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AUTOMATION OF A CARTESIAN POSITIONER FOR TRACKING A PYRANOMETER DURING EVALUATION TEST OF THE EMITTED IRRADIANCE UNIFORMITY BY A CONTINUOUS SOLAR SIMULATOR

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Abstract. *In accordance with American Standard, ASHRAE 93-2003, adopted for the tests with solar simulator of the Brazilian Label Program of the INMETRO, the average value of the incident irradiance in the plan of the collector must be evaluated with frequency during the tests of instantaneous thermal efficiency. For such, the projected area is divided in square shaped meshes with 15 cm of side, acceptable maximum shunting line is of ± 10% in relation to the average value of the measured irradiance. Currently, it is made use of a Manual Cartesian Positioning (scanner) used for the displacement of pyranometer and operated for the technicians of the laboratory. However, to reduce the time of use of the light bulbs, consumption of electric energy, errors and inherent risks of this manual operation, were developed an automatized scanner that uses stepping motors microcontrolled and supervised by LabVIEW™ language. The preliminary tests had been sufficiently promising and are being defined the stages of its definitive implementation, used instrumentation and the results gotten in comparison to the manual system. In the final stage, the evaluation of the spectral irradiance will also be made, with the inclusion of six filters EPPLEY: GG395, GG495, OG530, RG610, RG695 and RG780. This procedure must be repeated to each 500 hours of operation of the eight metal halide light bulbs, with individual power of 5000W, that they compose the solar simulator.*

Keywords: *Solar Simulator, Irradiance Uniformity, Automation, Spectral Irradiance.*

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1. INTRODUCTION

In December of 2004 at the Group of Studies in Energy (GREEN), located in the Pontifical University Catholic of Minas Gerais (PUC Minas), the first Solar Simulator of Continuous Flux of Latin America was installed and since the beginning of 2005, assays of instantaneous thermal efficiency for solar water collectors have being carried through in order to take care of the Brazilian Label Program - PBE, co-ordinated by National Institute of Metrology (INMETRO) with the support of ELETROBRÁS/PROCEL. The assays of instantaneous thermal efficiency are carried through in agreement with American Standard ASHRAE 93-2003 where the average value of the incident irradiance in the plan of the solar collector in test may be evaluated with regularity. Currently, for this evaluation, it is made use of a manually cartesian positioner (manual scanner) for displacement of a pyranometer operated by technicians of the laboratory. Therefore, the automation of the cartesian positioner becomes important in order to reduce the time of use of the light bulbs, consumption of electric energy, and mainly errors and inherent risks of the manual operation. In this paper, the stages of implementation of automatized scanner are presented which had been divided in: electric/mechanical project and microelectronic/power project. Moreover, also the initial results of the spectral evaluation of the light bulbs of the solar simulator are presented in order to inquire the aging of the same ones.

2. SOLAR SIMULATOR

2.1. Light bulbs

The solar simulator (Fig. 1 (a)) is composed by a system of 8 special light bulbs (Metal Halide Global, MHG) which totalize a nominal power of 40kW. This set illuminates uniformly an area of 2.80 m^2, which the emitted irradiance has an electromagnetic spectrum close to Sun spectrum (as specified in the CIE In. 85, Table 4, 1989). Light bulbs are energized by electronic power source (Eletronic Power Supply, EPS) whose performance stabilizes and optimizes the characteristics of the solar spectrum simulated, and also increase the time of life of the light bulbs in 35%. Moreover, the control of the irradiance emitted for the light bulbs is carried through by a dedicated computer in set with software, which facilitates the management and use of the same ones.

2.2. Artificial Sky

The known device as artificial sky (Fig. 1 (a)) is innovative among solar simulators installed in others internationals centers for assays of solar collectors. It importance is justified by simulation of radiating exchange conditions between the solar collector and the celestial vault. In agreement with Duffie and Beckmann (1991), the temperature of the celestial vault is lower to the ambient temperature about 6°C and 30ºC for tropical and cold regions respectively. The artificial sky has the purpose to reduce the temperature in the neighborhoods of the solar collector that is being assayed.

