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Response fitting in low-cost radiation sensors

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Abstract. To obtain low-cost solar radiation sensors with energy applications, small commercial photovoltaic cells have been adapted. With the purpose to evaluate the resulting thermal drifts, a temperature sensor has been connected to a small electronic circuit. The calibration curve provided by the cells supplier is not useful in this case because it is made for a constant 20ºC temperature. Besides, the additional circuit also affects the results. This work presents not only the design and implementation of the additional elements, together with the data acquisition system, but also the results of the calibration work, the fitting of new incident solar radiation functions regarding the temperature of the cell and the intensity of the resulting current, besides the validation of the results for four of these cells.

Key words

Cell, Radiation, Solar, Thermal drift, Photovoltaic.

1. Introduction

The solar radiation measurements are taken by instruments like pyranometers, which measure the global incident solar radiation, usually on horizontal surfaces. The thermopile technology is the most used for these elements. For applications with a minor degree of accuracy silicon based technology devices, very useful though for energy purposes, are used [1]. In this sense, in the market, there are some kinds of these low-cost and small dimensions elements, like the Kipp & Zonen SP_LITE [2].

The running of these cells is similar to the one of a photodiode, so the incident solar radiation, as well as the temperature, affects the response of this element. This technology is the one being used nowadays for electric generation photovoltaic cells, these determining factors also affect the electricity produced by them. It is known that when incident solar radiation has a high incidence angle on the cells, the efficiency is high, because of the low temperature of the cells, near to the calibration temperature of 20ºC. Nevertheless, when the solar radiation positive component increases considerably, the radiation induces an increase of the temperature and a decrease in efficiency levels can be observed [3].

To evaluate the influence that the temperature of the cell has on the response of the system, a temperature sensor has been added to a small solar cell. Then, its response has been measured and the results have been compared to the radiation measurements and to other weather conditions that have been consulted in the website of the University of Jaén Research Group MATRAS (Atmosphere Modelling and Solar Radiation [4]). With these data, a procedure of recalibration of the system, which is to be used as a radiation measurement device, has been evaluated.

2. Materials and methods

A. Devices

The measurement system that have been developed (Figure 1) has 2 sensors: a radiation sensor and a temperature one, which are connected to an analog-to-digital converter (ADC) with 4 channels and 8 bits.

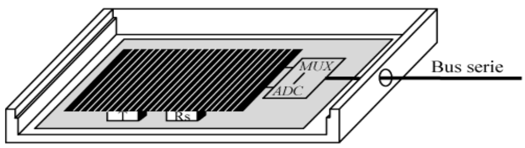


Fig. 1. General diagram of the designed sensor

To measure irradiance R (W/m^2), small high-efficiency single crystal silicon cells with dimensions: 3,5 x 5,5 cm, the ones provided by the supplier, together with the respective calibration curve (see Figure 2) have been used. This radiation sensor delivers an electric current I_P

(mA) proportional to the incident solar radiation, with an accuracy close to 275µA/Wm^{-2} (this accuracy changes from one sensor to the other and has to be obtained during the calibration process). The current flow has been converted into tension to be introduced in the converter (ADC) with a sensitivity close to 0.275 mV/Wm^{-2} using a shunt resistor R_S of 1 Ω.

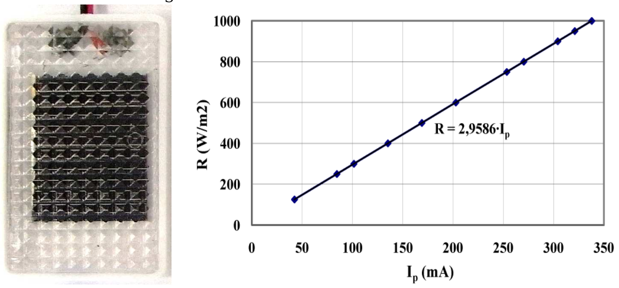


Fig.2. Radiation measurement element: a) Cell; b) Original calibration curve

Afterwards, a device to measure the temperature of the cell T_P (ºC) has been added. This sensor is an integrated one and provides a tension which is proportional to the temperature with a ratio of 10 mV/ºC and a minimum value of 0,1V for -40ºC. This device is connected with silicone to the radiation sensor to reduce the thermal resistance (see Figure 3).

