N.M. Samiudin[1], F. Hussain[1], M.Y.H. Othman[2], B. Yatim[2], H. Ruslan[3], K. Sopian[3], Z.Ibarahim[2]

[1]National Metrology Institute of Malaysia, SIRIM Berhad, Bandar Baru Salak Tinggi, Sepang 43900, Selangor, Malaysia
[2]Physics Department, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[3]Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

***(faridah_hussain@sirim.my)**

DEVELOPMENT OF SOLAR SIMULATOR FOR INDOOR TESTING OF SOLAR COLLECTOR

***RINGKASAN:** Kertas kerja ini membentangkan analisis prestasi sebuah simulator suria. Ianya bertujuan memenuhi keperluan menguji pengumpul suria di Institut Metrologi Kebangsaan Malaysia (NMIM). Simulator suria ini dibina menggunakan bahan tempatan yang sedia ada untuk menyokong rangka dan lampu halogen sebagai sumber cahaya. Analisis telah dijalankan pada empat nilai keamatan sinaran yang berbeza. Untuk mendapatkan keamatan sinaran yang diperlukan, kaedah yang digunakan adalah dengan membuka lampu-lampu tertentu manakala mematikan yang lain. Keseragaman sinaran itu kemudian dinilai dengan melakukan pengukuran pemetaan sinaran. Kajian ini telah menunjukkan bahawa simulator suria ini mampu menghasilkan sinaran dengan keamatan cahaya ~ 400 W/m^2, ~ 600 W/m^2, ~ 700 W/m^2 dan ~ 900 W/m^2. Ianya juga berjaya menghasilkan kebolehulangan pengukuran yang baik dengan ketidakseragaman yang rendah sekitar ± 5 % hingga ± 7 %.*

ABSTRACT: This paper presents the performance analysis of custom designed solar simulator. This work aims to cater the need for testing solar collector at National Metrology Institute of Malaysia (NMIM). The solar simulator was built using locally available material of supporting frame and halogen lamps as source of light. The analysis was carried out at four different irradiance intensities. To obtain the required irradiance intensity, the method used was by switching on certain numbers of the lamps while turning off the others. The uniformity of the irradiance was then evaluated by performing irradiance mapping measurement. This study has shown that the fabricated solar simulator was capable of producing irradiance intensity setting of ~ 400 W/m^2, ~ 600 W/m^2, ~ 700 W/m^2 and ~ 900 W/m^2. The solar simulator also managed to offer good repeatability of measurement with low non-uniformity that was within ± 5 % to ± 7 %.

Keywords: solar simulator, irradiance mapping, non-uniformity

INTRODUCTION

Recently, National Metrology Institute of Malaysia (NMIM), had successfully fabricated a solar simulator for indoor testing of a solar collector. The pattern of this solar simulator was adapted from the design of solar simulator developed by Nazari in 2007 (Nazari, 2007). The indoor test was facilitated with controlled environment facilities for solar irradiance intensity parameters; input temperature, ambient temperature, mass flow rate and wind speed. Controlled environment facilities were capable to reduce the evaluation time to measure the performance of the collector. American Society of Heating, Refrigerating & Air Conditioning Engineers (ASHRAE, 2003) suggested that this solar simulator should fulfil the requirements as follows:

a. Light source used should be the same as real solar spectrum and complied with the air mass standard of 1.5 solar spectrum.

b. Light spectrum produced should not be affected by input voltage variation to control the irradiance intensity of the light.

c. The light spectrum distribution on the solar collector testing area should be uniformed and irradiance mapping shall be executed to calculate irradiance intensity uniformity.

In the previous years, varieties of design and different types of light bulb were used to build solar simulator such as Compact Source Iodide (CSI), tungsten, tungsten-halogen and xenon. A lot of research works have been done to comply with the (ASHRAE, 2003) requirements. Currently, most of the commercial solar simulator available in the market use Xenon light bulb. However, the cost of solar simulator using Xenon bulb is tremendously expensive. Therefore, most of the research institutes and higher educational institutes use halogen-tungsten light bulb as an alternative. Although the Infra-Red effect is more obvious from this type of light bulb, it is cheaper and also easily obtained from local suppliers.

National Aeronautics and Space Administration (NASA)-Lewis laboratory, USA was one of the earliest agencies to fabricate a solar simulator (Ragsdale, 1974). The solar simulator was developed using 143 units of 300 W tungsten-halogen light bulbs. Diachronic reflector was used to reduce the Infra-Red ray radiated from the light bulbs. Beeson in 1978 had developed a solar simulator using 18 Thorn CSI 1000 W light bulbs arranged in hexagonal (Beeson, 1978). The effect of Infra-Red radiation from the light bulbs was filtered by placing two acrylic layers filled with water approximately 0.5 m above the test area surface.

