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Optimization of Lamps Configuration for a Large-scale Indoor Solar Simulator for PV Panels and Solar Collectors

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ABSTRACT

The current study presents investigations of a solar simulator design, development, and performance characterization for the application of photovoltaic (PV), thermal collector, and photovoltaic/thermal (PV/T) indoor experiments. The study highlights the research outcomes of the lamp configurations and numbers in the simulator to achieve an acceptable radiation distribution in the targeted area as per the ASTM standards. Tungsten Halogen lamps were used to mimic solar radiation due to their proximity to the solar spectrum of the visible and infrared band and relatively low cost. The results indicate that a solar simulator of Class-C for spatial uniformity and Class-A for temporal uniformity can be achieved with the application of Tungsten Halogen lamps if arranged properly and a range of radiation flux can be obtained to replicate the variation of solar flux during the daytime. It was observed that three to six lamps of 1kW arranged in specific configurations can provide solar radiation varying from 378 to 969 W/m^2 mimicking the daytime solar flux variation on an experimental area of 1200 × 520 mm^2.

1. Introduction

The clean energy transition is widely adopted at different word forums promoting wind, solar and other forms of renewable energy. Apart from several environmental, social, and sustainability factors, there are some adverse impacts, and it has some winners and some losers in the process. There are sparkling impacts on the coal and similar industries affecting the lives of millions [1]. However, the gradual adaptation of clean and sustainable energy resources is gaining great attention from the research community. Solar energy harvesting through solar thermal collectors and Photovoltaic (PV) panels is gaining momentum due to the reduced cost of PVs.

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The testing of PV panels and thermal collectors in an indoor environment requires solar simulator to replicate solar light. The solar simulator is used to mimic realistic optical and thermal conditions of the sun. It is used for indoor testing of photovoltaic and thermal systems or ground testing of space applications. The main component of the solar simulator is the light source that is responsible for offering a spectral composition similar to the sunlight. Currently, several types of lamps are used in designing solar simulators, including tungsten halogen, arc (metal halide, and xenon), and light-emitting diode (LED) lamps. The choice of the light source is influenced by the solar simulator's intended characteristics and application [2]. The Tungsten halogen and arc lamps area mainly used to wider spectrum of solar radiation; whereas LED lamps are mainly used for visible lights.

A standard is known as ASTM E927-19 [3] was developed by the American Society for Testing and Materials (ASTM) to categorize solar simulators based on three factors: spectral match (R_{SM}), spatial non-uniformity (S_{NE}), and temporal instability (T_{IE}). The spectral match quantifies the similarity between the produced spectrum by the lamps and the solar spectrum. The amount at which the output power varies across the test plane is known as spatial non-uniformity, which is one of the major criteria of solar simulator design. The temporal instability measures the variation of the produced power within the tested time. As shown in Table 1, the criteria were developed to categorize solar simulators as Class A, Class B, Class C, or Class U (unclassified). The solar simulator is categorized as an AAA solar simulator if all parameters are in Class A [4].

Table 1
ASTM E927-19 Classification of Solar Simulators [3]

Classification	Spectral match	Spatial non-uniformity	Temporal instability
Class A	$0.75 \leq R_{SM} \leq 1.25$	$S_{NE} \leq 2\%$	$T_{IE} \leq 2\%$
Class B	$0.60 \leq R_{SM} \leq 1.40$	$S_{NE} \leq 5\%$	$T_{IE} \leq 5\%$
Class C	$0.40 \leq R_{SM} \leq 2.00$	$S_{NE} \leq 10\%$	$T_{IE} \leq 10\%$
Class U	$R_{SM} > 2.00$	$S_{NE} > 10\%$	$T_{IE} > 10\%$

