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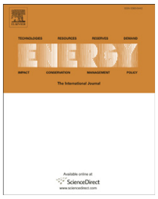

Optical performance of a solar dish concentrator/receiver system: Influence of geometrical and surface properties of cavity receiver

Sha Li [a], Guoqiang Xu [a], Xiang Luo [a, *], Yongkai Quan [a], Yunting Ge [b, **]

[a] National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, School of Energy & Power Engineering, Beihang University, Beijing 100191, China
[b] College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge, UB8 3PH, UK

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ABSTRACT

The optical performance of a solar dish concentrator/cavity receiver system based on the Monte Carlo Ray Tracing Method (MCRTM) was carried out under ideal optics. The study was precipitated by a need to analyze the influence of geometrical parameters and surface properties of a cavity receiver systematically and to understand the mechanism of the optical performance under various parameters. These include diameter ratio (the ratio of aperture diameter to absorber outer diameter), height ratio (the ratio of absorber height to absorber outer diameter) and sidewall absorptivity of cavity receiver. In addition, an optical efficiency of the absorber is defined and presented for the first time. The analysis indicates that the optical efficiency increases and then decreases with higher height ratio, while optical efficiency curves are reduced monotonically with diameter ratio. Simultaneously, the effects of the height and diameter ratios on optical efficiency are both influenced by sidewall absorptivity. Based on the results, a correlation of optical efficiency was further developed to quantify the influences of these factors. The maximum optical efficiency and its corresponding optimal height ratio from both simulation and correlation are presented and obtain reasonable agreement. The optimized selection of height ratio along with diameter ratio are suggested using this result. The height ratio is found to be a pure controlling parameter of the radiation flux distribution.

1. Introduction

Clean, environmentally-friendly solutions to the world's energy and pollution problems are urgently needed. The utilization of solar energy has attracted increasing interest from investigators worldwide [1–6]. Solar thermal power generation, in particular, is an important technology that utilizes solar energy extensively [7–10], and can be classified into three types based on concentrator type—dish, trough and tower systems. Of these three applicable structures, the dish/Stirling system has been paid the most attention in the field of solar thermal power generation owing to its merits of higher system efficiency and concentration ratio [11–13].

In a dish/Stirling system, the receiver is a crucial component that absorbs highly concentrated solar energy reflected from the concentrator and then transfers it to the working fluid within the Stirling engine. This involves the coupling of both optical and thermal effects. As the first step of solar thermal conversion, the optical performance can directly affect the efficiency of solar thermal conversion thereby the whole generation system. There is great potential for optical performance improvement via structural optimization in these systems [14–18].

Optical analysis of receivers can be divided into two main approaches. Firstly empirical formulas are utilized to approximate the optical efficiency of the receiver [19–28]. Though this method is computationally simple, it does not accurately resolve the true geometry of the receiver design. The alternative way is to accurately model the receiver geometry using the Monte Carlo Ray Tracing Method (MCRTM) [29–39] to obtain optical efficiency and radiation flux distribution. Compared to the empirical method, the MCRTM is more reliable and accurate and can offer more optical information [25]. Studies on optical analysis by the MCRTM can be further divided into three categories according to the different investigation points for the concentrator/cavity receiver system. These include the influence of the concentrator on radiation flux

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* Corresponding author.
** Corresponding author.
E-mail addresses: xiang.luo@buaa.edu.cn (X. Luo), yunting.ge@brunel.ac.uk (Y. Ge).

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Nomenclature

d_a	aperture diameter of the receiver, m
d_r	receiver diameter, m
D	outer diameter of absorber, m
D_c	opening diameter of concentrator, m
E_{ray}	radiation energy of each ray, W
f	focal length of concentrator, m
h	height of absorber to aperture, m
m	total number of the receiver inner surfaces
n	counter of the emitted ray
N	total number of the emitted ray
Q	solar radiation energy, W
Q_{total}	total solar energy emitted on the concentrator, W
$Q_{absorber}$	solar radiation energy received by the absorber, W
Q_i	radiation energy received by the i-th inner surface of the receiver
R_c	random number generated when ray falls on the concentrator
R_d	diameter ratio of receiver
R_h	height ratio of receiver
R_{hcr}	critical value of height ratio
R_{hmin}	minimum value of height ratio
R_{hopt}	optimal height ratio
R_{ri}	random number generated when ray falls on the i-th inner surface of the receiver
S_i	total number of ray captured by the i-th inner surface of the receiver