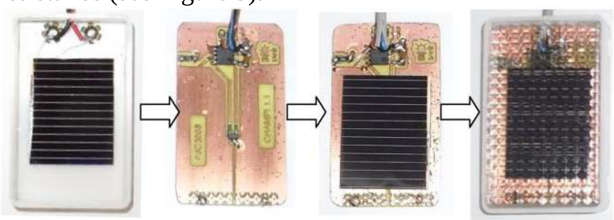


Fig. 3. Measurement device

Tensions generated by every sensor are digitized by 2 of the 4 available channels in the converter ADC. The converter ADC has a digital output (serial bus one-wire), which allows the connection of multiple measurement systems to an only data transmission wire.

The tension range at the converter ADC input goes from 0V to 2.56V, so the resolution obtained with the available 8 bits is 10mV/bit, namely, an accuracy close to 36 Wm^{-2} for the radiation measurement and close to 1ºC for the temperature measurement. The software adapts voltage signals to intensity and temperature values, and stocks these data in PC files.

B. Testing section

The extra elements added by us alter the response of the cell, so the original calibration provided by the supplier is no useful anymore, because in this calibration, it is necessary to take into account not only the response of the cell (current flow), but also its temperature for constant values of incident radiation.

The ideal calibration of the cell must be made with a solar simulation system. This equipment allows us to establish a similar radiation to the solar one with a similar spectrum and to fix a desired value. With these experimental devices it is possible to establish the air mass (m), which is the inverse cosine of the sun zenith angle θ_Z [5]. Calibrations in this kind of test bench are usually made with m = 1,5, because usually the cells are fixed facing south (solar azimuth angle: 0º) and this value squares with the medium value more characteristic in the other ones. Nevertheless, for configurations other than this, (solar azimuth angles other than 0º) the acceptability for this value of m cannot be guaranteed. Therefore, this equipment incorporates adequate complementary devices which modify m value and allow us to calibrate the cells taking into account a bigger number of conditions. As this equipment is not available to us, natural radiation has been used for our calibrations.

For the calibration, it has been taken different experimental measurements with natural radiation, with a horizontal position for the cell. In every test, the incident radiation value on horizontal surfaces R (W/m^2) has been consulted in the website of the University of Jaén Research Group MATRAS. MATRAS uses accurate devices located on the terrace roof of the same building where our measurements have been carried out. Two kinds of measurements have been taken: constant radiation ones (punctual measurements) and continuous measurement during a day.

In the first case and during several moments in a sunny day (from dawn to sunset), the current flow generated by the cell during 10 minutes, time enough to guarantee a negligible change in the incident solar radiation, has been measured. Nevertheless, it can be observed a change in the temperature of the cell during the length of every test, a change which also affects the intensity of the resulting current. Therefore, the cell must be cooled down at the beginning of every new test measurement. All data are stocked in PC files.

In the second case, intensity and temperature data of the cell have been measured nonstop during one cloudless day.

C. Response fitting

Once finalized these tests, radiation data R (W/m2) related to the intensity current flow generated by the cell I_P(mA) and to its temperature T_P (ºC) have been obtained. Meteorological parameters as temperature T_a (ºC) and environmental relative humidity H_r (%) are also taken into account. Absolute humidity x_a (kg water/kg dry air) is deduced from these data. Then, a multiparameter function is adjusted with these data to calculate radiation. As the response is nonlinear, it is necessary to turn to a least squares approximations using nonlinear techniques as those based on the Newton method [6]. The problem here is to find the shape of this function. For this purpose is resorted to the Firs Law of Termodynamics equation:

$$\alpha RS - Q_p = \frac{dU}{dt} + \dot{W} \qquad (1)$$

where radiation (R) can be shown as function of:

$$R=f\,(T_a, T_p, T_p^4, dT_p/dt, T_a, R_s\ldots) \qquad (2)$$

The responses of the system have been analysed and several possibilities with polynomial approximations, taking into account the number of input variables and its approximation degree, have been evaluated. To determine the suitability of the approximation function, the coefficient of determination of the adjustment function r^2 has been used [7].

3. Results

A. Punctual measurements analysis

Table I indicates weather conditions for the measurements (MATRAS website) taken one day of September 2008.

