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High flux solar simulators for concentrated solar thermal research: a review.

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Abstract

When the availability of solar radiation is not enough to develop experimental investigation in the field of concentrating solar energy, solar simulators are a widely employed solution. They represent a source of artificial light, which can be comparable with concentrated sunlight. Besides, they provide advantages such as better parametric control of the process under study. In this work, it is presented an extensive review of the high flux solar simulators that are available in the different solar energy research centers around the world. Many of them are similarly designed and have common elements. Others are based on different concepts and their particular features are also pointed out. The main applications of solar simulators reported in literature are discussed along the work and remarked then in a specific section.

Keywords

High flux solar simulators, arc lamps, concentrating solar energy, thermal applications

Abbreviations

CST: Concentrated Solar Thermal

DNI: Direct Normal Irradiation

CSP: Concentrated Solar Power

PTC: Parabolic Trough Collector

LFR: Lineal Fresnel Reflector

PDS: Parabolic Dish System

SPT: Solar Power Tower

LCOE: Levelized Cost of Energy

LED: Light Emitting Diode

HFSS: High Flux Solar Simulator

AM: Air Mass

SZA: Solar Zenith Angle

ASTM: American Society for Testing and Materials

CSI: Compact Source Iodide

IR: Infrared

UV: Ultraviolet

VIS: Visible

NIR: Near Infra-Red

CIEMAT: Centro de Investigación Energética Medioambientales y Tecnológicas

IMDEA: Instituto Madrileño de Estudios Avanzados

WSTC: Water Splitting Thermochemical Cycles

ETH: Eidgenössische Technische Hochschule Zürich

CCD: Couple Charge Device

PMMA: Polymethylmethacrilate

PC: Polycarbonate

CFD: Computational Fluid Dynamics

PSI: Paul Scherrer Institute

DLR: Deutschen Zentrums für Luft- und Raumfahrt

SFERA: Solar Facilities for European Research Area

UFL: University of Florida

GIT: Georgia Institute of Technology

KIER: Korean Institute of Energy Research

ANU: Australia National University

EPFL: Ecole Polytechnique Fédérale de Laussane

IET: Institute of Engineering of Thermophysics

KTH: Kungliga Tekniska Högskolan

ND: Neutral Density

HMI: Hydrargyrum Medium-arc Iodide

MIT: Massachusetts Institute of Technology

TEOTL: Test-Bed for Optical and Thermal absorber characterization

TIT: Tokio Institute of Technology

JFCC: Japanese Fine Ceramics Center

Th: Thermal receivers

TC: Thermochemical processes

VR: Volumetric Receivers

St: Stirling engines

CPV: Concentrated Photovoltaic

VMSR: Volumetric Molten Salt Receivers

MP: Material Processing at high temperatures

Mathematical expressions

η: System efficiency

$\dot{Q}_{rad}$: Radiative power

$\dot{Q}_{el}$: Electrical power

$\dot{q}''$: Average flux

A_{rec}: Receiver area

I_{arc} : Nominal direct current

V_{arc}: Nominal direct voltage

g_{λ}: Weigh given to a wavelength

I_{tot}: Total intensity

I_{λ}: Intensity for one wavelength

T_S: Stagnation temperature

σ : Stephane-Boltzmann constant: 5.67×10^{-8} W m^{-2} K^{-4}

Q_{mean}: Average heat

Q_{max}: Maximum heat

α: Truncation angle of ellipsoidal reflector

a: Major semi-axis of ellipse

b: Minor semi-axis of ellipse

c: Half distance between ellipse foci

F1: First focus of ellipse

F2: Second focus of ellipse

d_{arc}: Arc length

$d_{receiver}$: Receiver size

$d_{truncation}$: Truncation diameter of ellipsoidal reflector

1. Introduction

Concentrated solar thermal (CST) technologies are based on the use of optic systems to concentrate the solar radiation onto a small area. These technologies provide clean, reliable and environmentally friendly energy to be used in the form of heat, electricity or solar fuels [1].

Collecting the solar energy, which has relatively low density, is one of the main engineering tasks. For concentration, most systems use glass mirrors because of their very high reflectivity. Their capability of concentration is given by the solar concentration ratio, defined as the mean solar radiative power flux over the focused area, normalized to the direct normal irradiation (DNI) [2]. There are four major concentrating solar power (CSP) technologies: parabolic trough collector (PTC), linear Fresnel reflector (LFR), parabolic dish systems (PDS) and solar power tower (SPT). There is a clear distinction between the line-focusing systems, PTC and LFR, which concentrate solar radiation by 30 - 80 times, and the point-focus systems, PDS and SPT, with concentration factors of 200 to several thousand [3,4]. The concentrated radiation is then intercepted by a receiver, which contains the element that absorbs the heat, typically a thermal fluid for CSP plants or a reactant for thermochemical applications.

In CSP plants, turbines are usually moved by steam to generate electricity. The steam can be produced directly in the receiver or by means of a heat carrier. This thermal fluid provides flexibility to the plants and enhances energy security. Moreover, thermal energy can be stored for later conversion to electricity, e.g. when it is cloudy, after sundown or before sunrise. CSP plants can also be equipped with backup from fossil fuels, delivering additional heat to the system [5].

CSP plants are currently in medium to large-scale operation and supply electricity to electric systems of several countries. Main development of CSP plants has taken place on Southern Europe and the United States [6]. However, in recent years the CSP market is shifting to other countries such as Chile, India, Morocco, Mena region or South Africa.

Apart from electricity generation, other advanced applications of concentrating solar energy focus on the energy carrier production and raw materials processing [7]. The production of solar fuels, including hydrogen, is based on H_2O/CO_2 splitting and decarbonization processes (cracking, reforming, and gasification of carbonaceous feedstock) [8–11]. Other industrial applications are extractive metallurgy, ceramic material processing and calcination [12,13]. Unlike electricity production, these solar thermal and solar thermochemical approaches have not been yet developed in commercial scale.

Despite the progressive expansion of CSP plants and the development of new concepts, current R&D challenges are not few. Although the levelized cost of electricity (LCOE) is trending downwards according to IRENA [14], it should be still reduced to be able to compete with fossil fuels. To achieve that, a first focus should be placed on reducing the cost of the plant components, mainly the solar fields. A second focus should be placed on increasing the net electrical output of a given plant, reducing parasitic consumption as well as improving operational strategy. Finally, new concepts, such as more efficient thermodynamic cycles working at higher temperature, new receiver designs and improved collector field layouts, should be contemplated in order to achieve a general enhancement of the technology while cost decreases [15]. Another R&D challenge involves the increasing of availability/dispatchability of CSP plants. For such an objective, thermal and thermochemical storage concepts and technologies play a fundamental role [16]. For those locations where infrastructures to connect electricity plants to centralized electric systems may result expensive, modularity-based CSP systems may be also investigated and improved.

Thermochemical applications of CST technologies pose important challenges which are mainly related to the typical high temperatures. Reactors design to avoid heat losses, advanced materials for thermochemical processes or kinetic and thermodynamic studies to improve chemical conversion are some of the key topics faced by the current investigations. Thermochemical applications are in an earlier stage of the learning curve than CSP.

According to the above given overview, research topics on CST technologies are many and comprise different approaches. For experimental research, a high flux radiation source is usually essential. Solar furnaces are the most common facilities used to develop experimental tests [17–19]. For such a purpose, solar concentrators provided with sun-tracking system are another option, for instance, parabolic dishes [20]. However, these systems are disadvantageous in some cases. Since the radiation source is sunlight, research feasibility is conditioned by the weather and the moment of the day. For a high level of concentration, solar furnaces and parabolic dishes should be of large size, what requires the availability of much space and involve high costs. In contrast, solar simulators can present significant advantages in terms of size, cost and operational flexibility. A solar simulator is a device whose light source can offer similar intensity and spectral composition to the nature sunlight. Wang [21] classified solar simulators by taking into account their application field. Thus, space solar simulators were the first to be employed in order to simulate the space environment for earth satellite and other spacecraft testing in a ground-test facility. Afterwards, terrestrial solar cell started to be tested indoor using solar simulators with artificial sunlight different from that employed in space, that is, with different spectral distribution to take into account the effect of atmosphere. Since 2000, it is common the use of Light-Emitting Diode (LED) technology for PV solar simulators [22]. Other solar simulators are those called large solar simulators that are employed to test solar collectors. They are the simplest and cheapest because requirements on spectral composition are not high [23]. Finally, the high-flux solar simulators (HFSS) can offer not only a spectrum close to solar light, but also approximate high light fluxes to a real concentrated solar system. Their main components are a radiation source, which is a power lamp as similar as possible to the natural sunlight and a concentrator, which is generally an ellipsoidal mirror. According to its optical properties, any light ray leaving one focus of the ellipsoidal mirror will always pass through the other, where high concentration grade is achieved. Typical applications are solar thermal or thermochemical studies at high temperature. The aim of this article is to review the literature works involving these high-flux solar simulators and how they have been performed according to the research purposes they have been employed for.

