A STUDY ON CHARACTERISTICS OF INDOOR SOLAR SIMULATOR USING HALOGEN LAMP

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A report submitted
in fulfilment of the requirements for the degree of
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DECLARATION

I declare that this project report entitled "A Study on Characteristics of Indoor Solar Simulator Using Halogen Lamp" is the result of my own work except as cited in the references

Signature :..

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Date : 19/6/2021

APPROVAL

I hereby declare that I have read this project report and in my opinion this project is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :..

Name : Mohd Afzanizam Bin Mohd Rosli

Date : 16 July 2021

DEDICATION

This report is dedicated to my beloved parents.

ABSTRACT

Solar simulator is a device used to replicate the sunlight in term of its spectrum. Several types of lamps including Xenon arc lamps, LEDs, metal halide and halogen lamps were commonly used in the development of solar simulators. In order to determine the performance of a solar simulator, three characteristics had been set by the IEC 60904-9 which include the spectral match, spatial non-uniformity and temporal stability. With the presence of ASEL's solar simulator in UTeM, this paper presents a study conducted to define two important performance parameters of the solar simulator which are spectral match and spatial non-uniformity. Mathematical modelling method was applied to find the spectral irradiance spectrum of the light source; it was then be compared with the AM1.5G spectrum to determine the spectral match. Meanwhile, for spatial non uniformity experiment, irradiance mapping method was used where the reading of irradiance intensity at each coordinate across the map was measured. This study has shown that ASEL's solar simulator only managed to achieve the minimum requirement of spectral match at two wavelength bands which are 400-500nm and 500-600nm; whereas for 600-700nm range, the spectral match measured was beyond the range set. On the other hand, this study also reveals that the solar simulator tested was capable to produce percentage of spatial non-uniformity that complied to IEC 60904-9 standard. With average irradiance intensity of $981.98\ \mathrm{W}/m^2$ across the tested area of $104cm \times 80cm$, the percentage of spatial non-uniformity acquired was 8.42%.

ABSTRAK

Solar simulator adalah alat yang digunakan untuk meniru cahaya matahari dari segi spektrumnya. Beberapa jenis lampu termasuk lampu busur Xenon, LED, logam halida dan lampu halogen biasanya digunakan dalam pengstukturan simulator solar. Untuk menentukan prestasi simulator solar, tiga ciri telah ditetapkan oleh IEC 60904-9 yang meliputi padanan spektral, ketidakseragaman spasial dan kestabilan temporal. Dengan adanya simulator solar ASEL di UTeM, risalah ini membentangkan kajian yang dilakukan untuk menentukan dua parameter prestasi penting dari simulator solar iaitu padanan spektral dan ketidakseragaman spasial. Kaedah pemodelan matematik diterapkan untuk mencari spektrum sinaran cahaya sumber; kemudian ianya dibandingkan dengan spektrum AM1.5G untuk menentukan padanan spektrum. Sementara itu, untuk eksperimen spasial ketidakseragaman, kaedah pemetaan pancaran digunakan di mana bacaan intensiti penyinaran pada setiap koordinat di seluruh peta diukur. Kajian ini menunjukkan bahawa simulator solar ASEL hanya berjaya mencapai keperluan minimum padanan spektral pada dua jalur panjang gelombang iaitu 400-500nm dan 500-600nm; sedangkan untuk jarak 600-700nm, padanan spektrum yang diukur berada di luar jangkauan yang ditetapkan. Kemudian, kajian ini juga mendedahkan bahawa simulator solar yang diuji mampu menghasilkan peratusan ketidakseragaman spatial yang mematuhi standard IEC 60904-9. Dengan intensiti penyinaran purata $981.98\,W/m^2$ *di satah ujian yang berkeluasan* $104cm \times 80cm$*, peratusan ketidakseragaman ruang yang diperoleh adalah 8.42%.*

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LIST OF ABBREVIATIONS

QTH	-	Quartz Tungsten Halogen
LED	-	Light Emitting Diode
ERDA	-	Energy Research and Development Program
NASA	-	National Aeronautical and Space Administration
ASEL	-	Applied Solar Energy Laboratory
STC	-	standard test condition
SPD	-	spectral power distribution

LIST OF SYMBOLS

E_{max}	-	Maximum irradiance
E_{min}	-	Minimum irradiance
λ	-	Wavelength
$S(\lambda)$	-	Spectral irradiance
$P(\lambda)$ or $V(\lambda)$	-	Spectral photopic luminosity function
λ_i	-	Discrete wavelength
λ_p	-	Peak wavelength
$\Delta\lambda$	-	Spectral half width
$f(\lambda_i, \lambda_p, \Delta\lambda)$	-	Spectral distribution function

CHAPTER 1

INTRODUCTION

1.1 Background

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 is usually been used in a research lab where one of its main purpose is to study the characteristics of the solar PV module. The performance of a PV module will be tested to ensure its capability to perform in maximum power.

With the quick growth of the solar power system for the cause of cooling and heating, solar thermal system for heating, and electrical generation; the demand for solar PV panel is believed to increase as well. To fulfil this purpose, the research and development of the solar PV panel will be needed effectively. Testing process of a PV module surely will worked-well if the Sun is being used as natural light source. However, to test the PV module outdoor under the Sun is quite impractical as the condition of the light energy emit by the Sun is vary from time to time due to a certain condition such as the unstable weather. Thus, with the presence of solar simulator, 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.

The development of a solar simulator consists of 3 major components which include the light source, power supply and optical filters. However, for the optical filters, it is not necessarily needed as it is only used to modify the output of the beam. Meanwhile, 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). 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. Referring to the report, the standard that being set were; the air mass AM1.5G was selected as the spectral composition, 25°C air temperature and the standard illumination intensity was 1000W/m^2. Figure 1.1 below shows the comparison of the different type of lamp with solar irradiance at AM1.5G in term of its spectral irradiance at different wavelength [Honsberg and Bowden, 2019].

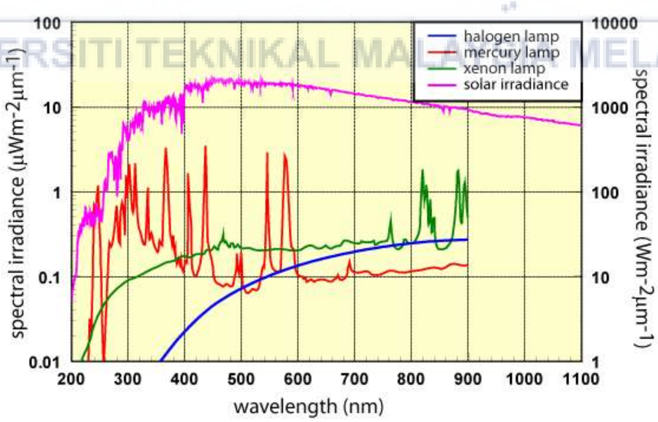


Figure 1.1: The comparison for different type of lamp with solar irradiance at AM1.5G in term of its spectral irradiance [Honsberg and Bowden, 2019]

As for this study, quartz tungsten halogen (QTH) is the one that been used as the light source for the solar simulator. Despite of the facts that it is quite far in term of spectral differences compare to other lamps, halogen lamp is widely been used due to its affordability and output which is acceptable to match the Sun. As an addition, LED is another type of lamp which is more promising compare to the halogen lamp where it can provide a stable light output over time and controllable output spectrum. However, there's other things that people always need to consider when using LED which is its quiet expensive compare to the others.

On the other hand, there are three international compliance standards that define solar simulator performance which are IEC 60904-9, JIS C 8904-9 and ASTM E 927-10. For each standard, there are three characteristics to be tested for classification of indoor solar simulator which includes spectral mismatch, irradiance non-uniformity and temporal instability. In general, the solar simulator will be classed as A, B, and C to define its performance for all the three characteristics. Table 1.1 below shows the classification of solar simulator based on its criteria as referred to IEC 60904-9 (2007) and ASTM E 927-10 (2010) standard.

Table 1.1: Classification of solar simulator as referred to IEC 60904-9 (2007) and ASTM E 927-10

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%

1.2 Problem Statement

In UTeM, there is one solar simulator that had been developed at the Applied Solar Energy Laboratory (ASEL) and it is used for the testing of solar photovoltaic (PV) module and solar thermal collector. ASEL's solar simulator which used quartz tungsten halogen (QTH) lamp as its light source was built with an adjustable racking system where the height of the light source from the PV module can be adjusted. However, the reliability of ASEL's solar simulator can't be proven yet as there's no concrete evidence that it had been classified in either class A, B or C set for the international standard set of 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 can't be analysed accurately. Moreover, the distribution of light and consistency of irradiance over an area has not yet been identified.

1.3 Objectives

The objectives of this project are:

1. To identify the spectral match between the light source spectrum and the standard spectrum AM1.5G as referred to IEC 60904-9.

2. To evaluate the distribution and consistency of irradiance over a test area in term of spatial non-uniformity according to IEC 60904-9.

1.4 Scope of Projects

The scopes of this project are:

1. This research will use ASEL's solar simulator and this study will focus to quartz tungsten halogen (QTH) lamp as its only light source.
2. This research will only refer to the international standard for solar simulator set by the IEC 60904-9.
3. Out of three characteristics which need to be tested for classifications of indoor solar simulator, this study will only focus on two characteristics which is the spectral match and spatial non-uniformity.
4. Measurement for the temporal stability will not be conducted in this research.
5. The behaviour of light shown in this research will be conducted at specific range of wavelength that will be specified later.
6. The evaluation of the PV performance will not be explained further in this research.

CHAPTER 2

LITERATURE REVIEW

2.1 I-V Curve

The main purpose of a solar simulator is being invented is to study the performance of a PV module or cell. In order to build a reliable solar simulator, it is important to know the characteristic of PV module as there is various factors which influenced its performance; this includes the temperature and irradiance simulate by the solar simulator. The characterization of a PV cell/module can be presented through the correlation of current vs voltages which also known as the I-V curve [Hamadani and Dougherty, 2015]. Measurement of the I-V curve is considered as one of the important properties of a PV system as it provides important evaluation parameters of PV modules such as the short circuit current, I_{SC}, the open circuit voltage, V_{OC}, the current and voltage at maximum power point, I_{mpp} and V_{mpp}, and the fill factor, FF [Khatib, Elmenreich and Mohamed, 2017]. Each of this parameter can be obtained through a practical simulation under the solar simulator. All the given parameters were as stated in the example of I-V curve as shown in Figure 2.1 below, except for the fill factor, FF where it is known as the ratio of maximum power to the product of V_{OC} and I_{SC}. The IV curve characteristics is usually been measure with respect to standard test condition (STC) which is air mass 1.5 global (AM1.5G) solar spectrum with total irradiance of 1000 W/m^2, and device operating temperature of 25°C.

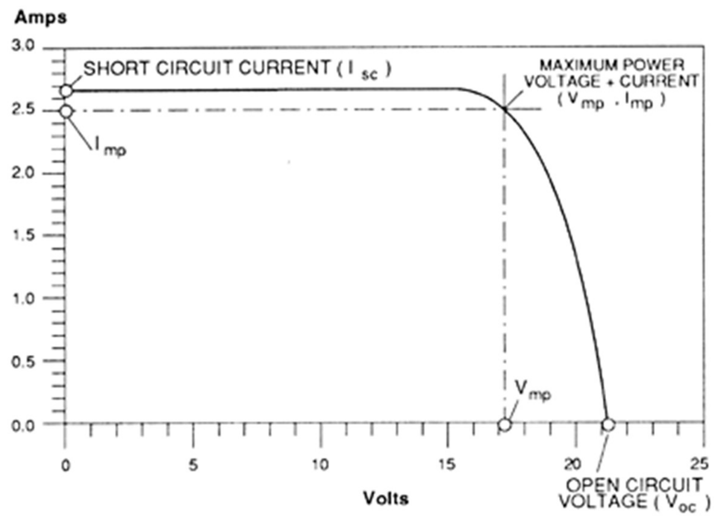


Figure 2.1: I-V Curve

The evaluation of the I-V curve of cells is usually being done in the laboratory testing with the presence of second cell, known as calibrated reference cell and it was used for the calibration process. By using this reference cell, the total irradiance of the solar simulator will be measured during the I-V testing. From the measurement obtained, the solar simulator will undergo adjustment process to ensure that the intensity of the solar simulator match with the intensity required by STC along with the testing cell which will be set to its nominal rating condition. However, the light source used by the solar simulator normally do not generate the true irradiance that will match the Sun. Here is where the calculation of spectral mismatch factor, M, will take place to correct each electrical current value from the I-V curve data.