Several researchers have investigated and proposed solar simulators based on lamp configurations and numbers. Meng *et al.,* [5] used 188 metal halide lamps with parabolic reflectors and 400 W power input to design a large-scale solar simulator. The amount of irradiance was controlled by switching off some lamps or by changing the distance between the lamps and the test plane. The highest irradiance measured was 1100 W/m^2. Regarding spectral match and spatial non-uniformity, the solar simulator's classifications were B and B, respectively. Xu *et al.,* [6] used 20, 150 W metal halide lamps to design a 130 cm × 80 cm solar simulator. The method of controlling the irradiance was changing the distance between each lamp and the distance between the lamps and the test area. It was found that the range of obtained irradiance was between 1008 W/m^2 and 1232 W/m^2 when the distance between the lamps and the test plane was 20 cm. In that situation, the calculated spatial non-uniformity and temporal instability were 9.56% (Class-C) and 1.2% (Class-B), respectively.

The tungsten halogen lamp is one of the most commonly used light sources in solar simulators. In this lamp, the electric current is passed through a tungsten filament which is surrounded by halogen gas, and the light is emitted due to the electric resistance of the filament. The emitted radiation from the halogen lamp is weaker in ultraviolet and stronger in infrared. However; Tungsten halogen lamps are widely used in solar simulators because of their low cost, and high intensity of light [7]. Grandi *et al.,* [8] proposed a solar simulator using a combination of halogen and LED lamps and achieved a Class B spectral match for a small experimental area of 12.5×12.5 cm^2. Several other authors have proposed solar simulators using different light sources in a single simulator [9–11]. However, these are mainly focused on small testing areas.

Hussain *et al.,* [12] fabricated a solar simulator to be used for indoor testing of solar collectors. The size of the target testing area was 0.636 m^2 and the simulator consists of 23 Philips 500 W halogen lamps. The achieved irradiance varied from 466 to 804 W/m^2. The intensity of radiation was controlled by turning off some of the lamps. It was stated that this strategy was adopted instead of utilizing a voltage regulator to maximize the life of the lights. The obtained spatial non-uniformity of each set of irradiances was satisfactory since it was less than 10%. Table 2 shows the characteristics of other solar simulators that were made of Tungsten halogen lamps.

Table 2
Characteristics of Tungsten Halogen lamp-based Solar Simulators

Author	Number of lambs	Lamp Power (W)	Test Plane Area (m^2)	Output Irradiance (W/m^2)
Moria *et al.,* [13]	8	500	0.4	500 - 1100
Salam *et al.,* [14]	36	50	0.55	1000
Yandri [15]	16	50	0.17	622
Agrawal *et al.,* [16]	28	500	2	600 - 800

Kim *et al.,* [2] designed a Class-C solar simulator using a combination of LED and halogen lamps to achieve a spectrum similar to the solar spectrum. Different colors (white, blue, cyan, purple) of LED lamps were used to emit the required ultraviolet and visible bands of the spectrum. The halogen lamps were used to provide light in the IR portion of the spectrum. Rosli *et al.,* [17] carried out an experimental investigation of an indoor solar simulator and evaluated spectral and spatial non-uniformity. The simulator used Tungsten Halogen lamps and the light spectrum closely matched with natural sunlight within specific wavelength ranges. For the 400-500nm range, the spectral match value was 0.40 (classified as Class C), and for the 500-600nm range, the value was 1.46 (classified as Class B) according to the international standard IEC 60904-9 [18]. The simulator demonstrated relatively uniform light distribution across the tested area with an average irradiance intensity of 981.98 W/m^2 and a spatial non-uniformity percentage of 8.42% over a tested area of 104 cm × 80 cm. The results ensure compliance with the minimum standard requirements set by IEC 60904-9.

Harun *et al.,* [19] conducted an experimental study on the flat plate absorber collector to assess its performance. The authors employed a solar simulator to imitate the solar spectrum, creating a controlled environment with a constant solar radiation intensity of 700 W/m^2. Horng *et al.,* [20] experimented to enhance the efficiency of solar panels utilizing PCM 36 as a cooling technology. They employed an indoor solar simulator (IEC 60904-9) having twelve 500 W Tungsten Halogen lamps to imitate the actual environment for the experiment.

