Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 57 (2014) 590 – 596
Energy Procedia

2013 ISES Solar World Congress

Optical analysis of a hexagonal 42kW$_e$ High-Flux Solar Simulator

Jian Li[a], José Gonzalez-Aguilar[a,]*, Carlos Pérez-Rábago[a], Hussein Zeaiter[b], Manuel Romero[a]

[a]*IMDEA Energía, Avda. Ramón de la Sagra 3, 28933-Móstoles, Spain*
[b]*Polytechnic University of Madrid. Ronda Valencia 3. 28012. Madrid. Spain*

Abstract

A 42-kWe high-flux solar simulator with hexagonal reflector symmetry has been designed, built and optically characterized at IMDEA Energy Institute, Spain. This facility makes possible the lab-scale generation of a quasi-uniform high radiation flux density and high stagnation temperatures and it will be used as a platform for analyzing processes under concentrating solar energy conditions; for instance, central receivers in concentrating solar power plants and solar fuel production process in thermochemical reactors. The high-flux solar simulator consists of seven reflector-lamp pairs arranged in the center and vertices of a regular hexagon. The 6-kWe Xe short arc lamps are allocated in the primary focus of the corresponding truncated ellipsoidal reflector. This hexagonal symmetry provides compactness and quasi-uniform spatial distribution of the radiation at the system common focal plane.

This work presents the experimental characterization of the solar simulator optical performance. Preliminary measurements indicate an average flux density at the focal plane of 3.5 MW/m^2 that means 3,500 suns (1 sun = 1 kW/m^2) and stagnation temperature of approximately 2,800 K.

Selection and/or peer-review under responsibility of ISES.

Keywords:high-flux solar simulator, optical characterization, flux distribution

1. Introduction

High-flux solar simulators are designed to recreate the high radiation intensity distribution usually met in concentrating solar systems. Compared with real solar concentrators, the high-flux solar simulators provide controlled conditions and allow conducting high-temperature thermal and thermochemical research without perturbations due to solar resource intermittency. Various facilities have been built for

---

* Corresponding author. Tel.: +34-91 737 11 20.
E-mail address: jose.gonzalez@imdea.org.

Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2014.10.213

different research purposes. A high-flux solar simulator for the study of high temperature and flux measurements was established at Lawrence Berkeley Laboratory, with peak fluxes up to 16 MW/m^2 [1]. A high-power linear Ar arc (200 kW electrical input) enclosed by an elliptical trough mirror, designed by ETH-Zurich, is capable of delivering up to 75 kW of continuous radiative power at peak fluxes exceeding 4250 kW/m^2 [2]. A high-flux solar simulator facility comprising an array of ten Xe arcs, built by Paul Scherrer Institute, can deliver over 50 kW of radiative power at peak fluxes exceeding 11 MW/m^2 [3]. DLR has a facility composed of ten 6 kW xenon short-arc lamps with elliptical reflectors. Daniel S. Codd in Massachusetts Institute of Technology used seven 1.5 kW metal halide outdoor stadium lights to simulate concentrating solar power heliostat output for studying optical melting and light absorption behaviour of molten salts [4]. University of Minnesota designed a high-flux solar simulator consisting of seven 6.5 kW$_e$ xenon arc lamp. It can deliver radiative power of approximately 9.2 kW over a circular area of 60-mm-diameter located in the focal plane [5, 6]. University of Florida built a 56 kWe facility providing peak flux levels in excess of 5000 kW.

A new 42 kW$_e$ high-flux solar simulator used for high-temperature solar thermal and thermochemical research has been built in IMDEA Energy, Spain. In this paper, we present the optical design and characterization of the high-flux solar simulator. The radiative power of the high-flux solar simulator at focal plane was measured by a charge-coupled device (CCD) camera and a calibrated water-cooled calorimeter.

2. Design of Solar Simulator

The elliptical reflector can provide a highly efficient transfer of radiation with radiation source located at the first focus and the target located at the second focus of the reflector. Thus, the ellipsoidal mirror is usually used to reflect and concentrate the light rays for high-flux solar simulator. The solar simulator with a big single ellipsoidal mirror is difficult to be fabricated and has limitations to adjust the source power output and distribution. The simulator with multi truncated ellipsoidal reflectors is flexible to adjust. In this facility, we adopt an array of seven lamp-reflector modules, as shown in Fig.1.