2.2 Solar Simulator Performance

The build-up of a solar simulator usually used several types of lamps as light source; quartz tungsten halogen (QTH) lamp, light emitting diode (LED) and Xenon arc lamp were frequently used due to its intensity and spectrum composition. 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 [Hamadani and Dougherty, 2015]. On a side note, irradiance is described as radiation flux received by a surface per unit area and its unit could be written as watts per meter square (W/m^2), while the radiant flux was only defined as watts (W). However, when irradiance is subjected per unit of wavelength, it is known as spectral irradiance and the units was commonly expressed as watts per square meter per nanometre (W/m^2.nm^-1)

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's slight difference between these two spectrums, it will be classified to either class A, B or C as stated in Table 1 previously. Worst case that might happened is that the solar simulator was not classified to any of those classes, and this indicate that the solar simulator had failed the test. 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 [Pavithran *et al*, 2014]. 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 2.1.

Table 2.1: 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).

$$SM = \frac{Actual\ Percentage\ of\ Irradiance}{Required\ Percentage\ of\ Irradiance\ (AM1.5G)} \tag{2.1}$$

The solar simulator performance based on spectral match is determined from its worst case among all the 6 intervals. Then, the formula for the actual percentage of irradiance is described as follow:

$$Actual\ Percentage\ of\ Irradiance = \frac{\int_{\lambda_n}^{\lambda_{n+1}} S(\lambda)d\lambda}{\int_{400}^{1100} S(\lambda)d\lambda} \tag{2.2}$$

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. The number of tests that need to be carried out to determined spatial non-uniformity 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. In general, the formula to determine this parameter can be assessed from the following relation:

$$Spatial\ Non-uniformity\ (\%) = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \tag{2.3}$$

From equation, E_{max} and E_{min} is being referred as the maximum and minimum irradiance measured throughout the test plane. In order to conducted this test, mapping method will be used where it'll required intensity map or intensity matrix of the test plane. This map is formed by dividing the test area into a number of blocks, and different block which indicate different coordinates will be tested by using detector for the measurement of irradiance. Figure 2.2 below shows the example of intensity map that been formed on a piece of *mahjong* paper.

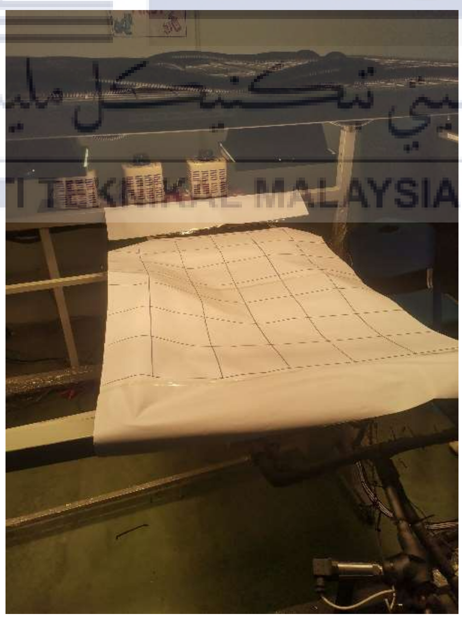


Figure 2.2: Intensity Map

2.3 Spectral Mismatch

The measurement of the spectral mismatch doesn't just concentrate at one approach only. As a matter of fact, with a complete equipment, data and information provided, the determination of spectral mismatch for solar simulator can be done by using a variety of approaches; this includes:

1. By using equipment such as spectroradiometer and reference cell
2. Mathematical modelling of the light source.

2.3.1 Mathematical Modelling of Light Source

The use of mathematical modelling of the light is another possible way to determine the spectral match of the solar simulator. 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 [Pavithran *et al.*, 2014]. 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. Luminous flux with the units of lumen usually been used to specify the light intensity. As the standard irradiance were defined with units of W/m^2; the luminous flux needs to be converted to illuminance with the unit of lux or $lumen/m^2$ before it will be converted to irradiance. The distribution of irradiance along the unit area of spectral distribution will form the spectral irradiance in $Wm^{-2}nm^{-1}$.

2.3.2 Photometric and Radiometric Principles

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 [Wang, n.d.]. 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 is usually been described with the unit of lumen (lm) where it measures the luminous flux. Table 2.2 below shows the radiometric and photometric units which is commonly used in calculation.

Table 2.2: Comparison Between the Unit of Radiometric and Photometric

	Radiometric		Photometric	
Quantity	Symbol	Units	Symbol	Units
Wavelength	λ	Nanometre (nm)	λ	Nanometre (nm)
Radiant and luminous energy	Q	Watts second, (Ws)	Q_v	Lumen seconds (lms)
Radiant and Luminous Energy Density	U	Watts seconds per m^3, (W/m^3)	U_v	Lumen seconds per m^3, (lms/m^3)

Radiant and luminous flux(power)	ϕ	Watts (W)	ϕ_v	Lumen (lm)
Irradiance and illuminance	E	Watts/cm^2, (W/cm^2) or Watts/m^2, (W/m^2)	E_v	Lux (lux; lm/m^2) or footcandle, (fc; lm/ft^2)
Radiance and luminance	L	Watts/m^2/steradian, (W/m^2/sr)	L_I	Lumens/m^2/steradians, (lm/m^2/sr)
Radiant and luminous intensity	I	Watts/steradian, (W/sr)	I_v	Candela (cd; lm/sr)

In order to perform a conversion between radiometric and photometric units, the photopic spectral luminous efficiency curve $V(\lambda)$ is the important parameter which need to be known [Derlofske and Taylor, 2000]. Photopic spectral luminosity function is a standardized function set by the Commission Internationale de I'Eclairage (CIE) which determines the reaction of the eye under the daylight or bright light conditions (photopic vision). The parameter for the photopic luminosity function $V(\lambda_i)$, along with its wavelength is tabulated in Table 2.3 below.

Table 2.3: Photopic luminosity function

Wavelength, λ(nm)	Photopic Luminosity Function, V	Wavelength, λ(nm)	Photopic Luminosity Function, V
380	0.000039	570	0.952
390	0.00012	580	0.87
400	0.000396	590	0.757
410	0.00121	600	0.631
420	0.004	610	0.503
430	0.0116	620	0.381
440	0.023	630	0.265
450	0.038	640	0.175
460	0.06	650	0.107
470	0.09098	660	0.061
480	0.13902	670	0.032
490	0.20802	680	0.017
500	0.323	690	0.00821
507	0.44431	700	0.004102
510	0.503	710	0.002091
520	0.71	720	0.001047
530	0.862	730	0.00052
540	0.954	740	0.000249
550	0.99495	750	0.00012
555	1	760	0.00006
560	0.995	770	0.00003

As an example, for this conversion of the monochromatic light with a specific single wavelength, the conversion of the luminous flux from the radiometric to photometric units can be done by directly multiply the photopic luminosity function value, $V(\lambda)$ at a specified wavelength 683 lm/W. 683 lm/W here is the value selected by the CIE that defines the peak of the photopic luminosity efficiency function which is at 555nm wavelength. However, the conversion become more complex if the light source used is not a monochromatic light, which by means a polychromatic light. For the polychromatic light with a continuous spectrum, the conversion of luminous flux from radiometric to photometric unit is specified as follows:

$$\phi_v = K_m \int_{380}^{830} \phi \, V(\lambda) d\lambda \tag{2.4}$$

Where K_m here is equal to 683lm/W, while ($V(\lambda)$ is the spectral photopic luminosity function.

On the other study that had been done by [Pavithran *et al*., 2014]., the conversion of photometric units of illuminance (lux or lm/m^2) to the radiometric unit of irradiance (W/m^2) was being carried out by using the conversion factor, CF as shown in formula below:

$$Irradiance = CF \times Illuminance \tag{2.5}$$

Where the conversion factor, CF is defined as;

$$CF = \frac{\sum_i f(\lambda_i, \lambda_p, \Delta\lambda)}{683 \times \sum_i f(\lambda_i, \lambda_p, \Delta\lambda) P(\lambda_i)} \tag{2.6}$$

$P(\lambda_i)$ here is known as the photopic luminosity function while $f(\lambda_i, \lambda_p, \Delta\lambda)$ is the spectral function distribution. The formula for spectral distribution is specified as follows:

$$f(\lambda_i, \lambda_p, \Delta\lambda) = \frac{g(\lambda_i, \lambda_p, \Delta\lambda) + 2g^5(\lambda_i, \lambda_p, \Delta\lambda)}{3} \tag{2.7}$$

Where; $$g(\lambda_i, \lambda_p, \Delta\lambda) = e^{-(\frac{\lambda_i - \lambda_p}{\Delta\lambda})^2} \tag{2.8}$$

As the irradiance value at a specific wavelength range is being calculated, the spectral irradiance of the light source can be obtained by using this formula:

$$S(\lambda) = Mean\ Irradiance \times \frac{f(\lambda_i, \lambda_p, \Delta\lambda)}{\int_{400}^{1100} f(\lambda_i, \lambda_p, \Delta\lambda) P(\lambda_i)} \tag{2.9}$$

The spectral distribution stated above represents the concentration of the quantity as a function of wavelength. It commonly named as the spectral power distribution (SPD) which describes how much power or light is being emitted at a specific wavelength; or else, it also can be described as the distribution of light across the different range of wavelength. To get better understanding, the term of SPD can be described as the concentration, intensity or energy as function of wavelength of any radiometric or photometric quantities. Figure 2.3 below shows the example of spectral distribution or SPD curve. The type of device which usually been used to evaluate this spectral power distribution is called a spectroscope.

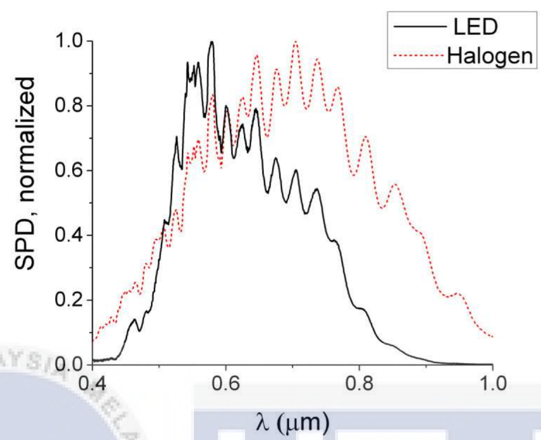


Figure 2.3: Example of spectral distribution curve

2.4 Study on Spatial Non-uniformity

The development of solar simulator which investigate about the uniformity of the irradiance intensity had been done before by some researches. Important parameter that usually been taken into account for the purpose of uniformity calculation was:

1. Type of light source used
2. Construction of intensity map
3. Surface area of intensity map
4. Height between light source and test area
5. Way to reduce the infrared radiation effect

As an example, in 1974, National Aeronautics and Space Administration (NASA) was among the earliest to produce a solar simulator by using 143 units of 300W halogen lamp.

As the purpose to increase the uniformity of irradiance, the infrared radiation effects had been reduced by using the diachronic reflector (Ragsdale and Namkoong, 1974). Meanwhile in 1985, a solar simulator with adjustable irradiance intensity from $400W/m^2$ to $1500W/m^2$ was been developed successfully by Garg *et al.* in 1985 (Garg *et al.,* 1985). This solar simulator is being completed with 14 units of Philips 1000W halogen lamps which was arranged in a hexagonal shape. In this research, the lamp is set at the height of 1.55m from the ground level and the covered area of distribution intensity that had been conducted was $120cm \times 120cm$.

