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Indoor Testing of Solar Systems: A Solar Simulator for Multidisciplinary Research on Solar Technologies

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The department of Mechanical Engineering in Cyprus University of Technology (CUT), recently commissioned a large scale solar simulator, to facilitate interdisciplinary research on solar systems. The simulator has been designed to simulate sunlight with respect to both intensity and spectrum. This paper will present results from a series of measurements carried out to calibrate the simulator including uniformity measurement of light intensity distribution and degree of light collimation. At the beginning, measurements of one single lamp were conducted to see its light uniformity in different rotation angles of the lamp lens and next tests for 4 lamps and 20 lamps were carried out to map the illumination intensity of the simulator. Subsequently, a real test was carried out concerning the performance characteristic curve of a polycrystalline PV panel. PV panels are generally very sensitive to the solar spectrum and they are ideal to check accuracy of the light produced from the simulator. Measurements have been carried out indoors with the use of the solar simulator as well as outdoors in natural sun in order to compare the performance curve of the PV for both conditions.

1. Solar Systems Worldwide

As the energy crisis escalates and the price of gas and electricity increase, there is an inevitable shift to solar energy which can be considered to be a unique opportunity to create a new clean energy economy. There are several solar energy technologies such as the solar thermal systems for heating, cooling and water heating, solar photovoltaics for electricity generation, solar architecture and artificial photosynthesis. All these technologies can have a considerable potential to solve some the world's energy problems.

Lately, solar power systems are experiencing a rapid growth worldwide, mostly in the countries with high amount of solar radiation. Solar technologies tap directly into the infinite power of the sun and use that energy to produce heat and power.

The total PV peak power capacity in the world in 2010 was 39.77 MWp while in 2012 increased to 102.02 MWp. ESTIF (2008), states that the solar heating installed capacity in Europe in 2008 was 19.08 MWth and in 2011 was 25.55 MWth.

1.1 Solar Systems Testing

Indoor tests of solar collectors is important because it is carried out under controlled conditions, thus there is a repeatability of the testing conditions which allows the optimization of the collectors based on same input energy and losses.

2. Solar Simulators

A solar simulator is a device that provides illumination approximating natural light. Solar simulators can be divided into three broad categories; continuous, flashed and pulsed.
The purpose of the solar simulator device is to provide a controllable indoor test facility under controlled laboratory conditions used for the testing of solar cells and other materials.
The light from the solar simulator is controlled in three dimensions:

1. Spectral content
2. Spatial uniformity
3. Temporal stability

2.1 Solar Simulator in CUT

A large scale solar simulator has been designed and constructed in the Department of Mechanical Engineering in Cyprus University of Technology, to facilitate multidisciplinary research on solar technologies. Such equipment enables the university to collaborate in the field of solar energy with local and national industries and other universities.
The simulator is used to imitate in an indoor controlled environment the radiation of the sun. For this purpose the simulator is designed to achieve uniform intensity distribution on the test plane, good spectral distribution, variable intensity level and flexibility. This indoor solar simulator facility allows performance evaluation and product certification of PV panels, solar thermal collectors, solar concentrators and other solar systems.
The solar simulator consists of a lamp array to produce simulated light, a large frame to provide support and operational flexibility and the control unit for operating the lamp array. The design of the solar simulator is very similar to the one designed in the University of Ulster (Deb Mondol et al., 2010).
The frame of the simulator where the lamps are attached is made of steel RHS components. The design of the simulator, allows to obtain uniform intensity of light on vertical, horizontal and inclined surfaces. Its design feature allows full testing of solar concentrating systems to be carried out as every direction of the sunlight incident on the concentrator aperture can be simulated. Additionally, the frame enables automated height adjustment from ground level up to 3 m above the ground. In addition to the full mobility for the lamp frame that enables tilt adjustment of the lamp array, the frame is also able to move along the laboratory floor allowing testing of a variety of arrangements.
The 2.15 m x 1.65 m x 0.35 m (length x width x depth) lamp frame consists of 20 (575 W) metal halide lamps arranged in 5 rows of 4 lamps and is capable of illuminating a test area of 2 m x 1.5 m with a maximum intensity of 1200 W/m^2. As described in the work of Meng et al. (2011), metal halide lamps, despite a higher energy output in the ultraviolet range and lower in visible range than natural solar light, are suitable for applications requiring the simulation of the full spectrum.
A unique dimming arrangement of each row of lamps allows the simulator to provide uniform intensity light under normal and non-normal incidence angle conditions. In order to cool the lamps during solar simulator's operation, there are two ducts at the ends of the aluminium housing which contain fans that force ambient air temperature to pass through the lamp holders.
Each lamp is equipped with a rotation symmetrical paraboloidal reflector to provide a light beam of high collimation. In order to achieve uniform distribution of light intensity on the test area, a lens is inserted in each lamp to widen the illumination of light. Special designed lenses at the aperture of the paraboloidal reflectors modify the angular distribution of the light to achieve the required overlapping between neighbouring lamps. The combination of reflector characteristics, lens and lamps ensures a realistic simulation of the beam path, spectrum and uniformity.
Additionally, the simulator is equipped with an external control unit which includes safety features to protect the system from power failure and overheating. Any fault in the system will be displayed on the simulator control panel. The intensity of the light on the test target can be controlled manually or automatically through the control unit. In the automatic mode, the user sets the desired intensity level of the light incident on the target area and the control unit makes all the necessary adjustments to the power output of each row of lamps to achieve the set intensity level. A maximum intensity of light up to 1200 W/m^2 can be set. In the manual mode, the dimming controls allow the user to increase the power output from either all rows of lamps simultaneously or from each individual row of lamps.