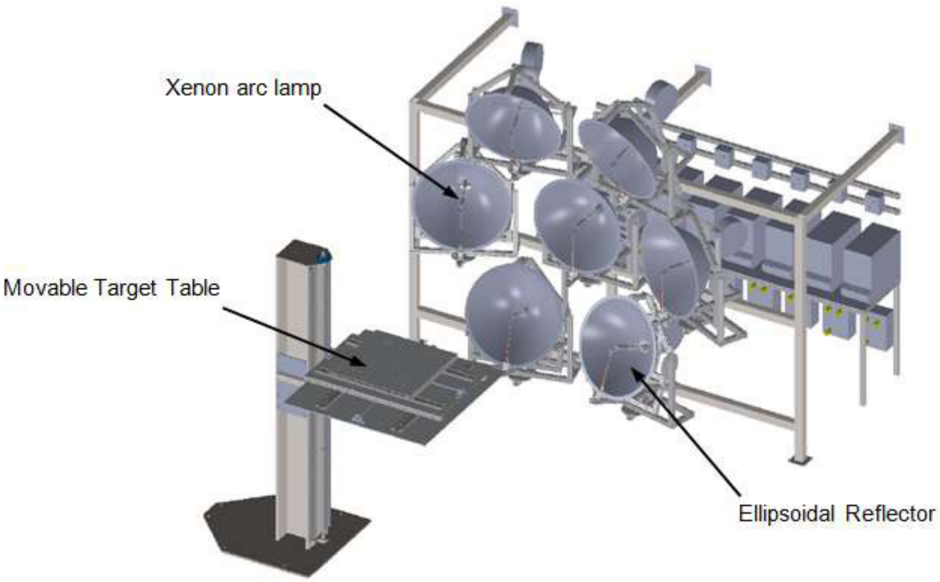

Figure 1. Schematic of the 42 kW_e high-flux solar simulator.

Selecting the dimensions of the reflector is a compromise between maximum radiation heat transfer efficiency, manufacture constraints and the minimum distance between the bulb and the reflector in order to avoid the reflector overheating. The distance between each lamp has been chosen large enough to allow the reflectors to be adjusted for different flux alignment. The light source of 6 kW Xenon arc is close-attached to truncated ellipsoidal reflectors. The semi-major axis of the ellipsoidal reflector is 1374 mm, and the semi-minor axis is 569 mm, which provides a focal length of 2,500 mm. The eccentricity is 0.91. The truncation diameter of the reflector is 750 mm. The aluminium alloy sheet is used as the reflector material, and the inner surface of the reflectors are covered with an aluminum and a polymer protective coatings.

3. Characterization

3.1. Measurement system

Energetic characterization of the high-flux solar simulator was characterized by using direct and indirect methods [7, 8]. In the first one, a series of images of the irradiance distribution on a water-cooled Lambertian target positioned at the focal plane were taken. A SiS1-p1010 CCD camera with 16-bit 1024×1024 pixels was used to record the concentrated radiation reflected from the target. The intensity of reflected concentrated radiation was so high that the absorptive-reflective neutral density filters were needed for CCD camera recording. A heat flux gauge of *Gardon* TG1000-1 was used to calibrate the CCD image, which was mounted in the hole of another aluminium plate. The surfaces of the *Gardon* gauge with Zynolyte coating and Lambertian target were at the same vertical plane, and their central points were also at the same horizontal line, as shown in Fig.2. All of them were mounted on a support and installed on the movable target table, which can be controlled by computer.

