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Improved spectral mismatch and performance of a phosphor-converted light-emitting diode solar simulator

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ABSTRACT

A phosphor-converted light-emitting diode (LED) solar simulator is an illuminance device that produced irradiance intensity and spectral close to the sunlight. It is determined as spectral mismatch, non-uniformity of irradiance, and temporal instability. This paper has improved the LED solar simulator (LSS) system to have a spectral distribution consistent with the AM1.5G spectrum at 100%. It was developed as a new prototype to have the AAA class spectral characteristics, time instability, and inconsistency according to IEC 60904-9. The results showed that an optimal approach was to use phosphor-converted natural white LED (pc-nWLED), combining a monochromatic near-infrared (NIR) (730, 800, 850, 940, and 1,000 nm) as well as the proposed LSS system capable of generating 1,000 W/m^2 irradiation over the test plane of 125×125 mm and operated continuously in a constant temperature LED state for at least 2 hours, therefore suitable for demonstration of solar cell features under standard test condition (STC) in the laboratory.

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1. INTRODUCTION

The renewable energy plan of the present alternative energy development plan (AEDP) of Thailand is projected to be 30% of the total energy production by 2037. Up to 55% of renewable energy is from photovoltaic energy systems [1], thus the solar-cell system plays a very important role. The testing efficiency of the solar-cells determine the maximum power (P_{MAX}), a short circuit current (I_{SC}) and an open circuit voltage (V_{OC}) of the solar-cell. It is, therefore, essential to the development of solar-cell system in Thailand [2]. The I-V characteristic of solar-cell system can be evaluated under specific conditions called standard test condition (STC). At STC, an irradiance is equal to 1,000 W/m^2, under AM1.5G of solar spectrum and temperature of 25 °C [3]–[6]. A solar simulator is an illuminance device that produces irradiance intensity and closes to the sunlight spectrum. It is very useful for indoor characterization of the solar-cell in the laboratory and many research segments.

However, the solar simulator has to pass its primary performance assessment in three criteria as the spectral mismatch, non-uniformity of irradiance, and temporal instability under IEC 60904-9, ASTM E 9or JIS C 8912 [7]–[10]. The solar simulator's spectra must cover a range of 400 to 1,100 nm; including the visible (VIS) spectrum (400 to 700 nm) and near-infrared (NIR) spectrum (701 to 1,001 nm). Since 2015, a solar simulator has been developed to use a combination of VIS and near-infrared light-emitting diodes (NIR

LED), for example, by mixing the VIS spectrum with blue, red, and white spectrum [3]–[5], [11]–[13] or with a mixed of blue, warm white, and cool white spectrum [14], [15] and combined with NIR spectrum of 730 to 740 nm, 840 to 855 nm, and 940 to 950 nm [3]–[5], [11], [14], [15].

Subsequently, the solar simulator is developed to have a VIS spectrum that mimics more AM1.5G spectrum, so more spectra were added to that range. Al-Ahmad *et al*. [16], [17] presented the 7 VIS spectra. Sun *et al*. [18] reported the 10 VIS spectra. López-Fraguas *et al*. [19] provided the 11 VIS spectra and Tavakoli *et al*. [20] presented the 12 VIS spectra. These make the spectral consistency of the AM1.5G in the visible range better than before.

In the NIR range, the number of spectrum cannot be increased greatly because of a limitation of LED technology. Most of the previous researches have used the combination of NIR LED between 3 to 6 different wavelengths of 701 to 1,100 nm [3]–[5], [11], [14]–[20]. The complexity of emitting of a light spectrum from a solar simulator to mimic the previous AM1.5G standard spectrum is the color-mix method as mentioned above. This creates a complexity in the design of light sources and how to control the light intensity.

Disadvantages of generating VIS spectrum with color-mixed method can be solved by using phosphor-converted white LED (pc-WLED) instead of mixing light spectrum with multiple monochromic colors of LEDs. Loan and Anh [21] presented a method that used continuous improvement of WLEDs, namely increasing the color uniformity of WLEDs. The study found that particle size and ZnO concentration had a significant effect on scattering in the phosphor layer. The improvement of scattering in the phosphor layer was considered the most effective. Depending on the production needs, manufacturers could choose the most suitable method. Nakajima *et al*. [22] presented a single ultraviolet-chip (UV) of phosphor-converted natural white LED (pc-nWLED) to apply as a solar simulator for a-Si and dye-sensitized solar cells. The results revealed at the spectral distribution in VIS spectrum of 350 to 750 nm. The spectral mismatch riched to the A class based on JIS C8933 standard.