On the next research conducted in 2016, a solar simulator had been developed by Samiudin *et al.* from National Metrology Institute of Malaysia for the purpose of indoor testing solar collector (Samiudin *et al.*, 2016). From the study, it shown that the solar simulator is able to produce a god percentage of non-uniformity which was within $\pm 5\%$ and $\pm 7\%$. The type of light source used is the halogen lamp; it is form from the combination of 17 units of 500W bulbs with reflector frame and the distance between centre of each light bulb was set at 30cm. On the other hand, this research also used a piece of 0.5cm lightproof acrylic to increase the uniformity of light and 3 unit of fans which functioned to minimize the infrared effects of the lamps. The acrylic piece was placed between the lamps and the test device; this was shown in Figure 2.4 below.

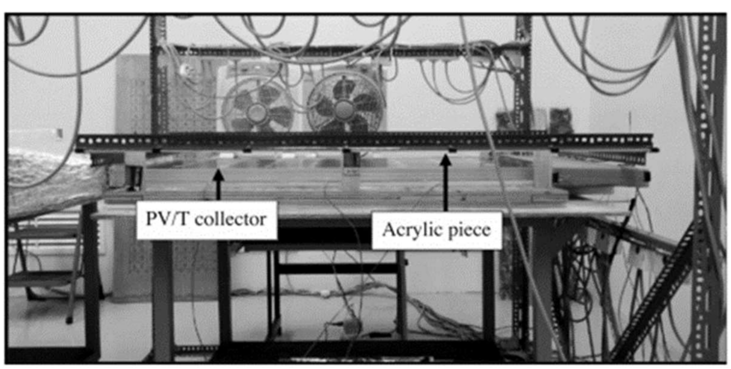


Figure 2.4: Placement of acrylic piece (Samiudin et al., 2016)

In order to get various intensity of irradiance tested in this research, the method that had been carried out was by turning on some of the lamps, while turned off the others. With this approach, this study had able to form the irradiance intensity value of 400 W/m^2, 600 W/m^2, 700 W/m^2 and 900 W/m^2. Next, this research also had used the mapping method by using intensity map to evaluate the non-uniformity of irradiance. With the surface area of 55cm x 117cm, this map is being divided into 230 sections which consists of 10 rows and 23 columns. The map used in this research was as shown in Figure 2.5 below along with the placement of device used to measure the irradiance intensity which is called a pyranometer. Pyranometer is the device used to measure the solar irradiance with the SI units of watts per meter square W/m^2. In order to take the reading of the irradiance intensity on the map, the pyranometer will be placed from one section to another until all the reading on every section was taken. To ensure the repeatability of the reading intensity that being taken, the test was repeated three times for each intensity.

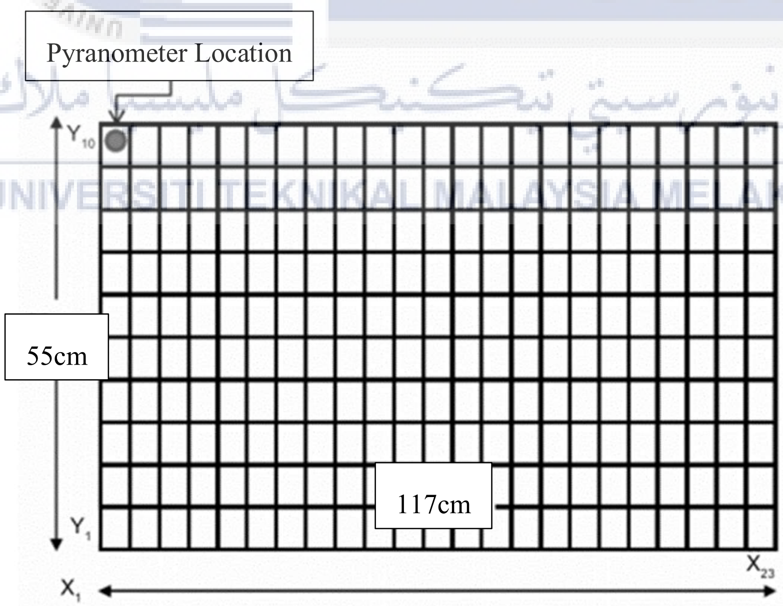


Figure 2.5: Intensity map and the placement of pyranometer (Samiudin et al., 2016)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology that was used in this project to ensure that the objectives set is achieved. The summarization for the methods used is presented in the flow chart shown in Figure 3.1. At the beginning of this research, an open literature review had been done; this is important to ensure that a thorough understanding related to this project was obtained. Next step was the general setup for ASEL's indoor solar simulator which was explained in section 3.2 below. Before the project was proceeded with any measurement, an inspection for all the devices used in this project was conducted to make sure that it'll work properly throughout the completion process. Then, the first measurement done was set to achieve one of the objectives which is to determine the spectral match of ASEL's indoor solar simulator. This was followed by performing the measurement of the spatial non-uniformity where it aimed to achieve the other objective. As both measurements were obtained, the results were used to attain main objective the experiment which was to determine the classification of ASEL's indoor solar simulator to either class A, B or C depending on its performance

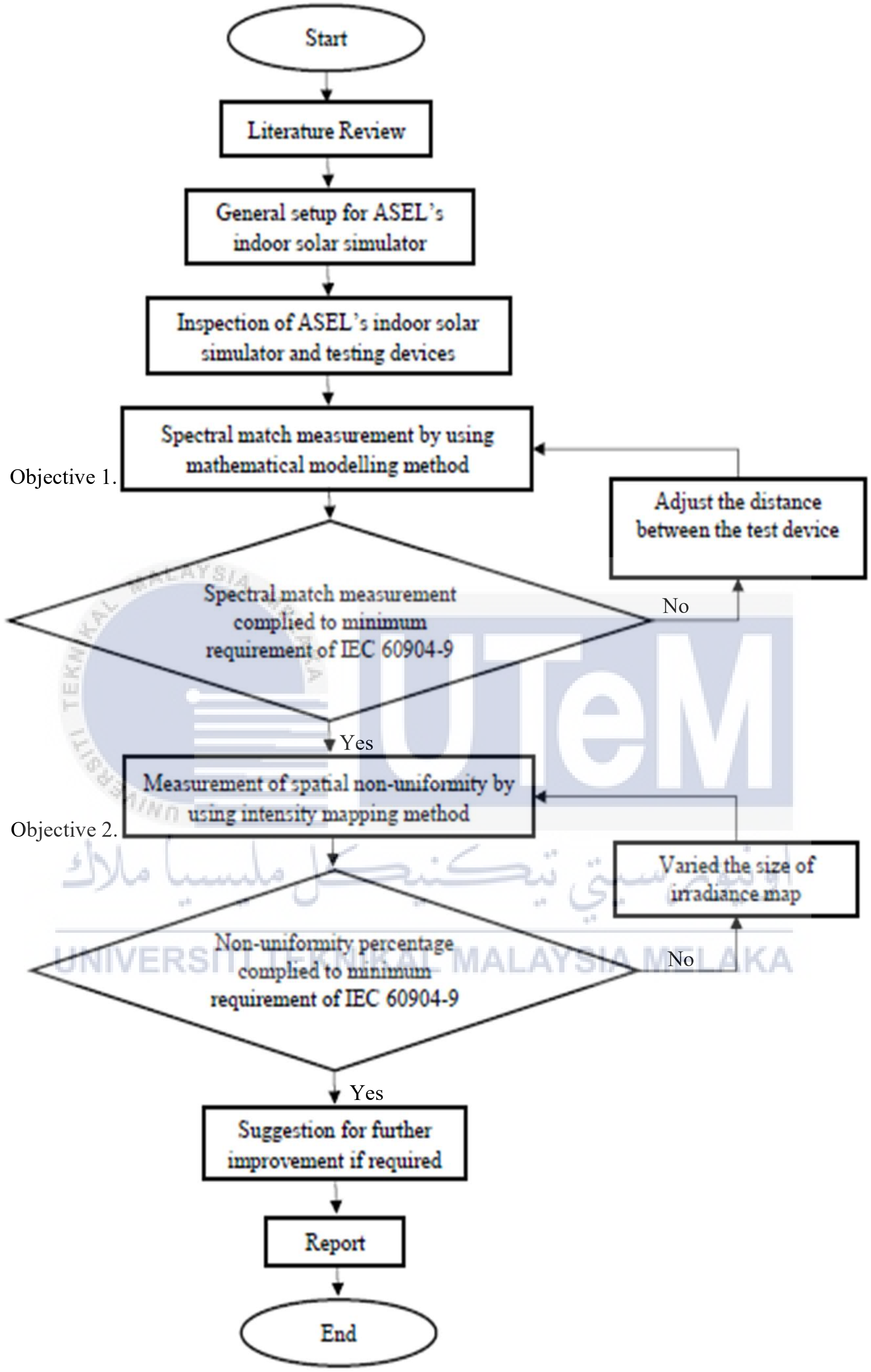


Figure 3.1: Flowchart of the methodology

3.2 General Setup for ASEL's Indoor Solar Simulator

The general experimental setup for this indoor solar simulator was as presented in Figure 3.2 below. The major components used in this setup included:

- 12 halogen lamps (light source)
- Racking and testing structure
- 3 voltage regulators
- PV solar panel

For the racking structure, it is made to be adjustable where the height of the light could be change to a workable distance. Meanwhile, the testing structure is used to place the device under test such as the PV module. Next, 3 voltage regulators set in this solar simulator is utilized to control the brightness of the lamp. Each of the voltage regulator is connected to AC power supply and used to power up 4 halogen lamps. With the adjustable brightness, the irradiance coming from the light source could be regulated as well by using the 3-voltage regulator. Figure 3.3 below shows the type of voltage regulator used in ASEL's solar simulator. On the other hand, this indoor solar simulator was also equipped with Prova 1011 solar system analyser where it is formerly used to measure the electrical parameter of the PV module. All of the components used in this experiment setup will undergo inspection to ensure that it will work properly throughout the research.

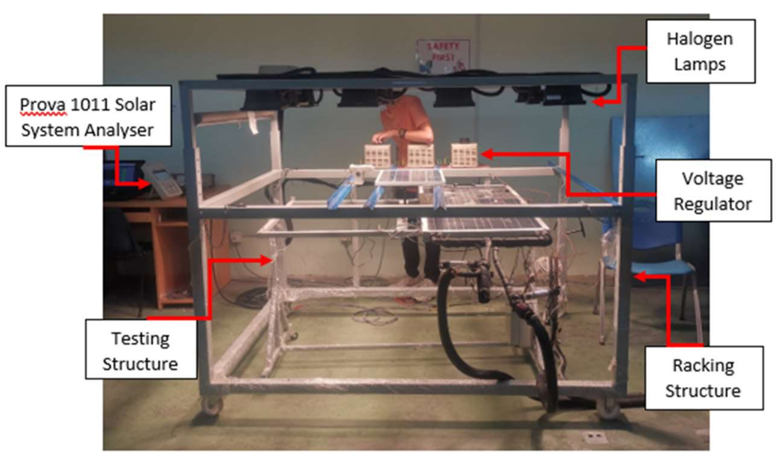


Figure 3.2: General experimental setup

Figure 3.3: Voltage regulator used in ASEL's solar simulator

3.3 Spectral Match Measurement

In order to gain better understandings on how the spectral match measurements were being done, Figure 3.4 below shows the flowchart of the spectral match measurement.