2.3. Manual Cartesian Positioner (Manual Scanner)

The manual cartesian positioner (manual scanner) used in the Solar Simulator is composed by one Kipp & Zonen pyranometer model CM21 which measures the irradiance emitted by the light bulbs. This is fixed on a aluminum bar which through winches, operated manually, puts into motion the sensor in axis x and y thus making possible, the sweeps of the whole area of assay for solar collectors, that is, the evaluation of irradiance uniformity as Fig. 1(b) show. The importance of this evaluation is due to simulated irradiance generally varied in intensity on the area of assay. Thus, for verification, the area is divided in square shaped meshes with 0.15 m of side, composed by a total of 160 measurements points, where pyranometer is dislocated, which the maximum and minimum measured may not deviates ±10% from the average value measurement (ASHRAE 93-2003).

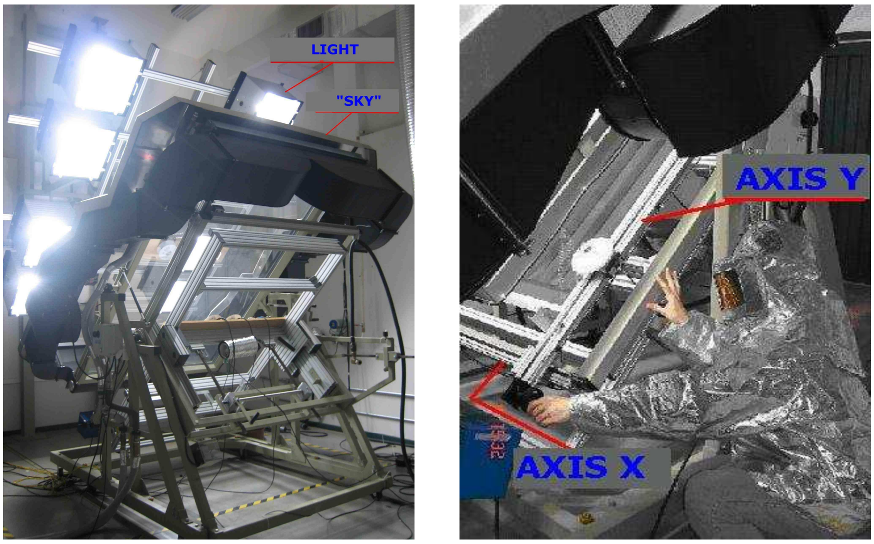


Figure 1. (a) Solar Simulator (b) Manual cartesian positioner /pyranometer/tecnician.

During the evaluation of uniformity, two technicians are necessary for realize the procedure as follows: the first one remains inside the area of assays, protected by specials clothes, eyeglasses and sun cream in order to protect itself mainly of ultraviolet rays (UV) produced by the light bulbs, realized the control of the manual scanner (Fig.1 (b)). The second technician, stay on control room supervising measurements gotten by pyranometer through a LabView® program.

It fits to stand out that for each point of the mesh it is necessary to wait 10 seconds, for respected the time constant of pyranometer thus preventing errors in the measures of irradiance. Therefore, to evaluate the uniformity in all area of assay (160 points) it are necessary a total of 40 to 60 minutes. This procedure is tiered for both of technicians but mainly for the technician who is inside of the area of assay due its “exposition”, even protected, of irradiance for a considerable period beyond generating a thermal discomfort caused by the heating of the assay place that can reach temperatures above 30ºC. Thus, ahead of this reality it is being developing the automation of manual scanner. The next items describe the stages of implementation of the autonomous system which had been called of electric / mechanical project and microelectronic /power project.

3. ELECTRIC / MECHANICAL PROJECT

The electric / mechanical system of the automatized cartesian positioner is constituted by two step motors and a coupling system. Below it follows the used methodology to sizing the motors and coupling.