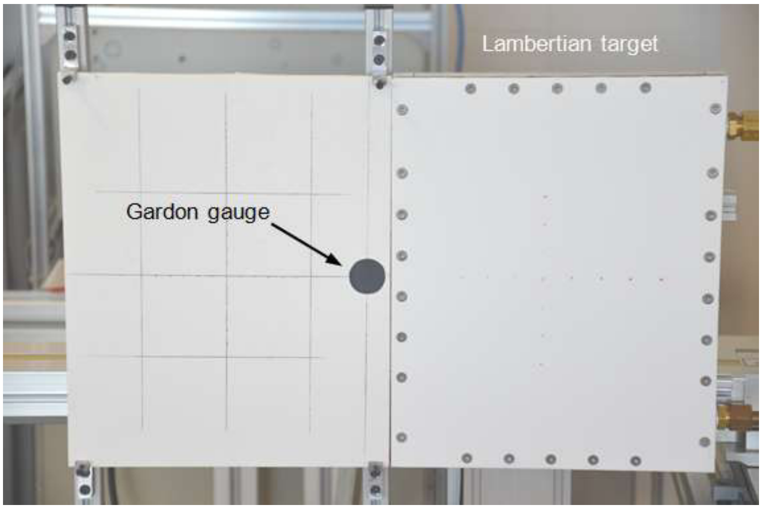

Figure 2. *Gardon* gauge and Lambertian target.

3.2. Measurement methods

Each unit composed of the Xenon short-arc lamp and the reflector was individually characterized. The tests were conducted after 20 minutes of operation with the unit in order to achieve steady conditions. Firstly, the Lambertian target was moved to position the spotlight on the centre of the target, and the flux distribution image was recorded by CCD camera at a fixed position. Then, the heat flux gauge was moved to the center of the spot to get the value of the maximum flux intensity. Later on the gauge was moved to the edge of the concentrating flux, and the value was recorded. The position coordinates of the movement of the target and gauge value were both recorded during the test.

After the test, the images taken by the CCD camera were processed in order to get the flux distribution of the solar simulator. The first step consisted in correcting the distortion of the images caused by the shooting angle of the camera, and to transform the coordinate unit of the image from *pixel* to *mm*. Then, the grayscale in the camera was converted in flux intensity using the two measurements carried out with the gauge. Assuming that the CCD camera has a linear response, a linear relationship between flux intensity and grayscale in the image can be determined, as shown in Eq. (1).

$$k = \frac{I_a - I_b}{G_a - G_b} \tag{1}$$

Thus, the flux intensity of every point in the image can be calculated by Eq. (2).

$$I_x = I_b + k\,(G_x - G_b) \tag{2}$$

where I_a, I_b and I_x are the flux intensity, G_a, G_b and G_x are the greyscale, and the k is a calibration coefficient.

The flux power of the solar simulator can be calculated by Eq. (3)

$$q = \sum_{j=1}^{N} I_j A_j \tag{3}$$

where q is the flux power, I_j is the flux intensity at the jth pixel with area A_j. The flux power density of the solar simulator can be calculated by Eq. (4)

$$\bar{q} = \frac{\sum_{j=1}^{N} I_j A_j}{\sum_{j=1}^{N} A_j} \tag{4}$$

The stagnation temperature T_s is the highest temperature that a blackbody receiver would reach for a given flux input with no losses, which can be calculated by

$$T_s = \left(\bar{q} / \sigma_{SB}\right)^{1/4} \tag{5}$$

where σ_{SB} is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).

3.3. Results

The flux distribution at the focal plane of high flux solar simulator with all seven Xenon arc lamps is shown in Fig. 3. In the test, the input current of each lamp is about 140 A. As seen from Fig. 3, the flux distribution is axisymmetric with 3,600 kW/m^2 of peak flux and a circular area of 20-mm-diameter in which the flux exceeds 3,000 kW/m^2. The power density and cumulative power over a circular target is shown in Fig. 4. The power density within a focal area with diameter of 30 mm is about 2,700 kW/m^2, and the cumulative power is about 2,000 W. For the diameter of 60 mm, the cumulative power is 5,300 W, and the power density is about 1,860 kW/m^2, which correspond to stagnation temperature achieving 2,400 K. Within the focal area of 200-mm-diameter, the cumulative power can reach 14,000 W.

