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NUMERICAL AND EXPERIMENTAL STUDY OF THE NON-UNIFORMITY IRRADIANCE OF A SMALL-SCALE SOLAR SIMULATOR

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Abstract. This paper focuses on the numerical and experimental non-uniformity study of a solar simulator using an array of 2x2 floodlights (AC 240 W / 230 V quartz tungsten halogen lamps) and a reflecting light tube for testing prototype (0.4×0.4 m) flat plate solar collectors. The irradiance distribution of a single floodlight over a test plane 1 m from the floodlight bulb is measured using a pyranometer. The 3D model of the solar simulator is built using SolidWorks and APEX optical add-in. The light source of the model is calibrated against the experimental results by apodization using a mathematical function. The irradiance of the solar simulator over the test plane is analyzed for various distances between the lower end of the light tube and the test plane (clearances) and different combinations of lit floodlights. The irradiance results sets are exported to a Mathcad worksheet used to fit a 4th order surface trough all data points and to compute the non-uniformity of irradiance over the test plane. The minimum non-uniformity occurs at a clearance of 115 mm. The experimental non-uniformity determined using the pyranometer on a 5×5 node grid over the test plane is 9.9%. The maximum difference between experimental and numerical non-uniformity is 5.2%.

***Key words*:** solar simulator, non-uniformity of irradiance, CAD, optical analysis, Mathcad.

1. INTRODUCTION

The solar simulator is a device that produces illumination similar to the natural sunlight. Solar simulators are used for indoor testing under laboratory conditions of solar collectors, photovoltaic systems and other devices. Solar simulators can be either used for performance measurements or endurance irradiation tests. The basic parameters of a solar simulator are: spectral match, non-uniformity of irradiance and temporal instability.

According to IEC 60904-9:2007 standard [1], the non-uniformity of irradiance on the test plane is defined as:

$$Nu[\%] = \frac{\left(G_{max} - G_{\min}\right)}{\left(G_{\max} + G_{\min}\right)} \times 100\%, \tag{1}$$

where $G_{\max}$ and $G_{\min}$ are the maximum and minimum measured irradiance values over the designated test area.

Depending on the value of the non-uniformity, solar simulators for testing photovoltaic devices are classified into three classes: A ($Nu \le 2\%$), B ($Nu \le 5\%$), and C ($Nu \le 10\%$).

A method for measuring the non-uniformity of irradiance of a large-area pulsed solar simulator using a silicon solar cell as a detector is reported in [2]. The authors analyze the factors that influence the reliability of the non-uniformity measurement and conclude that the most important factors are: (1) the performance of the solar simulator and (2) the repeatability of detector positioning on the nodes of the test plane grid.

The fabrication and testing of a low cost solar simulator for testing solar collectors are described in [3]. The light source consists of 23x500 W halogen lamps with build-in reflectors and individual on/off switch, powered directly from the AC 240 V grid. Irradiance was measured using a pyranometer at 65 locations on a 13×5 grid covering the test area (120×53 cm). Four measurements were made, with 7, 9, 11 and 13 lamps lit.

The mean measured irradiance values were: 466, 580, 686 and 804 W/m^2 respectively. The authors show that the average irradiance, the average uniformity and the percentage of non-uniformity meet satisfactorily the requirements of the ANSI/ASHRAE 93-2003 standard [4].

A hybrid LED-halogen solar simulator with the non-uniformity irradiance less than 5% on a 10×10 cm test plane is described in [5]. The light source of the simulator consisting of two types of white LEDs, four sets of monochromatic LEDs and a halogen lamp fixed at the top end of an aluminum light guide. The non-uniformity of the irradiation was measured for three lengths of the light guide: 20, 13.5 and 6.5 cm. The results showed that the non-uniformity is inversely proportional to the length of the light guide.

The design and evaluation of the performance of a six-spectral LEDs-based solar simulator according to the IEC 60904-9:2007 standard are presented in [6]. The LEDs of the light source have different wavelengths covering the spectrum from 380 to 1100 nm. The light source is fixed on a rectangular aluminum radiator placed at the top end of a light tube with four mirror walls with a length of 455 mm. The maximum irradiation measured on the 325×280 mm test plane was 1000 W/m^2 with a non-uniformity of only 1.9%, which allows the simulator to be used for testing the I-V characteristic of the medium-sized PV solar cells.

