A STUDY ON CHARACTERISTICS OF INDOOR SOLAR SIMULATOR USING HALOGEN LAMP

MUHAMMAD AIMAN DANIAL BIN HAMIZAN

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

A STUDY ON CHARACTERISTICS OF INDOOR SOLAR SIMULATOR USING HALOGEN LAMP

MUHAMMAD AIMAN DANIAL BIN HAMIZAN

A report submitted
in fulfilment of the requirements for the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

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 :...

Name : Muhammad Aiman Danial bin Hamizan

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%.*

ACKNOWLEDGEMENTS

Alhamdulillah. Praise to Allah SWT who has given me guidance and His blessings in completing this final year project.

I would like to take this opportunity to express my gratitude to every individual who have always been there to assists me in completing this report especially Dr. Mohd Afzanizam bin Mohd Rosli who always give me guidance and sacrifice his time and energy to make this research successful.

On the other hand, I wish to acknowledge to all persons who give supports, advices, and assistance that are directly or indirectly involved to the success of this final year project. Thank you so much. Special thanks to En. Zaid bin Nawam and my lab mate Fakhrul Akmar bin Fazli.

Lastly, thanks to my family members for always be with me and give their full support in everything I did especially in completing this report. Deepest thanks to my beloved parents for the unconditional love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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℃ 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].

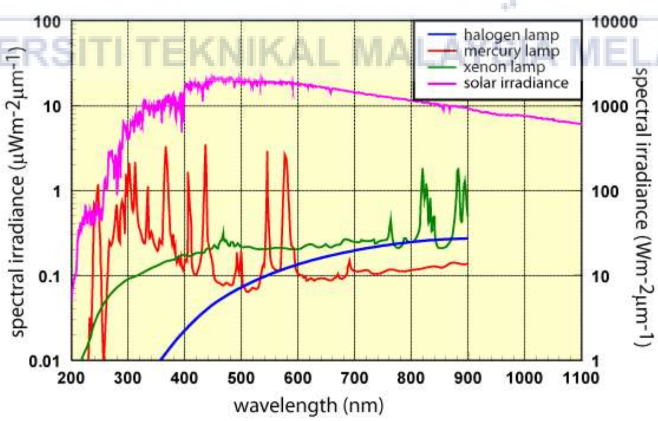

Figure 1.1: The comparison for different type of lamp with solar irradiance at AM1.5G in term of its spectral irradiance [Honsberg and Bowden, 2019]

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℃.

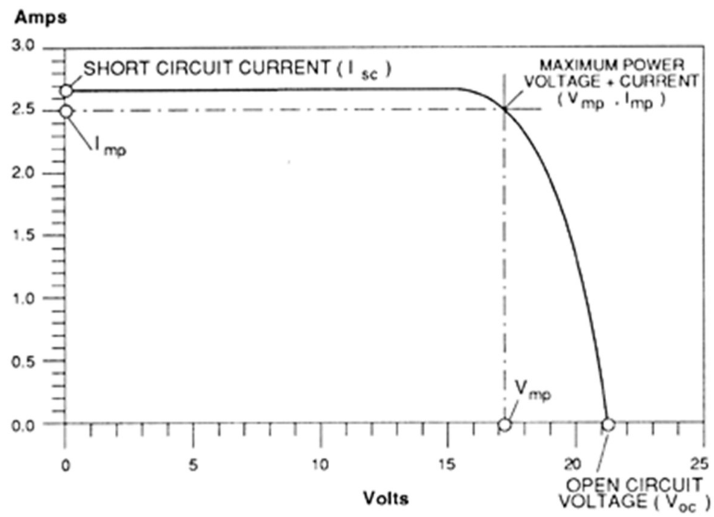

Figure 2.1: I-V Curve

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).

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

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:

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

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