the total irradiance as a function of temperature.

MATERIALS

Light Bulb Tungsten 12 Volt

Then, the focus of reference used to check the calibration of the sensor used is displayed in Figure 1.

B04 light sensor

Figure 2 shows the used sensor for light intensity, formed by a phototransistor ST-1KL3A of the Korean firm Kodenchi.

Transistor scheme is presented in Figure 3 along with its collector current characteristic vs. illuminance.

Figure 3 shows the wiring diagram of the sensor used to be able to find the emissivity (W/m2) of the tungsten bulb. There is a phototransistor of reference ST-1KL3A and a commercial of 10KΩ of precision resistance (the resistance was measured in the equipment XJ2811C LCR METER and it resulted 9.991 KΩ). In parallel to that resistance, there is a commercial, ceramic capacitor of 103 (it was measured on the computer XJ2811C LCR METER and the measurement resulted 8.787 pF).

SolarCell

For this work, a solar cell of low power (Figure 4) was used. The selection was made according to the options available on the market and by selecting the best electrical properties. The parameters taken into account were, among others, power, maximum voltage, maximum current, etc.

The electrical characteristics of the cells are:

- Size 54.50 mm x 54.50 mm
- Maximum power (Pm) = 0. 414W.

FIGURE 1. Focus of reference.

FIGURE 2. Illumination sensor.

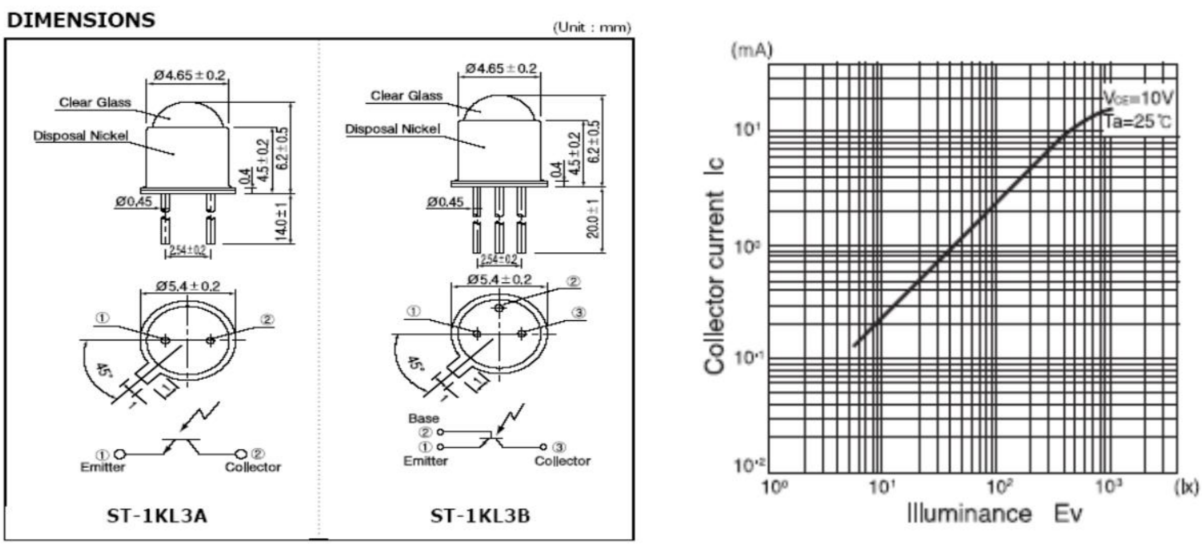

FIGURE 3. Diagram of the sensor lighting and its features opto-amperican.

- Maximum voltage of optimum work (Vm) = 4.6V.
- Maximum optimal active current (Im) = 90mA.
- Open circuit (VOC) voltage = 5V.
- Short circuit (ICC) current = 100mA.

Servo Motors

There are two servo motors used of series Towardpro MG9965 (Figure 5)

Specifications

- Weight: 55 g
- Dimensions: 40.7 x 19.7 x 42.9 mm approx.
- Torque of shaft: 9.4 kgf•cm (4.8 V), 11 kgf•cm (6 V)
- Operation speed: 0.17 s / 60th (4.8 V), 0.14 s / 60th (6 V)
- Operating voltage: 4.8 V 7.2 V
- Current range 500 mA--900 mA (6V)
- Dead band width: 5 µs
- Temperature range : 0 ° C - 55 ° C.

Arduino Mega 2560 (Figure 6)

Arduino Mega 2560 is an electronic plate based on the Atmega2560. It has 54- input / output digital pins (of which 15 can be used as

FIGURE 4. Used solar cell.

