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A comprehensive model for analysis of real-time optical performance of a solar power tower with a multi-tube cavity receiver

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HIGHLIGHTS

- An optical model for a solar power tower with a multi-tube receiver is developed.
- Solar radiation transfer from heliostat field to receiver is simulated integrally.
- Visual results of detailed solar flux distribution in the receiver are illustrated.
- Effects of tracking-error model and aiming strategy are investigated and analyzed.
- Real-time efficiency is evaluated, and yearly efficiency of 65.9% is revealed.

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ABSTRACT

A comprehensive model and corresponding code named after SPTOPTIC for analysis of the real-time optical performance of a Solar Power Tower (SPT) with a Multi-Tube Cavity Receiver (MTCR) were developed using Monte Carlo Ray Tracing (MCRT) method. After validation, the model was used to study the optical performance of the DAHAN plant. The model-obtained results show that the solar flux in the MTCR exhibits a significant non-uniformity, showing a maximum flux of 5.141×10^5 W m^{-2} on the tubes. A comparison of the tracking models indicates that it is a good practice to treat the tracking errors as the random errors of the tracking angles when considering the random effect on the solar flux distribution. Study also indicates that multi-point aiming strategy of tracking helps homogenizing the flux and reducing the energy maldistribution among the tubes. Additionally, time-dependent optical efficiencies were investigated, and the yearly efficiency for the energy absorbed by the tubes was found to be 65.9%. At the end of the study, the cavity effect on the efficiency was revealed quantitatively, which indicates that the optical loss can be reduced significantly by the cavity effect, especially when the coating absorptivity is relatively low. It is concluded that the present model is reliable and suitable for predicting both the detailed real-time solar flux and the real-time efficiency of SPT.

1. Introduction

Global energy consumption has increased rapidly with the economic growth over the past half century, and it has resulted in not only the tight global supply but also serious global environment issues. For example, the global warming caused by carbon dioxide emitted through fossil fuel combustion has become a pressing issue for years [1–3]. For solving these problems, renewable energy sources, including solar energy, wind energy, bioenergy, hydropower, geothermal energy, ocean energy, etc., are considered to be highly competitive candidates. Among these candidates, solar energy is the most bountiful resource. Efficient utilization of solar energy is being considered as one of the promising solutions to the challenges [4–8]. The Concentrating Solar Power (CSP) technology, mainly including the Solar Power Tower (SPT) [9–11], Parabolic Dish Collector [12–15], Parabolic Trough Collector [16–19], and linear Fresnel reflector [20–22], has become a promising choice to utilize solar energy during the past few decades [23,24]. Relatively, the SPT is considered as an advanced and promising technology for large scale utilization of solar energy [25].

A typical SPT consists of a heliostat field, a receiver mounted on a tower, thermal energy storage and conversion modules. There are four typical configurations of receivers including Multi-Tube Cavity Receiver (MTCR), Multi-Tube External Receiver (MTER), volumetric receiver, and direct-absorption receiver for SPT [26–28]. Among

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Nomenclature

A*, *B*, *C*, *D*, *E	aiming points of the heliostats
A_s	solar azimuth (rad, °)
A_h	azimuth of heliostat's center normal (rad, °)
DNI	Direct Normal Irradiance (W m^{-2})
d	coordinate value for aiming points (m)
e_p	power carried by each photon (W)
$E_t(i)$	power absorbed by *i*th tube (W)
G	tower base
H	center of each heliostat
H_o	height of aperture center (m)
I*, *N*, *R	incident/normal/reflection vector
$\boldsymbol{M}_1 \sim \mathbf{M}_{14}$	matrix
L_h	height of the heliostat (m)
n_t, n_h	number of absorber tubes/heliostats
N_p	total number of the photon traced in the field
N_{day}	ordinal number of a day in a year
O	aperture center
P	point
Q	solar power (W)
q_l	local solar flux (W m^{-2})
$\boldsymbol{R}_{te}$	tracking error (rad)
S_e	area of each element (m^2)
t_s	solar time (h)
W_h	width of the heliostat (m)
X, *Y*, *Z*	Cartesian coordinates (m)