Reference [7] describes the design and performance test of a multi-lamp solar simulator for testing solar collectors according to EN 12975-2:2006 standard [8]. The 2.7×2.8 m surface of the light source plane is filled with 12 metal halide lamps (six lamps of 1000 W and six of 2000 W). Each lamp has an on/off switch, so that different combinations of lit lamps can be made. The light source is fixed on a metal frame such that the distance between the light source plane and the test plane can be adjusted between 0.5 and 3 m. Thus, irradiation in the test plane can be set between 100 and 1000 W/m^2. The results of the tests performed at 1 m showed that the average irradiation and non-uniformity are 790 W/m^2 and 13.34% respectively, values that meet the requirements of EN 12975 standard.

The irradiance characteristics and optimization design of a large-scale solar simulator is described in [9]. The light source consists of 188x400 W halide metal lamps fixed on a steel frame with 4.5×3.88 m dimensions that can be moved vertically to produce different levels of irradiance. The lamps are divided into four groups that can be lit individually or in different combinations. The irradiance was measured in 143 nodes on a uniform square grid over the test area. The results of the measurements showed that the simulator can achieve an irradiance of 1000 W/m^2 with a non-uniformity of 4.27% over an effective area of 2×1.5 m^2, when the distance between the lamp array and the test area is 2 m. To increase the effective area, two rectangular metal mirrors were added on the longer sides of the solar simulator. The optimum tilt angle of the mirrors was estimated by simulations using the LightTools optical software at 20°. The made measurements validated the result of the simulations and showed that the effective area increased by 81.6% compared to the area before the optimization.

The design and commissioning of a virtual image solar simulator for testing prototype (0.5×0.5 m) flat plate thermal collectors is described in [10]. The light source composed of 4×420 W floodlights with tungsten halogen lamps is fixed to the top end of a reflecting light tube. The test plane was placed at a certain distance (clearance) from the lower end of the light tube. Irradiance over the test plane was simulated using a ray-tracing code written in Matlab. The measurements made using the pyranometer at 25 locations on a 5×5 grid over the test plane showed that the measured mean irradiance was 2.3% higher than the simulated one and the cross-sections through the center of the test plane are less uniform than it was expected from the simulation. The measured non-dimensional standard deviation for the tilt angle of –5.5° was 0.053, very close to predicted value.

The uniformity characteristic and calibration of a simple solar simulator using 16×50 W halogen lamps is reported in [11]. The 4×4 array of lamps is fixed on a 380×350 mm aluminum plate. The distance between the light source and the test plane was adjusted to 32, 37, 42 and 47 cm. The non-uniformity of the irradiance measured with a pyranometer on the test plane (360×360 mm) at those distances was 9.7, 9.0, 7.0 and 5.6%, respectively.

Paper [12] presents the optimization of the position of halogen lamps for a solar simulator used for research and education. The light source consists of two identical square modules placed next to each other. Each module has 4×500 W halogen lamps with built-in reflector, arranged perpendicular to each other and at the same distance from each other. This distance was varied from 10 to 25 cm, with a step of 5 cm and the irradiance over the test plane was measured using a pyranometer. It was found that the optimal distance between the lamps is 15 cm. In this case, the irradiance over the test plane with a surface of 0.4 m^2 is between 500 and 1000 W/m^2.

From the review presented above one may notice that most researchers have studied the non-uniformity experimentally, measuring irradiance over the test plane using a pyranometer for different configurations of the solar simulator. The experimental studies aimed to minimize the non-uniformity of irradiance by varying the following parameters: the distance between the light source and the test plane, the combination of lit lamps, the length of the reflecting light tube (or the tilt angle of the reflecting walls), the tilt angle of the lamps or the distance between them. There are also researchers who used optical analysis software to simulate the non-uniformity of irradiance over the test plane. However, there is a lack of papers that present a detailed modeling of the halogen lamps and the irradiance analysis over the test area using an optical analysis program.

This paper studies the irradiance non-uniformity of a small-scale solar simulator (SS^2) intended for research and education. The non-uniformity of irradiance of SS^2 is being studied as a function of two parameters: the clearance and the combinations of lit lamps, using ray-tracing simulation. The clearance for which the non-uniformity has the minimum value is then validated through measurements using a pyranometer. The purpose of the study is to determine the clearance and the combination of lit lamps for which the non-uniformity of irradiance over the DTA is less than 10%, as provided by the IEC standard for class C solar simulators.