2. Solar simulators versus nature sunlight concentrating systems

At ground level, the shape of the natural sunlight spectrum depends on different atmospheric parameters, such as water vapor, ozone, carbon dioxide, and clouds among others. However, under clear sky conditions, the air mass (AM) is the main factor that affects the spectral profile during the day and the year. It is related to the length of the optical path that the direct solar radiation travels through the atmosphere, and therefore, to the possibility of interaction with atmospheric gas molecules and aerosols: the longer the path, the greater the amount of attenuated radiation due to the interaction with matter (see Fig. 1). AM can be calculated without any measurement, it only depends on geographical location and time, and it is defined as a function of the solar zenith angle, SZA:

$$AM = \frac{1}{\cos SZA} \qquad (1)$$

The extraterrestrial solar radiation is the radiation coming from the sun that reaches the upper layers of the atmosphere. By agreement, an AM equal to 0 is assigned to the extraterrestrial solar radiation. The spectrum of the extraterrestrial solar radiation is close to that of a black body with a temperature of 5500 °C, according to the Planck's Law and taking into account the required correction because of the distance (see Fig. 1). Its integral over the whole spectrum agrees with the solar constant, 1367 W/m^2, which represents the power of solar radiation per unit area at the outer border of the atmosphere. It can vary around 3.3% according to the Earth-Sun distance.

Fig. 1. ASTM G173-03 reference extraterrestrial spectra (black), ASTM G173-03 reference solar direct normal spectral irradiance (DNI$_\lambda$) for an air mass equal to 1.5 (blue) [24,25], black body radiance for a surface at 5500°C (red line) normalized to the value of solar constant, and spectral DNI$_\lambda$ for several air masses.

During its travel through the atmosphere, the direct solar radiation is attenuated because of the scattering and absorption processes. After suffering such attenuation, significant changes are observed in the shape of the direct solar spectral irradiance at ground level, appearing the characteristic absorption valleys in certain spectral ranges (see Fig. 1). The attenuation represents, for instance, a 33% for the ASTM G173-03 Direct Normal spectral Irradiance (DNI_λ), in comparison with the extraterrestrial solar radiation.

These changes in the shape of the spectrum are not the only changes experienced by the solar radiation before to reach the receiver area of a CSP system. The natural sunlight has to be reflected on the optical elements (mirrors) which can modify the solar spectrum accordingly to their spectral reflectivity.

However, inside the [280-2500] nm spectral range, mirrors are developed with the highest possible reflectivity in order to avoid power losses. Therefore, the spectral distribution of solar radiation does not change so much for this spectral range. Fig. 2 shows the comparison of the DNI_λ reference spectrum (black line) and the spectral irradiance at the receiver (red line). The spectral distribution of the solar radiation at the receiver is calculated considering two reflections on 3M reflectors and without taking into account the concentration factor, for comparison purposes. It is important to highlight that the changes caused by the atmospheric instability or the air masses variations are more significant than those produced by the reflectance of the mirrors for this spectral range (see Fig. 1). Because of this, the ASTM G173-03 DNI_λ solar spectrum is the standard reference to compare the emitted spectrum by light sources of solar simulators in this paper [25].

Fig. 2. Specular reflectance of some commercial reflectors [26,27], spectral direct normal irradiance (DNI) at AM 1.5 (black line) and spectral distribution of the solar irradiance (red line) on the receiver of a solar furnace after a double reflection on 3M reflectors (heliostats and concentrators). Concentration factor is not considered.

The 99% of power of the ASTM G173-03 DNI_λ is limited between the 280 and 2500 nm wavelengths. The greatest amount of energy is mainly confined within the visible spectral range, from 400 to 700 nm. It falls abruptly in the UV region and it has a soft decrease in the near and far infrared.

The selection of the light source is a critical step into the design of a solar simulator. Generally, researchers aim at simulating the solar radiation as close as possible to the reference spectrum. On one hand, it is difficult to achieve a perfect fit with artificial radiation sources, especially when it is desired to consider the absorption valleys, ever-present in the natural light spectrum. To solve that problem, some authors suggest the use of spectral filters which are frequently employed in fields such as photovoltaics, flat-plate collectors, and photo-chemical processes [28–34], working with low-flux solar simulators. However, at high flux levels, the fitting of the artificial light spectrum shape to the natural light will be more or less important depending on the particular application. For instance, in thermal and thermochemical processes it is not a key factor, because the emitted irradiance covers the whole spectral range of interest. More details will be shown later.

Three types of lamps are widely used in high flux simulators: xenon arc, metal halide and argon.

The high pressure short xenon arc lamps produce light by passing electricity through ionized xenon gas at high pressure. They provide a brighter point source, which is necessary to produce a collimated high intensity light beam [35]. These lamps are characterized with the advantage of that the power variation does not change significantly the spectral balance of the emitted light, reducing the need of voltage supply stability [36].

Xenon arc lamps provide an excellent continuum in the ultra-violet and through the visible band with a stable spectral qualities [21]. However, they present strong emission lines in the [800 – 1000] spectral range, as it is shown in Fig. 3.

Nevertheless, xenon arc lamps present some disadvantages limiting their application, e.g.: high gas pressure of operation, which can achieve 40 bar, causing a high security risk; high cost because of the requirement of a complex and expensive power supply; power supply instabilities that generate amplitude instabilities in the lamp output [21,35–38]. Moreover, Alxneit and Dibowski recommend limiting the life time of these lamps to below 600 hours for research purposes [32].

Fig. 3. Standard ASTM G173-03 DNI$_\lambda$ reference and spectral emission of a xenon lamp, derived from [39].

Metal halide arc lamp are characterized by their high light efficacy over 90 lm/W, good spectral quality balance, close fitting with sunlight spectrum, long life time (>1000 hours) and relative inexpensive cost [21,40]. Additionally, it is possible to provide a high directional radiation power without any additional optical equipment as it was made with the sealed beam version of Compact Source Iodide (CSI)[21].

Although metal halide lamps also contain gases at high pressure, an advantage in comparison with Xe-arc lamps is that they have a secondary containment provided by an outer jacket. It helps to prevent unexpected impacts and to decrease the risk of injury and damage [37].

If the spectral distribution of metal halide arc lamp is compared with other lamps, CSI lamps have a high emittance in the infrared (IR) spectral range and low energy at the ultraviolet (UV) wavelengths (see Fig. 4). Another disadvantage of the CSI lamp is its low collimation quality, restricting its application in high collimation requirement areas, such as some applications of high concentrating solar simulators [21,35,40]. However, because of the high spectral distribution quality and low cost of modern metal halide lamps, they are widely used all over the world [38,39,41,42].

Fig. 4. Standard ASTM G173-03 DNI$_\lambda$ reference and spectral emission of a metal halide arc lamp, derived from [39].

Argon arc lamps have a similar spectral distribution to Xe-arc lamps and also show peaks of emission in the [750 – 1000] spectral range, see Fig. 5. The arc produces radiation at visible wavelengths with additional power in the near infrared (NIR) and UV regions of the spectrum [43].

Fig. 5. Standard ASTM G173-03 DNI$_\lambda$ reference and spectral emission of an argon arc lamp, derived from [39].

The power distribution of the lamps and reference spectrum over the wavelengths between 300 and 1000 nm is calculated for three different spectral ranges: UV [300, 400] nm, VIS [400, 700] nm and NIR [700, 1000] nm. The results are shown in Fig. 6 (Sun).

Fig. 6. Distribution of emitted radiation in the [300, 1000] nm spectral range. Comparison of the light sources and the DNI_{λ} reference spectrum.

The best fit with the natural sunlight is for the metal halide lamp spectral distribution. Its profile of distribution is quite similar in the [300, 700] nm spectral range, which corresponds to the UV plus VIS range, see Fig. 4. According to the results shown in Fig. 6, the spectral distribution for each spectral range does not differ so much from the sunlight, e.g., a 67% of the total power is emitted in the [300, 700] spectral range, while the sun emits a 63%.

On the contrary, in Fig. 3, the xenon arc lamp shows a flat low energy distribution shape in the visible spectral range with intense peaks above 800 nm. These peaks cause that the energy balance of emitted radiation shifts significantly further towards to the infrared region, as shown in Fig. 6. That means that a 49% of the total energy emitted by the lamp is emitted in this spectral range while a 37% is emitted by the sun. The intense infrared emission of xenon arc lamps needs either air cooling for low wattage lamps or water cooling for higher powered lamps. Furthermore, the reflectors are more disposed to damage and may require forced air to cool their surface [39].