Garg in 1985 developed a low cost solar simulator using 14 light bulbs of 1000 W halogen quartz (Garg, 1985). Its irradiance intensity could be adjusted from 400 W/m^2 to 1500 W/m^2 for 1 m × 1 m test surface area. The distance between simulator lamps and test area was 1.55 m. Meanwhile Tiris *et al*. in 1998 developed a solar simulator using 36 units of OSRAM HQI-E 400/N light bulbs (Tiris *et al*., 1998). The power of each light bulb was 400 W and successfully produced maximum average irradiance intensity of 790 W/m^2. Fan was used as a cooler to minimize the Infra-Red radiation effect.

Supranto *et al.* in 1999 from Universiti Kebangsaan Malaysia (UKM) had also built a solar simulator system using 45 units of 300 W CDX halogen light bulbs (Supranto *et al.*, 1999). The test surface area was 1.7 m × 3.6 m. The next solar simulator was also developed at UKM by Nazari in 2007 using 23 units of tungsten halogen light bulbs with power of 500 W each (Nazari, 2007). Two exhaust fans were used to filter the Infra-Red radiation produced by the lamps. The maximum average irradiance achieved was 707 W/m^2 with uniformity of ± 6.38 %. A solar simulator developed for this research work was based on the solar simulator created by Nazari in 2007. Some modifications have been made to suit this testing method.

Recently, more research works have been done to fabricate and produce solar simulator with a good and reliable performance. Codd in 2013 had designed and characterized a low cost, high flux and large area solar simulator (Codd, 2013). 1,500 W metal halide outdoor stadium lights have been used as the light source to simulate solar power concentration. The metal halide bulbs and ballasts were cheaper than typical xenon arc lamp solar simulator light source. The fabrication of this solar simulator was also unique because of the tilt angle and distance between the output aperture and the ground where it could be adjusted to accommodate test receivers of varying geometry.

There was another solar simulator developed by Agrawal in 2011, (Agrawal, 2011). The purpose of this solar simulator development was to perform indoor testing for a micro-channel solar cell thermal (MCSCT) tiles. It was a 3-phase lamp array with 28 tungsten halogen lamps having 500 W rated power for each lamps, 9,000 lumens and rated voltage and current respectively at 240 V and 11 A. An exhaust fan was used to avoid the overheating of cell. The availability of testing area was 1 m × 2 m and the irradiance of the simulator could be varied from 300 W/m^2 to 1,000 W/m^2.

Namin in 2012 developed tungsten halogen and LED solar simulators for solar cell characterization and electrical parameters determination (Namin, 2012). Seven components of the simulator were fabricated for solar cell characterization purpose consisting of one tungsten halogen simulator, four monochromatic (red, green, blue, and white) LED simulators, one multicolor LED simulator, and one tungsten halogen-blue LED simulator. A nonstandard test condition to test solar cells can be provided using this type of fabrication based on the methods recommended in the (IEC 60891 Standards, 2009), where the measured I-V curves were used to correct electrical parameters of the solar cell.

In National Metrology Centre of Singapore, Xu (2012) developed a standard solar simulator as the primary calibration system for solar photovoltaic cells (Xu, 2012). It was a multi-functional Differential Spectral Responsivity (DSR) measurement system for primary calibration of the Short-Circuit Current (SCC) of reference solar cells with world photovoltaic scale. A quasi-monochromatic probe beam used in the measurement was produced by 1,600 W Xenon discharge or 1,000 W halogen lamp. The system was capable to provide an uncertainty of less than 1 % for SCC measurement.

DEVELOPMENT OF SOLAR SIMULATOR AT NMIM

Recently, NMIM has involved in research work related to testing efficiency of solar collectors. Therefore, this work aims to develop an indoor low cost solar simulator to cater the need for testing solar collectors. The fabrication of the solar simulator consisted of halogen light bulbs and supporting frame. 17 units of light bulbs with the power of 500 W each were used. Each light bulb was installed together with its reflector frame. The combination of light bulb and reflector frame is known as halogen lamp. The glass lid that closes the reflector frame was removed to obtain maximum intensity from each light bulb. The light bulb used was manufactured by Philips. The light bulbs radiated white light was operated at rated voltage and rated current of 230 V and 4.0 A respectively. The life span of the light bulb was 2,000 hours. Each light bulb was capable of producing 84 W/m^2 of irradiance.