FIGURE 5. Towardpro MG9965 Servo motors.

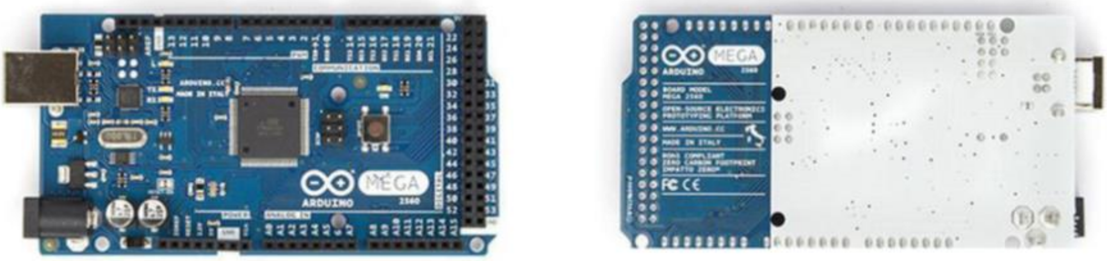

FIGURE 6. Arduino Mega 2560 35 plate

PWM outputs), 16 analog inputs, 4 UARTs (serial doors), a 16 MHz oscillator, a USB connection, a connector from power, an ICSP header, and a reset button. It contains everything needed to support the microcontroller, simply by connecting it to a computer with a USB cable or power with an AC adapter or the battery to DC to start. Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila.

With the voltage and the current and applying Ohm's law (Equation 5), the resistance of the tungsten bulb can be determined.

Measuring of electric power in the photocell and knowing the area of solar cell, the efficiency of the solar cell can be determined by:

$$\eta_{celda_j} := \frac{P_{EleCel_j}}{E_{celda_j} \cdot A_{celda}} \cdot 10^3 \quad (5)$$

RESULTS AND DISCUSSION

Determination of the Total Emission Powerof the Focus

Applying the equation, the resistance of the filament of tungsten lamp in variation with temperature was determined. R0 = 3.17 Ω / ° C, room temperature was 28 ° C, the filament resistance measured in a RLC gave 3.6 Ω (Figures 7 y 8).

Figure 9 shows the graph obtained from voltage and current of tungsten bulb when the supply voltage is varied from 4 V to 12 V, in this case is linear.

From the equation of absolute temperature of the filament that is given in K, it may be related

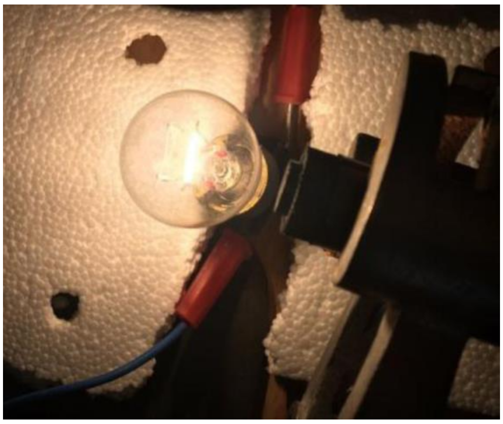

FIGURE 7. Measures taking of the light sensor.

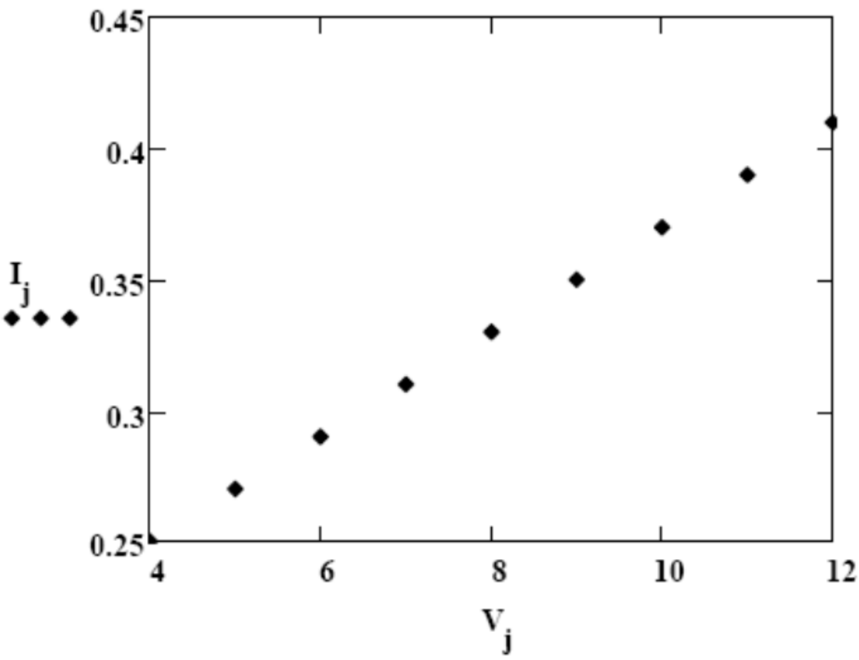

FIGURE 8. Graph of voltage vs. current.

