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# High flux solar simulators for concentrated solar thermal research: A review

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### ARTICLE INFO

# Keywordsc: High flux solar simulators Arc lamps Concentrating solar energy

### 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.

#### 1. Introduction

Thermal applications

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  $\rm H_2O/CO_2$  splitting and decarbonization processes (cracking, reforming, and gasification of carbonaceous feed-stock) [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

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ST Concentrated Solar Thermal  DNI Direct Normal Irradiation  CSP Concentrated Solar Power  PTC Parabolic Trough Collector  LFR Lineal Fresnel Reflector  FPS Parabolic Dish System  TC Thermochemical processes  SFT Solar Power  VR Volumetric Receivers  SFT Solar Power  LED Light Emitting Diode  HFSS High Flux Solar Simulator  AM Air Mass  SAM P Material Processing at high temperatures  SZA Solar Zenith Angle  ASTM American Society for Testing and Materials  CSI Compact Source Iodide  IR Infrared  UV Ultraviolet  UV Ultraviolet  UV Ultraviolet  VIS Visible  INIR Near Infra-Red  CIEMAT Centro de Investigación Energética Medioambientales y Tecnológicas  IMDEA Instituto Madrileño de Estudios Avanzados  WSTC  COLO Loughe Charge Device  PMMA Polymethylmethacrilate  PC Polycarbonate  PC Polycarb	Nomenclature HM			Hydrargyrum Medium-arc Iodide Massachusetts Institute of Technology
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	KTH		$d_{truncation}$	Truncation diameter of ellipsoidal reflector
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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 concentra-

tion, 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

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