The supporting frame structure was made of steel with dimension of 127 cm $\times$ 205 cm $\times$ 260 cm. It was meant to hold all the halogen lamps that were arranged in 5 rows as depicted in Figure 1. Distance between centers of each light bulb was approximately 30 cm. The distance between the lamp and the test area was approximately 160 cm. All lamps were arranged perpendicular (90 °) towards the solar collector test area to gain maximum irradiance intensity. Each lamp was connected to main switch outlets and every switch was individually installed as illustrated in Figure 1. Figure 2 shows a successfully developed solar simulator. A layer of 0.5 cm lightproof acrylic piece was positioned between the lamps and the collector. The distance between the acrylic to the collector was 1.7 cm. The acrylic piece was used to reduce the non-uniformity of the light dispersion of the lamps. Three (3) units of fans were placed between the lamps and acrylic piece to reduce the Infra-Red effect from the lamps. Figure 3 displays the location of acrylic piece between the lamps and the collector.

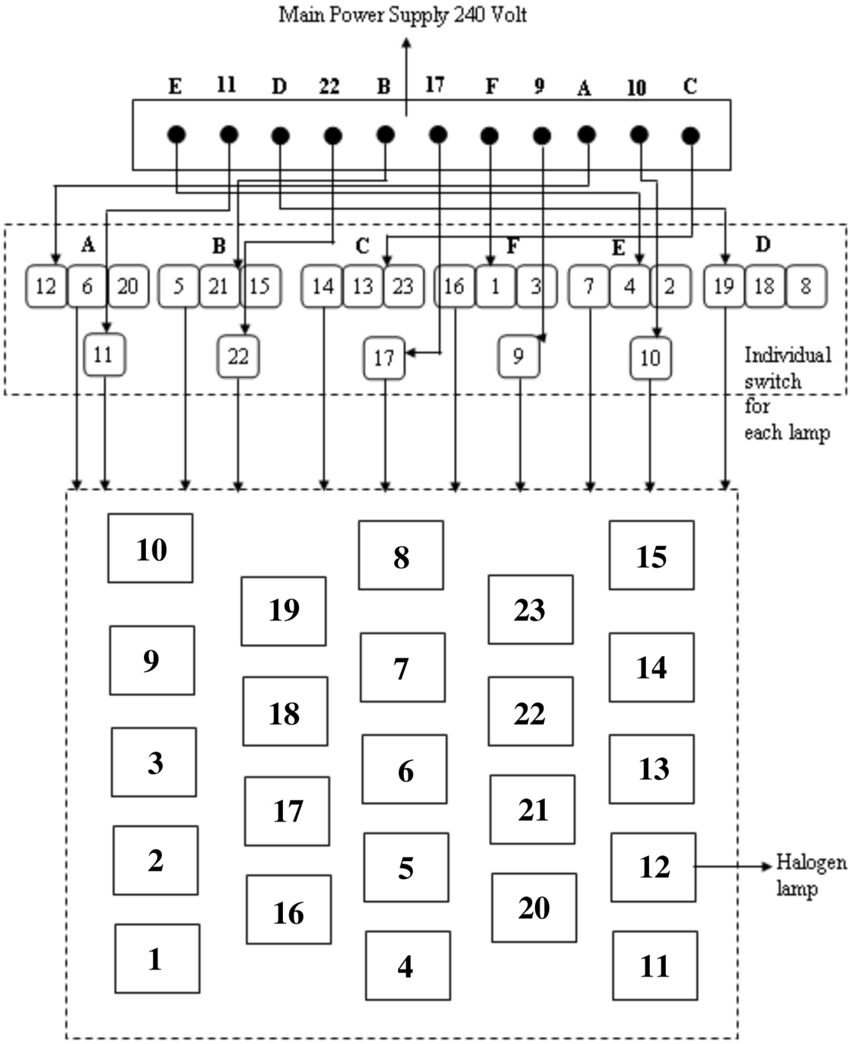

Figure 1. *The arrangement of halogen lamps and switch connectors*

Figure 2. *The successfully developed solar simulator*

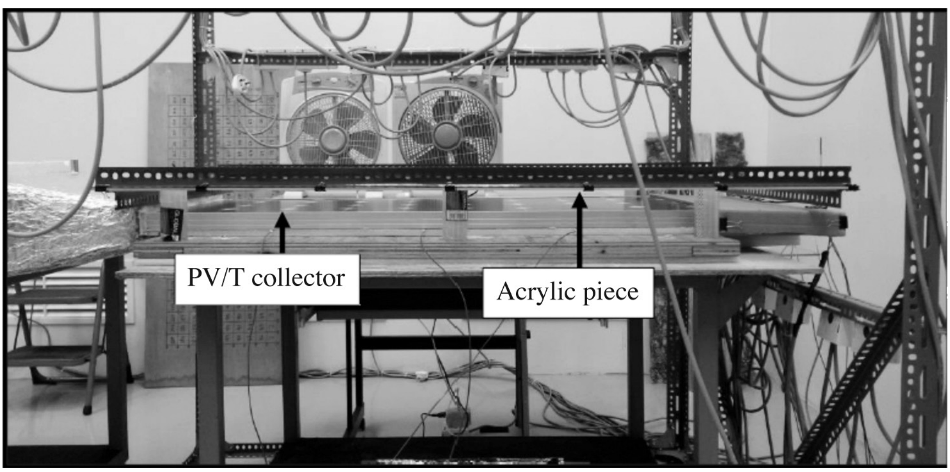

Figure 3. *The location of acrylic piece*

