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Analysis and improvement of solar flux distribution inside a cavity receiver based on multi-focal points of heliostat field

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HIGHLIGHTS

- A model of non-central focal process based on an arbitrary heliostat was proposed.
- A new grouping method for the heliostat field was proposed.
- A solar flux distribution inside the cavity receiver was optimized.

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ABSTRACT

The strong flux variations distributed on the surfaces of receiver during its service life can intensify material aging and thus deteriorate the thermal performance of material. Generally, the single focal point heliostat field, i.e., focusing at the centre of the aperture of a cavity receiver, could possibly result in an irregular flux distribution, which would have a very high peak value of flux density on the inner sides of the cavity receiver at a certain time of sun tracking. In order to give a maximum protection to the central receiver, in this paper, by taking the 1 MWe "DAHAN" solar tower power plant as the investigating subject, a multi-focal point model for finding the optimum configuration of focal points using an arbitrary heliostat has been developed. Based on the model, the pattern of solar flux distribution for different zones of the heliostat field is investigated to study how the pattern changes with date and time. From the simulation results, a new grouping method for the layout of the focal points of a heliostat field inside the cavity receiver is proposed. Then a popular optimization algorithm based on the TABU meta-heuristic method is developed to find the optimal flux distribution on the receiver surface. The objective is to flatten the flux distribution as much as possible by changing the aiming points of different groups. Simulation results show that the new multi-focal points system can provide a more secure way to safeguard the operation of the receiver system comparing to the traditional single focal point system.

1. Introduction

With the rapid economic growth, most of the countries have to face the increasing pressure in dealing with the resource depletion and global warming. Concentrating solar power (CSP), which is considered as the relatively inexpensive, more efficient and large capacity type of renewable energy technology, is gradually recognized and accepted by more and more countries [1–3]. According to the International Energy Agency (IEA), the foreseen CSP scenarios for the next years are very promising: 20 GW of installed capacity by 2020 and 800 GW by 2050 [4], and many former research projects have turned into profitable industrial power plants in the USA, Spain, and other countries [5].

Up to now, a great number of solar tower power plants have been built in many countries. However, most of them belong to the experimental type, and only several of them (such as PS20 and Gemasolar) have been commercialized in the world [6]. Life time of components is one of the technological bottle-necks in the development of solar tower power plant technology. The receiver, which is subjected to high and variable concentrated solar flux density is particularly affected: High, variable and non-homogeneous solar flux on the solar receiver walls results in strong stresses because of high temperatures, thermal shocks and temperature gradient that contribute to the reduction of the life time of this key component [7]. In order to avoid this situation and maintain the local flux density within the permissible range, it is inevitable to distribute the aim points of the heliostats in some way on the receiver aperture. When all heliostats of the solar field aim at the centre of the receiver aperture, the highest intercept is typically

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Nomenclature

A	solar azimuth (rad)
A'	azimuth of heliostat(rad)
ap	aiming point
$\underline{a}$	solar elevation (rad)
$\vec{a}$	solar ray unit vector (/)
E'	zenith of heliostat (rad)
ht	height of the tower (m)
M, m	non-central focal point on the aperture (/)
$\vec{n}$	unit normal vector (/)
N	number
P, p	arbitrary point on the surface of the heliostat (/)
Q	assigned heliostat in the heliostat field (/)
S	solution space(/)
X, x	x-coordinates (m)
Y, y	y-coordinates (m)
Z, z	z-coordinates (m)

Subscripts

cr	cavity receiver
g	ground coordinate system
$H/helio$	heliostat
h	heliostat coordinate system
sun	the sun
si	solar incident ray
sn	unit normal vector
sr	solar reflected ray
t	target coordinate system

obtained, but this constellation usually results in very high peak levels of the flux density [8]. Shifting a heliostat aim point off the centre of the aperture mostly results in an additional intercept loss. But, the best receiver performance is not necessarily achieved at the highest intercept. Depending on design and operation of the receiver, its efficiency depends on the flux level and profile [9].

"DAHAN", the pioneer MW solar tower power plant in China, has been erected successfully for two years. The central receiver with the cavity type using water/steam as the working fluid is adopted to collect the concentrated energy [10,11]. In the past two years, the tracking method with the single focal point located at the centre of the aperture was used to collect the concentrated energy. It was found that the incident solar flux was mainly distributed on the rear plane(central) as well as on the two lateral planes (left and right) inside the cavity receiver, with the peak flux density found at the centre of the rear plane while the lateral planes receiving just about half of the peak value by comparison [12]. In such a case, several heat absorbing tubes in the cavity receiver was deformed or bent and it posed a big risk to the safe operation of the receiver system. To ensure the safety of the plant, a new grouping method with multi-focal points in the tracking strategy of the heliostat field is highly needed!

A considerable effort has been made in the tracking strategies of the existing solar tower power plants for the last twenty years. For the Solar Two plant in Barstow (USA), two software systems-SAPS (static aim processing system) and DAPS (dynamic aim processing system) have been developed for the receiver protection mechanism[13–15]. During the operation, each heliostat is assigned to a predetermined aim level (top, centre or bottom) to provide a reasonable flux density in the receiver; For the CESA-I from CIEMAT-PSA (Spain), in order to avoid deterioration due to excessive thermal gradients in the receiver, maintaining an adequate flux distribution has been performed at the PSA by adjusting of individual heliostat group aiming-point coordinates and the number of heliostats in each group to keep absorber temperatures within the desired range[16]. For the THEMIS plant in France, An improved TABU optimization meta-heuristic method was developed to select the best aiming point for each heliostat. The goal is to flatten the flux density distribution while keeping the spillage within a reasonable range [7].

From the literature, it is known that the temperature distribution of the surfaces inside the receiver mainly depends on the specific geometry of the absorber, on the manufacturing materials, on the specific heat transfer performances between the absorber and the heat transfer fluid, and on the distribution of concentrated solar flux on the absorber [7]. The first three are strongly dependent on the design of the receiver. The latter is much more generic, it mainly depends on the management of the tracking and other factors. In this paper, our approach mainly aims at improving the management of the tracking. The objective is precisely devoted to the research of an optimized flux density distribution inside the receiver according to an open loop process, to flatten as much as possible the distribution of flux density on the inner planes and to minimize in the same time the spillage.

2. Description of the heliostat field

The heliostat field of "DAHAN" plant is composed of 100 heliostats, each with a size of 10 m by 10 m. For each heliostat, the mirror plane is spliced into 64 pieces of smaller curved surfaces, which finally form a big spherical surface (as shown in Fig. 1). The size, the curvature, the position, the orientation of these facets and the focal length of the supporting structure are known from the design specifications of each individual heliostat.

The final heliostat field which adopts the radial staggered layout is shown in Fig. 2. During operation, the low-density solar irradiation is reflected and concentrated into the cavity receiver to heat the working fluid, which is located at the 78 m height of the tower which has a full height of 118 m. All the heliostats arranged in 16 rows are set up in the area 300 m $\times$ 350 m with the receiver tower facing north.

As to the central receiver, the cavity structure is adopted to collect the concentrated energy, which is absorbed by the flowing working fluid (water/steam). The final geometry of the cavity

Fig. 1. Heliostat shape of "DAHAN" plant.