Energy 153 (2018) 113–125

Contents lists available at ScienceDirect

Energy

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

Aiming factor to flatten the flux distribution on cylindrical receivers

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ARTICLE INFO

Article history:
Received 30 October 2017
Received in revised form
15 March 2018
Accepted 2 April 2018
Available online 7 April 2018

Keywords:
Solar Power Tower
Heliostat spillage
Symmetric flux map
Flat concentration profile
FluxSPT tool

ABSTRACT

High incident flux gradients and hot spots lead to extreme thermal stresses that may damage and reduce the lifetime of central receivers. An aiming strategy based on a single parameter, k, named aiming factor, is developed to generate symmetric flux maps about the receiver equator. By means of this k factor, ranging between 3 (generally equivalent to equatorial aiming) and 0 (alternatively aiming to top and bottom borders), the solar flux incident on the receiver and the spillage losses can be controlled. For each sector in a heliostat field, the aiming factor values causing the flattest symmetric flux maps, k_{flat}, are deterministically found with a sweep and mesh shifting procedure. Results for Dunhuang solar power tower plant show that k_{flat} is fairly constant throughout the year, except near sunrise and sunset in east and west sectors, respectively./

1. Introduction

In Solar Power Tower (SPT) plants, direct radiation is concentrated by thousands of heliostats onto a tower-mounted central receiver, where a circulating working fluid is heated to eventually produce electricity [1]. Single equatorial aiming leads to the highest receiver interception, but also to unacceptable peak fluxes that have to be avoided or minimized. For successful operation of these plants, the heliostat field aiming strategy must protect the receiver from damage (thermal stress cracking, hot spots and corrosion), at the same time that the thermal output is maximized.

As long as SPT technology is being commercially deployed worldwide, the development of efficient aiming strategies is receiving great attention from the academic community in recent years. Metaheuristic methods, such as Tabu search and Genetic Algorithm, were applied to uniform the flux distribution in flat plate [2,3] and cavity receivers [4,5]. By means of an ant colony metaheuristic, the output of concentrated photovoltaic receivers [6] and molten salt receivers [7] was optimized. Astolfi et al. [8] proposed several optimization approaches to reduce the peak flux in a cylindrical receiver. A teaching-learning-based optimization was investigated to homogenize the flux on a flat receiver [9], and a closed-loop PID control was virtually implemented on Gemasolar plant [10]. Likewise, binary integer linear programming was virtually implemented on PS10 plant to homogenize the flux distribution on the flat plate receiver [11].

In Solar Two plant, two software systems controlled the field aiming: SAPS (static aim processing system) and DAPS (dynamic aim processing system). Using the first system, the target point of each heliostat was adjusted every 10 min because of sun movement, whereas heliostats causing overheating were removed from tracking with DAPS [12]. In PSA tower plant, named CESA-1, a knowledge-based heuristic selected the optimal aim points to control the air temperature in the volumetric receiver [13]; and, a distributed optimization algorithm was recently performed to uniform the flux distribution [14].

In order to procure symmetric flux maps, Vant-Hull suggested an aiming strategy where each row of heliostats is alternatively aimed to the top and to the bottom half of the receiver [15]. This strategy was further developed by the authors in Ref. [16], where it was succinctly introduced the concept of aiming factor.

The aiming factor approach [16], that has been utilized in recent references by these [17,18] and other [10,19] authors, relies on a single parameter to aim complete fields of heliostats. Because of the close relation between k aiming factor and spillage losses, the preliminary objective of the present work is to provide a thorough analysis on the influence of k factor on flux profiles and, ultimately, on spillage losses.

Recent research evidences that uniform flux distribution in receiver tubes plays a key role in reducing the peak thermal stress

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https://doi.org/10.1016/j.energy.2018.04.002
0360-5442/

Nomenclature

AC	Cell area in the receiver mesh [m^2]
AFD	Allowable flux density [W/m^2]
AM	Mirror area of the heliostat [m^2]
BR_k	Beam radius based on k [m]
C	Concentration ratio of flux density [−] = [suns]
D	Receiver diameter [m]
DNI	Direct normal irradiation [W/m^2]
F	Flux density [W/m^2]
f	Loss factor [−]
H	Receiver height [m]
k	Aiming factor [−]
$\mathbf{n}$	Heliostat normal vector
$RMSD$	Root Mean Square Deviation
$\mathbf{s}$	Sun vector
SR	Slant range [m]
$\mathbf{t}$	Target vector
X, Y, Z	Cartesian coordinate axes
Greek symbols	
ε	Elevation angle [rad]
η	Efficiency [−]
ω	Incidence angle [rad]
σ	Gaussian error [mrad]
Subscripts	
e	Effective
h	Heliostat
i, j, p	Nodes in receiver mesh
max	Maximum
si	Image plane system of coordinates
slp	Slope
sp	Spillage
st	Target system of coordinates
sun	Sunshape
trk	Tracking
Acronyms	
DAPS	Dynamic Aim Processing System
FluxSPT	Flux Solar Power Tower software tool
MCRT	Monte Carlo Ray Tracing
PID	Proportional Integral Derivative controller
PS10	Planta Solar 10 MW
PSA	Plataforma Solar de Almería
SAPS	Static Aim Processing System
SPT	Solar Power Tower
UNIZAR	Universidad de Zaragoza tool