Performance of solar collector developed was tested at four irradiance intensity values setting that were ~400 W/m², ~600 W/m², ~700 W/m² and ~900 W/m². The method used to get each of irradiance setting was by turning on some of the lamps, while the other lamps were turned off. The voltage of every lamp was maintained at 240 V all the time. As mentioned before, the fabricated solar simulator was based on the solar simulator created by Nazari in 2007, (Nazari, 2007). The modifications made to suit the testing method were the numbers of lamps turned on at each irradiance setting with the voltage maintained at 240 V and the usage of acrylic piece placed above the collector to reduce the non-uniformity of the light dispersion of the lamps. The proposed modifications differentiate the fabricated solar simulator as compared to other existing solar simulators mentioned in the literature.

Figure 4 to Figure 7 represent numbers of turned on lamps to gain the value of irradiance setting, respectively. At each irradiance intensity value, the irradiance mapping measurements were performed to get the value of irradiance non-uniformity.

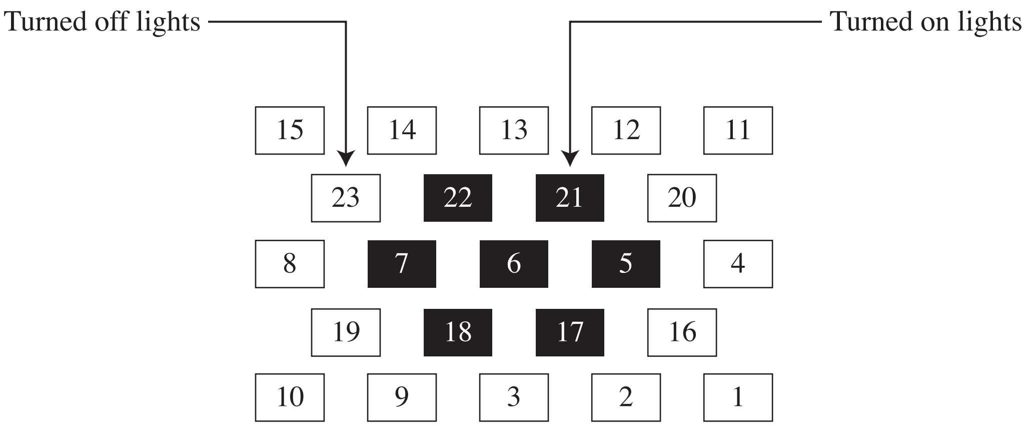

Figure 4. *Numbers of turned on light to attain irradiance intensity of ~400 W/m²*

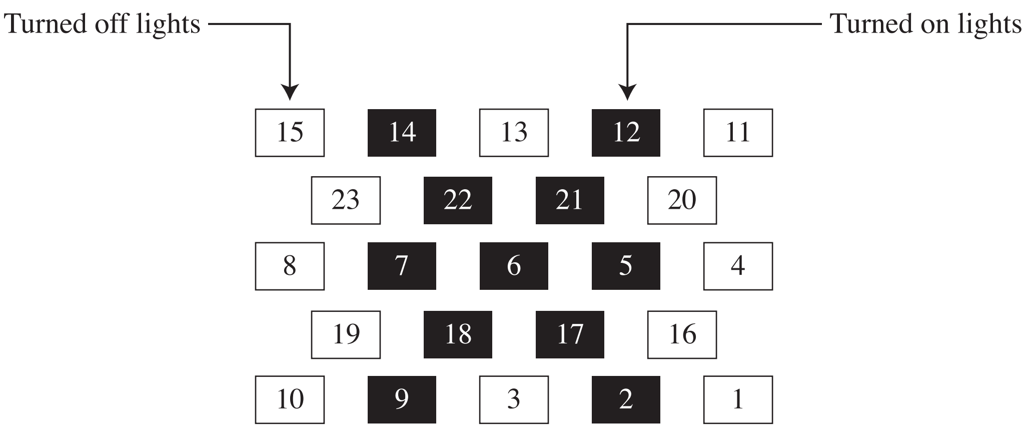

Figure 5. *Numbers of turned on light to attain irradiance intensity of ~600 W/m²*