In 2021, the authors had extended the concept of [22] to developed a LED solar simulator (LSS) based on pc-nWLED combined with infrared LED of 730, 850, and 940 nm, applying for Si-Solar cell characterization. Its performance assessment results met the AAA Class. The first prototype had 16 high-power chip on board (COB) LEDs of 4 different types. It produced an artificial irradiance of 1,000 W/m^2 on the test plane of 70×130 mm. The spectrum was matched of 99.6% from the reference spectrum (AM1.5G). In addition, it produced the spectral distribution over 400 to 1,100 nm range. From the results of the development of the 2021 LSS system, there were still several issues that needed to be improve such as (1) how to increase spectral match to be 100%. Even though the spectral match is marginal the A class, between 0.9 to 0.91 at wavelengths of 400 to 500 nm and 700 to 800 nm, and (2) how to increase the size of the test plane to enable testing the standard size of Si-Solar cell.

In this article, authors aimed to improve the 2021 LSS system: i) to offer a spectral distribution that matched to AM1.5G spectrum of 100% using COB LEDs, ii) to increase the size of the LED light source suitable for testing solar cell standard size of 125×125 mm, and iii) to develop the new prototype to meet the performance at the AAA class accordance to the IEC 60904-9 edition 2. The thermal management also needed to analysis.

2. METHOD

This section, it is explained the method of improving spectrum distribution, designing the artificial LED light source, cooling system and LED driver, and optimizing irradiance intensity and non-uniformity. The LED module's construction and design were deemed appropriate for the suggested solar simulator. The above methods are shown in the following subsections.

2.1. Improve a spectrum distribution

The 2021 LSS prototype had a spectral mismatch (SM) of 99.6% compared to reference spectrum because the 400 to 500 nm and 700 to 800 nm spectrum was not good enough. It was also found that there was only one light spectrum in the 900-1,100 nm range, causing the spectral distribution to be inconsistent with AM1.5G. The relative of spectral distribution of the 2021 LSS prototype represented by solid lines as Figure 1. It consisted of spectra of pc-nWLED, 730, 850 and 940 nm.

To improve SM better than before and to achieve artificial irradiance that is closest to natural sunlight, it will have a good effect on characterization of the solar cell, that is, more accurate. The authors then added a combination of 420, 800 and 1,000 nm LEDs as shown by the dotted line in Figure 1. Thus, the newly developed irradiance spectrum consisted of seven types of LEDs: 420 nm, pc-nWLED, 730, 800, 850, 940, 1,000 nm. The spectral profiles were simulated by the ColorCalculator V7.59 (software) for comparison with the reference spectrum of AM1.5G. Methods for designing and analyzing the optical power and electrical power of LEDs are described in section 2.2.

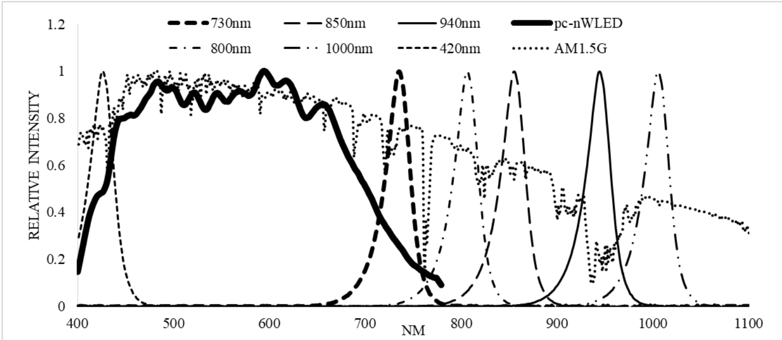


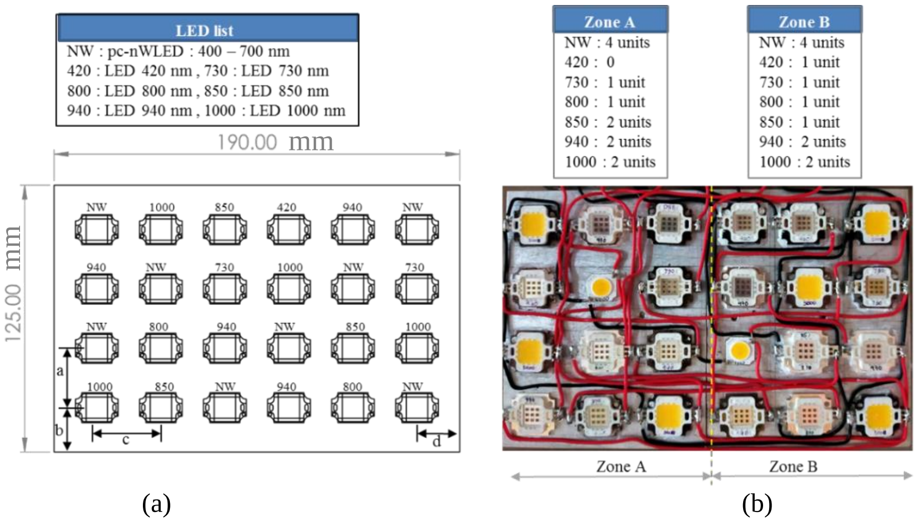
Figure 1. Comparison of normalized spectral profile of the proposed spectral to AM1.5G

2.2. Design of the artificial LED light source

For the solar simulator to be used, the proper LEDs must be designed and chosen. This section explains how to create an LED module with 7 clusters made up of all the LEDs. The above methods are shown in the following subsections.