to power supplied by the illumination sensor that is located in the following figure. It is possible to observe, in an excellent correlation (R2 = 0.978) with the Stefan-Boltzmann law of a dependency with T4.

Figure 10 shows the assembly for the measurement of the solar cell efficiency, with the diagram to estimate the power that comes to it from the filament.

Luminous flux reaching the photoelectric cell is obtained from the equation of the vector intensity of the electric field as a function of the filament. This was correlated with the one obtained by measuring the photocurrent of the phototransistor and they are consistent with a 96% of coincidence between both measurements of the luminous flux in the cell. Then the maximum error in the measurement of irradiance and, therefore, of efficiency does not exceed 4%.

The following graph (Figure 11) shows the relationship between the electrical power delivered by the photocell and the illuminance received from tungsten filament:

Measuring of electric power in the photocell and knowing the area of solar cell, the efficiency of the solar cell can be determined, in the Figure 12 the efficiency of the cell is shown with the flow that reaches the cell.

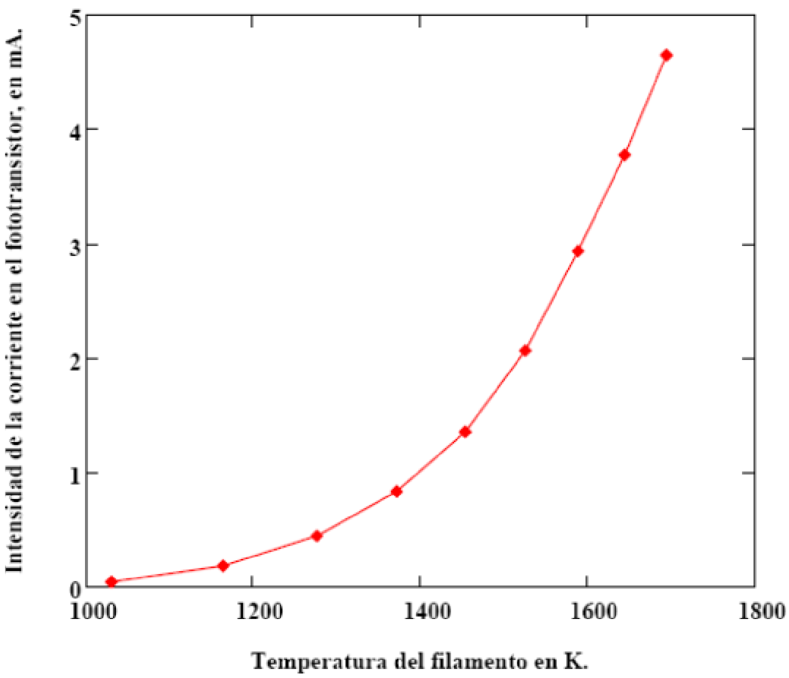

FIGURE 9. The relationship of lighting sensor collector current with the absolute temperature of the filament.

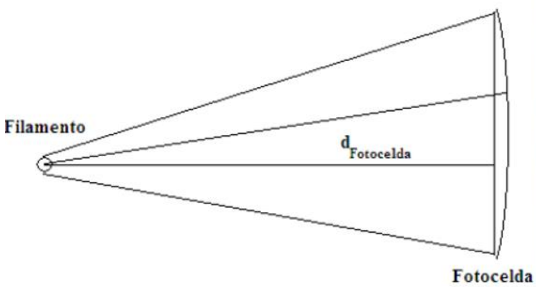

FIGURE 10. Measurement of the photocell efficiency.