2. METHODS

Two methods are used to study the non-uniformity of the small-scale solar simulator (SS^2): optical analysis and irradiance measurements with a pyranometer.

2.1. Non-uniformity derived from optical analysis

The optical design and analysis of the solar simulator is performed using APEX application add-in for SolidWorks, in a four-steps workflow [13]: (1) design of the SS^2 system (geometry and optical properties), (2) design of the light source of the system, (3) trace rays to simulate the system behavior and (4) analysis of the irradiance over the test plane to derive the non-uniformity.

2.1.1. System design

The SS^2 is modelled using SolidWorks and consists of three parts (Fig. 1): light source, reflecting light tube (RTL) and test plane (TP). The LT and the TP were modelled using extrude boss/base feature and then inserted into the system assembly, as shown in Fig. 1.

The reflectivity of the RTL inner surfaces is set to 0.88 for aluminum, while the upper surface of the TP is set as a perfectly absorbing one. The initial value of the clearance, C is 162.5 mm. During the simulations, this value was reduced to 142.5 mm, then to 122.5 mm and, finally, to 102.5 mm.

2.1.2. Light source's design

The light source is created by inserting four emitting rectangles (ER) from the APEX Light Source Library directly into the SS^2 assembly, representing the floodlights (FL). This was done because accurate modelling of the FL is very difficult to perform due to the lack of technical information regarding the dimensions and optical properties of the lamp and the FL parts. The power flux of the ER and its surface dimensions are set to 240 W and 123.8×152.4 mm, respectively, just like the FL.

In order to calibrate the ER, the distribution of irradiance of one FL over a plane surface 1 m away from it, is measured using an EKO MS-60 first class pyranometer (PYR). Measurements were made from 50 to 50 mm, along two orthogonal axes, x and y, which intersect at point 0. The y axis is parallel to the axis of the lamp and the point 0 is the projection of the midpoint of the lamp onto the plane surface. It has been found that the measured irradiation at the point 0 has a maximum value of 136 W/m^2.