Likewise, the spectral irradiance emitted by the argon arc lamps contrasts with the solar spectrum shape. As xenon lamps, they present high peaks of energy emission in the infrared spectral range and also, more radiation is emitted in the ultraviolet spectral range, see Fig. 6. This fact confines the visible emitted radiation to a 36% of the total emitted power against the 58% emitted by the sun.

However, under the point of view of thermal and thermochemical processes, the differences in the energy distribution of the emitted radiation in comparison with the solar spectrum may not play a major role. The aim of these processes is the production of heat from the incident radiation and it strongly depends on the receiver characteristics.

In this context, the receivers are designed to reduce the thermal radiation losses and trying to absorb the largest part of the incident solar radiation. For these reasons, the absorptance of an ideal receiver, surface or cavity, should approach that represented in Fig. 7. On one hand, a high absorptance means that the receiver absorbs a high percentage of the incident radiation in the considered spectral range, in this case, 300-2500 nm approximately. On the other hand, a low absorptance means a low emittance, according to the Kirchhoff law [44] and assuming the approach of local thermodynamic equilibrium. Consequently the radiation losses decrease. A low emittance in the thermal spectral range, beyond around 2500 nm for high temperatures (Fig. 7), prevents radiation losses.

Fig. 7. Black-Body radiance for 500°C and 750°C divided by a 10 factor, solar DNI and ideal surface absorptance for receivers [45].

Consequently, if the aim is to achieve high flux levels in order to reach high temperatures at the receiver, the relevant information is the percentage of the radiation transformed in process heat, i.e., the integral of the incident radiation power multiplied by the surface absorptance of the receiver in the entire spectral range of interest. This is the total radiant power that the surface achieves. In other words, it is the average flux intensity regardless of the wavelength. These calculations allow comparing the solar simulator with the natural concentrated sunlight. Hence, an accurate spectral fitting of artificial light is not as important as the flux intensity [46]. Alxneit and Schmit give a comprehensive elucidation in [47].

The high flux solar simulators reported in literature combine one of the mentioned arc lamps with optical systems for light concentration. Then, in the following sections the solar simulators mainly reported in literature so far are compiled. They are differentiated in single-lamp and multi-lamp solar simulator which, in most of the cases, have also a relation to the size and total power.

3. Considerations for solar simulators design.

Great majority of solar simulators presents arc lamps mounted inside of ellipsoidal reflectors. Normally the arc is located in order to occupy the closest focus (F1 in Fig. 8a) to the mirror. This way, the system is able to concentrate the radiation emitted by the lamp to the other focus (F2 in Fig. 8a and b) of the ellipsoid. Mathematically, the equation of an ellipse is the following:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad (2)$$

where a is the ellipse semi-major axis and b is the semi-minor axis. Other typical parameters that characterize an ellipse are the half distance between the foci, c, and the eccentricity, e. Those parameters are related to the previous ones by the following equations: $a^2 + b^2 = c^2$, and $\mathrm{e} = {}^{\mathrm{c}}/_{a}$.

Actually, the emitted light is concentrated around the theoretical secondary focus F2 and not exactly on a single point. Several matters affect the flux distribution on F2. First, a truncated ellipsoid instead of an entire one constitutes the reflecting surface. Thus, part of the radiation is lost to the environment and it is not reflected toward the receiver. In Fig. 8a, the angle α is called “truncation angle” and it is defined in a range from 0 to 180 degrees. It determines the size of the reflector and consequently the reflected power. The bigger the truncation angle the more the reflected radiative power.

Then, the arc of the lamp is not punctual and reflected radiation appears as a sort of cone with the vertex in the mirror and the base in F2 (see Fig. 8b). This fact provokes that radiation is not reflected and concentrated in the same way from each point of the ellipsoid. In particular, the longer the distance between the mirror point and F2, the more magnified the flux distribution onto the receiver. In addition, the receiver has also a finite area and it can collect only part of the reflected radiation. Hence, lower eccentricity and lamps with smaller arcs can reduce this effect, achieving higher flux in the second focus. This is probably the main reason why xenon short arc lamps have a widespread employ in this kind of technology.

Moreover, the anode, the cathode, the cables and structural elements of the lamps can partially shade the reflected light. Normally, the lamp is considered as a Lambertian source, but actually it is not. Flux distortions may be due to arc light intensity variations and to the lack of a homogenous emitting distribution, among other factors. Some authors affirm that a crucial factor for the system performance lied in the quality of the reflectors. Therefore, such elements have to be manufactured and polished as precisely as possible [34,48]. Clear explications of these concepts can be found in [34,39,48–50].

Fig. 8. a) Schematic of a truncated ellipsoid with ideal reflection for a punctual source and main geometrical parameters. (b) Schematic explication of reflections in an ellipsoidal reflector for an arc lamp placed in one of the foci.

Multi-lamp solar simulators are normally composed of identical units. A unit usually consists in the same configuration presented above, an ellipsoidal reflector and an arc lamp. Several authors proposed similar methodologies to design multi-lamp solar simulators [34,48,50,51]. Once the number of lamps is defined, the disposition of the lamps has to be carefully studied. Parameters as the number of lamps per rows, relative distances among lamps, focal length and inclination angles~~,~~ have to be optimized. The rim angle, ϕ_{rim}, represents the half cone angle of incident radiation at the target and it is analogous to the rim angle of solar concentrators for on-sun tests. That value is often reported for multi-lamp solar simulators.

In order to evaluate the performance of the system, the efficiency, η, is calculated as the ratio between the radiative power, $\dot{Q}_{rad}$, and the electrical power, $\dot{Q}_{el}$, (see eq. 3).

$$\eta = \frac{\dot{Q}_{rad}}{\dot{Q}_{el}} = \frac{\dot{q}'' \cdot A_{rec}}{\sum_i (I_{arc} \cdot V_{arc})_i} \qquad (3)$$

where $\dot{q}''$ represents the measured or estimated average flux within a receiver area, A_{rec}. Often, on flat receivers, those areas present circular shapes and η is indicated for different values of the radius. I_{arc} and V_{arc} are the nominal direct current and voltage of each lamp that composes the solar simulator. In some works, simulators efficiency is calculated comparing the radiation impinging on the receiver with the radiation emitted by the lamp. The second quantity depends on the lamp light conversion and a conservative value equals to the 50% of the lamp electric power is assumed [48,52].

In few cases, elliptical reflectors are not used and the arc lamp is coupled with a parabolic reflector. In this way, a collimated beam is generated but the radiation is not concentrated. Thus, other concentrating elements are needed to increase the radiative flux. As it can be seen in next sections, parabolic reflectors or Fresnel lens are the most used elements as secondary reflector.

In order to obtain a proper estimation of the flux distribution on the receiver and to take into account the above mentioned geometrical constraints, solar simulator designs are often carried out by means of ray tracing software. Main difficulties consist in reproducing properly the arc shape and brilliance [34,39,48,50,51,53]. In Fig. 8b, a schematic of a Xe-arc lamp is shown and a point-shaped cathode and a round-shaped anode are reproduced. The distance between them is defined as d_{arc} and it represents the arc length. Several geometries (i.e. spherical, cylindrical or a combination of them) have been simulated as light source in order to imitate the real arc shape and to estimate correctly the emitted radiation [34,48,50,53]. In some other cases, the arc brilliance declared by the supplier was implemented in the ray tracing simulations [51]. Other authors [39] photographed the arc to determine the real arc shape of a metal halide lamp, as shown later.

In the design stage, it is also necessary to evaluate limitations imposed by manufacturing processes, applications, mechanical stresses, spatial availability, safety, economical aspects and circumstantial constraints. For this reason, it does not exist a unique optimal design and a specific optimization has to be realized for each simulator. However, the design of such systems is carried out with the aim to maximize both the efficiency and the peak flux impinging on the receiver.

4. Single-lamp solar simulators

Since single-lamp solar simulators use the thermal power from a single lamp, they are generally less powered than those comprising more than one lamp (see next section). One of the oldest single-lamp HFSS belongs to Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), in Spain and was reported, for instance, in the PhD Thesis of Palero [54]. It was made up of a xenon lamp of 4 kW$_e$ and a concentrator which can reach fluxes of up to 1400 kW/m^2. Lamp and concentrator are placed inside a metallic housing. The complete device was provided by the company Wassmann that is devoted to projection and cinema solutions. Although the concentrator is defined as parabolic, that is probably a mistake. The correct term should be elliptical concentrator, according to the description of the experimental setup given by the author [54] and taking into account the different optical properties of parabolic and elliptical surfaces.