2.2.1. LEDs selection for the proposed solar simulator

According to section 2.1, the test plane of our solar simulator was of 125×125 mm or 0.015625 m^2. To achieve good light uniformity on the test plane, this light source was designed larger [5], [7], our LEDs panel was 190×125 mm or 0.02325 m^2. All LEDs were divided into 7 clusters: pc-nWLED, 420 nm, and 5 clusters of NIR. The pc-nWLED features were 5,000K CCT, CRI>96, 380 to 840 nm spectral wavelength, 10 W, 300 mA, 36 to 38V. The 420 nm blue LED specified as 10 W, 1,000 mA, 9 to 11V. The NIR LED consisted of i) 730 nm, 10 W, 7 V, 900 mA; ii) 800 nm, 10 W, 6 V, 1,000 mA; iii) 850 nm, 10 W, 6 V, 1,000 mA; iv) 940 nm, 10 W, 5 V, 900 mA; and v) 1,000 nm, 10 W, 5 V, 900 mA. Figure 2 showed the LEDs pattern on the flat side of aluminum heat sink which was 190×125×29 mm, there were 10 fins along the length of the heat sink, and each fin had an average thickness of 2.5 mm. A positioning and layout of each LEDs and a finished module were presented in Figures 2(a) and 2(b).



(a) (b)

Figure 2. The LEDs pattern on the flat side of aluminum heat sink: (a) positioning and layout of LEDs; a=30.85 mm, b=18.75 mm, c=33.75 mm, d=9.00 mm and (b) LED lighting module

2.2.2. LED lighting module

The LED module consisted of 7 clusters of LEDs. There was a unit in each cluster: the pc-nWLED of 8 units and the 420, 730, 800, 850, 940, and 1,000 nm LEDs of 1, 2, 2, 3, 4, and 4 units, respectively. This LED module was divided into two zones. There were 12 LEDs each so the total number of LEDs was 24 LEDs. The assembly detail was shown in Figure 2(b). The string voltage and current were designed to match the characteristics of each LED based on the manufacturer's data sheet. The optical output power (P_{OPT}) was determined by (1), (2):

$$P_{OPT} = G \times A_{eff} \quad (1)$$

$$P_{CE} = \frac{P_{OPT}}{P_e} \quad (2)$$

where G is the average irradiance (W/m^2), P_{OPT} is optical output power (W), A_{eff} is test area (m^2), P_e is electrical input power of LEDs (W), P_{CE} is power conversion efficiency (W).

To comply with IEC 60904-9 standard, the G of (1) can calculate by taking the irradiance from row 3 of Table 1 and A_{eff}=0.015625 m^2. The electric input power of LEDs (P_e) is calculated from (2). According to Table 2, the calculation and measurement of total electric power consumption were 131.18 and 136.50 W, respectively, as shown in Table 2. The proportion of the P_{OPT} of visible spectrum and NIR spectrum were of 56% and 44%, respectively. In (2), the P_{CE} is the ability of an LED to convert electrical power into optical power. The several references declare that the P_{CE} is around 15 to 35% [23]–[27]. It depends on a LED type, a model, and a forward current. Here, the P_{CE} of white LED according to [23] is estimated around 0.3 and P_{CE} of the NIR LEDs estimating by [24] is around 0.11 and the blue LED is 0.2.

Table 1. Requirement of irradiance distribution for solar simulator (IEC 60904-9) (AM1.5G)

Spectral interval (nm)	400-500	500-600	600-700	700-800	800-900	900-1,100	Total
Percentage of irradiance	18.4	19.9	18.4	14.9	12.5	15.9	100
Irradiance (W/m^2)	184	199	184	149	125	159	1,000

Table 2. Electrical characteristics of the proposed LED lighting module

	Wavelength range (nm)	LED				String	P_{OPT}(W) calculate	P_e(W) calculate	P_e(W) measure
		Type	String voltage (V)	String current (A)	Number				
Visible	400-700	420 nm	10	0.80	1	1	1.60	8	7
		pc-nWLED	36	2.00	8	1	8.86	63.00	70.00
Infrared	700-800	730 nm	11	0.85	2	1	2.33	20.73	23.20
		800 nm	11	0.85	2	1			
	801-900	850 nm	16	0.85	3	1	1.95	17.35	14.20
	901-1,100	940 nm	8.60	1.40	4	1	2.48	22.10	22.10
		1,000 nm	8.20	1.40	4	1			
			Total		24	7	16.24	131.18	136.50