In light of the above literature review, it can be concluded that a solar simulator based on halogen lamps can provide reasonable acceptability in terms of spectral match, spatial uniformity, and temporal stability to create large-scale solar experiments to mimic solar irradiance. The present study investigated and optimized several design parameters such as the number of lamps, arrangements of lamps, and distance between the simulator panel and the experimental plane.

2. Methodology
2.1 Design and Fabrication of Solar Simulator

The process of designing a solar simulator consists of the selection of the light source, the design and fabrication of the frame that holds the light source, and the thermos-electric control system, which is required for testing.

The light source is the heart of any solar simulator. Thus, the process of light source selection should be carried out carefully. The selection criteria of the light source in this study are color temperature, lifetime, cost, conversion efficiency, spectral match, and maintenance. The color temperature was chosen to be a selection criterion since the radiation of the lamps can be compared with the radiation of the sun based on color temperature. The color temperature of the sun was approximated to be 5777 K [7]. Several factors must be taken into account such as life cycle, cost, ease of operation, and heat produced apart from the standards discussed in Table 1 [21]. Table 3 presents a comparison among the different light sources for their maximum colour temperature, lifetime, conversion efficiency, and need for ballast and igniter.

Xenon lamps are the most suitable for colour temperature and closely match the solar spectrum; however, they suffer from high power consumption, short life cycle, high cost, and maintenance. Metal halide lamps come second to Xenon lamps for spectral match and colour temperature similar to tungsten Halogen lamps. The halogen lamps exhibit reasonable spectral match and lifetime but significantly lower cost, which makes it preferable for large-scale solar simulator applications where both infrared and visible parts of the spectrum are equally important.

Table 3
Properties of Different Light Sources and Selection Criteria

Selection Criteria	Xenon Lamps	Metal Halide Lamps	Halogen Lamps	LED
Maximum Colour Temperature	6000 K	5000 K	5000 K	3000 K
Lifetime	2000 hr.	3500 hr.	1000 hr.	20000 hr.
Conversion Efficiency	18.7 %	24.6 %	10.5 %	35 %
Need for Ballast and igniters	Yes	Yes	No	No

Further, maintenance was chosen to be a selection criterion since some types of lamps need additional components like ballast and igniters which require periodic maintenance. Based on that, criteria and considering the trade-off in the selection, the tungsten halogen lamps were selected with an input power of 1000 W.

The detailed drawing of the frame is shown in Figure 1 indicating the parts and their functions. The fabrication process of the frame was done in the engineering workshop at Sultan Qaboos University.