Palero [54] described a set of experimental tests to analyze the performance of different volumetric absorbers. The facility included an instrumented tubular receiver of variable inner diameter between 35 and 40 mm, inside which the absorbers were placed. Air was forced to cross the absorber while it was irradiated by the solar simulator. In this way, the absorption capacity and thermal behavior were tested under direct heating of high flux radiation.

IMDEA Energy (Madrid, Spain) acquired a 7kW$_e$ solar simulator in 2009 in the cinema solutions company Proyecson. It consists of a housing with a 7 kW$_e$ xenon lamp and an elliptical mirror inside it. Gomez *et al*. [55] presented an experimental characterization of this solar simulator by combining direct and indirect flux measurements techniques. It was found that the flux distribution concentrated by the solar simulator presents a non-periodic oscillation fluctuating preferably between 25 and 75 Hz with an average RMS-amplitude for a flux of 124 kW/m^2. Also, they found a progressive decrease and displacement of the maximum flux value, what could be related to the electrodes erosion. Fig. 9 shows the solar simulator with the arrangement employed by Gomez *et al*. for the characterization.

Fig. 9. 7 kW$_e$ solar simulator at IMDEA Energy. a) Housing on the left, positioning system employed for the characterization on the right. b) 7 kW$_e$ xenon lamp and elliptical mirror inside the housing. c) Lambertian surface that was used as target of the concentrated flux for the characterization [55,56].

Alonso *et al*. [57] coupled a directly irradiated solar reactor provided with a quartz window with the solar simulator. They presented the experimental characterization of thermal behavior and flow pattern of such a reactor. It was reported a radiation power up to 2.1 kW with a maximum peak flux of 2700 kW/m^2. The thermal characterization was compared with a numerical model which was presented by Bellan *et al*. [58]. Then, experiments were done in order to obtain kinetics of several metal oxides reductions when the solar simulator directly irradiated the sample. The most important find was the fact that effective kinetics of thermal reduction could be different for different heating methods. According to that, on sun experiments can be replaced by high flux radiation but not by other type of heat sources (where other heat transfer mechanism are mainly involved).

The group of IMDEA Energy was not the only that purchased its solar simulator in the company Proyecson. The same device can also be found in the Texas A&M University of Qatar since 2013 [52]. While IMDEA Energy has only reported the use of the solar simulator for thermal and thermochemical applications, this group also considers high concentration photovoltaic researches. Sarwar *et al*. [52] reported the solar simulator characterization procedure based on the flux mapping method.

Unlike IMDEA Energy device, this solar simulator was provided with a current intensity regulator. With an input current range of 113-153 A, it was found that different power levels yielded to different flux distributions. It was observed that with an input current of 153 A, the simulator delivers a peak flux of 3583 kW/m^2 at a circular target radius of 110 mm placed at the focal plane, while it was 2074 kW/m^2 at 113 A. The maximum flux was obtained in every case in the center of a Gaussian distribution. When operated with maximum input current of 153 A, the mean flux of the solar simulator at a circular target radius of 110 mm is 43.2 kW m^{2}, which is capable of obtaining a theoretical blackbody stagnation temperature of 1857 K. The flux concentricity is reduced after 10 mm diameter, which is due to the scattering from the reflector and it is quantified in the form of spectral standard deviation. The cumulative beam power was reported for 153 A with a value of 1642 kW at a circular target radius of 110 mm. In a study made for a photovoltaic cell size of 1.5 mm radius, authors reported that the solar simulator provides an average incident flux in the range of 1200-3000 suns (1 sun=1000 W/m^2). They found that temporal instability of radiative output was less than 3%. A conversion efficiency for 153 A and 110 mm radius was determined to be 47%.

Although IMDEA Energy and Texas A&M University of Qatar purchased the same device in the same provider, it is noticed that, apart from de current regulation effects, the maximum values of flux and power are different in both cases. Assuming there were no errors in the measurement procedures, the different values could be related to the accuracy of positioning the xenon arc in the focal of the elliptical mirror.

Gokon *et al.* employed a 6 kW$_e$ solar simulator to carry out thermochemical processes at high temperature. The solar simulator is a commercial equipment of Nihon Koki, particularly the model UXL-6000H. It consists in a 6 kW$_e$ xenon arc lamp and an elliptical concentrator. In this case, the reflector is vertically oriented. Hence, the xenon light is directed downwards and concentrated in the focal point, where a receiver is placed. For the study of ferrite-based water-splitting thermochemical cycles (WSTC), the employed receivers were different types of fluid beds [59]. Authors also carried out the gasification of coal coke in a fluid bed [60].

The intensity and distribution of the Nihon Koki concentrated Xe-lamp beam on the spot could be varied by changing the power supplied to the Xe-arc lamp. In their experiments, they also reported to operate under different flux intensity and distribution by changing the focal diameter of the spot. In fact, the focal diameter of the spot was varied from 4 to 5 cm. According to the information from consulted references, the operation strategy appears to consist in displacing the receiver closer and farther to the solar simulator. The energy flux density of the Xe-lamp beam spot was measured using a heat flux transducer with a sapphire window attachment. The maximum peak or central flux density measured was 2300 kW/m^2~~,~~ and the mean flux density was 880 kW/m^2.

With the same simulator, Gokon *et al*. [61] also reported the study of ferrite WSTC in a reticulated ceramic foam coated with zirconia which supported ferrites. In the same work, they also informed about another solar simulator of 6 kW$_e$ acquired from Cinemeccanica (model ZX-8000H). It was a horizontal solar simulator and was employed in an early stage of such an investigation [61]. In a different work in the same field, Gokon *et al*. al. [62] assigned a power of 7kW$_e$ to the Cinemeccanica ZX-8000H lamp. According to the diversity of data found in literature, this research group adopted the strategy to combine different couples of xenon lamp and elliptical mirror.

In 1990, it was installed at Berkeley Laboratory a single-lamp solar simulator with a power noticeably higher than the others above mentioned. They coupled a very high xenon lamp with a coated aluminum ellipsoid [63]. They reported the use of one xenon arc lamp of 20 or 30 kW$_e$ under pressure of several atmospheres. The concentrator had an 80 cm maximum diameter and was water cooled. Authors carried out calorimetric measurements using a flux gage model 1000-1 from Thermogage Inc and they scanned x, y and z directions. A light asymmetry was found in the lamp position respect to the optical axis, since the xy-isointensity lines did not shape a perfect circle. Using the 20 kW lamp, the simulator achieved a peak flux of about 16000 kW/m^2, and a 3 kW radiative power was measured inside a square with side 7 cm. Based on the electrical input of the lamp~~,~~ the conversion efficiency into radiation energy was 17 %. The solar simulator was successfully used for thermochemical processes, in particular studies on manganese oxides reduction.

Another very high powered single-lamp solar simulator belongs to the Swiss Federal Institute of Technology in Zurich (ETH). It counts with 200 kW$_e$ supplied by a single high pressure argon arc lamp. This solar simulator is the only one found in literature provided with an argon arc lamp. This is due to xenon lamps of such a high power are not available. Another particular feature of this device is its concentrator formed by elliptical trough mirrors, different from the truncated ellipsoid found in other solar simulators. Thus, this solar simulator provides a trough-type power flux distribution. The solar simulator is vertically held and it is able to provide a continuous 75 kW radiative power on a receiver placed under the concentrator. It was achieved a peak flux of 4250 suns and the stagnation temperature was calculated in 2900

K [64]. Data were obtained using a Lambertian target placed at the focal plane and a CCD camera whose images were calibrated with an absolute point Kendall radiometer.

The simulator was used for thermal and thermochemical applications. For instance, Nikulshina *et al*. [65] realized a thermochemical cyclic process of Ca-O carbonation and Ca-CO_3 calcination. They used a fluidized bed reactor fed by the simulator and were able to remove CO_2 from ambient air.