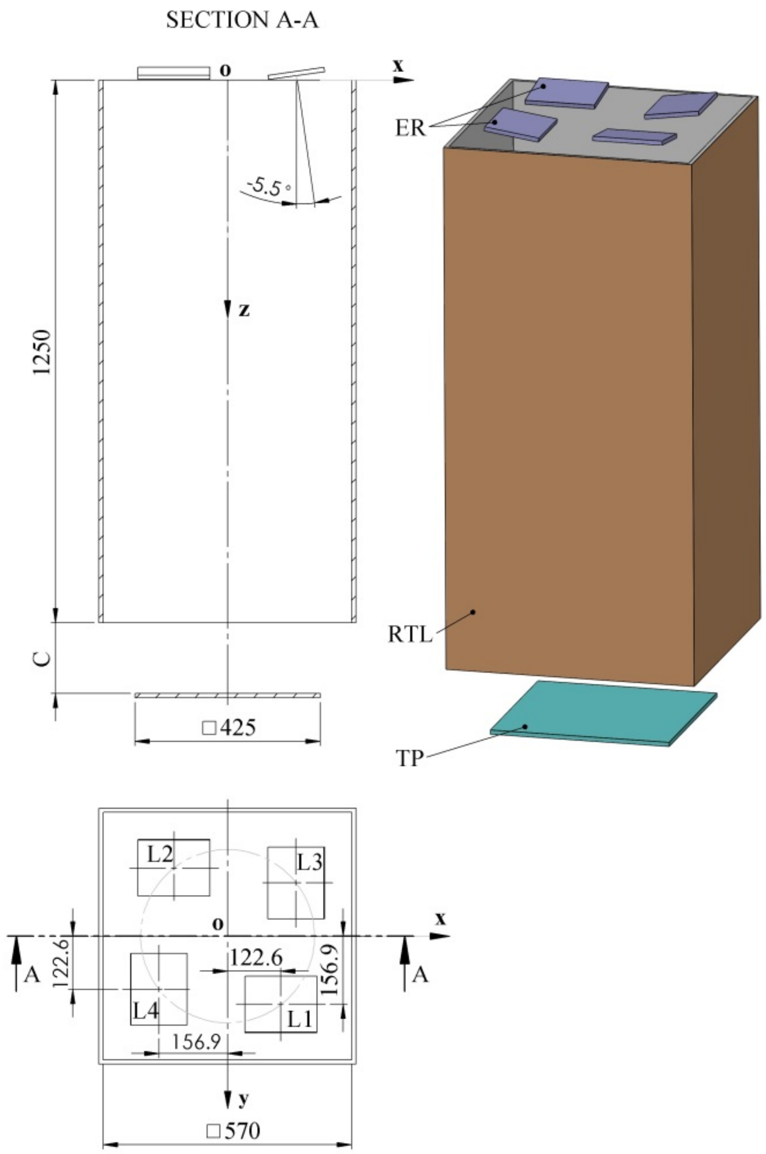

Fig. 1 – Small-scale solar simulator model for optical analysis.

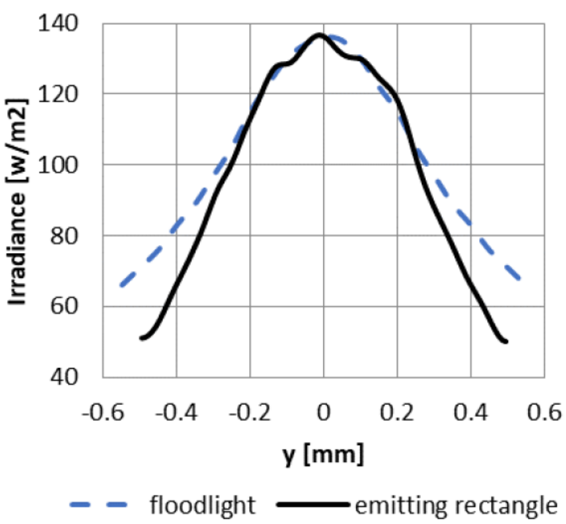

Fig. 2 – Distribution section at $x = 0$.

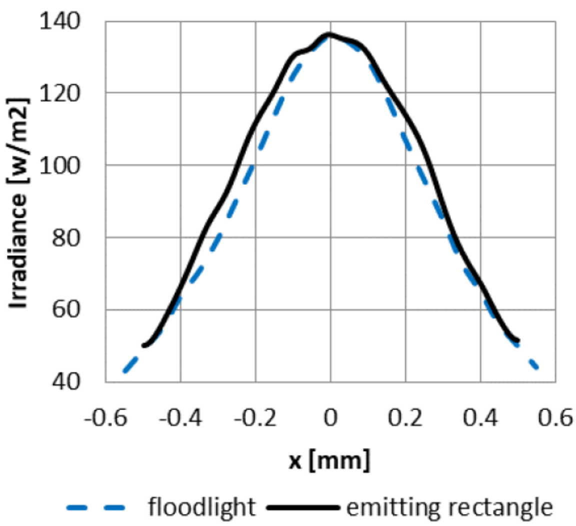

Fig. 3 – Distribution section at $y = 0$.

The irradiance distribution of one ER over a plane surface 1 m away from it is simulated using APEX, with several limiting angles of the distribution. It has been found that the ER distribution limiting angles for which the maximum simulated irradiance is equal to the one measured are: 50° for x axis half-angle and 50° for y axis half-angle. Further, the flux distribution of the ER is modified by apodization using APEX built-in mathematical functions. The best match between the experimental and the simulated distribution is obtained using the Gaussian fall-off function in direction cosine space, GDIS [13].

Figures 2 and 3 show the distribution sections of the FL measured irradiance and the ER simulated irradiance apodized with GDIS function.

2.1.3. Trace rays simulations

The initial number of light rays emitted by the ER is set to 10^6 and the final value is determined in a convergence study, after the analysis of irradiance is realized. For the simulation, all the APEX default settings related to the optical model and trace rays were used.

The on/off state of the ERs is set to five combinations: (1) L1 on, L1 L2 L3 off; (2) L1 L2 on, L3 L4 off; (3) L1 L3 on, L2 L4 off, (4) L1 L2 L3 on, L4 off, and (5) L1 L2 L3 L4 on.

