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Measurement of Spectral Match and Spatial Non-uniformity for Indoor Solar Simulator

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ABSTRACT

This paper presents a study on the measurement of spectral match and spatial non-uniformity of the indoor solar simulator available in Universiti Teknikal Malaysia Melaka (UTeM). This indoor solar simulator which was successfully fabricated at the Applied Solar Energy Laboratory (ASEL) had used the quartz tungsten halogen lamp as its only light source. Upon its fabrication, the reliability of ASEL's solar simulator has not been proved yet as there is no concrete evidence that it had followed the international standard set for solar simulator. Therefore, the motivation of this study had been set to determine the characteristics of the indoor solar simulator in term of its spectral match and spatial non-uniformity. The literature review conducted has revealed that there are few methods that been practiced to determine both cases. For the spectral match test, the experimental works chosen for this research was the mathematical modelling method. Meanwhile, for the spatial non-uniformity test, irradiance mapping method was used where the reading of irradiance intensity at each coordinate across the map was measured. At the end of this study, it shows that at 400-500nm and 500-600 wavelength range, the value of spectral match value obtained was 0.40 and 1.46 respectively; whereas for 600-700nm range, the spectral match measured was beyond the standard range set. On the other hand, this study also reveals that the solar simulator was capable to produce 8.42% of spatial non-uniformity across the tested area of 104cm x 80cm. The average irradiance intensity recorded for this test was 981.98 W/m^2.

1. Introduction

Demands to the energy supply had been increasing throughout the year; this was supported by few inevitable factors of increase in population and advancement of technology. By 2030, it is expected to see the rise of global energy demand, and this had increased the existing energy security concerns [1]. It is not possible to rely on non-renewable energy sources reliably to fulfil rising demand

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because doing so will have a significant negative impact on future generations [2]. In contrast with that, the cost of producing solar electricity is quickly falling and the efficiency of solar panels is continuously improving; this is an indication that the world may be on the cusp of a significant change in how we power our buildings [3]. Up to this day, abundance of technology had been developed to ensure the solar technology is fully utilized; this include the solar powered kite that was equipped with sensors to monitor the surrounding conditions such as temperature and pressure [4]. On the other hand, other technologies such as the use of photovoltaic thermal (PVT) system was purposely discovered to increase the efficiency of solar technology by taking the thermal energy away from the photovoltaic cells allowing them to work under lower temperature, hence increasing their efficiency [5]. The availability of these two technologies were to maximise the amount of sunlight received by the solar PV panel at the outdoor. Meanwhile, for the testing purpose of the solar PV panel, the solar simulation technology is the one that widely being used since its first introduce in 1960s. This technology was purposely being developed to cater the impractical condition of the light energy emit by the Sun which might be vary from time to time due to the uncertain condition of the Sun as the effects of unstable weather and etc. Even the option of using simulation work or mathematical modelling able to produce the expected results based on solar energy study, it still has a few drawbacks in term of accuracy and uncertain assumptions [6,7]. Thus, with the presence of this solar simulation technology, a more effective measure can be done for the testing of PV module as this device could provide a controllable test in a lab environment.

Solar simulation technology is a technology which was used to replicate the sun in form of its light energy. Solar simulator which also referred as 'sunlight simulator' is the name of device that usually been referred to this technology due to its ability to produce the same intensity and spectral composition like the natural sunlight. It has usually been used in a research lab where one of its main purposes is to study the characteristics of the solar PV module. The development of a solar simulator consists of 3 major components which include the light source, power supply and optical filters. The light source which is considered as the most important part in a solar simulator can be form by using a several kinds of lamps or a combination of different type of lamps such as: Xenon arc lamp, metal halide, quartz tungsten halogen (QTH) lamp and light emitting diode (LED). Among all these lamps, LED is the one that was desired the most due to its unique characteristics which could provide a narrow monochromatic output spectrum where its spectrum can be adjusted. The availability of LEDs in variety of colours and wavelength means that we can achieved the desired spectrum by picking up the led at the specific colour. On the other hand, the combination of several LEDs at certain colours would also provide a close match spectrum as AM1.5G.

In order to ensure that all these lamps which had been referred as the artificial sunlight is highly reliable, a standard was needed to identify what is referred as sunlight. Back in 1975 and 1977, a project had been conducted by Energy Research and Development Administration (ERDA) and National Aeronautics and Space Administration (NASA). As an outcome of this project, a report of the standard terrestrial photovoltaic measurement procedures along with a detailed description of a standard solar simulator had been issued at that time. As refer to the report, the AM1.5G had been selected as the spectral composition with air temperature of 25°C and standard illumination intensity of $1000W/m^2$. Figure 1 shows the comparison of the different type of lamp with solar irradiance at AM1.5G in term of its spectral irradiance at different wavelength [8].

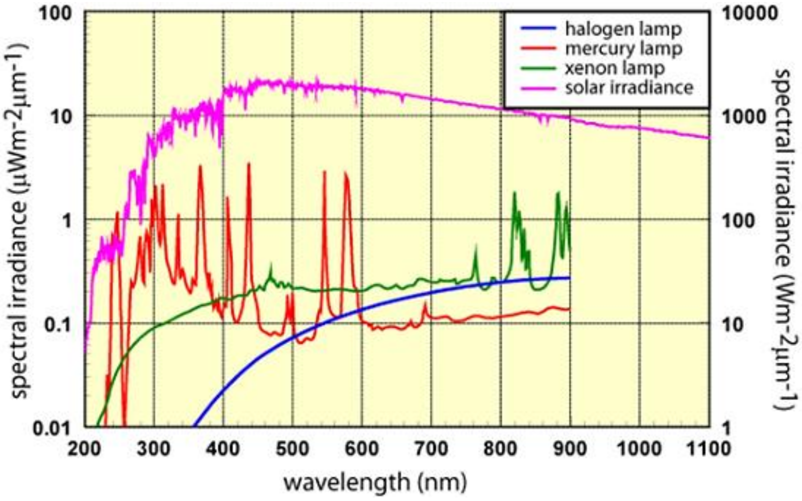

Fig. 1. Spectral match comparison between different type of lamps and AM1.5G

In order to ensure the light produced from the simulator was most alike with the light emit by the Sun, standard organization such ASTM and IEC had set 3 characteristics that need to be complied by the solar simulator. These characteristics which much focusing on the light irradiance can be categorized into spectral match, spatial non-uniformity and temporal instability. Therefore, this study was aimed to investigate the characteristics of the indoor solar simulator available at Universiti Teknikal Malaysia Melaka (UTeM) in term of its spectral match and spatial non-uniformity.

2. Experimental Setup

In Universiti Teknikal Malaysia, Melaka (UTeM), an indoor solar simulator was successfully developed in Applied Solar Energy Laboratory (ASEL). This solar simulator which also known as the ASEL's solar simulator was purposely used for the testing of solar photovoltaic (PV) module and solar thermal collector. Table 1 and Figure 2 below shows the technical features and the construction of ASEL's solar simulator.

