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Multi-objective optimization of the aiming strategy for the solar power tower with a cavity receiver by using the non-dominated sorting genetic algorithm

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HIGHLIGHTS

- Multi-objective optimization is performed for the aiming strategy in SPT.
- Trade-off between uniformity of solar flux distribution and optics loss is obtained.
- The solar flux distribution inside the cavity receiver is homogenized.
- Solar flux distribution is flattened at a minimum cost of optics loss.

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ABSTRACT

The extremely non-uniform solar flux distribution in the solar power tower plant can badly cause some crucial problems for the solar receiver such as the local hot spot, the thermal stress, and the thermal deformation. Homogenization of the solar flux distribution is an effective method to avoid these problems, and has become an important research topic. The objective of the present study is to homogenize the solar flux distribution on the inner surfaces within the cavity receiver while keeping the optics loss as low as possible by replacing the conventional single-point aiming strategy with optimal multi-point aiming strategies. Multi-objective optimizations of the aiming strategy for the solar power tower with cavity receivers are performed by using the non-dominated sorting genetic algorithm. The distribution of the aiming points on the cavity aperture and the allocation of the aiming points for each heliostat are optimized simultaneously. The following conclusions can be made: (1) The uniformity of the solar flux distribution on the aperture does not always signify the uniformity of the solar flux distribution on the inner surfaces, where the later one is what we are truly concerned about. Therefore, the optimization of the aiming strategy should take charge of the solar flux distribution on the inner surfaces rather than on the aperture. (2) The multi-objective optimization can provide the trade-off between the non-uniformity of the solar flux distribution and the optics loss in the form of Pareto optimal fronts. (3) The optimal aiming strategies provided by the multi-objective optimization can significantly homogenize the solar flux distribution on the inner surfaces within the cavity at a minimum cost of optics loss. (4) For the optimal aiming strategies at all time except the noon, there exists a west-east asymmetry of the aiming point distribution on the aperture. Moreover, the asymmetry gets less obvious as the time gets closer to the noon.

1. Introduction

In recent decades, the concentrating solar power (CSP) technologies have got more and more attention and made significant development [1–3] due to the increasing energy and environmental problems [4,5]. In CSP systems, the solar collectors are required to collect the scattered solar energy and concentrate it to achieve a higher energy density. According to the types of concentrators, there are mainly four categories of CSP systems: solar power tower (SPT) system, solar parabolic dish (SPD) system, parabolic trough (PT) system, and linear Fresnel

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Nomenclature

A	transformation matrices
A_s	solar azimuth angle (rad)
A_h	azimuth angle of normal vector of heliostat's central point (rad)
B	Gebhart factor
d	distance (m)
D	depth (m)
DNI	direct normal irradiance ($W \cdot m^{-2}$)
E_h	pitch angle of normal vector of heliostat's central point (rad)
F	solar flux ($kW \cdot m^{-2}$)
H	height (m)
N	number
P	aiming point
PF	peak solar flux ($kW \cdot m^{-2}$)
Q	solar energy (kW)
s	surface area (m^2)
w	solar energy carried by every solar ray (kW)
W	width (m)
(x,y,z)	Cartesian coordinates (m)
(U_x, U_y, U_z)	Cartesian vector

Greek symbols

α	absorptivity of surface
α_s	solar altitude angle (rad)
ρ	reflectivity
φ	latitude (°)
γ	longitude (°)
δ	declination of the sun (rad)
ω	solar hour angle (rad)
ϕ	installation angle of receiver (°)
σ	standard deviation (mrad)
σ_F	non-uniformity indicator of the solar flux
σ_F^*	normalized non-uniformity indicator of the solar flux
η_{loss}	percentage of the optics loss
η_{loss}^*	normalized percentage of the optics loss
ζ	random number
θ	angle between incident ray and normal vector of heliostat surface (rad)
θ_h	azimuth angle of heliostats (rad)
θ_i	pitch angle of incident ray in incident-normal coordinate system (mrad)
φ_i	azimuth angle of incident ray in incident-normal coordinate system (mrad)

Subscripts

a	aperture of cavity receiver
ap	aiming point
g	ground coordinate system
h	heliostat or heliostat coordinate system
i	incident-normal coordinate system
in	inner surfaces of the cavity receiver
r	receiver or receiver coordinate system
e	element
t	tower
k	heliostat indices
i,j,m	surface element indices
atm	attenuation
act	active
abs	absorbed
aff	affiliated heliostat
ast	astigmatic effect
tra	tracking error
cos	cosine
slo	slope error
tot	total
mai	main heliostat

reflector (LFR) system. The concentrated solar energy distribution in the solar receivers is extremely non-uniform, which consequently leads to the non-uniform temperature distribution (high local temperature and large temperature gradient). As a result, the solar receiver faces the following challenges [6–14]: (1) The high local temperature will cause the degradation of the absorbing coating, the degeneration of the heat transfer fluid, and even the overburning of the absorber; (2) The large temperature gradient will result in great thermal stress and thermal deformation, and even the structural failure of the solar receiver. With the development with $S-CO_2$ Brayton cycles in SPT, higher operation temperature is required [15–17]. Consequently, the challenges caused by the non-uniform solar flux distribution will be more severe. The challenges have attracted many scholar's attention, and numerous solutions have been proposed to homogenize the solar flux distribution in the solar receiver. For the PT system, Wang and He et al. [18] proposed a novel type parabolic trough solar collector to homogenize the solar flux distribution, in which the absorber was removed from the focal line of the parabolic concentrator and a secondary reflector was added, therefore, the concentrated solar flux can be distributed on both the top and bottom surfaces of the absorber tube; Tsai et al. [19] proposed a variable focus parabolic trough concentrator and optimized it to homogenize the solar flux distribution on the absorber tube. For the LFR system, a secondary reflector with two parabolic wings was used to obtain a relatively uniform distribution of the solar flux along the circumference in the study of Grena et al. [20]; Qiu and He et al. [21] studied the effects of five different schemes of aiming lines on the uniformity of the solar flux distribution. For the SPD system, Shuai et al. [22] proposed an upside-down pear cavity receiver with the aim to improve the uniformity of the solar flux distribution. For the SPT system, Tu et al. [23,24] made efforts to homogenize the solar flux distribution in the cavity receiver by modifying the geometric size of the receiver or by optimizing the solar absorptivity distribution on the absorber surface. In a conventional SPT system, all of the heliostats in the solar field aim at the center of the cavity receiver aperture or the equator of the external receiver [25–27]. Although the conventional single-point aiming strategy can ensure the lowest spillage loss, it can lead to an extremely non-uniform solar flux distribution. Therefore, replacing the single-point aiming strategy with the multiple-point aiming strategy is likely to be another effective approach to improve the uniformity of the solar flux distribution in the SPT system. The present paper will focus on the discussion about the multiple-point aiming strategy for homogenizing the solar flux distribution in the SPT system.

Several studies have been carried out to homogenize the solar flux distribution and reduce the peak solar flux by adopting the multi-point aiming strategy in SPT systems [9,10,27–33], some of which specifically dealt with the solar flux homogenization for the cavity receiver. Qiu and He et al. [33] recommended a five-point aiming strategy in the SPT system with cavity receiver. Their results showed that the five-point aiming strategy could significantly homogenize the solar flux distribution compared to the conventional single-point aiming strategy. However, their study was not based on an optimization process. Belhomme et al. [28] developed a method to optimize the heliostat aim points selection based on the ant colony optimization metaheuristic for the multi-point aiming strategy applied in the SPT system, with the aim