For each combination, the clearance C is set to 162.5, 142.5, 122.5 and 102.5 mm.

After the ray tracing simulation, the irradiation on a test area (TA) of the TP, is analyzed for each combination.

2.1.4. Analysis of irradiance

The bounds of the TA are –212.5 mm and +212.5 mm, while the data resolution is set to 85 on both x-axis and y-axis direction. The dimensions of the TA (425×425 mm) are slightly larger than those of the designated test area (DTA) (400×400 mm) in order to be able to calculate the values of the irradiation along the bounds of DTA by interpolation. The results sets irradiance file is exported from APEX to Mathcad. The file contains a table of comma separated values (CSV) with 7225 lines and three columns: x coordinate, y coordinate and simulated irradiance, $G(x,y)$. The Mathcad worksheet performs a 2D multivariate regression to fit the simulated irradiance data to a 4th order polynomial. It uses Mathcad's built-in function *regress* to perform the regression analysis and *interp* to define a polynomial function of irradiance, $f(x,y)$. This function is used by *CreateMesh* function to compute a nested array of three matrices: X, Y representing the coordinates of every point on a 80×80 nodes grid covering the DTA (from –200 to +200 mm, on both x and y axis), and G, the corresponding fitted irradiance. The maximum, the minimum, and the mean values of the matrix G are computed using the *max*, *min* and *mean* built-in Mathcad functions. Finally, the non-uniformity, Nu is computed using eq. (1).

A study was conducted on the convergence of the non-uniformity of one ER. Several successive simulations were performed with an increasing number of light rays. The first simulation was done with 10^6 light rays, the second one with 2×10^6 light rays and so on. It was found that the variation of non-uniformity decreases below 0.5% when the number of light rays increases from 9×10^6 to 10×10^6. Therefore, all subsequent simulations were performed with 10^7 light rays per ER.

2.2. Non-uniformity derived from irradiance measurements

Non-uniformity of irradiance method is based on IEC 60904-9:2007 standard.

2.2.1. Solar simulator manufacturing

The solar simulator was designed using SolidWorks based on the dimensions of the model used for optical analysis. Figure 1 shows the SS^2's main subassemblies: the light source (LS); the reflecting light tube (RTL), the supporting frame (SF) and the target plane (TP). The LS and the TP are parallel and fixed on the four legs of the RTL. The distance between the bottom end of the RTL and the TP (the clearance) can be continuously adjusted from 102.5 to 162.5 mm. The inner walls of the RTL are lined with aluminum foil to ensure a good reflection of the light rays emitted by the LS.

The LS consists of four 0201 model HEPOL commercial floodlights (FL) fitted with tubular Plusline ES Small 118 mm, 240 W/230 V, R7s, Philips lamp. The axis of the lamp is parallel to the TP and the tilt angle (measured between the normal line to the FL glass cover surface and the vertical line passing through the center of the FL lamp) is set to –5.5 degrees.

The TP consist of an acrylic square plate (0.6×0.6 m) fixed in the center of a square frame made from UD30 steel channels. It is mentioned that the designated test area (DTA) is a 0.4×0.4 m^2 centered on TP.