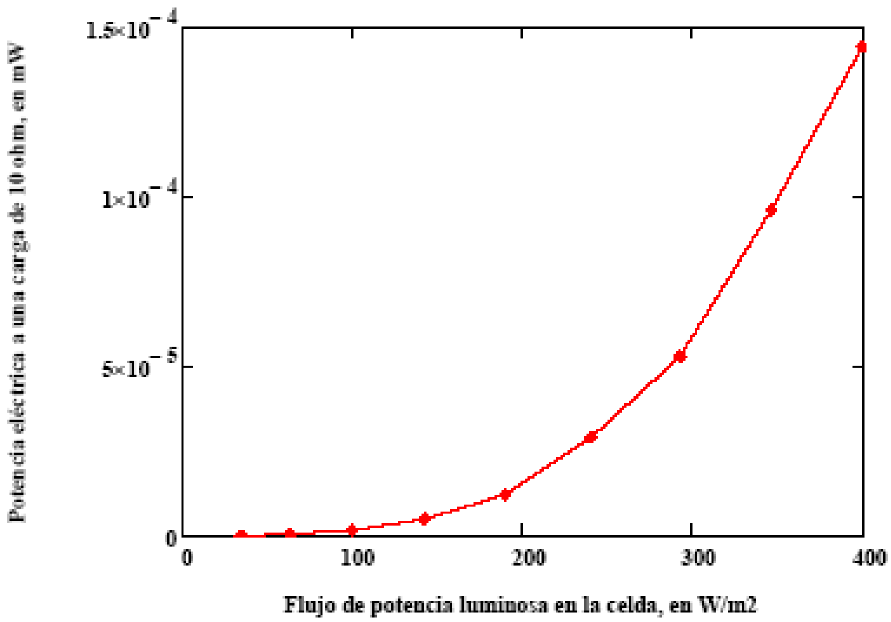

FIGURE 11. Electric power according to the luminous power.

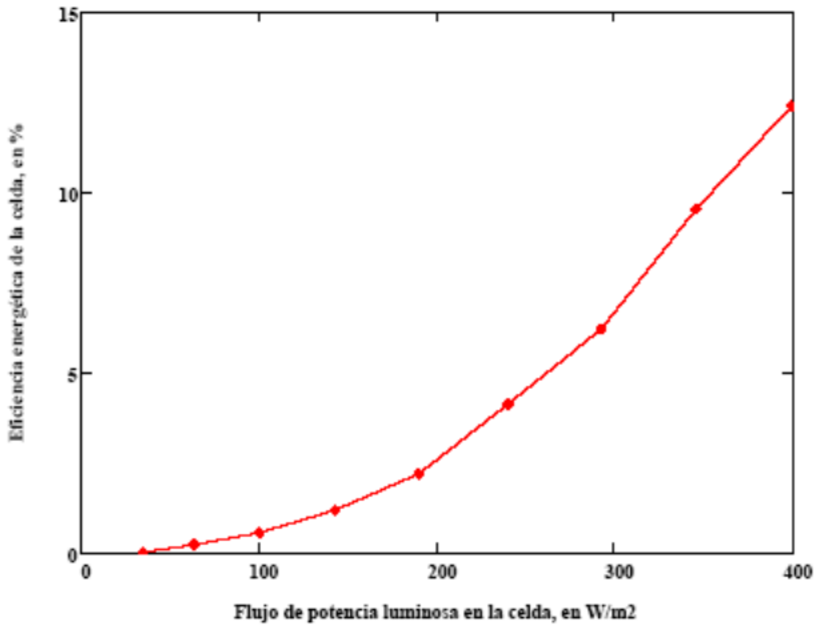

FIGURE 12. Efficiency of the cell with the flow coming into the cell.

Then with a maximum of 399,4 W/m^2 irradiance, this cell has a conversion efficiency of light energy into electricity of 12.4%.

CONCLUSIONS

- Regulated light sources with high precision tungsten incandescent lamps were developed, with power light controlled from 0 up to 400 W/m^2.
- Calibrated light radiation sensors were mounted in correspondence with light patterns sources developed, which allows obtaining a measurable response of photocells to luminous radiation.
- Four solar cells of high quality were studied for which the following mean values were obtained: an open circuit voltage Voc = 4.6 V, a current intensity in the short circuit Isc of 87 mA, with an irradiation of 399.6 W/m^2.
- The efficiency of conversion of solar energy into electricity by solar cells was 12.4%.

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Ivelisse Almanza Fundora, profesora, Universidad de Ciego de Ávila Máximo Gómez Báez, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba. Carretera a Morón km 9½, CP: 65300, Teléfono (33) 217009, Fax 5333 225768, e-mail: ivelisse@unica.cu
Regla Ramona García Fernández, e-mail: rgarcia@unica.cu
Francisco García Reina, e-mail: pancho@unica.cu

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