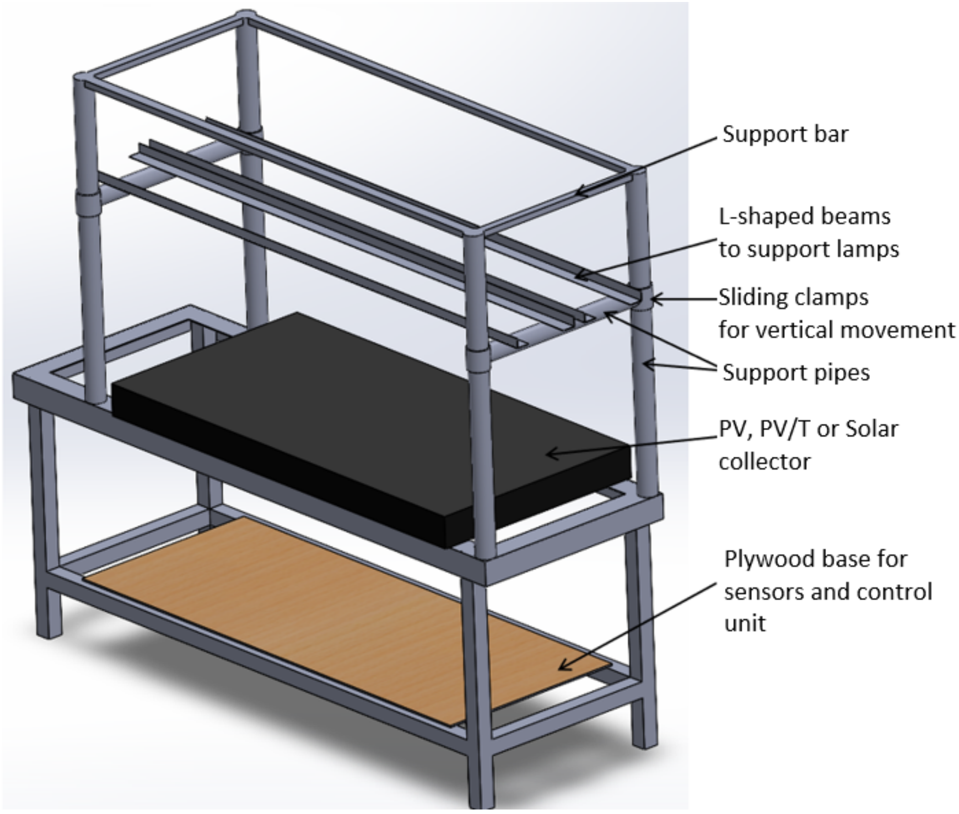

Fig. 1. Isometric View of the Solar Simulator Frame

3. Configuration Design

The aim of designing and testing the solar simulator is to select the best arrangement that achieves at most 10% special non-uniformity, 10% temporal instability, and 2% spectral match based on the ASTM standard that is specified in the ASTM Standards ASTM E927-19. The coming subsections describe the experiments that were conducted to achieve the required spatial non-uniformity and temporal instability.

3.1 Evaluation of Single Lamp Solar Simulator

This experiment aimed to evaluate and characterize the radiation distribution of a single lamp at different heights. In this experiment, the lamp was placed at four different heights from the test plane: 50, 75, 100, and 125 cm. At each height, the radiation sensor (Pyranometer) was moved in the test plane to measure the radiation along the axis of the lamp (X-axis) and perpendicular to the axis of the lamp (Y-axis). Also, 12 temperature sensors were distributed along the test plane to measure the temperature at different locations on the test plane. Figure 2 shows an illustration of the X and Y axis as well as the dimensions of the test plane and the floodlight. The results are presented in Figures 3 and 4, which show the radiation distribution of the single lamp at different heights along X and Y axes, respectively.