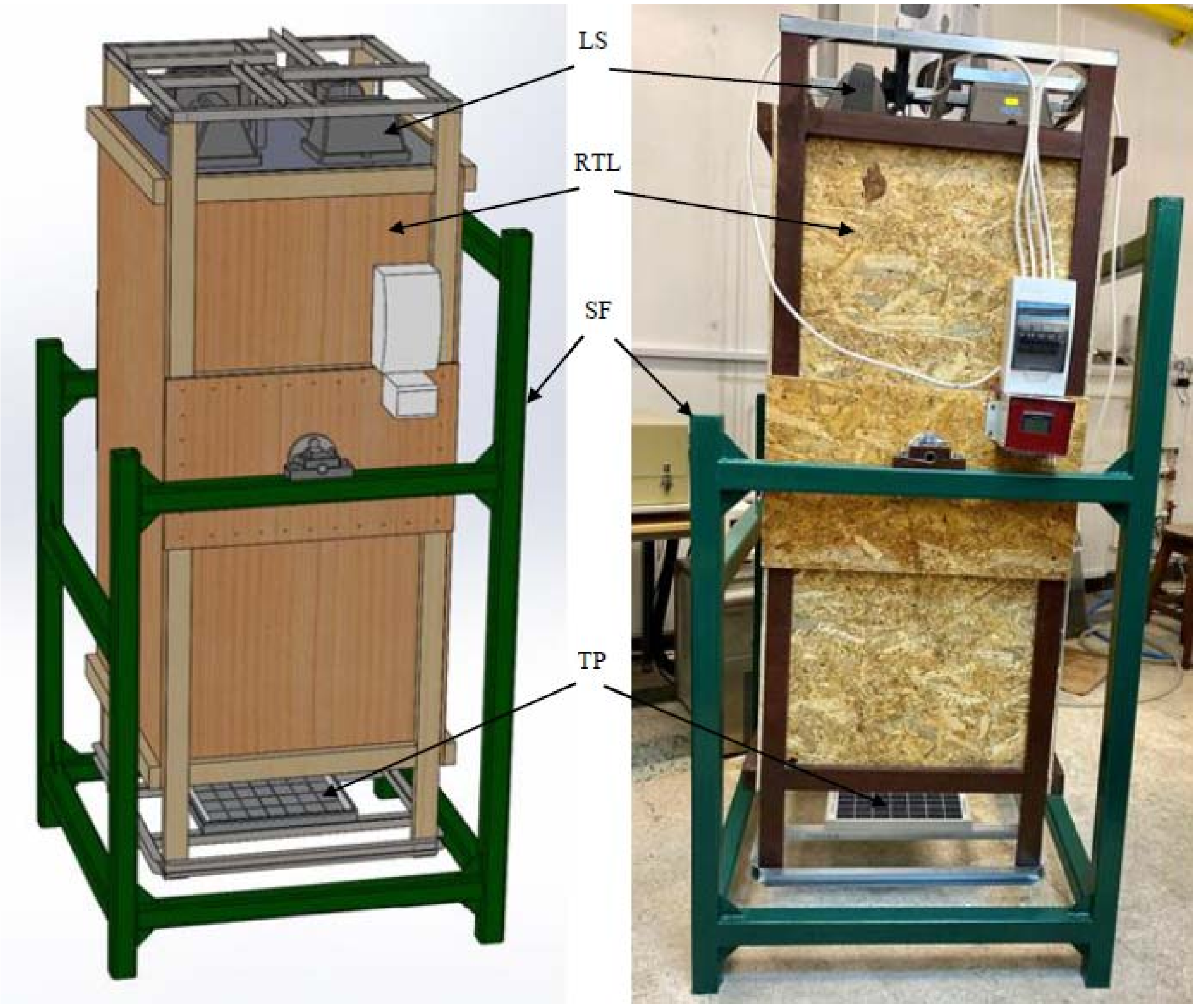

Fig. 4 – Virtual model (left) and real model (right) of the small-scale solar simulator.

The SS^2 is supplied with electricity from the 230 V single-phase AC grid through a 16 A residual current circuit-breaker (RCCB). The FL lamps are connected in parallel, each lamp being protected by a 6A miniature circuit-breaker (MCB). By switching on/off the MCBs, the FL lamps can be lit in any desired combination (one, two, three or all four). The active power consumed by the FL lamps is measured and displayed from second to second by the SIRAX BT 5400 power transducer (W).

The electric voltage supply of the lamps can be varied by turning the knob of the adjustable autotransformer (AA) 2.6 kW HNS Metrel. The SS^2 block diagram is presented in Fig. 5. The radiation produced by the lamps propagates through the RTL towards the TP. On the TP's top surface, 5 lines parallel to the bottom horizontal edge of the TP and 5 lines parallel with the vertical edge of the plate are drawn, from 100 to 100 mm. The points at the intersection of the lines form a 5×5 nodes grid evenly distributed over 400×400 mm DTP.

The irradiation is measured using the PYR in all 25 grid nodes and displayed by the multimeter A (FLUKE 87 V).