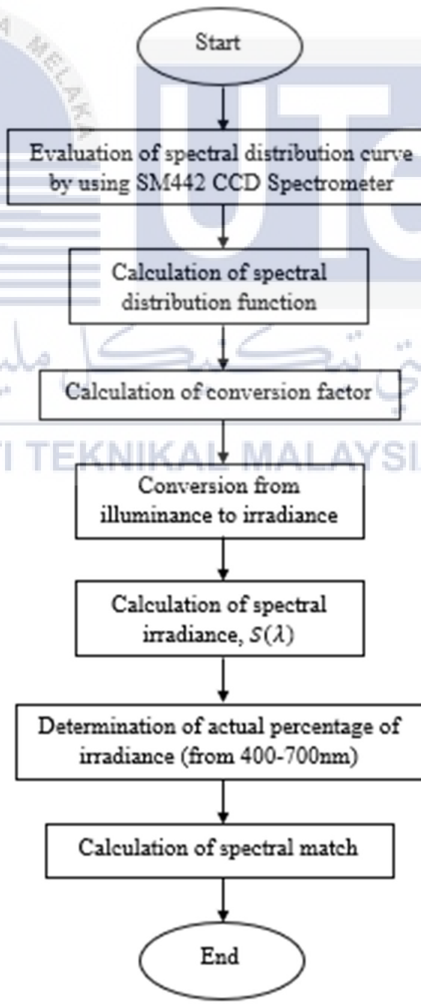


Figure 3.4: Flowchart of spectral match measurement

The approach used for the determination of spectral match is the mathematical modelling of the light source. This method will require the conversion of the light source intensity from photometric unit to radiometric. At the beginning of this experiment, the illuminance will be defined by using the lux meter which is shown in Figure 3.5 below. As this approach used had directly defined the illuminance, the conversion of luminous flux to illuminance is not necessary.

Figure 3.5: Lux meter

To ensure a proper data is gained in this research, the whole calculation stated below will be carried out at a difference illuminance. With the presence of voltage regulator, the illuminance data is taken for a number of sets by varying the amount of voltage supplied which is at 192V, 204V, 216V, 228V and 240V. The variety of data for illuminance taken will be tabulated Table 3.1. On the following method specified later, the process will only be conducted by one illuminance value which is the illuminance for 240V.

Table 3.1: Illuminance (lux)

Voltage Supplied (V)	Illuminance (lux)
192	
204	
216	
228	
240	

After the illuminance data for 240V is obtained, it was followed by the evaluation for the spectral distribution curve of the light source. Spectral distribution curve or spectral power distribution is a crucial parameter as it will be used to define the spectral distribution function, $f(\lambda_i, \lambda_p, \Delta\lambda)$. Spectral distribution curve was described as the light concentration, intensity or power emit at a unit wavelength of an illumination. In order to define this curve, a device named SM442 CCD Spectrometer will be used. The output of this device is represented in form of graph which indicates the spectral distribution, where the y-axis represents the light intensity with the unit of arbitrary units (a.u) while the x-axis represents the wavelength covered in nanometre (nm). To ensure that full intensity of light entering the spectrometer devices, this device will be placed directly below the tested halogen lamp. Figure 3.6 and Figure 3.7 showed the SM442 CCD Spectrometer used along with the placement of spectrometer directly below the halogen lamp.

Figure 3.6: SM442 CCD Spectrometer

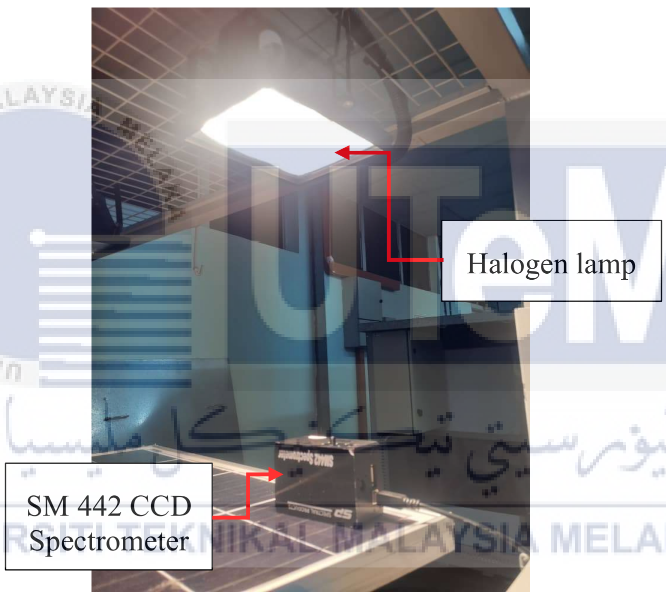


Figure 3.7: Placement of spectrometer devices directly under ASEL’s halogen lamp

The measurement of the spectral distibution curve is carried out by using the suggested software of SMProMX_5.6.0 along with the spectrometer. Figure 3.8 shows an example of the intensity graph formed in the software when the spectrometer is placed directly under ASEL’s halogen lamp.

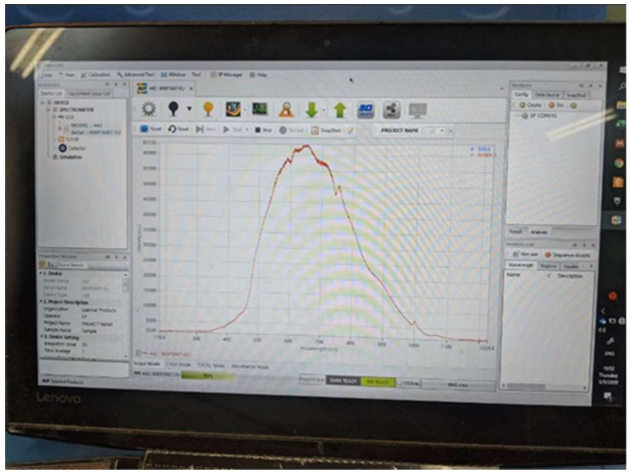


Figure 3.8: Example of intensity graph formed on SMProMX_5.6.0 software

As the spectral distribution curve is being identified, the calculation of the spectral distribution function will be performed by using the Eq. (2.7) and Eq. (2.8) shown before. The λ_p from the equation is the peak wavelength while the $\Delta\lambda$ is the spectral half width. Both of these parameters will be identified from the spectral distribution curve obtained by the spectrometer.

As this approach used the photometric to radiometric conversion to find the irradiance, it involved the value of photopic luminosity function as stated in Table 2.3 in the literature review. The difference set between the wavelength for standard the photopic luminosity function was specified at 10 nm. Thus, the spectral distribution function will be defined with the difference between consecutive wavelength, λ_i of 10 nm as well.

The identification of the spectral distribution will be followed by the calculation of the conversion factor, CF. This conversion factor is used for the conversion of the light intensity from the illuminance value to irradiance. The formula for this conversion was specified in Eq. (2.6). As the value of the conversion factor is obtained, the conversion of irradiance from the illuminance can be done by using the formula stated in Eq. (2.5). On the next following step, the determination of the spectral irradiance was done by using the formula stated in Eq. (2.9). The mean irradiance stated is the average irradiance calculated for every range of wavelength specified for the spectral match. As the research are set by using the data of photopic luminosity function, the calculation of spectral irradiance is only limited to the range of wavelength covered in this parameter which is between 380nm and 770nm. The spectral irradiance will be calculated for each spectral range and the summation of it will give the value of total spectral irradiance. This will be used for the calculation of spectral match by using the standard formula shown in Eq. (2.1) and (2.2). From here, the determination of the spectral mismatch is chosen by considering the worst case of all the spectral match obtained for every wavelength. The whole process specified above will be repeated for other illuminance value with voltage supplied of 192V, 204V, 216V and 228V.

3.4 Measurement of Spatial Non-uniformity

The method that will be used for the evaluation of spatial non-uniformity in this study is the intensity mapping method. However, the intensity map that will be constructed is not been considered by the section. In this research, the intensity map drawn will be labelled according to its coordinate across the map.

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. As the maximum illuminated area for this solar simulator is 1.87m x 1.39m, the setting for the area of the map will be set at an area that is smaller than it where the largest area for the intensity map drawn is 1.56m x 1.20m; this to ensure the illumination of the lamp cover the map area perfectly. For this study, 4 variation of intensity maps is set for the uniformity evaluation process and the difference between those maps is the size of the map which is 1.56m x 1.20m, 1.30m x 1.00m, 1.04m x 0.80m and 0.78m x 0.60m. Despite of the different in the intensity map sizing, the distance between coordinates for all maps were same which is 13cm height and

10cm long. With this set up of distance, the number of coordinates for the purpose of reading taken will be in the amount of 49 to 169 coordinates according to the size of map. To get better understandings regarding the calculation of the spatial non-uniformity using the intensity map system, Figure 3.9 below shows the example of one of the intensity maps that being placed under the ASEL's solar simulator.

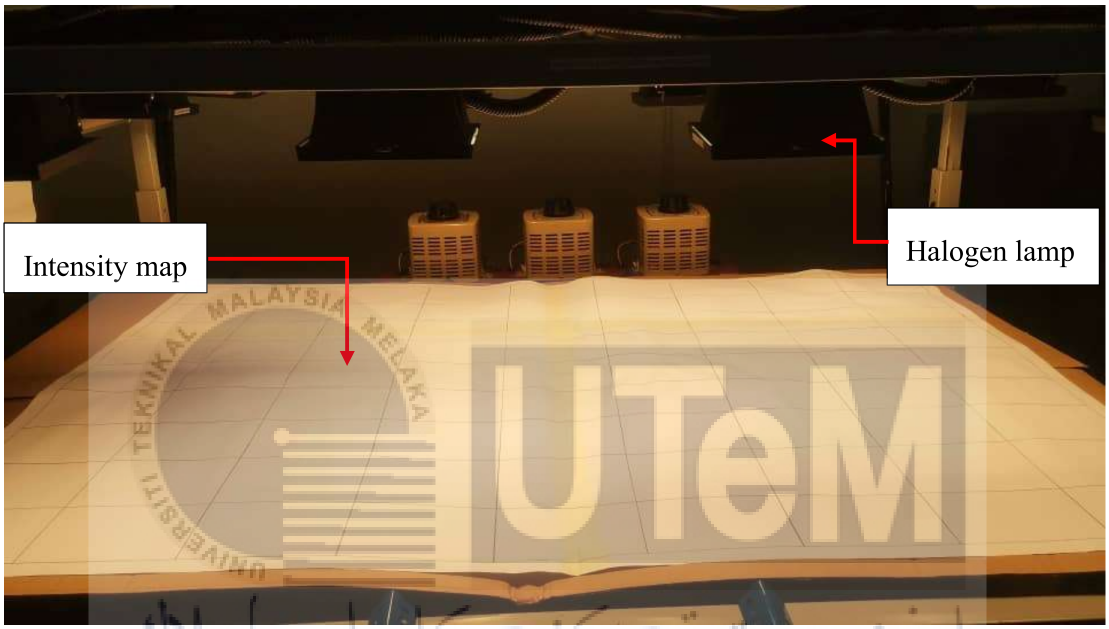


Figure 3.9: Placement of intensity map under ASEL's solar simulator

Next, the performance of ASEL's indoor solar simulator in term of its spatial uniformity will be tested at the voltage of best results obtained for the first experiment, spectral match. This to study the emission of irradiance at this voltage in term of its uniformity. In order to produce the emission of irradiance at this voltage, the voltage regulator which is part of ASEL' solar simulator will be used. All the 4 intensity maps formed which are varied in term of its sizing will be tested at the specified voltage. For the testing purpose of the irradiance measurement, a device named solar power meter will be used. This device will be placed on the top of each coordinate to ensure the reading was taken at the accurate range. Figure 3.10 below shows the placement of solar power meter at one of the coordinates on the intensity map. The solar power meter will be shifted from one coordinate to another until all coordinates were being measured.

