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Sun Simulator for Indoor Performance assessment of Solar Photovoltaic Cells

Ranga Vihari Parupudi[a], Harjit Singh[a*], Maria Kolokotroni[a]

[a] *Brunel University London, Institute of Energy Futures, College of Engineering, Design and Physical Sciences, Uxbridge, UB8 3PH, United Kingdom*

Abstract

This paper presents systematic design procedure and features of a sun simulator developed for testing low concentrating linearly focusing solar photovoltaic concentrators. The designed solar simulator comprises of a xenon short arc lamp and paraboloidal reflector for uniform radiative flux distribution on focal plane at desired radiation intensity. Initial inputs to the design process include reflector geometry (shape and size), surface properties of the reflector surface (reflectivity), distance of the reflector aperture from the illuminated area, rated lamp power, lamp geometry and orientation. These specifications were inputted in a ray tracing analyzer using COMSOL Multiphysics. The angular distribution of radiative intensity from the lamp was also accounted for. The proposed design is able to deliver a radiative intensity of 500 W/m^2 to test photovoltaic concentrators with aperture of up to 140 mm x 50 mm with a spatial non-uniformity of 4.5%.

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Keywords: Xenon short arc lamp; Paraboloidal reflector; Angular intensity distribution; Concentrator.

* Corresponding author.Tel.: +44 (0)1895 265468
E-mail address: Harjit.Singh@brunel.ac.uk

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1. Introduction

Sun simulator equipment is used to test solar energy generators, such as photovoltaic cells and panels, indoor under controlled and repeatable conditions. These use an electrically powered lamp to simulate sunlight over a focal plane providing uniformity, collimation and light spectrum matching day light. Testing solar photovoltaic (PV) cells indoor under solar simulator offers immediate results with repeatability and possibility to control testing environment. In contrast, testing solar photovoltaic cells outdoor under uncertainty of solar irradiance over time and other uncontrollable climatic and solar radiation variables makes it very difficult to understand and characterize the absolute impact of any specific interfering factor on the PV cell performance. For indoor solar simulator, basic requirements are that light spectrum should match the spectrum of day light and radiation should be uniformly distributed over the illuminated surface. Non-uniformity of radiation intensity causes hotspots to occur on PV cell plane resulting in localized high temperatures causing a drop in the cell conversion efficiency.

Table 1 details, past research studies reporting development of solar simulators for photovoltaic and thermal system testing. The simulators comprised of lamps such as xenon short arc lamps, metal halide lamps and light emitting diodes with truncated paraboloidal or ellipsoidal reflectors focusing radiation of required intensity on the focal area.

Table 1. Sun simulators reported for solar photovoltaic and thermal applications in previous studies.

Lamps used	Reflector type	Number of lamps	Rated power (kW)	Spot diameter, (mm)	Total output flux range (kW/m^2)	Sources
Xenon arc lamps	Ellipsoid	1	7	110	2-3.7	[1]
	Ellipsoid	7	6.5	600	3.2-3.3	[2]
	-	1	1.6	304; 330	0.9-1.5	[4,19]
Metal halide lamps	Ellipsoid	1	20	70	3	[5]
	Secondary conic concentrator	7	1500	380	60	[3]
	Ellipsoid	7	6	175	0.9	[6]
	Paraboloid	188	-	400 x 350	0.15-1.1	[7]
Light emitting diodes	-	12	1-2	270 x 250	0.1-1	[8]
	-	5		170	0.9	[9]
	-	-	-	50.8	0.1-1	[10]

According to ASTM E927-10 [11] and IEC 60904-9 [12], performances of solar simulator have been classified into three classes, A, B and C, see Table 2. The main criteria for this classification consist of spectral match, spatial non uniformity and temporal stability.

Table 2. Sun simulator classification criteria according to international standards [11, 12].