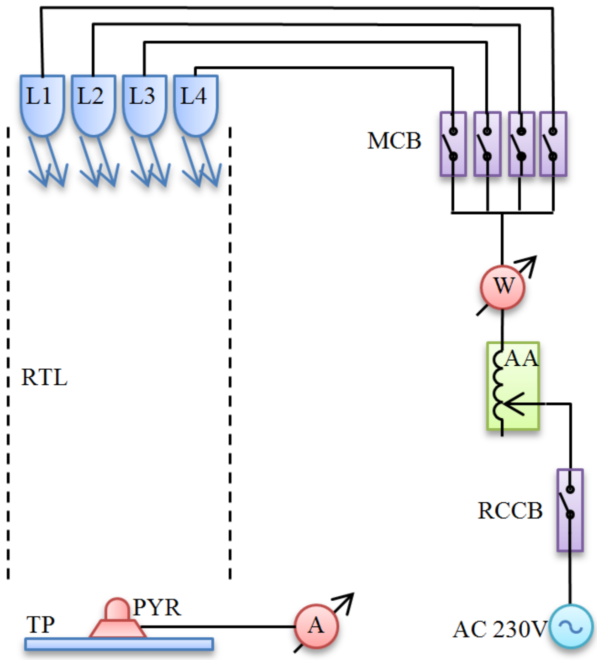

Fig. 5 – Block diagram of the small-scale solar simulator.

The 5×5 matrix containing the measured irradiance, for each combination of lit ER and each of the four clearances is written in a Mathcad worksheet. The measured non-uniformity, *Nu* is computed using eq. (1).

3. RESULTS AND DISCUSSIONS

Figure 6 presents the simulated non-uniformity vs. clearance for five different combinations of lit lamps. As one may notice, when clearance value drops from 160 to 120 mm, the non-uniformity of irradiance decreases by about 6% for all lamp combinations. From 120 to 100 mm, the non-uniformity increases slowly (L1), is constant (L1 L3) or decreases slowly for the rest of the combinations. The non-uniformity of the irradiation produced by a single lamp (L1) has a minimum value for $C = 115$ mm.

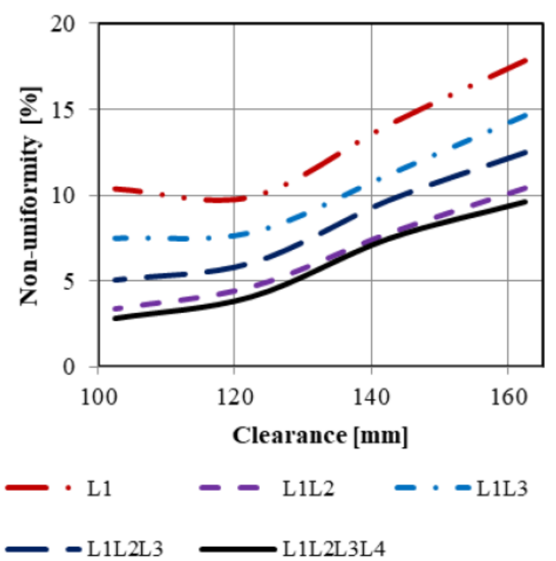

Fig. 6 – Simulated non-uniformity vs. clearance for different combinations of lit lamps.

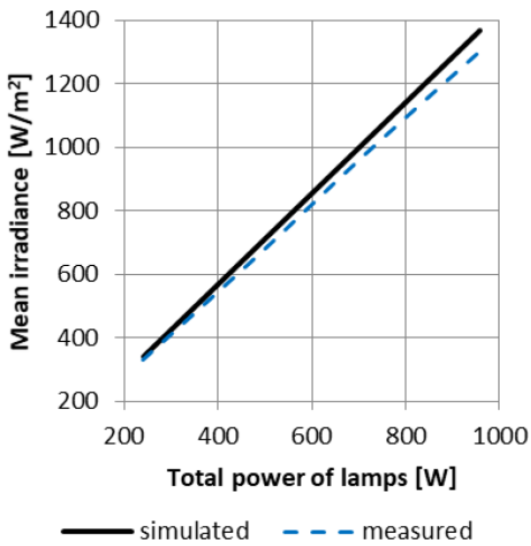

Fig. 7 – Relationship between mean irradiance and total power of lit lamps.

