Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 100 (2014) 179–194

SOLAR ENERGY

www.elsevier.com/locate/solener

Description and characterization of an adjustable flux solar simulator for solar thermal, thermochemical and photovoltaic applications

Jawad Sarwar [a], Grigoris Georgakis [a], Robert LaChance [a], Nesrin Ozalp [b,*]

[a] *Texas A&M University at Qatar, Mechanical Engineering Department, P.O. Box 23874, Doha, Qatar*
[b] *Katholieke Universiteit (KU) Leuven, Mechanical Engineering Department, 3000 Leuven, Belgium*

Received 7 October 2013; received in revised form 24 November 2013; accepted 5 December 2013
Available online 30 December 2013

Communicated by: Associate Editor Robert Pitz-Paal

Abstract

A high flux solar simulator for indoor performance assessment of systems in solar thermal, thermochemical and high concentration photovoltaic research offers repeatability under controlled climate conditions. This paper presents a new high flux solar simulator where a 7 kW xenon short arc lamp coupled with a truncated ellipsoid reflector is used as the light source. The flux mapping method is used to evaluate performance of this high flux solar simulator on the basis of flux distribution, temporal instability, spatial non-uniformity, peak flux, conversion efficiency and power intercepted on a circular target placed at the focal plane. The input current of the simulator is adjusted in the range of 113–153 A to quantify the maximum and minimum peak flux output per power settings of the solar simulator, which yield different flux distribution at different power level. A theoretical comparative analysis of manufacturer's sensor scaling factor of the circular foil heat flux gage with literature is performed and an optimum scaling factor of 491.46 kW m^{-2}/mV is selected to relate measured incident flux with CCD (charge-coupled device) camera's greyscale value of acquired image. It was observed that at an input current of 153 A, the simulator delivers a peak flux of 3583 kW m^{-2}, temporal instability of radiative output less than 3%, and cumulative beam power of 1.642 kW at a circular target radius of 110 mm placed at the focal plane. A conversion efficiency at 153 A and 110 mm radius was determined to be 47%. For a photovoltaic cell size of 1.5 mm radius, the solar simulator provides an average incident flux in the range of 1200–3000 suns with class 'A' temporal instability and class 'B' spatial non-uniformity. The simulator is capable of adjusting peak flux in the range of 2074–3583 kW m^{-2} and can produce a theoretical black body stagnation temperature of 1857 K.

Keywords: High flux solar simulator; Flux mapping method; Solar thermal; High concentration photovoltaic

1. Introduction

High temperature solar thermal and thermochemical research requires concentrated sunlight to achieve temperatures in the range of 500–2500 K (Krueger et al., 2011) to produce fuels, commodities and electricity while high-concentration photovoltaic (HCPV) systems operate at concentration ratios of 100 $\times$ or higher ($1\times = 1$ kW $m^{-2} = 1$ sun)[1]. HCPV uses photovoltaics cell (either single or multi-junction) which are semiconductor devices and are spectrally selective absorbers. Photovoltaics generate current when the incident solar spectrum matches with the spectral absorption properties of the semiconductor

* Corresponding author. Tel.: +32 476 616 342.
E-mail address: Nesrin.ozalp@kuleuven.be (N. Ozalp).

[1] In subsequent text, concentration ratio will be referred as '$\times$' for HCPV application while kW m^{-2} will be used for solar thermal and thermochemical application.