3.1. Step Motors

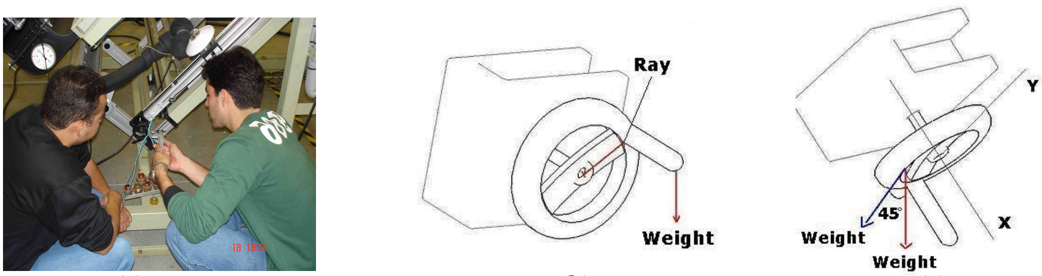
The step motor is an electric engine that converts a digital signal input into controlled mechanical movement. The rotation of its axis is given by steps that carries through the lesser possible angular displacement. This characteristic is one of the advantages of this type of engine, cause errors generated by positioning are not a parameter that is accumulative, thus allowing, a great precision in its applications.

3.2. Sizing of Step Motors

In order to size the step motors to execute the operation of "scanner" in the solar simulator, it was necessary determine the value of momentum in a given frequency of operation that agrees to a defined resolution. The frequency, for a motor with known resolution, is basically related with a necessary time for a pyranometer dislocates from the actual current point until the next point of irradiance acquisition. The momentum must be enough to win the attrition of the system and to speed up all the mass until the calculated frequency.

3.2.1. Momentum in function of load

As, for the case of the simulator, the attrition coefficients, as well as the static behavior of the system, it are very specific, was used an experimental method that constituted in inserting, gradually, diverse weights of equal masses and with a known ray distance in an attached scale to the winch in order to get the torsion momentum in the command pulley as Fig. 2 (a) shows. The tests for axis y (as showed in Fig. 2 (b)), it had consisted positioning objects of average weight of 1.890 N throughout the related axis. As the ray of the command pulley measures 0.0311 m, was gotten that, the biggest torsion momentum in function of load in axis y was of 0.461 N.m. The practical procedure for the determination of the biggest torsion momentum in relation to axis x was similar to the previous one, however, the winch, identical to the previous one, is inclined by 45º as it is shown in Fig. 2 (c). Being thus, the value of 0.449 N.m was gotten for the torsion momentum in relation to axis x.



(a) (b) (c)

Figure 2. (a) Experimental method (b) Torsion momentum on axis Y; (c) Torsion momentum on axis X.

3.2.2. Momentum in function of acceleration

In order to determine the momentum in function of the acceleration of the set, it were necessary to determine the total inertia of the system, the angle of step θ(s), the diameter of the internal pulley, the period of positioning and acceleration. In function of the availability in the market and for the excellent linear resolution that can be gotten, a step angle of 1.8º (θ(s)) was chosen. The distance to be covered by the set is the gaps between a point of attainment of the irradiance and another one, it corresponds to 0.15 m (L). The diameter of the internal pulley is known and measure 0.0478 m (D). Thus, the number of necessary pulses, that is, the number of steps needs to execute this movement is determined by the Eq. (1).

$$A[\,pulses\,] = \frac{L}{D} \cdot \frac{360^o}{\pi . \theta(s)} = 200 \qquad (1)$$

As one of the objectives of the project is to diminish the assay time, it was developed a routine, through MATLAB® software, in order to choose optimum running time. Through this routine, it was verified that a small reduction in the running time would imply in great increase in necessary momentum, increasing the cost of the engines and not diminishing significantly the total time of operation. Thus, the running time of 1 second was choosen, what it results in an estimate time for realize "scanner", without unexpected, of 24 minutes and operation frequency of 250 pulses per second.

For a linear acceleration with a time of t = 1 second, will be necessary a momentum for the acceleration of the system in accordance with the inertia and inertia momentum (Ma [N.m]) for each component until the operation frequency. Thus, the general equation of the machines for each axis is given by Eq. (2) and Eq. (3) as following:

For axis y:

$$\int_{0}^{t1} Ma.\frac{\varpi.t}{0,2}\,dt = \frac{1}{2} m_{pyaranometer}.\dot{X}^{2} + \frac{1}{2} I_{pulley}.\omega^{2}.2 + \frac{1}{2}.m_{header}.\dot{X}^{2} + \frac{1}{2} I_{motor}.\omega^{2} \tag{2}$$

For axis x:

$$\int_{0}^{t1} Ma.\frac{\varpi.t}{0,2}\,dt = \frac{1}{2} m_{pyranometer}\dot{X}^{2} + \frac{1}{2} I_{pulley}\omega^{2}.2 + m_{header}\dot{X}^{2} + \frac{1}{2}.m_{structure}\dot{X}^{2} + \frac{1}{2} I_{motor}\omega^{2} \tag{3}$$

Through out the routine in the MATLAB® software, it was also gotten, the value of the momentum for the acceleration in function of the momentum of inertia of the engine, that is, 1.575 and 0.490 N.m for axis x and y respectively. Therefore, the found momentum will be required to place all the structure in movement.

