Rectangular module for large scale solar simulator based on high-powered LEDs array

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ABSTRACT

The article describes a large scale of rectangular light source design comprised of six different types of high-power light emitting diodes (LEDs). The new modular based on the LED solar simulator with the greatest size using the symmetrical LED positioning method. The experiment provided the irradiation of the solar simulator in the class AAA over 416 cm^2. The rectangular LED module illustrated the uniform distribution of the irradiance across the sample plane area. It reached the class A of air mass 1.5 for global spectrum (AM1.5G) (1000 W/m^2) covering the 400 nm to 1100 nm wavelength range. The proposed system offered a spectral match of 100%, the temporal instability equivalent to 0.611%, and a non-uniformity of irradiance less than 2%. When the proposed solar simulator was tested in solar cell characteristics under standard test conditions, it was found that the short circuit current error between the sample solar cell under our solar simulator and the standard solar simulator was less than 0.538%. This proposed design is, therefore, an interesting design that can be applied easily and economically further for large scale solar simulators with its modular system.

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1. INTRODUCTION

Solar simulators are used in many illuminating applications such as photovoltaic, photo-electrochemistry, environment testing, photobiology, medical treatment, and so on. For photovoltaic applications, a solar simulator must meet the sun spectrum standards in accordance to International Electrotechnical Commission (IEC), American Society for Testing and Materials (ASTM) and Japanese Industrial Standards (JIS). This is also known as the air mass 1.5 for global spectrum (AM1.5G) and is equivalent to the global irradiance on the earth surface at an air mass 1.5 around 1 sun or 1000 W/m^2 [1].

In the past twenty years, light emitting diodes (LED) have played an important role in solar simulations as they are low costs, small power consumption, long life span, and can be combined for a specific spectrum [2]. Many previous studies tried to generate the light spectrum of solar simulator from 400 nm to 1100 nm (IEC 60904-9 and ASTM E27-9), by using two major principles which included 1) hybrid LED-halogen [2]-[4], that the visible LEDs (400 nm to 700 nm) were combined with far-red spectrum (700 nm to 1100 nm) from halogen lamp; and 2) Only selected multi color LEDs that matched the visible spectrum and far-red spectrum. To explain, these multi color LEDs may be six-colors without white light [5], six-colors using blue LED (400 nm to 420 nm) with the white spectral [6]-[11], eight to ten colors mixing blue light (410, 425, 455, and 490 nm) with red and infrared light (710 nm to 1020 nm) [12], [13].

Fraguas *et al*. [1] combined eleven visible spectra with three infrared spectra. Stuckelburger *et al*. [14] used ten visible spectra and infrared spectrum. Kerb *et al*. [15] presented the solar test platform which was based on self-calibrating LED. The LEDs were composed of eighteen spectra of ultraviolet (UV), visible and infrared. Linden *et al*. [16] presented the combination of ten visible spectra and eleven infrared spectra. Some of the previous study provided only the visible spectrum (400 nm to 700 nm) of LED solar simulator for characterizing on a Si solarcell with eight types of LEDs [17].

Moreover, Tavakoli *et al*. [18] reported the developed solar simulator with adjustable light intensity using a computer controlled via a microcontroller. The results in the value of an irradiance non-uniformity (S_{NE}) met at class A. For IEC and ASTM standards, the spectral match (SM) was likewise met in class A. The UV spectrum at 250 nm was included in their system but it was not necessary for testing the standard solar cell that he had referenced. Furthermore, a test area of their solar simulator was as small as 2.3 cm × 2.3 cm, which could not be used a solar cell in a standard size. These solar simulators were able to generate light that had the SM which corresponded to the class A standard by using the bread-type LEDs (high-power) or a multitude of surface-mount-device (SMD) type LEDs (mid-power). Moreover, it was also possible to generate the light with good uniformity but only on a small to medium size of the test plane, such as 1 cm^2 [1] to 260 cm^2 [10].

Another drawback was difficult to scale the structure of the light sources. For instance, the possibility to connect and expand as building blocks or as modules to create a large scale solar simulator was limited. However, in subsequent research, Al-Ahmad *et al*. [10] reported the construction of the hexagonally shaped modular array for large area solar simulator by employing 43 bread-type LEDs and was able to achieve the uniformity areas of 65 cm^2, 36 cm^2, and 20 cm^2 for class C, B and A, respectively. Additionally, the resulting spectral mismatch conformed to class A. The experimental results of a rectangular LED module with a test plane of around 1000 cm^2 by Watjanatepin and Sritanauthaikorn [5] indicated that SM was in class A and S_{NE} was less than or equal class C. However the light intensity on test plane was only 384 W/m^2, it has not satisfied for a solar cell test under the standard condition. Moreover, Linden *et al*. [16] presented the square array LED modular building blocks with the size of 10×10 cm^2 by using 100 SMD LEDs to generate light with class A uniformity and spectral mismatch.

The researches of Al-Ahmad *et al*. [10], Linden *et al*. [16], and Tavakoli *et al*. [18] required the complicated systematic control and structure. Additionally, the construction required many LED which meant that many LED drivers were implemented, thus, the complex control scheme and structure was added on. All was only for a test area by less than 100 cm^2 per module. According to the previous studies, no LED module had a test plane larger than 1000 cm^2. This research problem is how to improve the LED solar simulator to meet class AAA of IEC 60904-9 Ed.2 and 1000 W/m^2 irradiance.

The authors proposed the construction of the rectangular-type LEDs module with low complexity of the circuit assembly and printed circuit board (PCB) design. The ultra high-powered LEDs had applied to be the source for the irradiance of 1000 W/m^2. This work focused on a six-color LED solar simulator covering wavelengths from 400 nm to 1100 nm. The authors presented, with this study, how to increase the uniformity and irradiance in a rectangular geometry. The rectangular geometry provides an interesting application where it will become possible to expand the module by connecting different LED modules in order to achieve bigger test area of the solar simulator. Therefore, the objective of this study is to present an approach to construct a solar simulator with rectangular-type LEDs modules. The authors also devised a method of optimizing the number of LEDs that emit different wavelengths to meet the class A standard. This was achieved by studying the correlation with the irradiance on the test area and electrical input power of the LEDs where the distance from the test plane to the light source was kept constant. Lastly, the authors demonstrated that the experimental results indicated that the performance of the proposed rectangular LED modules was in accordance with the IEC 60904-9 Ed.2.