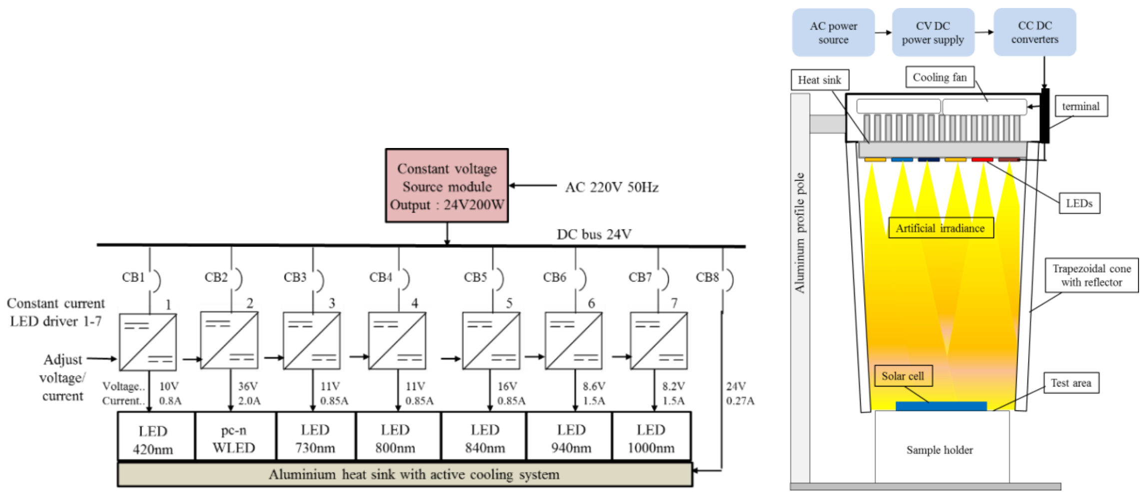
2.3. LED driver and cooling system

From the spectral interval in Table 2, the 7 LED drivers of the constant current dc to dc convertor were used for 7 LED clusters to cover that range. The LED driver 1 and 3 to 6 were the buck converter that supply dc power (according to Figure 3(a) column 4, 5) to LEDs 420, 730, 800, 850, 940, and 1,000 nm, respectively. LED driver 2 was a boost converter to convert the input voltage of 24 V to provide 36 V output voltage at 2.005 A. It was driven for a pc-nWLED of 8 units. The DC-bus input of all converters was 24V. It generated from a constant voltage source (CVS) of AC-to-DC invertor as shown in Figure 3(a). The total calculated electric power of the dc-bus and AC-to-DC invertor was 0.15433 W and 0.18156 W, respectively. The estimated efficiency of the AC-to-DC invertor and LED driver was 85%.

This ensured that all LEDs were continuously energized and in accordance with the designed rating. The AC-to-DC invertor of CVS type was 24 V, 200 W rated output, and 220 V 50 Hz input. All 24 LEDs were mounted on the same heat sink and were cooled by active air cooling system. The active cooling system consisted of 4 cooling fans (DC-brushless motor) 24 V, 0.27 A mounted on the rear fins of the heat sink. It was automatic running when the LED lighting module was operating. The model of our LSS prototype was shown in Figure 3(b).

2.4. Optimal irradiance intensity and non-uniformity

A reflector was made from a rigid foam board with 5 mm thick, and was covered with a 0.5 mm thick reflector sheet with a trapezoidal cone as shown in Figure 4. A light source area (LS) and test area (TA) were 190×125 mm and 125×125 mm, respectively. There were 9 different lengths d: 5/10/15/20/25/30/35/40/45 cm, that were 9 reflectors. The prototype of the 2022 LSS with trapezoidal cone was 30.05 cm length.



(a) (b)

Figure 3. System diagram: (a) diagram of the LED driver and cooling system and (b) model of LSS prototype

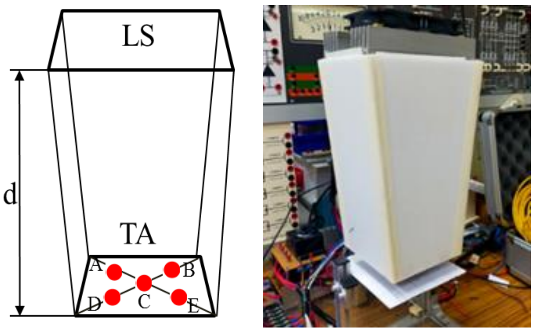


Figure 4. Trapezoidal cone and test area (TA)

The method of optimal irradiance and spatial non-uniformity (S_{NE}) is presented. It uses a trapezoidal cone of 5 cm length d. Irradiance was measured by a pyranometer at the center of the TA and a non-uniformity with our developed instrument. Then the trapezoidal cone length d was changed to 10 to 45 cm, and step size was 15 cm. The results of each of steps were recorded. The results were irradiance and S_{NE} varied with d indicated in Figure 5. The equation from the blue dot curve of Figure 5 was from the distance d=30.05 cm between LS and TA to achieve irradiance according to STC standard, irradiance=1000.21 W/m^2. At that distance on the red dot curve, S_{NE} equaled to 2.66%, which was in the B class according to IEC 60904-9. However, to achieve the A class, it should be S_{NE} ≤2.00%, distance ≥36.0 cm. In this article, the d of 30.05 cm was selected because it offered the irradiance of 1000.21 W/m^2 and the B class quality of solar simulator was high enough for characterizing the solar cells. However. The S_{NE} test at a distance of d 36 cm, will be presented in section 3.3.