3.3. Coupling of Motors

The coupling of the motors responsible for the displacement in the axis x will have to be carried through by the below side of the sustentation bar of the solar simulator. The engine will be screwed in an aluminum plate that will be fixed in the proper structure of the simulator. In this way, to carry through the transference of the power for the guide of movement of pyranometer (winch), it was opted to using a set of dentate leather strap and two pulleys as Fig. 3 shows.

The pulleys had been chosen in accordance with the external diameter, 0.138 m of axis of the current manual system. Aluminum pulleys had been selected with steps once a time that the leather straps will function inclined. Through the catalogue of the manufacturer of leather straps "SCHNEIDER" and ownership of the external diameter of the coupling, and the conditions of functioning (as momentum and rotation) the pulley was chosen that better fit to the system.

With the choice of adequate pulley the primitive diameter was gotten that together with the initial distance of the axis of the engine to the axis of the coupling was determined the length (0.255 m) and the step (0.005 m) of the leather strap beyond the tooth number (51) in order to facilitate the contact of the same one with the pulleys.

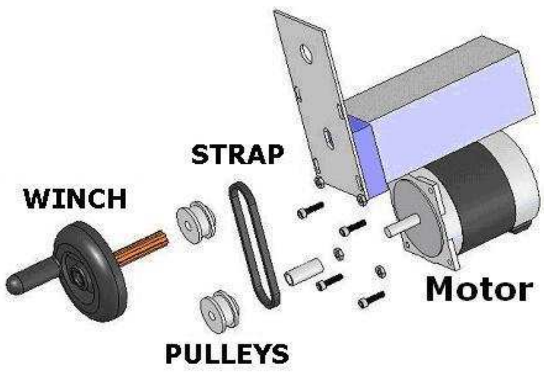


Figure 3. Coupling system of axis x.

This was the best option, once a time that the winch for manual movement is part of the set of the system and it does not have to be removed. Moreover, the permanence of the same one is fundamental so that it is possible to manually continue operating the scanner in case that some problem occurs in the automatized system. For the engine of the axis y the coupling it will be simpler and it will not depend on the system of pulleys, leather strap and winch.

4. MICROELECTRONIC/POWER PROJECT

4.1. Microcontrollers (PIC)

For the accomplishment of this project, was used a Programmable Integrate Circuit (PIC), that is, a microcontroller. This type of microcontroller possess a CPU that operates with a maximum clock of 20 MHz, with instructions cycle of 200 ns.

It is possible to record a code source program, in languages C++ or Assembly, through a compiler who generates a hexadecimal code (machine language) into the memory flash of the PIC. This process of writing is carried through by a programmer hardwired to a PC. Microcontrollers PIC have as great attractive the available amount of pins and functions. For this project, a model PDIP of 40 pins was chosen, with 33 pins of I/O. Initially, a study on the characteristics of the hardware of these microcontrollers and its programming language was made. The programming language C++ was chosen as standard for the implementation of the routines of displacement of the engines for being more considered "friendly" to the user.

The main idea was to introducing control logic of the displacement for step motors into the microcontroller. For this, functions of interruption of software for generation of sequences of pulses had been used that command the rotation of the axles of the step motors with the frequency and pre-defined ways.

The code bases on the idea that pyranometer may remain in fixed points for enough period to stabilization of the realized measure. Thus, the movement commanded by PIC must be enough necessary to always locate pyranometer in same points of the test area, that is, intervals of 0.15 m. This accuracy is guaranteed by using TIMER module of the microcontroller.