2. RESEARCH METHOD

2.1. The selection of LEDs to match the reference spectrum

In order to achieve the AM1.5G spectrum according to the IEC 60904-9 Ed.2 standard, many researchers proposed a method to reduce the number of LEDs still being able to generate the lights with a comprehensive spectrum that covered the range of 400 nm to 1100 nm. This method employed six divisions of the wavelengths which were 400 nm to 500 nm, 500 nm to 600 nm, 600 nm to 700 nm, 700 nm to 800 nm, 800 nm to 900 nm, and 900 nm to 1100 nm. Many researches [6]-[11] revealed six colors of LEDs in combination with the warm-white and cool-white lights. However, this study used one color of the LED per one wavelength division without using the white lights. To achieve this, the ultra high-power LEDs (chip-on-board package) were used. These LEDs were composed of 6 types which include blue LED of 450 nm, green LED of 525 nm, red LED of 625 nm, near-far red LED of 730 nm and 850 nm, and infrared LED of 940 nm as shown in Table 1. The authors simulated the spectral profile of the six types of LEDs and compared them to the AM1.5G spectrum standard in Figure 1 by ColorCalculator V 7.59. This comparison demonstrated that the LEDs used in this study well corresponded to the AM1.5G spectrum of the wavelengths of 400 nm to 1100 nm according the aims of the study.

Table 1. Characteristics of the selected high-powered LEDs

LEDs	Wavelength (nm)		Electrical specification	
	Peak	Range	V_{Fmax}(V)	I_{Fmax}(A)
Blue	450	398 – 506	34	1.5
Green	525	464 – 584	34	1.5
Red	625	574 – 660	24	1.5
Near-infrared	730	660 – 770	22	1.5
Near-infrared	850	770 – 886	18	1.5
Infrared	940	840 – 990	16	3.0

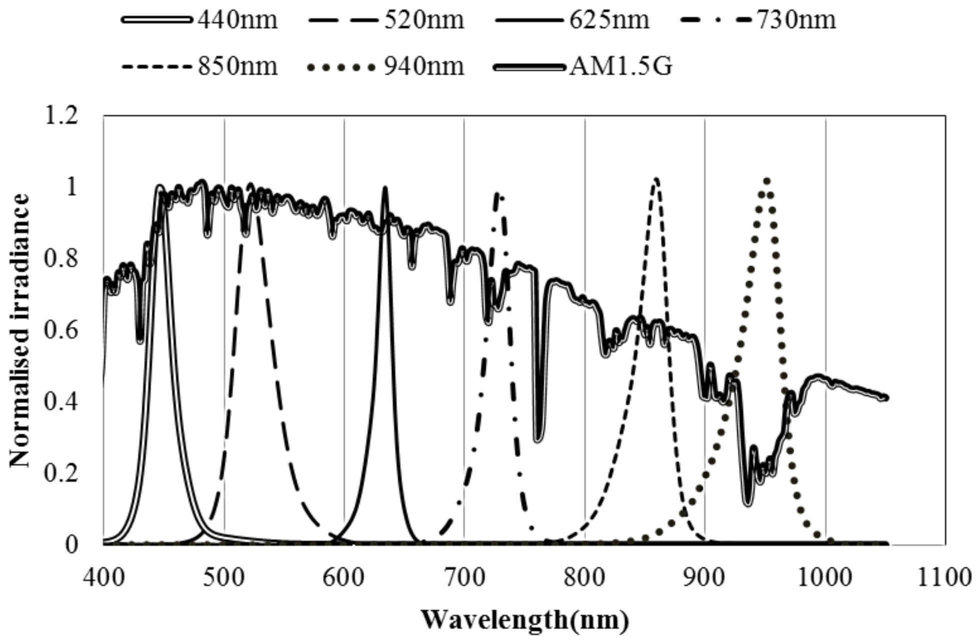


Figure 1. Comparison of the normalized spectral profile of the selected LEDs with the AM1.5G standard

2.2. The determination of the number of total LED on a rectangular module

The electrical characteristics of the high-powered LEDs, which were outlined in Table 1, were used in the solar irradiance and the input power of the LED measurements. The experimental model was represented in Figure 2 that was used to calculate the irradiance output per input power (irradiance per watt) of selected LED. The illuminance area was 16 cm^2 (4 cm × 4 cm), the test area was 64 cm^2 (8 cm × 8 cm) and the distance from the test plane and LED source was 30 cm. The pyranometer was the CMP3 model (Kipp & Zonen). One LED per each color was installed on the printed circuit board. This printed circuit board was placed in the middle of the mirror room. The input electricity was fed to each LED type according to 90 percent of the maximum electrical power. The voltage and current of LED were controlled by a constant-voltage/constant-current direct current (DC) converter. The irradiance was measured with a pyranometer by placing the light sensor at 30 cm away from the light generator. It should be indicated that this distance was more than what had been implemented [9], [10]. This was done in order to achieve that the best non-uniformity values according to the class standard. The experiments were then repeated for all the colors and the results were data for calculating the irradiance per watt values as displayed in Table 2. Based on Table 2, the lowest irradiance per watt was on the wavelength of 900 nm to 1100 nm and hence, the LEDs with this wavelength division were incorporated as many as possible.

Subsequently, the number of LEDs that are required to emit the total irradiance of 1000 W/m^2 must be calculated by the irradiance needed per each wavelength range to match the irradiance given by the IEC 60904-9 standard (given in columns 1 and 2 of Table 3). This calculation used the irradiance per watt from Table 2. For the input power of LED (C), which corresponded to column 4 of Table 3, the calculation was obtained by C = A/B. Once C had been obtained for all rows, it could be seen that the LED sources required a total input power of 456.20 W in order to achieve the irradiance is equal to 1000 W/m^2. The electrical power that must be fed to each color LED was summarized in column 5 of Table 3. Finally, the ratio between C and D was estimated into an integer in order to indicate the specific number of each LED color. Thus, the total amount was 14 LEDs. However, this study increased the blue LED from one to two pieces; therefore, the number of LEDs was totally 15. The system from this motivation offered the results in a better light distribution and also more balanced layout of the LED positions on the rectangular LED module.