Concentrators of the solar simulators are mirrors in every case showed so far. However, refractive lenses are a different kind of technology that can be used in solar concentration as primary optics. Languy *et al*. (Centre Spatial of Liege) [66] presented the performance of a solar simulator composed of an achromatic Fresnel doublet and a 700 W xenon arc lamp. According to the authors, the achromatic lens is supposed to combine the advantages of the mirrors (achromatism) and plastic lenses (good tolerance to manufacturing errors). Thus, they manufactured a flat Fresnel lens made of polymethyl methacrilate (PMMA) and polycarbonate (PC). Authors measured the length dispersion using an optical fiber translated by a 3-axis motorized system and two spectrophotometers able to cover a spectral range of 380 to 160 nm with a step of 20 nm. The focal distance was considered as the distance where the maximum energy was collected within the core of the fiber. A weigh (g_λ) was then attributed for each wavelength according to a blackbody of 5780 K. Finally, the total intensity I_{tot} was considered as given by the following equation:

$$\mathrm{I_{tot}} = \sum_{\lambda=380}^{1600\,nm} g_\lambda\, I_\lambda \qquad (4)$$

A comparison between experimental and theoretical focal distance (obtained by paraxial calculations and ray tracing simulations) showed an error close to 1%, which authors justified because the shrinkage of PMMA and PC were erroneously measured.

The performance of the Fresnel doublet was evaluated by summing the intensity maps of the focal plane. Then, the encircled energy was calculated and compared to the ray-tracing simulations using the same angular aperture as the solar simulator.

5. Multi-lamp solar simulators

Maximum electrical power of available Xe-arc lamps is 30 kW. If higher radiative power is required, an array of lamps is necessary. In these cases, each lamp is close-coupled to a truncated ellipsoidal reflector (or a different type of concentration system). Generally, all lamp-reflectors units have a common focal point [34]. Most of the solar simulators found in literature correspond to this type as it can be noted in the summary given in Table 1. Due to their higher power, they allow reaching higher temperature and offer conditions to be employed in many high temperature processes of different size. Moreover, multi-lamps solar simulators are flexible to generate other type of foci different from the focal point. For multi-lamps solar simulators, lots of prototypes and researches on peak flux and flux distribution have been done in the last decade. The power range of reported devices are very wide and they vary from double lamp simulators of few kilowatts for laboratory scale investigations to what could be considered “artificial solar furnaces” able to achieve concentrations of more than 10000 suns and power above 1 MW.

5.1 Solar simulators at Tokio Institute of Technology and Niigata University

Tamaura and Kaneco [67] reported the employment of a solar simulator composed of 2 xenon lamps of 5 kW_e (Ushiopex 5 kW x 2). Note that this solar simulator is comparable with single-lamp devices in terms of power and scale. However, authors searched for doubling the power of a single lamp and taking advantage of the possibility to irradiate from two different directions and to count with higher flexibility in the power control.

Authors used this solar simulator to investigate the oxygen releasing step of $ZnFe_2O_4$ for hydrogen production purposes. The samples were irradiated while they were placed inside a quartz tube through which air passed. The temperature of the sample was raised to a specified value in the range of 1600–1900 K. The power flux at the focal point of 8 mm diameter was about 2150 kW/m^2 measured by a heat flux transducer (Medtherm Co). The temperature was estimated from the calibration curve between the electric current of the Xe lamps and the temperature measured using a thermocouple (Pt–Pt/Rh). Such information allows for a more accurate control of the heating strategy required for a specific test.

As described before, the Niigata University research group [60–62,68] published several works in the field of thermochemical processes by the use of single-lamp solar simulators of different electrical powers. Later, in the same research field, other works were published by using a three xenon arc lamp solar simulator. Individual lamp power was 6 kW_e (SFS 6003A) or 7 kW_e (UXL-70SC), what implies total power of 18 or 21 kW_e. The lamps were vertically oriented and could deliver a variable radiative power by changing the current circulating in the source. When 7 kW_e lamps were used, an emitted power of 5.1 kW_{th} onto the 90 mm diameter receiver spot was measured and the peak flux and average flux were 4225 kW/m^2 and 903 kW/m^2, respectively [69].

In other works where three 6 kW_e lamps were used, the delivered power, the peak flux and the average flux on a 60 mm diameter spot were respectively 3.2 kW, 2085 kW/m^2 and 1122 kW/m^2 [70,71]. In a different publication, authors reported a peak flux of 7624 kW/m^2 [72]. Main investigations carried out with this device searched the production of solar fuels by means of decarbonisation processes (CO_2 or steam gasification of coke).

It is remarkable the variability of characteristics and data of solar simulators reported by Niigata University, even when they were used to applications in the same field and coupled to similar facilities. It seems they managed several combinations of the lamp-concentrator unit and presumably, they changed their configuration and relative position. Because of that, they reported new characterization results of the solar simulator in their different publications.

After their experiences with lower power devices, a large solar simulator was developed at Niigata University in 2013. The device was composed of nineteen 7 kW_e ellipsoidal xenon arc lamps that totalize 133 kW_e. The facility was mounted with beam-down configuration and is able to provide a 33.3 kW_{th} on a 200 mm diameter receiver with a peak flux higher than 3000 kW/m^2 and a mean flux of 1060 kW/m^2. This HFSS was conceived to realize thermochemical processes as done in smaller simulators at Niigata University, but also to study volumetric receivers [73,74]. Nakakura *et al.* [74] proposed a CFD model to predict the air and the wall temperature inside a SiC honeycomb volumetric receiver. CFD results were then compared with experimental results. In those experiments only seven or thirteen (depending on the experimental case) lamps were used instead of the nineteen available.

5.2 Solar simulators at PSI, DLR and similar devices

There are several high flux solar simulators installed at different centers around the world, which could be grouped together due to their similarities. They are composed of several lamps arranged in a y-z axis matrix which have a common focus. Each lamp comprises a xenon arc placed at one of the foci of a truncated ellipsoidal mirror. Unlike some other solar simulators, in which the concentrator is a commercial mirror for different application fields, these large solar simulators include prototypes of mirrors custom designed and built. Each source was mounted in identical ellipsoidal concentrators and each lamp-reflector unit was located according to geometric and practical aspects.

Chronologically, PSI and DLR were the first to report the construction of their multi-lamp solar simulators, both in 2007. Alxneit [32] evaluated both facilities in the framework of SFERA Project (Solar Facilities for European Research Area).

The solar simulator at PSI comprises 10 Xe-arc lamps of 9 mm electrode gap with truncated ellipsoidal specular reflectors [34]. There is a cooling system that cools each unit by means of a water circuit leading to the front electrodes. The power of every single lamp is 15 kW_e, what totalizes an electric power of 150 kW (Fig. 10).

Fig. 10. a) The high-flux solar simulator at PSI including the Venetian shutter b) frontal view of an experimental set up composed of the solar simulator and the receiver placed in the focal area.

Petrasch *et al.* [34] reported the design process which consisted in an optical design based on the ellipse geometrical properties, taking into account manufacturing considerations and a Monte Carlo ray-tracing. For the simulation, the electrodes of the lamp were assumed as cylindrical rods, the quartz bulb, which holds the electrodes, as a sphere and the glass tube as a cylinder. The quartz glass was considered a semitransparent gray medium with a hemispherical total absorptivity equal to 0.1. The arc was modeled as a diffusely emitting sphere and it was placed at the center of the spherical bulb. The elliptical mirrors were assumed to be specular gray surfaces, with a directional-hemispherical total reflectivity of 0.9. The selected target diameter was set to 60 mm. Three different Xe-arcs (Osram XBO 4000 W HS OFR, Osram XBO 10000 W HS OFR and Ushio UXW 15000 W) and three truncation diameters of the elliptical concentrators were initially evaluated. The combination of different focal distance (c) and different truncation diameter ($d_{truncation}$) led to different truncation angle (α).

Selected lamps were finally Ushio UXW 15000 W type and optimized geometrical parameters of concentrators were α=70 deg, 2c=3 m, $d_{truncation}$=0.95 m. For the fabrication of the solar simulator, aluminum alloy 1050 (DIN Al 99.5) sheet metal was used as the reflector material and it was covered with a specular protected coating. Adjustment of radiative power could be accomplished stepwise by individually switching on each Xe-arc as required. Finer tuning of power was possible by varying the electric current and modifying the opening percentage of a Venetian shutter placed in front of the solar simulator.

To characterize the solar simulator, a CCD camera was used to record the image on a 60 mm Lambertian target. A Kendal point radiometer was employed to obtain the calibration factor, which relates the grey values measured by the camera to the incident radiative flux. The solar simulator delivered 20 kW to the 60 mm diameter target. The mean flux was 6800 kW/m^2, which corresponds to a theoretical stagnation temperature of more than 3300 K. The numerical calculated mean flux using ray-tracing was 5900 kW/m^2 which, according to the authors, can be considered a good approximation. The total radiative power over a 240 mm diameter target was 50 kW.

There are several studies in literature which report different uses of the PSI solar simulator for experimental research in thermochemistry. Moreover, according to the fact that PSI solar energy group has been working on thermochemical cycles since decades, it is one of the main identified topics [8,75,76].