Table I. Weather conditions for punctual measurements (MATRAS)

Test No.	R(W/m2)	T_a (ºC)	H_r (%)	x_a (g/kg)
1	167	29,8	15,5	4,1
2	219	18	56	7,5
3	516	21,2	48,5	7,7
4	621	31	12	3,4
5	812	29,6	18	4,7
6	831	26,7	27,5	6,1

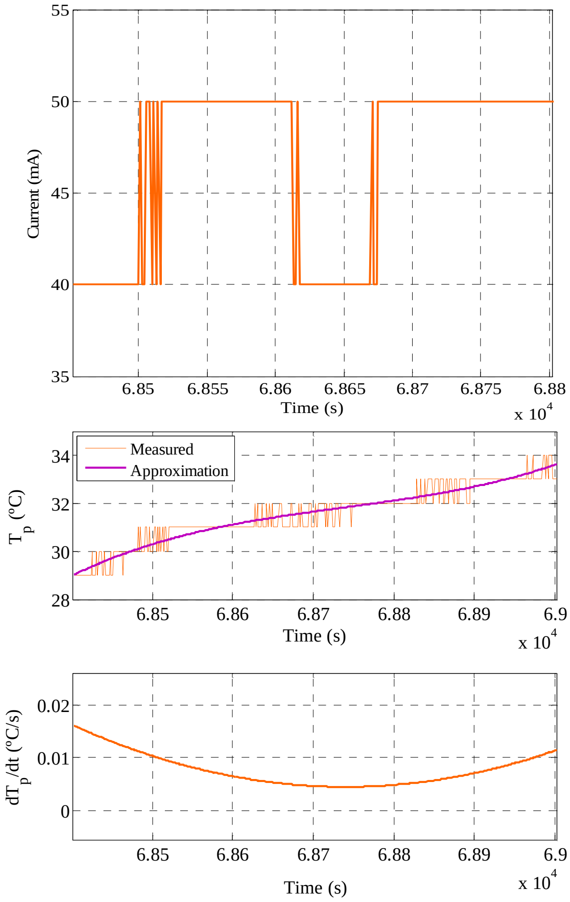
For test 1, 3 and 6, Figure 4 shows the results of the evolution of cell temperature T_P and of the intensity current flow, taking the ambient temperature condition as a starting point. From the following graphs, some considerations can be drawn:

The temperature cell data present plenty of ripple, due to the very small sampling time in the measurements (close to 3 seconds). Likewise, there are plenty of oscillations in the temporal response, due to the sensor itself. In any case, the temperature evolution during each experiment presents an exponential trend (though it has been approximated with polynomial functions of order 3), what is more accurately demonstrable for high irradiancies.

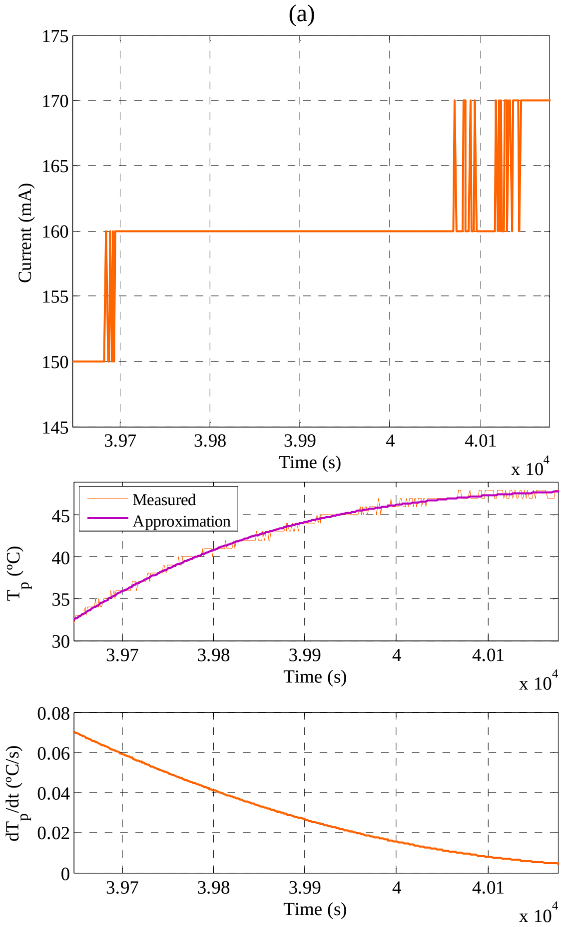
Regarding the generated current flow, there is no this ripple and the changes in the response occur only occasionally, in moments when certain oscillations occur as well. The ripple effect in temperature measurements appears as consequence of the sensor itself, while in the other case, there is a non-desired effect caused by the limited resolution of the measurement system, which is not able to read variations inferior to 10mA in the response of the system.