Table 1
Main technical features for ASEL's solar simulator

Characteristics	Specification
Type of lamp	Quartz-tungsten halogen lamp
Lamp power/unit	500W
No. of lamp	12 units
Total power	6kW
Max illuminated area	1291mm x 1782mm
Range of light intensity	100 – 1000 W/m^2
Spectrum	AM.15G
Solar simulator dimension	1888mm x 1388mm x 1518mm

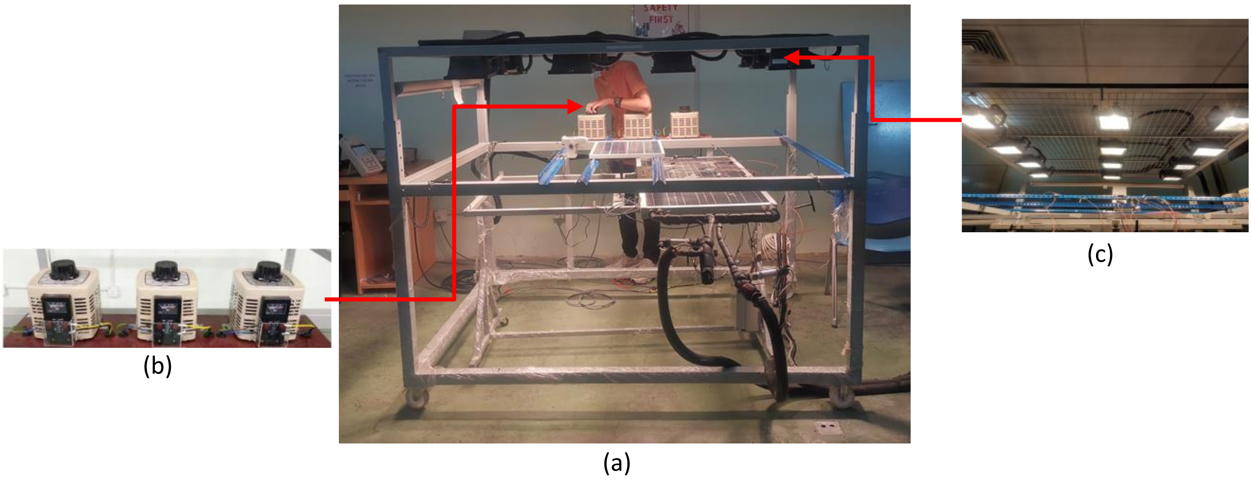

Fig. 2. (a) ASEL's indoor solar simulator (b) voltage regulator (c) halogen lamp

The construction of ASEL's solar simulator light source is a multi-lamps pattern with 12 lamps were arranged in 3 rows of 4 lamps each (Figure 3). This arrangement of lamps will create a large surface area which receive the same characteristics of light illumination. For each row, the lamps are being power up by using the voltage regulator shown in Figure 2(c). With the presence of this voltage regulator, the intensity of light emit by the lamps could be controlled by adjusting the amount of voltage supplied to the lamp.

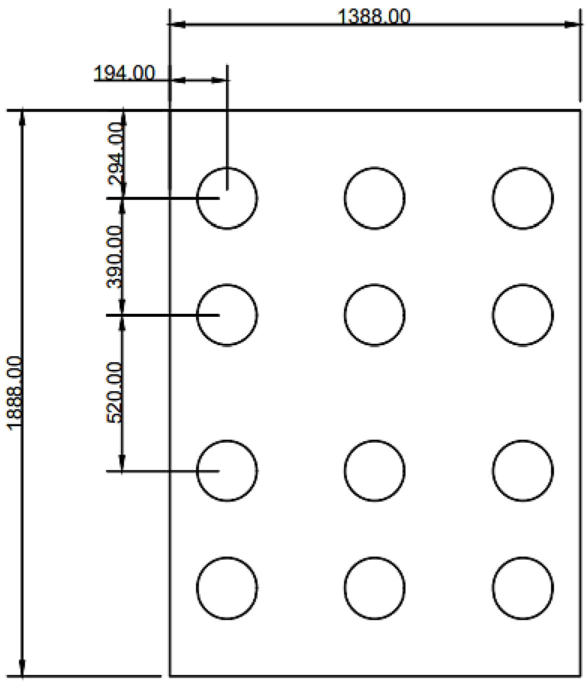

Fig. 3. Arrangement of lamps for ASEL's solar simulator

As for this study, even though a complete solar simulator was successfully being developed; however, the reliability of this solar simulator cannot be proven yet as there is no concrete evidence that it had followed international standard set for solar simulators. For the light source used, it generally does not exactly match with the AM1.5G. This mismatch factor of the light source spectrum and the daylight spectrum could affect the testing process of the device under test where its performance cannot be analysed accurately. Moreover, the distribution of light and consistency of irradiance over an area has not yet been identified.

3. Solar Simulator Performance Parameter

Despite of the variation of output produced by the light source, the evaluation of performance for a solar simulator are defined through these 3 common factors: 1. Spectral match, 2. non-uniformity of the irradiance and 3. temporal instability of the irradiance [9]. In order to determine the performance of the solar simulator, these three international compliance standards are the standards that been referred to; IEC 60904-9, JIS C 8904-9 and ASTM E 927-10. Generally, the solar simulator will be classed as A, B, and C to define its performance for all the three characteristics. If the simulator fails to meet any of the three classes, this indicates that they have failed to meet the requirement set. Table 2 below shows the classification of solar simulator based on its criteria as referred to IEC 60904-9 and ASTM E 927-10 standard [10,11].

Table 2
Classification of solar simulator based on its criteria as referred to IEC 60904-9 and ASTM E927-10 standard

Parameter	IEC-60904-9	ASTM E927-10
Spectral Match		
Class A	0.75-1.25	0.75-1.25
Class B	0.6-1.4	0.6-1.4
Class C	0.4-2.0	0.4-2.0
Spatial Non-uniformity		
Class A	≤2%	≤3%
Class B	≤5%	≤5%
Class C	≤10%	≤10%
Temporal Stability		
Class A	≤2%	≤2%
Class B	≤5%	≤5%
Class C	≤10%	≤10%

The spectral match is an important parameter in considering the performance of a solar simulator. It is a comparison between the spectrum simulated by solar simulator to the standard spectrum AM1.5G. If the simulated spectrum matched perfectly like the reference spectrum, the spectral match will be considered as 1. However, if there is slight difference between these two spectrums, it will be classified to either class A, B or C as stated in Table 2 previously. For this measurement, the range of wavelength that will be involved is from 400nm to 1100nm based on the international standards IEC and ASTM. These wavelength bands will be divided into six, where from 400nm to 900nm it was divided at every 100nm while between 900 to 1100nm, it was considered as one interval of 200nm band. For all the divided wavelength bands, each of it will contain a particular percentage of the total integrated irradiance. Later, the 6 percentage of irradiance obtained from the simulation light will be compared to those standard irradiance percentage of AM1.5G as specified in Table 3 below.