Parameters	ASTM E-927-10	IEC 60904-9
Spectral match		
A	0.75-1.25	0.72-1.25
B	0.6-1.4	0.6-1.4
C	0.4-2.0	0.4-2.0
Spatial non-uniformity		
A	≤3%	≤2%
B	≤5%	≤5%
C	≤10%	≤10%
Temporal stability		
A	≤2%	≤2%
B	≤5%	≤5%
C	≤10%	≤10%

This paper presents a systematic design of sun simulator developed for testing low concentrating linearly focussing solar photovoltaic concentrators. Led by extensive ray tracing analysis using COMSOL Multiphysics, a suitable lamp was selected and paraboloidal reflector designed to provide a radiation intensity of 500 W/m^2 whilst maintaining acceptable uniformity in flux distribution on the focal plane.

2. Methodology

2.1 Selection of light source and reflector

A solar simulator lamp should match the energy flux delivered and its stability on the focal plane, spatial uniformity and spectral distribution as shown in Table 2. Previous research studies and commercially available solar simulators have employed lamps such as xenon short arc lamps, metal halide lamps, and light emitting diodes [4, 10, 18]. Notably, light source selection for testing photovoltaic cells demands spectrum match with daylight for testing solar cells. Most conventional solar simulators use xenon arc lamps as light source which matches solar spectrum with high intensity output [4, 18]. However, xenon arc lamps are expensive, require forced cooling and have a short lifespan ranging from 2000 to 2500 hours. On the other hand, metal halide lamps used as cheaper and low power alternative for xenon short arc lamps have the drawback that their unfiltered spectrum does not match the solar spectrum [3]. Another alternative, light emitting diodes, though have lower costs and reduced input power requirements, suffer from a low radiative intensity output insufficient to test PV cells. In this study, a low-cost OSRAM XBO 1600W/HSCXL lamp [18] has been employed; justification for its selection and its performance is detailed in the following sections. To avoid complex simulator optics and to achieve high cost effectiveness, a reflector optical system using ALANOD MIROSIVER 4200AG [22] reflective surface was adopted. Figure 1 (a) shows the average spectral reflectance of the selected reflective surface to be approximately 98% in the visible range. Spatial intensity distribution for the XBO lamp obtained from the lamp manufacturer, OSRAM, is provided in Figure 1(b). The properties shown in Figure 1 were accounted for in the ray tracing model developed.

(a) (b)

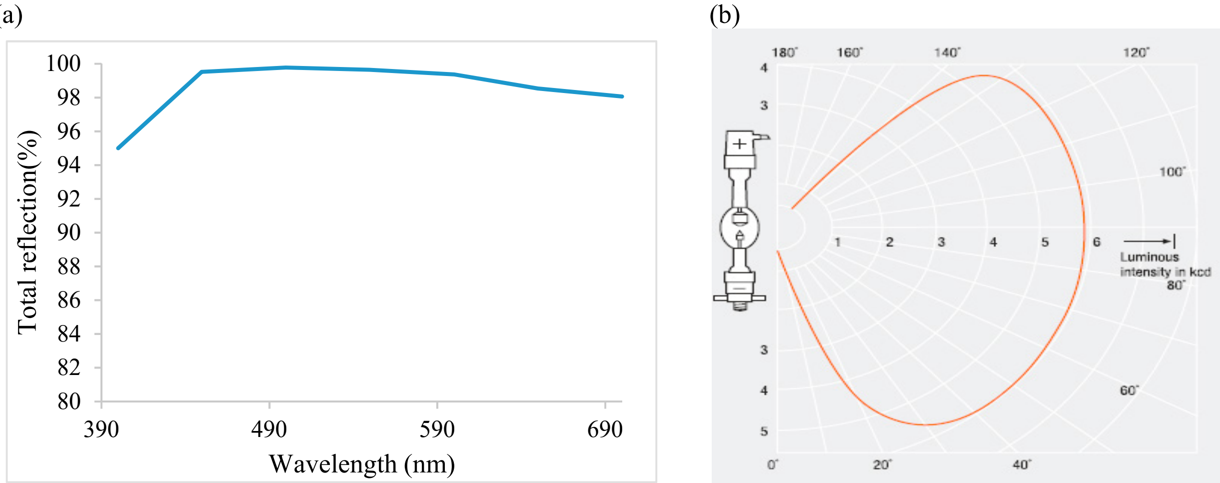


Figure 1. (a) Spectral reflectivity of MIRO SILVER reflector against visible wavelength [22]; (b) Spatial intensity distribution of XBO lamps [18]