DLR solar simulator is composed of 10 xenon short arc lamps of 6 kW$_e$ [32]. The electrodes are made of thorium-doped tungsten and their length varies between 9 mm (cold) and 7.5 mm (hot). In contrast to the 15 kW$_e$ water cooled lamps of PSI solar simulator, these lamps can be cooled by air, what reduces the complexity of the system. The dimensions of the space occupied by the ten lamps are 4.5 m x 3 m. The total weight of the solar simulator is 800 kg. The mirrors reflectivity in new conditions is 89%. While the electric power is 60 kW$_e$, the radiant power of the solar simulator is 20 kW. It is pointed on a target area of about 100 cm^2 at a distance of 3 m with irradiance greater than 4.1 MW/m^2. Real pictures of the solar simulator can be easily consulted by entering in DLR website [77].

The design was developed according to a procedure comparable to that of PSI HFSS. Both are comprehensively described and compared elsewhere [32]. It is noticeable that it occurred a problem related to the eccentricity selected for the DLR lamp-concentrator units. In order to achieve a long focal distance, the eccentricity had to be high, what resulted in placing the lamp only 8 cm close to the reflector (it was 20 cm in PSI HFSS). As a consequence much higher thermal loads took place on the reflective coating of the ellipsoidal mirror and it became damaged in only a few weeks of operation. Authors solved the problem by improving the properties of the coating material.

The average spectrum of the DLR HFSS radiation was recorded in the range 400-1000 nm applying a set of 20 band pass filters (which transmission curves were determined before). The spectrum consisted approximately of a suitably scaled black body spectrum of about 6000 K with the Xe emission lines superimposed. More UV radiation was significantly found at the center of the spot than at the outer regions. However, the relative contribution of Xe emission lines was lower at the center of the spot. Similar spectrum measurements were also found in PSI solar simulator.

Different experimental tests have been conducted using the solar simulator of DLR. For example, they have been reported high temperature electrolysis for hydrogen production [78]. The solar simulator allowed the production of superheated steam at 600 or 700 ºC inside the receiver and it was able to process a mass flow of 5 kg/h.

Analogously to the two previous cases, Minnesota University constructed a 45.5 kW_e solar simulator in 2010. It was initially designed with the objective of testing prototypes of high temperature solar receivers and reactors in a laboratory environment [31,48,79]. Following Steinfeld indications [49], the authors highlighted the importance to use a radiation source as small as possible in order to increase the optical efficiency of the system. Hence, they chose a 6.5 kW_e xenon arc lamp (XBO 6500W/HSLA OFR OSRAM) because it presented the smallest available arc size. The total number of implemented lamps was seven and they were arranged forming a matrix in the vertical plane. Each unit was equipped with a cooling system (a blower) and a rectifier. An exhaustive geometric and optic analysis using a Monte Carlo ray tracing software [80] was reported as part of the detailed design process [31,48]. The ellipsoids presented a 750 mm truncation diameter, a rim angle of 37.7°, a tilt angle for the peripheral units of 22.3° and a focal length of 2032 mm. Then, the eccentricity of the reflector was optimized using a ray tracing software and it was fixed in 0.89. Authors also studied the performance of the reflector as a function of the specular error for different target radius and they concluded that it was essential to manufacture the reflector as precisely as possible to obtain the highest flux and, at the same time, high efficiency for small target areas.

Similar to the previous one, in the same year, at University of Florida (UFL) it was designed and installed another solar simulator with the aim to study thermochemical cycles at low pressures. In this case, the device was composed of seven 6 kW xenon arc lamps and a peak flux of 4230 kW/m^2 was measured [81]. Erikson and Petrasch [82] studied an inverse method to calculate the flux distribution in the focal plane. They validated their model with other kind of concentrating devices: a parabolic trough and an elliptical trough simulator based on an argon long arc lamp.

Another solar simulator of similar design was developed at IMDEA Energy in 2013 and it was composed of seven 6 kW_e xenon arc lamps [83]. Maximum flux was approximately 3600 kW/m^2 that correspond to a stagnation temperature of 2800 K. Mean fluxes for 60 mm and 200 mm receiver spot diameter were 1860 and 450 kW/m^2. For the same spot diameter, cumulative powers were of 5.1 kW and 14 kW respectively. Authors highlighted the flexibility to adjust and focus each lamp individually. In this way, different pointing strategies were possible, for instance, lineal flux distributions could be obtained.

At Georgia Institute of Technology, GIT, a solar simulator of seven 6 kW_e Xe arc-lamps, similar to the ones at Minnesota University, Florida and IMDEA Energy, was built before 2015 [84]. Little information on this device has been found in literature. Neither enough data have been found about the design of the Korean Institute of Energy Research (KIER) solar simulator. However, characterization results of KIER simulator were reported by Chai *et al* [85] and they showed a peak heat flux of 3.019 kW/m^2 and a maximum power of 16.9 kW for the three xenon lamps coupled with elliptical reflectors.

5.3 Other solar simulators with different features

In this section there are compiled the descriptions and main characteristics of other simulators whose design differs somehow from those presented in previous sections.

At Institute of Engineering of Thermophysics (IET), belonging to the Chinese Academy of Sciences, several solar simulators shapes were studied [86–89]. Studies were carried out using ray tracing analyses with the main aim to realize an innovative tubular receiver for a Stirling Engine. A solar simulator composed of four 7 kW xenon arc lamps was constructed and it was used to validate the software simulations. The device presented a vertical orientation (as saw in the case of Niigata University solar simulators) and each lamp was located in one focus of an ellipsoidal reflector. Each lamp-concentrator unit was located inside a housing, which presumably helped to the unit mounting. The reflector had a 365 mm aperture diameter, a rear hole of 90 mm diameter; the semi-major axis was 429 mm and the semi-minor axis was 215.4 mm. The thick of the reflector was 5 mm and the material was borosilicate glass covered of a silver coated layer whose specular reflectance was 0.95 in the range 280-2500 nm [87].

Differently from most of the solar simulators presented so far, Wang *et al*. proposed and realized for the Swedish Royal Institute of Technology (KTH) a device for which no ellipsoidal reflectors were used [51]. The facility was created for research on solar thermal receivers (i.e.: a polygeneration system including a micro gas turbine), thermochemical reactors and material testing. It was composed of twelve 7 kW_e xenon arc lamps and each unit presented a paraboloid reflector and a silicone-on-glass Fresnel lens. The paraboloid allowed collimating the beam and the Fresnel lens concentrated the radiation into the receiver spot (see Fig. 11a and c).

Fig. 11. a) A schematic representation of the unit used in KTH - HFSS and b) brilliant distribution for OSRAM XBO/6000W HP lamp. c) Lamps disposition: front view and A-A section [51]. d) Firstly designed configuration for the KTH – HFSS: front and lateral view [90].

This system, designed in 2013, resulted ten times cheaper than another one theoretically proposed in a previous work of the same author [90]. In the first design, eight lamp-paraboloid mirror units reflected collimated beam on a secondary paraboloid dish that concentrated the radiation (see Fig. 11d). For the new design, a Fresnel lens was added to each unit and the paraboloid dish was removed. For both configurations, chosen lamp was NOYE-N7. Although this lamp presented a short arc, it was not a punctual source, hence, the authors carried out a detailed ray tracing analysis to study the flux generated by one unit. In such a study, authors scaled brilliance distribution from another xenon arc lamp (XBO 6000W/HP) with the same shape and geometry (see Fig. 11b), but with different electric power: 6 kW_e instead of 7 kW_e. Several arc positions around the focal point were analyzed in order to determine the maximum system efficiency. Then, to validate the ray tracing simulations for one unit, a comparison with experimental results was conducted. A peak flux of 6730 kW/m^2 and a radiative power of 19.7 kW were predicted from simulations with all twelve lamps focusing on a 20 cm diameter target placed at 1500 mm from Fresnel lenses.

At Zhejiang University, a multi-lamp solar simulator was also constructed and mounted in vertical orientation. The device was presented by Guo *et al*. [91] as the sum of nine Xe-arc lamps with different electrical power and it was composed of five lamps of 7 kW and the other ones of 10, 5, 3 and 1 kW for a total electrical power of 54 kW. Equally to the IET solar simulator, each individual unit is mounted inside its own housing. The general configuration is shown in Fig. 12b. This solar simulator was utilized for research on thermal receivers. In particular, studies on spiral solid particles receiver [92,93] and air-tube cavity receiver [94,95] were conducted. However, different configurations of such a device have been employed. In some cases, an array of five 7 kW Xe-arc lamps and ellipsoidal reflectors was used, achieving a peak flux of 700 kW/m^2 and a thermal power of 5 kW over a 10-cm-diameter aperture [92]. In other cases, the lamps were used with spherical reflectors and two more stages composed of parabolic reflectors were added to concentrate the light over the receiver area (see Fig. 12b) [93,94].