Table 3
Distribution for Percentage of Total Irradiance (AM1.5G)

Wavelength (nm)	Percentage of Total Irradiance (AM1.5G)
400-500	18.4%
500-600	19.9%
600-700	18.4%
700-800	14.9%
800-900	12.5%
900-1100	15.9%

As for spectral match, it was described as the ratio of the actual percentage of irradiance coming from the simulated light to the required percentage of irradiance (AM1.5G) [12].

$$SM = \frac{Actual\ Percentage\ of\ Irradiance}{Required\ Percentage\ of\ Irradiance\ (AM1.5G)} \tag{1}$$

whereas, formula for the actual percentage of irradiance is described as

$$Actual\ Percentage\ of\ Irradiance = \frac{\int_{\lambda_n}^{\lambda_{n+1}} S(\lambda)d\lambda}{\int_{400}^{1100} S(\lambda)d\lambda} \tag{2}$$

The $S(\lambda)$ indicate the irradiance distribution at a specific range of wavelength whereas the wavelength band will start from λ_n until λ_{n+1}.

Meanwhile, for the next solar simulator performance parameter which is the spatial non-uniformity; it can be defined as measurement of how uniform the distribution of irradiance that coming from the light source would be across the test plane. Uniformity of light is important across all solar applications as it could give a great effect to its efficiency. Even at the photovoltaic thermal applications, the uniformity of light across the testing area also needs to be determined to obtain effective test area as it effects the distribution of both irradiance and thermal application. This was stated in a study related to PVT applications conducted by Rosli *et al.,* [13] where the effective area was being determined to consider the edge loses that might affect the thermal efficiency. For the spatial non-uniformity experiment, the number of tests need to be carried out are differ based on the standard that been referred to. As for IEC standard, it requires up to 64 tests to specify spatial non uniformity; while for the ASTM standard, it only need the amount of 36 tests. As refer to the standard by IEC and ASTM, the formula to determine this parameter can be assessed from the following equation [10]. From Eq. (3), E_{max} and E_{min} is being referred as the maximum and minimum irradiance measured throughout the test plane.

$$Spatial\ Non-uniformity\ (\%) = \frac{E_{max}-E_{min}}{E_{max}+E_{min}} \tag{3}$$

For this spatial non-uniformity, the uniformity of the irradiance intensity can be increased by placing an acrylic piece in between the light source and the intensity map. This was stated in the study conducted by Samiudin *et al.,* [14]; where it shows that with the use of 0.5cm lightproof acrylic piece that been placed in between light source and intensity maps, the solar simulator managed to produce a good spatial non-uniformity percentage that was within $\pm$5% and $\pm$7%.

For the last parameter, which is the temporal instability, this test is needed to determine the stability of the solar simulator's output overtime to ensure that lamp fluctuations do not distort measurements. Temporal instability is defined by two parameters which are short term instability (STI) and long-term instability (LTI).

4. Spectral Match Measurement

One of the methods used to determine the spectral match of the solar simulator is to employ mathematical modelling of the light source. The required data to perform mathematical modelling method is the light source intensity, number of sources, distance from the light source and the spectrum distribution of the sources [15]. Distribution of irradiance of the light source at the spectral range of wavelength can be found if the light source has a known spectrum.

Light source intensity is the most important parameter to determine the spectral match as it affects the spectral irradiance. Hence, this method will apply the data taken from the light source and interpreted in a related mathematical equation to define its spectral match at the end. To determine the irradiance, a conversion approach will be used where the light intensity will be converted from illuminance to irradiance. This conversion was named as photometric to radiometric conversion. In order to gain better understandings on how the spectral match measurements were being done, Figure 4 below shows the flowchart of the spectral match measurement.

The term radiometry is referring to the analysation of light measurement in any segment of electromagnetic spectrum; this can be classified into ultraviolet, visible light and infrared light using the optical instruments [15]. On the contrary, photometry is only the subfield study of the radiometry where it is about the study of measuring visible light which only concerned to the human eye response. In context of radiation, radiometry will cover the overall radiation energy content, while the photometry is limited to the radiation which can be seen by human eyes. To get better understanding, the unit in radiometry was commonly specified in watt (W) which quantify the radiant flux or power. Meanwhile, the photometry has usually been described with the unit of lumen (lm) where it measures the illuminance. In order to perform the conversion of photometric units of illuminance (lux or lm/m^2) to the radiometric unit of irradiance (W/m^2), a conversion factor is required. The formula for this conversion of illuminance to irradiance is as follows [16].

$$Irradiance = CF \times Illuminance \tag{4}$$

where the conversion factor, CF is defined as equation below. $P(\lambda_i)$ stated in the equation below is the photopic luminosity function.

$$CF = \frac{\sum_i f(\lambda_i, \lambda_p, \Delta\lambda)}{683 \times \sum_i f(\lambda_i, \lambda_p, \Delta\lambda) P(\lambda_i)} \tag{5}$$