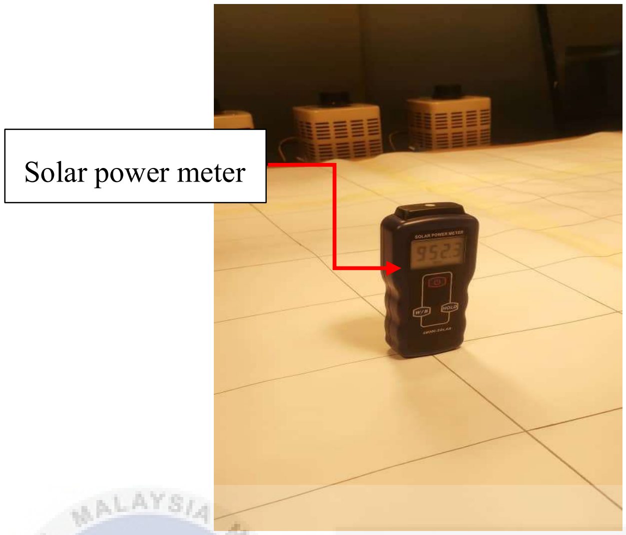


Figure 3.10: Placement of solar power meter for the measurement of irradiance

As all the reading is being taken, the percentage of spatial non-uniformity will be assessed by Eq. (2.3). For this measurement, the value of maximum and minimum irradiance for each setting will be used.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

In general, it is important for a solar simulator to have a light characteristic which complied to the international compliance standard such as the IEC 60904-9. This standard, IEC 60904-9 which stated about the solar simulator performance requirements is required as the solar simulator need to be classified to either class A, B or C for each of the three characteristics set before it could be used for any measurements or testing. The failure of the solar simulator to be classed in any of those classes will give a crucial effect to the device under test in term of its reliability where its performance cannot be measured accurately.

In this chapter, the results obtained from the experiments run in this project will be presented. Two major experiments had been completed where both of its were related to the characteristics required for the solar simulator performance as defined by the IEC 60904-9; the two experiments stated were regarding the spectral match and spatial non-uniformity. These two experiments done were affected by the light source used for the solar simulator which is the halogen lamp. Thus, all the variables used in this study such as the voltage supplied, height and size of test plane were all related to the light source and its distribution. On the other hand, the discussions made in this chapter are also based on the objectives of this study regarding the determination of the spectral mismatch and spatial non-uniformity of ASEL's indoor solar simulator along to its compliance to meet the minimum requirement of IEC-60904-9 standards which is in class C.

4.2 Spectral Match

In this section, the results of the spectral match along with the steps used to achieve the results will be presented and discussed. Spectral match as has been stated before, is a vital parameter for the solar simulator performance where it'll compare the matching of the standard spectrum known as AM1.5G and light spectrum from the solar simulator. Basically, this measurement will be conducted at a wavelength range of 400-1100nm; however, due to some limitations, the range of wavelength covered for this study is a bit differ. As been stated in the methodology, type of measurement used to find the spectral match is the photometric to radiometric conversion. One of the parameters required for this conversion is photopic luminosity function with wavelength range of 380-770nm; thus, the measurements of the spectral match will also be in this range which is 400-700nm.

4.2.1 Results of Spectral Match

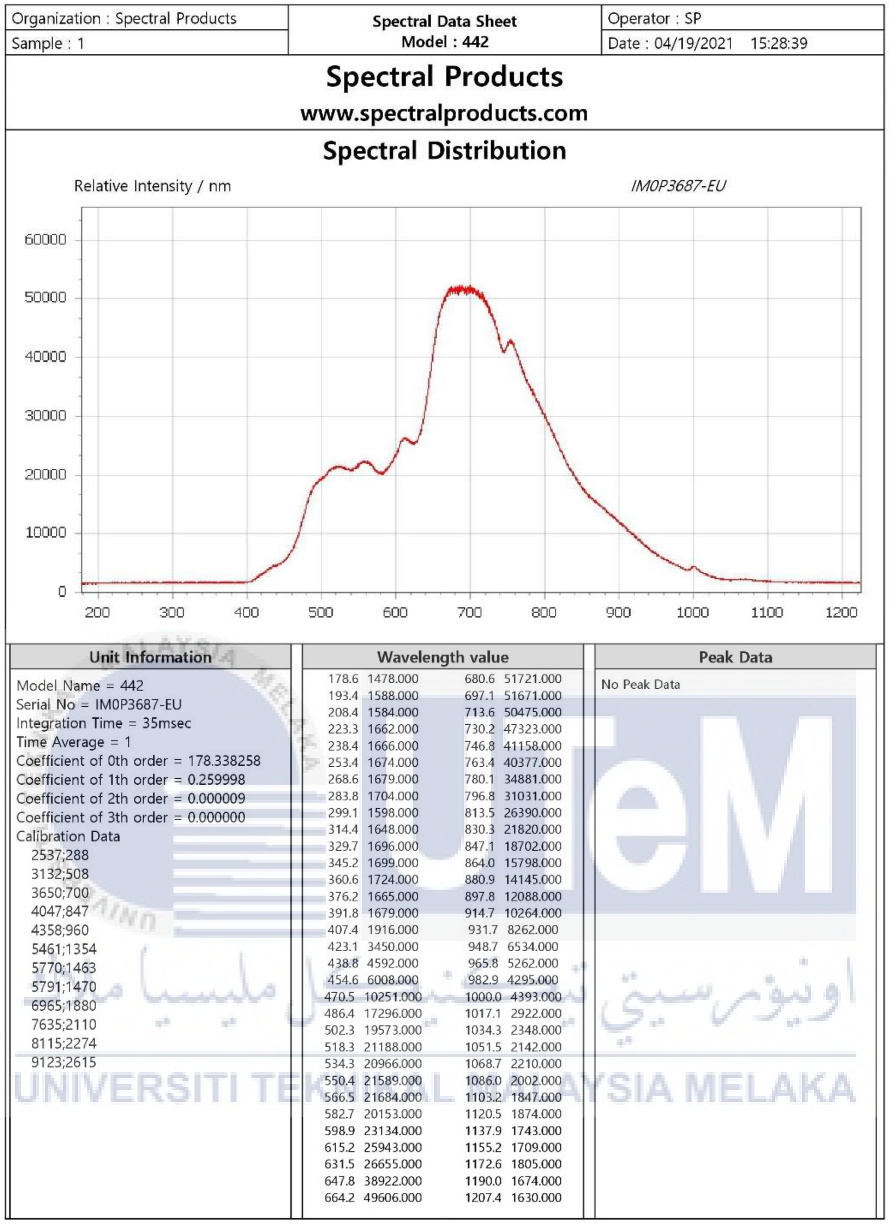
At the early step of the spectral match measurement, the data for the illuminance of the solar simulator's light source was being taken. This light intensity which brings the unit of lumens per square metre or lux was defined as the total amount of incident lights that falls on a surface area. 5 different sets of illuminance data were taken by using the lux meter; where to regulate from one data to another, voltage regulator was used as it will differentiate the amount of voltage supplied to the light source. Table 3.2 below shows the data of illuminance at 5 different voltages (192V, 204V, 216V, 228V and 240V). With the different values of illuminance taken for this study, it was expected that the conversion from illuminance to irradiance will give five different results of irradiance.

Table 3.2: Illuminance data at different voltages

No.	Voltage Supplied (V)	Illuminance (lux)
1.	192	18000
2.	204	20600
3.	216	26500
4.	228	30900
5.	240	33700

From Table 4.1 above, it is shown that the data of illuminance taken is increasing as the voltage supplied increase. The correlation of illuminance and voltage supplied can be easily explained through the factor that affect the brightness of the bulb. The brightness of a bulb is determined by the amount of power that being supplied to them. Power with the unit of watts (W) is the product of voltage and current; therefore, any increase of either voltage or current will increase the light intensity of the bulb. Illuminance with the unit of lux is the measurement of intensity in term of photometry. Thus, raising the brightness of the bulb is the same as increasing the light illuminance.

Next, the spectral distribution curve measurement or also known as the spectral power distribution was carried out at 5 different voltages supplied as stated in Table 3.2. This curve which will be used to form the spectral distribution function was measured with the help of a device named SM442 CCD Spectrometer. By using this spectrometer along with the suggested software of SMProMX_5.6.0, an intensity graph at a range of wavelength covered by the light source was being generate. Figure 4.1 shows the results of the spectral power distributions measurement presents in spectral data sheet that shows the graph of intensity vs wavelength for ASEL's halogen lamp measured at 240V.



Organization : Spectral Products	Spectral Data Sheet	Operator : SP
Sample : 1	Model : 442	Date : 04/19/2021 15:28:39

Spectral Products

www.spectralproducts.com

Spectral Distribution

Unit Information

Model Name = 442
Serial No = IM0P3687-EU
Integration Time = 35msec
Time Average = 1
Coefficient of 0th order = 178.338258
Coefficient of 1th order = 0.259998
Coefficient of 2th order = 0.000009
Coefficient of 3th order = 0.000000
Calibration Data
2537;288
3132;508
3650;700
4047;847
4358;960
5461;1354
5770;1463
5791;1470
6965;1880
7635;2110
8115;2274
9123;2615

Wavelength value

178.6	1478.000	680.6	51721.000
193.4	1588.000	697.1	51671.000
208.4	1584.000	713.6	50475.000
223.3	1662.000	730.2	47323.000
238.4	1666.000	746.8	41158.000
253.4	1674.000	763.4	40377.000
268.6	1679.000	780.1	34881.000
283.8	1704.000	796.8	31031.000
299.1	1598.000	813.5	26390.000
314.4	1648.000	830.3	21820.000
329.7	1696.000	847.1	18702.000
345.2	1699.000	864.0	15798.000
360.6	1724.000	880.9	14145.000
376.2	1665.000	897.8	12088.000
391.8	1679.000	914.7	10264.000
407.4	1916.000	931.7	8262.000
423.1	3450.000	948.7	6534.000
438.8	4592.000	965.8	5262.000
454.6	6008.000	982.9	4295.000
470.5	10251.000	1000.0	4393.000
486.4	17296.000	1017.1	2922.000
502.3	19573.000	1034.3	2348.000
518.3	21188.000	1051.5	2142.000
534.3	20966.000	1068.7	2210.000
550.4	21589.000	1086.0	2002.000
566.5	21684.000	1103.2	1847.000
582.7	20153.000	1120.5	1874.000
598.9	23134.000	1137.9	1743.000
615.2	25943.000	1155.2	1709.000
631.5	26655.000	1172.6	1805.000
647.8	38922.000	1190.0	1674.000
664.2	49606.000	1207.4	1630.000

Peak Data

No Peak Data

Figure 4.1: The graph of intensity vs wavelength for ASEL's halogen lamp measured at 240V

The unit used for the intensity is arbitrary unit (a.u) while the wavelength was measured in nanometre (nm). As the spectral measurement is conducted at the range of 400-700nm wavelength, the discussion regarding the halogen lamp intensity distribution will be explained within the visible light region which is in between 380nm and 780nm. Based on Figure 17, it is shown that the halogen lamp achieves a high intensity distribution at the wavelength range of around 700nm. Meanwhile, at low wavelength range from 400nm, the graph shows an increasing trend in term of intensity distribution until it reaches its peak value which is close to 700nm. Then, as it passes the peak wavelength range, the graph starts to decrease as it indicates the intensity distribution of the halogen lamp become lesser until it reaches the lowest value of zero at around 1100nm.

The explanation regarding the increasing and decreasing trend for the intensity distribution of a halogen lamp could be described through its light characteristics. At a visible wavelength range of 380nm-780nm, halogen lamp has a continuous spectrum which emits higher energy at a long wavelength compare to at the short wavelength (Bommel, 2020). This characteristic could be seen in the graph of Figure 4.1 as the intensity distribution is higher at long wavelength region of 650nm to 750nm compare to the lower wavelength region which is below 650nm. The wavelength interval of 650nm-750nm stated here is the red colour in the visible spectrum region; this shows that the concentration of red light in halogen lamp tested is higher compare to the other colour of yellow, green and blue which had a lower spectral distribution in the visible spectrum range. Then, as it passes through the visible spectrum range, it could be observed that the graph of intensity distribution is levelling off until it reaches zero at 1100nm. The decreasing of this intensity distribution could be understand by using the characteristic of the halogen lamp at the near-infrared wavelength where it tends to decrease as it entering this region because most of the energy is dissipated as heat in the infrared wavelength (Davidson, 1998). The spectral intensity distribution across the 5 different voltages shows the same trend where it increases at the visible spectrum region and decrease as it enters the near-infrared region; the only difference that it makes between the voltages are the peak wavelength and the level of intensity.