2.2 Optical simulations

Reflector geometry in COMSOL Multiphysics has been designed using parametric curve. This selection simplified the designing process using expressions while changing different parameters involved in the design two-dimensional (2D) geometry with model builder preference. The 2D geometry was then transformed into a three-dimensional (3D) model for ray tracing simulations. Optical simulations in COMSOL Multiphysics require input geometry of reflector, material specifications and geometrical optics allowing a time dependent study. The developed ray tracing model accounted for spatial intensity distribution around the lamp, lamp power rating, its dimensions and spatial intensity distribution and spectral reflectivity of the MIRO SILVER reflector. The following realistic boundary conditions and input parameters were employed:

- Ray properties specified to a wavelength of 500 nm
- Reflector walls quantified with a reflection coefficient 0.968 with primary wall condition to specular reflection
- Wall condition for focal plane set to freeze rays
- Total source power 1600 W
- Number of rays per release specified to 100000.

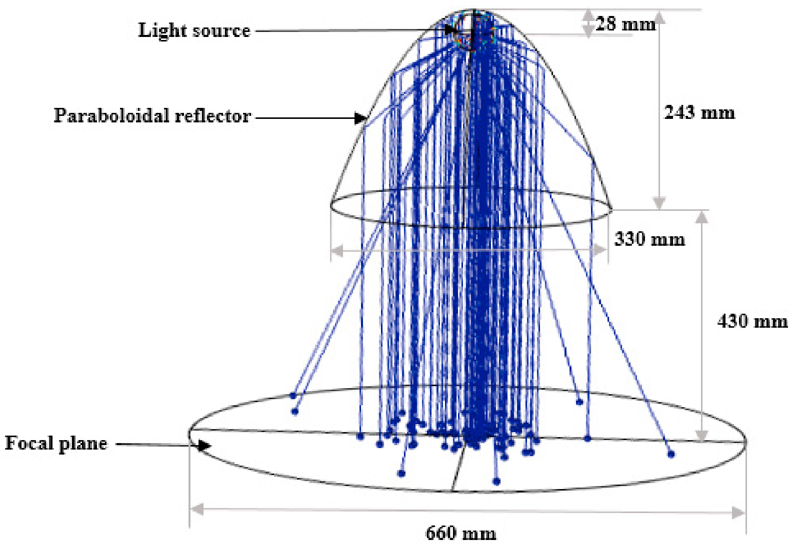


Figure 2. A 3D optical simulation in COMSOL Multiphysics with paraboloidal reflector reflecting radiation from the lamp positioned at the focus.

An example of ray optics model simulated in COMSOL Multiphysics using a paraboloidal reflector in conjunction with light source placed at the focus is shown in Figure 2. Radiation from the light source were reflected as a parallel beam along the axis of symmetry of the parabola. The distance from the aperture of paraboloid reflector and focal plane was set to 430 mm.

2.3 Governing equations

Ray optics module in COMSOL Multiphysics computes differential equations of first order for wave vector component in 3D coordinates (k), instant ray position (q) and angular frequency(ω) using equations (1) and (2) based on Snell's law and Fresnel equation [16].

$$\frac{\partial q}{\partial t} = \frac{\partial \omega(k)}{\partial k} \tag{1}$$

$$\frac{\partial k}{\partial t} = -\frac{\partial \omega(k)}{\partial q} \tag{2}$$

Spatial non uniformity refers to uniformity of illumination over focal plane. In simulations, this is particularly difficult to meet. Spatial non uniformity is calculated using equation (3) where $Imax$ is the maximum intensity on the test area and $Imin$ the minimum [15].