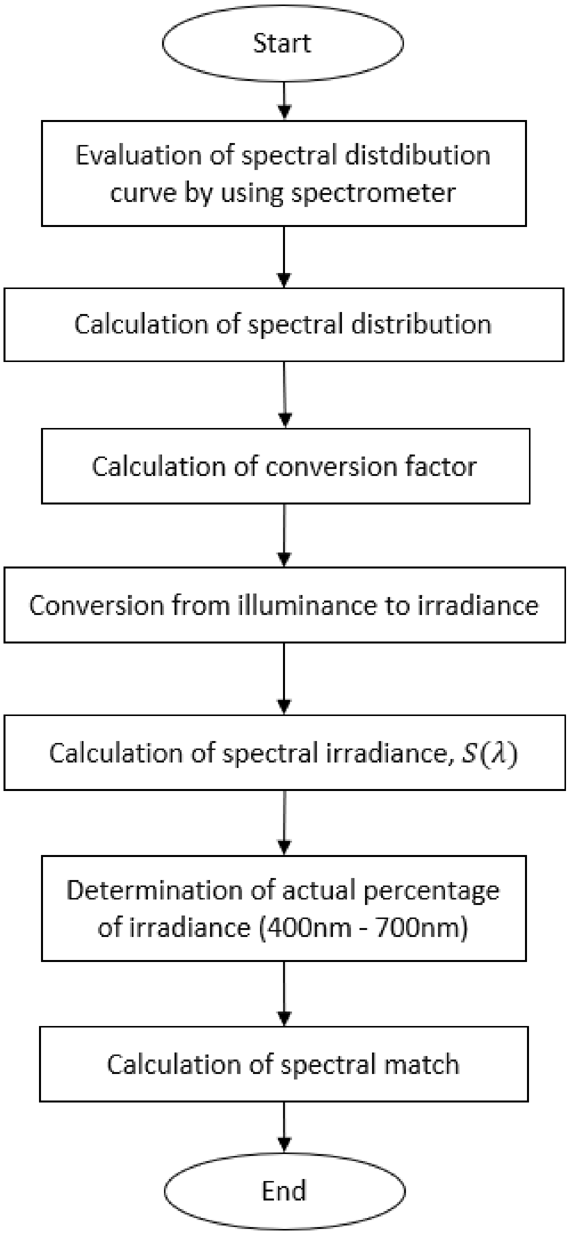

Fig. 4. Flowchart of spectral match measurement

One of the importance parameters needed for the calculation of conversion factor is the spectral power distribution where it was used to determine the spectral distribution function, $\sum_i f(\lambda_i, \lambda_p, \Delta\lambda)P(\lambda_i)$ as stated in equation above. This parameter which was also known as spectral intensity distribution was described as the concentration, intensity or energy as function of wavelength of any radiometric or photometric quantities. As for this experiment, the spectral power distribution will be determined with the help of a device named SM442 CCD Spectrometer as shown in Figure 5 below. This device along with the suggested software of SMProMX_5.6.0 will produce an intensity graph which also referred to as the spectral power distribution.

Fig. 5. SM442 CCD Spectrometer

As the spectral power distribution was obtained, the calculation for spectral distribution function was determined as follows [14].

$$f(\lambda_i, \lambda_p, \Delta\lambda) = \frac{g(\lambda_i,\lambda_p,\Delta\lambda)+2g^5(\lambda_i,\lambda_p,\Delta\lambda)}{3} \tag{6}$$

Where; $g(\lambda_i, \lambda_p, \Delta\lambda) = e^{-(\frac{\lambda_i-\lambda_p}{\Delta\lambda})^2}$ (7)

As the conversion of illuminance to irradiance was done by using the Eq. (4), the spectral irradiance, $S(\lambda)$ of the light source was calculated by using the formula given:

$$S(\lambda) = Mean\ Irradiance \times \frac{f(\lambda_i,\lambda_p,\Delta\lambda)}{\int_{400}^{1100} f(\lambda_i,\lambda_p,\Delta\lambda)P(\lambda_i)} \tag{8}$$

From here, the determination of the spectral match is defined by using the formula stated in Eq. (1) and Eq. (2). To ensure a proper data is gained in this research, the determination of spectral match was carried out at difference sets of illuminances; this was being done by varying the amount of voltage supplied to the light source.

5. Spatial Non-Uniformity Measurement

In the experimental stage, method used for the evaluation of spatial non-uniformity was the irradiance intensity mapping method where the maps were labelled according to its coordinate across the map. This map was placed on the test surface area of the solar simulator, and the measurement of irradiance at every coordinate was conducted by using a device named solar power meter, model SM206. This device able to measure the irradiance value from 1-3999 W/m^2 with resolution of 0.1 W/m^2 and sampling time of 0.5s. To begin with, the test surface area of the map will be set at an area which is smaller compare to the maximum illuminated area of the ASEL's solar simulator (1291mm x 1782mm).

For this study, 4 variations of intensity maps are set for the uniformity evaluation process and the difference between those maps is the size of the map; this was done to define the best surface area for ASEL' solar simulator. The size of intensity map set was 156cm x 120cm, 130cm x 100cm, 104cm x 80cm and 78cm x 60cm. Despite of the different in the intensity map sizing, the distance between coordinates for all maps were maintained which is 13cm height and 10cm long. With this set up of distance, the number of coordinates for the purpose of reading taken were in between 49 to 169 coordinates according to the size of map. To get better understandings regarding the formation of the intensity map, Figure 6 below shows the example for 130cm x 100cm map's size with the distance between coordinates of 13cm height and 10cm length.

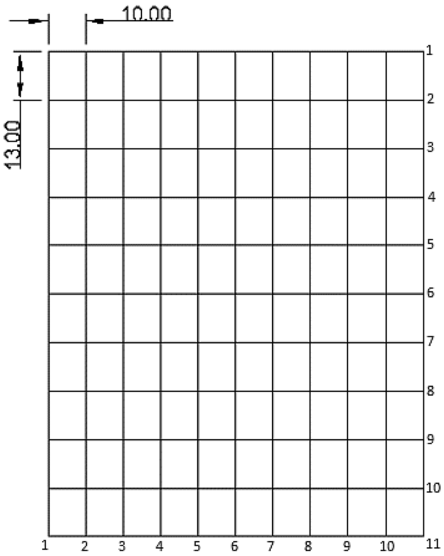

Fig. 6. 130cm x 100cm intensity map

For the testing purpose of the irradiance measurement, the solar power meter device will be placed on the top of each coordinate to ensure the reading was taken at the accurate range. The device will be shifted from one coordinate to another until all coordinates were being measured. The calculation of spatial non-uniformity will then be defined by using Eq. (3) stated before.

6. Results

6.1 Spectral Match Results

Table 4 below shows the results of the ASEL's solar simulator spectral match at each wavelength band between 400nm-700nm. Next to the value of spectral match obtained, the class of the spectral match for every wavelength band was classified to either A, B, C or '~'. For the spectral match value where the results obtained was beyond the standardised range set by IEC 60904-9, the class column will be filled with '~' sign.

Based on the results obtained for ASEL's solar simulator spectral match, it shows that in every measured supplied voltage, neither of them had successfully classified to the range set by IEC 60904-9 in term of spectral match. In order to be classified according to this standard, the irradiance exposure of a solar simulator should at least fulfil the minimum requirement which is class C for all those three characteristics. Class C characteristic for a spectral match specification means that for all measured wavelength bands, the worst-case classification that it should obtained is C. The finding of ASEL's solar simulator spectral match reveals that at 240V, it managed to achieve C class for two wavelength bands of 400nm-500nm and 500nm-600nm. However, the emission of irradiance at wavelength band of 600nm-700nm failed to comply to the minimum standard range set as the results obtained was beyond the minimum requirement; this had cause ASEL's solar simulator from be classed as a standard solar simulator.

Table 4
Spectral match and class obtained for ASEL's solar simulator

Voltage (V)	Spectral Match					
	400-500nm		500-600nm		600-700nm	
192	0.32	~	1.25	A	3.97	~
204	0.31	~	1.26	B	4.01	~
216	0.31	~	1.26	B	4.01	~
228	0.33	~	1.36	B	3.90	~
240	0.40	C	1.46	C	3.75	~

Figure 7 below presents the 240V halogen lamp irradiance spectrum that was overlaid with the standard spectrum of AM1.5G within the range 400-700nm. Both spectrum data was plotted at discrete wavelength of 10nm. 240V was chosen as the results obtained was the most convincing compared to the other results.