As the spectral distribution curve was obtained, the peak wavelength, λ_P and spectral half width, $\Delta\lambda$ data at every measured voltage was being taken from the graph. Both of these data were needed as the parameter to determine the spectral distribution function. Table 4.1 below shows the data of peak wavelength and spectral half width measured at the 5 different voltages. From the table tabulated below, it can be seen that the peak wavelength of every voltage lies at the red colour region in the visible spectrum range which is around 700nm.

Table 4.1: Peak wavelength and spectral half width at different voltages

No.	Voltage Supplied(V)	Peak Wavelength, λ_P(nm)	Spectral Half Width, $\Delta\lambda$(nm)
1.	192	701.5	186.8
2.	204	697.1	183.4
3.	216	695.7	182.3
4.	228	680.4	180.8
5.	240	680.6	196.1

Referring to the data measured above, the spectral distribution function, $f(\lambda_i, \lambda_p, \Delta\lambda)$ was calculated by using the equation (2.7 and (2.8) as stated in the methodology. λ_i in the equation is the value of discrete wavelength where it'll follow the value of discrete wavelength at the photopic luminosity function $P(\lambda_i)$ which will be specified later. The calculation for the spectral distribution function was done for the 5 different voltages at every discrete wavelength. Table 4.2 below shows the value of spectral distribution function calculated for 240V with the peak wavelength, λ_P of 680.6nm and spectral half width, $\Delta\lambda$ of 196.1nm.

Table 4.2: Spectral distribution function, f $(\lambda_i, \lambda_p, \Delta\lambda)$ for 240V

Discrete wavelength, λ_i (nm)	$g(\lambda_i, \lambda_p, \Delta\lambda)$	$f(\lambda_i, \lambda_p, \Delta\lambda)$
380	0.095392436	0.031802745
390	0.111245179	0.037093085
400	0.129059434	0.043043682
410	0.148949692	0.049698775
420	0.171013643	0.057102061
430	0.195327417	0.065298689
440	0.221940700	0.074339233
450	0.250871885	0.084286436
460	0.282103407	0.095225575
470	0.315577454	0.107279082
480	0.351192231	0.120625579
490	0.388798992	0.135522564
500	0.428199994	0.152330476
507	0.456717652	0.165487138
510	0.469147580	0.171534045
520	0.511344515	0.193754655
530	0.554445700	0.219745656
540	0.598061347	0.250361679
550	0.641761628	0.286493943
555	0.663499712	0.306892546
560	0.685082787	0.328966961
570	0.727534616	0.378398269
580	0.768609176	0.435031489
590	0.807790544	0.498562729
600	0.844565355	0.567989084
610	0.878433838	0.641512947
620	0.908921022	0.716534583
630	0.935587771	0.789756421
640	0.958041279	0.857406032
650	0.975944688	0.915563221
660	0.989025488	0.960554294
670	0.997082424	0.989358803

680	0.999990639	0.999965675
690	0.997704900	0.991619668
700	0.990260766	0.964915699
710	0.977773669	0.92172446
720	0.960435932	0.86496242
730	0.938511845	0.798245956
740	0.912330963	0.725487307
750	0.882279863	0.650495653
760	0.848792664	0.576639599
770	0.812340609	0.506610481

Observation from the table above shows that the maximum value of spectral distribution function was obtained at 680nm; this is due to the maximum intensity wavelength was recorded at 680.6nm for 240V. The increasing and decreasing value of spectral distribution function, $f(\lambda_i, \lambda_p, \Delta\lambda)$ also shows that its trend is similar to the graph in Figure 4.1, where the intensity starts to decrease after passing the peak wavelength.

On the next step of spectral match measurement; conversion factor was calculated by using equation (2.6) as stated before. This conversion factor was used for the conversion of illuminance with the units of lux to irradiance in W/m^2. The calculation of this factor will involve the value of photopic luminosity function, $P(\lambda_i)$. This standard function which has been published by the Commission Internationale de l'Éclairage (CIE) has provided a correlation between the radiometric and photometric quantity such as the luminous intensity (Goodman, 2016). From the equation stated, the summation of product between spectral distribution function, $f(\lambda_i, \lambda_P, \Delta\lambda)$ and photopic luminosity function, $P(\lambda_i)$ was required in order to form the conversion factor. Table 4.3 shows the product of spectral distribution function and photopic luminosity function at the discrete wavelength, λ_i for 240V voltage supplied.

Table 4.3: $f(\lambda_i, \lambda_P, \Delta\lambda)P(\lambda_i)$ at 240V

λ_i(nm)	$f(\lambda_i, \lambda_P, \Delta\lambda)$	$P(\lambda_i)$	$f(\lambda_i, \lambda_P, \Delta\lambda)P(\lambda_i)$
380	0.031802745	0.000039	1.24031E-06
390	0.037093085	0.000120	4.45117E-06
400	0.043043682	0.000396	1.70453E-05
410	0.049698775	0.001210	6.01355E-05
420	0.057102061	0.004000	0.000228408
430	0.065298689	0.011600	0.000757465
440	0.074339233	0.023000	0.001709802
450	0.084286436	0.038000	0.003202885
460	0.095225575	0.060000	0.005713535
470	0.107279082	0.090980	0.009760251
480	0.120625579	0.139020	0.016769368
490	0.135522564	0.208020	0.028191404
500	0.152330476	0.323000	0.049202744
507	0.165487138	0.444310	0.07352759
510	0.171534045	0.503000	0.086281624
520	0.193754655	0.710000	0.137565805
530	0.219745656	0.862000	0.189420755
540	0.250361679	0.954000	0.238845041
550	0.286493943	0.994950	0.285047149
555	0.306892546	1.000000	0.306892546
560	0.328966961	0.995000	0.327322126
570	0.378398269	0.952000	0.360235152
580	0.435031489	0.870000	0.378477396
590	0.498562729	0.757000	0.377411986
600	0.567989084	0.631000	0.358401112
610	0.641512947	0.503000	0.322681012
620	0.716534583	0.381000	0.272999676
630	0.789756421	0.265000	0.209285451
640	0.857406032	0.175000	0.150046056
650	0.915563221	0.107000	0.097965265
660	0.960554294	0.061000	0.058593812
670	0.989358803	0.032000	0.031659482
680	0.999965675	0.017000	0.016999416
690	0.991619668	0.008210	0.008141197
700	0.964915699	0.004102	0.003958084
710	0.92172446	0.002091	0.001927326
720	0.86496242	0.001047	0.000905616
730	0.798245956	0.000520	0.000415088
740	0.725487307	0.000249	0.000180646
750	0.650495653	0.000120	7.80595E-05

760	0.576639599	0.000060	3.45984E-05
770	0.506610481	0.000030	1.51983E-05

The formation of the table above will be proceeded with the calculation of conversion factor. Table 4.4 below presented the value of conversion factor obtained for 240V along with other voltage supplied.

Table 4.4: Conversion factor at different supplied voltage

No.	Voltage Supplied (V)	Conversion factor
1.	192	0.007866
2.	204	0.007656
3.	216	0.007587
4.	228	0.006514
5.	240	0.006216

As the conversion factor was determined, the conversion of illuminance (lux) to irradiance (W/m^2) was being done by using the following equation.

$$Irradiance\ (W/m^2) = Illuminance\ (lux) \times Conversion\ Factor$$

Table 4.5 below are the value of irradiance acquired after it was being converted from illuminance at the given voltage supplied.

Table 4.5: Irradiance acquired at given voltage

No.	Voltage Supplied (V)	Illuminance (lux)	Irradiance (W/m^2)
1.	192	18000	141.58
2.	204	20600	157.71
3.	216	26500	201.07
4.	228	30900	201.30
5.	240	33700	209.50

Observation from table above shows that the intensity of irradiance increases as the amount of voltage supplied to the light source increase. This correlation between voltage and irradiance of the light source is similar to the relation of voltage and illuminance where both of them will increase when the amount of power supplied to the light source increased.

The value of irradiance shows in Table 4.5 is the total irradiance acquired at the range of wavelength between 400nm to 700nm. In order to determine the spectral match, the value of irradiance supplied at a specific wavelength band need to be identified. As for this experiment, the whole wavelength range of 400nm-700nm were divided into 3 bands which are 400nm-500nm, 500nm-600nm and 600nm-700nm. The amount of irradiance supplied at those specific wavelength bands are known as the spectral irradiance and it was defined through equation (2.9). By using the data of spectral irradiance measured at every wavelength range, the calculation of spectral match measurement of the light source was defined through the equation specified in (2.1). Spectral match as specified by IEC-60904-9 is the comparison between the required percentage of irradiance which had been standardised and the actual percentage of irradiance coming from the light source. This actual percentage of irradiance was described as the ratio of spectral irradiance measured at specific wavelength bands to the total integrated irradiance (from 400nm-700nm) as stated in equation (2.2). In Table 4.6 below, the results of the ASEL's solar simulator spectral match at each wavelength band between 400nm-700nm was displayed. 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.

Table 4.6: Spectral match and class obtained for ASEL’s solar simulator

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

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. Even though the outcome gained wasn’t the best results to be concluded of for this experiment, the voltage supplied at 240V is considered as the best voltage that could be suggested for ASEL’s solar simulator as two out of three wavelength range measured were able to comply with the minimum standard requirement. The analysation regarding the spectral match results obtained and the future work that need to be done were specified in the subsection below.

4.2.2 Analysation of ASEL's Solar Simulator

Figure 4.2 below shows the graph of spectral match vs wavelength (nm) at different supplied voltage that had been plotted according to Table 13 above.

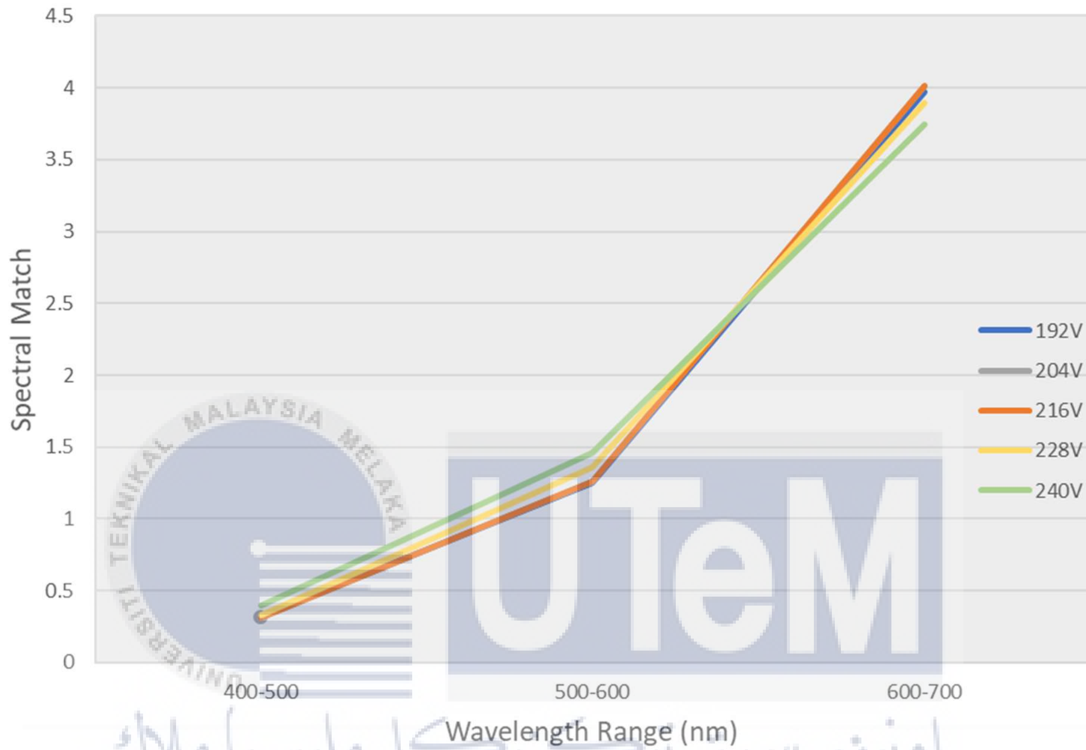


Figure 4.2: Spectral match vs wavelength range (nm) at different supplied voltage