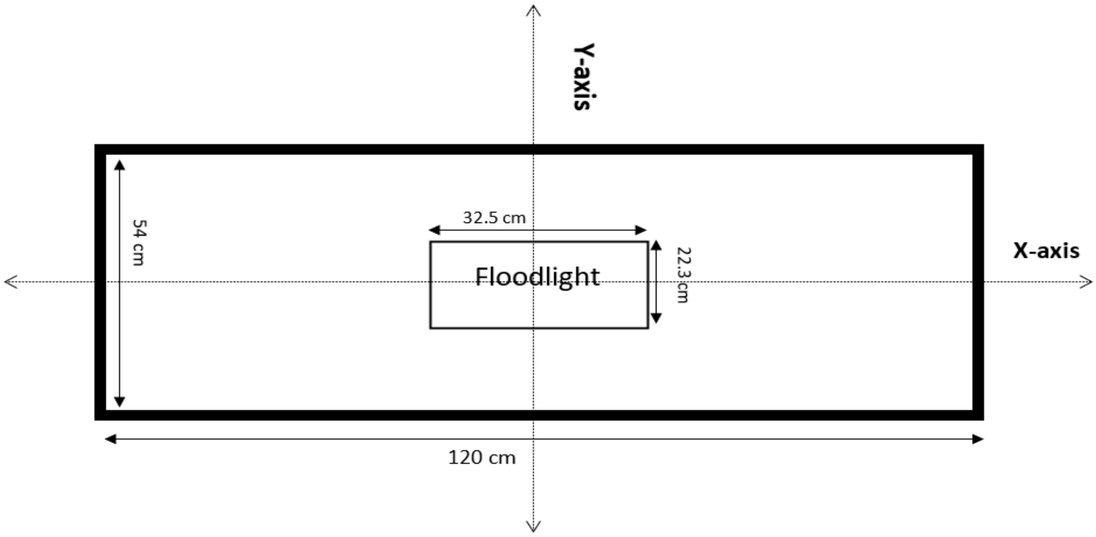

Fig. 2. Illustration of Single Lamp Radiation Test

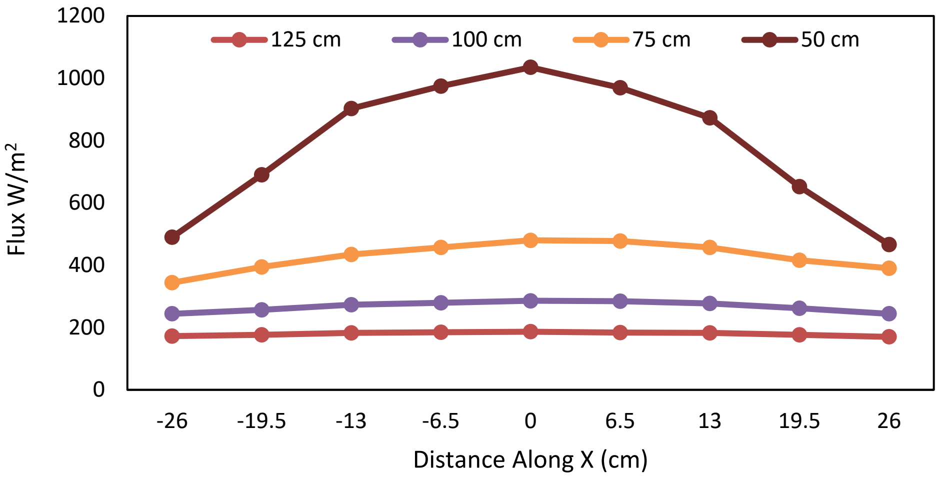

Fig. 3. Radiation Distribution of Single Lamp at Different Heights Along X-Axis

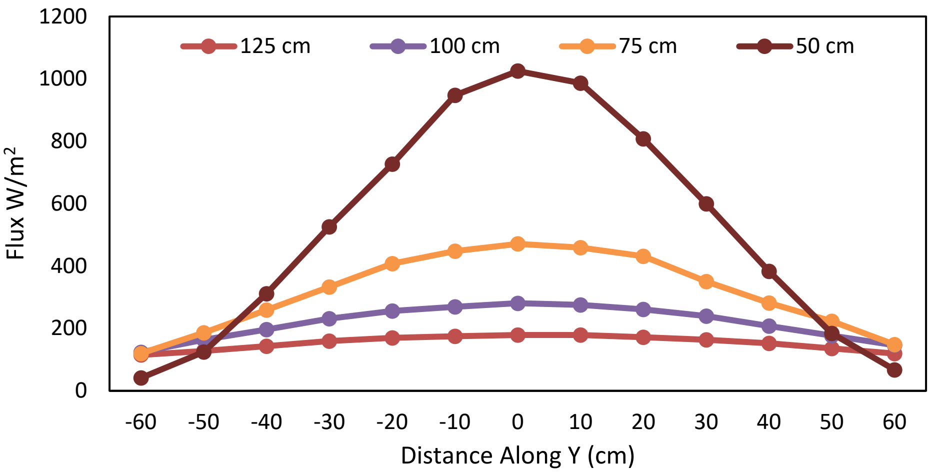

Fig. 4. Radiation Distribution of Single Lamp at Different Heights Along Y-Axis

From Figures 3 and 4, it is obvious that the radiation curve is almost flat at heights 100 and 125 cm along both X and Y axes in contrast with the radiation at heights 70 and 50 cm. However, at heights 100 and 125 cm the amount of radiation is small compared to the heights 50 and 75 cm. Moreover, at heights 50 and 70 cm the temperature measurements show that there are some regions in which the temperature exceeds 60°C.