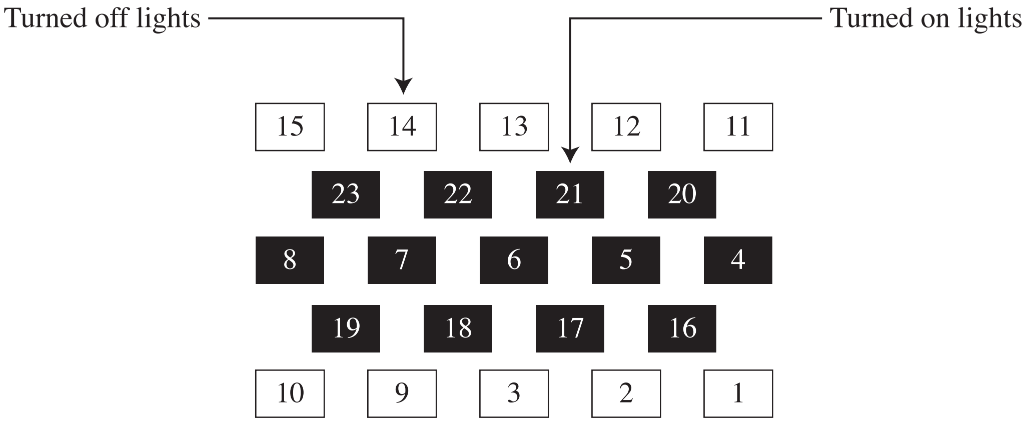

Figure 6. *Numbers of turned on light to attain irradiance intensity of ~700 W/m²*

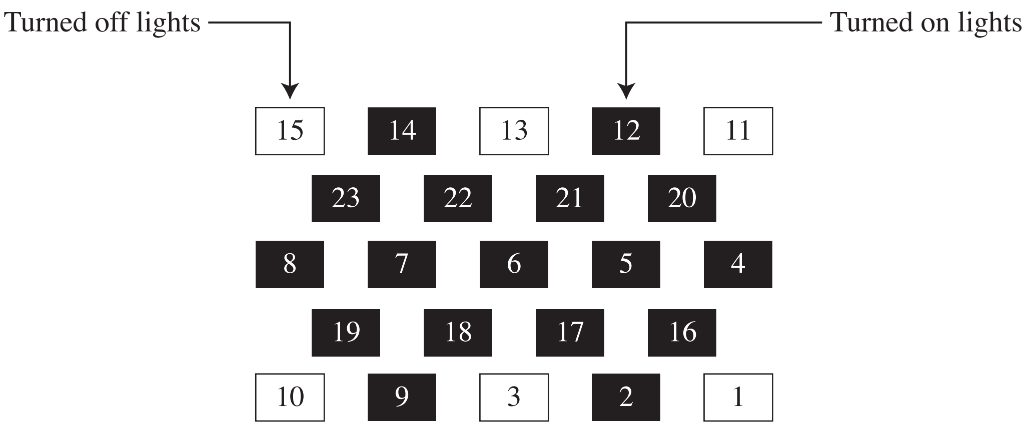

Figure 7. *Numbers of turned on light to attain irradiance intensity of ~900 W/m²*

EVALUATION OF FABRICATED SOLAR SIMULATOR

The fabricated solar simulator was evaluated for its non-uniformity of irradiance dispersion. A good solar simulator would have a small non-uniformity value, indicates the irradiance from the lights was dispersed uniformly onto the testing area. In order to measure the value of non-uniformity, irradiance mapping method was carried out. Distance between the lamps and the mapping area was approximately 160 cm. A unit of pyranometer of Licor brand was located on the mapped grid area. Area of the mapping grid was 55 cm × 117 cm which was equivalent to the surface area of the solar collector that was tested. The mapping area was divided into 10 rows and each row had 23 columns. The total amount of the mapped area measured was 230 sections as shown in Figure 8. The pyranometer's readings were taken after the irradiance intensity was stable. The pyranometer was shifted from one section to another until all sections were being measured. The mapping of the irradiance intensity at each setting of intensity value was repeated three times. The reason of repeating the mapping was to ensure the repeatability of reading at each setting of intensity value.