In any case, there are drift effects due to the fact that the conditions showed in Table I are not constant during the test and although the changes are very little, non-desired effects can occur in the response. The occasional appearance of clouds during the test leads to results which are non comparable to the results given by the weather station.

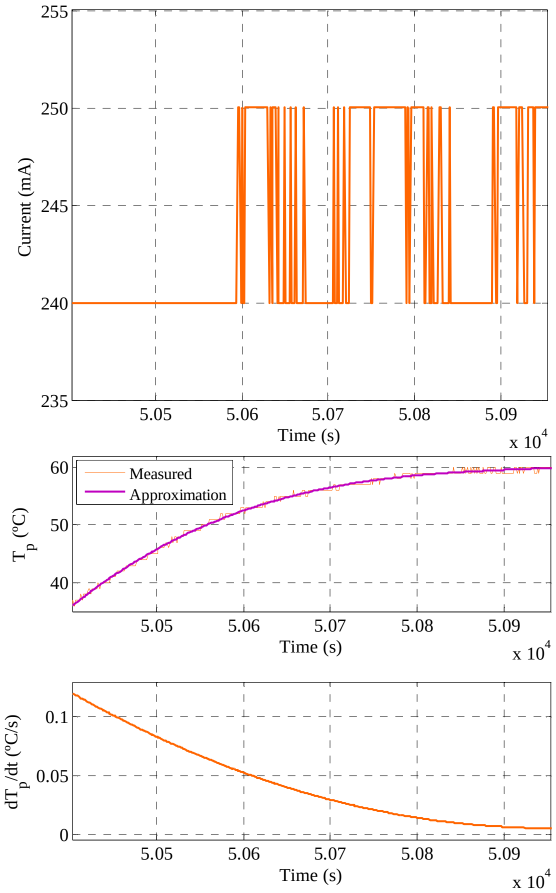
Consequently, from these results it is deduced that to use this device as a measurement system (even though the data collection is made every few seconds) is preferable to use higher time slots, so the cell temperature has time enough to stabilize. Similarly, these data have to be dealt with trying to eliminate the ripple as much as possible.



(a)



(c)



(c)

Fig. 4. System response for punctual tests (see Table I): a) Test 1; b) Test3; c) Test 6

With these data, it is searched an approximation polynomial function among the functions indicated in Table II, with a_j coefficients associated to I_P, T_P, x_a variables and to thermal drift $dT_p/d\tau$. Variables are previously scaled in an interval (0,1) to improve the efficiency of the identification procedure [6].

Table II. Evaluated fitting functions

No. of variables	Equation	Variables from which they depend
2	$R_2 = a_0 + a_1 I_p$	I_P
3	$R_3 = R_2 + a_2 T_p$	I_P, T_P
4	$R_4 = R_3 + a_1 x_a$	I_P, T_P, x_a
5	$R_5 = R_4 + a_4 T'_p$	I_P, T_P, x_a, $dT_p/d\tau$
6	$R_6 = R_5 + a_5 I^2_p$	I_P, T_P, x_a, $dT_p/d\tau$
7	$R_7 = R_6 + a_6 T^2_p$	I_P, T_P, x_a, $dT_p/d\tau$
8	$R_8 = R_7 + a_7 x^2_a$	I_P, T_P, x_a, $dT_p/d\tau$
9	$R_9 = R_8 + a_8 T'^2_p$	I_P, T_P, x_a, $dT_p/d\tau$
10	$R_{10} = R_9 + a_9 I^3_p$	I_P, T_P, x_a, $dT_p/d\tau$
11	$R_{11} = R_{10} + a_{10} T^3_p$	I_P, T_P, x_a, $dT_p/d\tau$
12	$R_{12} = R_{11} + a_{11} x^3_a$	I_P, T_P, x_a, $dT_p/d\tau$
13	$R_{13} = R_{12} + a_{12} T'^3_p$	I_P, T_P, x_a, $dT_p/d\tau$

The 2 first functions do not provide reliable results in the fitting. The value of r^2 for its own fitting is below 0,98. From the third function onward, this term reaches high values, above 0,99 (Figure 5 presents the correlation graph for one of these tests with punctual data). This means that, with this procedure, it is not possible to estimate correctly the value of radiation, if only direct measurements variables are taken into account.