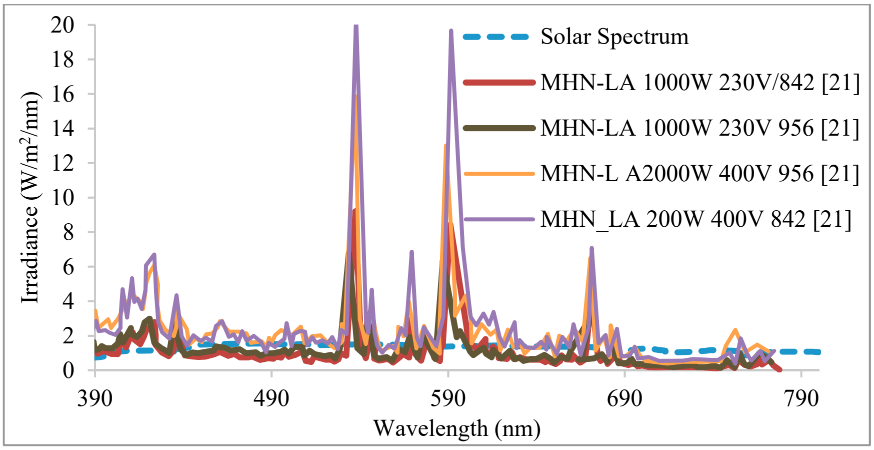
$$\text{Non-Uniformity (\%)} = \frac{Imax - Imin}{Imax + Imin} x\ 100 \qquad (3)$$

2. Results and discussion

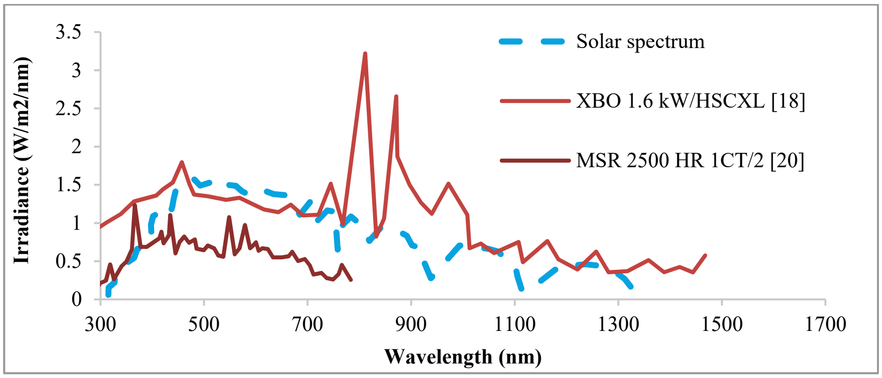
3.1 Lamp

Solar photovoltaic cells are highly sensitive to light source spectrum, hence high spectral quality is preferred. The electrical output of semiconductors varies with spectral absorption and reflectance. Several lamps with the colour temperature close to that of sun (6000 K) were investigated and their spectral power distribution compared with the reference solar spectrum AM 1.5, as shown in Figure 3. Metal halide lamps [21] emit most of the spectral power distribution over visible wavelength range and a smaller amount in infrared range. However, they produce significant peaks within the range 540 nm-600 nm which tends to mismatch solar spectrum, see Figure 3 (a). In contrast, Xenon short arc lamp [20] were found to match a broader range of solar spectrum in visible wavelength range without any significant peaks as seen in Figure 3 (b). Based on its better spectral matching, XBO 1.6 kW/HSCXL whose output spectrum closely resembled solar spectrum, was chosen. Other specifications of chosen lamp include diameter 46 mm, length 236 mm, and rated power 1600 W. A low power rating (1600 W) allows the lamp to be run on a single phase 220 V power line.

(a)



(b)



Figures 3. Spectral power distribution of (a) metal halide and (b) xenon short arc lamps investigated.