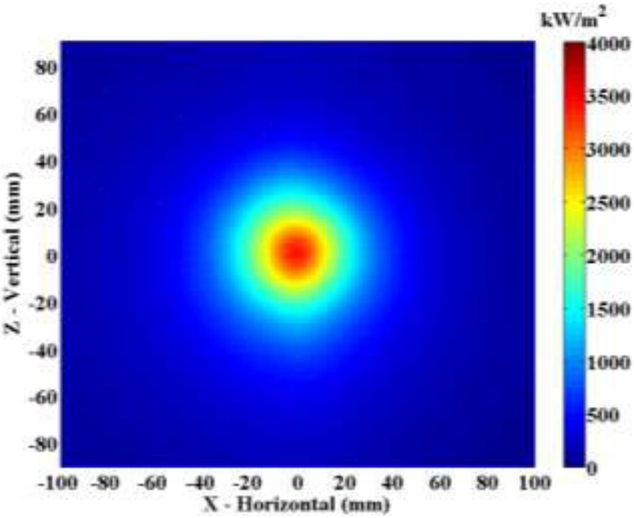

Figure 3. Flux distribution at the focal plane of solar simulator.

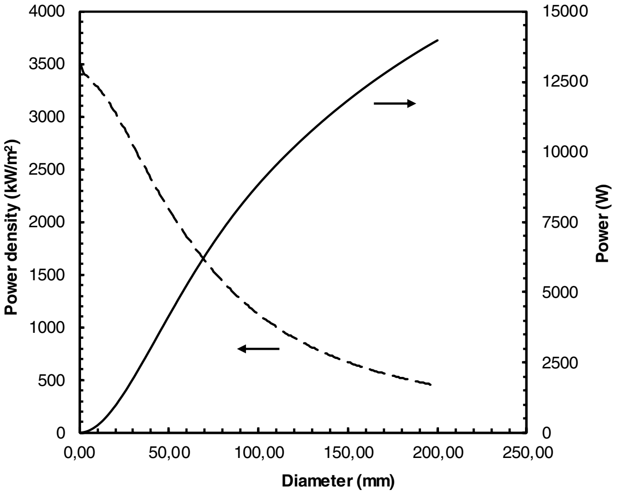

Figure 4. Cumulative power and power density of flux as a function of diameter.

The alignment of seven lamps of the high-flux solar simulator can be adjusted in order to use different pointing strategies. Based on the flux distribution of each lamp, the flux distribution of all the seven lamps aligned onto a vertical axis can be estimated. As example, Fig. 5 and Fig. 6 show the flux distribution of all the seven lamps with the realignment, of which the central distance between flux distributions of each lamp is 30 mm. The width of flux distribution over 800 kW/m^2 is about 30 mm, and the length is about 180 mm. From the tests, we can know that the flux distribution is not very uniform because of the different performance of each lamp, and the alignment should be adjusted according to the requirements of specific tests.

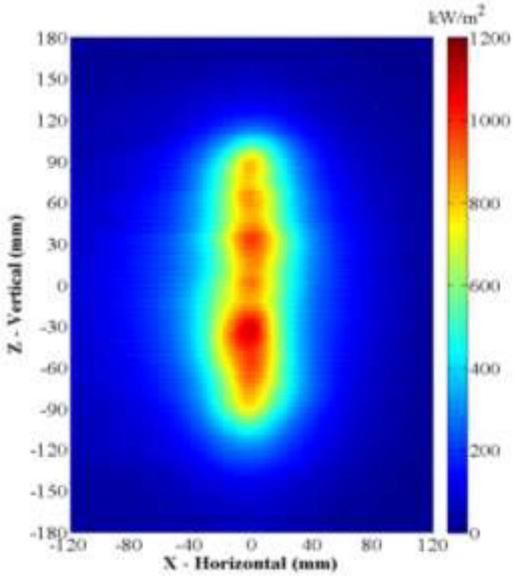

Figure 5. Front view of the flux distribution of seven lamps aligned on a vertical axis.