3. Tests carried out

A series of tests were carried out to calibrate the simulator including uniformity measurements of light intensity distribution and degree of light collimation.

The first two experiments deal with the light uniformity of the lamps for normal incidence area. As mentioned before, the lamps were equipped with lenses. It was expected that those lenses would affect the uniformity on the light in the normal incidence if they were rotated in different positions. For this purpose, the first two experiments were carried out for three different rotation angles of the lenses of the lamps as shown in Figure 1 (for horizontal and vertical positions). Various measurements of the total irradiance in each case were carried out at many points on the grid of the nominated test plane of the target area.

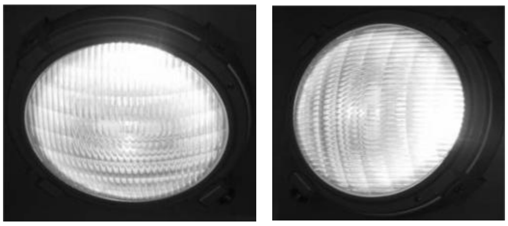

Figure 1.The rotation angles of the lamp lens.

Initially, three measurements of the intensity of one single lamp were conducted to see its light uniformity in three different rotation angles of the lamp lens while is placed horizontally, vertically and in 45º. Measurements have been taken on a specific area of normal incidence of 1.6 m x 1.3 m placed perpendicularly 1.8 m away from the simulator.

In the second experiment, three measurements of the intensity for 4 lamps were conducted to investigate again the light uniformity in three different rotation angles of the lenses. Measurements have been taken on a specific area of normal incidence of 1.3 m x 1.2 m placed perpendicularly 1.8 m away from the simulator as shown in Figure 2.

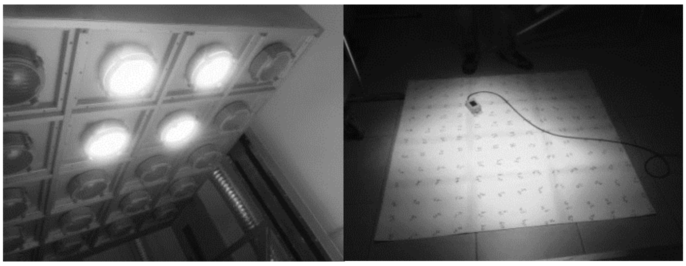

Figure 2. Test No.2 with 4 lamps – left picture shows the simulator and right is the measurement area.

For the third experiment, the best rotation angle of the lenses that gives the biggest area of high intensity was selected and all 20 lamps of the simulator were lighted up for one measurement to investigate the light uniformity of the whole solar simulator.

The last experiment is a real experiment and concerns the generation of the performance characteristic curve of a polycrystalline PV panel with dimensions 1.30 m x 0.86 m as shown in Figure 3. This panel is initially tested outdoors recording also the solar intensity and incidence angle, and afterwards these conditions have been reproduced indoors with the solar simulator and a new performance curve is obtained which is compared to the outdoor one.