It can be concluded from the results that at heights 100 and 125 cm, the radiation can be increased by adding more lamps without significant change in the flatness of the radiation curve. Also, the radiations at heights 50 and 75 cm are not uniform. To achieve uniformity, more lamps should be added but that is not applicable due to the expected significant increase in the temperature along the test plane. However, this can be mitigated by using lower power lamps but more in numbers.

3.2 Evaluation of Three Lamps Solar Simulator

In this experiment, the radiation of three lamps was tested at heights 100 and 125 cm. One lamp was placed at the center of the test plane (X=Y=0) and the remaining two lamps were placed at a variable distance (K) from the lamp that is located at the center as shown in Figure 5. The spatial non-uniformity (S_{NE}) was calculated for each trial by measuring the radiation at different points along the X and Y axis. Then the maximum ($I_{max,S}$) and minimum ($I_{min,S}$) values of the measured irradiance were used in Eq. (1) to calculate the spatial non-uniformity (S_{NE}). Table 4 shows the spatial non-uniformity, and the average radiation in each trial is calculated as [21].

$$S_{NE} = \frac{I_{max,S} - I_{min,S}}{I_{max,S} + I_{min,S}} \times 100\% \tag{1}$$

The measurements for I were taken at a spatial distance of 5 cm over the entire experimental area.

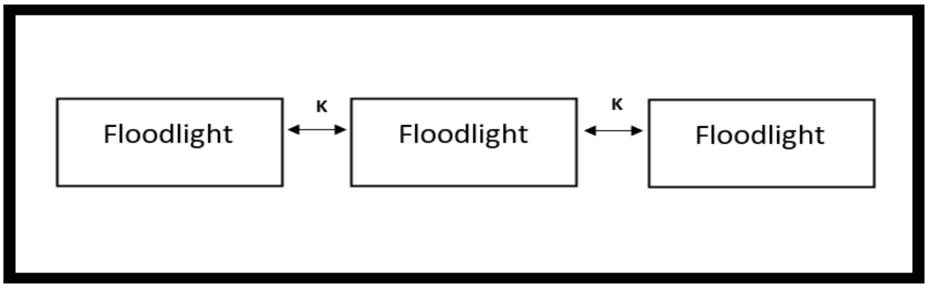

Fig. 5. The Arrangement of the Floodlights at Three Lamps Radiation Test

Table 4
Spatial Non-Uniformity and Average Radiation of Three Lamps at Different Arrangements

Trial number	Height (cm)	Description	Special Non-Uniformity	Average Radiation (W/m^2)
1	125	Three lamps, $K = 32cm$	20%	418.45
2		Three lamps, $K = 40cm$	18%	403.56
3		Three lamps, $K = 45cm$	14%	390.45
4		Three lamps, $K = 50cm$	9%	377.78
5	100	Three lamps, $K = 32cm$	26%	533.34
6		Three lamps, $K = 56cm$	17%	455.55
7		Three lamps, $K = 66\ cm$	10%	410.55

From Table 4, it can be concluded that the results are consistent. The spatial non-uniformity decreases when increasing the distance between the lamps because the radiation spread along the entire test plane rather than concentrating at the centre. Also, the average radiation decreases when increasing the distance between the lamps. This is due to the dissipation of the radiation out of the test plane. The satisfied trials are numbers 4 and 7 in which the resulting spatial non-uniformity was not exceeding 10%, and the average radiations of these two trials are 377.78 and 410.55 W/m^2, respectively. However, the standard flux requirements for solar experiments are not met, which requires an increase in the number of lamps.