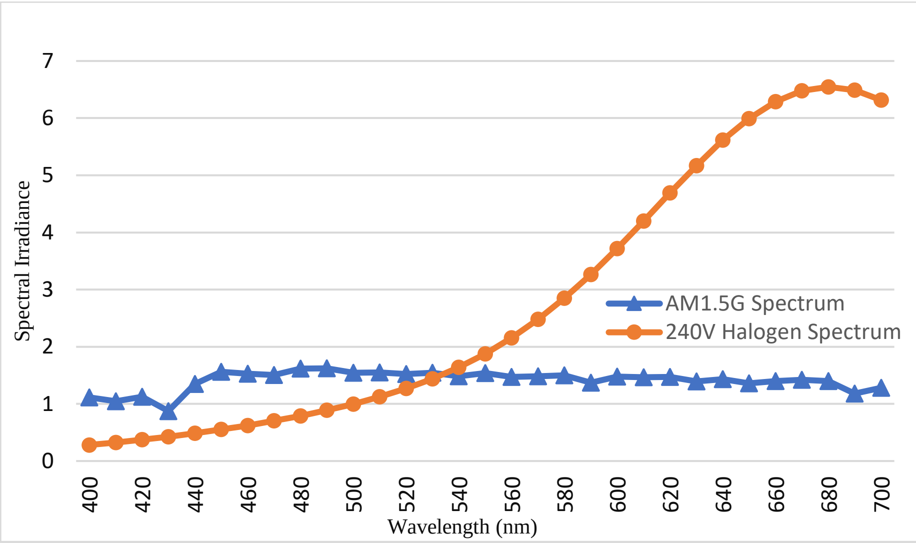

Fig. 7. Graph of 240V halogen irradiance spectrum vs AM1.5G spectrum

According to the graph above; in between 400nm-500nm range, the value of spectral match acquired is 0.4. Even this value is successfully achieved the minimum standard set, it can be seen from the graph that the emission of irradiance at this region is lower compare to the AM1.5G. Meanwhile, at 500nm-600nm, the value of spectral match obtained is 1.46. In spite of the slightly lower amount of irradiance produce compare to the standard spectrum at the beginning of this region, but due to significant increase from approximate 535nm to 600nm, this had caused the total spectral irradiance value obtained in 500nm-600nm region is higher than the AM1.5G. However, the difference that it makes is still acceptable as the spectral match value was still in the standard range set.

Next, the large deviation that can be seen between the halogen and AM1.5G spectrum in 600nm-700nm wavelength range can be supported with the spectral match value acquired which is 3.75. This value is by far so unlikely with the spectral match requirement as the maximum value set is only 2. In comparison to the required spectrum, this implies that the quantity of the irradiance spectrum produced by the halogen lamp at this region is much higher. Thus, to conclude this result, the simulated irradiance spectrum of the halogen lamp was only acceptable for the range of wavelength 400nm to 600nm, whereas from 600nm to 700nm the irradiance spectrum recorded need to be fixed as it was far beyond the standard range set.

In accordance with the spectral match value acquired at every voltage, Figure 8 to Figure 10 shows the plot of spectral match vs voltage at the specified wavelength range. The line of blue, yellow and red shown represent the upper and lower limit of class A, B and C respectively; this limit was as referred to the IEC 60904-9 standard. As portrayed in Figure 8 above, the emission of irradiance at the 400-500nm wavelength was lower compared to the standard irradiance. The low irradiance emission at this region could be explained by the deficiency of the blue part in the visible spectrum of the tungsten halogen lamps output [17]. Meanwhile, the 600-700nm region shows a completely different phenomenon as the emission of irradiance at this region is higher compared to the standard irradiance emission; it can be seen in Figure 10 as the irradiance emit for all voltages was beyond the red line set indicates that none of the irradiance emit by given voltage was able to achieve the minimum class set. This is due to the characteristics of halogen lamp which is high at the near infrared region (NIR).