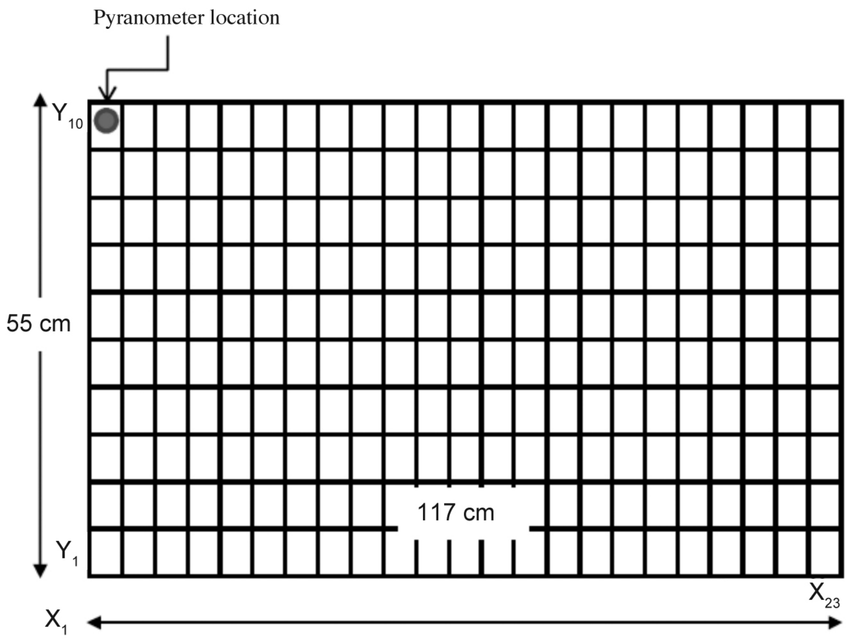

Figure 8. *The mapping area of solar simulator*

RESULTS AND DISCUSSION

The solar simulator developed was successful in producing suitable irradiance intensity value as required to measure the performance of solar collector. The measurement was repeatedly done and results obtained at each setting of irradiance intensity value were good. The value of average irradiance intensity as well as the percentage of irradiance non-uniformity is shown in Table 1. The solar simulator mapping measurement had been repeatedly done three times at each setting of irradiance value. The purpose of repeating the measurement was to ensure the reliability of the solar simulator to reproduce similar value of irradiance at each setting point. The measurement result is shown in Table 1. Irradiance value for each setting point was taken from the average of three readings. Percentage of non-uniformity was calculated at each mapping process. The lowest value of average irradiance intensity obtained was 398 W/m^2 with non-uniformed irradiance percentage of 7.0 %. The highest value achieved was 864.3 W/m^2 with non-uniformed irradiance percentage of 5.0 %.

Based on the result shown in Table 1, the solar simulator irradiance uniformity was more uniform at higher value as compared to lower value. However according to (ASHRAE, 2003), it meets the Class III requirement for solar simulator where the maximum performance of a solar collector tested at the minimum range of irradiance shall be at least 790 W/m^2 and the ambient temperature during the measurement was specified to be between 15 °C to 30 °C. During the testing period, the ambient temperature shall not vary more within ± 1.5 °C and the uniformity of the irradiance shall be within ± 10 %. The air flows of 150 mm above the collector shall be maintained at the speed of 3.5 m/s. Based on the experiment results above, the solar simulator developed had sufficiently meets the above requirement and capable to perform indoor simulation in testing of a solar collector.

Table 1. Measurement of irradiance intensity and percentage of non-uniformity

Irradiance intensity, (W/m^2)	Repeated mapping set	Average irradiance intensity value, (W/m^2)	Percentage of non-uniformity, (%)
~400	1	404	7.1
	2	394	6.8
	3	396	7.1
	Average	398.0	7.0
~600	1	589	6.6
	2	596	7.3
	3	586	6.2
	Average	590.3	6.7
~700	1	689	5.1
	2	689	5.1
	3	690	5.3
	Average	689.3	5.2
~900	1	877	5.1
	2	851	5.1
	3	865	4.9
	Average	864.3	5.0

The average value of irradiance intensity was derived using equation (1). The percentage value of non-uniformity of irradiance was determined from equations (2) and (3) (Othman,1989).

$$\overline{S_i} = \frac{\sum_{i=1}^{N} S_i}{N} \qquad (1)$$

$\overline{S_i}$: Average of irradiance intensity

S_i : Measured irradiance intensity

N : Total data taken at different position

$$\delta\overline{S_i} = \frac{\sum_{i=1}^{N} \left| S_i - \overline{S_i} \right|}{N} \qquad (2)$$

$$\frac{\delta\overline{S_i}}{\overline{S_i}} (100\%) \qquad (3)$$

Patterns of irradiance mapping for each intensity setting are shown in Figure 9 to Figure 12. The distribution of irradiance on the mapping area concluded that the irradiance value is higher at the centre of the test area and decreases to the edge. These differences contributed to the value of non-uniformity. For example, at ~400 W/m^2, due to few numbers of lamps being switched on, the irradiance was less scattered. Therefore the non-uniformity was the highest, ± 7.0 % as compared to mapping at ~ 900 W/m^2. With more lamps being switched on at ~900 W/m^2, the non-uniformity was reduced to ± 5.0 %.