0038-092X/$ - see front matter
http://dx.doi.org/10.1016/j.solener.2013.12.008

Nomenclature

a_{ij}	coefficients of transformation matrix
A_i	area of incident flux at nominated step (m^2)
A_j	area of each pixel (m^2)
A_{tot}	total area of incident flux (m^2)
AM1.5	air mass 1.5 solar spectrum
CCD	charge-coupled device
HCPV	high concentration photovoltaic
HFSS–SERL	high flux solar simulator at sustainable energy research laboratory
L	length of heat flux gage (m)
N	total number of pixels
P_{arc}	power at the arc (W)
P_i	power at nominated step (W)
P_i^{com}	cumulative power at nominated step (W)
$R^*_{t,c}$	contact resistance ($m^2\ KW^{-1}$)
c_p	heat capacity of water ($J\ kg^{-1}\ K^{-1}$)
k	heat conductivity of heat flux gage ($W\ m^{-1}\ K^{-1}$)
qi	incident flux at nominated step ($W\ m^{-2}$)
qj	incident flux at each pixel ($W\ m^{-2}$)
$\bar{q}$	average flux ($W\ m^{-2}$)
q_{cond}	heat loss by conduction ($W\ m^{-2}$)
q_{conv}	heat loss by convection ($W\ m^{-2}$)
q_{max}	maximum incident flux at selected area ($W\ m^{-2}$)
q_{min}	minimum incident flux at selected area ($W\ m^{-2}$)
q'_{max}	maximum incident flux at nominated time ($W\ m^{-2}$)
q'_{min}	minimum incident flux at nominated time ($W\ m^{-2}$)
q_{rerad}	heat loss by re-radiation ($W\ m^{-2}$)
q''_{sim}	incident flux at heat flux gage ($W\ m^{-2}$)
r	target radius at focal plane (m)
S	spatial non-uniformity
S_d	standard deviation of incident flux
t_{ins}	temporal instability
T_b	black body temperature (K)
T_G	heat flux gage temperature (K)
T_{inv}	transformation matrix
T_{target}	Lambertian target temperature Lambertian
ΔT	temperature difference of inlet and outlet water Lambertian
u,v	cartesian coordinates of transformed plane
x,y	cartesian coordinates of original plane
α	total hemispherical absorptivity of the gage coating
σ	Stefan Boltzmann constant 5.67×10^{-8} - $W\ m^{-2}\ K^{-4}$
η	conversion efficiency

material. Multi-junction photovoltaic cells for HCPV application have achieved conversion efficiencies greater than 43%, (Philipps et al., 2013) but are sensitive to the incident solar spectrum, (Green, 1982; Herrero et al., 2012; Luque and Hegedus, 2003). The mismatch between the spectrum of incident light and the spectral selectivity of the photovoltaic cells results in a reduction of the conversion efficiency. Another factor that affects conversion efficiency of HCPV is spatial non-uniformity of the incident solar energy. Non-uniform illumination produces hotspots and raises the working temperature of the photovoltaic cells which concomitantly decreases conversion efficiency, (Emery et al., 1996; Fertig et al., 2013; Radziemska, 2003) and increases ohmic losses, (Cooper et al., 2013; Herrero et al., 2012; Katz et al., 2006; Victoria et al., 2013). Variation in solar intensity poses challenges of repeatability in performance assessment of solar thermal systems in outdoor conditions, leading to the development of indoor laboratories incorporating simulative sunlight to conduct endothermic processes. The most convenient tool for solar thermal, thermochemical and HCPV research in indoor conditions is a high flux solar simulator capable of providing an artificial source of concentrated radiation with a spectral distribution approaching that of the air mass 1.5 spectrum ‘AM1.5D’, (ASTM-G173, 2006). Solar simulators employ various types of lamps to imitate the sun such as xenon arc lamps, argon arc lamps, metal halide lamps, high pressure sodium vapor lamps, mercury vapor lamps and incandescent spotlights, (Meng et al., 2011) operating as either a continuous simulator or pulsed simulator, (Chawla, 2013). A notable example custom built continuous solar simulator includes a 75 kW high flux argon arc lamp which is capable of achieving a peak flux higher than 4250 kW m^{-2}, (Hirsch et al., 2003). Another example continuous simulator with seven 1500 W metal halide lamps achieves a peak flux of 60 kW m^{-2}, (Codd et al., 2010) while a multi-lamp continuous solar simulator utilizing metal halide gas discharge lamps coupled with parabolic specular reflectors was also developed, (Meng et al., 2011). It has been found that xenon arc lamps achieve emission spectrum closely to sunlight as compared to metal halide lamps, (Codd et al., 2010). Xenon emission spectrum can also be adjusted using filters to achieve suitable spectrum for terrestrial photovoltaic cell testing, (Alphaomega, 2013a; Newport, 2013b; Spectrolab, 2013b). Examples of continuous solar simulators for solar thermal and thermochemical research using xenon arc lamp include: a 20 kW or 30 kW single xenon arc lamp placed at the focal point of an aluminum coated ellipsoid reflector achieving a peak flux of 16,000 kW m^{-2} with a 3 kW total flux onto an area of $7 \times 7\ cm^2$, (Kuhn and Hunt, 1991), a 60 kW high flux simulator with ten 6 kW xenon short arc lamps delivering