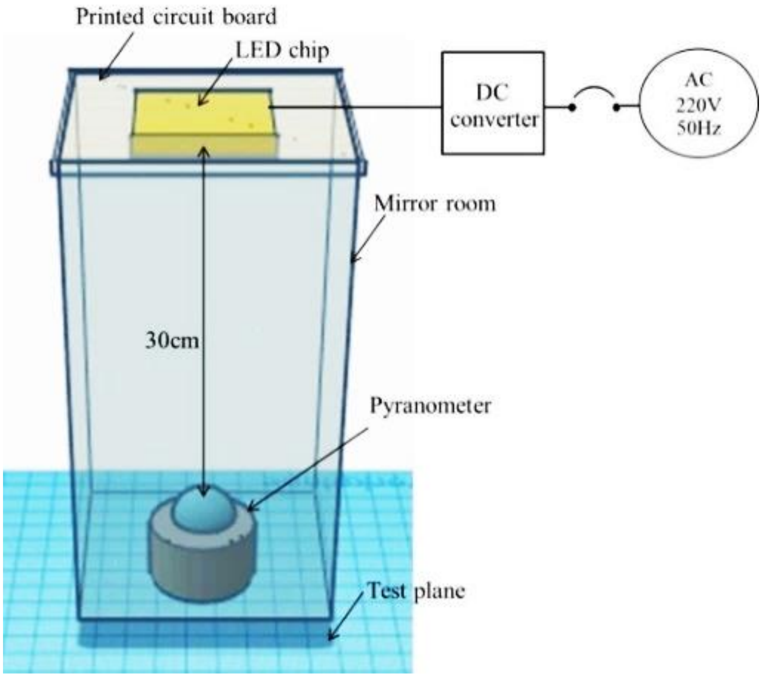


Figure 2. The experimental model

Table 2. Pre-experimental results of the irradiance per watt of the selected LED

Wavelength (nm) Range	Selected LED	LED input power (W)	Irradiance (W/m^2)	Irradiance per watt
400 – 500	450	46	222	4.83
500 – 600	525	46	88	1.91
600 – 700	625	32	209	6.53
700 – 800	730	30	82	2.73
800 – 900	850	24	710	29.58
900 – 1100	940	43	30	0.70

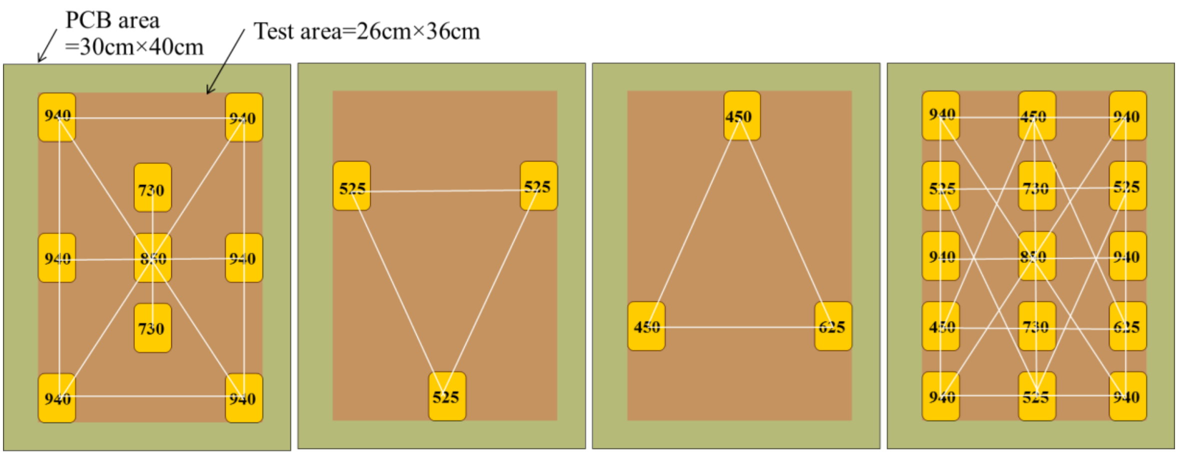
Table 3. The number of LEDs and power in each wavelength range

IEC 60904-9 Ed.2.0 Wavelength range (nm)	Irradiance^A (W/m^2)	Irradiance per watt^B	Input power^C (W)	LED power^D (W)	Number of LED^E
400 – 500	184	4.83	38.13	50	2
500 – 600	199	1.91	104.02	50	3
600 – 700	184	6.53	28.17	36	1
700 – 800	149	2.73	54.51	33	2
800 – 900	125	29.58	4.23	27	1
900 – 100	159	0.70	227.14	43	6
Total	1000		456.20		15

2.3. The design of the LED rectangular module

The design of the simulator module used a 30 cm away from the light generator and the test plane which is equivalent to the tests conducted in the previous section as Figure 1. This effectively resulted in an illuminance area of 16 cm^2 for each LED with a 64 cm^2 test area. Based on the comparison of the test plane ratio at the height of 30 cm, the authors selected the 15 ultra high-powered LEDs per a LED module. Hence, this design could theoretically result in an increased area of test plane by a factor of 15 times which is equivalent to 960 cm^2 (15×64 cm^2). This study proposed a design with a test area of 26 cm × 36 cm = 936 cm^2. The PCB size was about the same as the LED module which was slightly bigger than the test plane with dimension of 30 cm × 40 cm = 1200 cm^2 [5]. The illustration was provided in Figure 3(a).

The motivation for this PCB size was that additional space must be spared for the installation of additional equipments, such as a terminal block. The 15 LEDs were composed of two 450 nm LEDs, three 525 nm LEDs, one 625 nm LED, two 730 nm LEDs, one 850 nm LED, and six 940 nm LEDs as shown in column 6 of Table 3. Figure 3(a) demonstrated the distribution of the infrared group LEDs to create the maximum balance on the PCB. Figure 3(b) showed the layout position of the 525 nm LEDs and Figure 3(c) presented the layout position of the 450 nm and 625 nm LEDs. Figure 3(d) illustrated the positioning of the layout for the 15 LEDs for both the infrared and visible light groups by the symmetrical LED positioning method.