Fig. 12 a) Photograph of five 7 kW Xe-arc lamps at Zhejiang University [95]. b) Configuration with parabolic mirrors to concentrate the light over the receiver area [93].

University of Swinburne developed a solar simulator based on an array of 6 kW metal halide lamps arranged in a circular pattern. A real photograph is shown in Fig. 13. In contrast to criteria exposed by other authors, Ekman and Brooks [96] declared, after doing a literature revision, that metal halide lamps emit a spectral distribution closer to the sunlight than xenon. Such a solar simulator was constructed with the objective of testing an electric hybrid receiver at high temperature. A uniform flux density distribution was found at the focal point. Authors related this feature to the fact that metal halide lamps have a longer arc length than xenon lamps. A preliminary analysis on the flux characteristics consisted in a ray tracing model. The method described for ray tracing analysis was based on using a single image of the arc (with cylindrical shape) with the asymmetry fully accounted and using it to generate a monochrome ray set or ray file. Simulated results indicated a peak flux of approximately 700 kW/m^2. However, experimental measuring of the flux~~,~~ realized using a Gardon gauge, registered a peak flux of 927 kW/m^2 and a power of 12 kW on a receiver aperture of 175 mm in diameter [39].

Fig 13. Photograph of the University of Swinburne solar simulator [96].

University of Adelaide in 2012 [37] also proposed a solar simulator of metal halide lamps. Besides it has been mentioned that xenon light spectrum match to sun spectrum better than other artificial lights, these authors found two problems arising from the use of xenon arc lamps in an array. Firstly, the unit cost of xenon arc lamp is very high. Secondly, the xenon arc bulbs are highly pressurized, making them vulnerable to explosion. This risk particularly affects an array of lamps, because one explosion would cause another one and so on. In contrast, metal halide lamps have a secondary containment for pressured gases, what makes them safer. The same authors went in depth in the comparison between xenon and metal halide lamps, in a study that used time-resolved measurements of the radiation intensity of both type of solar simulators. More details can be found here [97]. Authors selected the Hydrargyrum Medium-arc Iodide (HMI) 6000 W/SE metal halide lamp for the solar simulator design. Concentrators were efficiently designed to compensate the loss of efficiency due to the low cost lamps. According to the authors, the levelized cost of radiative flux for the current lamp system is 70% less compared with large solar simulators reported before this one.

The solar simulator was designed to create a line focus to be applied, for example, in the integration of solar radiation with traditional combustion in turbulent environments technologies. They considered a total of 30 lamps of 6 kW_e to achieve an average radiant heat flux of 1 MW/m^2 within an area of 800 mm × 150 mm and to achieve an estimated uniformity (Q_{mean}/Q_{max}) of 68% within a plane of 400 mm × 100 mm. Another theoretical study considered 23 lamps instead of 30 and proposed the option to switch the simulator configuration between line and point focus [98]. It has not been found in literature any report of construction and demonstration of this solar simulator.

Another solar simulator with metal halide lamps was designed at Sandia National Laboratory by Boubalt *et al*. [99] to study absorber materials for CSP. The device was composed of four 1.8 kW metal halide lamps coupled with elliptical reflectors. Experimental results for one lamp showed an irradiance of 257 kW/m^2 on a 25.4 mm spot. An estimation of the whole system performance was carried out by the use of a ray tracing software. Simulated results showed a maximum flux of 1140 kW/m^2 and an average irradiance of 878 kW/m^2 over a 25.4 mm spot.

5.4 Lower flux solar simulators

In this section, two solar simulators, which are denominated high flux solar simulator by their authors, are presented~~,~~ although the range of flux are noticeably lower than the other solar simulators included in this review. It should be taken into account that the denomination "high" is subjective. Note that the applications for which these solar simulators are conceived differ from the other and they require lower temperature. They can be included in the typically called medium temperature concentrating solar energy applications.

At Massachusetts Institute of Technology (MIT) a low cost solar simulator was built in 2010. [38]. A real picture and a detailed scheme are shown in Fig. 14. The unit was designed for CSP thermal testing and it was conceived to cost less than 10000 USD. The employed type of lamps was metal halide. The device was composed of seven primary ellipsoidal concentrators and a secondary hexagonal-conical concentrator. The simulator could achieve a peak flux of 60 suns in the center of the outlet of the secondary concentrator and an average flux of 45 suns. Flux distribution was estimated by means of a 29 mm diameter aluminum disc and a thermocouple. Then, a calorimetric experiment was conducted. When the disc achieved a steady-state temperature, an average value of the flux was calculated through an energy balance for the disc. Afterwards, the system was cooled down to ambient temperature, the disc was moved in radial direction and the experiment was repeated in order to evaluate the temperature and flux distribution along the outlet radius. Both parameters presented slight higher values in the center, decreasing with radial offset.

The simulator was used to heat and keep molten nitrate salt in a volumetric receiver. A cylindrical receiver was placed below the simulator at the output aperture and it was equipped with eight thermocouples to measure temperature inside the salt and at receiver walls. Results showed a good stratification along the 250 mm receiver length, although this stratification was not present in the upper part of the cylinder. Temperature registered after eight hours showed an increasing profile from 240 °C to approximately 330 °C.

Fig. 14. a) a picture of the MIT solar simulator and b) a sketch of the same device, where (1) is the frame; (2) light mounting frame; (3) MH light; (4) pivot tube; (5) lifting winch; (6) tilt adjustment plate; (7) secondary concentrator [38].

In the framework of a collaboration of several Japanese companies, a solar simulator was built with the aim to test tubular receivers. Okuhara *et al*. [46] presented a modular device composed of twenty unit that is suitable for parabolic trough or central receiver technologies. One unit consists in a 5 kW Xe short arc lamp mounted inside an elliptical reflector, a fly’s eye lens and a Fresnel lens. The elliptical concentrator first concentrates the light beam, then the light is homogenized through the fly´s eye lens and finally the Fresnel lens linearly focuses the radiation (see Fig. 15). According to the receiver characteristics, the system can be configured to focus on a 4 m-long or 2 m-long tube.

Fig. 15. Schematic representation of one unit of Okuhara *et al*. solar simulator [46].

The operating current for the standard tests was set in 75% of the maximum in order to guarantee the same irradiance during their lifetime over 500 hours. In this way, Okuhara *et al*. [46] achieved a peak and an average flux of 37.7 and 18 kW/m^2 respectively for the first configuration, while more than 90 and 51.8 kW/m^2 for the second one. With this system, researches on the circulation of water or oil as heat transfer fluid for parabolic trough were carried out.

6. Summary of the solar simulator features

In Table 1, main characteristics of the devices presented in previous sections are summarized. When information about a specific parameter was missed and it was possible to calculate it, the result was inserted in the table according to equation 3 and 5. When no information about the year of construction was available, the year of the oldest publication relative to the simulator was reported in the table. The stagnation temperature,T_S, was calculated from equation 5.

$$T_S = \sqrt[4]{\dot{q}''/\sigma} \qquad (5)$$

where σ is the Stephane-Boltzmann constant: 5.67x10^{-8} W m^{-2} K^{-4}.

As it can be noticed in Table 1 and Fig. 16, most of the simulators have a total power below 50 kW$_e$ and a peak flux below 5000 kW/m^2. In Fig. 16, the size of the circles corresponds to the power of the single lamp mounted in the simulators (most of the simulators use similar power lamps in a range of 5-7 kW$_e$). Only one solar simulator uses an argon lamp. Such a simulator is the ETH one and currently it represents the system with the highest power. In addition, this simulator contains the highest power individual lamp. In the case of metal halide simulators, only few devices have been built and they present reduced radiation fluxes.

Fig. 16. A graphical view of solar simulators classified by peak flux vs electric power. The color corresponds to the lamp type and the size of the circle to the electric power of a single lamp.

Table 1. Summary of high flux solar simulators.

7. Main applications of HFSS

In Table 1, the main applications of the cited solar simulators are exposed. In some cases, the information is obtained from the results of the investigations reported by the authors. Other publications involve the design and characterization of the solar simulator and indicate those applications for which the solar simulator is conceived.

Most of the reported applications are studies on thermochemical processes, which take place in a solar reactor. Solar reactors are particular cases of solar receivers where the absorber heat is employed to carry out endothermic chemical reactions. Steinfeld [2,8] explained the thermodynamics of solar thermochemical processes assuming them as thermal processes which maximum efficiency is the product of the absorption and Carnot efficiencies. If such efficiency is represented as a function of the operating temperature in the reactor for different concentrations, the result is the well-known graph showed in Fig 17.