For the interface of the microcontroller with the step motors I-MAG_REV2 board was used. This board configuring the functioning of the microcontroller and offers others diverse applications, as a serial communication, Ethernet, USB, etc. For the final phase of the project, it is planned to carry through the substitution of the control using microcontroller PIC for instrumentation compatible with National Instruments. This instrumentation will be use in set with a software of control developed in LabVIEW® language.

4.2. Power Electronic Circuit

PIC Microcontroller is capable to supply maximum current of 25 mA and 5 Volts in each one of its pins of I/O. As the designed motors for the project they require high power, which cannot directly be supplied by microcontroller pins, was develop a power circuit that took care of this necessity.

The power electronic circuit is based on MOSFET components and power drivers; that can offer a load power up to 30 Volts and 5 Amperes. In Fig. 4, we can observe schematic power control circuits for used step motors.

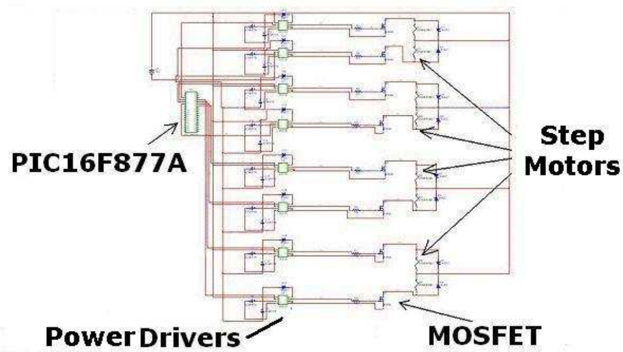


Figure 4. Control and power circuit diagram.

5. EVALUATION OF THE SPECTRAL IRRADIANCE

The objective of this part of project is to evaluate the emitted irradiance spectrum by metal halide light bulbs of the solar simulator. In accordance with standard ANSI/ASHRAE/93-2003, this evaluation is fundamental for the assays of thermal efficiency of solar collectors that are carried through for the Brazilian Label Program (PBE/INMETRO). The knowledge of the spectral bands, ultraviolet (UV), visible (VIS) and infra-red (IR) rays will allow to inquire spectral evolution of the irradiance, guaranteed for the manufacturer, beyond propitiating new studies, research and new assays in equipments and materials for use in solar thermal, photovoltaic, automotive industry and polymers.

5.1. Methodology

For the spectral evaluation of the light bulbs of the solar simulator, it was used two pyranometers Eppley model PSP. The first one, called standard, was tested with the origin filter, that is, filter WG295 that in accordance with the manufacturer, measures the spectral interval of 295nm until 2800nm. The second pyranometer, beyond the WG295, had been used six filters (GG395, GG495, OG530, RG610, RG695 and RG780) with different wavelengths, which its spectral below limits are initiated in 395, 495, 530, 610, 695, 780nm respectively, and all have one same superior limit of 2800nm, as it can observe in Fig. 5.