Greek symbols

α_s	solar altitude (rad, °)
α_h	altitude of heliostat's center normal (rad, °)
α_r	altitude of the MTCR (rad, °)
α_t, α_w	absorptivity of coating/cavity wall
δ	declination (rad, °)
η	efficiency (%)
η_{att}	atmospheric attenuation (%)
θ, θ_t	angle variables on the tubes (°)
θ_i	incident angle on surface (rad, °)
θ_h	heliostat's azimuth in the field (rad, °)
ξ	uniform random number between 0 and 1
$\rho_{t,s}$, $\rho_{t,d}$	specular/diffuse reflectance of coating
ρ_{h1}, ρ_{h2}	reflectance/cleanliness of heliostat
$\rho_{w,s}$, $\rho_{w,d}$	specular/diffuse reflectance of the wall
σ_E	energy maldistribution index among the tubes (%)
σ_{te}, σ_{se}	standard deviation of tracking/slope error (mrad)
φ	local latitude (rad, °)
ω	hour angle (°)

Subscripts

g, h, r, t, w, l	ground/heliostat/receiver/tube/wall/local parameter
i	instantaneous or incident parameter
d,y	daily/yearly parameter
T,H,R	tube/heliostat field/receiver symbol for efficiency

these configurations, the MTCR has been widely applied for the high efficiency [29]. In the SPT using a MTCR, the heliostats will track the sun and concentrate the sun rays into the MTCR firstly. Then, the solar radiation will be absorbed by the absorber tubes and walls after multiple reflections. It is commonly known that the absorbed solar flux on the tubes is exceedingly uneven and varies greatly over time, which would result in extreme fluctuant non-uniform temperature and stress, and lead to negative effects on the performance and safety of the system [30–32]. Hence, the accurate simulation of the real-time solar flux in MTCR and real-time optical efficiency of the system is of great importance for the performance optimization, system design, and safe operation of the SPT [33,34].

Many studies have focused on this topic, and computer codes have been developed, such as UHC, DELSOL and HFLCAL based on convolution methods, MIRVAL, HFLD and SOLTRACE based on Monte Carlo Ray Tracing (MCRT) [33,35]. In convolution methods, the solar flux concentrated by an elementary mirror is considered with an equivalent error cone calculated by convolutions of Gaussian distributions of the sun shape, the slope and tracking errors of the mirror [35]. MCRT is a statistical method in which a number of random solar rays are generated and traced in the collector [36]. In MCRT, the sun shape and the slope and tracking errors of the surfaces are calculated by probability density functions. The interactions (absorption, reflection, refraction, etc.) with the surfaces are determined by Monte Carlo method for each ray. The flux in an elementary surface in the receiver is proportional to the number of rays absorbed in the element. These tools have also been applied in performance prediction and optimization of the SPT. Vant-Hull et al. [34] used UHC to design the aiming strategies and control the incident flux on the cylinder receiver of Solar Two plant. Salomé et al. [9] used HFLCAL to control the incident flux on the MTCR's aperture of THEMIS plant. Rinaldi et al. [37] computed the incident flux on the simplified tube panels of a MTCR in PS10 by DELSOL3. Mecit et al. [38] used MIRVAL to compute the incident flux on the aperture of a particle receiver in the heliostat field at the National Solar Thermal Test Facility of Sandia National Laboratories. Yao et al. [39] developed HFLD and used it to compute the incident flux on the MTCR's aperture in DAHAN plant and optimize the heliostat field. Similar work has been done for DAHAN by Yu et al. [40], and the time-dependent incident flux on the simplified tube panels was revealed. Yellowhair et al. [33] used SOLTRACE to evaluate some novel complex receivers with fins for the enhancement of the solar radiation absorption. Sanchez-Gonzalez and Santana [41] also used SOLTRACE to simulate the incident flux on a cylinder receiver, and the results are used to validate a projection method for flux prediction.

Garcia et al.[35] indicated that the convolution methods and most MCRT models are limited to standard receiver geometries such as flat plate, cylinder, and simplified cavity receiver without considering the tubes and cavity effect, although they can predict the real-time optical performance which includes the real-time flux and efficiency. It is also found that there is almost no limit on geometries in SOLTRACE. However, it has no function to predict the real-time performance, because the sun position and heliostat tracking angles cannot be updated automatically in the code. The current status is that no studies have developed a model to manage both the complex geometry with complex optical processes in the MTCR of a SPT and the prediction of real-time optical performance.

To provide better studies to the optical system of SPT, present work focuses on developing a comprehensive optical model using Monte Carlo Ray Tracing (MCRT) [36,42]. The main contributions are summarized as:

(1) The originality of this work is that an optical model which can manage both the complex geometry with intricate optical processes in a Solar Power Tower (SPT) using a Multi-Tube Cavity Receiver (MTCR) and the prediction of the real-time optical performance which consists of the real-time flux and optical efficiency was developed. A realistic SPT was simulated to illustrate the application of the model.