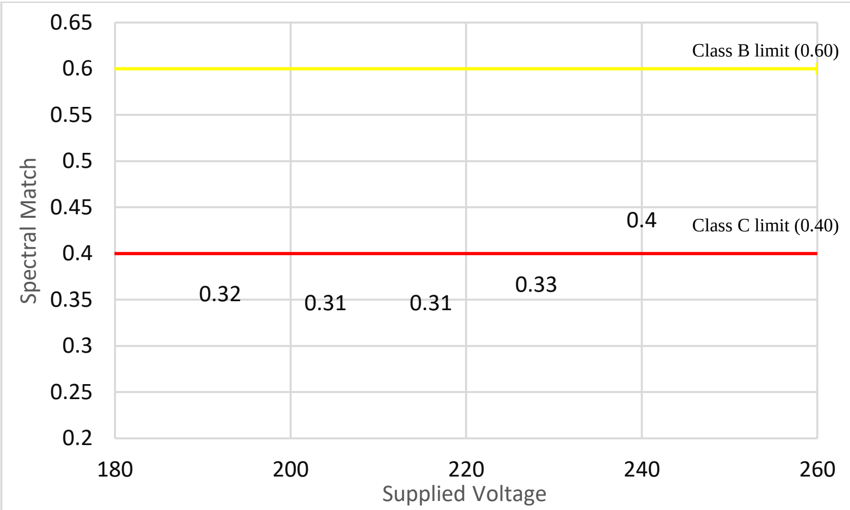

Fig. 8. Spectral match vs voltage for 400-500nm wavelength

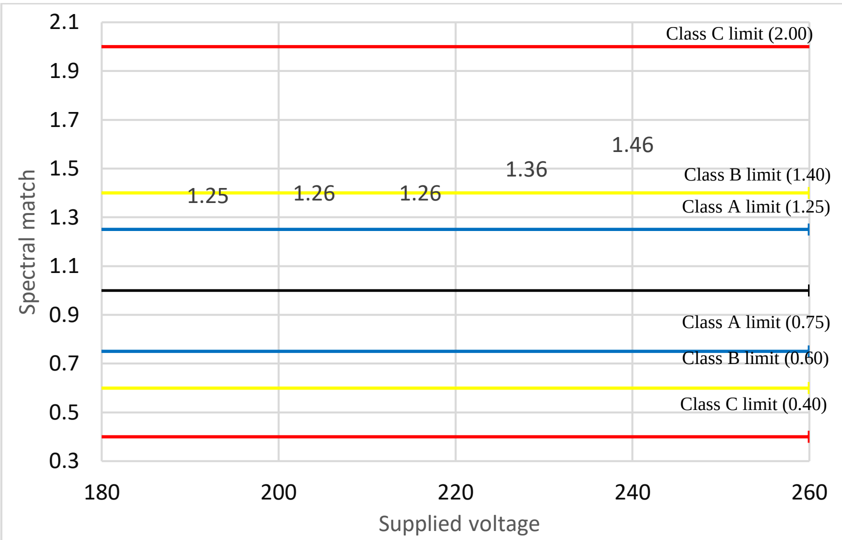

Fig. 9. Spectral match vs voltage for 500-600nm wavelength

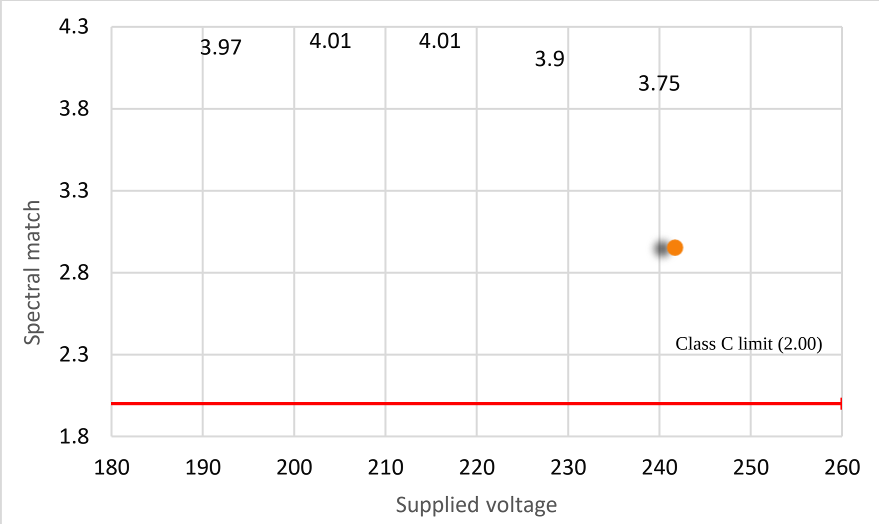

Fig. 10. Spectral match vs voltage for 600-700nm wavelength

6.2 Spatial Non-Uniformity Result

The results obtained regarding the spatial non-uniformity of the ASEL's solar simulator was shown in Table 5 below. This experiment was conducted at 240V supplied voltage as it was considered as the best voltage for spectral match measurement. Based on the results shown in Table 5, 3 out of 4 tests carried out was able to produce the spatial uniformity that complied to IEC 60904-9 with average irradiance intensity that was closed to 1000 W/m^2. Three intensity maps with the sizing area of 130cm x 100cm, 104cm x 80cm and 78cm x 60cm acquire non-uniformity percentage of 9.02%, 8.42% and 8.49% respectively; these had classified them in class C for spatial non uniformity. From these three results, it specifies that the best testing area that should be applied for ASEL's solar simulator was 104cm x 80cm. Even though the average irradiance intensity measure at this area was lower compared to the other area, but due to the lowest non-uniformity of irradiance obtained at this area had indicated it as the best. Besides, the study also reveals that in order to obtain effective irradiance uniformity, the maximum test size area that should be used was 130cm x 100cm as it gained the highest percentage of uniformity which is still within the standard range set by IEC 60904-9.

Table 5
Spatial non-uniformity of ASEL's solar simulator at different intensity map

Size of intensity map (cm^2)	Average irradiance intensity (W/m^2)	Spatial Non-uniformity (%)
156 x 120	990.10	10.15
130 x 100	991.41	9.02
104 x 80	981.98	8.42
78 x 60	981.93	8.49

The pattern of irradiance intensity recorded across all of the 4 maps tested are as illustrated in Figure 11 to Figure 14.

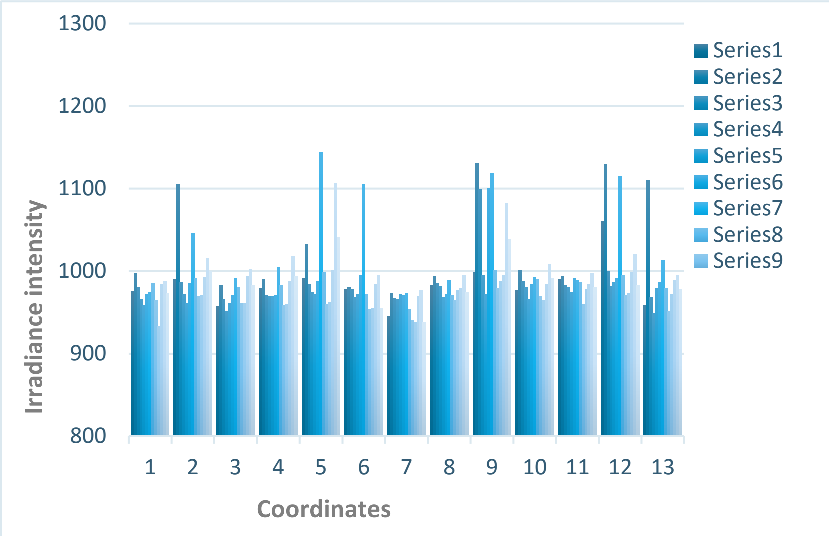

Fig. 11. Irradiance mapping at 156cm × 120cm area with spatial non-uniformity percentage of 10.15%

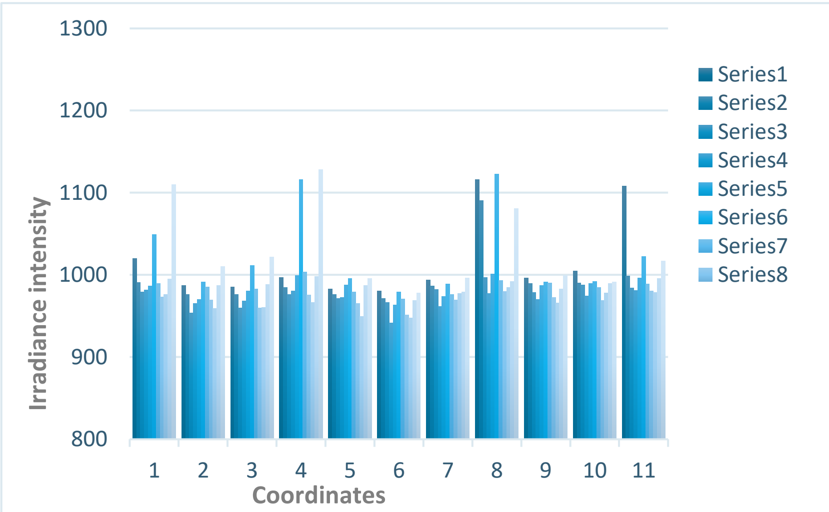

Fig. 12. Irradiance mapping at 130cm × 100cm area with spatial non-uniformity percentage of 9.02%