3.2 Reflector Geometry

Reflector geometry dedicates the level of uniformity in radiation intensity delivered over the focal plane. The best collimation results are achieved using paraboliodal reflector configuration, when the light source is positioned at the focus, whereas ellipsoidal reflector results in poor collimation due to its optical properties [23]. In this study, a paraboloidal reflector able to achieve uniformity of <±5% in conjunction with XBO 1.6kW/HSCXL lamp was designed and numerically tested employing ray tracing module of COMSOL Multiphysics. Lamp was assumed both ways, vertically and horizontally, held inside the reflector. The distance of the lamp from the focal plane of reflector was varied to investigate its effect on the uniformity over the target area. The reflector is assumed to be vertically above the illuminated area in a beam down arrangement, as shown in Figure 2. Table 3 lists focal lengths of the paraboloidal reflectors investigated with simulation runs identified by Vs for vertically held lamp and Hs for horizontally held lamp.

Table 3. Focal lengths of the paraboloidal reflector simulated.

Vertical orientation		Horizontal orientation	
Simulation identity	Focal length of parabola (mm)	Simulation identity	Focal length of parabola(mm)
V0	28	H0	28
V1	30	H1	30
V2	40	H2	40
V3	50	H3	50
V4	60	H4	60

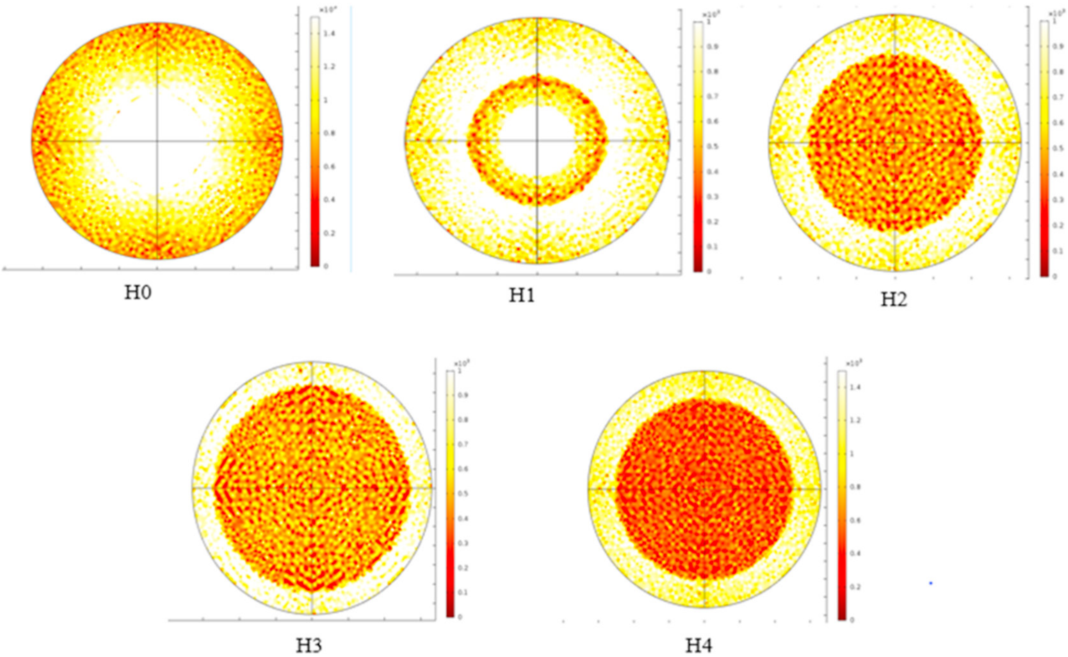


Figure 4. Flux maps of illuminated area over a focal plane of radius 330 mm while lamp is horizontally oriented.

Figure 4, presents flux maps of illuminated area over a focal plane of radius 330 mm when the lamp was horizontally held. Ray tracing simulations were performed as presented in Table 3. For focal length of 28 mm (H0 in Figure 4), high intensity was found to be narrowly focussed around the centre of target area. As the focal length was increased up to 60 mm (H1-H4 in Figure 4), the high intense region moved to boundary of target area. In order to identify region with the target uniformity of ≤±95%, the focal plane was divided into number of segments. A segment measuring 140 mm x 50 mm, the size of linearly concentrating PV system to be tested using the developed solar simulator, was identified.