(a) (b) (c) (d)

Figure 3. Layout of the LED module: (a) Group of Infrared LEDs, (b) Group of green LEDs, (c) Group of blue and red LEDs, and (d) All colors

(a) (b) (c)

Figure 4. LED module: (a) parts of the LED rectangular module consisting of 1) 12 units of cooling fan (24V 0.2A), 2) Thin-fin heat sink, 3) 40 cm × 30 cm PCB, and 4) 15 high-powered LEDs array; (b) A prototype of the rectangular LED module of the solar simulator: cooling fan side (left) and LEDs side (right); and (c) DC converter driver unit

2.4. The assembly of the rectangular LED module prototype

The major parts of a rectangular LED module prototype consisted of: 1) cooling fans, 2) aluminium heat sinks, 3) a printed circuit board (PCB), and 4) a high-power LEDs array. Figure 4(a) illustrated the components of the rectangular LED module as followed: 15 of high-power LEDs (50 W each) a high-power LEDs array installed on the PCB. Figure 4(b) presented the prototype of the LED rectangular module. The PCB dimension was 40 cm × 30 cm. The position of the components corresponded with the layout in Figure 3(d). To achieve that, the LEDs were soldered on the bronze stripes of the rectangular PCB unit. The LEDs could be categorized into 6 circuits according to the six specific types of LEDs. Each circuit was driven by one set of a DC converter which could adjust the electrical input power of the LEDs freely. This DC converter unit was shown in Figure 4(c). Three sets of the thin-fin aluminium heat sink with the dimension of 6.9 cm × 3.7 cm × 34 cm were attached to the back of the LEDs by applying a thin layer of the silicone grease between the LEDs and the heat sink. This setup allowed the extraction of heat from the LED junction. On the top of the heat sink, 12 units of the cooling fan (8 cm × 8 cm, 24 V 0.2 A) cooling fans were installed to dissipate the heat when all the LEDs were operated. These cooling fans were connected in parallel to the DC converters (24 V 3 A). This setup allowed the operating temperature of the LEDs to be maintained at around 38 ˚C to 40 ˚C (measured at the junction of the heat sink and the LEDs by the infrared thermometer).

The measurement procedures were based on the IEC 60904-9 Ed.2 2007-10 standards [19]. The compact array spectrometer (CAS140CT -154, instrument system, Germany) was used to measure the light spectrum and irradiance. The data analysis was performed by the Specwin Pro software on the SM. The S_{NE} was measured by dividing the test area into 6 by 6 equal cells. Each cell size was 6 cm × 4.33 cm (26 cm^2). The motivation behind this cell division was that the size of the pyranometer (CMP3 Kipp & Zonen) sensor that used to measure the irradiance diameter of 4.2 cm. Therefore, the short side of the test area could not be divided smaller than 4.2 cm. In order to quantify S_{NE}, the pyranometer was placed in the center of each cell and used to measure and to record the irradiance of all 36 cells. The values were then computed for S_{NE}. The temporal instability was measured by the long-term method as outlined by the IEC standard [19]. The classification of the solar simulator performance was in Table 4. The experimental system was illustrated in Figure 5. The mirror room dimension was 26 cm × 36 cm × 30 cm and was constructed by using the 3 mm sheet of mirror.

Table 4. Classification of the solar simulator performance [6]

Performance parameters	Class A	Class B	Class C
Spectral match (SM)	0.75 – 1.25	0.6 – 1.4	0.4 – 2.0
Spatial uniformity (S_{NE})	≤ 2%	≤ 5%	≤ 10%
Temporal instability (T_{IE})	≤ 2%	≤ 5%	≤ 10%