3.3 Evaluation of Four Lamps Solar Simulator

In This experiment, the radiation of four lamps was tested at heights 100 and 125 cm. The aim of using four lamps is to achieve higher average radiation than the maximum resulting average radiation of using three lamps (410.55 W/m^2). The approach to achieve the best arrangement was the same as the experiment of three lamps. The selected arrangement of the floodlights is shown in Figure 6, and it was used for both heights 125 cm and 100 cm. Table 5 shows the resulting spatial non-uniformity and average radiation after placing the lamps at heights 125 cm and 100 cm above the test plane. Based on the results, the required spatial uniformity was achieved in both heights but the uniformity at height 125 cm is higher than that of height 100 cm. Further, experiments were conducted with more lamps to achieve higher incidence flux.

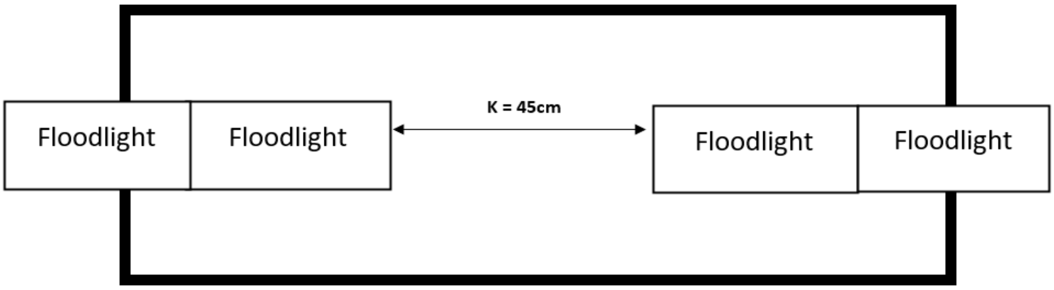

Fig. 6. The Arrangement of the Floodlights at Four Lamps Radiation Test

Table 5
Spatial Non-Uniformity and Average Radiation of Four Lamps at Different Heights

Height (cm)	Special Non-Uniformity	Average Radiation (W/m^2)
125	9%	472
100	10%	582.5

3.4 Evaluation of Five Lamps Solar Simulator

In this experiment, the radiation distribution of five lamps was tested at 125 cm height. The arrangement of the lamps is shown in Figure 7. Due to using a higher number of floodlights and to achieve more flexibility in changing the distance between them, the floodlight was rotated 90°. The best observed spatial non-uniformity and average radiation were 13% and 496 W/m^2, respectively at =10 cm. Thus, the experiment was not repeated at a height of 100 cm since the lower height results in lower uniformity as concluded from previous experiments.

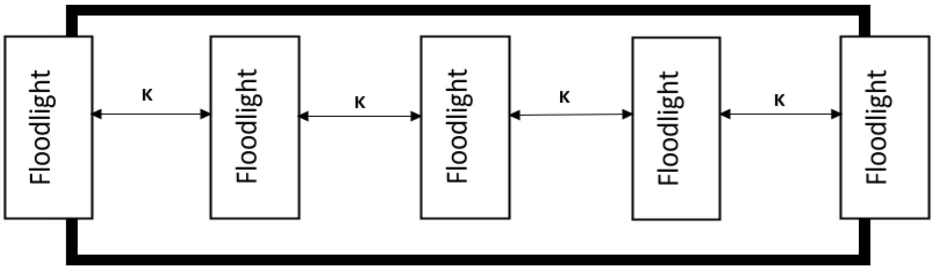

Fig. 7. The Arrangement of the Floodlights at Five Lamps Radiation Test

3.5 Evaluation of Six Lamps Solar Simulator

In this experiment, the radiation of six lamps was tested at heights 125, 100, and 75 cm. The arrangement of the lamps that are shown in Figure 8 was identical at each height. To select that arrangement, different values of *K* were tried until reaching the required results. Table 6 shows the resulting spatial non-uniformity and average radiation after placing the lamps at heights 125, 100, and 75 cm. Based on the results, the required spatial uniformity was achieved at all heights and the spatial non-uniformity is almost the same at all heights. The results are useful for designers testing new PV and PV/T modules intended to enhance electrical and thermal efficiency by conducting experiments in an indoor environment using solar simulator.