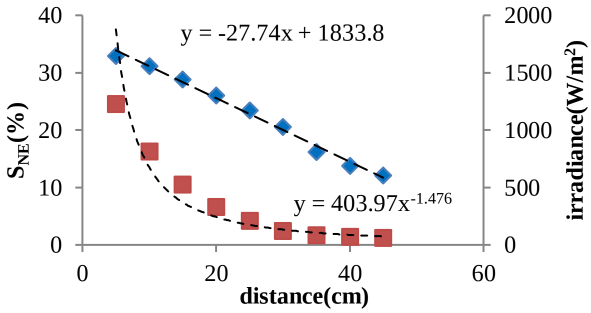


Figure 5. Relationship of irradiance and non- uniformity with distance

3. RESULTS AND DISCUSSION

This section, it is shown the results and discussion the spectral mismatch, temporal instability, non-uniformity, and thermal analysis. All analyzes were based on experimental results of LED lighting modules designed to fit the proposed solar simulator. The above results are shown in the following subsections.

3.1. The spectral mismatch

The spectrometer model CAS 1 4 0 CT (Instrument System, Germany) and Specwin-Pro software were used measure and analyze the distribution of artificial light spectral from the proposed LEDs system. They were placed at the center of a TA of 125×125 mm (point C of Figure 4) for 3 minutes after the solar simulator was powered on and recorded the results. The LEDs were operating in a stable optical output. The proposed spectral measurement results compared to AM1.5G were shown in Figure 6. In analyzing the SM at each wavelength range, the proposed SPD met to the A class in all wavelengths at SM 0.98 to 1.03 as shown in Figure 6. When assessing spectral compliance from our 2022 LSS system, the results matched to AM 1.5G spectrum completely of 100%. That shows the author's idea of improving SM by adding LEDs in the 400, 800, 1,000 nm range was satisfied. As a result, SM of the proposed SPD in the range of 400 to 500 nm and 700 to 800 nm closed to 1.00 and accorded to research objectives.

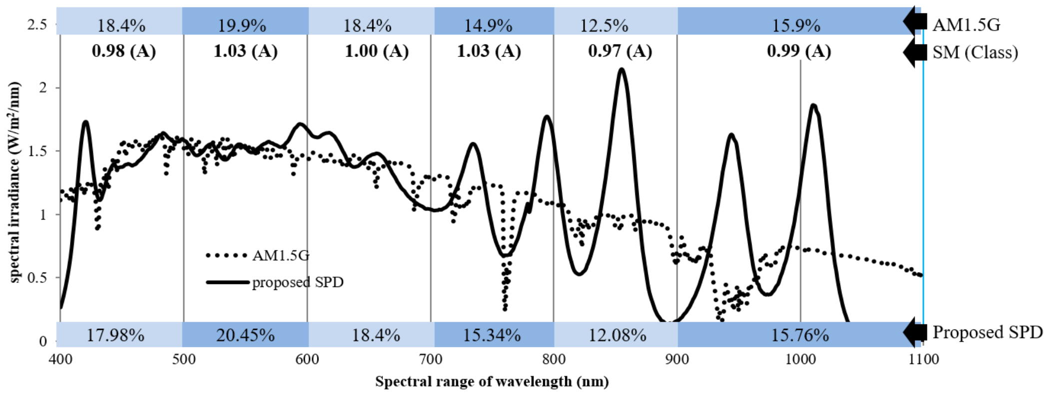


Figure 6. Measured and evaluated results of the proposed SPD comparing to the AM1.5G spectral

The SM results were compared with the results by Al-Ahmad *et al.* [16], [17], Sun *et al.* [18], López-Fraguas *et al.* [19] and Tavakoli *et al.* [20]. They were in the A class as well but they used a lot of LEDs in the 400 to 700 nm range, and 7 to 11 types while the proposed system used only two types of LEDs (pc-nWLED+LED 420 nm). It was also found that past LSS using a warm white and cool white LED such as the work of Watjanatepin [3] and Esen *et al.* [28] obtained SM at the B class which was inferior to SM's request. Even though Esen *et al.* [15] developed his LLS with SM at the A class, SM at wavelength 800 to 900 nm almost dropped out of the A class at 1.25. The proposed pc-nWLED method has shown greater advantages compared to many reseaches [15]–[19], [21], [28], [29].