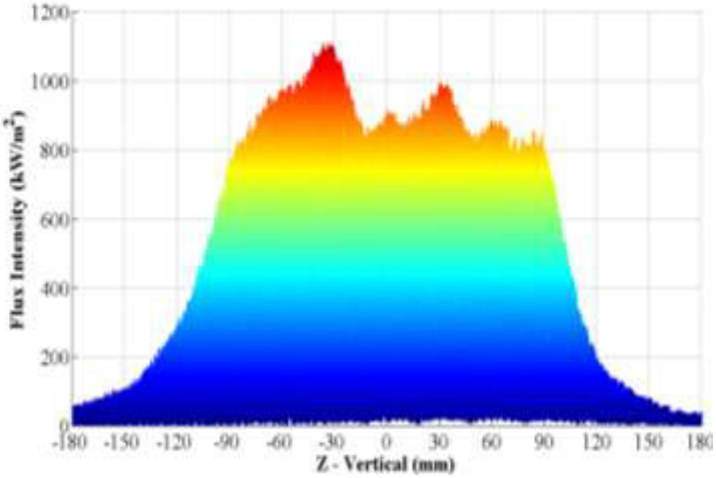

Figure 6. Cross-section view of the flux distribution of seven lamps aligned on a vertical axis.

4. Conclusions

This study presented the design and characterization of the high-flux solar simulator recently installed at IMDEA Energy. The facility is composed of seven 6kW$_e$ Xenon short-arc lamps. The truncated ellipsoidal reflectors are used to concentrate the radiation, of which the semi-major and semi-minor are 1374 mm and 569 mm. The truncation diameter of the reflector is 750 mm. The high-flux solar simulator was characterized by cooling Lambertian target and calibrated *Gardon* gauge. When the radiation of all the lamps is concentrated onto a common point, single aiming point, the flux density exceeds 3,000 kW/m^2, within the central circular area of 20-mm-diameter, and the peak flux intensity is 3,600 kW/m^2. When all the seven lamps are aligned on a vertical axis with 30 mm spacing between aiming points, the width of flux distribution over 800 kW/m^2 is about 30 mm, and the length is about 180 mm. It is expected that these values increase after fine adjustment of lamp position with respect to the corresponding reflector.

Acknowledgements

The authors gratefully acknowledge the Community of Madrid and the Structural Funds of the European Union funding SOLGEMAC Program (S2009/ENE-1617) for the Program R&D and the Spanish Ministry of Economy and Innovation through Plan Nacional I+D+I number ENE2011-29293. JGA thanks the financial support of "Ramón y Cajal" programs.

References

[1] Peter Kuhn, Arlon Hunt, A new solar simulator to study high temperature solid-state reactions with highly concentrated radiation. *Solar Energy Materials* 1991;24:742-750

[2] D. Hirsch, P.v. Zedtwitz, T. Osinga, J. Kinamore, A. Steinfeld, A new 75 kW high-flux solar simulator for high-temperature thermal and thermochenical research. *Journal of Solar Energy Engineering*, 2003;125:117-120

[3] Petrasch J., Coray P., Meier A., Brack M., ect., A novel 50 kW 11,000 suns high-flux solar simulator based on an array of Xenon Arc Lamps, *Journal of Solar Energy Engineering* 2007; 129:405-411

[4] Daniel S. Codd, Andrew Carlson, Jennifer Rees, etc., A low cost high flux solar simulator. *Solar Energy* 2010;84:2202-2212

[5] K.R. Krueger, J. H. Davidson, W. Lipinski, Design of a new 45 kWe high-flux solar simulator for high-temperature solar thermal and thermochemical research. , *Journal of Solar Energy Engineering* 2011; 133:011013

[6] K.R. Krueger, W. Lipinski, J. H. Davidson,Operational performance of the university of Minnesota 45 kWe high-flux solar simulator, *Journal of Solar Energy Engineering* 2013; 135:044501

[7] A. Kröger-Vodde, A. Holländer, A., CCD flux measurement system PROHERMES, *J. Phys. IV France*, 1999; Pr3-649-Pr3-654.

[8] R. Gardon, An instrument for the direct measurement of intense thermal radiation, *Review Sci. Instruments*, 1953; 24 (5), 366-370.