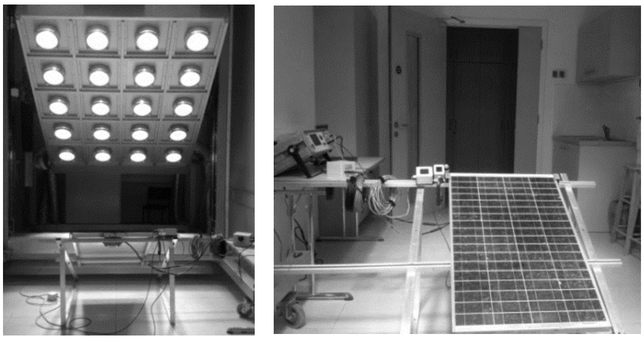

Figure 3. Experiment No.3 to obtain the characteristic curve of a PV indoors and outdoors.

4. Results

4.1 Light Uniformity for normal incidence for 1 lamp

The irradiance contours at the target area for the first experiment are shown in Figures 4 to 6. From a general point of view it can be said that the light is uniform in the area plotted. Moreover, as can be observed, the area with higher intensity is the one presented while the lens of the lamp was placed in 45º.

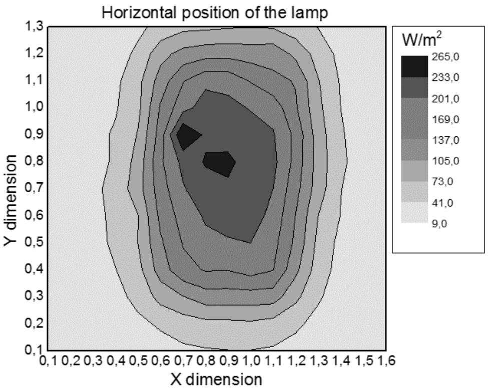

Figure 4. Light intensity contour plot for one lamp while the lens is in horizontal position.

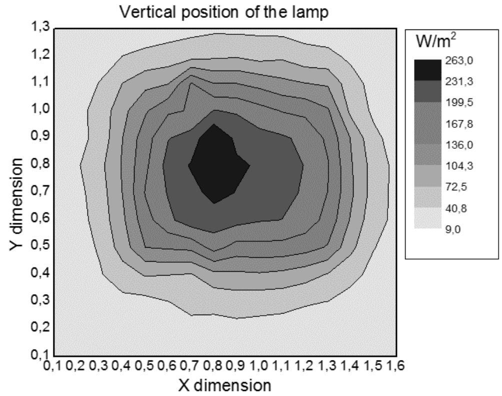

Figure 5. Light intensity contour plot for one lamp while lens is in vertical position.

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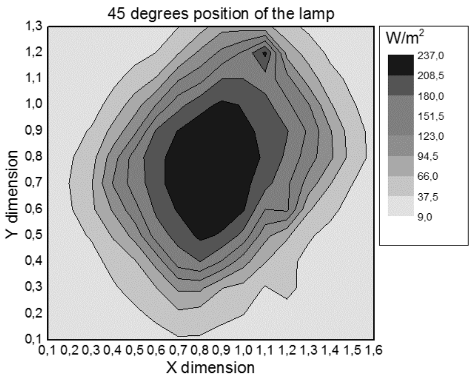

Figure 6. Light intensity contour plot for one lamp while lens is placed in 45º.

4.2 Light Uniformity for normal incidence for 4 lamps

The results from the second experiment are shown in contour graphs in Figures 7 to 9. Again the overall conclusion is that the light is quite uniform in the area plotted as there are not many fluctuations between high and low intensity points. Additionally, the position of the lens that provides higher intensity in a bigger area is 45º.

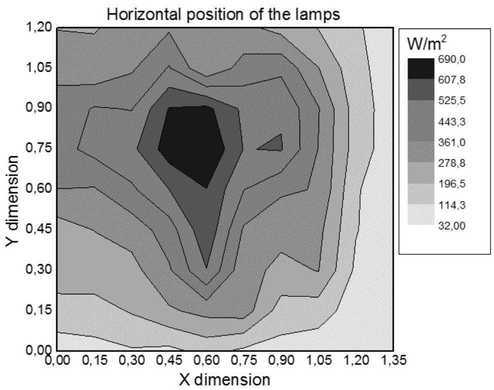

Figure 7.Light intensity contour plot for 4 lamps while the lenses are in horizontal position.

