ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

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

Alessandro Gallo[a,b], Aitor Marzo[a,c], Edward Fuentealba[a,c], Elisa Alonso[a,c,*]

[a] Universidad de Antofagasta, Centro de Desarrollo Energético Antofagasta, Avda. Angamos, 601, Antofagasta, Chile
[b] Doctorado en "Ciencias Aplicadas al Medio Ambiente" (RD99/11), University of Almeria, Spain
[c] Solar Energy Research Center (SERC Chile), Santiago de Chile, Chile

ARTICLE INFO

Keywordsc:
High flux solar simulators
Arc lamps
Concentrating solar energy
Thermal applications

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

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

* Correspond author at: Universidad de Antofagasta, Centro de Desarrollo Energético Antofagasta, Avda. Angamos, 601, Antofagasta, Chile.
E-mail address: elisa.alonso@uantof.cl (E. Alonso).

http://dx.doi.org/10.1016/j.rser.2017.01.056
Received 11 February 2016; Received in revised form 9 November 2016; Accepted 9 January 2017
1364-0321/

Nomenclature

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

Symbols

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: 5.67x10^{-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

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