Acrylic piece placed above the PV module was to enhance the uniformity of the scattered irradiance. Therefore, measurements had been carried out to compare and observe uniformity of the scattered irradiance. Table 2 shows the comparison results between the use of acrylic piece and without the acrylic piece. The results show that the acrylic piece was capable to enhance the uniformity of the scattered irradiance. At ~ 400 W/m^2, the percentage of non-uniformity improved from ± 8.9 % to ± 7.0 % and at ~ 900 W/m^2, the percentage of non-uniformity improved from ± 7.8 % to ± 5.0 %.

Table 1. Measurement of irradiance intensity and percentage of non-uniformity

Irradiance (W/m^2)	Non-uniformity without acrylic piece (± %)	Non-uniformity with acrylic piece (± %)
400 W/m^2	8.9	7.0
600 W/m^2	7.6	6.7
700 W/m^2	6.9	5.2
900 W/m^2	7.8	5.0

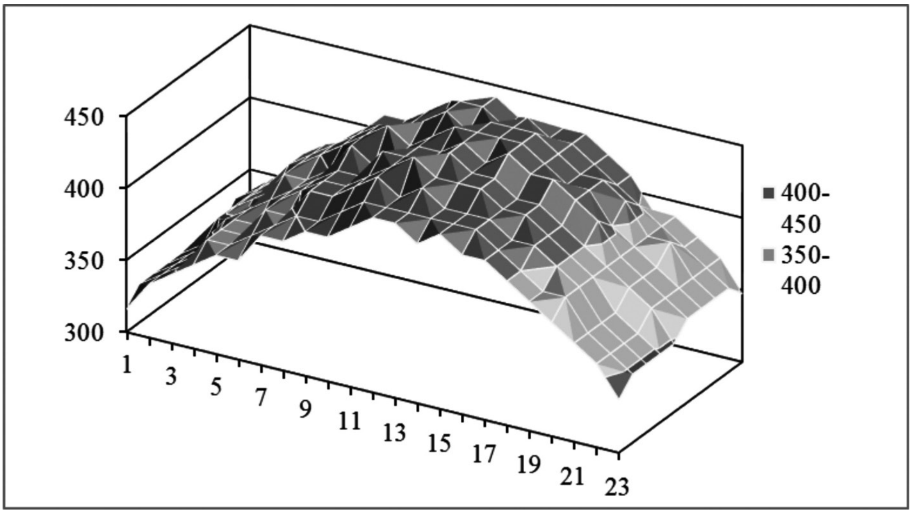

Figure 9. *Mapping of irradiance intensity at 398 W/m^2 with percentage of irradiance non-uniformity of 7.0 %*

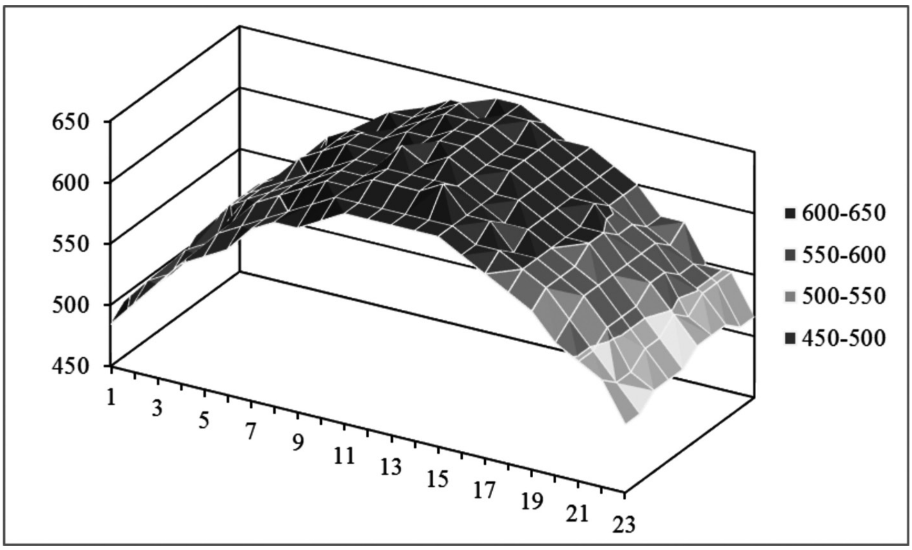

Figure 10. *Mapping of irradiance intensity at 590.3 W/m^2 with percentage of irradiance non-uniformity of 6.7%*