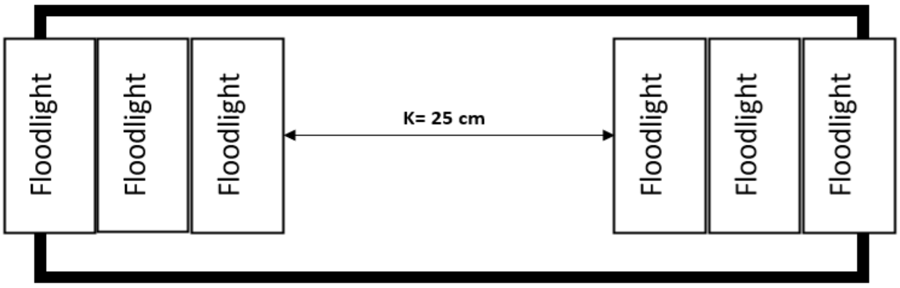

Fig. 8. The Arrangement of the Floodlights at Six Lamps Radiation Test

Table 6
Spatial Non-Uniformity and Average Radiation of Six Lamps at Different Heights

Height (cm)	Special Non-Uniformity	Average Radiation (W/m^2)
125	9%	571.2
100	9%	723.3
75	9%	969

3.6 Evaluation of Temporal Instability

The variation of emitted flux with time is critical and a measure of the temporal instability of irradiance (T_{IE}). The variation is measured over time and the degree of instability is defined the same way as that of spatial non-uniformity; however, using the maximum and minimum values over time. The temporal instability of irradiance can be expressed as:

$$T_{IE} = \frac{I_{max,T} - I_{min,T}}{I_{max,T} + I_{min,T}} \times 100\% \qquad (2)$$

$I_{max,T}$ and $I_{min,T}$ are defined as maximum and minimum values of irradiation on the intended surface during experimentation.

Temporal instability is independent of the arrangement of the lamps. Thus, measuring the temporal instability in one arrangement is sufficient.

To measure the temporal instability of the lamps, the pyranometer was fixed on the test plane at the arrangement of four lamps and it is allowed to record the measurements of the radiation for 10 minutes with a sampling time of 1 second. After that the results were saved and the maximum and minimum values were used to calculate the temporal instability. The maximum and the minimum values were 620 and 604 W/m^2, respectively. The resulting temporal instability using those values is 1.3%, which is within the acceptable limit based on Table 1 for Class-A solar collectors. Further light configuration and numbers can be optimized and trade-offs can be obtained through an AI tool such as Deep Neural Network, which is a powerful tool to optimize complex engineering problems [22].

4. Conclusions

A solar simulator was designed based on tungsten halogen lamps. To validate the solar simulator, spatial non-uniformity, and temporal instability were measured based on ASTM E927-19 standards. The spatial non-uniformity of the designed solar simulator was tested at different heights and different arrangements. Table 7 summarizes the acceptable trials in which the special uniformity was satisfied. Also, the temporal instability of the light sources was tested, and it was found to be 1.3%. Based on the ASTM E927-19 classification of the solar simulators, the designed solar simulator belongs to Class-C and Class-A for spatial non-uniformity and temporal instability, respectively.

Table 7
Summary of the Acceptable Trials for Measuring Spatial Non-Uniformity

Height (cm)	Description	Spatial Non-Uniformity	Average Radiation (W/m^2)
125	Three lamps, $K = 50cm$	9%	377.78
	Four lamps, $K = 50cm$	9%	472
	Six lamps, $K = 25cm$	9%	571.2
100	Three lamps, $K = 66\ cm$	10%	410.55
	Four lamps, $K = 50cm$	10%	582.5
	Six lamps, $K = 25cm$	9%	723.3
75	Six lamps, $K = 25cm$	9%	969

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