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Optimal heliostat aiming strategy for uniform distribution of heat flux on the receiver of a solar power tower plant

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A B S T R A C T

Temperature distribution on the receiver surface of a solar power tower plant is of great importance. High temperature gradients may lead to local hot spots and consequently failure of the receiver. The temperature distribution can be controlled by defining several aiming points on the receiver surface and adjusting the heliostats accordingly. In this paper, a new optimization algorithm which works based on the principles of genetic algorithm is developed to find the optimal flux distribution on the receiver surface. The objective is to minimize the standard deviation of the flux density distribution by changing the aiming points of individual heliostats. Flux distribution of each heliostat is found by using the HFLCAL model [1], which is validated against experimental data. The results show that after employing the new algorithm the maximum flux density is reduced by an order of magnitude. The effects of number of aiming points and size of the aiming surface on the flux density distribution are investigated in detail.

1. Introduction

In a solar power tower plant, the receiver plays an important role of intercepting reflected solar radiation from the heliostat field and transferring thermal energy to the heat transfer fluid. The main challenge associated with this process is the high temperature gradient at the receiver surface which may lead to local hot spots, and consequently, degradation and failure of the receiver [2]. The temperature distribution on the receiver surface depends on the design of the receiver, thermophysical properties of the absorber, heat transfer fluid, and the heat flux distribution [3]. Distribution of the heat flux on the receiver surface is the only factor which is closely connected with the performance of the heliostat field. Therefore, it can be controlled by defining several aim points and adjusting the heliostats.

Two aiming techniques were described by Kistler [4]. One technique, which is called one-dimensional smart aiming, is to focus the heliostats along the height of the receiver until the spillage loss starts to increase. The heliostats that are closer to the tower are usually focused at the top or the bottom of the receiver while those which are farther are aimed closer to the center of the receiver surface. The two dimensional smart aiming is similar, except the images are distributed in two dimensions. This technique is usually recommended for rectangular cavity apertures or flat plates, as using other shapes of the receivers may lead to increase in the spillage loss. Although these methods perform well, the technological development of thermal receivers and increasing size of the power plants demand more sophisticated aiming strategies.

In a paper presented by Garcia-Martin et al. [5] an automatic closed-loop control method was developed to optimize the temperature distribution within a volumetric receiver at PSA power plant. The method is based on measuring the temperature at different points on the receiver surface and transferring the power from one area to another by changing the aiming points of the heliostats when the temperature reaches a maximum tolerance value. In another study, Salomé et al. [3] presented an open loop approach to control the flux distribution on the surface of a flat plate receiver. In this method, a set of aiming points are defined and a grid is formed on the surface of the receiver. Then, an optimization algorithm called “TABU+ specific neighborhood” is used to find the best aiming point for each heliostat. The objective is to minimize the flux spread, F_{max}–F_{min}, while keeping the spillage loss above a predetermined value. At the first step all heliostats are focused on the center of the receiver. At each iteration, one heliostat is selected and its aiming point is changed. If the modification leads to an improvement in the objective function, it will be saved for the next iteration. It was shown in the paper that the spread of the flux density is decreased by 43% with an added spillage loss of 10% using the proposed algorithm.

Optimization in engineering design has always been a subject of interest to engineers. The genetic algorithm (GA), as one of the

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Nomenclature

A_m	mirror surface area (m^2)
$\cos w$	cosine factor
D	distance between the center of the heliostat and the aim point (m)
d	square root of the heliostat area (m)
F	flux density $\left(\frac{kW}{m^2}\right)$
F_{max}	maximum flux density $\left(\frac{kW}{m^2}\right)$
F_{min}	minimum flux density $\left(\frac{kW}{m^2}\right)$
f	focal distance (m)
f_{at}	atmospheric attenuation factor
H_t	image dimension in tangential plane
I_D	direct normal irradiation $\left(\frac{kW}{m^2}\right)$
m	number of heliostats
n	number of aiming points
P_h	total power sent by a heliostat
P_c	crossover probability
P_m	mutation probability
P_{mm}	second mutations probability
$\cos rec$	incidence cosine of the reflected central ray from the heliostat on the receiver surface (°)
W_s	image dimension in sagittal plane
ρ	reflectivity factor
σ_{HF}	effective deviation (mrad)
σ_{sun}	sunshape error (mrad)
σ_{bq}	beam quality error (mrad)
σ_{ast}	astigmatic error (mrad)
σ_t	tracking error (mrad)
σ_s	mirror slope error (mrad)

most popular optimization techniques, has been found very useful in solving complex real-world design optimization problems since it works with a population of candidate solutions, not a single point in the search space. This helps to avoid being trapped in local optima as long as the diversity of the population is well preserved [6].