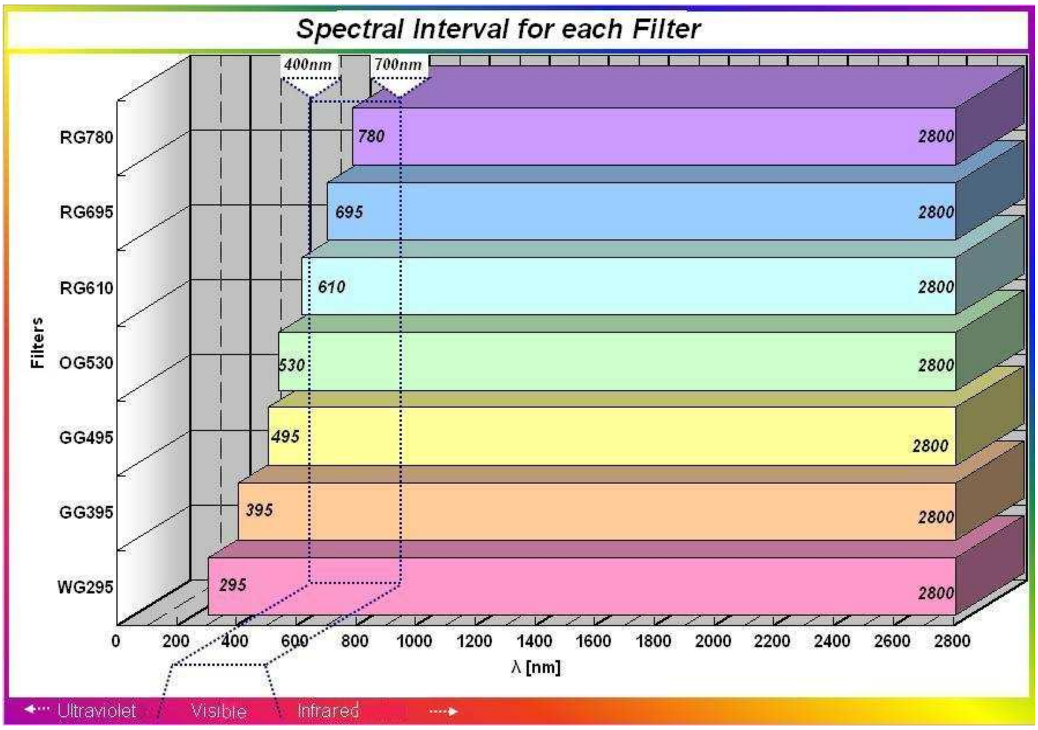


Figure 5. Spectral interval for each filter

The two pyranometers had been placed in the center of the solar simulator assays benches. The filters used in the assembly are illustrated in the Fig. 6 (a) / (b). All the data had been collected and stored by datalogger Campbell Scientific/CR10X.

To guarantee the stabilization of spectrum, 15 minutes are necessary, in accordance with manufacturer, to heat the light bulbs of simulator. Passed this period was initiated the measurement of the irradiance with an equal power level of 70% of nominal value. At this time, both pyranometer were using filter WG295 and had remained with the same filter per 7 minutes. After this interval of time, filter WG295 was substituted by filter GG395 in PSP, Fig. 6 (c), remaining with the same 7 minutes. As considered by Arild Gulbrandsen (1978), the seven minutes for each filter is necessary for the stabilization of the irradiance measured for the PSP. This procedure was repeated for all filters and restarted for other different levels of power: 75%, 80%, 90% and 100%. It fits to stand out that for the changed of power level for another one, was expected 5 minutes before measuring the irradiance emitted for the lights bulbs.

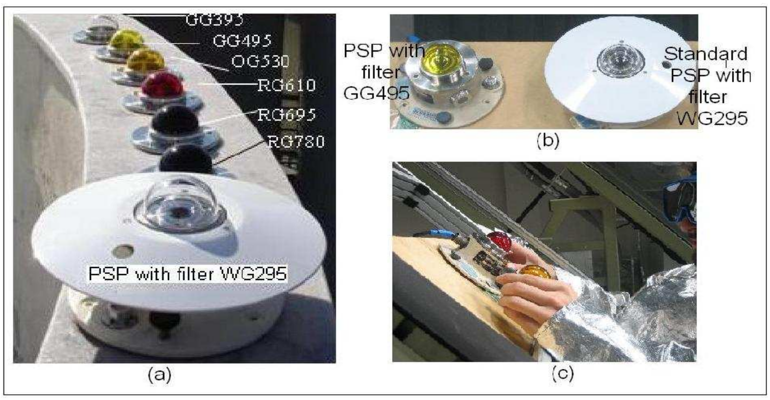


Figure 6. (a) Filters used; (b) Sensor on benchmark of solar simulator; (c) Substitution of filters during test.

In whole test, the ambient temperature was monitored, as well as the inlet and outlet temperatures of artificial sky. The influence of the increase of the temperature in pyranometer can cause errors of precision in the measurement as was evidenced by Qiand and Tsay (2000). Thus, the test was divided in two days: in the first the power of 70, 75 and 80% had been used. In second, power of 90 and 100%. The collected data had been treated, analyzed and compared with the data considered for the standard ASTM G159-98, which suggests spectral solar tables.