To get reliable approximations, it is necessary to take also into account thermal drift (see Figure 4) and absolute humidity. The value of $dT_p/d\tau$ complements the temperature T_P data in the fitting. The problem is that this function can be determined from a smooth approximation to the T_P evolution (exponential or polynomial approximation), so the data must be presented for a long enough time slot (between 5 and 10 minutes).

Regarding absolute humidity x_a (determined with relative humidity and ambient temperature), its value represents a local effect and it is used as an atmospheric clearness index as well as it explains, partly, variations in incident radiation in the previous and subsequent moments to the solar midday, when incident radiation shouldn't change. There are also other local effects as airborne dust, but theirs consequences on the system are difficult to evaluate.

To check its effectiveness, these results have been compared to other continuous real measurements that were taken another day (February 2009). The fitting results for one of the cases can be observed in Figure 6 (for the function of Figure 5), where a poor fitting can be observed.

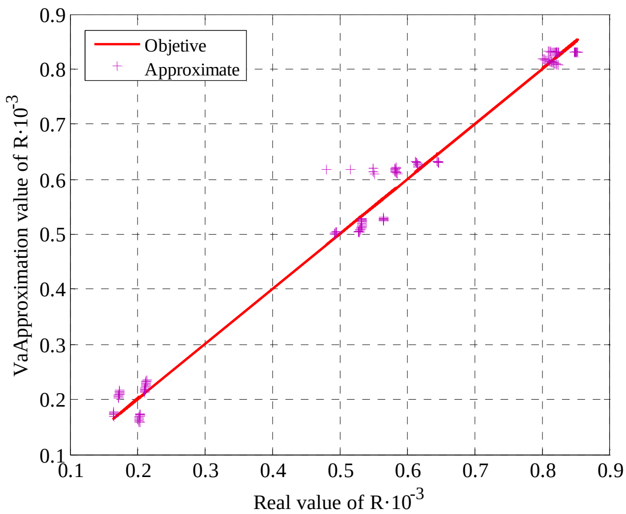


Fig. 5. Correlation graph for approximation function 9 (see Table II)

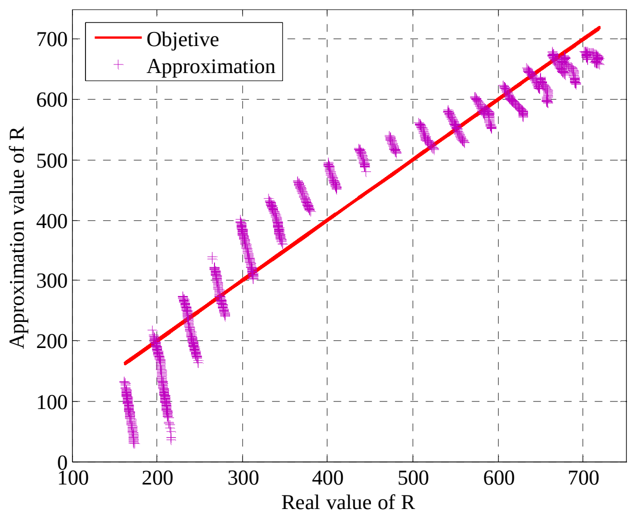


Fig. 6. Correlation graph for approximation function 9 (see Table II) applied to continuous measurements.

Initial calibration with punctual data establishes few conditions, as in the set of continuous data (see Figure 6) reliable results are not obtained. Besides, in every test, I_P and T_P vary, but not x_a, a variable that it is necessarily to be taken into account, because previous approximations (see Figure 5) have been evaluated with accuracy enough. This lack of fitting can be explained because of the huge amount of calibration and conditions measurements that has to be taken and because of the high number of comparisons made with a high number of output data.

B. Continuous measurements analysis

The same procedure is carried out with continuous data. In this case, the intervals between data of the total set are longer and function coefficients are identified for Table II. Afterwards, the results are validated with the total measurements. In a first evaluation, data from the ascending radiation curve are taken till the solar midday (18th February 2008). Figure 7 presents these ascending data.

