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Multi-objective optimization of the solar absorptivity distribution inside a cavity solar receiver for solar power towers

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ABSTRACT

The solar flux distribution on the receiver of a solar power tower is usually not uniform, which can cause a number of problems for the energy efficiency and system safety, particularly, the local hot spot and the thereby caused thermal stress and thermal deformation. Therefore, homogenization of the solar flux distribution is critical and important. The objective of the present study is to homogenize the solar flux distribution while keeping the optical loss (reflection loss) as low as possible through optimization of the distribution of the solar absorptive coating. An integrated approach coupling the Monte-Carlo ray tracing method and the Gebhart method is applied to simulate the process of the solar radiation transfer in the solar power system. The multi-objective optimization of the distribution of solar absorptivity is performed by using the non-dominated sorting genetic algorithm. The following conclusions are drawn from the study. (1) The improvement of the uniformity of the distribution of solar flux can lead to more reflection loss due to the fact that more solar energy is distributed on the position with greater view factor to the aperture; (2) The Pareto optimal front obtained from the multi-objective optimization provides the trade-off between the non-uniformity of the solar flux distribution and the reflection loss. (3) The optimal solar absorptivity distribution provided by the Pareto optimal front can significantly flatten the solar flux distribution at a minimum cost of optical loss. (4) The optimal distribution of the solar absorptivity is approximately opposite to the distribution of solar flux projected onto the active surfaces from the heliostat fields.

1. Introduction

Due to the increasing energy consumption and the growing environmental problem in the recent decades, the world is experiencing a transition from fully using fossil-based energy to using more renewable energy and less fossil fuels (Avila-Marin et al., 2013; Behar et al., 2013; Li and Tao, 2017). Concentrating solar power (CSP) technology, as one of the promising technologies of renewable energy, has got more and more attention in the recent time(Du et al., 2017a; Ho and Iverson, 2014; Li et al., 2017). Among all the CSP technologies, the solar power tower (SPT) can offer the greatest potential for the high efficiency and the ease of scaling up. The cavity receiver is one of the widely used receivers in a SPT. In a conventional cavity SPT plant, the concentrated solar energy is not uniformly distributed inside the cavity receiver. The non-uniformity of the solar flux distribution in the SPT system is more severe due to its point-focusing than those in other types of CSP including parabolic trough collectors and linear Fresnel reflectors. The extremely non-uniform solar flux distribution can lead to the non-uniform temperature distribution inside the receiver. The thereby caused large temperature gradient can cause the following safety problems of solar receivers (Du et al., 2016; He et al., 2016; Irfan and Chapman, 2009; Sánchez-González et al., 2016; Salomé et al., 2013; Wang et al., 2010; Wang et al., 2015; Zheng et al., 2015). First, a high local temperature tends to cause the degradation of the absorptive coating, decomposition of the heat transfer fluid, and over-heating of the absorber tube. Second, a large temperature gradient on the absorber tubes will lead to great thermal stress and thermal deformation, and even structural failure of the solar receiver. Recently, with the development of SPT technologies with $S{-}CO_2$ Brayton cycles (Besarati and Yogi Goswami, 2013; Besarati et al., 2015; Wang and He, 2017; Wang et al., 2017a), higher operation temperature is desired, and consequently the challenges caused by the non-uniform solar flux distribution will be more severe.

The problems caused by the non-uniform distribution of concentrated solar flux have drawn significant attention, and several solutions of homogenizing the solar flux distribution have been proposed. Optimizing

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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	the number of photon
p	position
Q	solar energy (kW)
S	area of each zone used in the optimization process (m^2)
s	area of each element used in the solar flux calculation process (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
$\eta_{ref,loss}$	percentage of the reflection 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)

subscript

a	aperture of cavity receiver
ave	average
g	ground coordinate system
h	heliostat or heliostat coordinate system
i	incident-normal coordinate system
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
eff	effective
tra	tracking error
cos	cosine
slo	slope error
tot	total
mai	main heliostat

the geometry of the cavity receiver is one classical approach to control the solar flux distribution. Tu et al. (Tu et al., 2014) investigated the effect of the cavity depth on the solar flux distribution and determined a suitable depth for a given cavity receiver. Daabo et al. (Daabo et al., 2016) analyzed both the solar flux distributions and the optical efficiencies of three cavity receivers with different geometric shapes (cylindrical, conical, and spherical). Another effective approach to flatten the solar flux distribution in SPT is to substitute the single-point aiming strategy with the multi-point aiming strategy which can reduce the peak value and the gradient of the solar flux distribution at the expense of optical efficiency (Astolfi et al., 2016; Belhomme et al., 2013; Besarati et al., 2014; Binotti et al., 2016; Qiu et al., 2016; Sánchez-González et al., 2016; Sánchez-González and Santana, 2015; Salomé et al., 2013; Yu et al., 2014; Wang et al., 2017b). For example, Salomé et al. (Salomé et al., 2013) optimized the multi-point aiming strategy to flatten the solar flux distribution on the receiver aperture based on TABU meta-heuristic optimization algorithm. The additional spillage loss was remained lower than a threshold in their optimization process. Besarati et al. (Besarati et al., 2014) also performed optimizations of the multi-point aiming strategy by using genetic algorithm to minimize the flux spread (i.e. the difference between the maximum value and the minimum value of the solar flux) on the receiver aperture while keeping the spillage loss lower than an acceptable value. Optimizing the solar absorptivity distribution of the cavity receiver can also be an alternative option to flatten the solar flux distribution, which has not been well considered. Most of the previous studies related to the optimization of solar absorptivity aimed to improve the receiver efficiency by adopting novel coating with high solar absorptivity. Only the work carried out by Tu et al. (Tu et al., 2015) focused on improving the uniformity of the solar flux distribution by optimizing the solar absorptivity of the coating inside the solar receiver. However, changing the solar absorptivity of the coating may result in the change of the reflection loss. Unfortunately, the change of the reflection loss caused by the change of the solar absorptivity was not taken into account in their work (Tu et al., 2015). In fact, the optimization method of the solar absorptivity distribution was not mentioned in their work.

The objective of the present paper is to homogenize the solar flux distribution inside the cavity receiver while keeping the optical loss as low as possible by optimizing the distribution of the solar absorptivity. An integrated approach of simulation coupling the Monte Carlo ray tracing (MCRT) method and the Gebhart method published in the author's previous work (Wang et al., 2016) is used to simulate the entire solar radiation transfer process in SPT, including the solar radiation transfer process in the heliostat field and the multiple-reflection process of solar rays inside the cavity. The multi-objective optimization of the solar absorptivity distribution will be performed by using the non-dominated sorting genetic algorithm (NSGA-II). The trade-off between the non-uniformity of the solar flux distribution and the reflection loss in the form of Pareto optimal front is provided and the optimal distribution of the solar absorptivity is recommended for the particular case studied.