Fig. 17. Variation of the ideal efficiency of a solar thermal/thermochemical process as a function of the operating temperature.

Depending on the concentration ratio, there is an optimum temperature that maximizes the efficiency and it varies between 1000 and 2100 K for uniform power distributions with concentrations between 1000 and 20000 suns. These ranges of temperature and concentration fit very well with the values reachable using HFSS (except the cases mentioned in section 5.4).

More recent investigations focus on addressing material processing and metallurgical processes using high flux solar radiation. DLR is pioneer in the solar remelting of aluminium which was experimentally tested in a rotary kiln. Maximum temperature required in the solar reactor is 800 ºC for the process, as described in [100]. Such a value is easily reachable by HFSS as that reported by DLR in [32]. Note that for achieving a stagnation temperature of 1073 K, the required concentration is only 75 suns, which is much lower than the radiation flux of all the reviewed HFSS. Very similar analysis for justifying the use of HFSS can be done to other type of material processing. Ahmad *et al*. [101] carried out glass melting experiments using the PSI 50 kW_{th} solar simulator. They controlled the temperature at the outer surface of a crucible, which contained the melting material. At this point, they reached temperatures of 1450 ºC, therefore, higher values should be achieved inside the crucible. In their paper, Ahmad *et al*. [101] presented a comparison between the solar irradiance spectrum and the spectral absorptance of melting glass to highlight the agreement between maximum intensities of both spectrums. It is relevant in the case of glass because it is transparent to the solar radiation in a wide range of wavelength. For cases like this one, the discrepancy between the spectral power distributions of the solar simulator compared to real solar radiation have to be particularly taken into account. Several research groups who have developed solar simulators include material testing among the target applications of their facility. In case of the treatment of materials whose absorptance presents high spectral dependency, the selection of the lamp has to be done carefully.

Solar simulators have been employed to study the performance of volumetric absorbers. Such devices consist in porous wires or either metal or ceramic. They operate in central receiver concentrating solar systems in a temperature range of 800 and 1500 ºC [102] depending on the material they are formed of and the power cycle to which they are coupled. Palero [54] realized three sets of experimental assessment of volumetric absorbers performance using a solar simulator, a solar furnace and a central tower facility. The first campaign, carried out in a 4 kW_e solar simulator, was justified by the convenience of starting the analysis in a lab scale facility. Moreover, the author highlighted that a solar simulator offered the possibility of working under constant radiation flux and without dependence on the weather. However, operational limitations were mainly related to the volumetric absorber maximum size, which were solved by moving to the higher scale concentration systems. It is important to remark the similarities of the experimental setups mounted in each facility. All of them include the volumetric absorber element, air as thermal fluid, which is propelled by a suction apparatus, instruments for temperature and flow measurement and acquisition and finally the radiation source. Gomez-Garcia *et al*. [103] coupled their TEOTL (Test-Bed for Optical and ThermaL absorber characterization) apparatus to the 7 kW_e solar simulator at IMDEA Energy (see Fig. 18). The light from the solar simulator passed first through a light homogenizer because authors saw the pertinence of using concentrated radiation with uniform distribution. Note that this solar simulator includes an ellipsoidal mirror that concentrates the radiation in a focal point.

Fig 18. Experimental facility implemented by Gomez-García *et al*. [103]: (1) high-flux solar simulator, (2) intake module, (3) light homogenizer, (4) volumetric absorber, (5) exhaust module, (6) air inlet (from blowers), (7) thermal imaging camera.

The need of uniform radiation to test volumetric receivers is also exposed by Codd *et al*. [38] besides their solar simulator was conceived to heat molten salts volumetric receivers and work at lower flux and temperature than other HFSS. The work of Nakakura *et al.* [74] is another example of the use of solar simulator to study the performance of volumetric receivers. They used a multi-lamp high power solar simulator although they employed different number of lamps to vary the input power. In this work, authors did not report the use of a homogenizer element.

Other applications of solar simulators have been mentioned in the previous section of the present review. In general, parametric requirements in terms of flux, temperature, spectral intensity of light and radiation distribution on the target have been pointed out as the main criteria to take into account to feed a high temperature process with a solar simulator. Nevertheless, it should be noticed that no solar simulator is supposed to be employed for one single application, so a flexible design is always desirable.

8. Outlook and further developments of solar simulators

According to the information reported by authors and compiled in this work, it could be said that two tends prevail in the current development of novel solar simulators. On one hand, research groups with consolidate experience in the use of solar simulators aim to develop larger devices able to supply high power comparable to solar furnaces. It is the case of the new project for a larger solar simulator that DLR presented in SolarPaces 2015 with the name of SynLight. It will consist in 149 lamps, each one of 7 kW_e for a total power of 1043 kW_e. Such a high flux solar simulator would be the largest existing in the world so far. It is expected to achieve temperatures higher than 3500 °C with very high heating rates. Main applications of the system will be the testing of CSP components in pilot scale and solar chemistry under extreme conditions. More information can be found in Institute of Solar Research of DLR website [104,105].

Another future solar simulator is being developed by Australia National University (ANU) in collaboration with the Ecole Polytechnique Fédérale de Lausanne (EPFL) [106]. According to its design characteristics, it can be grouped together with the PSI and DLR simulators reported in section 5.2. It will be composed of 18 radiation modules of 2.5 kW_e with a total power of 45 kW_e. In 2014, it was reported the optical design, predictive radiative characteristics and engineering. Authors predicted a total radiative power of 15.4 kW and a peak radiative flux of 9.5 MW/m^2. This solar simulator, like those at Minnesota University, Florida University and IMDEA Energy, will use an air cooling system composed of one fan coupled with each radiation unit. This cooling system in based in the one of DLR solar simulator instead of PSI.

On the other hand, no expensive solar simulators, including those commercialized as cinema projectors and the low-cost home-made devices, are generally selected by newly established research groups. The main advantage is the possibility to start novel investigations in CSP field without a high investment of time and economic resources. For instance, the authors of the present review have recently acquired a 7 kW_e solar simulator in Proyecson with similar characteristics of those of IMDEA Energy and Texas A&M University of Qatar. It will be devoted to carry out experimental investigations on solar metallurgical processes, mainly on copper extraction from concentrates. It is the first laboratory facility devoted to such an application and will allow for the procurement of the initial results.

9. Conclusions

A review on the high flux solar simulators designed and applied to thermal processes has been presented. The solar simulators consisted on an artificial source of light, the most similar to sunlight as possible, and an optical system to concentrate the light. They can substitute concentrating solar systems to carry out thermal researches, with the objective of analysing the behaviour of processes under high flux radiation. Moreover, they have the advantages of flexibility and weather independent operation.

Three types of arcs have been used in lamps of solar simulators: xenon, argon and metal halide. Different opinions have been found on which type of arc produces a light closer to the sunlight. By direct comparison with the Standard ASTM G173-03 $DNI_{\lambda,}$ it could be affirmed that is the metal halide spectra which is more similar. However, for thermal (and thermochemical) purposes the differences in the energy distribution of the emitted radiation in comparison with the solar spectrum may not play a major role since the most important parameter is the absorptance of the receiver/absorber. Another discrepancy among different authors has been detected in relation to the convenience of using shorter arcs (xenon) or longer ones (metal halide). While shorter arcs allow for higher concentration levels, longer arcs give rise to a more uniform flux. The pertinence of selecting one or another would depend on the research requirements. On the other hand, an argon arc has been only found in the case of a single-lamp solar simulator of very high power.

The optical system mostly employed in solar simulators is the elliptical reflector, although some others have been found. Geometrical parameters of the reflector are a key factor in the solar simulators design.

Some of the solar simulators are commercial equipment generally acquired from the cinema industry. The found examples correspond to single-lamp solar simulators of power lower than 10 kW. However, most of the solar simulators are composed of several lamp-reflector units and are custom designed and built. Although in some cases the power is still lower than 10 kW, many of the multi-lamp solar simulators have very high power and can be considered as “artificial solar furnaces”.

Vertical and horizontal orientations of the lamp-reflector unit have been found indistinctly. It has to be in consonance with the position of the experimental setups that are coupled to the solar simulator. However, in most of the cases, it is the solar simulator, which is firstly built, what introduce the interrogative of why is selected one or another orientation. Actually, the reasons that justify the selected orientation have not been found in the works reported by the authors.

Along the review, different uses have been associated to the solar simulators. Although some authors conceived their HFSS for one specific application, it is common to provide the devices with elements that improve their versatility. Even though, it has been seen how the same solar simulator has been used by different authors to very different applications such as thermochemistry and CPV.

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