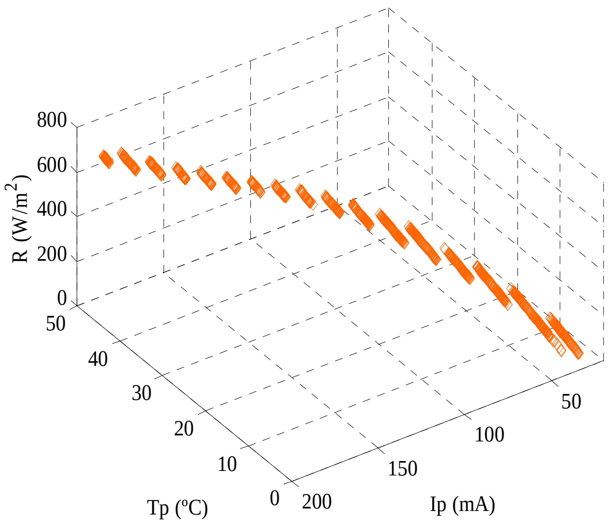
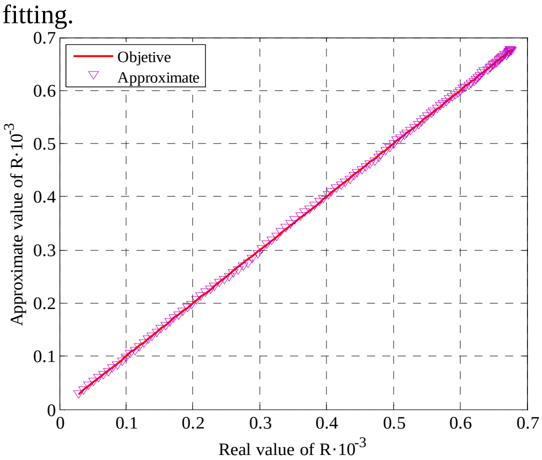
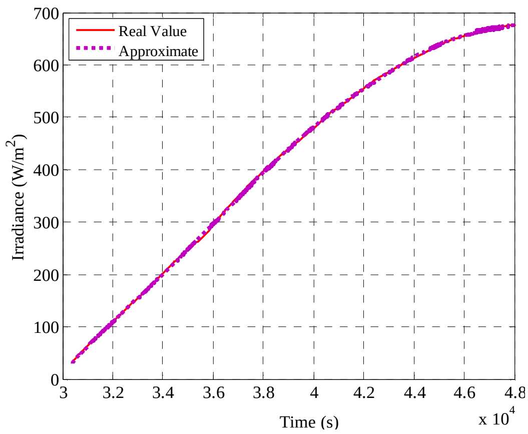


Fig. 7. Experimental measurements and comparison with irradiance (midday)

In this analysis, I_p and T_p data are enough to determine the results with reliability, for a 0,9996 r^2 value. This value goes up roughly linearly until the value of 0,9999 for 10 coefficients and it only presents very smalls variations when the number of coefficients goes up to 13. Figure 8 presents the results of approximation for one of the fitting.



(a) Correlation

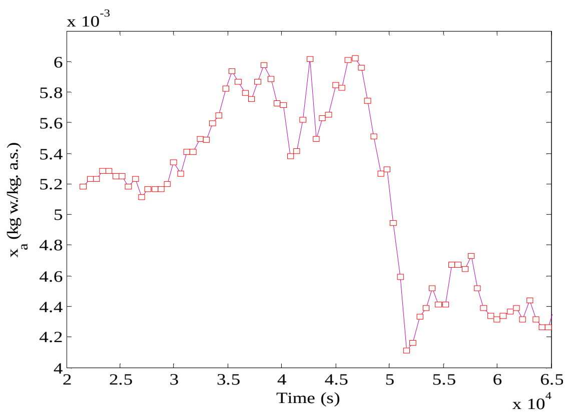


(b) Radiation results

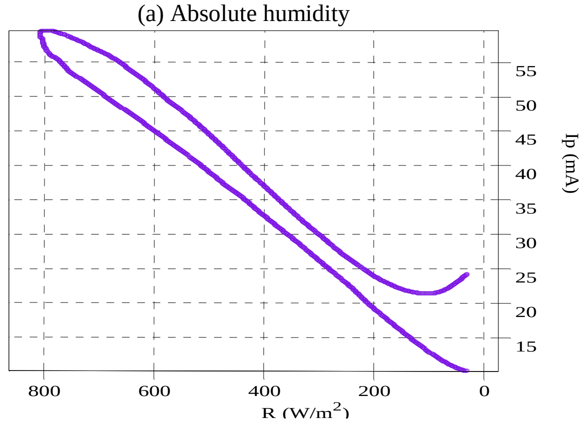
Fig. 8. Comparison of results (midday) for approximation function number 9 (see Table II) for continuous measurements

In this evaluation, the variation of the cell temperature is low in a sunny day, but it goes up according to radiation. As our analysis is done in a bright day, at midday, ambient air humidity also varies along the morning, due to radiation, though this fact does not affect significantly the fitting.