Greek symbols

α	sidewall absorptivity of receiver
α_r	receiver surface absorptivity
α_{ri}	absorptivity of the i-th inner surface of the receiver
$\eta_{optical}$	optical efficiency, %
ρ_c	reflectivity of concentrator
φ_{max}	maximum rim angle of concentrator, °

Subscripts

1ref	first reflection
c	concentrator
cr	critical point
dir	direct incidence
hopt	optimum value
max	maximum
min	minimum
nref	multiple reflection
ref	reflection
ri	the i-th internal surface of the receiver

Abbreviations

DNI	direct normal insolation, W/m^2
MCRTM	Monte Carlo Ray Tracing Method

distribution or optical efficiency [29–32], the effect of the receiver on optical performance [33–36], and the impacts of both the concentrator and the receiver on optical performance of the system [37–39]. Riveros-Rosaset al. [29] took several optical configurations of the concentrator into account, and the best arrangement was determined by comparing the optical results in terms of maximum peak concentration and cost effectiveness and other considerations. León et al. [30] designed a set of compound Fresnel Lens based on an integrated multi-objective optimization process in order to achieve 1000 °C on the receptor area with concentrated solar energy. Abbas et al. [31] presented an approach to analyze and optimize the performance of Fresnel arrays including circular-cylindrical and parabolic-cylindrical mirrors with different reference positions, and a new mirror layout was determined to keep a constant radiation on the receiver. Qiu. et al. [32] investigated the effects of slope error, time and location on the optical performance of a linear Fresnel solar reflector using molten salt as part of their study. Shuai et al. [33] investigated the radiation flux distribution of cavity receiver considering six classical cavity geometries in comparison. Based on the results obtained and the concept of equivalent flux, a new geometry of upside-down pear cavity was proposed which showed a better spatial uniformity than earlier cavities. Similarly, Xie et al. [34] compared the optical efficiency and concentration ratio results under three different cavity receivers, and the optimal structural design was determined after detailed thermal analysis. Asselineauet al. [35] integrated the MCRTM with stochastic optimization and applied this strategy to optimize the geometrical configuration of a concentrated receiver with maximum efficiency. Wang et al. [36] conducted an optical analysis on two different cylindrical cavity receivers with bottom surface convex for the purpose of solving the dead space problem and improving the optical efficiency of the receiver. The influencing factors of the cavity receiver considered included the height of the surface convex, the cavity wall absorptivity as well as the pointing and alignment errors, and the conclusion went to that the BSIC receiver can satisfy the purpose. Li et al. [37] analyzed the radiation flux profiles on the receiver surface under different comparisons such as faceted real concentrator and ideal parabolic concentrator, real sun and simulated light source, varied aperture positions and receiver shapes. Subsequently the flux profiles were adopted as boundary conditions for further thermal analysis to obtain the temperature distribution results. Mao et al. [38] simulated the radiation flux distribution of receiver considering the impacts of incident solar irradiation, aspect ratio and system error. Chen et al. [39] conducted an optical performance on the impacts of structure parameters and alignment error of receiver and slope error of concentrator for a porous media receiver.

There is a lack in the existing literature of a systematic investigation on optical performance of a solar dish/cavity receiver system using MCRTM. Some studied and compared the optical performance of different receiver types, making it vague which geometrical or optical factor most affected the optical efficiency. Even on a fixed receiver type, only limited influential parameters were analyzed. In addition, most of the studies described the results superficially, while a quantitative analysis of how the geometric parameters affected the optical performance was limited. In the present study, we quantitatively characterize the height ratio (R_h), diameter ratio (R_d) and sidewall absorptivity (α) of a receiver to cover both geometrical and surface properties. An understanding of the effect of these parameters will provide insight into how to improve the optical performance of a system and provide a reference analysis for optimization of other geometries. The objectives of this study are: (i) to analyze the influence of geometric and optical factors of a cavity receiver on the optical performance of the concentrator/cavity receiver system, (ii) to understand how these factors affect optical efficiency and radiation flux profile of the absorber, and (iii) to develop a function which enables the prediction of optical efficiency with these parameters.