According to the graph above, the plot of spectral match for all supplied voltage shows no big difference as the results obtained at all wavelength range are close to each other. The emission of irradiance at the range of 600nm-700nm was the dominant one as the value of spectral obtained are the highest compare to other wavelength range. However, this dominant percentage of irradiance is not good because the spectral match value obtained was beyond the C class with the value of 2; This indicate that the irradiance exposure by the ASEL's halogen lamp at this wavelength range was too high. Meanwhile, at 500nm-600nm, the value of spectral match measured for all supplied voltage was perfectly placed within the standardised range. As stated by IEC 60904-9, the classification of spectral match was 0.75-

1.25 (class A), 0.6-1.4 (class B) and 0.4-2.0 (class C). Thus, with the value of 1.25, 1.26, 1.26, 1.36 and 1.46 measured at voltage of 192V. 204V, 216V, 228V and 240V respectively; this reveals that the emission of spectral irradiance spectrum by ASEL's halogen lamp between 500nm-600nm was close to the Sun's spectrum AM1.5G. The spectral irradiance exposure at this range was considered as the most ideal compare to the other wavelength range. Next, for 400nm-500nm range, spectral match acquired at 240V supplied voltage was the only one that complied to the minimum standard. The percentage of irradiance by other supplied voltages were too low compared to the standard spectral irradiance. Considering the minimum value at class C which is 0.4; in order to comply with IEC 60904-9, the least percentage that should be gained at this wavelength range is 7.36%. Only spectral irradiance of the 240V was able to achieved this minimum percentage whereas the for the other voltage, the percentage of irradiance obtained was below 7.36%

4.2.3 Spectral Irradiance of 240V Halogen Lamp vs AM1.5G Spectrum

As been stated before, the main purpose of a solar simulator was being designed is to simulate the Sun's incident light. In order to compare the irradiance spectrum that coming from the Sun with the irradiance of a solar simulator, there are three recognised standard spectrum that can be used which are AM0, AM1.5D and AM1.5G. The standard spectrum that commonly used as a reference for specification of a solar simulator is the AM1.5G where the G is stands for global. For this spectrum, both direct and diffuse radiation were being accounted.

Figure 4.3 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.

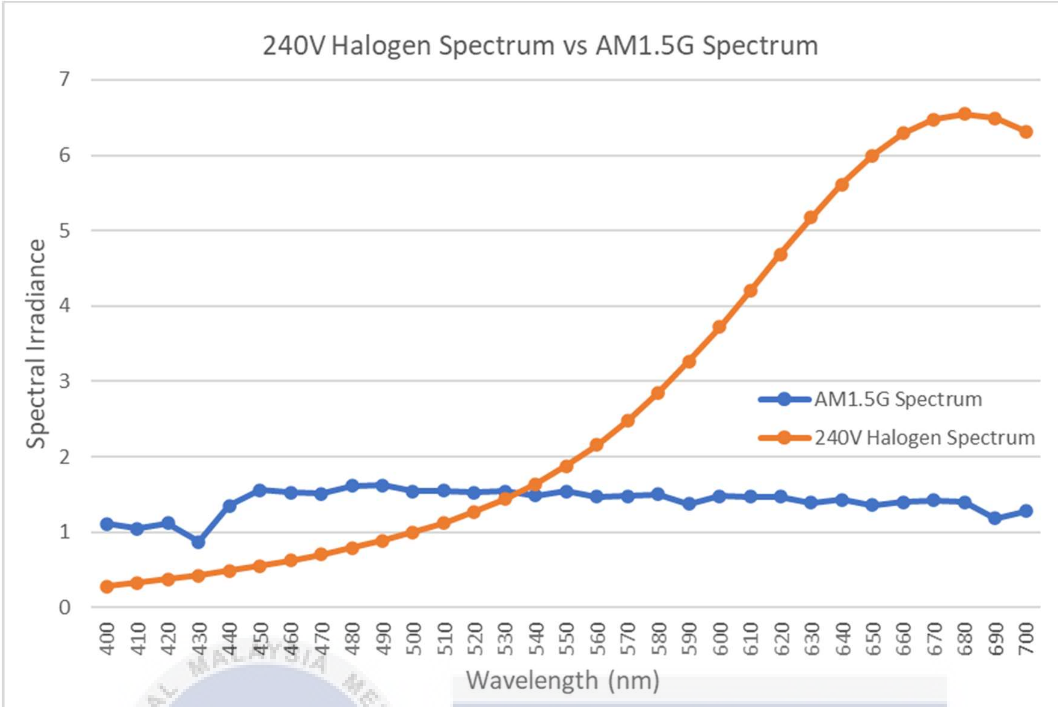


Figure 4.3: Comparison between 240V halogen spectrum and AM1.5G spectrum

The results of the spectral match obtained for ASEL's solar simulator as presented in Table 4.7 previously can be clearly understand from the comparison between 240V halogen spectrum and AM1.5G spectrum shown. Even though none of the voltages supplied are able to produce a light emission that could minimally match the standard set; 240V halogen light emission was chosen as it represents the best results obtained with 2 of its wavelength bands achieved the minimum standard with spectral match of 0.40 and 1.46 at wavelength range 400-500nm and 500-600nm respectively. According to the spectral match specification set by IEC 60904-9, it is known that the best value of spectral match could obtained is 1; this indicates that the tested light source spectrum is 100% match with AM1.5G. Meanwhile, if the amount of irradiance emitted is lower or higher than 1, the resultant spectral match value will be <1 and >1.

Relating the above graph comparison with the spectral match measurement obtained at 240V; 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.

4.3 Spatial Non-uniformity of ASEL's Solar Simulator

Spatial non-uniformity for a solar simulator was defined as the uniformity of irradiance exposure emit by the light source across the tested plane. Through this experiment, it'll specified that the illumination of irradiance at some tested areas are higher and some are just poorly illuminated. Therefore, this spatial non-uniformity experiment was done to identify the percentage of uniformity by the ASEL's solar simulator as referred to IEC 60904-9. According to this standard, a solar simulator can be classified to either class A, B or C with the spatial non-uniformity percentage of $\leq 2\%$, $\leq 5\%$ and $\leq 10\%$ respectively. Besides, the purpose of this experiment wasn't just focussing on the distribution, but it is also important to determine the maximum effective area and also to find the best sizing area for the testing purpose. The spatial non-uniformity measurement for ASEL's solar simulator had been carried at the supplied voltage of 240V. 240V was determined as it was being considered as the best supplied voltage to produce the most convincing results for the first experiment regarding the spectral match. As stated by IEC 60904-9, a solar simulator should be capable to produce an effective irradiance intensity of 1000 W/m^2 across the test plane, before it could be used for any standard test condition measurement. With respect to that, this experiment had also measured the average irradiance intensity across the intensity map.

According to the spatial non-uniformity test carried out for ASEL's solar simulator, it reveals that this solar simulator was able to produce a uniform emission of irradiance as required. The test which used the irradiance mapping method for the measurement purpose had been carried out using 4 types of intensity map which differ in term of its size. In order to ensure the reliability of the reading taken, the irradiance measurement was repeated for three times at each coordinate. Table 4.7 below show the results of spatial non-uniformity test for ASEL's solar simulator at different size of intensity map. The percentage of spatial non uniformity was derived by using equation (4.7), whereas the average irradiance intensity was calculated from equation (4.8). From the results, it can be observed that the percentage of spatial non-uniformity obtained were varied for each map.

$$Spatial\ Non-uniformity\ (\%) = \frac{\max irradiance - \min irradiance}{\max irradiance + \min irradiance} \times 100\% \quad (4.7)$$

$$Average\ irradiance\ intensity = \frac{Total\ irradiance\ intensity}{Number\ of\ coordinates} \quad (4.8)$$

Table 3.7: Spatial non-uniformity of ASEL's solar simulator at different intensity map

Size of intensity map	Number of coordinates	Average Irradiance intensity, (W/m^2)	Spatial Non-uniformity, (%)
$156cm \times 120cm$	169	990.10	10.15
$130cm \times 100cm$	121	991.41	9.02
$104cm \times 80cm$	81	981.98	8.42
$78cm \times 60cm$	49	981.93	8.49

Based on the results shown in Table 4.7, 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 $130cm \times 100cm, 104cm \times 80cm$ and $78cm \times 60cm$ 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 compare 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. The pattern of irradiance intensity across all of the 4 maps tested are shown in Figure 4.4 to Figure 4.7 below.

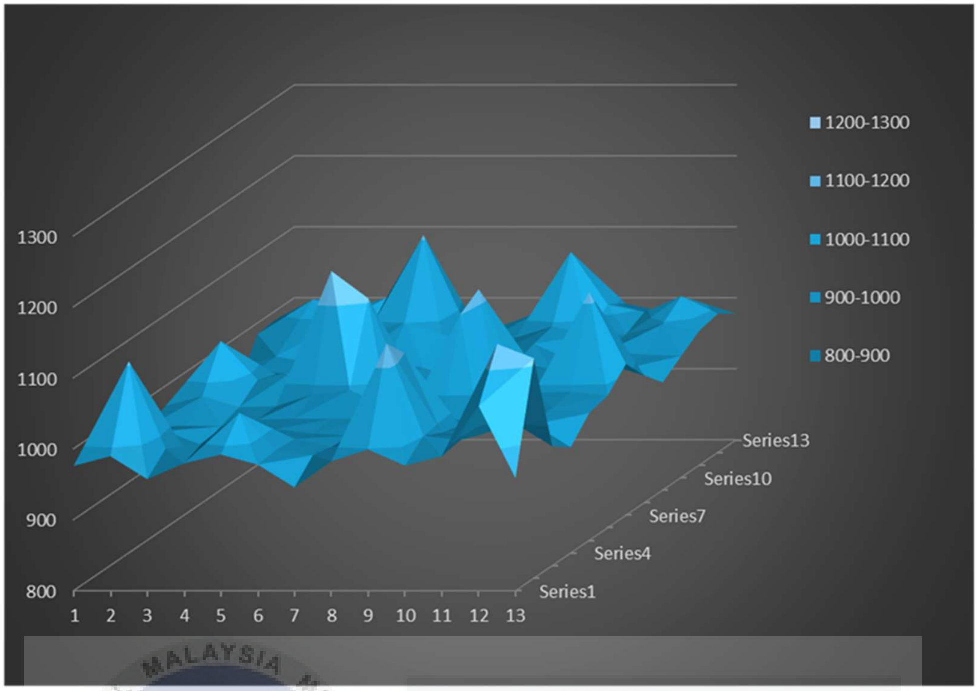


Figure 4.4: Irradiance mapping at 156cm×120cm area with spatial non-uniformity percentage of 10.15%