One can also observe that the combinations L1 L2 L3 L4 and L1 L2 have the lowest non-uniformity values. This is likely because the lamps of these combinations are symmetrical with respect to the center of the light tube (lamp L1 is symmetrical with lamp L2, and lamp L3 with lamp L4). The largest non-uniformity values are found in the combinations L1 and L1 L3, in which the lamps are asymmetrical with respect to the center of the light tube. The combination L1 L2 L3 has an average non-uniformity value, which lies between the values of the other combinations.

Given that the maximum allowed non-uniformity value is 10%, the clearance value was set at C = 115 mm and the non-uniformity of the irradiance was measured for L1, L1 L2, L1 L2 L3 and L1 L2 L3 L4 lit lamps combinations. The L1 L3 combination was excluded due to its high non-uniformity value. The average values of the irradiance over the DTA, as well as the relative standard deviation (*RSD*, defined as the ratio between the standard and the mean deviation) of the measured data are centralized in Table 1.
The simulated mean irradiance values resulted from two, three or four lit lamps combinations is a multiple of the mean irradiance resulting from one lamp, because within the simulation all the lamps are identical, and the irradiative flux is additive.

Actually, the lamps are not identical, due to the manufacturing and assembly tolerances of their parts. Measurements made using each of the four lamps showed that the mean irradiance of one lamp differs from the average irradiance of the four lamps with a maximum of ±2.3%. As a result, there is a difference between simulated and measured mean irradiance, which does not exceed 5%. This difference is almost twice as large as that reported in the paper [10].

Table 1

Simulated and measured mean irradiance values at C=115 mm

Lit Lamps Combination	**Simulated mean *G* [W/m^2]**	**Measured mean *G* [W/m^2]**	**Simulated *RSD* [%]**	**Measured *RSD* [%]**	**Simulated *Nu* [%]**	**Measured *Nu* [%]**
L1	341.9	329.9	4.33	7.34	9.93	15.3
L1 L2	683.8	651.6	1.63	4.67	4.65	9.7
L1 L2 L3	1025.7	985.5	2.01	4.99	6.02	10.5
L1 L2 L3 L4	1367.6	1302.9	1.46	5.57	4.11	9.9

Figure 7 explains the linear relationship (the correlation coefficient is 0.99995) between measured mean irradiance and total power of lit lamps, which allows the determination of the electrical power required to obtain the desired average irradiance level.

The simulated RSD data from Table 1 shows that the highest level of dispersion around the mean irradiance occurs when only one lamp is lit, and the lowest level takes place when all four lamps are lit. The simulated non-uniformity of the irradiance presented in Table 1 shows the same behavior as the simulated RSD: the maximum value can be found for one lit lamp and the minimum value for four lit lamps. The correlation coefficient between simulated RSD and simulated non-uniformity is 0.99, so it can be concluded that between the two variables there is a strong statistical relationship. Also, from Table 1 it can be noticed that the measured RSD is, on average, 3.3% higher than the simulated RSD for all combinations. It should be mentioned that the measured RSD of 5.57% for lit lamps combination L1 L2 L3 L4 is close to the one reported in the paper [10], which was 5.3%.

The same is observed regarding the non-uniformity: the measured non-uniformity is greater than the simulated one, on average by 5.2%. Most likely, there are two causes for this difference: the modeling of the light source used in raytracing and the heating of the pyranometer during measurements under the action of the infrared radiation emitted by the lamps. The first cause can be eliminated by replacing the GDIS apodization function with a numerical function. The second one can be reduced by inserting a cold-sky filter between the bottom end of the light tube and the test plane.

Further research on spectral match and temporal instability of the irradiance should be performed for complete characterization of the small-scale solar simulators.

4. CONCLUSIONS

A small-scale solar simulator using halogen incandescent lamps for testing prototypes of flat-plate solar collectors has been designed, manufactured, and tested. To achieve uniform illumination of the target plane and to reduce the number of lamps, a tube with reflective interior walls was placed between the lamps and the target plane.

Non-uniformity of the irradiance depends on the combination of lit lamps and the clearance. From all the combinations of lit lamps, only the combinations of two and four symmetrical lamps with respect to the axis of the light tube have a non-uniformity value lower than 10%, provided that the clearance is 115 mm.

There is a linear relationship between the average irradiance over the designated test area and the total power of the lamps. The setting of a certain level of irradiance between 400 and 1200 W/m^2 can be done by changing the supply voltage of the lamps and/or by changing the combinations of lit lamps.

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