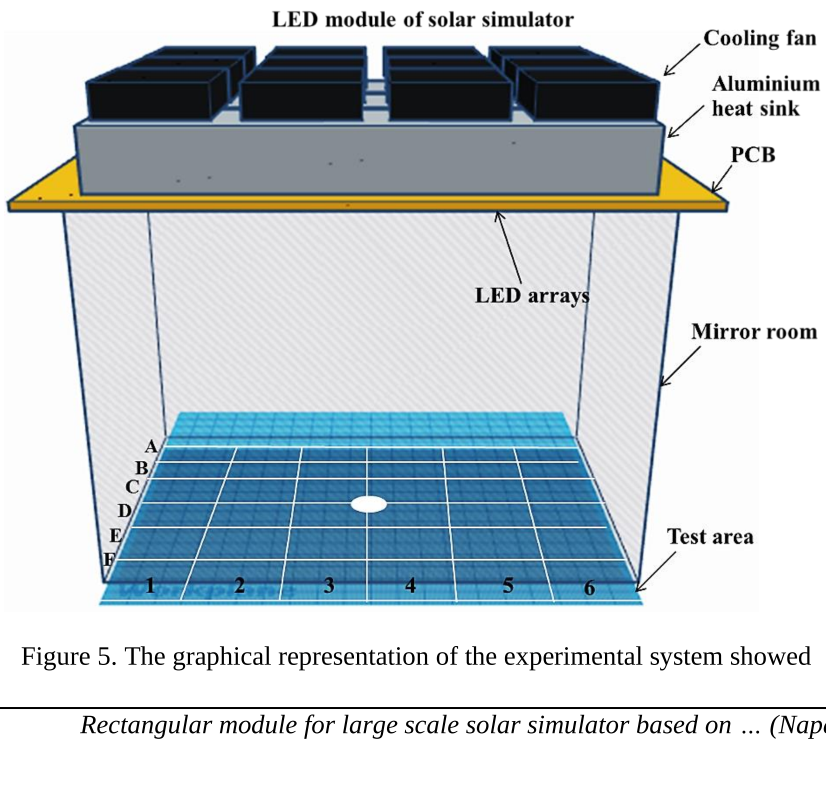


Figure 5. The graphical representation of the experimental system showed

3. RESULTS AND ANALYSIS

3.1. Spectral distribution and SM of LED module

The SM of our LED solar simulator was measured on the six-wavelength range defined by the IEC standard and specified in Table 5. For each of the wavelength intervals, the SM fit in with 0.75 to 1.25 (or ± 25% from AM1.5G) range required for class A. The overall 1.00 of SM was across all of the six wavelength intervals. This showed the perfect SM met to the IEC 60904-9. However, in wavelength of 900 nm to 1100 nm range, the lowest value of the SM was 0.93 but it indicated in class A which was acceptable and was compared with the six-color LED solar simulator. This proposed rectangular LED module offered the better SM than the valve from the module of Watjanatepin [7], Al-Ahmad *et al*. [10], and Esen *et al*. [11] in every subinterval. They used the combination of the white LEDs and the blue LEDs (450 nm) be a source of 400 nm to 700 nm range. This source was difficult to tune-up the SM to the reference spectrum in wide wavelength range. The proposed module was easier tuning in the specific narrow spectral range than the others as shown in Table 6.

Comparing with the results of Novickovas *et al*. [9], our LED module offered a better value of the SM in the visible range (400 nm to 700 nm), but the SM in infrared range differed from the reference and the results of Novickovas *et al*. [9]. It showed that our SM in the 800 nm to 900 nm range was +0.022 greater and in the 900 nm to 1100 nm range was -0.076 less. In addition, Fragus *et al*. [1] used many LEDs up to 12 different wavelength sets for covering 400 nm to 1100 nm. Their results showed that the SM value was very consistent with the results of the proposed experiment in the range of 400 nm to 700 nm and 900 nm to 1100 nm, but the SM only in the 800 nm to 900 nm wavelength differed from the reference and our proposed method. The SM of each research was shown in Table 6. It indicated that the LED light builder with a SM by 1.00 was not based on the number of LED colors that must be used more than or less than 6 colors. For example, Fraguas *et al*. [1] applied for a 14-color LED, Kerb *et al*. [15] used an 11-color LED, and Linden *et al*. [16] chose a 23-color LED. All modules provided a SM in class A.

This was from properly current and voltage control for LEDs module which was provided a percentage of irradiance closely to the percentage of the irradiance reference. However, the solar simulator offered the spectrum that mostly approached to the AM1.5G spectrum. It would obtain a good spectral response. It was also affected to the photo current of solar cell under the solar simulator light nearly or equally to the photo current of solar cell under the reference spectrum.

Table 5. Spectral irradiance of a SM of a LED rectangular module prototype

Wavelength Range(nm)	6 LED spectral irradiance W/m^2	%	AM1.5G Irradiance (%)	SM	Class
400 – 500	184.01	18.32	18.4	1.00	A
500 – 600	205.73	20.48	19.9	1.03	A
600 – 700	184.92	18.41	18.4	1.00	A
700 – 800	151.91	15.13	14.9	1.02	A
800 – 900	129.60	12.90	12.5	1.03	A
900 – 1100	148.17	14.75	15.9	0.93	A

Table 6. Comparison of SM of a LED rectangular module prototype and previous researches

Wavelength Range (nm)	SM results: Proposed spectral	Fraguas *et al.* [1]	Watjanatepin and Sritanauthaikorn [5]	Watjanatepin [7]	Novickovas *et al.* [9]	Al-Ahmad *et al.* [10]	Esen *et al.* [11]
400 – 500	1.00	1.02	0.97	1.23	0.98	0.80	1.14
500 – 600	1.03	0.99	0.99	1.40	0.95	1.09	1.07
600 – 700	1.00	1.06	1.01	0.92	1.03	1.05	0.76
700 – 800	1.02	1.11	0.99	0.85	1.05	1.07	1.15
800 – 900	1.03	0.83	1.08	0.80	1.01	0.85	0.94
900 – 1100	0.93	0.94	0.96	0.63	1.01	1.08	0.92

Figure 6 showed more definitive comparison between the SM values in each subset of the proposed spectrum (6 LED SM%) was a bold dash and a reference spectrum (AM1.5G) was a line. The dot line was a class A upper limit and the thin dash line was class A lower limit. It revealed that the proposed spectrum was consistent with AM1.5G and in class A which was met to the research goal. The measured spectral distribution of the proposed LED solar simulator was shown in a black thick line. The spectral distribution was completely covered on 400 nm to 1100 nm of wavelength. We had calibrated the proposed spectrum to the AM1.5G spectrum under the spectrum mismatch calculator [20]. The calibration result indicated that the total irradiance of the LED solar simulator was 1004 W/m^2, compared with the AM 1.5G by 1000 W/m^2.

However, the correlated color temperature (CCT) was measured by Lighting Passport^{TM} smart spectroradiometer from Taiwan. In general, the approximated CCT of the natural overhead daylight at noon is between 5600 to 6000 K [21]. The light emitting from the LED module provided the average CCT of 5670 K which was averaged from 5 measurement values at the test area center (not show data). The measurement results showed that the proposed system did not mimic the natural sunlight spectrum, however it still gave the CCT that was consistent more than the natural sunlight. Since, the LED color mixed method controlled the light in each range for the artificient-light spectrum match met the class A of IEC 60904-9. Therefore, it offered the satisfied CCT.