However, many researchers generated the LED spectrum to match the AM1.5G by a color mixed method, all yield was very good SM result in the A class. Nakajima *et al.* [22] also used a single chip of pc-nWLED but only obtained an SPD that covered 350 to 750 nm wavelength and met an A class.

The novelty of this study is that the authors' proposed method reduces the number of monochromic colors LEDs required in the 400 to 700 nm wavelength range. Significantly reduce the design complexity and cost of the LED irradiance control unit. The pc-nWLED mixed infrared LEDs, should be interesting approach to develop in next-generation LSS.

3.2. Temporal instability

The analysis of the temporal instability is according to IEC 60904-9 for the A class. It found that the long term instability (LTI) must be less than or equal to 2% and the shot-term instability (STI) must be less than or equal to 0.5% [8], [9]. The irradiance was measured at 5 times a point at the respective A-E positions on the TA as shown in Figure 4 after turning-on our LSS and waiting 3min until the LEDs operation in stable condition [2]. It was measured for continuously 60 min each. The measuring instrument was the Pyranometer. The measurement result of irradiance on the TA at 5 positions were shown in Figure 7. The LTI was analyzed by (3):

$$\textit{Temporal instability, non-uniformity} = \pm\left[\frac{E_{MAX}-E_{MIN}}{E_{MAX}+E_{MIN}}\right]\times 100\% \quad (3)$$

where E_{MAX} is maximum irradiance and E_{MIN} is minimum irradiance. The results showed that LTI in all measured point of 1.14% to 1.64%, average of 1.42%. It was classified as the A class. The measured values detailed in Table 3.

Table 3. Experimental results of LTI at the specific point

Measurement Point	A	B	C	D	E	Average
E_{MAX} (W/m^2)	1012	1021	1011	1021	1022	1017.4
E_{MIN} (W/m^2)	983	998	985.75	988	989.5	988.85
LTI (%)	1.45	1.14	1.26	1.64	1.61	1.42
Class	A	A	A	A	A	A

For STI analysis, the change in irradiance was analyzed over a short period of 2 seconds that more than the sampling time at which the data logger acquired data for V-I characteristic of the solar cell. The results were randomly drawn from all five measurement locations: P, Q, R, S, and T, respectively as shown in Figure 7(a) to 7(e), and analyzed for the STI by (3). The results indicated that the STI was between 0.03% to 0.1% and was also classified as the A class.