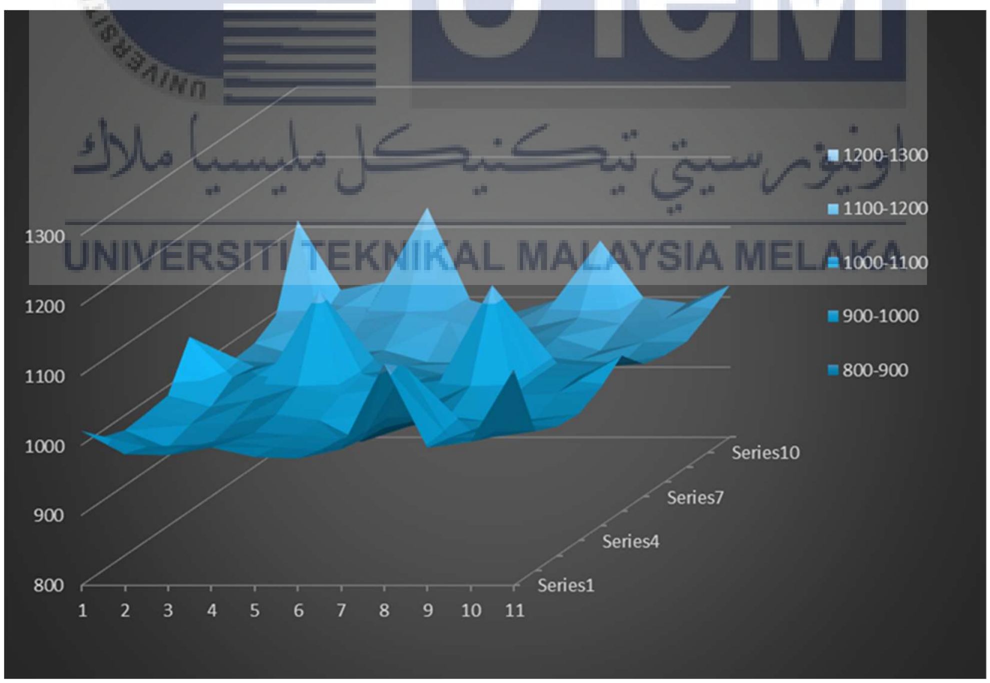


Figure 4.5: Irradiance mapping at 130cm×100cm area with spatial non-uniformity percentage of 9.02%

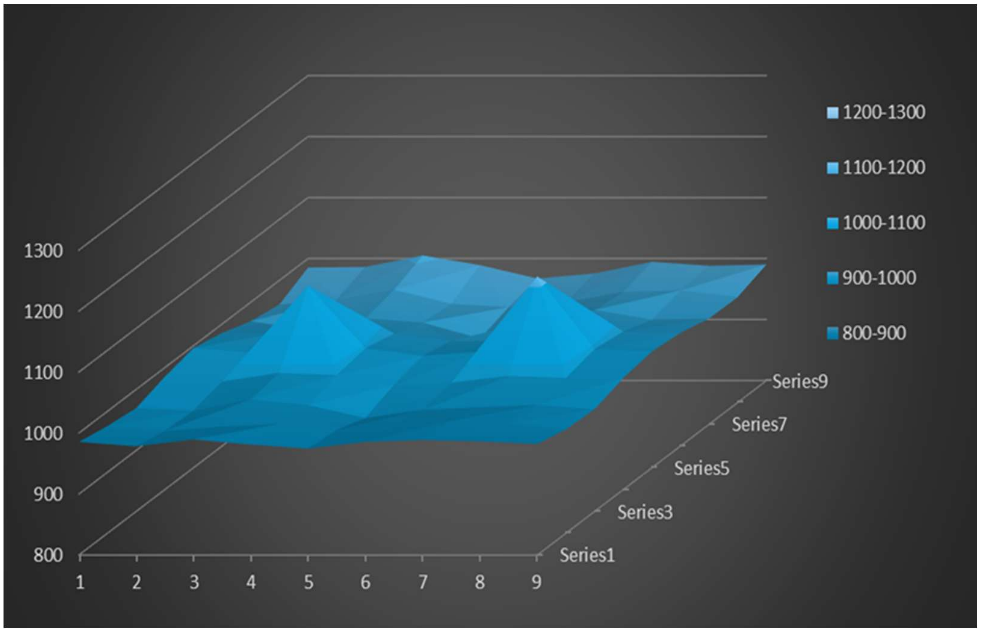


Figure 4.6: Irradiance mapping at 104cm×80cm area with spatial non-uniformity percentage of 8.42%

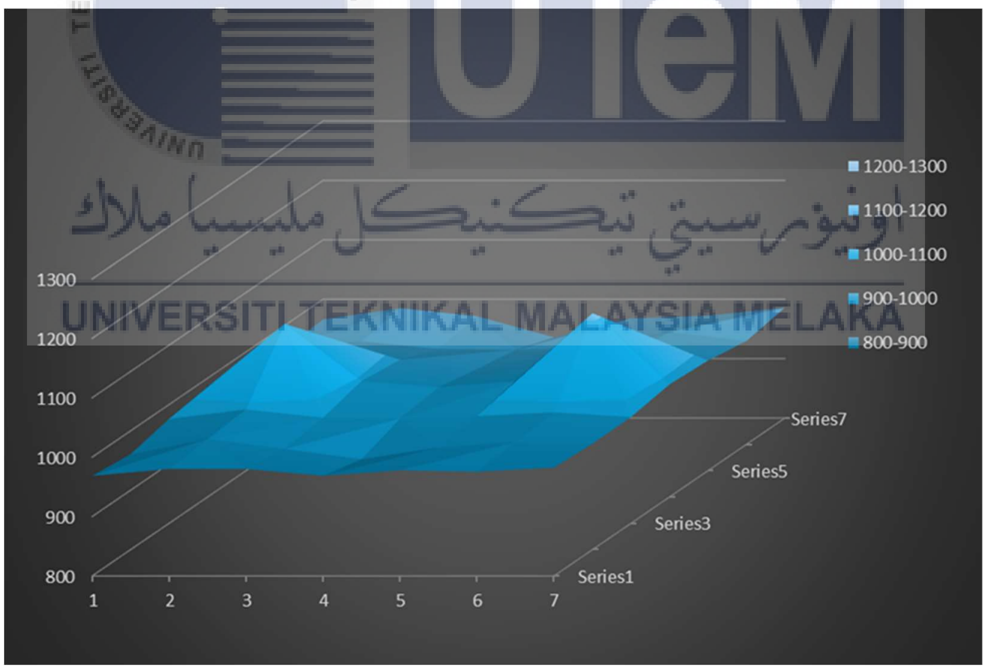


Figure 4.7: Irradiance mapping at 78cm×60cm area with spatial non-uniformity percentage of 8.49%

From the irradiance intensity mapping shown above, it can be observed that the emission of irradiance was higher at the coordination area where the halogen lamp was placed directly above it. This was shown in Figure 4.4 and Figure 4.5 where the size of both intensity maps formed (156cm x 120cm and 130cm x 100cm) was larger than the installation area of all 12 ASEL's halogen lamps. Due to this, the coordinates in the map were lies directly below the halogen lamp record the emission irradiance that was higher compare to the other coordinates. Thus, from Figure 4.4 and Figure 4.5, it can be seen there's about 12 peaks which indicates high intensity of irradiance from the halogen lamp which is directly above it. These had caused the spatial non-uniformity measured was a bit high because of the difference between the high and low irradiance emission is quite much.

Meanwhile, the non-uniformity at the mapping area of 104cm x 80cm and 78cm x 60cm is lower compare to the both map state before; this can be seen in Figures 4.6 and 4.7, where the number of locations with higher emission irradiance recorded is fairly low. Next, the comparison at smaller size tested area between these two sizes of maps also reveals that the irradiance uniformity recorded by 104cm x 80cm area was better than at 78cm x 60cm size.

As a conclusion, 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 981.98 W/m^2 and spatial non-uniformity percentage of 8.42%, the suggested tested area that should be used for any testing purpose was 104cm x 80cm.

4.4 Future Work

In this experiment, due to some inevitable constraints of time and costs, the final results obtained may not convincing enough as ASEL's solar simulator didn't manage to meet the minimum requirement set by IEC 60904-9 for the spectral match. Meanwhile, for the spatial non-uniformity case, even the experiment specified that ASEL's solar simulator was successfully achieved the minimum standard set, but there's still some work that can be done to improve the uniformity of irradiance emission.

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 applied in this experiment.

- Combination of tungsten halogen lamp with LED light
- 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. LED is a semiconductor light source with an adjustable spectrum due to its unique characteristics which could provide a narrow monochromatic output spectrum. 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 a number of LEDs at certain colours would also provide a close match spectrum as AM1.5G. As for this experiment, the mismatch of irradiance spectrum was detected low and almost out of the standard range for 400-500nm while it was too high at 600-700nm wavelength band. In the wavelength spectrum, the 400-500nm region lies in the blue part spectrum whereas the 600-700nm was in the red region. With the help of LED arrays in this experiment, it could cover the emission of irradiance that coming from the halogen lamp. As specified by (Johns, n.d.), the range of wavelength stated for blue and red LED arrays are 450-480nm and 640-700nm respectively. Thus, the solution to this matter could be provided by combining the ASEL's tungsten halogen lamp with the blue and red LED arrays. However, this combination of halogen lamp and LEDs should be followed with varying the height and position of every light source; this to prevent the high emission of irradiance at a specific range of wavelength.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this section, the conclusion of this study will be made to specify either the objective stated is achieved or not. Correspondingly, in order to improve the results obtained, a few recommendations will be discussed in this section.

Objective 1: To identify the spectral match between the light source spectrum and the standard spectrum AM1.5G as referred to IEC 60904-9.

The study of the spectral match was conducted at 3 wavelength bands of 400-500nm, 500-600nm and 600-700nm. Method used to define the spectral match is the mathematical modelling where by using the data of spectral intensity distribution and illuminance of the light source, the spectral irradiance at specified wavelength will be determined. 5 different voltages of 192V, 204V, 216V, 228V and 240Vwere used to vary the light intensity output. As stated by the IEC 60904-9, the spectral match of a solar simulator is considered at the worst case of spectral match obtained; thus, to achieve a standard solar simulator, the spectral match obtained at all measured wavelength bands have to be within the standard range set.

Based on the finding of this study, it shows that the best results were obtained at 240 supplied voltages where it managed to produce the spectral irradiance that complied to IEC 60904-9 at 2 out of 3 measured wavelengths. At 400-500nm, the spectral match obtained was 0.40 (class C); whereas at 500-600nm, the value of spectral match was 1.46 (class C).

However, ASEL's solar simulator still didn't manage to achieve the objective set as the spectral match obtained at 600-700nm region was beyond the minimum requirement set.

Objective 2: To evaluate the distribution and consistency of irradiance over a test area in term of spatial non-uniformity according to IEC 60904-9.

The spatial non-uniformity test was conducted at supply voltage of 240V. The method used for this test was irradiance mapping method where intensity maps which contained specific numbers of coordinates were formed. To evaluate the irradiance intensity distribution, the measurement of irradiance for all coordinates were taken. 4 types of maps were used in this study where each map was differed in term of its size.

Based on the finding of its study, it shows that ASEL's solar simulator had produced percentage spatial non-uniformity of 8.42%; this is in the class C of IEC 60904-9 standard. With the average irradiance intensity of $981.98W/m^2$, the best tested area that could be suggested for any measurement was $104cm \times 80cm$. As a conclusion, ASEL's solar simulator was able to produce good irradiance distribution which complied to the IEC 60904-9.

5.2 Recommendation

In order to improve the results obtained for this study, there are a few recommendations that can be considered for future reference.

For the spatial non-uniformity purpose; the uniformity of the irradiance intensity can be increased by placing an acrylic piece in between the light source and the intensity map. Besides, a unit of fan can also be placed to blow up the heat at this area. Both of the acrylic piece and fan were recommended to minimize the infrared effect coming from the lamp.

Next, a symmetric placement of mirrors which surround the testing area will also be required to increase the uniformity of the light. This to reduce the wastage of light which emitted beyond the test area. If a mirror is being placed around the testing area, the light emission that goes beyond the test plane will be reflected back by the mirror. Hence, it will increase the amount of light falls on the test plane.

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