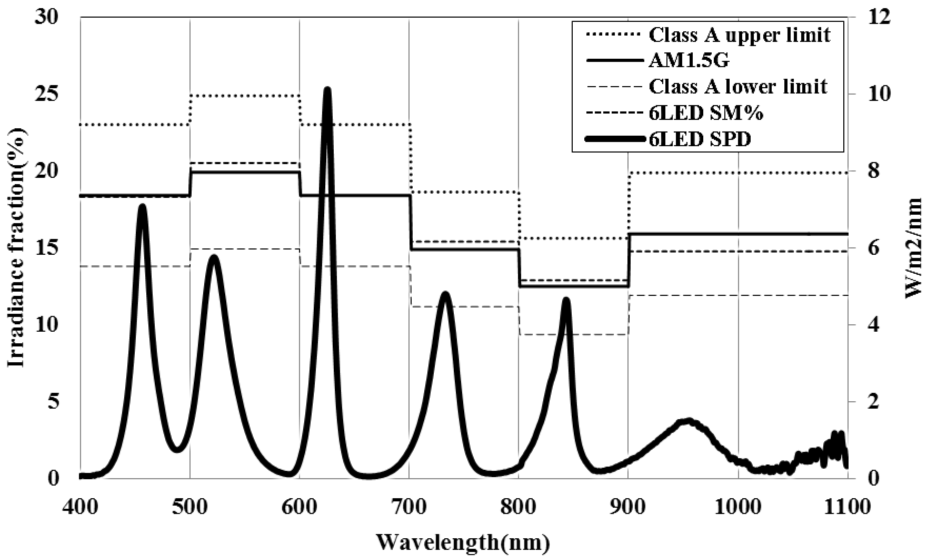


Figure 6. The measured results of SM of the rectangular LED solar simulator compared to AM1.5G, Class A lower and upper limit criteria

3.2. Irradiance non-uniformity of LED module

From Figure 5, the irradiance area on the test plane was divided in 36 equal cells as followed as A1 to A6 until F1 to F6. The pyranometer with data reading device from Kipp & Zonan was applied to measure irradiance on the area A1 to F6. The experiment was repeated in three times. The experimental results were average in each area and selected the maximum and minimum values. Then the S_{NE} was calculated. The experimental results revealed that the proposed rectangular LED module prototype offered the good light distribution onto the test area as shown in Table 7. The maximum irradiance value was about 1018 W/m^2 at E3 and E4 which were a central part of the light test plane. The minimum irradiance was about 932 W/m^2 at A1. It affected to S_{NE} on a test plane that was satisfied to class B (4.38%) and class A (1.97%) on 936 cm^2 and 416 cm^2, respectively. However, the test area indicated S_{NE} less than 2% over middle area, which was a large enough area for testing the standard solar cells size of 156 mm by 156 mm.

Table 7. Measured results of irradiance on the test plane region of 6×6 irradiance cells

	1	2	3	4	5	6
A	**932**	943	950	977	973	970
B	935	**979**	998	1006	1005	981
C	943	1001	1013	1014	1010	986
D	954	998	1014	1014	1015	993
E	946	1006	**1018**	1018	1006	985
F	950	990	992	978	991	975

Class B of 936 cm^2 Class A of 416 cm^2

The appearance of the minimum irradiance on an edge or the top corner on the test plane of solar simulator was corresponding with the light character with the other recent researches as a rectangular plane [1], [7], [13], [15] or a hexagonal plane [10]. The irradiance can be improved by increasing the distance away from the LED light source to the test plane, but it will significantly decrease the light intensity. In addition, a diffuser which distributed light from the light source to the test plane had improved the S_{NE}. On the other hand, it had reduced the intensity of the light. The authors presented a new light source that made from the rectangular LED module by using 15 high-power LEDs on the test area and a mirror reflection without diffuser (Figure 5). To confirm the proposed rectangular LED module could provide the S_{NE} at class A on the test area of 416 cm^2. It provided the irradiance by 1007 W/m^2.

Comparing the S_{NE} of this research and the previous researches, it showed that the proposed rectangular LED solar simulator module could provide the $S_{NE} < 2\%$. This was not different from the report of Bliss *et al*. [13], Linden *et al*. [16], and Stuckelberger *et al*. [14] with the test area by 400 cm^2, 400 cm^2, and 322 cm^2, respectively. These areas were slightly smaller than the proposed test area. However, Bliss *et al*. [13] did not use only the light source from the LED, but they used 8-colors LED mixed with halogen lamp. In addition, Stuckelberger *et al*. [14] used the 12-colors LED and Linden *et al*. [16] used the 23-colors LED as a light source. It also corresponded to the system of Novickovas *et al*. [9] that provided the $S_{NE} < 2\%$ on 7.84 cm^2 of test area. The results of Fraguas *et al*. [1] offered the $S_{NE} < 2\%$ with the small test area only 1.0 cm^2. Al-Ahmad *et al*. [10] created a hexagonal LED modular solar simulator and a S_{NE} was in class A on a 20 cm^2 hexagonal light test area. However, this proposed contribution provided better S_{NE} on larger test area than the results of Namin *et al*. [2], Bazzi *et al*. [6] Watjanatepin [7] and Esen *et al*. [11] but similar to SM of Watjanatepin and Sritanauthaikorn [5].

In general, the S_{NE} is the parameter of the solar simulator that is the most difficult to meet with the standard because it must be properly positioned and the appropriated distance between the LEDs used as light source. It should therefore optimize between the designer's desired irradiance and the distance between the light source and the test plane. The experiment results showed that the symmetrical LED positioning and distance that the authors presented was a method that offered the S_{NE} was quite good. In the other words, it was not lower than class B. Therefore, it is possible to apply the rectangular LED solar simulator or to develop by integrating more than one module to create a large-scale solar simulator that the performance would meet the standards for further development.

3.3. Irradiance temporal instability of LED module

The focus of this study was to test only the long-term instability. Due to the limitations of the proposed light source control system of the solar simulator was only for the stable mode, it could not be suitable in pulse mode. The stability of the distribution of the light intensity was determined at 2 second intervals by measuring the irradiance with placing the pyranometer at the center of the test plane. The authors recorded in one-hour (1-h) period to consider how the stability of the transient instability of the irradiance of our solar simulator prototype when it worked over a period. The measured irradiance over the interval was shown as black line in Figure 7. When the solar simulator was turned on, the light intensity would be increased in the first 3 minutes. After that the light intensity slightly rose until almost stable. Thus, this solar simulator prototype took 3 minutes for a warm-up.