Figure 5 shows the radiation intensities achieved along the length of concentrator (dimension 140 mm) for different the cases when lamp was horizontally held. Spatial non-uniformity has been calculated using Equation 3 along the length of concentrator when placed on the focal plane of the reflector. It can be seen in Figure 5, the configuration achieved a non-uniformity of 14% lowest among all the geometries simulated. Clearly, a solar simulator comprising of paraboloidal reflector in conjunction with the horizontally held lamp, adopted in this study, was unable to deliver target non-uniformity of <±5%.

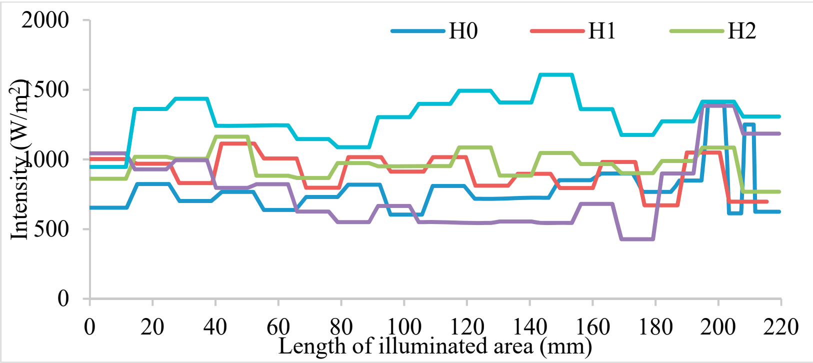


Figure 5. Intensity distribution across length of concentrator with parabolic reflector at a distance of 430 mm from the reflector.

Figure 6 shows flux maps of the illuminated area when lamp was held in vertical orientation. For the case V0 (Table 3.1), the incident flux distribution was wide-spreaded over the focal plane in a shape of doughnut with the least intensity regions (shown by the dark brown spot) limited to the central area. As the focal length was increased to 60 mm (cases from V1 to V4), the size of low intensity region increased. This affected the uniformity on the focal plane.

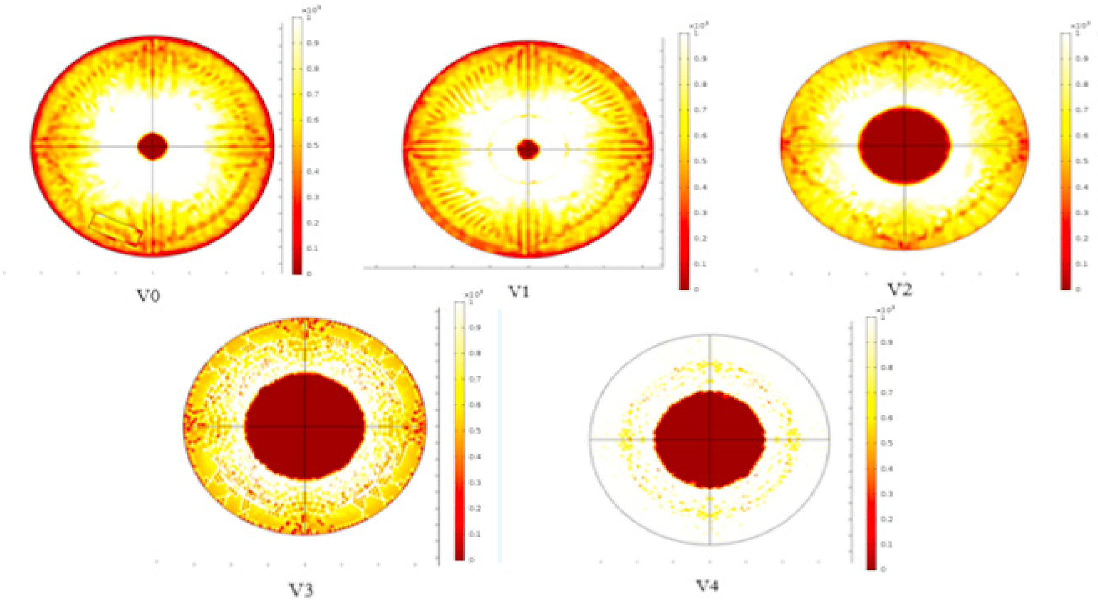


Figure 6. Flux maps of illuminated area over a focal plane of radius 330 mm predicted for the vertically oriented lamp.