5.2. Initial Results

The energy emitted by the simulator and absorbed by each filter, given as practical energy, was well next to the theoretical energy suggested by tables, in the corresponding spectral interval to each filter, of standard ASTM G159-98. However, the filters had collected different amounts of irradiance, for different power levels being that the energy percentage was remained constant. Thus, in accordance with the Fig.7, the WG295 got the biggest approach between the energies practical and theoretical with the power level of 80%. Filters GG495, OG530, RG610, RG695 had gotten the biggest approach with the equal power level 90%. The RG780 was come close to the theoretical value with the 100% power. Between the filters, the OG530 presented the lesser difference between the energies: 0.4%. And the RG610 presented the biggest difference between the energies: 6.3%.

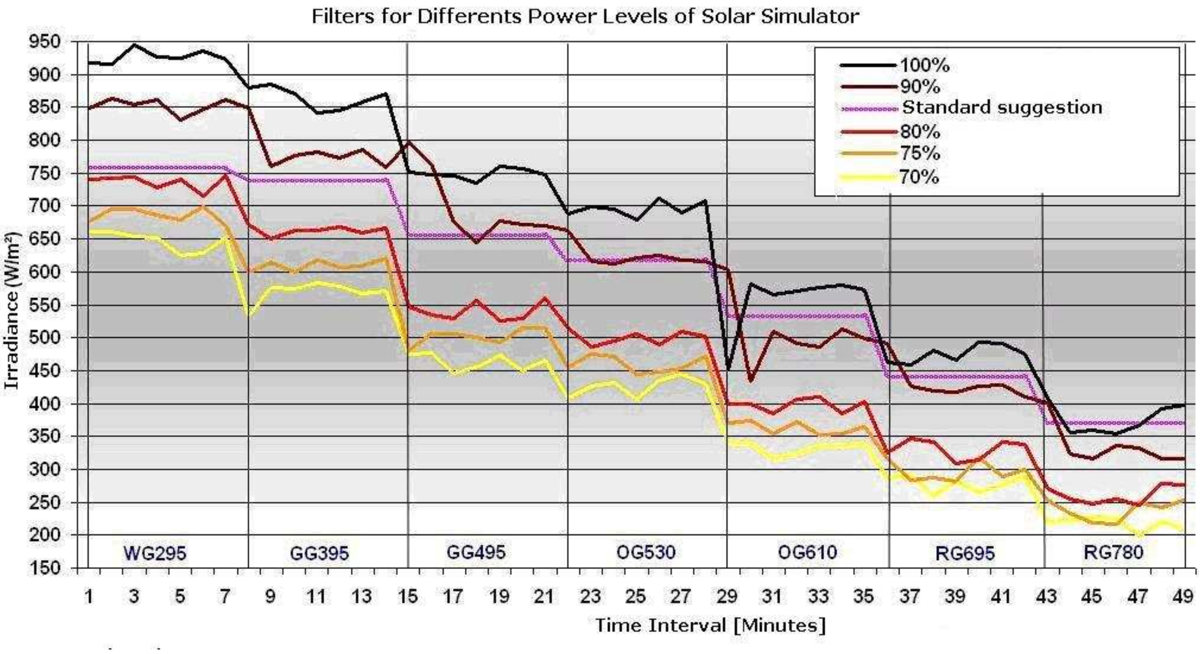


Figure 7. Curves for different filters and power levels for simulator compared with an energy suggested by standard ASTM G159–98.

This initial study became possible to evaluate the spectral division of the energy emitted by the light bulbs of simulator. Such fact is important to direct the power level in the simulator for determined type of application. However, it is necessary still to verify the contribution of each wavelength for this energy, that is, to quantify the spectral distribution emitted by the Solar Simulator.

6. CONCLUSION

In this work, the implementation stages for automation the manual scanner of the solar simulator had been presented. It fits to stand out that, currently, the projects mechanical/electric and microelectronic/power are in integration phase, being that the first tests with all integrated system it already meet in progress. In relation to the evaluation of the spectral irradiance emitted by the light bulbs of the solar simulator, the comparison between the theoretical energy fraction will be carried through, in the spectral interval for each filter, calculated through the formula of Pivovonsky and Nagel (1961), indicated by Duffie and Beckman (1991), with the energy absorbed for the pyranometers in the practical one. For this, it is being developed a program in LabVIEW ^{TM} language for the calculation of the energy fraction. Being thus, soon, the results of the automation of "scanner" and of the spectral analysis will be divulged in future works.

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