Over the past decade, genetic algorithm has been extensively used for the optimization of solar thermal systems [7]. Varun and Siddhartha used GA to optimize the thermal performance of a flat plate solar air heater [8]. Loomans and Visser applied GA for the optimization of a solar water heater system [9]. Godarzi et al. [10] employed GA to optimize the performance of a solar absorption chiller. GA and artificial neural network were used together by Kalogirou [11] to find the optimum combination of the collector area and storage-tank size for a solar industrial process heat system. Baghernejad and Yaghoubi [12] conducted an exergoeconomic analysis and optimization of a 400 MW integrated solar combined cycle system using GA. Ahmadi et al. [13] investigated multi-objective optimization of a solar dish Stirling engine using GA by considering three objective functions, i.e. output power, overall thermal efficiency, and rate of entropy generation. Cabello et al. [14] developed a program based on GA to find the optimal size of the solar collector area, thermal storage and power of the auxiliary system in a direct steam generation power plant.

In this paper, a new optimization approach based on the principles of GA is proposed to find the optimal flux distribution on the receiver surface of a solar power tower plant. The objective is to minimize the standard deviation of the flux density distribution on the receiver surface by changing the aiming points of individual heliostats. The HFLCAL method [1] is used to find the flux distribution of individual heliostats and is validated against experimental data. After presenting the optimization methodology, the final results are provided and the influences of different parameters are investigated.

2. Flux density model

The flux density on the surface of a receiver can be found numerically or analytically. In the numerical approach, called Monte Carlo ray tracing method, a large number of rays are generated and traced through different optical stages. A flux map on the receiver surface can be generated from the intersection of the reflected rays and the surface. SolTrace software [15], developed by the National Renewable Energy Laboratory (NREL), can be used to predict the flux density distribution on the receiver surface accurately using the Monte Carlo ray tracing method. Although the numerical method is very accurate, it requires large computational time.

Two well-known analytic models that are used to evaluate the flux density and interception efficiency are the UNIZAR model from the Universidad de Zaragoza [16] and the HFLCAL model from DLR (the German Aerospace Center) [1]. According to [17], both of these models are appropriate tools though HFLCAL is simpler and slightly more accurate than UNIZAR. The HFLCAL model is used in this study to evaluate the flux density distribution of each heliostat on the receiver surface. The flux map resulting from the entire field is generated by superimposing the flux densities of the individual heliostats.

2.1. HFLCAL Model

In the HFLCAL model a circular normal distribution is used to find the flux density distribution on the receiver surface, given as [3]:

$$F(x,y) = \frac{P_h}{2\pi\sigma_{HF}^2} \exp\left(-\frac{(x-x_t)^2 + (y-y_t)^2}{2\sigma_{HF}^2}\right) \tag{1}$$

where P_h is the total power reflected by a heliostat, σ_{HF} is the effective deviation, and (x_t, y_t) are the coordinates of the aiming point on the receiver surface. P_h is given as:

$$P_h = I_D \cdot A_m \cdot \cos w \cdot f_{at} \cdot \rho \tag{2}$$

where I_D is the direct normal irradiation $\left(\frac{kW}{m^2}\right)$, A_m is the mirror area, $\cos w$ is the cosine factor of the angle between the sun ray and the normal to the heliostat surface, f_{at} is the atmospheric attenuation factor, and ρ is the reflectivity of the heliostat.

The effective deviation, σ_{HF}, is the result of the convolution of the four Gaussian error functions, namely, the sun shape error due to the non-uniform distribution of the solar intensity across the sun disk (σ_{sun}), the beam quality error due to the mirror slope error (σ_{bq}), the astigmatic error representing any extra deformation of the reflected ray if the incident ray is not parallel to the mirror's normal (σ_{ast}), and the tracking error (σ_t). σ_{HF} is given as [17]:

$$\sigma_{HF} = \frac{\sqrt{D^2\left(\sigma_{sun}^2 + \sigma_{bq}^2 + \sigma_{ast}^2 + \sigma_t^2\right)}}{\sqrt{\cos rec}} \tag{3}$$

where D is the distance between the center of the heliostat and the aim point, and cos *rec* represents the cosine of the angle between