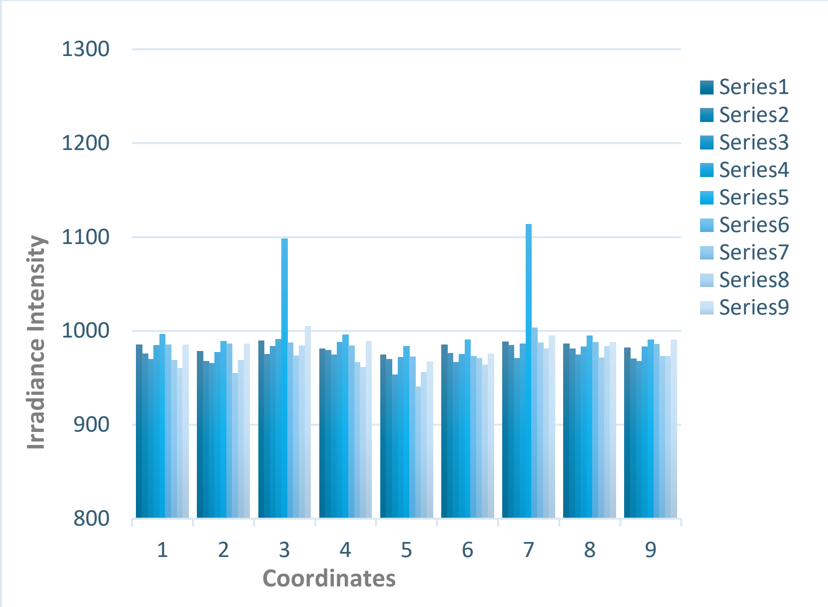

Fig. 13. Irradiance mapping at 104cm × 80cm area with spatial non-uniformity percentage of 8.42%

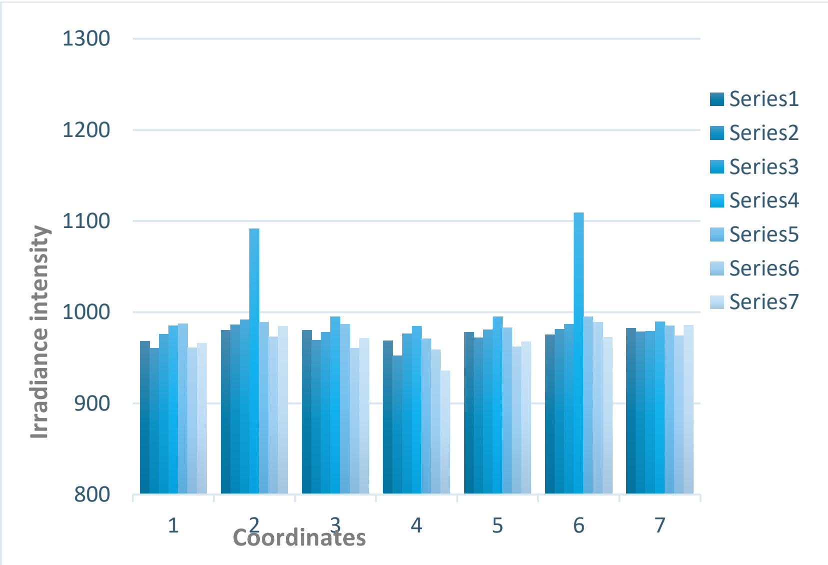

Fig. 14. Irradiance mapping at 78cm × 60cm area with spatial non-uniformity percentage of 8.49%

Based on the graph shown in Figure 11 to Figure 14, it shows that the distribution of the spatial non-uniformity at all irradiance mapping area recorded area was almost alike. However, the difference can be seen from the percentage of spatial non-uniformity recorded along with the number of 'peak' irradiance intensity recorded which indicates its non-uniformity distribution. The percentage recorded shows that the distribution was best achieved at the mapping size of 104cm x 80cm. With the percentage of 8.42% which is the lowest compared to the others, this proved that the distribution of spectrum at this area had the best uniformity. This was also shown in the graph where only at 2 points, the irradiance intensity recorded was slightly higher than the irradiance at the other parts. Meanwhile, the higher percentage of distribution at 156cm x 120cm and 130cm x 100cm can be related with the graph drawn in Figure 11 and Figure 12. With the higher percentage of distribution of 9.15% and 10.02%, this was supported by its irradiance intensity recorded on the graph shown where at some points, the irradiance intensity recorded was much higher than the average. This also indicates that the non-uniformity at this mapping area was higher.

To sum it up, the suggested test area that should be applied for any testing under ASEL's solar simulator was 104cm x 80cm. With the spatial non-uniformity percentage of 8.42%, the maximum irradiance value for this test surface area was $1113.7W/m^2$ measured at 5,7 coordinates; whereas the minimum irradiance value was 940.7 measured at 7,5 coordinates. The percentage error of deviation from the maximum irradiation for the 104cm x 80cm area was as shown in Table 6; this value was calculated at every coordinate across the map. From Table 6, it shows that the highest percentage error of irradiation (8.42%) calculated was at the 7,5 coordinates; this was due to the lowest irradiance emit at this point.

Table 6
Percentage error of irradiation for 104cm x 80cm test area

Percentage error of irradiation (%)									
Coordinates	1	2	3	4	5	6	7	8	9
1	6.11	6.48	5.91	6.33	6.67	6.11	5.96	6.06	6.28
2	6.60	7.01	6.64	6.41	6.92	6.57	6.15	6.34	6.89
3	6.92	7.13	6.19	6.67	7.77	7.07	6.84	6.66	7.02
4	6.14	6.51	5.81	5.99	6.80	6.62	6.06	6.22	6.23
5	5.56	5.93	0.69	5.58	6.19	5.85	0.00	5.64	5.85
6	6.12	6.07	6.00	6.17	6.77	6.74	5.20	5.99	6.10
7	6.96	7.67	6.72	7.07	8.42	6.85	6.02	6.82	6.73
8	7.39	6.97	6.16	7.33	7.61	7.19	6.34	6.21	6.75
9	6.12	6.07	5.13	5.92	7.04	6.60	5.64	5.98	5.86

7. Conclusion

As a conclusion, the approaches that had been applied for both experiments managed to identify the objectives for this study regarding the spectral match and spatial non-uniformity. For the spectral match test that was carried out using the mathematical modelling method, it shows that at low wavelength range of 400-500nm and 500-600nm; ASEL's solar simulator able to produce a spectral match value of 0.40 and 1.46 respectively. In accordance with the international standard IEC 60904-9, this spectral match value was classified in class C and B at the given wavelength range. Meanwhile, for the spatial non-uniformity test, this study found out that ASEL's solar simulator was able to produce a solar simulator that complied to IEC 60904-9 standard in term of its spatial non-uniformity. With the average irradiance intensity of $981.98W/m^2$ and spatial non-uniformity percentage of 8.42%, the suggested tested area that should be used for any testing purpose was $104cm \times 80cm$ to comply to the minimum standard requirement set by IEC 60904-9.