[20], which is the most limiting factor in the most irradiated receiver panels [17]. In this respect, the main purpose of the work is to formerly find the flattest possible flux distributions, objective for which the symmetric aiming methodology is adopted.

The manuscript is structured as follows. First, for a single heliostat it is defined the aiming factor in order to estimate the size of the beam and consequently point the heliostat. Dunhuang SPT plant, case study used throughout this work, is introduced in Section 3. Section 4 analyzes the effect of the aiming factor approach on the receiver spillage. For the whole field of heliostats, symmetric aiming is applied in Section 5. And Section 6 explores the aiming to achieve uniform flux profiles. At the end, the Appendix describes the flux map shifting procedure.

The flux distributions by heliostat fields have been computed with the convolution-projection method reported in Ref. [16] and experimentally validated in Refs. [16,21]. The resulting in-house software FluxSPT is available for free download from the link in Ref. [22]. FluxSPT currently contains three existing SPT plants of moderate, medium and large size, namely: Dunhuang, Gemasolar and Crescent Dunes.

2. Aiming factor

The proposed aiming strategy is based on a single parameter, k, named aiming factor. For a single heliostat, this Section describes: first, the estimation of the beam size as a function of k factor; and, then, the determination of the aim point. This aiming strategy is implemented in the FluxSPT software tool [22].

2.1. Beam radius

The present aiming strategy relies on a proper estimation of the size of the beam incident on the receiver. In principle, a particular size cannot be defined for the beam reflected by a heliostat. In the following, it is introduced a calculation procedure on the basis of k aiming factor.

The flux density distribution on the image plane produced by a focusing heliostat follows an essentially circular Gaussian distribution with effective standard deviation σ_e. This evidence, supported by measurements and MCRT simulations, is inherently included in well-known convolution models as: UNIZAR [23], DELSOL [24] and HFLCAL [25].

Herein, it has been adopted the analytic function on the image plane by UNIZAR, where the effective standard deviation (σ_e) results from the convolution of sunshape (σ_{sun}), mirror slope (σ_{slp}), and tracking (σ_{trk}) errors. In the effective error equation, ω_h stands for the incidence angle on the heliostat.

$$\sigma_e = \sqrt{\sigma_{sun}^2 + 2(1+\cos\omega_h)\sigma_{slp}^2 + \sigma_{trk}^2} \tag{1}$$

By analogy with a circular normal distribution, 68%, 95% and 99.7% of the total flux is within the cone of aperture angle from heliostat center equal to σ_e, $2\cdot\sigma_e$ and $3\cdot\sigma_e$, respectively. Therefore, it can be defined a factor k, generally ranging between 0 and 3, that gives an idea on the energy that lies within $k\cdot\sigma_e$, in line with the 68-95-99.7 rule for normal distribution.

The radius of the beam (BR) on the image plane (si), that normal to the main reflected ray (or $\mathbf{t}$ target vector), is derived from the cone geometry. For a given SR slant range (distance from the heliostat to the receiver), the beam radius is function of the k factor, as declared in Eq. (2). Obviously, the higher the k value, the larger the estimated beam circle is.

$$BR_k^{si} = SR\cdot\tan(k\cdot\sigma_e) \simeq SR\cdot k\cdot\sigma_e \quad (k\cdot\sigma_e << 1rad) \tag{2}$$

Fig. 1 displays the flux distribution produced by a heliostat in both a 3D view (left) and a 2D view (center), as well as the vertical profile through the target point (right). Red circles outline the beam circumferences for three k values: 1, 2 and 3. Instead of flux density, F, in W/m^2, the distribution is quantified in concentration ratio of flux density, C, taking advantage of its independence of instantaneous direct normal irradiation, DNI. The concentration ratio of flux density is dimensionless, as derived from Eq. (3), while also can be expressed as the number of instantaneous suns focusing on the