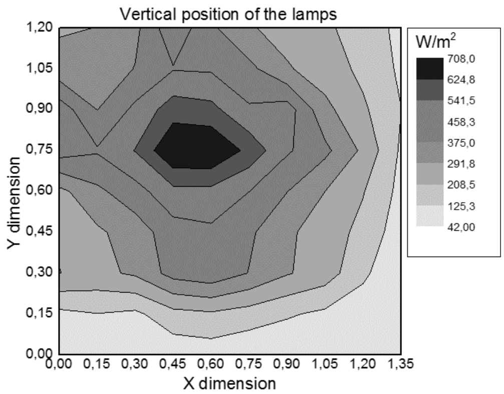

Figure 8. Light intensity contour plot for 4 lamps while the lenses are in vertical position.

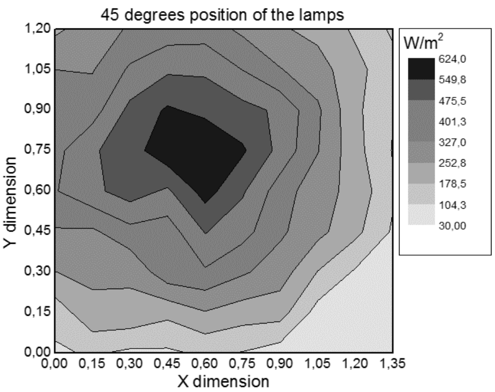

Figure 9. Light intensity contour plot for 4 lamps while lenses are placed in 45º.

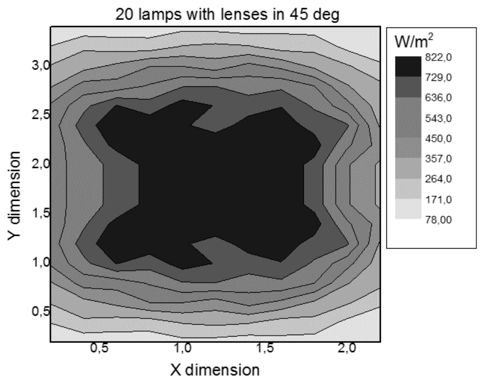

Figure 10. Light intensity contour plot for 20 lamps while lenses are placed in 45º.

4.3 Light Uniformity for normal incidence for 20 lamps

From the previous experiments presented, it was concluded that the position angle of the lamp lenses that gives the biggest area of high light intensity is the one of 45º. Consequently this position is selected as the optimum and used for the third experiment. All the lamps of the simulator were switched on with their lenses positioned at rotation angle of 45º. The measurements have been carried out on an area of normal incidence with dimensions 2.2 m x 3.2 m. The solar simulator's light intensity contour map is presented in Figure 10.

The experimental data shows that the area giving the desired uniformity higher than 700 W/m^2 only accounts for about 24 % of the full area illuminated by the solar simulator.

4.4 Real test on Solar PV panel

The comparison of the two measurements carried out outdoors in natural sun and indoors from the solar simulator in specific solar intensity and incidence angle has been made with the comparison of the characteristic curves of the PV panel obtained indoors and outdoors. As said before, PVs are sensitive to the uniform intensity of light and spectrum which will show the capacity of the solar simulator to reproduce both. Figure 11 shows the power- voltage P-V graphs for the two measurements. The difference between the maximum power from the outdoor P-V curve and the indoor P-V curve is only 2.2 %. This shows that both tests were carried out at the same intensity and spectrum characteristics of the input light.

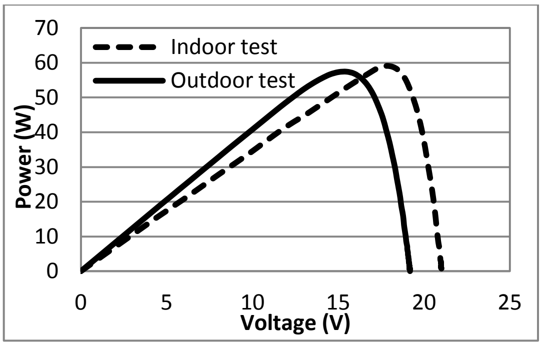

Figure 11.P-V curve of the panel of the indoor and outdoor tests.

5. Conclusions

This paper described the detailed characteristics of a new solar simulator designed to represent sunlight at any surface in any inclination and distance. The results show that the illuminated area can be homogeneously irradiated by the solar simulator. It is important to mention that, understanding the performance, limitations and strengths of solar simulation equipment can lead to more effective and more reliable test results.

Acknowledgments

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