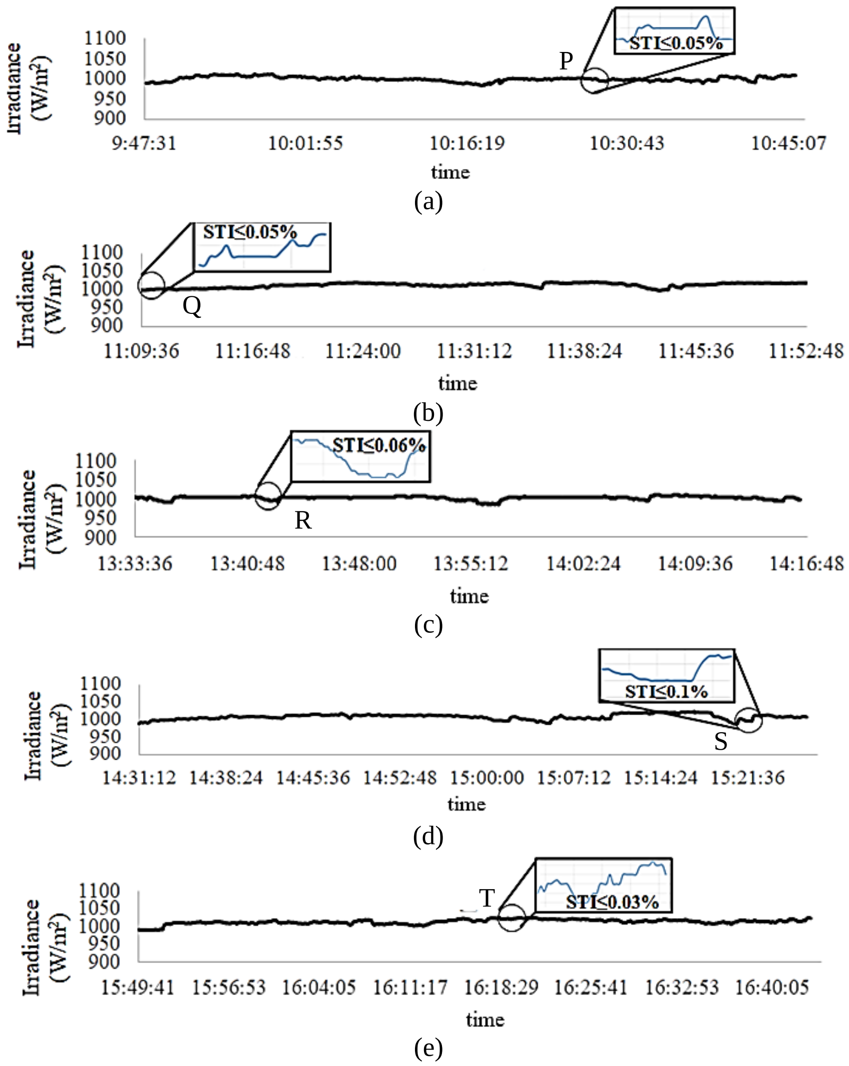


Figure 7. Presenting the STI measurement results from LSS which measured all 5 positions: (a) at position P, (b) at position Q, (c) at position R, (d) at position S, and (e) at position T

Our LTI and STI were compared with other LSS in the past. The details were presented in Table 4. The LSS light sources using COB LEDs or COB mixed with high-power LEDs [2]–[4], [28] tend to produce higher LTI/STI than using high-power LEDs or surface mounted device (SMD) LEDs [1], [14], [16], [19]. This is because COB is a multi-chip structure with relatively high current density resulting in higher operating temperatures than high-power or SMD LEDs. Besides the type of LED affects the temporal instability of the LSS, the choice of cooling system for the LED panel is also very important because a good cooling system decreases the temperature and maintains temperature stability during operation [2], [4], [28]. Therefore, a copper heat sink with water cooler [18] or Peltier active cooling system [23] will greatly reduce the heat of the LED. An attractively alternative cooling system is a heat sink with air cooling.

Table 4. Comparison of the temporal instability

References	LED types	LTI (%)	STI (%)	Cooling technic
López-Fraguas *et al*. [19]	SMD	0.4528	-	Al. heat sink with cooling fan
Novičkovas *et al*. [4]	hi-power	0.25	0.1	Al. Heat sink with cooling fan
Sun *et al*. [18]	hi-power	0.3	-	Cu. Heat sink with water cooling
Al-Ahmad *et al*. [14]	hi-power	< 0.1	< 0.01	Al. heat sink with cooling fan
Al-Ahmad *et al*. [16]	hi-power	0.31	0.17	Al. heat sink with cooling fan
Esen *et al*. [28]	COB+hi-power	1.86	1.087	Active cooling
Watjanatepin *et al*. [2]	COB+hi-power	0.61	-	Al. heat sink with cooling fan
Watjanatepin [3]	COB	1.038	0.29	Al. heat sink with cooling fan
Our LSS	COB	1.42	< 0.1	Al. heat sink with cooling fan

3.3. Non-uniformity

The new LSS system had revised from 2021 version. This LSS had a larger TA of 125×125mm that was for testing the standard-sized solar cells. It is in line with the goals of this research. To fit the dimensions of the pyranometer (CMP3, Kipp and Zonen) available in our laboratory, the TA was divided into 4×4 equal sections, 31.25×31.25 mm. Next, a pyranometer was used to measure spectral irradiance at the center of each of the segments (total of 16 points) at a distance of 30.05 and 36.00 cm between the light sources, respectively (detail from section 2.4). Before starting each measurement, the LSS system was turned on for 3 minutes for warming up and wait until the LED panel temperature equals room temperature. This experiment was performed at room temperature of 25±1 °C, RH 60±10%. The measurements were repeated five times and the mean value was analyzed for the S_{NE} by (3). The results were revealed in Figure 8. The analysis results showed that S_{NE} met to A class at a distance of d= 36.0 cm of 1.84% and achieved a B class at 30.05 cm of 2.34%. The maximum/minimum of irradiance at d of 36.00 cm and 30.05 cm were equal to 1,019:973 W/m^2 and 897:864 W/m^2, respectively.

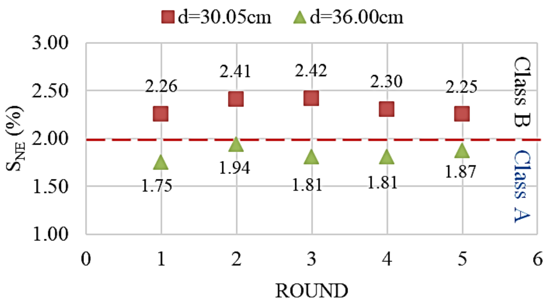


Figure 8. Experimental results of S_{NE} (%) at the different distance between the light sources

The measurement results of irradiance and S_{NE} were consistent with the data from the graphs shown in Figure 5. The results confirmed that our LSS system could provide an S_{NE} met to the A class of S_{NE} ≤2% when adjusted for d=36 cm. However, the Si solar cell testing under STC, it can be done by adjusting the distance d of 30.05 cm. The new prototype of LSS had a performance test according to IEC 60904-9 achieved the AAA class. That was, SM met the A class, LTI=1.42% and STI <0.1%, and S_{NE}=1.84%, according to the research objectives.