8. Future Works

Due to some inevitable constraints encounter during the experiments, the final results obtained may not convincing enough as there are few improvements that could be done to obtain a better result. The results of spectral match obtained for this study show that the halogen lamp failed to achieve the required percentage of irradiance at 600nm-700nm wavelength due to the emission of irradiance that was too high in this region. In order to provide a solution regarding this issue, below are some of the approaches that can be considered for the future work

i. Combination of tungsten halogen lamp with LED light
ii. Varied the height of the light source

From the experiment that had been carried out, it shows that the problem with ASEL's halogen light source is the emission of irradiance spectrum at the 400-500nm is quite low while at the 600-700nm region the emission was too high. Thus, the combination of tungsten halogen lamp with the LED light source is one of the possible approaches that can be used to solve this problem.

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References
[1] Khattak, Muhammad Adil, Mohammad Azfar Haziq Ayoub, Muhammad Ariff Fadhlillah Abdul Manaf, Mohd Faidhi Mahru, Mohd Ridwan Mohd Juhari, Mira Idora Mustaffa, and Suhail Kazi. "Global energy security and European Union: A review." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 11, no. 1 (2018): 64-81.
[2] Rosli, Mohd Afzanizam Mohd, Muhammad Zaid Nawam, Irfan Alias Farhan Latif, Safarudin Ghazali Herawan, Noriffah Md Noh, Siti Nur Dini Noordin Saleem, and Faridah Hussain. "The Effect of Variation in Mass Flow Rate and Solar Irradiance on Temperature Uniformity and Thermal Performance of Photovoltaic Thermal: A Simulated CFD Study." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 91, no. 2 (2022): 106-119. https://doi.org/10.37934/arfmts.91.2.106119
[3] Wei, Chee Kar, and Abdul Yamin Saad. "The potential of solar energy for domestic and commercial buildings in Malaysia." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 75, no. 3 (2020): 91-98. https://doi.org/10.37934/arfmts.75.3.9198
[4] Ishak, Muhammad Irfan, Riazul Islam Thakur, Chila Kaewpraek, Yap Boon Kar, Kazi Sajedur Rahman, Kuaanan Techato, Md Akhtaruzzaman, Sieh Kiong Tiong, and Nowshad Amin. "An Innovative Approach for Environmental Monitoring by Solar Powered Kite." *International Journal of Integrated Engineering* 12, no. 5 (2020): 257-265.
[5] Rosli, Mohd Afzanizam Mohd, Irfan Alias Farhan Latif, Muhammad Zaid Nawam, Mohd Noor Asril Saadun, Hasila Jarimi, Mohd Khairul Anuar Sharif, and Sulaiman Ali. "A Simulation Study on Temperature Uniformity of Photovoltaic Thermal Using Computational Fluid Dynamics." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 82, no. 1 (2021): 21-38. https://doi.org/10.37934/arfmts.82.1.2138
[6] Abdullah, Amira Lateef, Suhaimi Misha, Noreffendy Tamaldin, Mohd Afzanizam Mohd Rosli, and Fadhil Abdulameer Sachit. "Hybrid photovoltaic thermal PVT solar systems simulation via Simulink/Matlab." *CFD Letters* 11, no. 4 (2019): 64-78.
[7] Sachit, F. A., Noreffendy Tamaldin, M. A. M. Rosli, S. Misha, and A. L. Abdullah. "Current progress on flat-plate water collector design in photovoltaic thermal (PV/T) systems: A Review." *Journal of Advanced Research in Dynamical and Control Systems* 10, no. 4 (2018): 680-89.
[8] Honsberg, Christiana, and Stuart Bowden. "PVEducation." *PVEducation*. Accessed June 19, 2021. https://www.pveducation.org/.
[9] Paranthaman, M. Parans, Winnie Wong-Ng, and Raghu N. Bhattacharya, eds. *Semiconductor materials for solar photovoltaic cells*. Vol. 218. Switzerland: Springer International Publishing, 2016. https://doi.org/10.1007/978-3-319-20331-7
[10] IE Commission. "IEC 60904-9: 2020 Photovoltaic devices-Part 9: Classification of solar simulator characteristics." *International Electrochemical Committee, Geneva, Switzerland* (2020).
[11] ASTM Committee E-44 on Solar Geothermal and Other Alternative Energy Sources. *ASTM E927-10(2015)-Standard Specification for Solar Simulation for Photovoltaic Testing*. ASTM International, 2015.
[12] Hamadani, Behrang H., and Brian Dougherty. "Solar cell characterization." In *Semiconductor Materials for Solar Photovoltaic Cells*, pp. 229-245. Springer, Cham, 2016. https://doi.org/10.1007/978-3-319-20331-7_8

[13] Rosli, Mohd Afzanizam Mohd, Sohif Mat, Kamaruzzaman Sopian, Mohd Yusof Sulaiman, Elias Ilias Salleh, and Mohd Khairul Anuar Sharif. "Thermal performance on unglazed photovoltaic thermal polymer collector." In *Advanced Materials Research*, vol. 911, pp. 238-242. Trans Tech Publications Ltd, 2014. https://doi.org/10.4028/www.scientific.net/AMR.911.238

[14] Samiudin, N. Mohamad, F. Hussain, M. Othman, B. Yatim, M. Ruslan, K. Sopian, and Z. Ibrahim. "Development Of Solar Simulator For Indoor Testing Of Solar Collector." *Journal of Industrial Technology* 24 (2016): 27-42. https://doi.org/10.21908/jit.2016.3

[15] Mohan, MV Abhay, Jishnu Pavithran, K. Lijo Osten, A. Jinumon, and C. P. Mrinalini. "Simulation of spectral match and spatial non-uniformity for LED solar simulator." In *2014 IEEE Global Humanitarian Technology Conference-South Asia Satellite (GHTC-SAS)*, pp. 111-117. IEEE, 2014. https://doi.org/10.1109/GHTC-SAS.2014.6967568

[16] Gomes, Jonas, Luiz Velho, and Mario Costa Sousa. "Radiometry and Photometry." In *Computer Graphics*, pp. 489-508. AK Peters/CRC Press, 2012. https://doi.org/10.1201/b11857-23

[17] Namin, Anon, Chaya Jivacate, Dhirayut Chenvidhya, Krissanapong Kirtikara, and Jutturit Thongpron. "Construction of tungsten halogen, pulsed LED, and combined tungsten halogen-LED solar simulators for solar cell-characterization and electrical parameters determination." *International Journal of Photoenergy* 2012 (2012). https://doi.org/10.1155/2012/527820