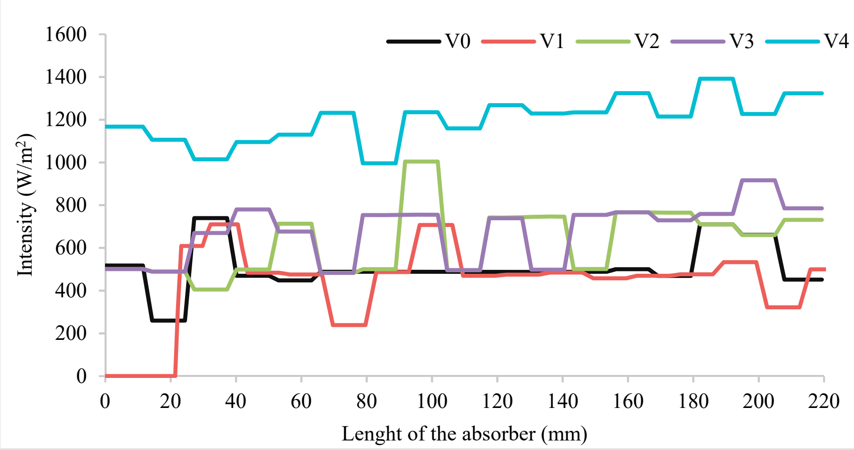


Figure 7. Intensity distribution across the length of concentrator with parabolic reflector at a distance of 430 mm from the reflector.

Figure 7 shows variation in radiation intensities along rectangular strips measuring up to 220 mm along (50mm wide) on the focal plane for the cases considering a vertically held lamp. The configuration V0 achieved non uniformity of ±4.5% along an illuminated strip measuring 140 mm x 50 mm. which was the highest uniformity of radiation intensity delivered among all geometries analysed. The exact location of this best uniformity area is shown on Figure 6 by a rectangle.

4. Conclusion

In this paper, a systematic design of sun simulator has been developed to test linearly focussing photovoltaic concentrator of with aperture measuring up to area 140 mm x 50 mm. Employing ray tracing analysis using COMSOL Multiphysics a paraboloidal reflector in conjunction with a xenon short arc lamp (XBO 1600 W/HSCXL) has been designed and its ability to illuminate focal plane with target non-uniformity of ≤±5% established. Several simulations were performed varying focal lengths of the paraboloidal reflector and changing lamp orientations (horizontal or vertical) to identify the best configuration to achieve the intended non uniformity. The best reflector design (shape and size) to be V0 with focal length 28 mm, is currently being manufactured in the laboratory of Brunel University, UK. The non-uniformity for the selected paraboidal reflector-lamp combination is predicted to be ±4.5%, superior to the target value. This irradiance uniformity on the focal plane qualify for class B classification as set by both, American and European standards.

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References

[1] Sarwar J, Georgakis G, LaChance R, Ozalp N. "Description and characterization of an adjustable flux solar simulator for solar thermal, thermochemical and photovoltaic applications." *Solar Energy* 100 (2014):179-194.
[2] Krueger, K.R., 2012. Design and characterization of a concentrating solar simulator. PhD, University of Minnesota.
[3] Codd D, Carlson A, Rees J, Slocum A. "A low cost high flux solar simulator." *Solar Energy* 84 (2010): 2202-2212.
[4] Newport. [Cited: Oct. 22, 2018]. Oriel Sol3A Class AAA Solar Simulators. Available: https://www.newport.com/f/class-aaa-solar-simulators
[5] Kuhn P, Hunt A. "A new solar simulator to study high temperature solid-state reactions with highly concentrated radiation." *Solar Energy Materials* 24 (1991):742-750.
[6] Ekman B, Brooks G, Akbar Rhamdhani M. "Development of high flux solar simulators for solar thermal research." *Solar Energy Materials And Solar Cells* 141 (2015):436-446.