The proposed LSS system had very good S_{NE} performance classified in the A Class. This was not different from the results of studies by Watjanatepin *et al*. [2], [3], Novickovas *et al*. [4], Al-Ahmad *et al*.

[14], [17], Sun *et al*. [18], López-Fraguas *et al*. [19], and Stuckelberger *et al*. [29] who reported that the S_{NE} test result ranged from 1.34% to 1.97%, and were also classified as the A Class. For the structure of their LED panels, it was found that the layout of the LEDs was symmetrical. There was a relatively small distance between each type of LED [4], [14], [17], [19]. That is, if the LED density per unit area is high, it will affect the S_{NE} in the TA to a low level and offer the A class quality. Another variable that affects S_{NE} was i) the distance from the light source that inverses with S_{NE} and ii) if the temperature of the LED increases, S_{NE} will increase slightly. Normally, the LED panel size which the most of developers designed larger than TA [4], [17], [19] excepting some reserchers [2], [3], [14], [29]. Our LED panel was designed to be a larger size than the TA because it will affect the reduction of S_{NE} on the TA. However, to maintain the stability of the S_{NE} throughout the LSS operation, the temperature at the junction of the LED must be kept constant because the temperature of the LED increases, then the S_{NE} value increases accordingly.

3.4. Thermal analysis

The LSS system used an LED as a light source which had to keep the temperature constant during its operation and not so high that would affect to irradiance intensity, temporal stability and non-uniformity. Normally, the light intensity of an LED changes constantly as its temperature changes and it will not change when the input temperature reaches a stable point. Therefore, the analysis of the temperature was during continuous LSS operation for approximately 2 hours by using a 4 channel digital temperature logger with k-thermocouple. Three sensors were installed, the 1st sensor was installed at the center of the rear of the heat sink (T HS), the 2nd sensor measured on the metal base of the LED chip (T LED) mounted in front of the heat sink, and the 3rd sensor measured the ambient temperature in the laboratory (T amb). The measurement results were shown in Figure 9. It showed that the heat sink with cooling fan for LED cooling system could stabilize the LSS temperature for 10 min after turned-on. When the LSS was running continuously, the LED temperature had a maximum and average value of 37.5 °C and 36.9 °C, respectively. While the temperature at the heat sink had a maximum and average value of 33.0 °C and 32.1 °C, respectively. The average temperature in the laboratory was 24.1 °C. From the results of the thermal management of LED based solar simulator by Tavakoli *et al*. [20], the heat sink temperature was consistent but the proposed LED temperature was approximately 1.5 to 2 °C higher. From the results, it can be explained that the heat sink of the proposed system had less fins, it resulted in higher thermal resistance and decreases the cooling efficiency.

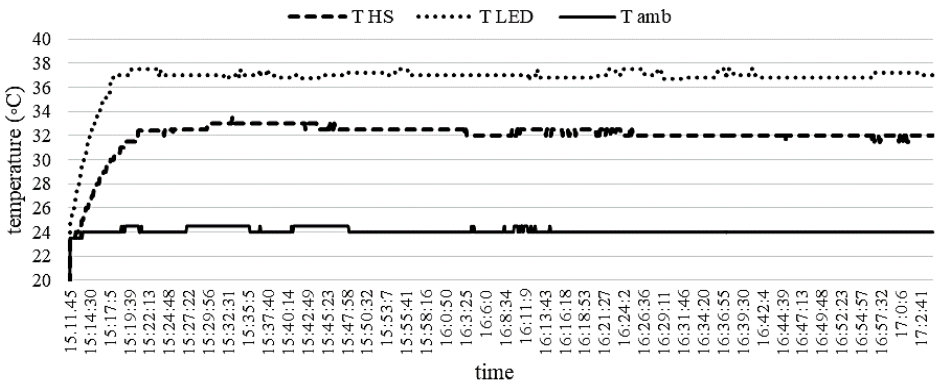


Figure 9. Temperature of the LED (small dot line), heat sink (large dot line), and ambient (back line) for around 2 hours

4. CONCLUSION

Our LSS system provided the spectral distribution matched to AM1.5G spectrum of 100%. The TA had been optimized to fit for the solar cell standard size of 125×125 mm. The novel LSS system provided the performance to meet the AAA class spectral mismatch, temporal instability, and non-uniformity in accordance to the IEC 60904-9 and accordance with the objectives of the research. The results confirmed that the pc-nWLED combined monochromic NIR (730, 800, 850, 940, and 1,000 nm) was a suitable method for generating spectral irradiance consistent with reference spectrum (AM1.5G). In addition, the proposed LSS could generate the irradiance of 1,000 W/m^2 over the test plane of 125×125 mm. The proposed LSS system could work continuously in a state where the LED had a stable temperature for at least 2 hours. Therefore, it was suitable for used in our laboratory and demonstration of solar cell characterization under STC.

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