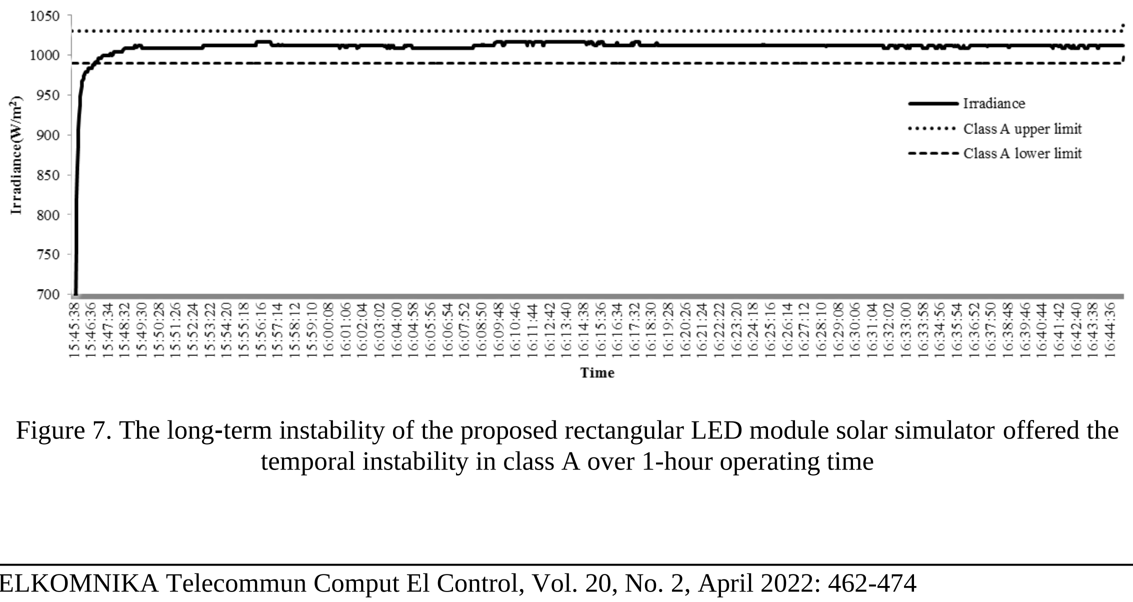


Figure 7. The long-term instability of the proposed rectangular LED module solar simulator offered the temporal instability in class A over 1-hour operating time

Subsequently, it noticed that there was no drop of irradiance and it converged to steady state between class A upper and lower limit lines over the experimental 1-h period. During the experiment, the LEDs light was not blink. The average of irradiance without the warm-up period was 1004 W/m^2. Figure 7 indicated the long-term instability of the rectangular LED module solar simulator over 1-h period. It was also demonstrated that the system offered a very good stability of 0.611% over this period. This was significantly longer than the required time to collecting I and V measurement (usually around 1 or 2 minutes once) and stayed in the ± 2% requirement for IEC 60904-9, class A.

The authors found that, over the 1-h period, the temperature of the LED which was measured at the heat sink was low in the safely operating range. It was between 26.2 °C to 31.6 °C. This result showed that the cooling system by the heat sink with cooling fans worked well.

Comparing the long-term instability from the proposed rectangular LED solar simulator with previous researches [1], [7], [10], [14], [16] which light source was LED, their results confirmed that all temporal instability was less than 2%. This was the advantage of the LED based light source because the characteristic of the LED driver circuits with the switching regulator type was good. In this experiment, the authors selected the buck converters in constant-voltage and constant-current modes. This plays very important role since the LED light spectra (including intensity) will keep constant if the LED power input from the DC convertor is not changed. It was well controlled to keep the steady current. This caused no little blink that was invisible. It was confirmed by the experiment results in Figure 7. By the way, the temperature control of high- power LED was well done below 32 °C. This was a positive effect on the light quality and relatively constant light intensity. Thus, LED of bread type, SMD type, or high-power type (chip-on-board) provided the temporal instability that met to class A criteria. Although the long-term instability from the proposed solar simulator was indicated in class A, the warm-up time took approximately 180 s. When these results were compared to the report of Fraguas *et al*. [1], the LED solar simulator, that was developed by using 34 of SMD LEDs, indicated that the long-term instability was better than this study. The value is equal to 0.4582% (class A) with the warm-up time of 60 s. However, the study results of Novickovas *et al*. [9] which used the SMD LEDs similar to the study of Fraguas *et al*. [1] indicated that the long-term instability was well within class A after several minutes for an initial warm-up period which is in accordance to our study. An interesting point is that the types of LEDs or the power rating of LEDs may have affected the warm-up time of the LED solar simulator.

Therefore, it was appropriate to be the light sources for solar simulators. Based on the long term temporal instability test of the rectangular LED solar simulator prototype, it confirmed that it was the highest performance as the standard requirement. It had stability in light control and used the suitable cooling techniques such as active cooling for long operating time. It was also possible to be developed to a large area solar simulator by combining more than 1 module. Nonetheless, a combination of 2 to 4 modules should be studied in S_{NE} that would be still satisfied to IEC standard.

In summary, the proposed method was simple and based on real experimental design and installation. The LED rectangular module (30 cm × 40 cm) with the symmetrical LED positioning method was presented. The performance of the probationary results of the proposed large-scale solar simulator with six-colors LED fulfilled the SM, the S_{NE}, and the long-term temporal instability in class A. The average irradiance on the test plane was 1004 W/m^2. The proposed LED solar simulator with the large area of the test plane of 416 cm^2 and 936 cm^2 achieved in class A and B, respectively. They were large enough to test the largest solar cell (210 mm × 210 mm) and larger than many previous studies and it solved our research problem. Furthermore, the proposed concept of the rectangle LED modular system could be developed into a large-scale solar simulator for PV module applications.

3.4. Characteristic test of solar cell under a LED solar simulator prototype

Based on previous topics, we presented the performances of the LED solar simulator prototype according to IEC standards and it confirmed that the results placed in class AAA. The characteristic of a mono crystalline silicon solar cell under LED solar simulator prototype was introduced. It was compared with the results of the solar cell test from the manufacturer by a xenon lamp solar simulator class AAA. In this experiment, the authors used solar cell, series M12514Y, from Bangkok Solar Company (BSC), Thailand. The M12514Y's size was 6.5 cm × 12.5 cm, which was called a solar cell sample. The light output spectrum of this simulator was set to AM1.5G as informed in section 3.1. The temperature of the test device was controlled to 25 °C as STC [22]-[27] required. The experiment of this solar cell sample was repeated for 3 times and then averaging the measured voltage and current for plotting the current-voltage (I-V) curve. The test condition was experimenting in a control room with 24 °C ± 2 °C of temperature and 50% ± 20% of humidity.