The second step is to analyse the procedure with daily data. For this, a maximum of measurements are taken during a determined day (March 2009).A process of hysteresis appears due to the brightness of the day. Therefore, incident radiation is different in the decreasing period regarding to the increasing one. In this sense, there is a clear variation in atmospheric absolute humidity (see Figure 9). In any case, in the tests that have been carried out until now, it was not possible to use all the data due to problems related to the running of the cell during the test itself.



(a) Absolute humidity



(b) Relation R-I_p

Figure 9. Data for a single day

When the results were evaluated, a good fitting was observed, though the r^2 values did not reach 0,9999 (the best approximation being for 13 coefficients with a value of 0,9998), as it can be observed in Figure 10. In this case, absolute humidity does have a crucial importance for the fitting of the data (see Figure 9). In any case, the temperature cell evolution is moderate, so the thermal drift is not considerable enough to alter the approximation.

C. Discussion

The previous procedure is repeated completely with 3 extra cells and the results are similar to the previous ones, so the procedure is validated for all of them.
Having regard to all these results, it is deduced that the procedure is a reliable starting point for a recalibration of the system. Nevertheless, it will be necessary to increase the number of punctual trials, as well as to use continuous data for the maximum of yearly data.

In the first case, it would be appropriate to use a solar simulator, due to the level of precision needed for the atmospheric constant data (radiation, temperature and ambient humidity).

In the second case, the data analysis during the whole year presents the maximum possible of situations needed to be able to work in statistical terms in a global approximation function, including cloudy sky data.

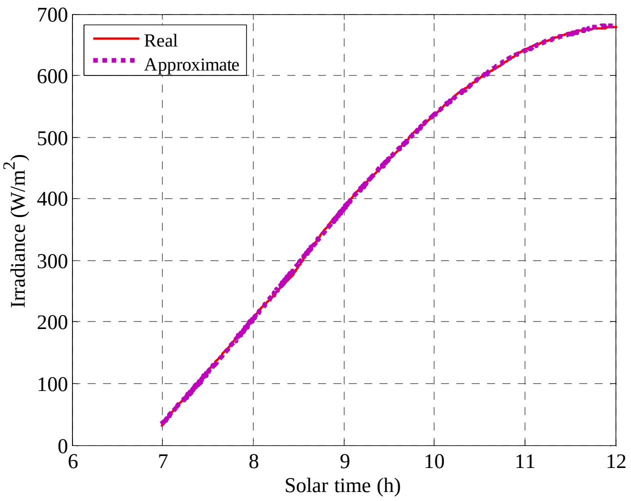


Fig. 10. Comparison of radiation results for one day data and continuous measurements using function 13

4. Conclusions

Several ways of recalibrating a solar radiation measurement system on the basis of a silicon cell have been evaluated. The importance of cell temperature (and thermal drift) for the system response, as well as the importance of other atmospheric parameters, like relative humidity and ambient temperature, from which it is deduced the ambient absolute humidity as an extra parameter for the evaluation, have been proved. The results are only partial, because the tests have not provided yet many data. In any case, this is a starting point to establish a global procedure.

The advantage of punctual tests is the possibility to determine the temperature evolution of the cell when the other conditions are constant (radiation and humidity). Among the disadvantages, there is the tedious task of testing, as well as the difficulty related to variable atmospheric parameters; that is why the use of a solar simulator is recommended. Regarding the continuous tests, the experimental measurements are carried out in a simple manner, because the data are automatically registered in PC files. Nevertheless, the temperature evolution has a drift very difficult to observe for match conditions. The procedure to follow in the future must consider both aspects combination and must redefine and enlarge punctual trials, as well as recalibrate continuously according to the acquisition of new data. In this sense, extra and complementary functions to the ones defined in Table II and based on the statistic analysis of data must be looked for.

For the use of these cells having an inclination and an earth azimuth angle other than 0º, it would be also appropriate to include among the approximation functions variables the exact time when the datum is collected. This indicator determines all angles related to radiation, mainly its incidence angle or the zenith angle θz.

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