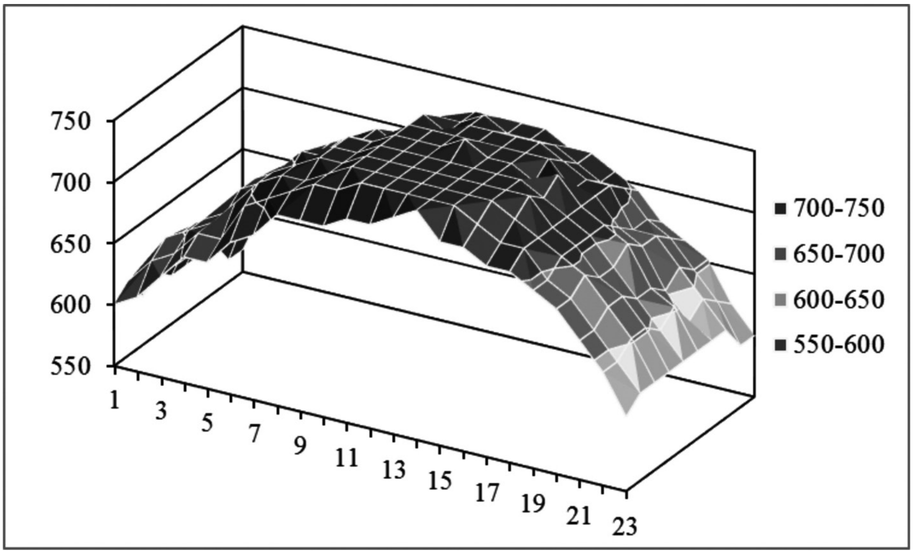

Figure 11. *Mapping of irradiance intensity at 689.3 W/m²*
with percentage of irradiance non-uniformity of 5.2 %

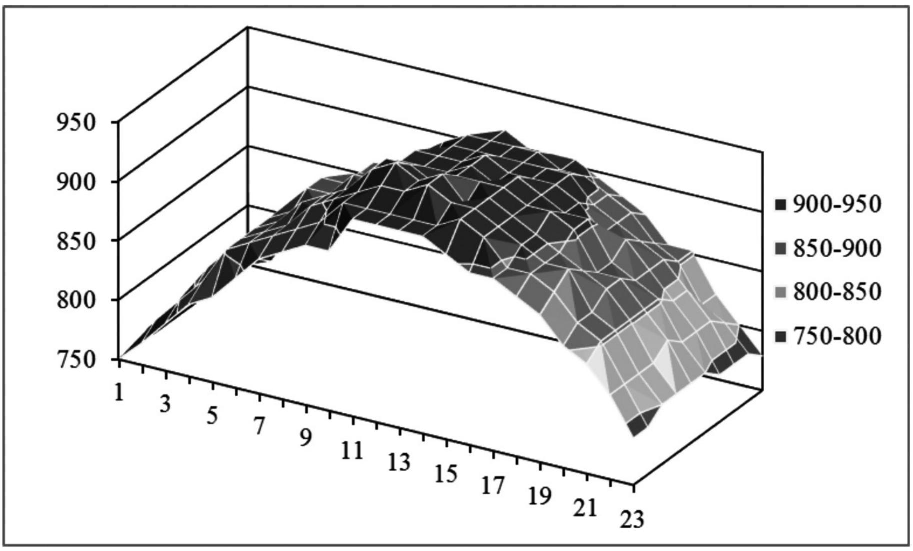

Figure 12. *Mapping of irradiance intensity at 864.3 W/m²*
with percentage of irradiance non-uniformity of 5.0 %

CONCLUSION

A development of an indoor solar simulator using low cost materials with simple design for solar collector testing was successfully established. The results proved that good uniform irradiance intensity output was produced. It also showed good repeatability with low non-uniformity from ± 5 % at 864 W/m^2 to ± 7 % at 398 W/m^2. This research work can be further improved by increasing the testing area size, non-uniformity improvement and spectral distribution of the irradiation light implementation.

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ABBREVIATION

S_i : Measured irradiance intensity

$\overline{S_i}$: Average of irradiance intensity

N : Total data taken at different position

i : Number of measurement point

W : Watt

m : meter

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