[7] Meng Q, Wang Y, Zhang L. "Irradiance characteristics and optimization design of a large-scale solar simulator." *Solar Energy* 85 (2011):1758- 1767.
[8] Sabahi H, Tofigh A, Kakhki I, Bungypoor-Fard H. "Design, construction and performance test of an efficient large-scale solar simulator for investigation of solar thermal collectors." *Sustainable Energy Technologies and Assessments* 15 (2016):35-41.
[9] Namin A, Jivacate C, Chenvidhya D, Kirtikara K, Thongpron J. "Determination of solar cell electrical parameters and resistances using color and white LED-based solar simulators with high amplitude pulse input voltages." *Renewable Energy* 54 (2013):131-137.
[10] Newport [Cited: Oct. 22, 2018]. Verasol-2 LED Class AAA Solar simulator. Available: https://www.newport.com/f/class-aaa-led-solar-simulators.
[11] ASTM International [Cited: Oct. 22, 2018]. ASTM E927 – 10 Standard Specification for Solar Simulation for Photovoltaic Testing. Available: https://www.astm.org/DATABASE.CART/STD_REFERENCE/E927.html.
[12] IEC Webstore [Cited: Oct. 22, 2018]. Photovoltaic devices - Part 9: Solar simulator performance requirements. Available: https://webstore.iec.ch/publication/3880
[13] Tawfik M, Tonnellier X, Sansom C. "Light source selection for a solar simulator for thermal applications: A review." *Renewable and Sustainable Energy Reviews* 90 (2018):802-813.
[14] Esen V, Saglam S, Oral B. "Light sources of solar simulators for photovoltaic devices: A review". *Renewable and Sustainable Energy Reviews* 77 (2017):1240-1250.
[15] Kohraku S, Kurokawa K. "New methods for solar cells measurement by LED solar simulator." *In Photovoltaic Energy Conversion* (2003) Proceedings of 3rd World Conference on 2003 May 18 (Vol. 2, pp. 1977-1980). IEEE.
[16] Bazzi AM, Klein Z, Sweeney M, Kroeger KP, Shenoy PS, Krein PT. "Solid-state solar simulator." *IEEE Transactions on Industry Applications* 48(4) (2012):1195-202.
[17] Kushare M, Jhaveri A, Bhargav A. Radiation heat transfer analysis of spectrometer's Dewar Cooling Assembly. In Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2017 16th IEEE Intersociety Conference on 2017 May (pp. 793-799).
[18] OSRAM [Cited: Oct. 22, 2018]. Professional and Industrial Applications. Available:https://www.osram.co.uk/pia/ecat/Specialty%20lamps/uk/en/GPS01_1027369/PP_EUROPE_UK_eCat/.
[19] Spectrolab [Cited: Oct. 22, 2018]. X-25B Steady State 1-Sun Simulator. Available: http://www.spectrolab.com/illumination.html.
[20] Philips [Cited: Oct. 22, 2018]. MSR Hot restrike. Available:http://www.lighting.philips.com/main/prof/conventional-lamps-and-tubes/special-lamps/entertainment/film-studio/msr-hot-restrike/928104905114_EU/product.
[21] Philips [Cited: Oct. 22, 2018]. Master MHN_LA. Available:http://www.lighting.philips.co.uk/professional-product-catalog/lamps/high-intensity-discharge-lamps/quartz-metal-halide/dmhnla/928071305130_EU.
[22] Alanod [Cited: Oct. 22, 2018]. ALANOD® MIRO® – optimum reflection. Available: https://www.alanod.com/en/reflection/miro/ .
[23] Domínguez C, Antón I, Sala G. "Solar simulator for concentrator photovoltaic systems." *Optics Express* 16 (2008)14894.