The solar cell current and voltage measurement and recording system was semi-automatic and was controlled by microcontroller which was a custom-made system developing for our laboratory. The solar cell had been measured after a start-up time of 3-min for all LEDs to stabilise expanded in prior of the measurement. The current and voltage were measured by sampling rate of 1 second. They were saved to the memory card and then plotted the I-V curve by using spread sheet software.

Figure 8 showed the current-voltage (I-V) curves of a sample benchmark to the I-V curve of the standard solar cell tested by the xenon lamp solar simulator from BSC. The line with square was indicated the I-V characteristic of a sample solar cell. It was averaging the current and voltage by repeating the experiment and measuring these parameters in three times. The device parameters were indicated in Table 8. The short circuit current mismatch between the sample solar cell under the proposed solar simulator and under the xenon lamp solar simulator was very small. It was less than 0.538%. It also showed that the design of the solar simulator by using the high-power LED provided alternatively reasonable cost-effective to commercially available simulators.

In the aspect of cost-effectiveness, this LED module is suitable for testing many solarcells. It yields continuous tests without turning light on-off because this module can continuously run for 1 hour and the temporal instability performance stays within in class A. The proposed LED module requires lower maintenance than the gas discharge lamps because it does not use any optical devices such as lens, filter, and diffuser. The required preventive maintenances are the light intensity test and the cooling system at the pre-process stage because the light stability depends on the quality of the DC converter driving LED system under the constant current and voltage and the LEDs operating temperature. These mentioned implementations will give the proposed large-scale LED solar simulator a long operating life along with good performance. In addition, the LED solar simulator prototype will be developed to a variable spectra module with digital control for other applications.

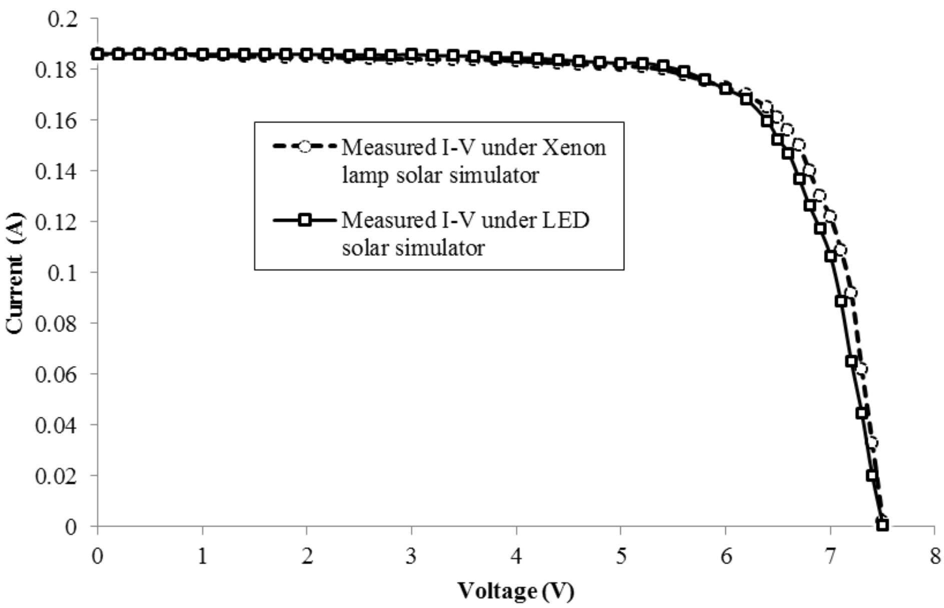


Figure 8. Measured I-V characteristics for the mono crystalline solar cell under LED solar simulator prototype compared to under a xenon lamp solar simulator

Table 8. Measured electrical parameters of the sample solar cells under LED solar simulator prototype and under the xenon lamp solar simulator

	I_{sc} (A)	V_{oc} (V)	I_{pm} (A)	V_{pm} (V)	P_m (V)	FF (%)
Xenon lamp solar simulator	0.186	7.530	0.173	6.206	1.074	76.657
LED solar simulator	0.187	7.504	0.172	6.182	1.068	76.424
Error (%)	0.538	0.345	0.867	0.387	0.528	0.303

4. CONCLUSION

A rectangular LED module solar simulator was designed by using ultra high-power LEDs chip covered wavelength of 400 nm to 1100 nm. The performance of LED solar simulator approached to the class AAA in accordance with IEC 60904-9 Ed.2.0. The results presented that the proposed symmetrical LED positioning method could actually be used to design a large area solar simulator. Moreover, the symmetrical alignment of the high-power LEDs resulted in a S_{NE} was less than 5% which was also met in the performance rating standard of the solar simulator.

This idea was proposed as an alternative simple way to design an LED module of the solar simulator across the rectangular sample test plane with large area of 416 cm^2 and 936 cm^2. The module achieved in class A and B respectively. The 15 ultra high-powered LEDs had emited the average irradiance of 1004 W/m^2. In addition, it could reduce the complexity of the LED circuit and the electrical control of power. It meant that this proposed system was one of the methods to reduce the cost of construction on the large-scale solar simulator. The solar cell that tested under the proposed LED solar simulator had an error of the short circuit current which was differed from under the standard xenon lamp solar simulator by less than 0.54% which was accepted for the education case. The experimental results were also confirmed that the proposed LED solar simulator performance was high and met the research objective. Rather, the concept of a LED module for a solar simulator had been researched by many researchers since 2018 but this proposed rectangle LED moduar structure was new, the largest module and using least LED number, comparing the past. Moreover, the connection of the modules can be the solar simulator for actually studying the PV module. It is thus challenge to the research to develop a high performance of LED solar simulator on the next.

The future work, this design concept will be further developed to create a large area solar simulator using multiple modules. Then, it will be studied the characteristics of the non-uniformity of the multimodules connection following the IEC standard. It should consider the impact of the light area that each module overlaps.

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